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Life Cycle Assessment of a Single-Family Residence built to Passive House Standard

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MASTER THESIS

for

Stud.techn. Oddbjørn Dahlstrøm
Spring 2011

Life-cycle assessment of a single-family residence built to passive house standard

Livssyklusanalyse av en enebolig bygd etter passivhusstandard

Background and objective.

Significant reductions in operational energy use of residential buildings for heating, hot water provision and air conditioning is possible with new technologies, including well-insulated and air-tight building shells. Such buildings require different building materials and construction techniques. Reduced energy consumption during the use phase of the building is exchanged for increased material input and cost during the construction phase. Past literature studies indicate that the trade-off usually is beneficial at least with respect to life-cycle energy use and greenhouse gas emissions, but the benefit of increased insulation and reduced air leakage diminishes with increasing specifications.

The objective of this study is to assess the environmental costs and benefits of moving to a passive house compared to today's standard, TEK07/TEK10, using the case of a single-family residence designed by Nordbohus for a location in Stord, Western Norway. The answer should be provided through a life-cycle assessment of the complete building shell of the two design alternatives of the house.

The following questions should be considered in the project work:

1. What are the components of the two buildings shells?
2. What are the life-cycle inventories of the various components?
3. What is the life-cycle inventory of building construction and maintenance?
4. How do the combined LCIs compare assuming the same heating system? Norwegian, Nordic and EU electricity mixes should be considered.
5. Provide an analysis of the impacts – what are the elements, activities and stressors that contribute significantly to the results?
6. Provide a discussion or analysis of how the implementation of different ventilation and heating systems will affect the environmental performance of the two building designs.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his 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 analyzed 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.

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.

One – 1 complete original of the thesis shall be submitted to the authority that handed out the set subject. (A short summary including the author's name and the title of the thesis should also be submitted, for use as reference in journals (max. 1 page with double spacing)).
Two – 2 – copies of the thesis shall be submitted to the Department. Upon request, additional copies shall be submitted directly to research advisors/companies. A CD-ROM (Word format or corresponding) containing the thesis, and including the short summary, must also be submitted to the Department of Energy and Process Engineering

Department of Energy and Process Engineering, 17. January 2011

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"What's the use of a fine house if you haven't got a tolerable planet to put it on?"

Henry David Thoreau, 1817-1862

Preface

This report represents my Master Thesis, conducted the last semester in the MSc Industrial Ecology Programme, class of 2011. This thesis is written at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology, NTNU, in Trondheim, Norway, the spring 2011.

The objective of this thesis was to assess the environmental costs and benefits of moving to a passive house from today's building standard TEK07. One TEK07 and one passive house model of the same wooden framework house design were analyzed, in cooperation with the building company Nordbohus AS. The environmental costs and benefits for both houses were analyzed in a cradle to grave life cycle assessment. The thesis has been quite challenging since the gathering of complete material needs, construction energy consumption, transportation distances and waste treatment procedures for two complete houses was time consuming and to a certain extent, detailed. It has been really interesting to analyzing a Norwegian passive house with respect to environmental impacts, and the learning outcome from the building industry has been great. In the end, I'm very satisfied with the assessment and the overall results.

I would like to thank everybody who has provided relevant data and support for this project. Several producers of building products were very helpful in providing data.

I would also like to thank all my fellow students at the Industrial Ecology Program for your inspiration, and for being such a good and social group during these two years at NTNU.

A special thanks go to my supervisor, Prof. Edgar Hertwich and co supervisor Rolf André Bohne, Silje Eriksen from Nordbohus AS, Kjersti Foldvik from SINTEF Byggforsk and Kari Sørnes, for great guidance and good cooperation since the fall of 2010.

Last but not least I would like to thank Kendra Sandstrand for her patience, support and proof reading during the semester. It was always good to know you were waiting for me at home after some long days at Gløshaugen.

Oddbjørn Dahlstrøm

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Trondheim, Norway
June 14th 2011

Abstract

Two complete *cradle to grave* life cycle assessments are conducted for the comparison of a house built after today's building standard, TEK07, and a passive house built after the Norwegian Standard NS 3700:2010. Both houses are projected by the building company Nordbohus AS, and are to be constructed in Stord, on the west coast of Norway. The usable floor area, BRA, is 187 m^2 for both houses, and a lifetime of 50 years is assumed. The houses are constructed with a wooden framework, insulated with mineral wool in the walls and roof, and have a ground lever floor of reinforced concrete on a layer of expanded polystyrene. The passive house has, compared to the TEK07 house a different foundation, 15 cm more mineral wool in the outer walls, 5 cm more in the roof, and better insulated windows and doors. In addition, the thermal conductivity for the outer wall insulation is reduced for the passive house.

The house life cycle is divided into several phases. Construction of the house, waste treatment of materials connected to the construction, surface finish and maintenance of the house during the lifetime, water and electrical energy consumption during the house operation and finally demolition and waste treatment of the materials after the end of the house lifetime. Transportation of workers and materials to the construction site, as well as to waste treatment plant, are included.

Generic data from Ecoinvent 2.0 database is used, but some processes are modified to satisfy Norwegian production information. The Nordel electricity mix is used for Norwegian production and house electricity consumption. SimaPro 7.1.8 is used to process the data, and the ReCiPe method, hierarchist midpoint version 1.03 is used for the impact assessment. It is assumed that both houses have the same heating system, and cover 100% of the energy needs from electrical energy.

For the 50 year life cycle, the passive house has 20% less impacts to climate change than the TEK07 house. For the other categories assessed, the passive house has between 10-20% lower impacts than the TEK07 house. The only exception is impacts to freshwater ecotoxicity, where the passive house impacts are increased with 7% from the TEK07 house. The TEK07 house has impacts to climate change with 1,6 tons CO_2 eq/m^2 useful floor, while the passive house 1,3 tons CO_2 eq/m^2 useful floor. Cumulative energy demand is 55 GJ/m^2 and 42 GJ/m^2 respectively. The construction phase is responsible for 13%, waste treatment of materials connected to construction 1%, surface finish and maintenance 6% and end of life waste treatment 4% of overall climate change impacts for the TEK07 house. Water and electricity consumption during the operation are thus responsible of 76% of the TEK07 life cycle climate change impacts. For the passive house, this is 19%, 1%, 7%, 6% and 67% respectively.

Main activities contributing to the overall impacts are transportation of materials, workers and waste to and from the construction site, diesel combusted in building machines, production and incineration of EPS/XPS and paint, waste treatment of wood ash, and production of cement and ceramic tiles.

A sensitivity analysis of energy consumed by the construction dryer, frequency of house maintenance, a change of house consumption electricity mix to the Norwegian and UCTE electricity mix, and a change to different heating systems for both houses is carried out.

The overall conclusion is that it is environmentally beneficial to build, operate and waste treat a passive house compared to a house following the TEK07 building standard.

Sammendrag

To komplette *vugge til grav* livssyklusanalyser er utført for å sammenlikne et hus bygget etter dagens TEK07 standard mot et hus bygget etter den norske passivhusstandarden NS 3700:2010. Begge husene er prosjektert av Nordbohus AS, og skal bygges på øya Stord på vestlandet i Norge. Bruksarealet for hvert hus er 187 m^2 BRA, med en levetid på 50 år. Husene har et reisverk i tre, er isolert med mineralull i vegger og tak, og har et armert betonggulv på grunn isolert med ekspandert polestyren. Passivhuset har, sammenliknet med TEK07 huset, en annerledes type ringmur, et 15 cm tykkere lag med mineralull i ytterveggene, 5 cm økning i taket og bedre isolerte vinduer og dører. Den termiske konduktiviteten er i tillegg redusert på isolasjonen brukt i ytterveggen i passivhuset.

Huser er delt inn i flere livssyklus faser. Konstruksjon av huset, avfallsbehandling av bygningsavfallet som oppstår under konstruksjonen, overflatebehandling og vedlikehold av huset under brukstiden, forbruk av elektrisitet og vann under brukstiden, og tilslutt riving og avfallsbehandling av materialene etter husets levetid. Transport av arbeidere og materialer til byggeplassen samt av materialer til avfallsanlegg er inkludert

Generisk data fra *Ecoinvent* 2.0 er brukt i analysen. Noen prosesser er modifisert til å tilfredsstille norske produksjonsforhold. Strømbruk i Norge, både for forbruk og for materialer produsert i Norge, er basert på *Nordel* strømmiks. *Simapro* 7.1.8 er brukt til å behandle all data, og *ReCiPe*, hierarkistisk midtpunkt versjon 1.03 er brukt for konsekvensanalysen. Det er antatt at begge hus har samme oppvarmingssystem og at 100 % av alt energibehov er dekket av elektrisk energi.

Passivhuset har 20 % lavere påvirkning til klimaforandring enn TEK07 huset, for hele levetiden på 50 år. For påvirkning til andre utslippskategorier har passivhuset 10-20 % lavere påvirkning. Det eneste unntaket er for påvirkning til ferskvanns øko-toksisitet kategorien, hvor passivhuset har 7% høyere påvirkning enn TEK07 huset. Påvirkning til klimaforandring er for TEK07 huset 1,6 tonn CO_2 eq/m^2 BRA mens for passivhuset 1,3 tonn CO_2 eq/m^2 BRA. For akkumulert energi har TEK07 huset 55GJ/m^2 BRA og passivhuset 45GJ/m^2 BRA. For totale påvirkninger til klimaforandring for TEK07 huset er 13% fra huskonstruksjonen, 1% fra avfallsbehandling av konstruksjonsavfall, 6% fra overflatebehandling og vedlikehold, og 4% fra anfallsbehandling av byggavfall etter at huset er revet. Vann og elektrisitetsforbruk har 76 % av påvirkningen til klimaforandring for TEK07 huset. For passivhuset, disse andelene er henholdsvis 19%, 1%, 7%, 6% og 67%.

Aktiviteter som bidrar mest til klimaforandring kategorien er transport av materialer, arbeidere og avfall til og fra byggeplassen, forbrenning av diesel i gravemaskin og kran, produksjon og avfallsforbrenning av EPS/XPS og maling, avfallsbehandling av aske fra treforbrenning og produksjon av sement og keramiske fliser.

Det er også gjennomført en sensitivitetsanalyse av energiforbruket for byggtørker, hyppighet av husvedlikehold, forandre forbruksstrømmiksen fra *Nordel* til *Norwegian* og *UCTE* strømmiks, og konsekvensene ved implementering av forskjellige typer oppvarmingssystem for begge hus.

Hovedkonklusjonen fra denne analysen er at det er miljøvennlig å bygge, drifte og avfallsbehandle et passivhus sammenliknet med et hus bygget etter TEK07 standard.

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1 Introduction

"The buildings we live and work in account for 40% of the Norwegian energy consumption and 40% of the Norwegian material use. Globally, buildings have a share of 30% of world energy consumption and are accounting for 21% of world climate gas emissions" (SFFE, 2011).

Mainly, all houses built before 1940 were built without insulation. In an effort to reduce the draft in these houses, old rags, used shoes, sawdust, wood chips, paper and newsprint could be used as insulation. From the 1960s, natural wool was used as insulation. A thickness of 75-100mm wool in the walls and 60-75mm wool in the roof was normal the first years. In the building regulations from 1987, TEK87, 150mm mineral wool was required in walls and 200 mm in the roof. The insulation thickness requirements increased in TEK97, and were 200 mm for the walls and 300mm for the roof. (Falldalen, 2008)

There has been a fast development of more energy efficient buildings since 1997, both for office buildings and residential homes. From July 1st 2010, all offices and residential homes in Norway must be energy labeled in order to create more consciousness concerning the energy consumption in the building sector. This scale is ranged from A to G, where a building built after minimal requirements of TEK07, normally gets classified as C. (NVE, 2010). To get classified as B, the concept "*low energy building"* is used, and for classification A the *"passive house*" is used. (Dokka and Hermstad, 2006).

In order to reduce building energy consumption and to be classified with energy label A or B, there is a need for a more energy efficient building envelope that reduces the building heat losses considerably. Some major building elements are highly insulated building walls, floors and roofs. The building must also be sufficiently air tight in order to reduce unwanted air leakages. A balanced heat recovery ventilation system with an efficiency rate of over 80 %, and advanced window and door technology with U values of or below 0,8 W/m^2K are also needed to reduce the overall energy needs.

A passive house has increased material inputs compared to the TEK07 house, to reduce the building heat loss and energy requirements during the house operation phase. There is a concern, from an industrial ecology perspective, when including the increased material requirements and energy use for the material production, transportation and waste handling, makes the passive houses as environmentally beneficial as they are stated to be.

It is therefore important to consider environmental impacts occurring in the whole life-cycle of the two buildings, from raw material extraction to waste treatment, to get a good basis for environmental decisions. Life cycle assessment (LCA) is a tool used for these calculations. When comparing a life cycle assessment of the TEK07 house and the passive house, the numbers of years before the environmental costs and benefits for the passive house equals the TEK07 house standard can be calculated.

The building company Nordbohus AS has projected a TEK07 model and a passive house model using the same house design, the Stord house.

1.1 The TEK07 house standard

A construction built after the TEK07 standard, is a building that meets the minimum requirements in the building code regulations from 2007. This building code defines several factors for a constriction, among others, the U value of walls, floors, roof, and windows. All new construction built after August 1st 2009 must follow these requirements. Maximum annual energy need is 125 kWh/m^2 + 1600/BRA. Minimum 40% of the net energy requirements for space heating and warm water must be from other sources than electrical and fossil energy. (TEK, 2007)

A new building code, TEK10, came into force from July 1st 2010. It is in the period from July 1st 2010 to July 1st 2011 optional to follow the TEK07 or TEK10 building regulations. The main difference from the TEK07 code is requirements of O&M documentation and a treatment plan for waste during construction and demolition. The heat exchanger efficiency requirement is increased from 70% to 80% and installation of a fuel oil boiler is banned. Technical requirements such as U values are the same in TEK07 and TEK10.

The Stord TEK07 house will satisfy the TEK10 regulations.

1.2 The passive house standard

The definition of 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."* (Feist, 2007). This concept was developed in Germany May 1988 by Bo Adamson and Wolfgang Feist, and has since then been widely and successfully used in Germany and Austria. Some basic principles are shown in figure 1-1.The main criterion is that the annual energy used for space heating should not exceed 15 kWh/m^2.

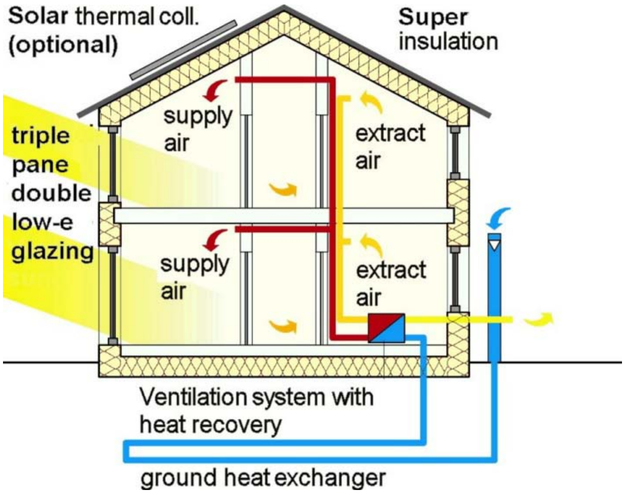


Figure 1-1: Basic principles of a passive house (Passivhaus, 2011)

Since the Norwegian construction policy and climate differs from the German, a Norwegian definition of passive and low energy residential buildings was published April 2010, NS 3700:2010. National adjustments from the original definition are given in this standard. The annual energy used for space heating is dependent on the useful floor area (up to 250 m^2) and the local annual mean temperature. 50% of the energy required for warm water heating must be provided by alternative, non fossil or electric energy sources. (NS, 3700:2010). 3 types of energy efficient buildings are mentioned in the standard: low energy house class 2, low energy house class 1 and passive house.

1.3 The objective and scope for this thesis

The objective of this study is to assess the environmental costs and benefits of building a passive house compared to today’s standard, TEK07.

It was found during the data collection, that the area with high uncertainty when it comes to the construction phase inventory was the electrical consumption for the building drying process. There is lack of data available for this consumption since this electricity is addressed the owner of the building and not the construction company. (Eriksen, 2011) In addition, there is an increased concern of moist, and mold growth, in walls in highly insulated buildings, if the building materials are not dried correctly during the construction.

It is beyond the scope for this thesis to go in depth in this issue, but some general moist theory and heat energy calculations are presented to give a brief overview as this is a topic related to the passive house construction dryer energy demand.

2 Reviews

There are many previous reports that have analyzed the embodied energy in house construction materials and life cycle energy of buildings. Ramesh et al. (2010) has conducted a review, *Life cycle energy analysis of buildings: An overview,* where primary energy from 73 cases from thirteen countries are assessed. Sartori and Hestnes (2007) have in their literature survey, *Energy use in the life cycle of conventional and low-energy buildings: A review article*, assessed 60 cases from nine countries. In the mentioned reviews, 39 cases from both studies are the same case.

Several factors differs in the assessed reports, such as building materials, construction country, thermal properties of the building, total lifetime, included service and maintenance during construction and the type of energy used for operational heating. "For this reason, it would be inappropriate to directly compare the cases against each other" (Sartori and Hestnes, 2007).

Both residential and office buildings are included in the review of Ramesh et al. (2010). In general, 80-90% of life cycle energy is from the operating phase, and 10-20% is embodied in materials. The life cycle energy category includes embodied energy from raw material mining, building material production, transportation to construction site, building shell construction and renovation, operation energy (heating, hot water, appliances and lightning), building demolition, transport to a waste treatment plant and energy consumed at the landfill site or at the recycling plant. (Ramesh et al., 2010)

19 of these 73 cases are analyzing wood houses in Norway and Sweden, table 2-1. The results from the review are scaled up to meet the same cumulative energy unit as in this thesis, GJ per m^2 useful floor area for 50 years of operation. The case numbers are the numbers used in the review. (Ramesh et al., 2010)

Table 2-1: Embodied energy from houses constructed in Norway and Sweden, (Ramesh et al., 2010)

Nr	*Country*	*Size [m^2]*	*Embodied [GJ/m^2]*	*Operating [GJ/m^2]*	*Lice cycle [GJ/m^2]*	*Reference*
25	Norway	110	4,5	12	16	[4]
22	Norway	110	2,3	21	24	[4]
23	Norway	110	2,2	24	26	[4]
38	Sweden	120	7,0	22	26	[5]
21	Norway	110	2,5	27	30	[4]
24	Norway	110	1,6	30	32	[4]
16	Sweden	138	4,1	44	48	[2]
14	Sweden	130	5,0	47	52	[2]
8	Sweden	1190	5,9	49	53	[1]
15	Sweden	129	4,9	49	54	[2]
6	Sweden	1190	5,9	53	57	[1]
5	Sweden	1190	6,1	54	58	[1]
3	Sweden	1190	5,9	57	60	[1]
2	Sweden	1190	5,9	58	62	[1]
4	Sweden	1190	5,9	58	62	[1]
7	Sweden	1190	5,9	58	62	[1]
11	Sweden	1190	5,9	58	62	[1]
1	Sweden	1190	5,8	59	63	[1]
19	Sweden	1190	6,3	58	64	[3]
Average		**682**	**4,9**	**44**	**48**	

[1] - (Adalberth, 1999), [2] - (Adalberth, 1997), [3] - (Adalberth et al., 2001), [4] - (Winther and Hestnes, 1999), [5] - (Thormark, 2002)

The average embodied energy in materials is 4,9 GJ/m^2, building operation 44 GJ/m^2 and a total life cycle embodied energy of 48 GJ/m^2.

A research by Brunklaus et al. (2010), *Illustrating limitations of energy studies of buildings with LCA and actor analysis*, draws this conclusion when comparing a conventional house against a passive house in Sweden:

> Care is needed when drawing environmental conclusions from energy studies. Although passive houses have a low energy use; the environmental impacts are not automatically lower. Additionally, the life cycle is changeable. All actors in the life cycle, such as the building constructor, municipalities, material producer, and residents, can improve a building's environmental burden. […] Conventional houses can be equally good environmentally in terms of global warming, acidification, or radioactive waste as typical passive houses with electrical heating depending on the actors' choices. (Brunklaus et al., 2010)

This research compares three passive houses and four conventional houses using LCA. The Nordel electricity mix is used for heating energy. One scenario, *the green choice*, uses a 95% hydropower and 5% wind power electricity mix. One assessed passive house type, Lindås, has wood as a main construction material. This house has an energy need of 68 kWh/m^2 floor. The house has a lifetime of 50 years.

Life cycle climate change impacts from the Lindås passive house is 870 kg CO_2 eq /m^2 considering the Nordel electricity mix and 200 kg CO_2 eq/m^2 in the green choice scenario. For the terrestrial acidification potential, the life cycle impacts are 4 kg SO_2 eq/m^2 and 1,5 kg SO_2 eq/m^2 respectively. Material production has a share of 20% of total climate change impacts, and 35% for the terrestrial acidification potential.

In a study from Norman et al. (2006), the energy use and climate change impacts are estimated from an economic input-output life cycle assessment. A low- and high density case study in the city of Toronto in Canada is analyzed. For a lifetime of 50 years, impacts to climate change from construction materials are 370 kg CO_2 eq/m^2 for the low density study, and 455 kg CO_2 eq/m^2 for the high density study. The total climate change impacts are 2,0 tons CO_2 eq/m^2 and 2,2 tons CO_2 eq/m^2 respectively.

Sørnes, K. (2010) conducted a *life-cycle assessment of a single family residence conforming to the new standard TEK 07* as a Master Project fall 2010, MSc Energy and Environment, NTNU Trondheim. This is a cradle to gate study of the Stord TEK07 house. From this study, the overall primary energy use is 2,08 GJ/m^2 and 111,6 kg CO_2 eq.

In general, there are many reports available that analyze embodied life cycle energy. Complete life cycle analyses concerning climate change impacts are also available, but the results differ from each study according to the system boundaries and construction materials. Other impact categories than climate change are less, if at all, emphasized.

3 Methodology

All the calculations for this thesis are done in the LCA software program Simapro (Pre, 2008), and the data is further treated in MS Excel.

3.1 Life Cycle Assessment methodology

"The objective of a Life Cycle Assessment is generally to perform consistent comparisons of technological systems with respect to their environmental impacts" (Strømman, 2010).

The Life Cycle Assessment (LCA) framework is defined by the International Organization for Standardization (ISO) in the 14040 standard (14040:2006). LCA addresses the environmental aspects and potential environmental impacts throughout a product or a systems life cycle. The entire life cycle of the defined product or system is studied and consists of several phases: production (raw material extraction and acquisition, through energy and material production and manufacturing), use, end of life treatment and final disposal. (ISO, 14040:2006)

A LCA can be divided into four parts, as shown in figure 3-1: goal and scope definition, inventory analysis (LCI), impact assessment (LCIA) and interpretation.

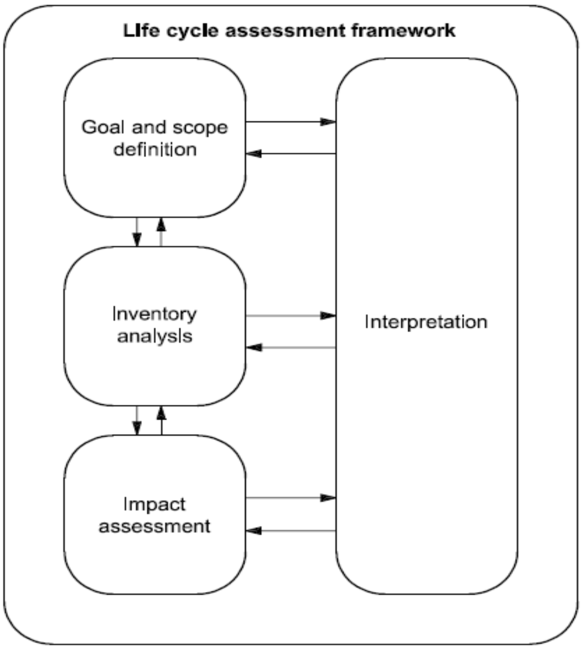


Figure 3-1: Stages of an LCA

By including all life stages of a product or system in the analysis, there is a smaller chance to make environmental decisions based on the wrong foundation. LCA does normally not address economical or social aspects. (Bauman and Tillman, 2004)

3.1.1 Goal and scope definition

This phase defines the study. The goal describes the reason for doing an analysis and who the intended users of the results are. The scope describes and defines the product or system being analyzed, the functional unit and system boundaries.

To outline a product or systems life cycle, a functional unit of the analyzed product or system must be defined. This is a quantitative measure and reflects the goal of the study. Inputs and outputs in the system are related to this functional unit. A functional unit can for example be "1 km driven of a petrol car" or "1 MJ of electricity produced from an offshore wind power plant, delivered to end user". A functional unit is necessary to ensure comparability of LCA results, especially when assessing different systems. It ensures comparisons are made on a common basis.

A system boundary must be defined. Several unit processes and flows should be taken into account, which should fulfill the functional unit. Some of the included processes and flows are as follows: (ISO, 14040:2006)

- Inputs and outputs of raw material acquisition
- Materials and energy required for production and construction of defined product/system
- Materials and energy required for operation and maintenance during the use phase
- Waste amounts and impacts from end of life treatment of the product or system

3.1.2 Life Cycle Inventory

The life cycle inventory analysis (LCI), involves all the data collection, for the system described under the goal and scope definition in 3.1. Calculation procedures are made to quantify relevant inputs and outputs in the defined life cycle system. (ISO, 14040:2006)

Data for each process within the system boundary can be classified under major headings, including: (ISO, 14040:2006)

- Energy inputs, raw material inputs, ancillary inputs and other physical inputs
- Products, co products and waste
- Emissions to air, discharges to water and soil
- Other environmental aspects

It can sometimes be time consuming and difficult to conduct the data collection for each process within the defined system. Issues may be identified during this process that requires a redefinition of the previous defined goal and scope.

After gathering data for all selected processes in the system, the so called foreground system (a production recipe of the analyzed product), the data can be connected to a background inventory database. For example, the needed electricity for drying the framework during the construction is 6000 kWh. This is calculated from actual time used and the dryers' power consumption. However, it is not easy to get a hold of the inputs, outputs and emissions taking place at the power plant that produces the 6000 kWh. Off course, it is possible to include the power plant in the system boundaries, and thus investigate different power plants. But this would be extremely complicated and difficult if all included processes must be analyzed this way. There are several background databases where this detailed inventory data is available. The most used database, Ecoinvent 2.0 (2007), includes over 4000 datasets, and "contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services" (Ecoinvent, 2007). By connecting the required energy demand to this database, emissions for producing the needed electricity can be found. The data collected from a background database is called "generic data".

When analyzing a system, the studied processes would often consist of several inputs and outputs flows. In order to share the fair amount of impacts when considering multiple inputs and outputs, some allocations procedures must be defined (ISO, 14040:2006). In for example a cogeneration plant of heat and power (CHP), allocation must be done to split the share of impacts to one produced kWh of heat and one produced kWh of electricity.

3.1.3 Life Cycle Impact Assessment

The inventory analysis is complete when all the necessary data is gathered. An inventory analysis consists of a long list of data and must be associated with specific environmental impact categories. This step is the life cycle impact assessment and it consists of 3 mandatory elements: Selection of impact categories, classification, and characterization. (ISO, 14040:2006)

The impact categories can be determined in two levels: midpoint and endpoint. The midpoint level consists of several impact categories that are based on environmental mechanisms which relatively easy can be measured in a laboratory. The endpoint categories are fewer, but are not that easily measured as the midpoint levels. Take the climate change (global warming) effect as an example. Several gases contribute to this effect (CO_2, CH_4, N_2O etc) by absorbing infrared radiation in the atmosphere. Some of this increased absorption of energy is re-radiated back to earth. Less energy, measured as heat, radiates to outer space and thus increases the earth temperature. All gases and emissions that contribute to this effect are aggregated (characterized) into the climate change midpoint impact category. The climate change effect can, as the next step, disturb human health and natural ecosystems which again can cause change of biodiversity and species loss. This effect can be measured in *damage to human health* endpoint impact category, measured in DALY (disability-adjusted life years). To calculate how human health is reacting on climate change “depends on a number of subjective assumptions […] and should be used with care” (RIVM et al., 2009 - p. 14). By normalizing, weighting and grouping the endpoint results, it is possible to aggregate the endpoint damages into a single score value.

Midpoint impact categories are in the range of 10-18 different categories, while endpoint categories are three: damage to human health, damage to ecosystems and damage to resource availability. Midpoint categories are problem orientated and based on a scientific background but can sometimes be difficult to interpret, while endpoint categories are damage orientated and easier to interpret but have higher uncertainty. (RIVM et al., 2009)

3.1.3.1 Midpoint Impact categories

The chosen impact assessment method, ReCiPe midpoint method, hierarchist version (RIVM et al., 2009) includes 18 midpoint impact categories. This method has 3 perspectives: individualist, hierarchist and egalitarian. Each perspective has its own assumptions and the differences are:

Individualist: This perspective is based on a short time interest (20 years for climate change and terrestrial acidification), technological optimism and substances that have a complete proof regarding their effect are included.

Hierarchist: based on the most common policy principles regarding time frame (100 years for climate change and terrestrial acidification). Substances may be included, if there are a consensus regarding their effect. This is often considered as the default model. (RIVM et al., 2009).

Egalitarian: is the most precautionary principle, with an extremely long time frame (500 years for climate change and terrestrial acidification). It there is an indication regarding the effect of substances, they are included.

The hierarchist perspective is chosen for this report.

To select impact categories one should reflect upon the goal and scope for the study and cover all environmental problems of relevance. The study should not contain too many categories, as it would lower the practicality of the results. (Bauman and Tillman, 2004, p 136). The following impact categories in table 3-1 are used in this study. All impact categories are by the ReCiPe method version (RIVM et al., 2009) except the cumulative energy demand (CED). CED is a method published by Ecoinvent version 2.0 and expanded by PRé Consultants (Frischknecht R., 2003).

Table 3-1: Impact categories included in this study

Impact category		*Unit*	*Description*
CC	**Climate change**	kg CO_2 eq	To air, global. Emissions who contributes to the greenhouse effect by increased infra-red radiative forcing in the atmosphere.
HT	**Human toxicity**	kg 1,4-DB eq	To urban air, site-sensitive. Effect of toxic substances to human environment. Air emissions of heavy metals are specifically large contributors
POF	**Photochemical oxidant formation**	kg NMVOC	To air, site-sensitive. Formation of ground-level ozone, indicated as “summer smog”. “Ozone is a health hazard to humans because it can inflame airways and damage lungs” (Goedkoop et al., 2009).
PMF	**Particulate matter formation**	kg PM_{10} eq	To air, regional air quality. Particles in the air generated by mainly combustion of fossil fuels. Causes health problems for airways and lungs.
TA	**Terrestrial acidification**	kg SO_2 eq	To air, site-sensitive. Inorganic gases (sulfates, nitrates and phosphates) may dissolve in water and change acidity in, e.g., soil and groundwater. Acid rain.
FE	**Freshwater eutrophication**	kg P eq	Both to freshwater, site-sensitive. Nutrient-rich compounds released into water bodies. Can cause algal bloom which may lead to an adverse ecological effect.
ME	**Marine eutrophication**	Kg N eq	
TET	**Terrestrial ecotoxicity**	kg 1,4-DB eq	To industrial soil, site-sensitive. Risks of damage to ecosystems on land by emissions of toxic substances.
FET	**Freshwater ecotoxicity**	kg 1,4-DB eq	To freshwater, site-sensitive. Risks of damage to freshwater bodies, as a result of emissions of toxic substances to air, water and soil.
MET	**Marine ecotoxicity**	Kg 1,4-DB eq	To marine water, site-sensitive. Risks of damage to marine ecosystems by emissions of toxic substances.
MD	**Metal depletion**	kg Fe eq	The depletion of metals and minerals can be described as the decrease of available reserve of minerals due to extraction and use.
CED	**Cumulative energy demand**	GJ eq	Accumulated total primary energy required, fossil and renewable.

Table 3-2 includes all impact categories not included in this study and the justification of why not included.

Table 3-2: Impact categories not included in this study

Impact category		*Unit*	*Description*
OD	**Ozone depletion**	Kg CFC-11 eq	To air, global. Stratospheric ozone concentration. Consumption of OD substances (Montreal Protocol) is reduced to zero since 2010 in the EU. (DG-CLIMA, 2011). Not included because of less relevance.
IR	**Ionizing radiation**	Kg U^{235} eq	To air, global. Releases of radioactive material to the environment. Main source is fuel for nuclear power plant (Appendix A), hence not included since dependent on chosen electricity mix.
ALO	**Agricultural land occupation**	m^2yr	Occupation of agricultural and urban land in a given time and region. Transformation of natural land in a region. Not included due to uncertainty for local (Norwegian) conditions. Land use is not quantified in the LCA data for wood products, the MIKADO project (Wærp et al., 2009).
ULO	**Urban land occupation**	m^2 yr	
NLT	**Natural land transformation**	m^2	
WD	**Water depletion**	m^3 water	Regional. The aggregated amount of water needed to fulfill the functional unit. 98% of water use is from use phase (Appendix B), thus not included as a category. .
FD	**Fossil fuel depletion**	Kg oil eq	Crude oil feedstock, global. It includes only non renewable energy. Cumulative energy demand replaces FD to include both non- and renewable energy.

3.1.4 Interpretation

In this phase, the findings from the LCA and LCI should be considered together, and analyzed. Results should be provided that are consistent with the defined goal and scope. Limitations of the study should be discussed. Results that are consistent with the defined goal and scope should be provided, as well as a conclusion. (ISO, 14040:2006)

3.2 Construction drying

3.2.1 Water content in wood

Wood is a hygroscopic material, which means it would be in equilibrium with the water content of its surrounding environment. The amount of water in a piece of wood is measured as the moisture content (MC), and is expressed as the relationship of the mass of water in a piece of wood and its weight oven dried (oven dry means 0% MC).

If an oven dried piece of wood is exposed to a humid environment, the wood fiber cells will start to absorb water. The water is first held in the cell walls until they are totally saturated. An average MC of 28% is the fiber cell walls saturation point for spine and spruce, at 20°C. This water is called bounded water, as it is bounded to the wood. Any additional water absorbed by the wood will fill up the cavities in the cells, and is thus called free water. Changes to the MC below the fiber cell wall saturation point can cause the wood to shrink or swell. When the fiber cell walls are saturated, the dimensions of the wood will not change even if it absorbs more water. (Treteknisk, 2006)

Planed structural timber arriving at a construction site must have a MC under 20% (Treteknisk, 2007). This is mainly because most of the shrinking of the wood applies when the MC drops from 28% to 20%. By assuring all wood is below 20% MC, the chance of deformation of the framework when the wood is further dried is reduced.

3.2.2 Mold

Another important factor, perhaps the most important, when consider wood drying is the possibility of mold growing in the construction. Mold formation is dependent on several conditions in the wood. Good mold conditions is a MC over 20% and a temperature in the range of 10°C and 45°C. The best way to prevent mould growth is to make sure the wood is not in contact with water during the construction phase.(Treteknisk, 2009). Mold can also grow in gypsum- and particle- boards, insulation material and painted walls.

"There is increasing evidence that mould growth indoors in damp buildings is an important risk factor for respiratory illness. Mould-related symptoms are likely the result of irritation, allergy or infection" (Chapman et al., 2003, quoted in WHO 2004 p - 8). Fung and Hughson (2003) concludes that heath effects as allergy, infection, irritation and toxicity are caused by fungal bioaresol exposure.

3.2.3 Methods for construction drying

There is a possibility of sealing in wet framework during the building envelope construction. When the air- and vapor- tight barriers are added the framework, it will prevents the moisture from the materials to evaporate and thus increase the good conditions for mold growing inside the wall. By drying and dehumidifying the air inside the building before the barriers is added, the wood will release its moisture until it is in equilibrium, and in doing so lower the risk for mold growth. A dried wall will also reduce and/or eliminate cracks and leaks in the finishing surface. The following three methods are used for construction drying, see figure 3-2. (Byggforsk, 474.533:2006).

3.2.3.1 Natural drying

This method is based on drying with warm and dry outdoor air. The method could be time consuming and should only be used when there is a stable weather forecast ensuring the right conditions.

3.2.3.2 Overpressure with heating and ventilation

This is the normal and traditional way to dry up the building framework. Heated air is blown into the building, creating an overpressure. The heated air absorbs more moisture than cold air, and is after some time ventilated out from the building. This method is energy intensive since outside air has to be heated to a certain temperature. Another problem regarding this method is the risk of condensation, when warm air hits colder outer walls. (Byggforsk, 474.533:2006)

3.2.3.3 Air dehumidifier

There are two types of dehumidifiers, condensation and absorption.

Condensation dehumidifier

Air with high relative humidity (RH) is blown over some cold coils inside the dehumidifier and den reheated. Since the incoming air is cooled almost to the freezing point, massive condensation takes place at the coil which then dries up the air. The condensation is drained away or collected in a bucket. The air is then reheated to room temperature and blown back out of the dehumidifier. (Byggforsk, 474.533:2006)

Absorption dehumidifier

In an absorption dehumidifier, moisture is extracted in a desiccant material. Air with high RH is blown over a material, often silica gel, which contains a vast number of microscopic pores where water is absorbed. When the absorption material is saturated, a rotor rotates it to a warm area where it is dehumidified with hot air. This warm and moist regenerated air is led out of the construction. (Byggforsk, 474.533:2006)

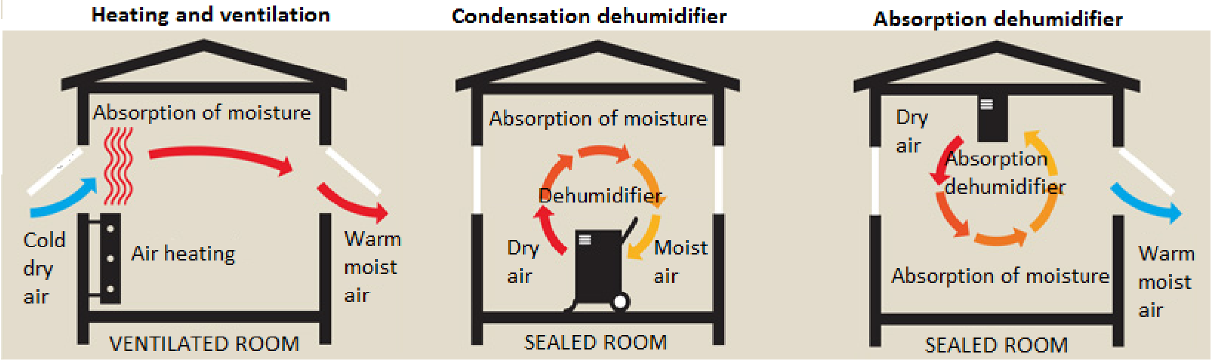


Figure 3-2: Different types of construction drying, (Ramirent, 2010)

3.2.4 *Preferred method*

There is some uncertainty by the specialists regarding the right method for construction drying. A survey done by Levanger et al. (2010) investigate how the construction industry deals with building drying. 34 site managers were asked, and of them 64% use normally the overpressure method with or without a dehumidifier, while 23% uses dehumidifiers. Type of method chosen is based on previous experiences. Only 8% chose method based on external consultant companies or producers recommendations.

One conclusion from the study is that the construction companies know why it is important to dry the framework, but there is some lack of knowledge when it comes to choosing the best method.

For further research in this topic, Project 53 “Highly insulated constructions and moist” Geving and Holme (2010) from SINTEF Byggforsk, is recommended.

4 System description

In this chapter, both house types and the construction area Stord are described. The functional unit and its system boundaries are also presented.

4.1 Stord, Norway

Both houses are projected to be constructed at Stord in Norway.

4.1.1 Location

Stord is an island on the west coast of Norway, located between Stavanger and Bergen as shown in figure 4-1. The distance from Oslo is 430 km. The municipality center is Leirvik.

Figure 4-1: Location of Stord at the west coast of Norway, (Gulesider, 2011)

4.1.2 Weather conditions

The Norwegian Meteorological Institute (MET, 2011) is responsible for registering climate data from weather stations all over Norway. For Stord, the nearest station is Stord Airport, which is about 12 km from Leirvik. A normal temperature is defined by MET as the mean annual temperature in a period of 30 years. The mean temperature is from 1971 to 2000. (Byggforsk, 451.021:2009) and the relative air humidity (RH) is the average humidity in the period from 2006 to 2010. Data collected by MET for Stord Airport is presented in figure 4-2, with an annual mean temperature of 7,4°C and relative humidity of 78%. For the energy need calculations, the simulation program Simien (ProgramByggerne, 2011) uses Bergen as a reference city with an annual mean temperature of 7,8°C.

The local weather conditions are important to take into consideration when constructing the building, and calculating required energy for the operation phase.

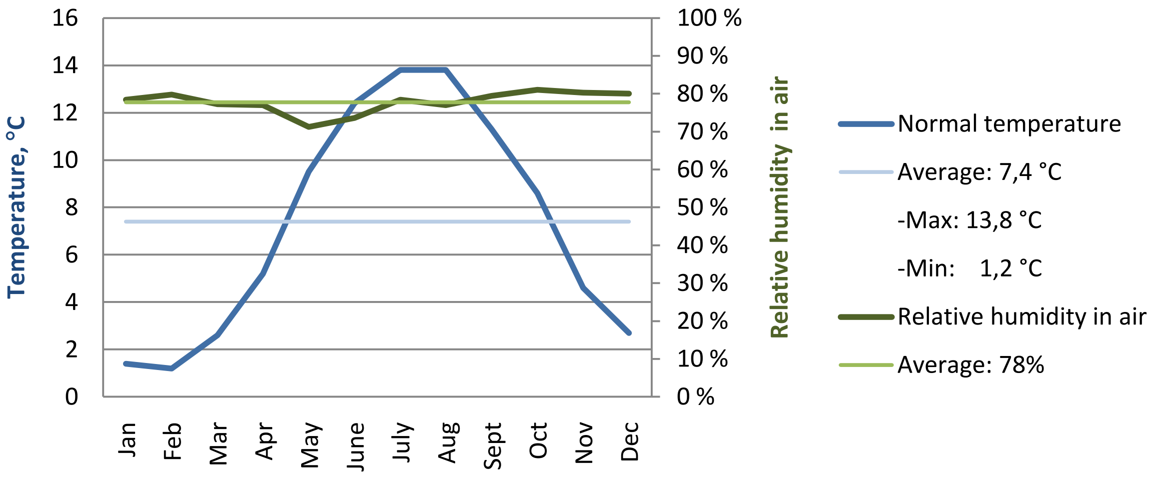


Figure 4-2: Normal temperature (in the period from 1971 to 2000) and average relative humidity for Stord.

4.2 The analyzed Stord house

The analyzed houses are projected by the building company Nordbohus AS. Both house types are visually the same and the design is a typically wood based 2 floors single family residence built for Norwegian customers in Norway. This house model has all roof insulation above the 2nd floor ceiling, leaving the attic cold. Figure 4-3 presents the outer façade for both houses. In general, the ground floor is insulated with EPS, while the outer wall, 1st level floor and ceiling are insulated with mineral wool. Both house types have 15 windows, 1 outer door consisting mostly of glass, and two XPS insulated outer doors. A technical drawing of the house is presented in figure 4-4.

Total useful floor space is 187 m^2 BRA and heated air volume is 446 m^3 for both houses.

Figure 4-3: The façade for the Stord house

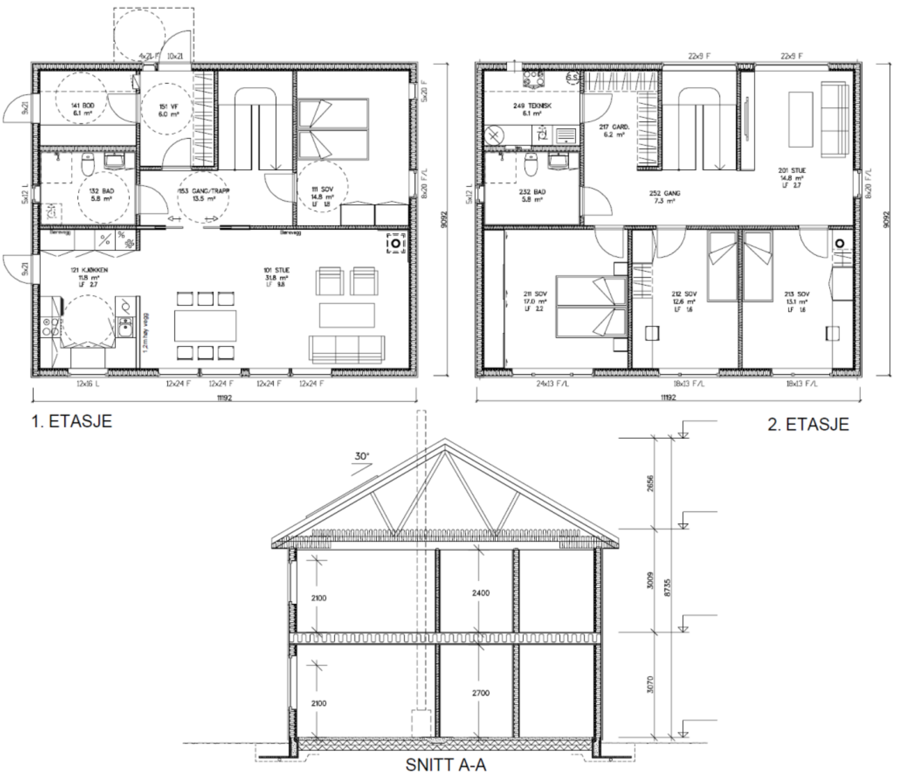


Figure 4-4: Technical drawing and floor plan for the Stord house

A heat loss budget for both buildings is presented in Table 4-1and table 4-2. The tables also includes element requirements from the TEK07 (2007) and passive house NS3700:2010 regulations and actual values for the two house models. The green marking in the tables notes if the actual building element has a better characteristic than required by the regulation, and red marks if it is lower. For the TEK07 house both the outer wall and thermal bridge value is lower than required values. By following the NS3031:2010 the heat loss from elements with lower characteristics can be redistributed to elements with better characteristics as long as the total heat loss parameter, H'', is as required. Both the TEK07 house and the passive house have a lower total heat loss parameter, H'', than required by the regulations.

Table 4-1: Minimum element requirements, Stord TEK07 house elements and heat loss calculations

TEK07 house		*Requirement*	*Stord TEK07 house*			*Description*
BRA: Heated volume:	187 m^2 466 m^3	U value, [W/(m^2K)]	U value, [W/(m^2K)]	Net area, [m^2]	Heat loss [W/K]	
Outer wall		≤ 0,18	0,22	172	37,8	*200mm A37*
Ceiling (cold attic)		≤ 0,13	0,12	94	11,3	*350mm A37*
Ground floor		≤ 0,15	0,13	92	12,0	*300mm EPS*
Windows, doors		≤ 1,2	1,17	40	46,8	*Double layer*
Thermal bridge value, normalized		≤ 0,03	0,05		9,4	
Heat exchanger efficiency		≥ 70%	80%			
SFP ventilation [kW/(m^3/s)]		≤ 2,5	1,5	Ventilation	14,8	
Air leakage 50 Pa [air change/h]		≤ 2,5	2,5	Infiltration	26,9	*Moderate shield*
Ventilation air change [m^3/hm^2]		≥ 1,2	1,2			
H: Heat loss coefficient [W/K]		≤ 160			**159**	
H'': Heat loss parameter [W/(m^2K)]		≤ 0,85			**0,85**	

Table 4-2: Minimum element requirements, Stord passive house elements and heat loss calculations

Passive house		*Requirement*	*Stord TEK07 house*			*Description*
BRA: Heated volume:	187 m^2 466 m^3	U value, [$W/(m^2K)$]	U value, [$W/(m^2K)$]	Net area, [m^2]	Heat loss [W/K]	
Outer wall		$\leq 0{,}15$	0,12	172	20,6	*350mm X33*
Ceiling (cold attic)		$\leq 0{,}13$	0,09	94	8,5	*400mm A37*
Ground floor		$\leq 0{,}15$	0,09	92	8,3	*300mm EPS*
Windows, doors		$\leq 0{,}8$	0,08	40	32,0	*Triple layer*
Thermal bridge value, normalized		$\leq 0{,}03$	0,03		5,6	
Heat exchanger efficiency		$\geq 80\%$	81%			
SFP ventilation [$kW/(m^3/s)$]		$\leq 1{,}5$	1,5	Ventilation	14,1	
Air leakage 50 Pa [air change/h]		$\leq 0{,}6$	0,6	Infiltration	6,5	*Moderate shield*
Ventilation air change [m^3/hm^2]		$\geq 1{,}2$	1,2			
H: Heat loss coefficient [W/K]		≤ 103			**95,6**	
H'': Heat loss parameter [$W/(m^2K)$]		$\leq 0{,}55$			**0,51**	

In a simulation where the technical elements of the passive house is compared to the Norwegian passive house standard NS 3700:2010, are all requirements for of the passive house standard met. (Appendix C). The annual energy used for space heating is for the passive house 18,4, kWh/m^2.

Nordbohus has estimated an economical lifetime of 50 years for both houses. The lifetime of 50 years is also used in order to make the results comparable to other studies. In the review done by Sartori and Hestnes (2007) 60 studies, all with a lifetime between 30 and 100 years, are assessed. 34 out of the 60 studies assumed a lifetime of 50 years.

4.3 Functional unit

For this study, the following functional unit is used:

50 years of 1 m^2 useful floor area of a residential wooden house, including the whole building life cycle: construction, maintenance, operational energy and water, and end of life treatment.

This functional unit does not differ between the two building systems. By generalizing the functional unit it is possible to make a fair comparison between the building designs. This functional unit could be used for all types of building systems, as long as the building fulfills the requirements for the 1m^2 useful floor area. It is possible to compare the results to other studies since the results are presented as per 1 m^2 and not the total BRA.

Other house properties as indoor health, soundproof abilities, different maximum indoor temperatures and the need for different ventilation system and maintenance are not considered in the functional unit.

It is assumed a house user that consumes the exact energy as stated in the energy budget (Appendix D).

4.4 System boundaries

Figure 4-3 presents the system boundaries for the functional unit. This system is the same for both houses, and has five main parts (shown in blue color). Building machines such as excavators and cranes combust diesel fuel during their operation for the **house construction**. Tools and building driers consume electrical energy, and workers are transported back and forth from their homes and to the construction site. Raw material is extracted, transported, processed and transported to the site.

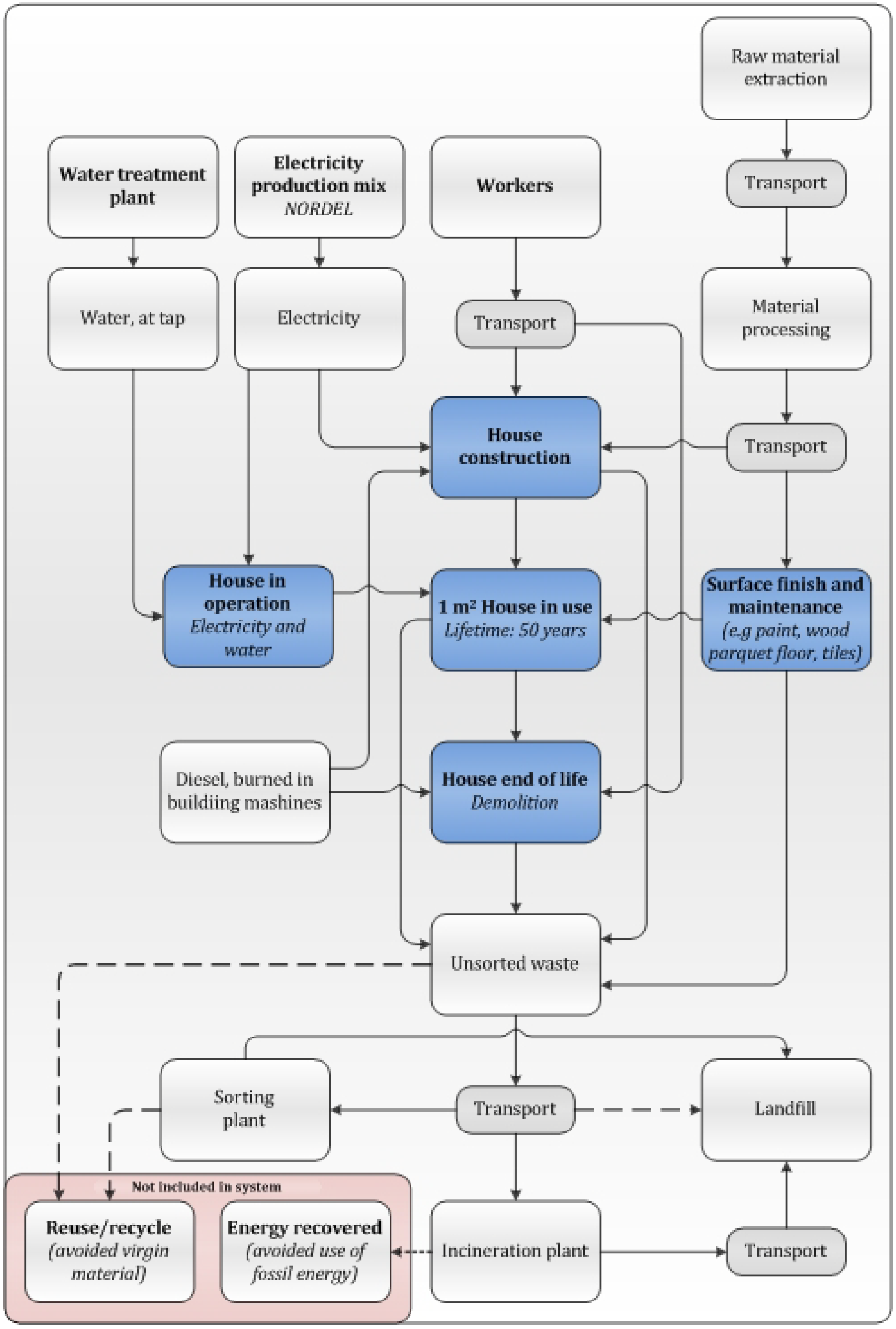


Figure 4-5: Flowchart for the functional unit and its system boundaries.

The house is divided into two parts in the use phase. **Surface finish and maintenance** requires material inputs during its lifetime. Painting the walls, changing windows and wood floor parquet are examples of elements included in this phase. Inputs to the **house in operation** include tap water and electricity.

After 50 years of operation, the house is **demolished** and all materials further treated as waste. The house demolition phase requires diesel burned in building machines and transportation of workers. Waste is also produced in both the house construction and maintenance phase as well.

In this system, it is assumed that all waste is sorted in two different fractions. One fraction is transported to a sorting plant, while the other fraction is send to a municipal incineration plant. Materials included in the sorting plant fraction include glass, metal parts, cement and mineral wool. After sorting, the non recyclable fraction is transported to an inert material sanitary landfill. Ash from the incineration is further transported to a residual material landfill. The materials produced during a recycling and energy recovered when waste is incinerated is not included in this system. Dotted arrows in the flowchart are flows that are left outside the system boundaries.

All main parts and elements in the system are further explained in chapter 5.

5 Life Cycle Inventory Analysis

The life cycle inventory analysis is the basis which further impact assessment analysis is dependent on. Life cycle impacts of a system reflect the materials, energy and waste data found in this inventory analysis. This chapter reviews the background for used data, and presents assumptions made during the collection. Justification of chosen environmental data is also presented.

The life cycle inventory is divided into house construction, house in use and house end of life. The description is, unless noted, the same for both the TEK07- and passive- house. For technical drawings, see Appendix E, and for complete inventory list, Appendix F.

5.1 House construction

The construction phase includes all processes from an untouched property is chosen until the completion of the house construction.

Material lists for the TEK07 house and passive house is provided by Nordbohus (Eriksen, 2011), and is further aggregated into 1st level floor, walls, roof, windows and doors. Inputs from construction energy, groundwork and foundation, ground floor, electricity and plumbing are based on calculations and contact with external companies.

5.1.1 Construction energy

The construction energy phase consists mainly of groundwork, machines and tools used during construction, electrical energy required for the drying process and transportation of workers to and from the construction site. Some materials are also included: glue for particleboards, chemical anchor for mounting the ground beam to the foundation and all nails and screws needed in the construction.

The data collection for the construction energy was quite challenging. The data is site specific and was not given by Nordbohus as this data cannot easily be generalized. In addition, the houses are still theoretical projects and not under construction during the time being analyzed, which gives little, if any, real site specific data. Several building companies and construction actors were assessed to get an as complete and specific inventory as possible.

5.1.1.1 Machines and tools used during construction

All the excavation is done using a 16 ton excavator. The excavator is transported 20 km to the construction site. During the construction period a crane is used to lift trusses and tiles to the roof. This is assumed to be a crane mounted on a lorry, and that the lorry has the engine on idle while the crane is in use. A total of 10 days of crane use with a diesel consumption of 20 l/day is assumed by Sørnes (2010) after a conversation with Transportsentralen in Oslo. Refining of diesel, transportation to a regional storage and emissions from the combustion on site is included in the diesel combusting process.

An air compressor (2 hp), saw (1,3 kW) and other electrical tools, including screwdrivers, drills and lights (1,5 kW) (DeWalt, 2011) are assumed to be used 50% of the total working hours.

5.1.1.2 Construction drying and use of tent

Power required for a construction dryer

The framework in the passive house consists of 300mm I-beams with softwood flanges and plywood web. This framework has a lower total mass than the 198 mm solid structural softwood for the TEK07 house. In addition, the surface/volume ratio is bigger for the I-beam framework. These factors can contribute to less energy requirements for drying the passive house wood framework. (Berge, 2011). The amount of other construction materials as concrete and insulation must also be considered when calculating construction drying requirements.

The theoretical energy required for the overpressure method can be calculated by using the specific heat capacity, c, definition,

$$c = \frac{Q}{m\Delta T} \tag{1}$$

where Q is the quantity of energy [J] transferred to a substance of mass m *[kg]*, changing temperature by ΔT *[K]* = $T_2 - T_1$, and measured in Joule per kilogram-degree Kelvin [J/kg K]. When the specific heat capacity, c *[J/kgK]*, is known, formula 2 can express the energy Q needed to raise the temperature of a given mass. When calculating with temperature differences, Kelvin can be replaced by Celsius.

$$Q = mc\Delta T \tag{2}$$

The specific heat capacity for air in the range of 0°C to 25°C is 1,006 kJ/kg C and air density at 0°C is 1,293 kg/m^3 (Haynes, 2011a). Total volume of air inside the houses, including attic for both houses, is 710 m^3. SINTEF Byggforsk (474.533:2006) recommends a temperature over 15°C and at least 2 air changes per hour when using overpressure as drying method. By using the min, max and annual mean temperature in Stord, figure 4-2, and an inside temperature of 20°C the following dryer power is required:

Table 5-1: Power required for drying the building with the overpressure method

Temperature, ℃	*Power required, [kW]*
1,2	9,6
7,4	6,5
13,8	3,2

This theoretical power calculated in table 5-1 does not include thermal energy from workers, tools and equipment on site, or solar energy.

The recommended air change rate when using a dehumidifier is 1 change per hour. (Byggforsk, 474.533:2006). The recommended models in table 5-2 are based on total house volume and based on information from the different companies.

Table 5-2: Power required for drying the building with dehumidifier, recommended by two companies

Company	*Type of dehumidifier*	*Recommended model*	*Max power consumption, [kW]*	*Reference*
F-Tech	Absorption	1 * CR400B	2,0	(Horn, 2011)
	Condensation	1 * AD790	1,7	
Danthrem	Absorption	2 * AD400B	3,96	(F-Tech, 2011)
	Condensation	1 * CDT60	1,12	

From table 5-1 and table 5-2 the required powers for different drying methods are presented. It is in the range between 1 kW and 10 kW, depending on the method and actual climate. As a general rule, the dehumidifiers use less energy than the overpressure method.

It is assumed a power consumption of 6 kW for an average dryer, for both houses.

Time required for a construction dryer

There is no standard way to calculate the required time needed for a perfect drying. This is dependent on several variables, such as moisture content in the materials at the construction start, conditions for the materials stored at site, time of year, local weather conditions and if the building is sealed during construction. Inside temperature, thickness of the wall, chosen drying method and equipment used contributes as well to the final energy demand. "Worst case" scenario is when all wood materials are saturated with moisture, a moisture content (MC) of around 30%. (Berge, 2011)

As a general rule, the drying should start when the construction is airtight and last until all indoor painting is done. No heat should be used inside the building before the interior vapor barrier is mounted. (F-Tech, 2011).

SINTEF Byggforsk has in Project Report 53 researched *high insulated structures and moisture* (Geving and Holme, 2010). "It will take, as a general rule, 0,5 - 2 weeks (typical 1 week), or 20% - 50% (typical 40%), longer time to dry wood to under 12% MC", when starting from 30% MC and increasing from 150mm to 400mm insulation thickness, independent on time of year (Geving and Holme, 2010 - p. 51).

Figure 3.16, p 32, in the previous mentioned report, shows time calculated for drying when assuming worst case scenario of 30% MC in the wood. The climate data is in Oslo, April to June. The time needed to get to 12% MC (60% RH) is for a wall with 250mm insulation 6,5 weeks while for a 400 mm wall 8 weeks. (Geving and Holme, 2010)

It is therefore assumed for the TEK07 house a drying time of 6,5 weeks while for the passive house 8 weeks. It is also assumed a dryer that is used 24 hours a day, 7 days a week.

Energy required for a construction dryer

The number of weeks, power use and total energy consumed for a construction dryer is plotted in figure 5-1. The green area is based on the previous assumptions and where the total energy requirement for both houses is. From best case, with no drying required, to 12 weeks with 10kW, the total difference is 20000 kWh. This is approximately the same energy requirement as the TEK07 house consumes in operation for one year.

This also shows the importance of not using overpressure with heat as a drying method. Using dehumidifiers reduces the total energy requirement. As a general rule, using 6 kW of power (red line in figure 5-1) for x week(s) is the equivalent of using x kWh of energy. Therefore, the required energy for drying the TEK07 house is 6500 kWh, and 8000 kWh for the passive house.

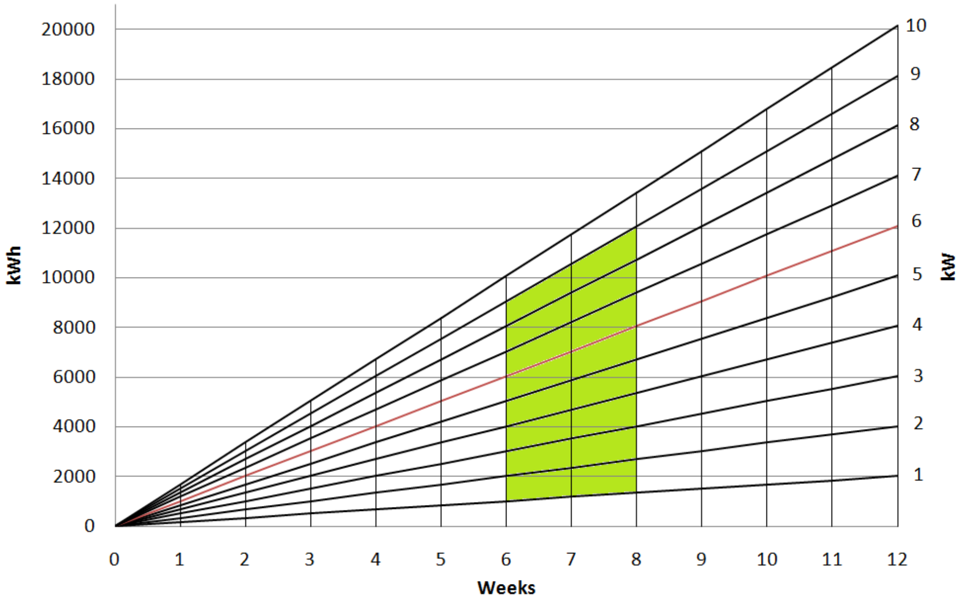


Figure 5-1: Total energy required for drying the building dependent on no of weeks and power used by dryer

5.1.1.3 Tent

It I a possibility of covering the construct site by a tent. This tent can be used as a shelter for the construction materials and reduce the uptake of moisture compared to normal outdoor storage. The time required for the drying process is therefore assumed to be shorter, compared to normal construction, when using a tent during the construction phase.

There is also a possibility of using prefabricated elements in the house construction. Elements, such as walls and roofs, are prefabricated in a factory and transported to the construction site where it is mounted to other prefabricated elements. This construction method is also assumed to reduce the energy needed for the drying process, as the materials are better protected from moisture uptake.(Eriksen, 2011)

5.1.1.3 Workers

The excavation work, transportation of masses and the casting of foundation and ground floor at a construction site, such as the one at Stord, will take 118 hours for the TEK07 house and 107 hours for the passive house. The total amount of hours used by carpenters is calculated by Nordohus. 844 hours are used for the TEK07 house and 880 hours for the Passive house. It is assumed by the building company that the carpenters are well trained and have experience with the new construction methods for a passive house and hence don’t use extra time for trial and failure. Hours used for mounting the electrical system are given by external electric companies. External companies were also contacted for plumbing hours, but no answers were given. Plumber hours are therefore assumed to be in the range of electrical hours. (Belsvik, 2011, Selven, 2011, Eriksen, 2011). The total amounts of hours are presented in table 5-3.

It is assumed a transport distance of 10 km one way, from home to the construction site for all workers. Normal working day is 7,5 hours a day, and all workers drive their own car.

Table 5-3: Total amount of work time estimated for both houses, for the construction phase

Element	*TEK07 house*	*Passive house*
Groundwork and foundation	118 hours	107 hours
Carpenter	844 hours	880 hours
Electrician	120 hours	135 hours
Plumber	120 hours	120 hours
Total	1202 hours	1242 hours

It should be noted that the total amount of plumber hours should be higher for the passive house than noted in table 5-3. From the NS 3700:2010, 50% of the energy required to heat warm water must be from alternative energy sources, such as a solar heating system or an air-to-water heat pump. Since this analysis assumes the same heating system for both houses, this excess material and hours for mounting the alternative energy systems are excluded.

5.1.1.4 Materials and environmental data.

The amount of glue for particleboards, chemical anchor for mounting of ground beam to the foundation and all nails and screws are given by Nordbohus (Eriksen, 2011). Technical data for the chemical anchor is provided by Motek chemical anchors (Lykre, 2011). Electricity consumed at the construction site is Nordel electricity mix, low voltage. Generic background data from Ecoinvent (2007), is further used.

5.1.2 Groundwork and foundation

This sub process includes all materials and transport required to construct the groundwork and house foundation.

5.1.2.1 Groundwork

It is assumed that the property consists of flat land that is easy to handle, e.g. clay and soil. For the TEK07 house 0,9 meter must be dug down from the ground surface, and 1,0 meter for the passive house. It must also be dug with the same depth as previous noted 1,5 meter outwards outside the foundation, for both houses. (Eriksen, 2011).

5.1.2.2 Foundation

There is a difference between the foundation wall for the TEK07 and passive house (Appendix E-1). For the TEK07 house, the foundation wall consists of four homogeneous layers: fiber cement board, EPS, reinforced concrete and EPS. (Eriksen, 2011) The foundation wall for the passive house is shown in figure 5-2 and differs in the way that there are two mixed reinforced concrete and EPS layers. This foundation wall is designed for passive houses with I beams as the wooden framework. (Byggforsk, 2010, Eriksen, 2011)

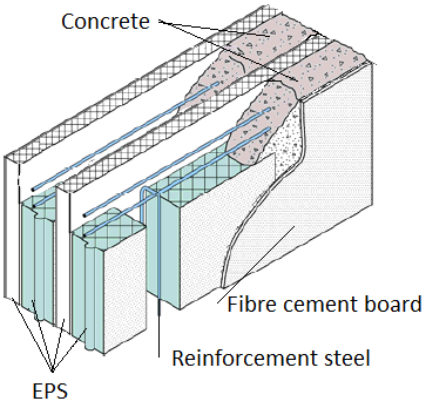


Figure 5-2: Foundation wall for the passive house, modified from Byggforsk (2010)

Both foundation walls stand on a reinforced concrete foundation footing. Outside insulation of extruded polystyrene (XPS) is added to reduce the risk of frost in the ground. A sill membrane based on bitumen is fitted on top of the foundation wall and equalizes the pressure from the ground beam.

Production of concrete, expandable polystyrene (EPS) and XPS is modified Ecoinvent processes where the electricity mix is changed to be Nordel, since all production is assumed to be in Norway. (Glava, 2011, Norbetong, 2010). The reinforced steel production is also modified from Ecoinvent, to include Nordel and 100% recycled steel. (Celsa, 2009, Sørnes, 2010).

5.1.2.3 Gravel, drainage and radiation protection

It is assumed that all of the mass dug up from the property is pollution free and 70% of the masses are driven 30 km away to a local stone-crushing and mass treatment plant. An equivalent mass of gravel for drainage is transported from the same plant back to the construction site. One round of drainage pipe is laid outside the foundation while one and a half round of radon pipe is laid under the ground floor with an up-to-roof exhaust pipe.

Plastic for drainage and radiation pipes are polyethylene (PE), produced in Europe. Extrusion of plastic pipe is included. All other types of plastic and rubber used is also produced in Europe, molded or extruded.

5.1.3 Floor

The floor is divided into ground level floor, 1st level floor and staircase.

5.1.3.1 Ground level floor

The ground level floor consists of EPS on planed gravel. The EPS thickness is 300 mm for both houses, but there is a difference in the compressive strength for the EPS. The type is S80 for the TEK07 house and S150 for the passive house. Between the EPS insulation and the concrete floor, there is a combined radon and vapor barrier. This barrier is sealed with butyl rubber and tape in all gaps and joints to make it 100% sealed.

The main ground floor is 80 mm concrete type C25, reinforced with a K189, Ø6 steel net.

5.1.3.2 1st level floor

This floor separates the ground and 1st level, and is the same for both houses (Appendix E-3). Water resistant particle board with *melamine urea formaldehyde (MUF)* resin is used as a main floor. The floor framework is 300 mm I-beams with 200 mm A37 mineral wool insulation. There is additional 100 mm insulation 1 m out from the outer edges all around the house, to fill up the gap and reduce thermal bridges. Both ceilings are covered with gypsum boards. The ceiling gypsum boards under the attic are mounted on a steel suspension system.

Info from Forestia (2010) is used as input data for the floor and wall fiberboards, see Appendix G for complete data. I-beams, structural planed timber, laminated wood, rough panel and wood sheathing are analyzed by SINTEF Byggforsk in the Mikado project (Wærp et al., 2009). Ecoinvent processes are used for mineral wool (rock wool) and gypsum board production, assuming Nordel electricity mix.

5.1.3.3 Staircase:

The staircase is the same for both houses and consists of 17 steps. It is assumed that the steps and the mid-plate are made of laminated wood, while the supportive pillars and hand railings are made of structural wood. The steps and mid-plate ate covered with 3 coats of acrylic varnish while the remaining parts as painted with 3 coats acryl water based paint

Paint and varnish are modified Ecoinvent processes with Nordel electricity mix

5.1.4 Wall

The wall is divided into outer and inner walls.

5.1.4.1Outer wall

Figure 5-3 - (Rockwool, n.d.) shows the different outer wall types.

The main difference between the TEK07 outer wall (Appendix E-3) and passive house outer wall (Appendix E-2) are insulation thickness and different types of wood in the timber framework. The outside of the wall is painted timber cladding (1). Both houses have the same windbreak system (2), which consists of a windbreak foil (PP) and 12mm windbreak sheets. Windbreak sheets have many gaps and mainly support the framework, while the plastic foil provides most of the air tightness. The framework in the TEK07 house is of 36*148mm structural timber (3) while for the passive house it is a 300 mm I-beam (4). It is the thickness of the wood framework that defines the space available for insulation (5).

For the TEK07 house the insulation is 150mm A37, while for the passive house 300mm X33. Mineral wool has different thermal conductivity; A37 and X33 defines the used type. In order to protect the interior water vapor barrier (6) from unwanted penetration, as nails for photo frames etc, 50 cm of furring strips (7) with insulation is added the inside of the vapor barrier. Wall particle board (8) with *urea formaldehyde (UF)* resin is mounted as an inner wall.

The total insulation thickness for the TEK07 house is 200mm and the passive house 350mm.

Production input for the windbreak sheets, *Hunton asphalt vindtett*, is found in an EPD made by SINTEF Byggforsk (Hunton, 2011)

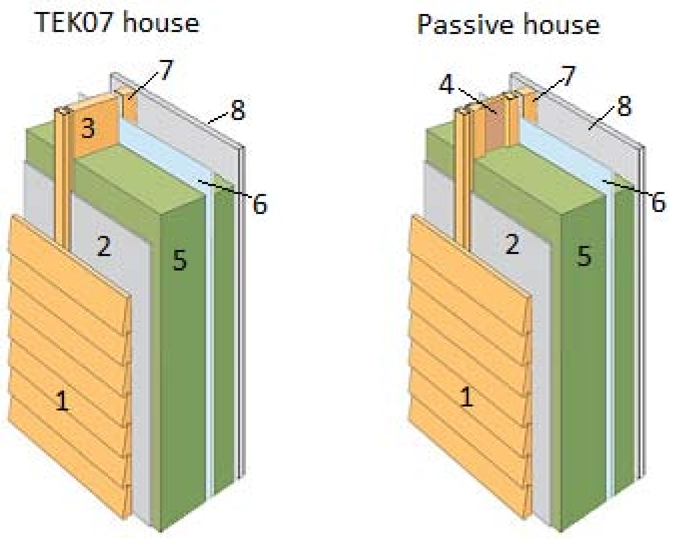


Figure 5-3: The wall designs for the TEK07 house- and passive- house

5.1.4.2 Inner wall:

The inner walls are the same for both houses (Appendix E-4). The load carrying walls are 148mm thick while the non load carrying walls have a thickness of 98 mm. All inside walls have 50 mm insulation, and wall particle boards as an outer layer. In the calculations, the results are not divided into load carrying and non load carrying walls.

5.1.5 Roof

The TEK07 and passive houses consists of almost an identical roof unit (Appendix E-5). The roof is a cold type, meaning all insulation is fitted above ceiling leaving the attic non-insulated. This closed, cold space, will have the same temperature as the outside climate and must be ventilated to prevent condensation (Emmit and Gorse, 2010, p. 302). The roof unit is divided into the following processes: outer roof and roof truss, ceiling with insulation and rain gutter including a snow protector.

5.1.5.1 Outer roof and roof truss:

The outer roof consists of concrete roof tiles as an outer protector, mounted on wood battens. A diffusion-open membrane of polyurethane (PU) and polypropylene (PP) is installed as a protective under roof under the tiles. This under roof is waterproof and acts as a windbreak. Bitumen sealing string and tape is for the passive house added in all under-roof joints. The roof truss is of structural timber and produced off site.

The concrete roof tiles are produced in Norway. (Moiner, 2009)

5.1.5.2 Ceiling with insulation

The ceiling consists of 350mm A37 insulation for the TEK07 house and 400 mm A37 for the passive house. A vapor barrier is mounted under the insulation. For the TEK07 house this barrier is a polyethylene foil (PE), while for the passive house a reflective vapor barrier is installed. This reflective vapor barrier consists of five layers of PP, PE, welded fabric, PE and a reflective aluminum foil. (Byggforsk, 2009). A reflective vapor barrier can substitute the additional 5 cm of insulation. When the reflective aluminum foil is towards 5 cm captivity it reflects radiant heat back to the room.

Important parts of the weather protection system are rain gutters and roof snow protectors. All these parts are produced of zinc- and powder coated (galvanized) steel.

5.1.6 Windows and doors

5.1.6.1 Windows

The author completed a LCA of modern window production in Norway the fall 2010 (Dahlstrøm, 2010). That master project analyzed two window producers in Norway, Nordan and Uldal, looking at the production of windows with an U value of 1,2 and 0,8 W/m^{2}K. Windows used in TEK07 house have an U value of 1,2 W/m^{2}K and for the passive house 0,8 W/m2K. An outside aluminum cladding is installed on all windows. Painted linings are mounted inside to make sure the windows fits to the different wall thicknesses.

5.1.6.2 Doors

Doors from a Norwegian producer, Trenor, is assessed for production data, see 0 for details. Outer doors have an U value of 1,0 W/m^{2}K for the TEK07 house while 0,8 W/m^{2}K for the passive house. The door consists of a door leaf, door frame, lining, paint and hardware. Inner doors are the same for both houses.

All doors are modeled without windows.

5.1.7 Electricity and plumbing

5.1.7.1 Electricity

The Stord house is installed with an electrical system in accordance with NEK 400:2010 . There is no difference in the requirements for the TEK07 house or the passive house.

Included power points are all power outlets, lamp switches and connectors for heated bathroom floors, kitchen stove, hot water tank and washing machine. Every point is installed in a HDPE wall box. 350 m electrical cable is installed, based on the assumption that a cable is installed around the circumference and up to the ceiling in all room. The length for 1st floor is doubled, as to include TV and radio antenna. The cable is installed in a corrugated plastic pipe. A powder coated steel fuse box is also included.

The production of these materials are generic and found in the Ecoinvent database(2007),.

5.1.7.2 Plumbing

A tap water and sewage system is installed. High pressure PE-X pipes (with pipe in pipe) and a 40mm sewage pipe are installed to every tap point. A 110mm sewage pipe is mounted from the toilets.

It is assumed that the connection grid for both the electrical and plumbing system is available at the building site. 5 meters of cables and pipes is added to connect the house system with the onsite grid.

5.1.8 Transport

Transportation of all materials is included in the analysis. For products that have one known producer, for example Litex wet room boards that are produced in Sandefjord in Norway, that specific transport distance is used. When the product is assumed to be produced in Norway, but the exact location is unknown, a distance of 500 km is used. This assumption is based on the 430 km travel distance between Stord and Oslo. 500 km of transport allows the product to be transported from anywhere in the eastern part of Norway and to the construction site. For materials produced in Europe, the middle of Germany is used as a reference distance. Transport to Stord is assumed to be done by a transport lorry, 20-28 t, fleet average. When from Germany, a transoceanic fright ship from Denmark to Norway is included.

5.1.9 Waste during construction

During the construction phase, most of the materials transported to the site are uncut and in bulk amounts. Sørnes (2010) pointed out a study by Monahan and Powell (2010) which points out the concern of waste during construction in the UK. "On site construction typically has contingency and error related over ordering, amounting to approximately 10% of all materials brought to site, with 10–15% of the materials imported to a construction site being exported as waste" (Monahan and Powell, 2010). 10 % of uncut and bulk materials, such as wood and plastic barriers, are assumed by Nordbohus to be waste during construction. (Eriksen, 2011) . It is not assumed to be any construction waste from mineral wool, since this wool already is pre cut and adjusted during in the factory.

The process **waste during construction** presented in the result chapter includes impacts from production of the (wasted) material, impacts from transportation to a waste treatment plant and from the waste treatment. The process **house construction and surface finish in year 0** includes therefore only impacts from actually constructing the house, independent on the waste amount created during the construction.

5.2 House in use

The house in use phase is divided in two parts. Surface finish and maintenance covers all service of the building envelope, while house in operation is the total water- and electricity- consumption, during 50 years of use.

5.2.1 Surface finishes and maintenance

> Surface finishes are particularly important. Finishes form the interface between building users and the building and hence affect the way in which we interact and perceive our built environment. Surfaces are seen, touched and smelt by building users. Colors, or the lack of it, affect our psychology and the atmosphere of our buildings (Emmit and Gorse, 2010, p-564).

A surface finish should provide durable, visually attractive and low maintenance surface to floors, inner- and outer- walls, ceiling and roof. This section is divided into painting, bathroom and floor cover. Service lives for all elements are presented in table 5-4.

Surface finishes for year zero, before the house is in operation phase, are one coat primer and two top coats of paint on outdoor walls, two coats of paint on indoor walls and ceilings, complete bathroom covers and wood parquet floor covers.

Furniture, kitchen equipment, interior decoration, electronic equipment and other furnishing are not included in this study. All these products are user specific and cannot be standardized.

The material inputs are calculated on the basis of area covered, and 10% waste is included for painting, bathroom- and floor- cover.

Table 5-4: Service life and number of cycles for the different surface finish elements

Component	*Service life [years]*	*Number of life cycles [n]*	*Description*
Paint wall, outdoor	8	7	*3 coats year 0, 2 coats per cycle*
Paint wall, indoor	10	5	*2 coats per cycle*
Paint ceiling, indoor	10	5	*2 coats per cycle*
Bathroom	30	2	*Panel, wet room plates, tiles*
Floor covering	20	3	*Varnished parquet floor*
Roof tiles and under roof	30	2	*Tiles, vapor and windbreak, sealing*
Rain gutter and snow protector	30	2	*Powder coated metal parts*
Windows and outer doors	30	2	*Including painted lining*

5.1.2.1 Painting

Both outdoor- and indoor- walls and ceilings are painted at regular intervals. The outside wall has one coat of primer and two top coats during the building construction, and two new top coats every 8th year. (Wærp et al., 2009) . For the inner walls and ceilings it is assumed two coats during the construction and two new coats on all surfaces in a ten year period.

Outdoor paint is assumed to be solvent based and indoor paint water based, both produced in Norway.

5.2.1.2 Bathroom

Included in the bathroom finishes are rough panel, wet room board, bitumen sealing, cement paste, joint filler and ceramic tiles. The wet room boards are assumed to be produced by Litex in Sandefjord, Norway and consists of XPS and glass fiber reinforced plastic (Byggforsk, 2008). The ceramic tiles and cement paste are assumed to be produced in Central Europe. Wet room boards have an estimated lifetime of 50 years. (Litex, 2011). Ceramic tiles are, when installed correctly, assumed by SINTEF Byggforsk (571.508:2008) to have a long lifetime.

It is assumed a complete renovation of both bathrooms take place in the house after 30 years. (Byggforsk, 700.320:2010)

5.2.1.3 Floor parquet

Parquet floor is used as a surface finish on floors, both on the concrete floor and 1st level floor particle boards. The type of parquet used in this analysis is three layers engineered wood, total 14mm thick. Six coats of a water based acrylic varnish create the top coats. The floor is assumed installed floating, glue free. Parquet is assumed produced in Norway.

Nebel et al. (2004) did a Life Cycle Assessment of Wood Floor Covering for the German Flooring Industry in 1998 where different types of floor covers were analyzed. In that analysis the lifetime of floating multilayer parquet is set to 10 years, but according to European producers this lifetime is set to 20 years. (Boen, 2010, Barlinek, 2011).

5.2.1.4 Roof tiles, under roof, rain gutters and snow protectors

Lifetime of roof tiles is 50 years (Moiner, 2009) and for under roof is it assumed to be like the building lifetime (Icopal, 2011). The rain gutters have a technical lifetime of 30 years. (Icopal, 2007)

Both Monier (n.d.) and Icopal (n.d.) recommends on a general basis to renovate the outer roof every 30th year. It is therefore assumed a complete renovation of roof tiles, under roof, rain gutters and snow protectors take place after 30 years.

5.2.1.5 Windows and doors

All windows and outer doors are replaced after a life of 30 years (Dahlstrøm, 2010, Byggforsk, 700.320:2010). U values for the new windows and doors are assumed to be the same as those replaced.

5.2.2 House in operation

House in operation provides water and electricity to the house during the 50 years lifetime.

5.2.2.1 Water

Statistics Norway has, based on reports from the municipal waterworks, estimated an average water consumption of 195 l water per person per day. (SSB, 2010). When assuming that both the TEK07 and passive house occupy 4 persons, 285 m^3 of water is annual consumed.

5.2.2.2. Electricity

The TEK07 and passive house annual energy consumption is simulated by Nordbohus (Eriksen, 2011) in the computer program Simien (ProgramByggerne, 2011). Energy requirements for hot water, lighting and technical equipment for the TEK07- and passive- house are from NS 3031:2010 and NS 3700:2010 respectively.

For all windows facing south, automatic sun screens are added on the exterior side for both house types. These screens are often made of fiberglass or aluminum with tiny louvers, and reflect 65%-85% of the incoming solar radiation. Interior shades are mounted on windows facing east.

Nordbohus simulated the summer temperature inside the houses (Appendix I), and for the passive house the exterior screens mounted on the windows facing south were replaced by interior shading. Due to increased solar heat gain the net heating demand for the passive house was reduced from 18,4 kW/m^2 to 15,2 kW/m^2. The maximum indoor temperatures in the kitchen and living room, on the other hand, were increased from 25,9°C to 39,9°C. The maximum temperature for the 1st floor sleeping rooms increased from 26,0°C to 33,7°C. This shows the importance of fitting the appropriate solar screens to avoid indoor overheating. (Eriksen, 2011) Maximum temperature for a comfortable indoor environment is defined in NS 15251:2007 as 26°C.

Both houses meet this temperature requirement with installation of exterior sun screenings on windows facing south. The main façade is facing south in the energy calculations.

The simulated energy need is found in Appendix D, and is:

- TEK07 house: 21032 kWh/year
    - 112,5 kWh/(m^2 year)

- Passive house: 14939 kWh/year
    - 79,8 kWh/(m^2 year)

The annual simulated energy requirements from Simien (Appendix D) is based on the NS 3031:2010, while the passive house simulation (Appendix C) is based on NS 3700:2010

The simulated net required energy as presented is not the same as delivered electrical energy.

> A significant share of the net heat requirements [in a TEK07 house] must be covered by other energy sources than electricity and / or fossil energy (at end-user). This share is about half, or minimum 40% of the net energy requirement for space heating (including ventilation air heating) and warm water, calculated by NS 3031:2010 .
>
> There is for passive houses and low energy houses a requirement that the heating system must use a significant share other energy sources than electric- and fossil- energy. The calculated delivered electric- and fossil- energy must be less than the net required energy minus 50% of the energy required for warm water (NS, 3700:2010).

One way of covering the non electricity and fossil fuel requirements for the TEK07 house is to use biofuel, for example wood burned in a stove.

The main difference in these requirements is that in the passive house 50% of the energy for warm water heating must come from alternative sources. Examples of alternative sources are: air-to-water heat pump, geothermal heat pump or solar heat system.

It is assumed the same heating system for both houses, meaning all required energy simulated in Appendix D, is covered by 100% electricity, Nordel low voltage.

A life cycle assessment of complete heating and ventilation systems for the Stord TEK07 and passive house is conducted by Kari Sørnes in her Master Thesis spring 2011, MSc Energy and Environment, NTNU Trondheim.

5.3 House end of life

5.3.1 Demolition energy

Due to high requirements of waste sorting it is assumed 50 hours of manual work for the demolition process. The use of excavator with demolition equipment is assumed to be 100 hours. An increase of 20% hours is assumed extra for the passive house due to more waste sorting and transportation. All assumptions are based on contact with an external machinery, transport and demolition company Tverås Maskin og Transport AS (2011), and presented in table 5-5.

Table 5-5: Hours used for the demolition

House type	*Manual work*	*Excavator*
TEK07 house	100 hours	50 hours
Passive house	120 hours	60 hours

5.3.2 *Building waste treatment*

Waste during construction, surface finish and maintenance waste and all materials from house end of life generate a lot of waste.

14%, or 1,24 million tons, of total generated waste in Norway 2004 was waste from construction, renovation and demolition. Tiles and concrete waste was around 50% of this waste amount. (SSB, 2006). Figure 5-4 shows the different treatment methods for all building waste for 2004. 38% is sent to landfill, 27% energy recovered and 18% material recovered.

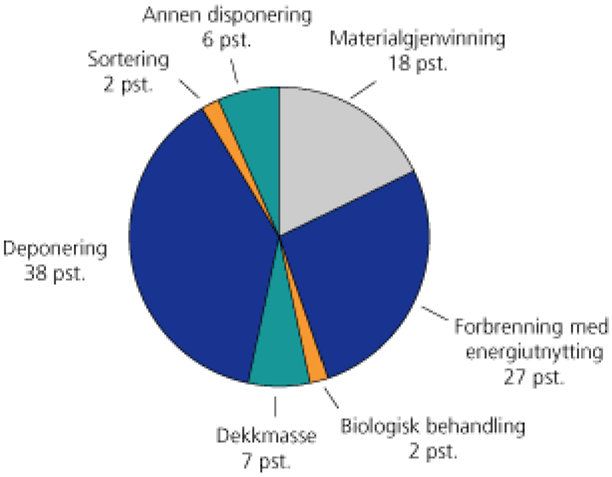


Figure 5-4: Treatment methods for building waste in 2003, (SSB, 2006)

A National Action Plan for construction waste was introduced in Norway in 2001, with a revised version published 2007. (NHP, 2007). This action plan has three main goals, which are

- All hazard waste should be treated in the right facilities
- All construction and demolition waste should be minimized, and the highest possible recycling and proper treatment of the waste should be emphasized.
- 80% of building and construction waste should by 01.01.2012 be recycled

Recycling is defined as material recovery for all fractions. For cardboard, paper, plastic, bitumen roof sheets and wood products energy recovery is also included in the recycling definition. (NHP, 2007)

It is not assumed any material recycling for the Stord houses. Fractions that can be energy recovered, such as EPS, XPS, plastic, rubber, sealing, paper, wood and particle boards, are transported to a municipal incineration plant with an energy recovery system. All other fractions are transported to a sorting plant.

Transport distance to waste treatment plant:

Avfall Norge (2007), quoted in Raadal and Modahl (2009), completed a benchmark study in 2006 about waste data for packaging, from 15 inter-municipal waste companies in Norway. The weighted average transport distance from waste source to an incineration plant is measured to 85km. The distance to a material recovery plant differs with the different fractions, and is from 150 km to 900 km.

The distance of 85 km is used for all waste, both incinerated and sorted, and assumed done by a transport lorry, 3,5-20 t, fleet average.

5.4 Softwood assumption

Softwood of pine and spruce is used for the house construction. One of the producers, Moelven, has stated the following environmental responsibility in the production of their timber:

> The raw wood material we use will come from a sustainable forest management that takes into account economic, social and ecological conditions. Our processing companies buy raw material from our [Moelvens] sawmills or from external suppliers that use only raw materials that do not come from controversial sources(Moelven, 2011).

Mainly, all timber produced in Scandinavia is from sustainable forestry (Wærp et al., 2009). 95% was certified sustainable in Norway in 2003 (Treteknisk, 2004). There are two major independent forest certification schemes worldwide, Forest Stewardship Council (FSC) and The Programme for the Endorsement of Forest Certification (PEFC) that promotes sustainable forestry. Both schemes are certified by a 3rd part to ensure high quality.

It is assumed that all timber used in the house production is from sustainable forestry.

The environmental data for softwood used in this thesis is from the MIKADO Project - LCA of Norwegian wood products (*Livsløpsanalyser av norske treprodukter)*, by SINTEF Byggforsk in collaboration with Norwegian Institute of Wood Technology (*Norsk Treteknisk Institutt)* and The Norwegian Forest and Landscape Institute (*Norsk Institutt for Skog og Landskap)*. (Wærp et al., 2009)

MIKADO presents an Environmental Product Declaration (EPDs) for various wood products from Norwegian production: timber cladding, structural timber, I-beam and rough panel. In addition to the presented EPDs, more background data from the MIKADO project were collected directly from Kjersti Folvik from SINTEF Byggforsk (2010).

Timber and biomaterial binds CO_2 from the atmosphere when growing through photosynthesis. Treating this is a topic of discussion in LCA analysis. One could argue that this binding must be included in the analysis. For example, if the wood is from a sustainable forest, chopping down one tree induces growth of a new tree, and thus bounds more CO_2 than not cutting down the first tree. 1 kg of wood product should therefore have a negative impact on CO_2 emissions (e.g. minus x kg CO_2 emissions per kg wood produced). This creates on the other hand emissions when dealing with wood waste treatment (burning), since the bounded CO_2 is released back to the atmosphere again.

It is assumed a neutral CO_2 cycle in this project, CO_2 emissions from burning wood and CO_2 bounded when growing are set to zero. (Wærp et al., 2009)

Timber products from the MIKADO project have a density of 500 kg/m^3 and are having a moisture content of 14 % - 18%.

5.5 Electricity production mix assumption

Electrical energy is used in the production of the different materials and for the house in operation phase. Emission occurring from generating electricity must therefore be included in the life cycle assessments. Since Norway is connected to Scandinavia and Europe via international electricity grids, NordPool (2011), there must be a justification of which production mix it should be accounted for.

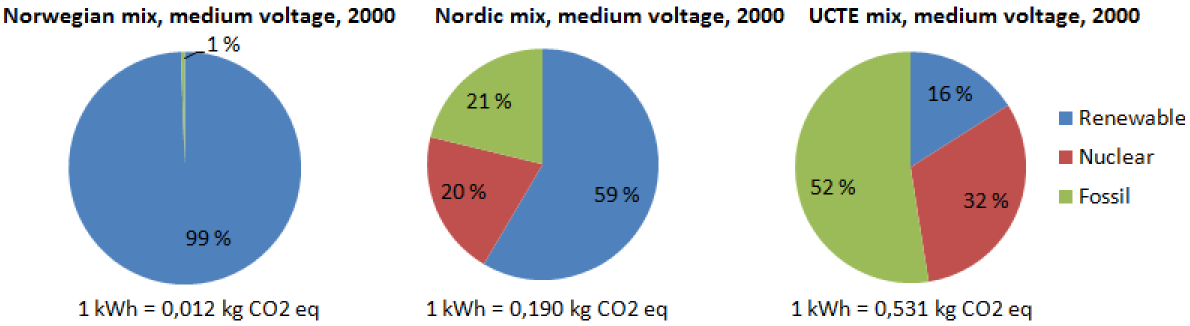


Figure 5-5: 3 types of electricity mixes share of renewable, nuclear and fossil energy sources, (Ecoinvent, 2007)

Figure 5-5 shows the different shares of renewable, nuclear and fossil fuel energy sources, which are the most relevant electricity sources for Europe and Norway (Ecoinvent, 2007). Climate change impacts are calculated per kWh produced, and there is a significant difference between the Norwegian and European production mix. It is important to notice that the Norwegian mix is the electrical production mix, and does not reflect the mix that is consumed in Norway. The Norwegian mix is what Norway produces, and not what Norway consumes. As Norway is connected to the mentioned grids, electricity is bilaterally traded. Amounts of hydropower produced vary throughout the season, and thus imports and exports will vary the same way. In periods with no import, electricity at grid would be generated by 99% hydropower. Similarly, when Norway imports electricity, some of that electricity could be generated from nuclear or fossil fuels somewhere else in Scandinavia. The Norwegian consumption mix varies throughout the season, and cannot be determined on a daily basis. Environmental impact calculations based on a purely Norwegian production mix will most likely give lower impacts than what actually occurs.

One could argue that it is best to calculate electricity impacts with the former Union for the Coordination of the Transmission of Electricity (UCTE) production mix, today a part of the European Network of Transmission Systems Operations for Electricity (ENTSOE-E, 2011). This is the annual average production mix of the Continental European countries, with a reasonable share of renewable, nuclear and fossil fuel electricity generation. The results would be conservative and, for Norwegian use, it is a high probability that the actual impacts are lower than calculated. This could also urge for lower energy consumption by the customer. As a result, Norway and Scandinavia, with its high share of renewable energy generation could lose its competitive superiority as producers of green electricity. For example, if aluminum production in Norway is calculated with European electricity mix, it would not be any better to produce aluminum in Norway (with hydropower electricity) than any other place in Europe.

One could also argue, that, when deciding upon an electricity mix, to choose a marginal mix. This example is taken from Weidema et al.(1999):

Most Norwegian electricity is produced by hydro-power plants. If we analyze a change that involves a small increase in electricity consumption in a Norwegian industry, the actual power plant that will be used to produce this small (marginal) amount of additional electricity is likely to be a fossil-fuel based power plant. This is because Norwegian hydro-power is in practice limited to the present capacity. As the increased demand for electricity cannot be covered by hydro-power, it causes an increase in the

Norwegian import of (fossil-fuel based) electricity from Denmark [, Sweden or Finland] (since adequate transmission capacity is available between the two countries) or alternatively, the Norwegians may decide to build a fossil-fuel based power station to make up for the increase. In both instances, the technology will be the same (modern, unconstrained), but the geographical position of the marginal power plant may be determined by other factors. The logic is equivalent if you move from a high electricity demand to a lower electricity demand. This would mean that less electricity would have to be imported from Denmark or alternatively, that less non hydro Norwegian electricity would be needed.(Weidema et al., 1999).

Based on this method, it is possible to choose between all types of generation technologies, depending on the defined time, goal and scope of the study. A marginal production mix becomes complex when wind power and Combined Heat and Power (CHP) plants are involved, as in Denmark (Lund et al., 2010). Wind power generation, as with hydropower, generation is dependent on weather conditions and seasons, which makes the production mix fluctuate. Marginal energy could in one hour be wind power, and the next hour nuclear power. Since the European Union has decided to increase the share of renewable energy by 20-30% by 2020, marginal energy production might be greener in the future. (Lund et al., 2010)

There is also a difference when choosing electricity mixes for the production, use and end of life phase. For the house construction, where used materials already are produced, an electricity mix based on today’s situation is reasonable. The results will reflect on the actual situation today. For the use phase, it could be hard to justify today’s production mix as relevant for the next 40-50 years (or even a longer period). If the European Union reaches its goals of more renewable energy in 2020, emissions pr produced kWh, could actually be lower than the calculated scenarios.

It is therefore assumed for all products produced within Scandinavia, to use the Nordel production mix, medium voltage. Products imported from rest of Europe and World are assumed produced by a UCTE production mix.

6 Life Cycle Impact Assessment

This chapter presents the environmental impacts from the life cycles of the TEK07 house and passive house. First, the total life cycle from cradle to grave is presented. Then the main result is disaggregated in the following sections: construction and surface finish (year 0), surface finish and maintenance (including waste treatment, year 1 to 50), end of life treatment (year 50) and house in operation (electricity and water, year 1-50). By disaggregating the total impacts for each life cycle phase, a more thorough understanding of the system is possible.

For all charts in this chapter, each category is normalized to total impacts from the TEK07 house. It is therefore easy to see the relative difference between the two houses, for all impact categories. Since all categories have different units, and measure different environmental impacts, it is not possible to compare them to each other.

The results discussed and presented in the following figures, **are pr functional unit, 1m^2** floor area with a lifetime of 50 years. For all results, except part 5.1.2, the characterized, ReCiPe, hierarchist midpoint method version 1.03 is used. (RIVM et al., 2009)

6.1 Total life cycle results

6.1.1 Total lifecycle, characterized

The total impacts for constructing, maintaining, operating, demolishing and waste treating both houses, are presented in table 6-1. The results are divided into total house impacts, and pr functional unit. Table 6-1 presents total climate change impacts of 297 tons CO_2 eq for the TEK07 house and 241 tons CO_2 eq for the passive house. By assuming the same electrical heating system for both hoses, the total climate change impacts are reduced with 56 tons ton CO_2 eq during a lifetime of 50 years, when choosing to build a passive house instead of a TEK07 house. This is the equivalent to a daily reduction of 3,07 kg CO_2 eq/day for the whole house, or 16,3 gram CO_2 eq pr m^2/day. For the cumulative energy demand, the total reduction is 24057 GJ for the whole house, or 13,1 GJ pr m^2.

Table 6-1: Total life cycle impacts for the TEK07 house and passive house

	Total, house		*Pr functional unit, m^2 floor*		
	TEK07	*Passive house*	*TEK07*	*Passive house*	*Unit*
Climate change	296694	241285	1587	1290	kg CO2 eq
Human toxicity	61689	52374	330	280	kg 1,4-DB eq
Photochemical oxidant	826	736	4,42	3,94	kg NMVOC
Particulate matter formation	496	425	2,65	2,27	kg PM10 eq
Terrestrial acidification	1043	868	5,58	4,64	kg SO2 eq
Freshwater eutrophication	3,36	2,94	0,02	0,02	kg P eq
Marine eutrophication	265	234	1,42	1,25	kg N eq
Terrestrial ecotoxicity	200	162	1,07	0,87	kg 1,4-DB eq
Freshwater ecotoxicity	801	853	4,28	4,56	kg 1,4-DB eq
Marine ecotoxicity	874	783	4,68	4,19	kg 1,4-DB eq
Metal depletion	37778	30517	202	163	kg Fe eq
Cumulative energy demand	10364	7907	55,4	42,3	GJ eq

The total life cycle climate change impacts pr m^2 floor area is 1,59 tons CO_2 eq for the TEK07 house and 1,29 tons CO_2 eq for the passive house. All impact categories are further presented in figure 6-1, which also divides the total impacts for each life cycle phase. Numbers from table 6-1, pr m^2 floor, is added on the side of the chart.

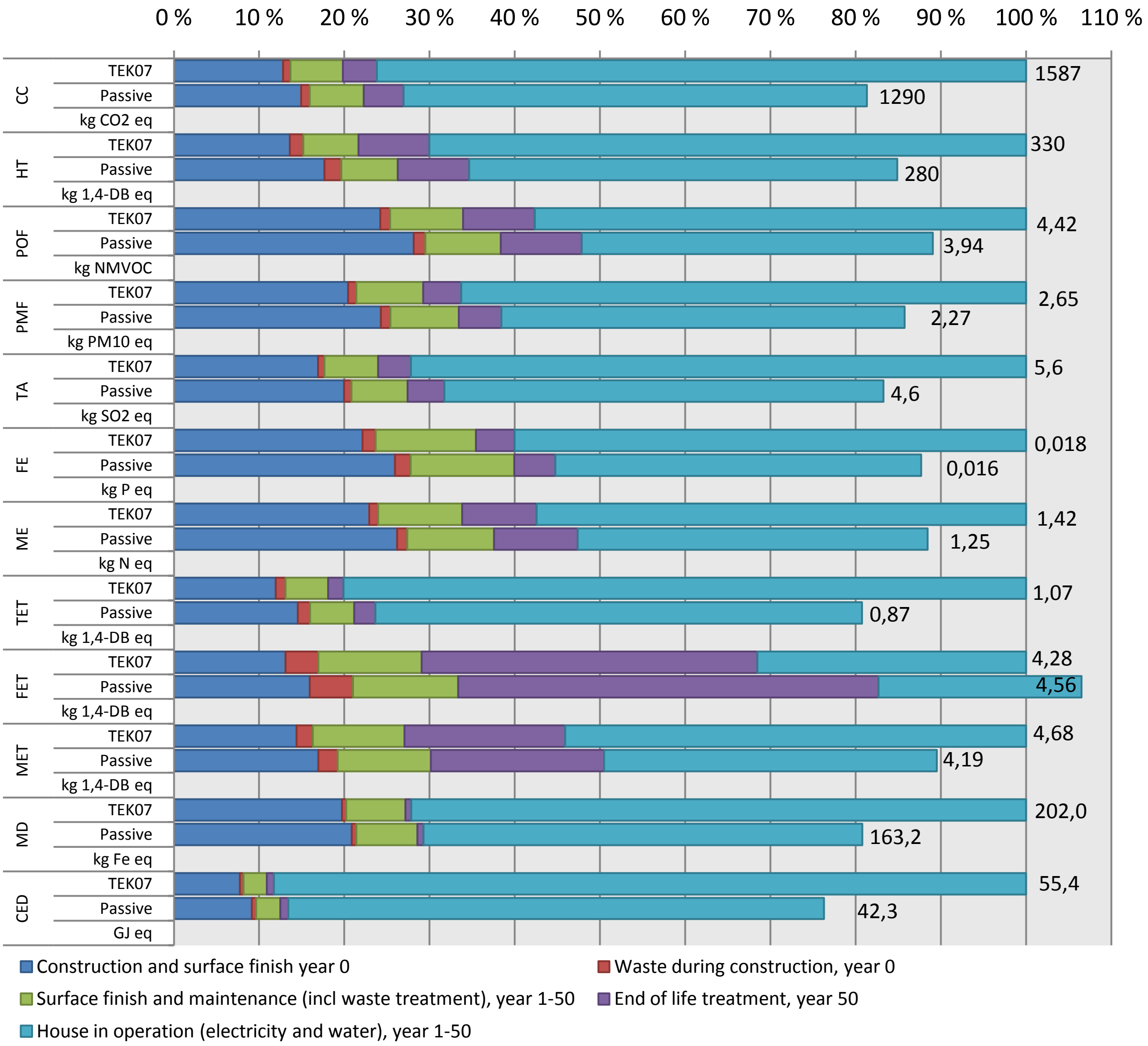


Figure 6-1: Total life cycle impacts for the TEK07 house and passive house

Figure 6-1 is quite interesting. It shows that all of the life cycle phases, except house in operation, have a higher contribution for the passive house in all impact categories. This is obvious, since the passive house has a higher material input than the TEK07 house, and thus more impacts. In the climate change category for the TEK07 house are 13% of total impacts from the construction phase. Waste during construction contributes with 1%, maintenance of surface finish 6%, end of life treatment 4% and house in operation 76% of total CO_2 eq impacts. For the passive house this is 19%, 1%, 7%, 6% and 67% respectively, with a total of 81% of TEK07 house climate change impacts. It is interesting to observe, that by increasing construction and end of life treatment climate change impacts with 13%, from 381 kg CO_2 eq to 426 kg CO_2 eq, an overall reduction from the TEK07 house climate change impacts of 19% is possible. When excluding the house operation climate change impacts, 55-60% is from the construction phase and 40-45% from waste treatment and house maintenance.

The relative share of impacts is around the same for the first 8 categories, as for the climate change category. Total impacts are around 15% lower for the passive house than the TEK07 house, in these categories. For the freshwater ecotoxicity impact category, the passive house has actually 7% more impacts than the TEK07 house. For both this category and the marine ecotoxicity category, the end of life treatment phase is a much larger contributor than in the other categories. This is mainly due to incineration of polystyrene products (EPS/XPS) and steel (in wood) pieces, as well as disposal of inert materials (concrete/bricks) to inert landfill. As there is more material in the passive house, there will be more treatment of waste. A deeper analysis of this is provided in chapter 6.3.1.

It is almost zero impacts from waste treatment in the metal depletion potential category. This is the extraction of Fe equivalents as raw material and thus has insignificant impacts from sorting or incinerating materials. The TEK07 operation phase contributes with 88% of the cumulative energy demand, while the contribution is 83% for the passive house.

A passive house has in general a reduction between 10-20%, with an average of 13%, in all impact categories, based on the assumption of 100% electrical energy for heating.

6.1.2 Total lifecycle, single score – endpoint

A single score, endpoint indicator, is presented in figure 6-2. The endpoint indicator Europe ReCiPe H/A, hierarchist average endpoint method version 1.03 is used. "It refers to the normalization values of Europe, with the average weighting set" (RIVM et al., 2009).

"Midpoint impact assessment continues to support more scientifically based decision analysis. Endpoint and damage analysis provides additional support when a smaller or single environmental indicator is desired. Many of the recent proposals attempt to develop both midpoint and endpoint analyses which are consistent in framework." (Bare, 2009)

Categories defined as others are: ozone depletion, photochemical oxidant formation, ionizing radiation, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, urban land occupation and metal depletion.

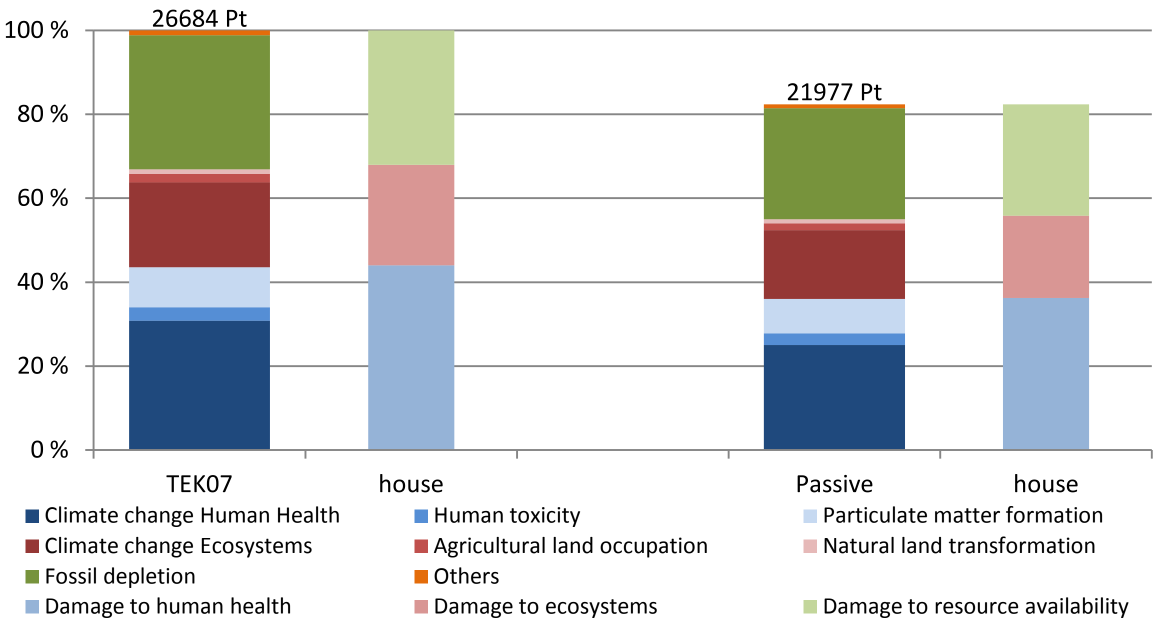


Figure 6-2: Single score, endpoint indicator, with the normalization values of Europe and the average weighting set

For each house, the total score is in the column to the left divided into several categories, as climate change to human health, human toxicity, etc. There are three big contributors from the categories: climate change human health (30%), climate change ecosystems (20%) and fossil depletion (32%). These contributors are aggregated into the three damage categories in the right column: 44% damage to human health, 24% damage to ecosystems and 32% damage to resource availability. Particulate matter formation is also a relative large contributor to damage to human health.

According the normalization values of Europe and the average weighting set, the passive house has a reduction of 18% damage to human health, ecosystems and resource availability, compared to the TEK07 house.

6.2 Life cycle results disaggregated

The 5 lifecycle stages from figure 6-1 are in the following chapters disaggregated to find the contributing elements.

6.2.1 Construction and surface finish year 0, including waste during construction

Figure 6-3 presents the impacts from the construction phase and surface finish for year 0, including waste treatment for the waste that occurs during the building constructions, divided into the contributing elements. The largest contributor to climate change is the floor with 21% for the TEK07 house. For the passive house, both the floor and walls each contributes with 20% of the total CO_2 eq.

The passive house has between 15-30% higher impacts in all impact categories, except for metal depletion, compared to the TEK07 house.

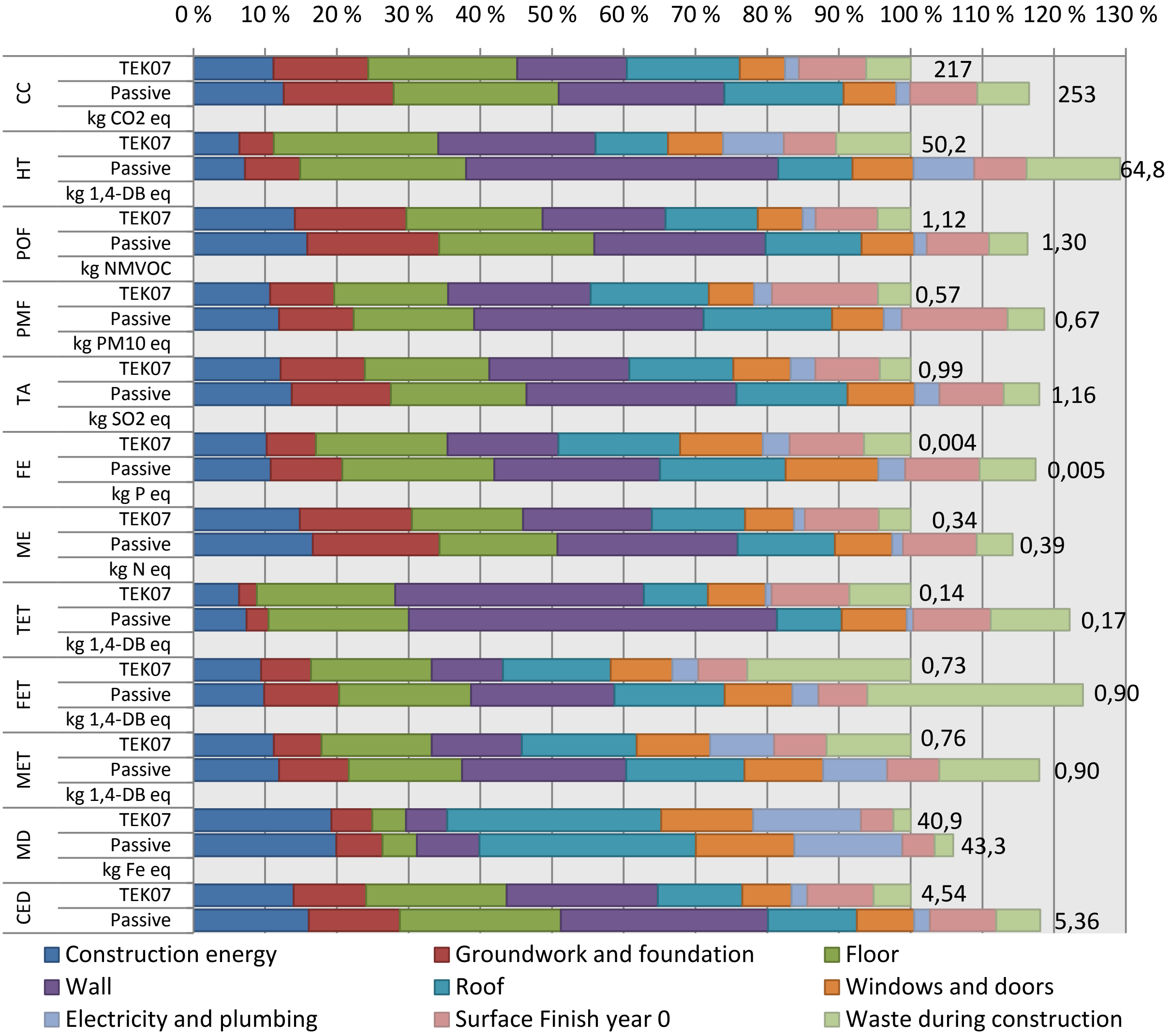


Figure 6-3: Impacts from construction and surface finish year 0, including waste during construction

Climate change impacts to construction, surface finish and waste treatment during the construction is a total of 217 kg CO_2 eq/m^2 for the TEK07 house and 253 kg CO_2/m^2 eq for the passive house, per m^2 useful floor, a difference of 36 kg CO_2 eq.

Construction energy, groundwork and foundation, floor, walls and roof are the five major elements for the house construction, with 60-70% of impacts in all categories.

Windows and doors, and surface finish year 0 have relatively the same share of impacts, with 5-10% each in all categories. Electricity and plumbing have less than 5 % of total impacts, except for metal depletion which is over 10%. For the waste treatment, the contribution is around 5% in all categories except human toxicity and terrestrial-, freshwater and marine ecotoxicity.

The main difference between the TEK07 and passive house is the impact share from groundwork and foundation, and the walls. This is, for climate change, due to more EPS and reinforcing steel for the passive house in the foundation, and more mineral wool in the walls.

Impacts to climate change for the passive house construction phase are further analyzed.

Elements contributing to the floor are the ground level floor (64%) and 1st level floor (35%), and for the walls the outer walls (84%) and inner walls (16%).

In the groundwork and foundation the elements are gravel, drainage and radon pipes (34%), the foundation wall 33% and excavation (17%). As for the construction energy, 45% of the 10% impacts are from energy requirements for the drying process. 30% is from combustion of diesel in machines and 15% from transport of workers.

The main elements in the surface finish in year 0 are bathroom (51%), parquet floor (28%) and indoor wall painting (9%). In the treatment of waste from the construction phase, waste from the floors (38%), walls (24%) and surface finish (16%), are the biggest contributors.

6.2.2 *Surface finish and maintenance (including waste treatment), year 1-50*

Figure 6-4 shows the impacts for the surface finish, maintenance and waste treatment of these materials during the buildings lifetime. Chapter 5.2.1 provides a description of the different elements. The total impacts are almost the same for the TEK07 house and passive house, the latter with 2-3% higher impacts is all categories. Production of different windows, and doors, are responsible for the increased impacts for the passive house.

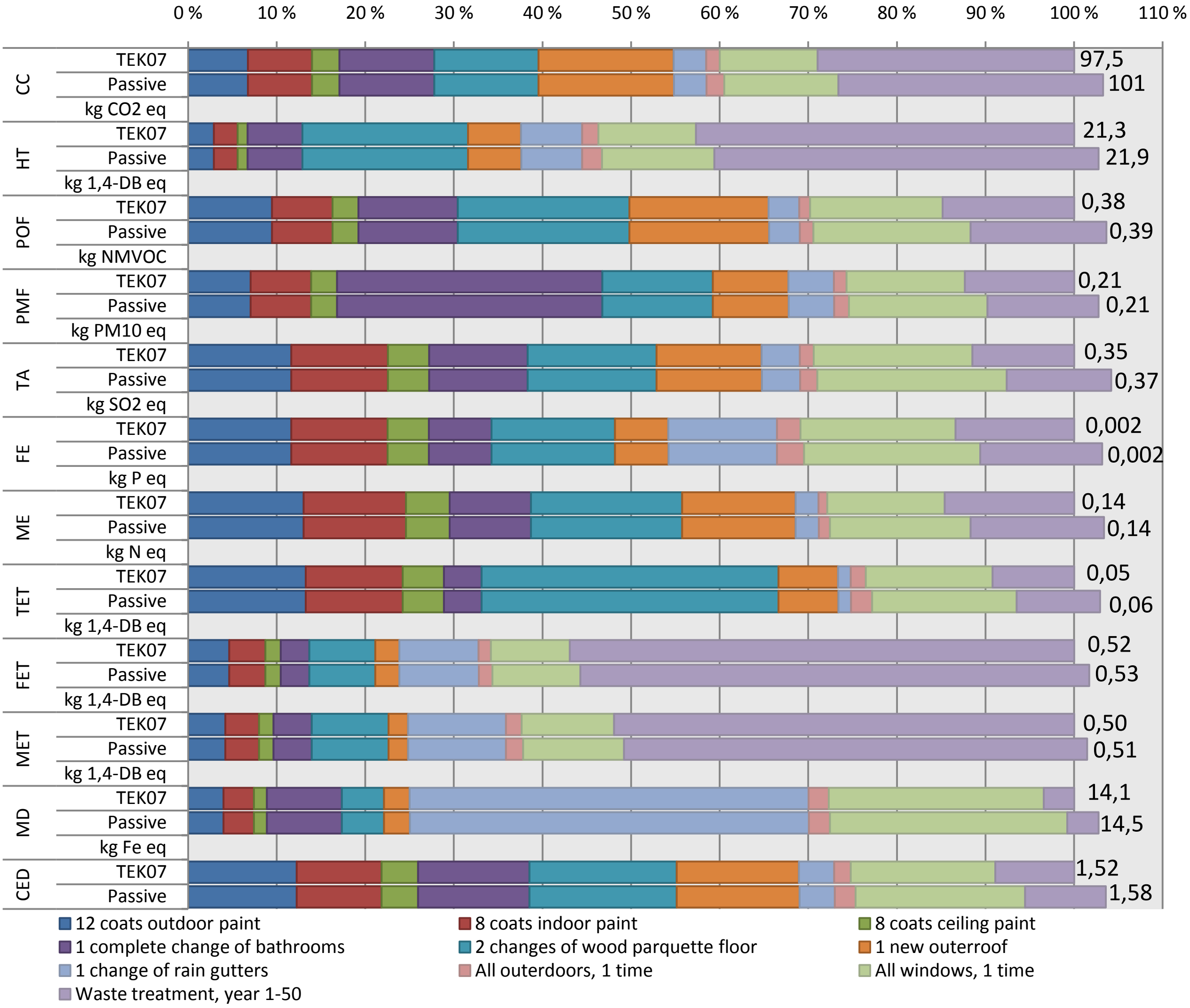


Figure 6-4: Impacts from surface finish and maintenance (including waste treatment), year 1-50

For climate change, human toxicity, freshwater and marine ecotoxicity, the waste treatment process is the largest contributor. Waste treatment is also on average the largest contributor with 23% in all categories. A complete change of windows during the lifetime is the element causing most impacts in all categories with 16%. Renovation of bathrooms, wood parquet floor and outer roof is also relatively large is some impact categories.

6.2.3 *End of life treatment, year 50*

The end of life treatment of the house is also disaggregated to get an overview of the contributing elements, figure 6-5. There is an increase in impacts of around 10% from the TEK07 house to the passive house, for all impact categories except terrestrial eco toxicity category. This is also shown in figure 6-1, where this is the only category having overall higher impacts for the passive house than TEK07 house.

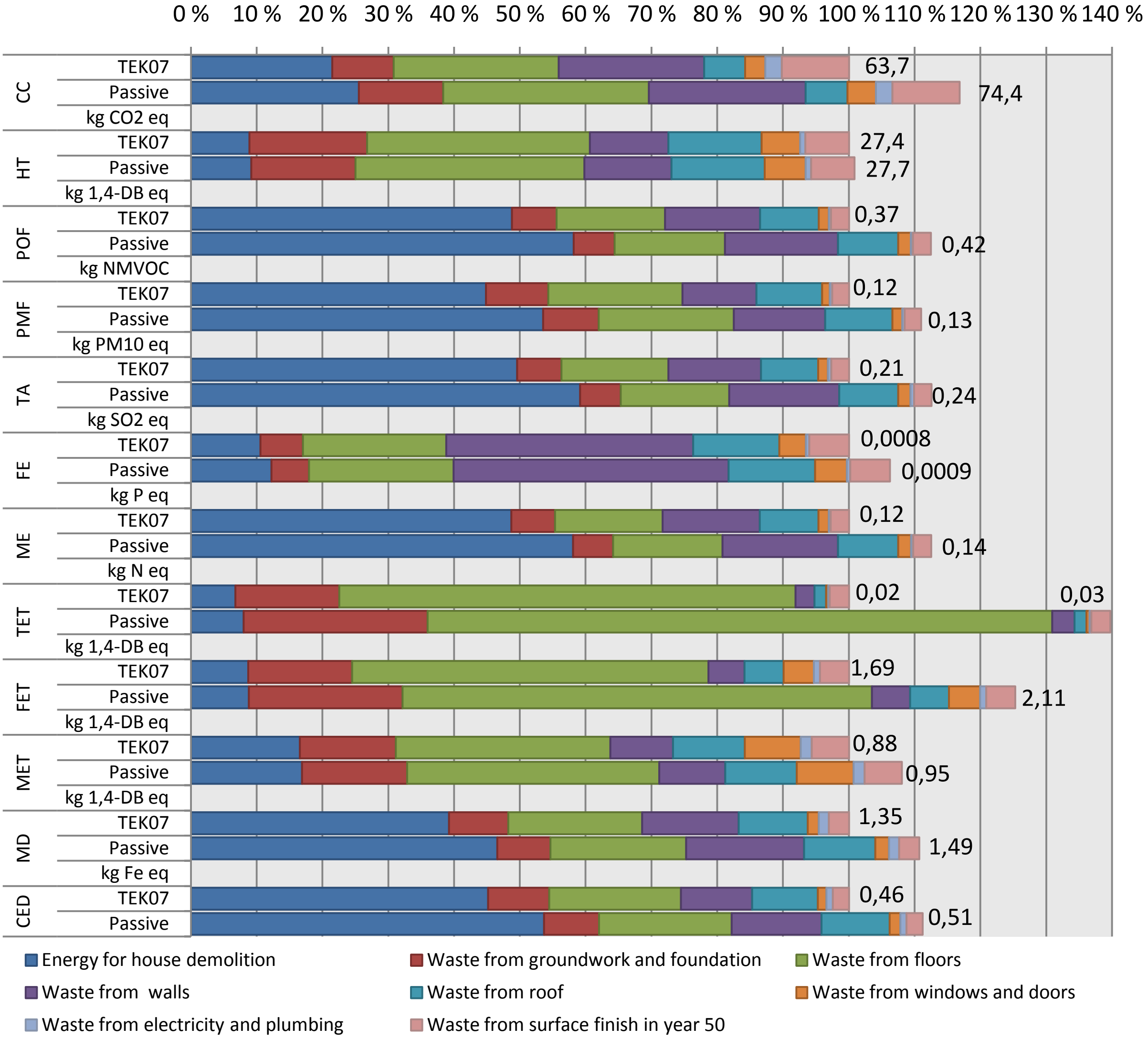


Figure 6-5: Impacts from the end of life treatment of the houses

Energy for house demolition is a large contributor in all categories. This energy is diesel burned in building machines and transportation of excavator. The other big contributor to waste treatment impacts is waste from floors. Disposal of concrete to a sorting plant and incineration of expanded polystyrene are the activities most responsible for these impacts. A deeper analysis of the contributing activities and stressors are presented in chapter 6.3.1.

Waste treatment of the groundwork and foundation, walls and roof are also elements responsible for impacts.

6.2.4 *House in operation (electricity and water), year 1-50*

The house in operation life cycle phase is presented in figure 6-6. It is clearly to see which element contributes to most of the impacts. Electricity consumption is responsible for almost all impacts in all categories, except in the freshwater ecotoxicity category. Processes for the water supply network and waterworks are responsible for the increased share in this category. The passive house has 70% less impacts than the TEK07 house, in all categories.

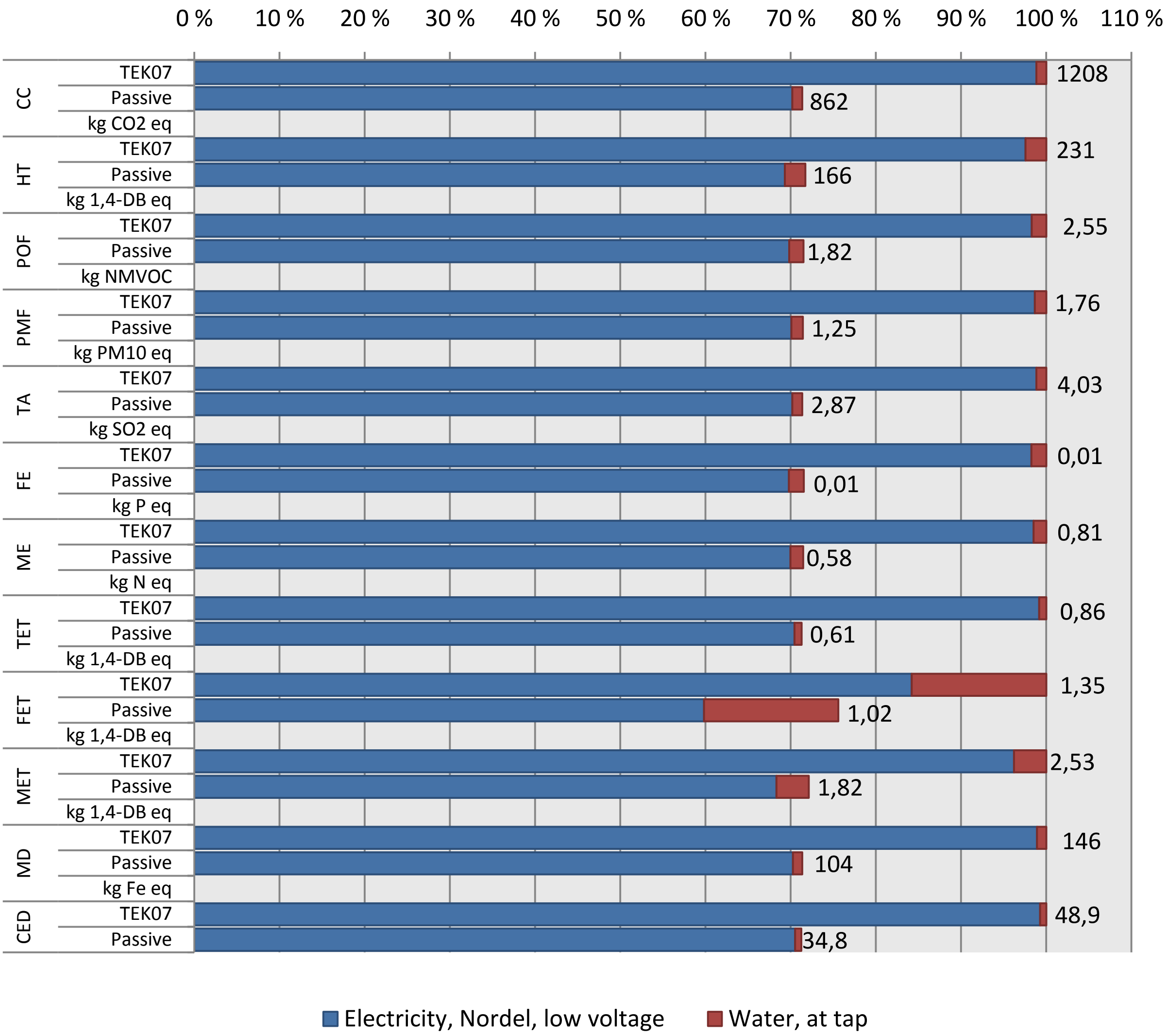


Figure 6-6: Impacts from operation of the houses

6.3 Analysis

The life cycle impacts of constructing, maintain and waste treat the Stord TEK07- and passive- house in Norway is further analyzed. It is of interest to find the activities and stressors contributing significantly to the results, and where in the supply chain these activities are. An advanced contribution analysis is performed to get a more thorough understanding of the system. A sensitivity analysis is also carried out to find out how the total impacts varies when some input parameters are changing, how robust the analysis is.

Figure 6-7 presents the yearly climate change impacts, pr year (kg CO_2 eq/(m^2 year)) and accumulated throughout the houses lifecycle (kg CO_2 eq/m^2). Highest impacts occur during the construction of the house, in year 0. The passive house has around 40 kg CO_2 eq higher impacts during the first year. Impact of maintenance is added in regular intervals, with higher impacts in year 20, 30 and 40. The passive house has around 7 kg lower climate change impacts each year during the operation phase, years 1 to 50.

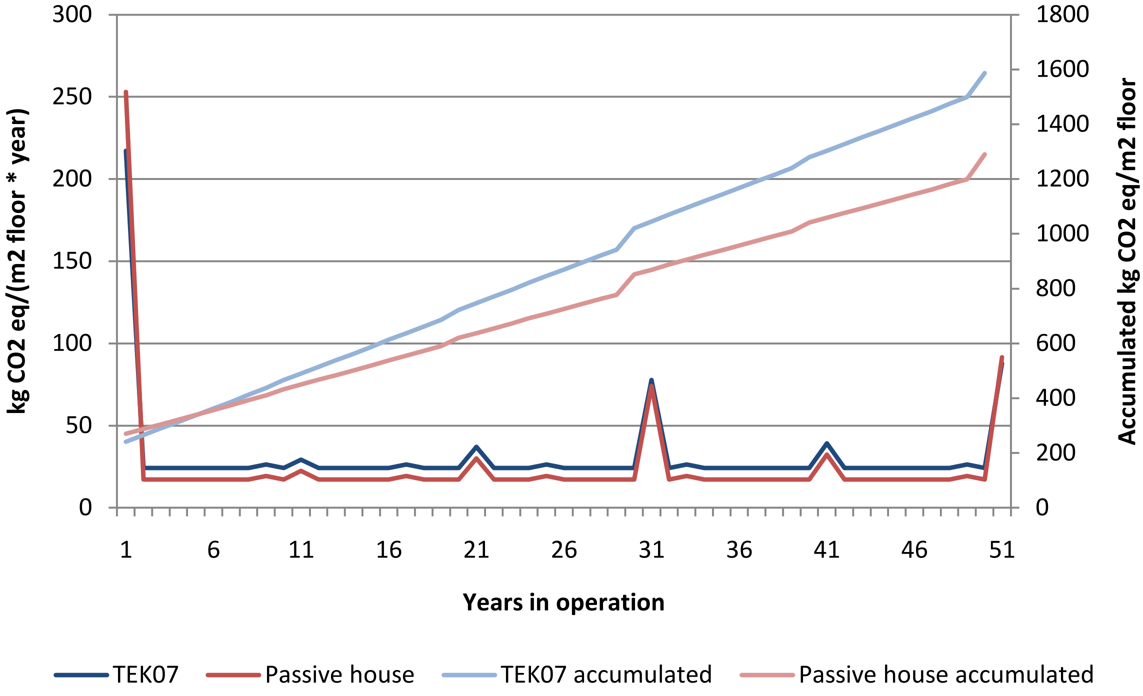


Figure 6-7: Yearly impacts to climate change for the Stord houses, pr year and accumulated

The point where the two accumulated lines cross is when the increased 40 kg CO_2 eq from the passive house construction compared to the TEK07 house construction is offset by an annual reduction of 7 CO_2 eq, due to reduced electricity consumption in the passive house. For the Stord houses, this time is theoretically 5 years, 1 month and 20 days. This mean, when constructing a passive house and assuming both houses are using the same electrical heating system, it takes only 5 years before the increased material production and transport for the passive house are equalized the TEK07 house climate change impacts.

6.3.1 *Advanced contribution analysis*

All impact categories are broken down to find out which activities and stressors cause the different impacts. The breakdown of contributing processes is done in SimaPro (Pre, 2008) and is an effective way to analyze the overall system. The network tree available in SimaPro is further assessed to analyze where in the supply chain the impacts originate.

The house operation phase (electricity and water consumption during the use phase) is not included in these analyses. The house operation phase has a share of 76% and 67% of the climate change impacts for the TEK07 house and passive house respectively, and have relatively same share for the other impacts categories as wall. By including the house in operation in this analysis, the results would only show impact for electricity production, and not impacts related to the house construction, maintenance and waste treatment.

Processes included in this advanced contribution analysis are house construction, waste during construction, surface finish and maintenance year 1 to 50, demolition and end of life treatment. Contribution of the following activities and stressors are relatively almost the same for both the TEK07- and passive- house, some activities changing 0-2% in some impact categories. Therefore, the presented activities and stressors are an average for both the TEK07- and passive- house.

All transportation associated to the Stord house is aggregated into one activity: Stord transportation. This is transportation of materials (lorry 20-28t) to construction site and for maintenance materials, waste to treatment plant (lorry 3,5-16t) and workers back and forth during their homes and the construction site for the house building and demolition.

6.3.2.1 *Climate change*

Table 6-2 shows the different activities and stressors causing the climate change impacts. 18% of all CO_2 eq impacts are from Stord transportation and diesel burned in building machines. These impacts are linked to CO_2 emissions from combusting fossil diesel in the engine.

Table 6-2: Main activities and stressors causing climate change impacts

Activity		*Contribution of total impact*
Stord transportation		12%
Disposal, paint, to municipal incineration		7%
Diesel, burned in building machine		6%
Clinker, at plant		5%
Disposal, expanded polystyrene, to municipal incineration		5%
Polystyrene, expandable, at plant		4%
Stressor	*To compartment*	*Relative impact*
Carbon dioxide, fossil	Air	92%
Methane, fossil	Air	5%

Disposal of paint and expandable polystyrene (EPS) to a municipal incineration plant have 12% of the impacts, while clinker at plant, which is a main ingredient in cement (and rock wool), and EPS have 9% of total impacts. The passive house has a lower share of polystyrene impacts, and larger impact for paint incineration than the TEK07 house.

Fossil CO_2 and methane to air are responsible for 97% of total climate change impacts.

6.3.1.2 Human toxicity

Activities and stressors contributing to human toxicity are presented in table 6-3. Disposal of inert material and wood ash to a sanitary landfill and land farming, and incineration of wood, are main activities with 49% of total impacts.

Disposal of concrete and building bricks are the biggest contributors to the inert material landfill impact. Wood ash impacts are from the incineration of wood, both from furnace heat during timber production and end of life treatment of wood products. The impacts from copper are mainly from electrical cable used in house, but also for the electrical distribution network. Manganese, phosphorus, mercury and arsenic ion are the stressors contributing the most, with 68%, to water, soil and air.

Table 6-3: Main activities and stressors causing human toxicity impacts

Activity		*Contribution of total impact*
Disposal, inert material, to sanitary landfill		19 %
Disposal, wood ash mixture, pure, to sanitary landfill		13 %
Disposal, wood ash mixture, pure, to landfarming		10 %
Disposal, wood untreated, to municipal incineration		7 %
Copper, primary, at refinery		6 %
Stressor	*To compartment*	*Relative impact*
Manganese	Water	37 %
Phosphorus	Soil	11 %
Mercury	Air	11 %
Arsenic, ion	Water	9 %

6.3.1.3 Photochemical oxidant formation

Main activities that contribute to the photochemical oxidant formation impact category are Stord transportation (25%) and diesel, burned in building machine (19%). A total of 45% of the photochemical oxidant formation impacts are related to direct diesel combustion in transportation to or on the construction site.

Main stressors are nitrogen oxides (NO_x – 76%) and non-methane volatile organic compounds (NMVOC – 15%) to air.

6.3.1.4 Particulate matter formation

Combustion of diesel in building machines and Stord transportation contributes with 24% of total particulate matter formation (PMF) impacts, table 6-4. Basalt is a volcanic rock used in rock wool production. 9% of the PMF impacts originate from ceramic tiles production. Nitrogen Oxides (NO_x) and particulates 0<10 um, to air, are the stressors responsible for 84% of total impacts. Sulfur dioxide (SO_2) is contributing with 14% of total PMF impacts.

Table 6-4: Main activities and stressors causing particulate matter formation impacts

Activity		*Contribution of total impact*
Diesel, burned in building machine		12 %
Stord transportation		12 %
Basalt, at mine		11 %
Ceramic tiles, at regional storage		9 %
Stressor	*To compartment*	*Relative impact*
Nitrogen oxides	Air	35 %
Particulates, < 2.5 um	Air	30 %
Particulates, > 2.5 um, and < 10um	Air	19 %
Sulfur dioxide	Air	14 %

6.3.1.5 Terrestrial acidification

The contributing activities and stressors for the terrestrial acidification (TA) potential are found in table 6-5. The main activities are Stord transportation (15%) and diesel burned in building machines (12%). Production of rock wool is contributing with 8% of total impacts. Natural gas, sour, burned in production flare is from the production of crude oil production, which again is raw material for diesel production. Titanium dioxide sulphate is further processed to white pigments used in paint production. Another 3% of impacts are from production of expandable polystyrene.

Airborne nitrogen oxides (NO_x) and sulfur dioxide (SO_2) emissions are 92% of all stressors contributing to TA impacts.

Table 6-5: Main activities and stressors causing terrestrial acidification impacts

Activity		*Contribution of total impact*
Stord transportation		15 %
Diesel, burned in building machine		12 %
Rock wool, at plant		8 %
Natural gas, sour, burned in production flare		5 %
Titanium dioxide at plant, sulphate process, at plant		4 %
Polystyrene, expandable, at plant		3 %
Stressor	*To compartment*	*Relative impact*
Nitrogen oxides	Air	51 %
Sulfur dioxide	Air	41 %

6.3.1.6 Eutrophication

For freshwater eutrophication, the main activities are disposal of basic oxygen furnace wastes to a residual material landfill (29%), disposal of pure wood ash mixture to land farming (15%) and disposal of untreated wood to a municipal incineration plant (9%). The disposal of oxygen furnace wastes to a landfill is from the production of low alloyed- and reinforced- steel. Ash to land farming is waste from wood chips burning in furnace for timber production.

The main stressors are phosphate to water (74%) and phosphorous to soil and water (16% and 10% respectively).

Main contributors for marine eutrophication potential (ME) impacts are Stord transportation (28%) and diesel burned in building machines (20%). Other activities are process-specific burdens in municipal waste incineration and wood chips, from forest, mixed, burned in furnace 300kW.The process specific burdens in the incineration plant are due to wood burning as the end of life treatment of timber materials in the houses.

The main stressor contributing to ME is nitrogen oxides (NO_x) to air, with 92% of all impacts.

6.3.1.7 Ecotoxicity

Impacts from terrestrial (TET), freshwater (FET) and marine (MET) ecotoxicity impacts are presented in table 6-6.

Disposal of wood ash to land farming is the highest contributor to terrestrial ecotoxicity, with 67% of the impacts. Burning wood chips in an industry furnace used for drying timber is the activity contributing the most to this impact. Disposal of expandable polystyrene (EPS) in a incineration plant has impacts in all three ecotoxicity indicators, with highest contribution in the freshwater ecotoxicity indicator.

Disposal of concrete and building bricks to an inert material landfill are the activities contributing most to the inert material to landfill ecotoxicity impacts. Disposal of steel to incineration plant has 9% and 12% of the freshwater and marine ecotoxicity impacts. This disposal is mainly from screws, nails and other steel parts in wood products that are not removed before the incineration process. Disposal of paint to an incineration plant is also contributing to the freshwater and marine ecotoxicity impacts.

Table 6-6: Main activities and stressors causing impacts to ecotoxicity

Activity		*Terrestrial*	*Freshwater*	*Marine*
Disposal, wood ash mixture, pure, to land farming		67 %	-	-
Disposal, expanded polystyrene, to municipal incineration		10 %	40 %	11 %
Disposal, inert material, to sanitary landfill		-	12 %	16 %
Disposal, steel, to municipal incineration		-	9 %	12 %
Disposal, paint, to municipal incineration		-	5 %	7 %
Stressor	*To compartment*	*Terrestrial*	*Freshwater*	*Marine*
Phosphorus	Soil	71%	-	-
Nickel, ion	Water	-	26%	36%
Bromine	Water	10	41%	9%
Vanadium, ion	Water	-	11%	16%

Terrestrial ecotoxicity stressors are phosphorous to soil and bromine to water. Nickel ion, bromine and vanadium ion are stressors to freshwater and marine ecotoxicity. For the nickel ion stressor, the main activity is burning of steel waste (in wood products) in an incineration plant and disposal of smelter slag to landfill from steel production. The bromine stressor is from the EPS/XPS waste incineration process.

6.3.1.9 Cumulative energy demand

The shares of fossil and renewable energy consumed in the two houses are presents in figure 6-8. This chart is divided into two parts, one part showing cumulative energy used for the life cycle phase assessed in the advanced contribution analysis, and the other part showing the total life cycle (including electricity and water in the operation phase) of both houses. For the first part, mainly non renewable fossil energy is consumed. Energy consumed in the total lifecycle is one third non renewable fossil, one third non renewable nuclear and one third renewable (both biomass and water) energy.

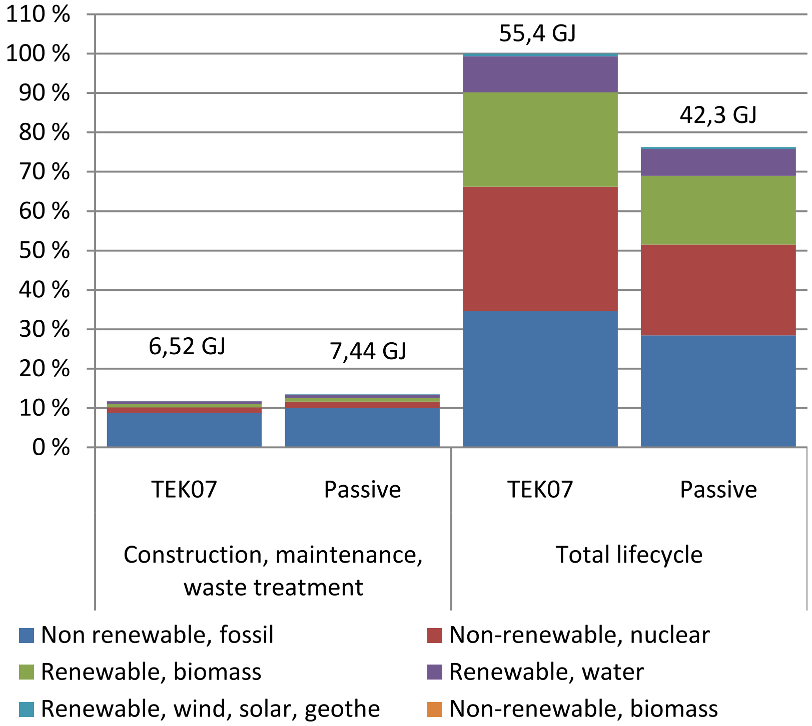


Figure 6-8: Share of fossil, nuclear and renewable energy in the lifecycle

6.3.2 *Climate change impact from transportation*

The different shares of transportation directly linked to the construction of the Stord passive house is shown in figure 6-9. Transportation of material to the construction site and house maintenance is responsible of three quarters of the total transportation impacts. Compared to the construction, maintenance and waste life cycle phase, the climate change transportation impacts are responsible for 15% of total CO_2 eq.

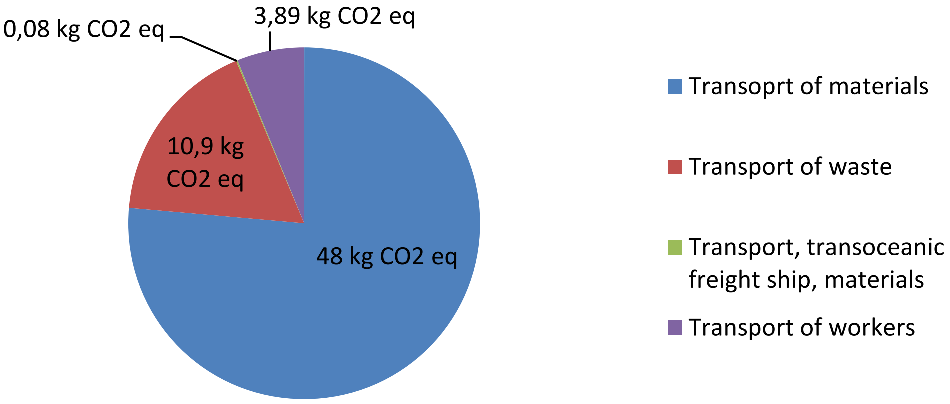


Figure 6-9: Share of transportation for the climate change impacts

17% of the total transportation climate change impacts are from transportation of waste products, both during the construction and after end of house life. Transportation of workers is 6% of the total transportation CO_2 eq impacts. Mostly all products are produced in Norway and do not use the ferry from Denmark to Norway, thus the low impacts from this category.

6.3.3 Sensitivity analysis

A sensitivity analysis is provided to see how the system reacts on changes in different input parameters. The following sensitivities are analyzed:

- Energy for a construction dryer
- House maintenance frequency sensitivity
- Norway, Nordel and UCTE operation electricity mix
- Implementation of different heating systems for both houses

6.3.3.1 Sensitivity of energy for dryer

As presented in figure 5-1, there is a quite a big difference in the total energy required for construction drying. The sensitivity of different energy requirements for a construction drier is calculated. This provides an understanding of how a change in the dryer power consumption and time has for the overall lifetime impacts. Climate change impacts and cumulative energy demand are considered for the following scenarios.

The baseline scenario and changes of total climate change impacts are based on the passive house impacts.

The energy requirements for this sensitivity analysis are taken from figure 5-1. A dryer with an effect of 1 kW for 2 weeks as a minimum and 9 kW for 12 weeks as a maximum is considered. This power consumption and period of time should cover most of the different drying methods.

Table 6-7: Sensitivity of climate change impacts due to different dryer energy requirements

Scenario	*Energy [kWh]*	*CC impacts [kg CO_2 eq]*	*CED [GJ eq]*	*Changes of CC impacts from construction*	*Change of CC impacts from total house lifecycle*
Min: 1kW, 2 weeks	500	0,57	0,02	-3,6%	-0,7%
Baseline, 6 kW, 8 weeks	8000	9,09	0,37	-	-
Max: 9kW, 12 weeks	18000	20,4	0,83	+4,8%	+0,9%

Table 6-8 presents the results. The climate change impacts are from 0,6 kg CO_2 eq/m^2 for the 500 kWh drier consumption to 20 kg CO_2 eq/m^2 for the 18000 kWh drier consumption. When using the dries as today, the impacts are 9 kg CO_2 eq/m^2 floor.

When just considering the construction of the house life cycle phase, factors deciding the different construction drier methods are in the range of 20 kg CO_2 eq/m^2 floor. When reducing power and time consumption from the baseline scenario to the minimum, a reduction of 3,6% of climate change impacts is possible. If the power and time consumption is increased to a maximum, 4,8% more kg CO_2 eq/m^2 floor is emitted.

This difference, compared to the total passive house lifecycle impacts, is around 1% plus or minus from total climate change impacts. This mean, for an optimal scenario where the materials are protected from rain and snow at the construction site and the lowest power and time for construction drier is used, 0,7% of total house climate change impacts can be reduced.

6.3.3.2 Surface finish and house maintenance sensitivity

Surface finish and maintenance, including waste treatment from year 1 to 50, contributes with 7% of total life cycle climate change impacts for the passive house. The surface finish and house maintenance frequency is in the baseline study based on the assumption that the technical lifetime of the different elements decides the changing time.

There is an ongoing discussion about what to include when it comes to surface finish and maintenance of a building. It is on a general level difficult to have a standard, as this phase it totally dependent on the user. For example if the user is by mind and action really conscious about making environmentally good choices, the building surface finish frequency will possibly be affected from that mindset compared to a user who does not have the same aspects and follows all the recent interior design fashions.

How often should the walls and ceilings be painted? What about a complete bathroom renovation or new kitchen design?

One way to analyze this is to follow the technical service life of the products. By following the technical lifetime given by the producer for every product in the house, a reasonable interval for when a product must be replaced is estimated. A product has also an esthetical lifetime. By following the latest trends and design, a wall color or floor cover can be changed before the technical lifetime occurs. On the other hand, a product can also be in used longer than the intended technical lifetime.

Another way to determine the actual replacement of building components is to access the National Statistics Companies; in Norway Prognosesenteret. By comparing information on annual sales reports of building materials against totally new constructed floor area for a given year, it is possible to obtain the share of building material going to new construction and the old building stock. (KlimaTre, 2011)

The Norwegian Social Research, NOVA (NOVA, 2010) has researched the conditions for living and residences in Norway 2007, and has found that around 10% of the 3212 households asked had changed the floor, wall or ceiling materials the recent year. Change of windows and doors, and renovation of a bathroom was also an activity done the recent year by around 10% of the households who attended the survey. "When renovating a bathroom, often the whole room is renovated and not just pasts of it.[…] a bathroom is assumed to have [compared to a survey numbers from 2004]an average lifetime of 20 years" (NOVA, 2010p. - 43).

When changing the elements lifetime, it is possible to see the overall effect on different lifetimes. Two scenarios are investigated, one assuming a short product lifetime and the other assuming a long lifetime, as presented in table 6-9. The assumptions for the short lifetimes are based on a house user that follows new interior design. The user redecorates the all walls often. Bathrooms and floor covers are also renovated with a higher frequency than the base scenario. Roof tiles and rain gutters follow the baseline lifetime, as these products are not assumed to be replaced before the end of their technical lifetime. Windows and outer doors have also a shorter lifetime in one scenario.

A user in the long service life scenario extends the technical lifetimes to the maximum. Exterior and interior painting is not frequent. For all other elements that requires maintenance, it is assumed a lifetime that lasts the lifetime for the house.

Table 6-8: Service life for components when assuming short and long lifetime

Component	*Short service life, [yr]*	*Service life baseline [yr]*	*Long service life [yr]*
Paint indoor wall	5	10	20
Paint ceiling	5	10	20
Paint outdoor	5	8	15
Bathroom	15	30	50
Floor covering	10	20	50
Roof tiles and under roof	30	30	50
Rain gutter and snow protector	30	30	50
Windows and outer doors	20	30	50

Results:

Table 6-10 presents the results from the different lifetime scenarios. The results are given for climate change impacts and cumulative energy demand. Chances of climate changes impacts are relative to the impacts from baseline service life and the total passive house life cycle CO_2 eq impacts.

Table 6-9: Sensitivity of climate change impacts due to different lifetime scenarios

Scenario	*CC impacts [kg CO_2 eq]*	*Cumulative energy demand [GJ eq]*	*Changes of CC impacts from baseline*	*Total house lifecycle change of CC impacts*
Short service life	221	3,49	+70%	+7%
Baseline service life	130	2,05	-	-
Long service life	46,0	0,69	-35%	-6%

Impacts of climate change are between 46 and 220 CO_2 eq/m^2, comparing the different service lives. Considering just the impacts from the surface finish and house maintenance sensitivity life cycle phases, different service lives changes the result from -35% to +70%. Compared to the total passive house CO_2 eq impacts, a change of service life scenario and house user maintenance frequency results in a range of -6% to +7% from the baseline scenario.

When not considering the electricity consumption, the user can affect the total climate change impacts of the house lifecycle in a range of -6% to +7%, depending of the frequency of surface finish and maintenance of the house.

6.3.3.3 Norway, Nordel and UCTE operation electricity mix

Figure 6-10 shows the total life cycle impacts for both houses, with three different electricity mixes considered. The notations T and P are for the TEK07 house and passive house respectively, while NO, NOR and UCTE stand for the Norwegian-, the Nordel - and the UCTE- electricity mix, se figure 5-5 as a reference. All numbers are normalized to the TEK07 house consuming the Nordel electricity mix (baseline study - T-NOR), for each impact category.

This scenario is quite interesting. The more impact intensive the energy mix pr produced kWh is, the bigger the difference between the TEK07 and passive house impacts is. The Passive house has relatively much lower total impacts for all categories compared to the TEK07 house when the UCTE mix is considered. A passive house is clearly environmentally beneficial in a lifecycle analyses that just considers the UCTE mix.

When the UCTE electricity mix is assumed, the passive house has 25% less impacts to climate change compared to the TEK07 house. It is only when considering the UCTE electricity mix that the passive house has less impacts in the freshwater ecotoxicity potential. For both the Norwegian and Nordic electricity mix, the passive house has more impacts in this category.

Considering the Norwegian electricity mix, the passive house has 4% increased CO_2eq impacts compared to the TEK07 house. The passive house has also higher impacts in several others categories as well, in this scenario.

One could from this graph conclude that passive houses are not environmental beneficial, compared to the TEK07 house, in a region that produces and consumes only clean and renewable energy. If the production of energy has no impacts, it does not matter how much energy that is consumed anyway. An example from Ekvall et al. (2005) highlights this issue.

Consider a house or region connected to small hydropower plant (or for example photovoltaic cells) that is adapted to the local consumption. This electricity production and consumption is nearly emission free when this area is self-sufficient with electricity. The power plant can sometimes produce more electricity that this area consumes, and is thus connected the national grid to sell this excess electricity from its production. The consequence then, when using electricity in this region, is that less electricity produced from this hydropower plant might not be available to the national grid, and thus more electricity needs to be produced from other sources. It is therefore no environmental difference in consuming electricity in this region or from anywhere else in the national grid system. In an analysis, this problem can be avoided if the region is not connected to the national grid and thus cannot sell excess electricity. As a further consequence, less renewable electricity is available on the marked. What was planed as god for the total environment is not analyzed as good in this system if one does not take into account the marginal changes and production capacity the small hydropower plant has. (Ekvall et al., 2005)

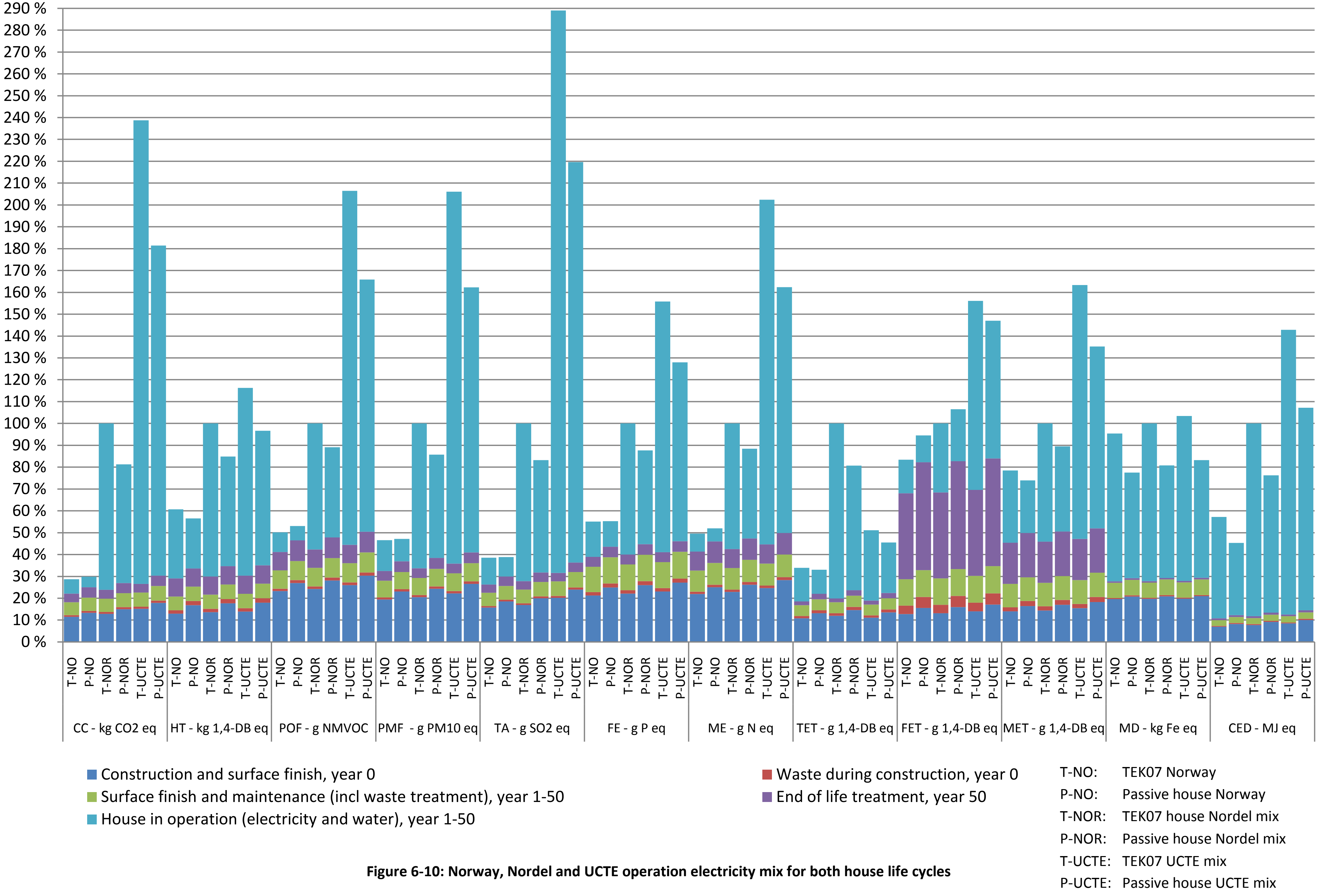


Figure 6-10: Norway, Nordel and UCTE operation electricity mix for both house life cycles

If producing electricity in Norway and continental Europe is assessed, the *other production sources* for electricity could be coal, gas and nuclear power plants. (Ecoinvent, 2007). What this thesis does not include is the effect of selling excess (clean Norwegian) electricity to other markets. As the cumulative energy demand category shows, the passive house uses less energy pr m^2 for the whole life cycle for all three electricity mixes. When considering future scenarios the goal should always be to, in general, use as little energy as possible and with a high share from renewable sources. The excess clean energy can be sent to other regions which not have that clean energy production

Even though the passive house has, with the given system boundaries, slightly higher climate change impacts that the TEK07 house, a system considering the Norwegian electricity mix is considerably more environmental beneficial than considering the other electricity mixes. Overall reduction is 70% of impacts to climate change when considering the TEK07 house from the Nordic to Norwegian electricity mix. This reduction is 60% for the passive house.

6.3.3.4 Implementation of different heating systems for both houses

It is assumed that both the TEK07- and passive- house have the same heating system and that the total energy need is covered with 100% electricity. This assumption does not reflect the real situation for these houses, since the building codes requires a certain amount of energy for space heating and warm water must be covered from alternative sources. (TEK, 2007, NS, 3700:2010)

These alternative sources can be central- or district- heating systems, different heat pumps, pellets-, wood- or bio- stoves, or biogas system. (TEK, 2007). The solutions are many, and a combination of some scenarios with different energy sources such as wood heat, solar heating system and heat pumps, are conducted to see the overall changes of climate change impacts for the TEK07 and passive house operation phases. It must be noted that for the solar heating system and heat pumps, only the required electricity for operating the systems are included. Production, maintenance and waste handling of these systems are not included, neither is the installation, required pipes nor water tank system. For the wood energy system, a complete life cycle assessment of wood heating is used, where the production of the stove is included, but the installation and waste treatment of the stove and wood-ash is not (Solli et al., 2009). For calculations, see Appendix K.

It is in the first scenario for the TEK07 house assumed that 40% of the energy requirement for space heating and warm water is provided by wood energy. (Eriksen, 2011) In the study by Solli et al. (2009), *Life cycle assessment of wood-based heating in Norway,* the environmental impacts from wood based household heating is assessed. This study assumes that the combustion of wood is climate neutral. There will still be impacts to climate change related to the incomplete combustion of the wood and upstream processes. (Solli et al., 2009). For the second scenario, 65% of the space heating requirements are covered by an air-to-air heat pump. This equals 40% of the total energy for space heating and hot water, and thus the requirements in TEK07 (Appendix K). In the third scenario, 50% of the warm water- and 60% of space heating- requirements are covered by a solar heating system and wood energy respectively.

Three scenarios are also calculated for the passive house. In the first scenario, 80% of the space heating requirements and 70% of the warm water requirements are assumed to be covered by a heat pump. (Eriksen, 2011). For the second scenario 50% of annual energy requirements for warm water are covered by a solar heating system. While it is in the third scenario assumed 50% of annual energy requirements for space heating and warm water are covered by the solar heating system. This assumption is based on the report from Andresen (2008), SINTEF Byggforsk, where the annual coverage from a solar heating system in Bergen is estimated.

The results are presented in Figure 6-11. The different choices of heating systems reduce impacts to climate change in a range of 20-30% from the base heating system scenarios. When considering the entire Stord house lifecycles, a reduction of 15% of total CO_2 eq impacts are achieved for both houses.

Wood burning has lower impacts than an air-to- air heat pump, when only considering climate change impacts for the TEK07 house. In a scenario with a solar heating system that covers 50% of the warm water requirements and energy from wood combustion covers 60% of the space heating requirements, the total impacts to climate change is lower compared to the passive house that only considers electrical energy. This is in line with the study to Brunklaus et al (2010), where it was stated that “conventional houses can be equally good environmentally in terms of global warming

[…] as typical passive houses with electrical heating depending on the actors' choices". This mean, without considering life cycle impacts of the solar heating system, and only impacts to climate change, a house built after TEK07 has potential to increase its environmental performance.

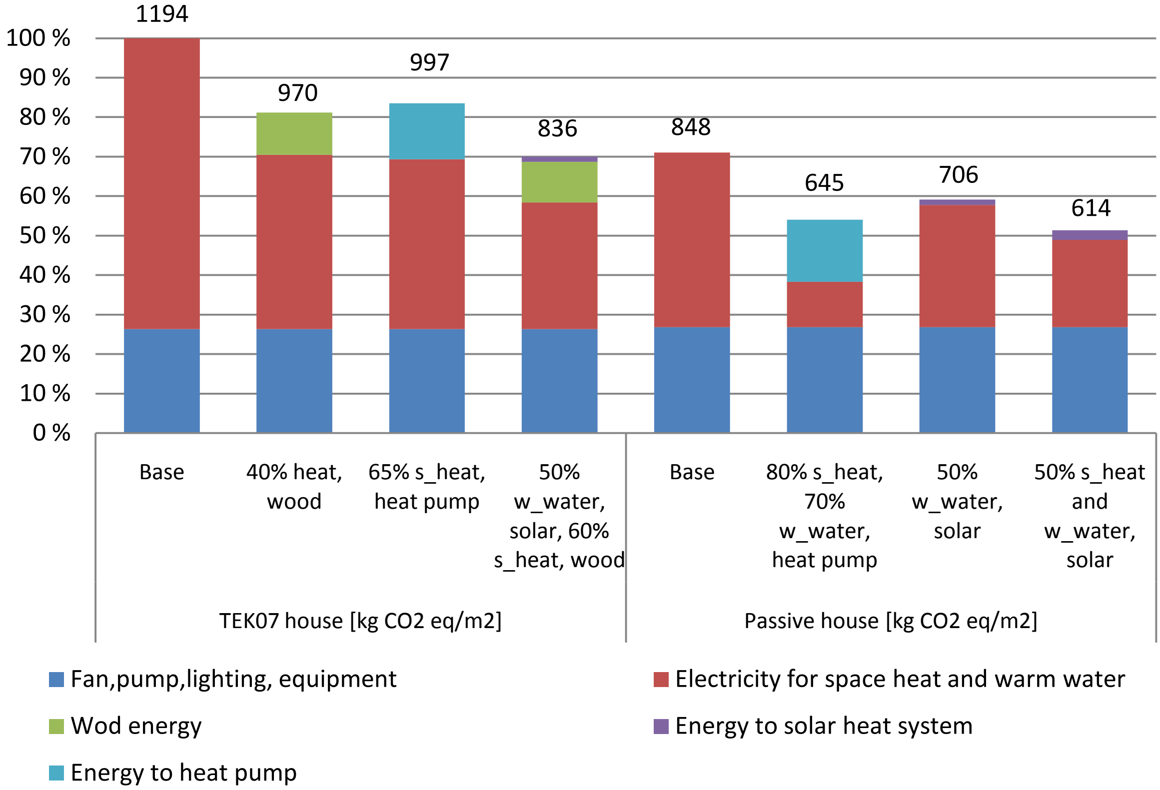
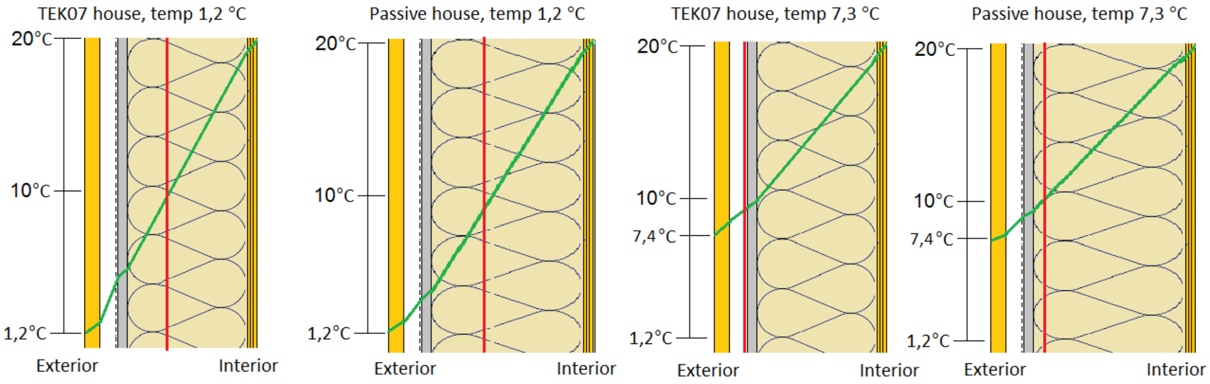


Figure 6-11: Impacts to climate change for different heating systems

All scenarios for the passive house have lower climate change impacts than the *best* scenario with solar heating system and wood energy for the TEK07 house. The least impacts are from the scenario with 50% of space hating and warm water energy covered by a solar heating system. By taking the whole life cycle impacts to climate change into consideration, and using the *best* TEK07 energy scenario compared to the *worst* passive house scenario, with 50% warm water from the solar energy system, the impacts are 1229 kg CO_2eq/m^2 and 1148 kg CO_2 eq/m^2 for theTEK07- and passive house respectively. In order to avoid problem shifting, the production, installation and maintenance of the different systems should also be included, as well as other impact categories. The photochemical oxidation- and particular matter- formation category should be included for wood combustion, as "products of incomplete combustion, such as methane, dioxin, NMVOCs, PAHs, and particulates (such as PM2.5) are the dominant contributors to most impact categories" (Solli et al., 2009).

6.3.4 *Wall temperature gradients for the TEK07 house and passive house*

Both the TEK07 house and passive house are designed and constructed with a sealed vapor barrier on the interior side of the outer wall. The consequence of not sealing this barrier completely during the construction phase, or penetrating it during the user phase, is more critical the thicker the insulation layer is. Figure 6-12 is demonstrates this, and is calculated for the two Stord house models. Warm air can contain more water vapor than cold air. When air with high relative humidity (RH) cools, it will at one point contain more water vapor than it can hold and the excess water vapor condensates. With an inside temperature of 20°C and 50% RH, the dew point of air is 9,25 °C (Appendix J). By using two outdoor temperatures at Stord, Stords normal minimum (1,2 °C) and Stord annual mean temperature (7,4°C), the temperature gradients through the outer wall can be calculated. Complete temperature gradient calculation is found in Appendix J


TEK07 house, temp 1,2 °C

Passive house, temp 1,2 °C

TEK07 house, temp 7,3 °C

Passive house, temp 7,3 °C

Figure 6-12: Temperature gradient (green) and dew point (red – 9,25 °C) for the different walls and outside temperatures.

When the outside temperature is at the normal minimum of 1,2°C, the dew point is in the middle of the insulation for both house types. The dew point is, when using the Stord annual mean temperature, with a minimal margin in the air cavity between the wind barrier and outer wood covering for the TEK07 house. For the passive house wall, the dew point is still inside the insulation layer.

This means, for the annual mean temperature at Stord and assuming an inside temperature of 20°C and 50% RH, any water vapor escaping throughout the interior walls water barrier condensates first when it is out of the insulation layer and thus will not increase the risk of mold growth. For the passive house, on the other hand, any excess water vapor that escapes condensates inside the insulation layer even at the annual mean temperature at Stord. When building walls after TEK07 and passive house standard it is of high importance to make sure the interior water barrier is completely sealed and 100% water vapor tight.

7 Discussion

The passive house has higher impacts, from the construction and end of life treatment, in all categories, than the TEK07 house, as presented in figure 6-1. However an overall impact reduction between 15% and 20% is achieved for the passive house, in all categories, when the house operation phase is included. The only exception is the freshwater ecotoxicity impact category, which is 6% larger for the passive house than the TEK07 house. This means that when constructing a passive house, there will be a shift in the share of total impacts. In a passive house, the house users are directly responsible of a lower share of total house impacts, while external companies get a larger share. Types of building materials, methods for construction drying, transportation distances and waste treatment decisions are choices made by external projecting companies.

The share of climate change impacts linked to the construction and waste treatment phases, changes from 18% to 25% when constructing a passive house. The importance increases in these external companies to choose environmental friendly materials and construction/waste treatment methods to keep these life cycle impacts as low as possible. 23% of impacts from the external companies are related to waste treatment and after house life handling.

The house user, on the other hand is responsible for 82% and 75% of TEK07 and passive house impacts to climate change respectively. The largest share of these impacts is related to the electricity consumption for space heating, warm water, lightning and equipment. Impacts related to the surface finish and maintenance are 8% and 12% of the user impacts to climate change.

A single score endpoint category is also included to compare the total life cycle for both houses. The passive house scores 18% less points than the TEK07 house. For both houses, there is 44% damage to human health, 24% damage to ecosystems and 32% damage to resource availability, according to the normalization values of Europe, with the average weighting set from ReCiPe. Climate change to human health, particular matter formation, climate change ecosystems and fossil deletion is weighted as the elements causing most damage.

It is from the advanced contribution analysis in chapter 6.2.1 found some elements, activities and stressors contributing significantly to the house lifecycle impacts.

The contributing elements to the construction category for the passive house are the floors (20%), walls (20%), roof (15%), groundwork and foundation (13%), construction energy (10%), surface finish in year 0 (8%), windows and doors 6%), waste treatment of waste from the construction phase (6%) and lastly electricity and plumbing (2%).

The main stressors contributing in the impact categories are carbon dioxide (CO_2), manganese, phosphorus, non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), particulates, sulfur dioxide (SO_2), nickel ion and bromine.

Direct combustion of diesel for the Stord transportation and building machines is a major contributor for the climate change (CC - 18%), photochemical oxidant formation (POF - 44%), particulate matter formation (PMF - 24%), terrestrial acidification (TA - 27%) and marine eutrophication (ME - 48%) impact categories. In this thesis, the fleet average lorry from Switzerland, 2005 (Ecoinvent, 2007), is used for all transportation of materials to the construction site (20-28t) and waste to the treatment plant (3,5-16t). An average passenger car in Europe, 2005, is used for transporting the workers. The transport share is 75%, 17% and 6% respectively.

The EU regulates emissions from light-and heavy duty vehicles, and in 2005 the Euro III emission standard was implemented for heavy duty vehicles. All vehicles registered after 2008 must follow the Euro V emission standard, and from 2013 the Euro VI standard. These European standards define the maximum emission for carbon oxide (CO), hydro carbons (HC), nitrogen oxides (NO_x), particulates matter (PM) and smoke allowed for heavy vehicle road transport. (EC, 2010). When the average transportation fleet slowly is upgrading from the Euro III to the Euro IV and V emission standards, and in the future the Euro VI standard, the impacts from transportation should be reduced significantly. The maximum limit of emissions is reduced by 92% for NO_x and 90% for PM, from the Euro III to the Euro VI standard.

Wood ash is a residue from incineration of wood products and wood chips. Disposal of wood ash and incineration of wood are major contributors to the human toxicity (HT - 30%), freshwater eutrophication (FE - 24%), ME (8%) and territorial ecotoxicity (TET - 67%) impact categories. Mainly 2 activities contribute to the impacts, wood chips burned in furnace for timber production drying and the incineration of wood from house end of life in a municipal incineration plant. Ecoinvent assumes 25% of the ash from wood burned in furnace is sent to land farming, 25% to a municipal incineration plant and 50% to a sanitary landfill. Slag and residues from the municipal incineration process are land filled. (Ecoinvent, 2007),. These impacts can be reduced if wood products are reused instead of incinerated when the house is demolished. Landfill and land farming areas receiving wood ash should have the right equipment and be approved by external risk managing authority.

Disposal of paint and EPS/XPS to a municipal incineration plant contribute with 12% to the CC, 10% to TET, 45% to freshwater ecotoxicity (FET) and 18% to the marine ecotoxicity (MET) impact categories. Painted timber should be energy recovered in municipal incineration plants. EPS and XPS should be reused and material recycled instead of incinerated.

Production of insulation materials such as EPS/XPS and mineral wool (rock wool) contributes to the CC (4%), PMF (11%) and TA (11%) impact categories. Waste during construction should be minimized to lower the overall production of materials, and there could be an increase in the material reuse.

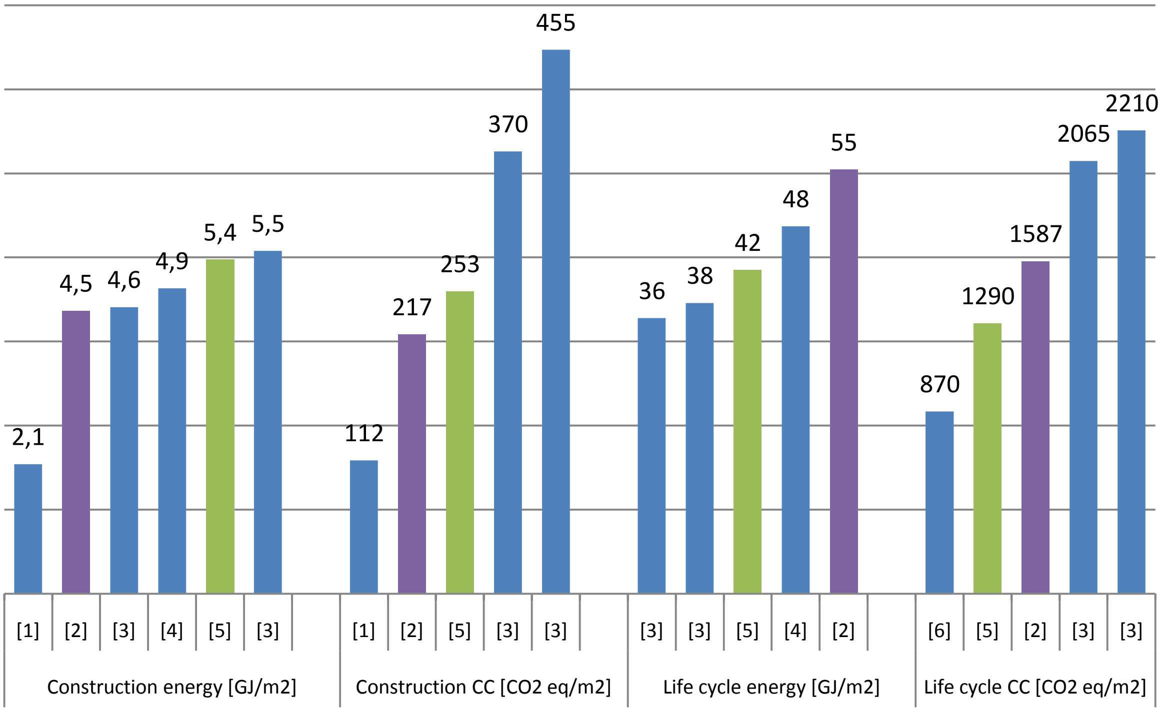
Production of clinker for cement, ceramic tiles and disposal of building bricks to a sanitary landfill contributes in the following impact categories: CC (5%), HT (19%), PMF (9%), FET (12%) and MET (16%). These materials should have a service life as long as possible and recycled when they reach the end of life.

Electrical cables, steel production and metal waste treatment have impacts in the HT (6%), FE (29%), FET (9%), MET (12%) and MD (100%) impact category. Recycling of metals and electrical cables should be emphasized; as well as removing metal parts from wood before the wood is incinerated.

The high uncertainty, when it comes to the construction drier power and time, has a relative low contribution to the construction climate change impacts. The range is from -3,6% to +4,8% from the base scenario. This range was assumed to be bigger at the start of the analysis, according to the general concern in the topic. For the whole life cycle, the range is -0,7% to +0,9%. Nevertheless, if the optimal drying solution is estimated during the house projecting phase and not at the construction site, these impacts can be as low as possible. The range from the scenarios is, for the whole house (187 m^2), between 106 kg CO_2 eq and 3800 kg CO_2 eq, with the base scenario at 1700 kg CO_2 eq.

The sensitivity in the surface finish and house maintenance frequency has a relative high change of total impacts to climate change. The range is between -35% and +70% for impacts to climate change when only considering the surface finish and maintenance life phase. Different service times for the different elements changes the overall impacts to climate change in the range of -6% to +7% from the base scenario.

Figure 7-1 compares the Stord houses to the previous reviewed studies. The TEK07 house is marked in purple and the passive house in green. Embodied energy in the construction materials, impacts to climate change from production of the house and materials, life cycle energy and life cycle climate change impacts are also presented in the figure



[1]-(Sørnes, 2010) [2]-(Stord TEK07) [3]-(Norman et al., 2006)
[4]-(Ramesh et al., 2010) [5]-(Stord passive house) [6]- (Brunklaus et al., 2010)

Figure 7-1: Impacts from the Stord houses compared to other studies

The presented results have all different system boundaries and are analyze different building types. Therefore, the results cannot be directly compared. These studies took place in a time range from

1997 to 2010. None of the previous studies includes incineration of the building materials after the building demolition or waste treatment of waste during construction.

The reason why the previous study of the Stord TEK07 house by Sørnes (2010) has lower impacts than the TEK07 house in this study is the lack of some materials. “The operation phase, disassembly and waste management are excluded. The focus is on the production of materials, the transportation and construction of the house. […] Windows and doors are not included in the study […] neither [is] the foundation nor chimney” (Sørnes, 2010).

The analyzed Stord houses are in range of previous studies, both for the construction phase and the total life cycle, for embodied energy and climate change impacts.

8 Uncertainty

Both houses have a total floor area of 187 m^2. Since the inside area for both houses are the same, the total outside area of the passive house has increased with approximately 8%, from 101,8 m^2 to 110,1 m^2. The increased land area occupied by the passive house can have some negative impacts as for example if the property already is regulated for the TEK07 standard. According to the Planning and Building Act (MD, 2008) in Norway, it is not permitted to build a construction closer than 4 meters from the surrounding properties. This can be an issue in urban areas with less available space for properties and must therefore be considered during the construction phase. Less available floor area inside a passive house can be a result of these property regulations.

Another issue that differs between the two house designs is the increased awareness of site specific adjustments for the passive house construction. In order to gain as much “free” energy from nature as possible, the main façade with most of the windows (façade 1) should be facing south. The house can then take advantages of passive solar heat through the windows. The effect from a photovoltaic cell or a solar heating system is also highest when the systems are facing south. The passive house should also interact with the surrounding landscape, such as vegetation and buildings to increase the natural wind barriers. Wind protection has a direct impact on the ability to save energy in a house. Cold wind will cool down the outer facades and increase the internal heat loss and infiltration. The effect is biggest with cold wind during the winter. In addition, wind shielding is of great importance for the outdoor comfort. (Dokka and Hermstad, 2006, Våge et al., 2009).

The implications of increased passive house area and time for finding a good property are not considered in this thesis.

It is also assumed that the carpenters and house constructers are well trained and don’t use ant extra time for trial and error. From figure 6-12 is it clear that small errors with the vapor barrier can have big consequences for the moisture content in the wall, and potential increased mold growth. It is for the passive house in this analysis included a bitumen sealing string and tape in all joints for the vapor barrier in the wall and roof.

There is an uncertainty regarding the lifetime of the house. It is assumed in this analysis that the house is demolished in year 50.This is a lifetime used in previous studies (Ramesh et al., 2010) and makes the results more comparable. From figure 6-7, it is calculated that the environmental costs and benefits for the passive house is equal to the TEK07 house after 5 years in operation. This means that the longer lifetime the two houses has, the more environmentally beneficial is the passive house compared to the TEK07 house, when assumed the same surface finish and maintenance frequency.

Others uncertainties are divided into four parts.

8.1 Construction

Amounts of materials needed for the TEK07- and passive- house constructions are, except for the groundwork and foundation, provided by the building company Nordbohus AS, and thus accurate. Amounts of concrete, EPS, XPS and gravel for the groundwork and foundation are estimated on the basis of volume calculations. There are many different types of premade EPS moulds for the foundation, which all have slightly different shapes. Nevertheless, the calculated amounts should be in a close range of the real situation. For the transportation of masses and gravel, the travel distance of 30 km might be a bit long. There is also a possibility of using the masses in other construction projects close to the Stord house constriction site. Also, the assumption that 70% of the masses is transported away and replaced with gravel might also be a bit high. These are factors that are totally dependent on each project and difficult to get the exact data. The transport of masses, gravel and production of gravel is 7% of impacts to climate change in the construction phase, and 1% for the total life cycle. For sure, there must be some transportation and production of gravel so the uncertainty for these products is high, but it does not affect the overall result significantly.

The energy consumption for the construction drying process (and electrical tools) also has a high uncertainty, but from the sensitivity analysis, little impact on the overall results.

The material input for the production of the staircase and doors are based on technical drawings. Energy for the production of these elements is not included based on the assumption that the contribution is low.

For the electricity and plumbing materials, the lengths of cable and pipes are based on the technical drawing of the house and assumptions on which room to include. All rooms on the ground level have two cable inputs, rooms on the 1st floor have one cable input. Warm and cold tap water pipes as well sewage pipe is added to each room that is assumed to have a tap system. These amounts should be in the same lengths as actually used. There is a higher uncertainty in the assumption that the electrical-, water- and sewage- grid is available at the construction site. If this is not available, more use of an excavator and materials is needed in order to be connected these systems. Compared to the total lifecycle impacts, the effect of changes in the available grids is assumed relatively small.

As presented in the sensitivity analysis, there is a high uncertainty for the surface finish and maintenance frequency. Overall lifecycle climate change impacts changes in a range between -6% and +7% compared to the total impacts for a long- and a short- service life scenario.

Generally, a higher degree of uncertainty will be acceptable for maintenance components than for components intended to function without maintenance for the life of the building. ISO 15686-1:2011

8.2 Materials

All impacts are based on materials and generic data from the Ecoinvent 2.0 database. Some modifications are done to the pre defined processes. For all products assumed to be produced in Norway or Scandinavia, the electricity mix is changed from the UCTE mix to the Nordel mix. This change is just for the first round (using concrete as an example) meaning the production of concrete has Nordel mix, but the production of the Portland cement and other inputs has the original UCTE mix.

For all low alloyed steel, aluminum and plastic the processing of materials is included. Section bar rolling is included for the steel products, section bar extrusion for aluminum profiles and injection molding and extrusion of film and pipes for the different plastic products. The mineral wool used in the analysis is rock wool, based on production data from 1998. Both rock- and glass- wool have the same thermal performance in the buildings, but since there is an EPD for Rock Wool available (Rockwool, 2009) from the production in 2002, this wool type was chosen in order to compare the

Ecoinvent process with this EPD. For the same functional unit as in the EPD, the used Ecoinvent process has around 20% increased impacts to climate change and 5% higher cumulative energy demand. Therefore, the impacts from the mineral wool used in this analysis might be higher than from the actual production. The difference in climate change impacts, when reducing the mineral wool impacts with 20%, is a reduction of 0,6% for the total life cycle CO_2 eq.

Impacts from wood production are based on the Mikado Project, from SINTEF Byggforsk (Wærp et al., 2009). All wood products, except the particle boards, are assumed with an average density of 500 kg/m^3. Since the wood weight depends on the moisture content, this weight might differ from the wood weight used in the Stord houses. However, the overall difference to the impacts, when changing the density of the wood, are assumed to be relatively small.

The Mikado project does not include wood particle boards. Byggma Forestias factory Brakereidfoss produces particle boards, and was in 1997 ranked as the 7th largest producer of particle board worldwide. This factory made an environmental report in 2009 (Forestia, 2009), where their total inputs and outputs are described

Particle boards are used as the subflooring for the 1st level and at the inside walls. The subfloor board differs from the wall board in the way that it is moisture resistant. By changing the resin from urea formaldehyde resin (UR) to melamine urea formaldehyde (MUR) the moisture resistant characteristic of the board is improved. (Hse et al., 2007).

In the Mikado project, all energy used for the sawmill- and wood-drying- process are allocated to the sawn wood/timber product. These are the most energy intensive processes in the wood production and are required to ensure a good timber quality. Impacts further up in the wood supply chain, such as water use in the sprinkler system and energy use for offices and administration are allocated to both sawn wood and wood chips according to volume.

8.3 Transportation

Impacts from transportation have some uncertainty. The transportation distance of 500 km for materials produced on the eastern part of Norway might, for many products, be high. For the transportation of materials, 80% of the climate change transportation impacts are related to the construction of the house and 20% to materials for surface finish and maintenance in the years 1 to 50. For the construction transportation, 26% is related to transport of masses and gravel, 19% to materials for the wall (insulation), 10% to floor materials and 10% to roof materials. This means that the previous mentioned uncertainty in transportation distance for masses and gravel is also the process contributing highest to the transportation impacts. Even though a product is produced nearby Stord, that product might require inputs produced other places in Europe. Transportation of raw materials is included in the Ecoinvent processes, but this distance is based on specific or European average data only, and not the total distance close to Stord.

Distance to the waste treatment plant is based on a previous report (Avfall-Norge, 2007). For the workers, the distance is based on an assumption for 10 km one way. It is reasonable to assume all workers have their own car, as these cars include personal tools and equipments.

There is also an uncertainty regarding the transportation emission standards. Swiss and European fleet average standards are assumed for this analysis, but the Norwegian average fleet might differ.

8.4 Electricity

There is a high uncertainty in the presented analyses regarding the electrical energy consumption in the house operation phase. The total energy needs are based on an energy simulation, and does not reflect the actual house user. Standard values for lightning, technical equipment and warm water are found in the NS 3031:2010 standard. For example, a passive house user might use much more warm water than assumed in the standard value, and a TEK07 house user less warm water than this value. By assuming the same *standard* user in both houses, a fair comparison can be made.

The electricity mixed used in this thesis, presented in figure 5-5, are using statistics for the respective regions mixes in year 2000. By assessing the background data for the Norwegian household emission calculator, Klimakalkulatoren, updated CO_2 eq impacts are used. (Klimaløftet, 2010)

Table 8-1: Comparison of electricity mixes from year 2000 to 2009

Electricity mix	*Household calculator*	*Year*	*Medium volt used*	*Year*
Norwegian mix	0,033 kg CO_2 eq/kWh (+imports)	2007-2009	0,012 kg CO_2 eq/kWh	2000
Nordel mix	0,186 kg CO_2 eq/kWh	2006-2008	0,19 kg CO_2 eq/kWh	2000
European mix	0,56 kg CO_2 eq/kWh	2004	0,53 kg CO_2 eq/kWh	2000

Table 8-1 give a comparison of the different climate change impacts and years the power mix is taken from. For the Norwegian production mix the new numbers includes imports and are over double the CO_2 eq as the 2000 data.

The new Nordel production mix has almost the same impacts as the 2000 mix, and will not contribute to a relative big difference for the calculations. This increases the reliability factor of the climate change impacts when assessing electricity produced from the Nordel mix.

For the European power mix the difference is also relative small. An increase from 0,53 kg CO_2 eq/kWh to 0,56 kg CO2 eq/kWh is an increase of 5% for climate change impacts.

This comparison shows only climate change, and some differences could occur in the other impact categories.

8.5 Waste

"The disposal option 'sorting plant' includes dismantling, the sorting plant process and the final disposal of non-recycled fractions" (Althaus et al., 2004). Especially for gypsum, the sorting plant process causes much higher impacts than recycling or final disposal.

> Gypsum ($CaSO_4\,2H_2O$) is a harmless, inactive mineral with exceptionally good indoor climate characteristics. It can be disposed without risk in inert material landfills. There, it will dissolve to calcium ions and sulphate ions, both with little environmental risk. When gypsum is disposed in a reactive sanitary landfill as part of a sorting fine fraction, different processes occur. The dissolved sulphate (SO_4^{2-}) will be metabolised by the anaerobic microbes in the landfill and converted to sulphide (S^{2-}). Sulphide is mainly precipitated with iron ions (FeS) or it can be transferred to the landfill gas as gaseous dihydrogen sulphide (H_2S). In the latter case, the H_2S is oxidised to sulphur dioxide SO_2 either by incineration or flaring of the landfill gas or by atmospheric oxidation. Sulphur dioxide is a serious pollutant which contributes to acidification and secondary particle formation (winter smog). (…) So, while direct final disposal of gypsum in an inert material landfill is hardly burdensome at all, the disposal via sorting plant (where it cannot be recycled) and fine fraction will create entirely different burdens. (Althaus et al., 2004)

Therefore, gypsum board is transported directly to a final disposal, and disposed in separate cells. (MD, 2004)

There is a possibility that not all materials disassembled from the house during the demolition are waste, and thus some uncertainty is connected to this life cycle phase. For example, windows, doors, structural timber and insulation material can be reused in other construction, and hence reduce the production of new materials. The waste treatment in this analysis is divided into two parts, one to a sorting plant and the other to a municipal incineration plant. Sorting materials for recycling and recover energy in a waste incineration plant creates products and energy available for a new life cycle. There is an uncertainty if these new products, when reducing extraction of raw materials and production of fossil energy, should be credited the Stord house life cycle as *reduced* impacts. It is in this study not credited any gains from a potential material recycling or energy recovered in the incinerator, based on the assumption of "worst case scenario".

8.6 Further work

This study includes, to a certain detail, all the required materials and energy needed in the productions and maintenance of a single family residence built to TEK07 house standard and a passive house standard. Treatment of waste during the construction and for waste after the demolition of the house is also included.

For the building construction, different types of solutions could be compared. For example the question of building the house under a tent versus using prefabricated elements in the construction should be assessed, or estimating the changes in the overall impacts using different framework systems such as I-beam or massive structural wood. There is also a possibility of using concrete as the 1st level floor.

For the house maintenance, different surface finishes and solutions should be compared. It was in this study only assumed ceramic tiles for the bathroom and parquet wood floor.

Several different scenarios for the home user could also be interesting, as the house operation energy is responsible for 76% and 67% of life cycle climate change impacts. What is the effect of having different lifestyles?

A complete life cycle costing analysis (LCC) should also be carried out for these houses. The environmental costs and benefits of moving to a passive house should be compared to the economical costs and benefits.

As well as the economy, the social- and health- aspect of moving to a passive house should be analyzed thoroughly.

9 Conclusions

The building company Nordbohus AS has projected one TEK07 model and one passive house model of the same building design. The building design is Stord, with a wooden framework and mineral wool insulation in the walls and roof. The total useful floor area is 187 m^2 BRA.

The main focus of this study has been to assess the environmental costs and benefits of moving to the passive house model from the TEK07 house model. A complete life cycle assessment of the two house models is conducted to find the environmental impacts of these two house models.

Material input for the walls, floors and the roof are provided by Nordbohus, for both the TEK07- and passive house building. Other material inputs are based on volume and area calculations.

The results are assuming the same electrical heating system for both houses. The total life cycle climate change impacts pr m^2 floor area are 1,59 tons CO_2 eq for the TEK07 house and 1,29 tons CO_2 eq for the passive house, over a 50 year lifetime. The cumulative energy demand is 55 and 42 GJ respectively. This includes material production, transportation of materials to the construction site, energy for the house construction, operation electricity and water consumption, surface treatment and house maintenance during operation, energy for demolition and treatment of waste from the construction- and after the demolition- process. Since the system boundary include impacts from sorting- and incineration- of the waste, but not includes the gains of recycled materials or recovered energy, the results are somewhat conservative. Impacts from waste treatment are in average for all categories 9% for the TEK07 house and 11% for the passive house. From the sorting plant process, materials that cannot be recycled are land filled.

The results are in range of previous studies.

For the TEK07 climate change category, 13% of total impacts are from the construction phase. Waste during construction contributes with 1%, maintenance of surface finish 6%, end of life treatment 4% and house in operation contributes with 76% of total CO_2 eq impacts. For the passive house this is 19%, 1%, 7%, 6% and 67% respectively, with a total of 81% of the TEK07 house.

It is found that transportation and diesel combusted in building machines, disposal of wood ash to landfill and land farming, production of and incineration of expendable and extruded polystyrene and paint, production of mineral wool, disposal of concrete, building bricks and ceramic tiles to landfill and incineration of metal in wood pieces, are the most contributing activities to overall impacts.

The sensitivity of several factors are tested, and it is found that different power and time for construction drying changes the passive house impacts to climate change with ± 1%. When testing different service life frequencies, the change of impacts to climate change is in the range of ± 7% kg CO_2 eq.

Impacts related to surface finish and maintenance of the houses is 8% and 12% of the user impacts to climate change. Electricity and water consumption is responsible for the rest of the *house user* impacts.

Passive houses are the more environmentally beneficial the more impact intensive the consumption electricity mix is. The Norwegian electricity mix is considered in one scenario, and, when not including the effect of exporting excess energy to other regions, operating impacts to climate change for both the Stord houses are almost equal.

In some scenarios, different heating systems are assumed. The TEK07 house has in one scenario 50% of the warm water requirements covered by a solar heating system and 60% of the space heating covered by wood energy. Climate change impacts from this heating system equals the passive house CO_2 eq impacts, when the passive house is only using electrical energy for warm water- and space-heating.

The main conclusion is that the passive house is environmentally beneficial compared to the TEK07 house. Several scenarios and sensitivities are performed, but the result from these tests change mostly the total impacts for both houses and not the relative difference between the houses. When considering the increased climate change impacts from material production and house construction, together with the reduced impacts from electricity consumption, the environmental offset time for the passive house, compared to the TEK07 house, is theoretically 5 years, 1 month and 20 days.

This means that when constructing a passive house and assuming both houses are using the same electrical heating system, it takes only 5 years before the increased material production and transport for the passive house are equalized to the TEK07 house climate change impacts.

References

ADALBERTH, K. 1997. Energy use during the life cycle of single-unit dwellings: examples. *Building and Environment,* 32**,** 321-329.

ADALBERTH, K. 1999. Energy use in four multi-family houses during their life cycle. *International Journal of Low Energy and Sustainable Buildings,* 1.

ADALBERTH, K., ALMGREN, A. & PETERSEN, E. H. 2001. Life cycle assessment of four multifamily buildings. *International Journal of Low Energy and Sustainable Buildings,* 2**,** 1–21.

ALTHAUS, H.-J., KELLENBERGER, D., DOKA, G. & KÜNNIGER, T. 2004. Manufacturing and Disposal of Building Materials and Inventorying Infrastructure in ecoinvent (8 pp). *The International Journal of Life Cycle Assessment,* 10**,** 35-42.

ANDRESEN, I. 2008. Prosjektrapport nr 22: Planlegging av solvarmeanlegg for lavenergiboliger og passivhus. En introduksjon. SINTEF Byggforsk.

AVFALL-NORGE 2007. Benchmarkingsstudie gjennomført for 15 kommuner/avfallsselskaper med data for 2005, data oversendt fra NGIR v/Erlend Kleiveland 25.03.08.

BARE, J. C. 2009. Life cycle impact assessment research developments and needs. *Clean Technologies and Environmental Policy,* 12**,** 341-351.

BARENBRUG, A. W. T. 1974. *Psychrometry and Psychrometric Charts, 3rd Edition*, Cape Town, S.A.: Cape and Transvaal Printers Ltd.

BARLINEK. 2011. *FDV Dokumentasjon, Barlinek 14mm limfri lakkert parkett* [Online]. Available: http://www.barlineknorge.no/Artykuly/sertifikater/fdv-barlinek-09-eik-standard.pdf/at_download/file [Accessed 22.04.2011].

BAUMAN, H. & TILLMAN, A.-M. 2004. *The Hitch Hiker's Guide to LCA*, Studentlitteratur AB.

BELSVIK, H. K. 2011. Installatør hos Gauldal Installasjon AS.

BERGE, H. J. 01.04 2011. *RE: Masteroppgava.BYGGFUKT: Re: Fwd: Spørsmål om byggtørking, betraktninger*

BOEN. 2010. *FDV Dokumentasjon for Boen Parkettgulv* [Online]. Available: http://www.boen.no/FDV_Lamell_des2010_e7YEX.pdf.file [Accessed 22.04.2011].

BRUNKLAUS, B., THORMARK, C. & BAUMANN, H. 2010. Illustrating limitations of energy studies of buildings with LCA and actor analysis. *Building Research & Information,* 38**,** 265-279.

BYGGFORSK. 451.021:2009. Byggforskserien 451.021 - Klimadata for termisk dimensjonering og frostsikring.

BYGGFORSK. 474.533:2006. Byggforskserien 474.533 - Byggfukt, Uttørking og forebyggende tiltak.

BYGGFORSK. 571.508:2008. Byggforskserien 571.508 - Keramiske fliser, typer og egenskaper.

BYGGFORSK. 700.320:2010. Byggforskserien 700.320 - Intervaller for vedlikehold og utskifting av bygningsdeler.

BYGGFORSK, S. 2004. *Teknisk Godkjenning, Hunton Asfalt Vindtett* [Online]. Available: http://swedish.hunton.no/assets/svenske%20produkter/vindtett_teknisk_%20godkjennelse.pdf [Accessed 17.03.2011].

BYGGFORSK, S. 2008. *Teknisk Godkjenning, Litex wet room system* [Online]. Available: http://tjenester.byggforsk.no/prodok/ntg/2296/2296g.pdf [Accessed 07.04.2011].

BYGGFORSK, S. 2009. *Teknisk Godkjenning, Air Guard® reflekterende dampsperre* [Online]. Available: http://tjenester.byggforsk.no/prodok/ntg/20004/20004g.pdf [Accessed 21.04.2011].

BYGGFORSK, S. 2010. *Teknisk Godkjenning, Nordic Ringmursystem* [Online]. Available: http://www.grunnmur.no/publisher_grunnmur/file/TG2125.pdf [Accessed 25.03.2011].

CELSA. 2009. *Miljørapport, Celsa Armeringsstål AS, Mo i Rana* [Online]. Available: http://www.mip.no/miljo/miljoinfo_fra_bedrifter/celsa_armeringsstal_as/495/Celsamiljorapp2009N.pdf [Accessed 06.04.2011].

CHAPMAN, TERR AI, JACOBS RL, CHARLESWORTH EN & JR, B. E. 2003. Toxic mold: phantom risk vs. science 2003 *Annals of Allergy, Asthma & Immunology,* Sep 2003**,** 222-32.

DAHLSTRØM, O. 2010. *LCA of the building envelope elements of a wood-based passive house: Modern highly effective windows.* Master Project, NTNU.

DEWALT. 2011. *Power Tools* [Online]. Available: http://www.dewalt.no/powertools/ [Accessed 06.02.2011].

DG-CLIMA. 2011. *European Commission Climate Action, Protection of the ozone layer* [Online]. Available: http://ec.europa.eu/clima/policies/ozone/index_en.htm [Accessed 20.05.2011].

DOKKA, T. H. & HERMSTAD, K. 2006. Energieffektive boliger for fremtiden - En håndbok for planlegging av passivhus og lavenergiboliger. *In:* BYGGFORSK, S. (ed.).

EC, E. P. A. O. T. C. 2010. *Transport & Environment, road vehicles* [Online]. Available: http://ec.europa.eu/environment/air/transport/road.htm [Accessed 10.02.2010].

ECOINVENT 2007. Ecoinvent 2.0. Swiss centre for Life Cycle Inventories.: Swiss centre for Life Cycle Inventories.

EKVALL, T., TILLMAN, A. & MOLANDER, S. 2005. Normative ethics and methodology for life cycle assessment. *Journal of Cleaner Production,* 13**,** 1225-1234.

EMMIT, S. & GORSE, C. A. 2010. *Barry's Introduction to construction of Buildings, SE*, Wiley-Blackwell.

ENTSOE-E. 2011. *European Network of Transmission System Operators for Electricity* [Online]. Available: https://www.entsoe.eu/home/ [Accessed 27.04.2011].

ERIKSEN, S. T. 2011. Civil Architect at Nordbohus, Trondheim.

F-TECH. 2011. *Dry building* [Online]. Available: http://www.f-tech.no/default.aspx?pageId=1043 [Accessed 28.04.2011].

FALLDALEN, R. 2008. Isolering i gamle trehus.

FEIST, W. 2007. *The Building Physics Calendar: Passive Houses in Practice, p 675-741*.

FOLVIK, K. 2010. Background data from the MIKADO project.

FORESTIA. 2009. *Miljøredegjørelse for Braskereidfoss 2009* [Online]. Available: http://forestia.byggma.no/dm_documents/Milj%C3%B8redegj%C3%B8relse_Braskereidfoss_09_q4ojs.pdf [Accessed 28.04.2011].

FORESTIA. 2010. *FDV Dokumentsjon - Forestia Gulv Standard og Ekstra* [Online]. Available: http://www.forestia.no/dm_documents/FDV_0310_Forestia_Gulv_MNJX1.pdf [Accessed 25.04.2011].

FRISCHKNECHT R., J. N., ET.AL 2003. Cumulative Energy Demand, V 1,06.

GEVING, S. & HOLME, J. 2010. Prosjektrapport nr 53: Høyisolerte konstruksjoner og fukt, analyse av fukttekniske konsekvenser av økt isolasjonstykkelse i yttervegger, tak, kryperom og kalde loft. SINTEF Byggforsk.

GLAVA. 2011. *Isolation for buildings* [Online]. Available: http://www.glava.no/produkter/byggisolasjon/ [Accessed 03.03.2011].

GOEDKOOP, M., HEIJUNGS, R., HUIJBREGTS, M., SCHRYVER, A. D., STRUIJS, J. & ZELM, R. V. 2009. ReCiPe 2008, Report I: Characterisation.

GULESIDER. 2011. *Map services from gulesider.no* [Online]. Available: www.gulesider.no [Accessed 21.02.2011].

HAYNES, W. M. 2011. CRC Handbook of Chemistry and Physics, 91st Edition (Internet Version 2011), Section 12: Thermal Conductivity of Ceramics and Other Insulating Materials. *CRC Press/Taylor and Francis, Boca Raton, FL.*

HORN, A. 17.03.2011 2011. *RE: Dantherm Air Handling AS.*

HSE, C.-Y., GU, G. & PAN, H. 2007. Melamine-modified urea formaldehyde resin for bonding particleboards. *Forest Products Journal,* 58**,** 56-61.

HUNTON. 2011. *NEPD nr: 213E, Hunton Asfalt Vindtett (Bitroc) 12 mm,* [Online]. Available: http://www.epd-norge.no/getfile.php/PDF/EPD/Byggevarer/NEPD213HuntonAsfaltVindtett.pdf [Accessed 04.06.2011].

ICOPAL. 2007. *FDV Dokumentasjon, Takrenne, stål* [Online]. Available: http://www.icopal.no/upload/icopalno/fdv/fdv-staalrenne.pdf [Accessed 29.04.2011].

ICOPAL. 2011. *FDV Dokumentasjon, Ventex Supra, diffusjonsåpent undertak* [Online]. Available: http://www.icopal.no/upload/icopalno/fdv/fdv-ventex%20supra.pdf [Accessed 29.04.2011].

ICOPAL. n.d. *Hvordan sjekke taket ditt?* [Online]. Available: http://www.icopal.no/AboutIcopal/Hvordan%20sjekke%20taket%20ditt.aspx [Accessed 18.05.2011].

ISO 14040:2006. Principles and framework, Environmental Management - Life Cycle Assessment - ISO 14040. International Standard.

KLIMALØFTET. 2010. *Design of a household emissions calculator* [Online]. Available: http://klimakalkulatoren.no/media/2382/bakgrunnstall_til_klimakalkulator_201010.pdf [Accessed 22.05.2011].

KLIMATRE 2011. KlimaTre LCA forum, Sintef Byggforsk Oslo, 15.03.2011.

LEVANGER, H., KREKVIK, V., KOLVIK, G., KAARSTAD, I. K. & TANGEN, K. 2010. *Energibesparelser og konsekvenser ved balansert lufttrykk kontra overpressing ved uttørking av bygg.* Bachelor, Osllo University College.

LITEX. 2011. *FDV-Dokumentasjon* [Online]. Available: http://www.litex.no/files//Litex%20Membranplater%20og%20r%F8rkasser.pdf [Accessed 24.04.2011].

LUND, H., MATHIESEN, B. V., CHRISTENSEN, P. & SCHMIDT, J. H. 2010. Energy system analysis of marginal electricity supply in consequential LCA. *The International Journal of Life Cycle Assessment,* 15**,** 260-271.

LYKRE, I. 2011. Product manager, Motek: Anchor and Firestop, (Hilti chemical anchors).

MD, M. O. T. E. 2004. FOR 2004-06-01 nr 930: Forskrift om gjenvinning og behandling av avfall , Vedlegg II: 2.2.1. Kriterier for mottak av gipsavfall.

MD, M. O. T. E. 2008. Lov 2008-06-27 nr 71: Lov om planlegging og byggesaksbehandling (plan- og bygningsloven). *§29-4.* lovdata.no: Lovdata.

MET. 2011. *Norwegian Meteorological Institute - eKlima* [Online]. Available: www.eklima.no [Accessed 27.04.2011].

MOELVEN. 2011. *Råvarer fra holdbart skogbruk* [Online]. Available: http://www.moelven.com/no/Om-Moelven/Ansvar/Miljo/Alle-sagbruk-er-miljosertifiserte-/ [Accessed 25.03.2011].

MOINER. 2009. *FDV: Zanda Protector Betongtakstein* [Online]. Available: http://www.monier.no/fileadmin/bu-files/no/downloads/pdf/FDV-2009/Zanda_Protector_FDV_2008-11-05.pdf [Accessed 01.03.2011].

MONAHAN, J. & POWELL, J. C. 2010. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings,* 43**,** 179-188.

MONIER. n.d. *Hvordan står det til med taket ditt?* [Online]. Available: http://www.monier.no/ta-vare-paa-ditt-tak/hvordan-staar-det-til-med-taket-ditt.html [Accessed 18.05.2011].

NEBEL, B., ZIMMER, B. & WEGENER, G. 2004. Life Cycle Assessment of Wood Floor Coverings - A Representative Study for the German Flooring Industry (11 pp). *The International Journal of Life Cycle Assessment,* 11**,** 172-182.

NEK 400:2010. Electrical low voltage installations, NEK 400:2010 4th ed. standard.no.

NHP 2007. Nasjonal Handlingsplan for bygg- og anleggsavfall, 2007-2012.

NORBETONG. 2010. *NEPD nr 136N: Ready mixed concrete, Norway* [Online]. Available: http://www.epd-norge.no/getfile.php/PDF/EPD/Byggevarer/NEPD136NFabrikkbetong.pdf [Accessed 12.05.2011].

NORDPOOL. 2011. *Nordic Power Marked* [Online]. Available: http://www.nordpoolspot.com/PowerMaket/ [Accessed 13.03.2011].

NORMAN, J., MACLEAN, H. L., M.ASCE & KENNEDY, C. A. 2006. Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions. *Journal of Urban Planning and Development,* 32.

NOVA. 2010. *Norsk institutt for forskning om oppvekst, velferd og aldring: Bolig og levekår i Norge 2007* [Online]. Available: http://www.reassess.no/asset/3998/1/3998_1.pdf [Accessed 23.05.2011].

NS 3001:2007. Calculation of energy performance of buildings, Method and data , NS 3001:2007. Norwegian Standard.

NS 3031:2010. Amendment A1, Calculation of energy performance of buildings, Method and data , NS 3031:2010. Norwegian Standard.

NS 3700:2010. Criteria for passive and low energy residential buildings, NS 3700:2010. Norwegian Standard.

NS 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, NS EN 15251:2007. Norwegian Standard.

NVE. 2010. *Energimerking* [Online]. Available: http://www.energimerking.no/no/ [Accessed 09.03.2011].

PASSIVHAUS, B. 2011. *Basic Principles* [Online]. Available: http://www.passivhaus.org.uk/standard.jsp?id=17 [Accessed 23.04.2011].

PRE. 2008. *SimaPro 7.1.8* [Online]. Available: http://www.pre.nl/simapro/ [Accessed 01.02.2011].

PROGRAMBYGGERNE 2011. Simien 5.006.

RAADAL, H. L. & MODAHL, I. S. 2009. Avfall Norge: Klimaregnskap for avfallshåndtering. Fase 1: Glassemballasje, metallemballasje, papir, papp, plastemballasje og våtorganisk avfall.: Østfoldforskning.

RAMESH, T., PRAKASH, R. & SHUKLA, K. K. 2010. Life cycle energy analysis of buildings: An overview. *Energy and Buildings,* 42**,** 1592-1600.

RAMIRENT. 2010. *Tørketeknikker* [Online]. Available: http://www.ramirent.no/torketeknikker.aspx [Accessed 26.02.2011].

RIVM, CML, CONSULTANTS, P., NIJMEGEN, R. U. & DELFT, C. 2009. *ReCiPe midpoint method, hierarchist version, V 1,03* [Online]. Available: http://www.lcia-recipe.net/ [Accessed 16.03.2011].

ROCKWOOL. 2009. *NEPD nr 131N: Rockwool Isolation* [Online]. Available: http://www.rockwool.no/files/RW-NO/Klima%20og%20miljø/NEPD131NRockwool.pdf [Accessed 13.05.2011].

ROCKWOOL. n.d. *Yttervegg med trestendere* [Online]. Available: http://guiden.rockwool.no/konstruksjoner/yttervegger/yttervegg-med-trestendere?page=1384#section_1397 [Accessed 05.06.2011].

SARTORI, I. & HESTNES, A. 2007. Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings,* 39**,** 249-257.

SCHEUNEMAN, E. C. 1982. Estimating temperature gradients and dew point temperatures for building envelopes. *In:* DIVISION OF BUILDING RESEARCH - NATIONAL RESEARCH COUNCIL OF CANADA, O. (ed.).

SELVEN, S. 2011. Avd. leder Aalmo AS Elektriker.

SFFE. 2011. *Energibruk og effektivisering* [Online]. Senter for fornybar energi. Available: http://www.sffe.no/?page_id=63 [Accessed 01.06.2011].

SOLLI, C., REENAAS, M., STRØMMAN, A. H. & HERTWICH, E. G. 2009. Life cycle assessment of wood-based heating in Norway. *The International Journal of Life Cycle Assessment,* 14**,** 517-528.

SSB. 2006. *1,2 millioner tonn avfall fra byggvirksomhet* [Online]. Available: http://www.ssb.no/emner/01/05/avfbygganl/ [Accessed 03.02.2011].

SSB. 2010. *KOSTRA: Kommunal vannforsyning, 2009* [Online]. Available: http://www.ssb.no/emner/01/04/20/vann_kostra/ [Accessed 03.05.2011].

STRØMMAN, A. H. 2010. *Methodological Essentials of Life Cycle Assessment*.

SØRNES, K. 2010. *Life-cycle assessment of a single family residence conforming to the new standard TEK 07.* Master Project, NTNU.

TEK, S. B. E. 2007. *Revisjon av Teknisk Forskrift 2007* [Online]. Available: http://www.be.no/beweb/info/energikurs07/Energi-veilederkurs/Foredrag/02NyeEnergikrav.pdf [Accessed 09.11.2010].

THORMARK, C. 2002. A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and Environment,* 37**,** 429–435.

TRENOR. 2010a. *Sandvik innerdør* [Online]. Available: http://www.trenor.no/Customers/trenor/documents/Salgsark%20doerer%2009/Sandvik1_2_.pdf [Accessed 13.05.2011].

TRENOR. 2010b. *Vikna ytterdør* [Online]. Available: http://www.trenor.no/Customers/trenor/documents/Salgsark%20doerer%202010/Vikna1_2_3_.pdf [Accessed 13.05.2011].

TRETEKNISK 2004. Tre og Miljø. *In:* INSTITUTT, N. T. (ed.).

TRETEKNISK 2006. Fokus på tre, nr 38: Trefuktighet - tørking.

TRETEKNISK 2007. Fokus på tre, nr 43: Konstruksjonsvirke.

TRETEKNISK 2009. Fokus på tre, nr 51: Soppskader på tre.

TRIOVING. 2009. *NEPD, nr 123N. Dørlås. Doorlock* [Online]. Available: http://www.epd-norge.no/getfile.php/PDF/EPD/Byggevarer/NEPD123N%20TrioVingDormiljo.pdf [Accessed 20.05.2011].

TVERÅS, F. 2011. *RE: Tverås Maskin og Transport AS.*

VÅGE, M., MARRABLE, H., BURGOLD, J. & NIELSEN, H. K. 2009. Kurs i planlegging og bygging av passivhus. *In:* UNIVERSITETET I AGDER, F. F. T. O. R. (ed.).

WEIDEMA, B. P., FREES, N. & NIELSEN, A.-M. 1999. Marginal Production Technologies for Life Cycle Inventories. *The International Journal of Life Cycle Assessment,* 4**,** 48-56.

WHO 2004. Fourth Ministerial Conference on Environment and Health, Review of evidence on housing and health.

WINTHER, B. N. & HESTNES, A. G. 1999. Solar versus green: the analysis of a Norwegian Row House. *Solar Energy,* 66**,** 387–393.

WÆRP, S., GRINI, C., FOLVIK, K. & SVANÆS, J. 2009. Livsløpsanalyser (LCA) av norske treprodukter. SINTEF Byggforsk.

APPENDICES

Appendix A Ionizing radiation network

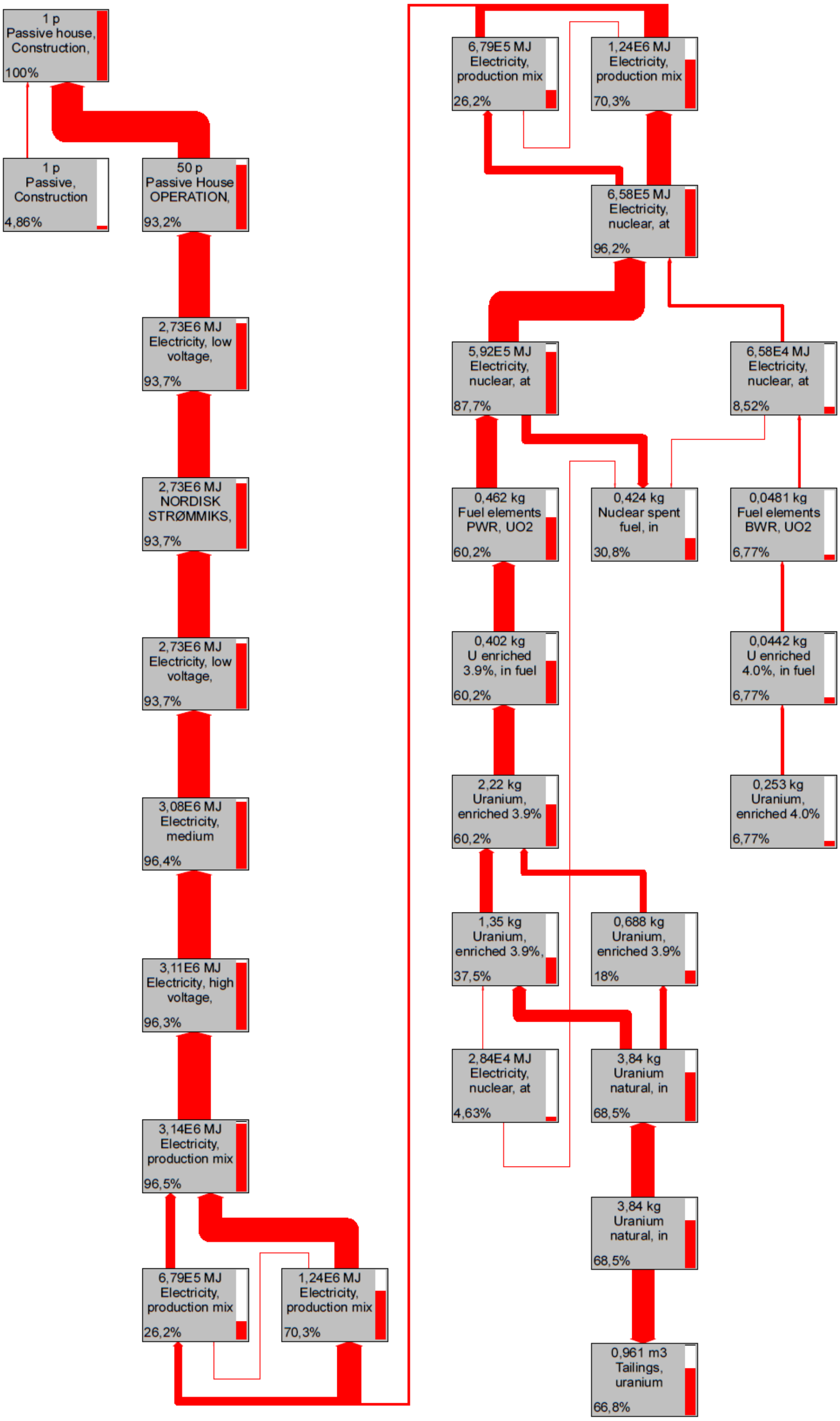


Figure A-1: Network for the ionizing radiation impact category

Appendix B Water depletion potential network

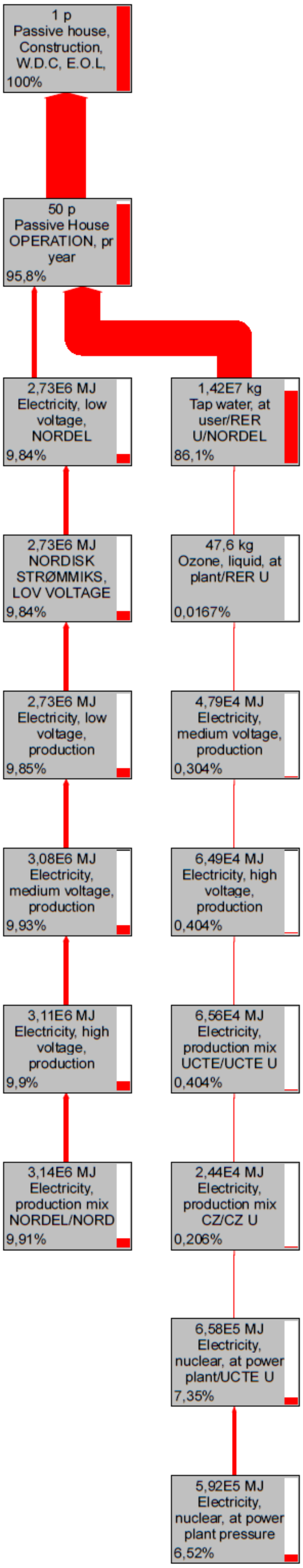
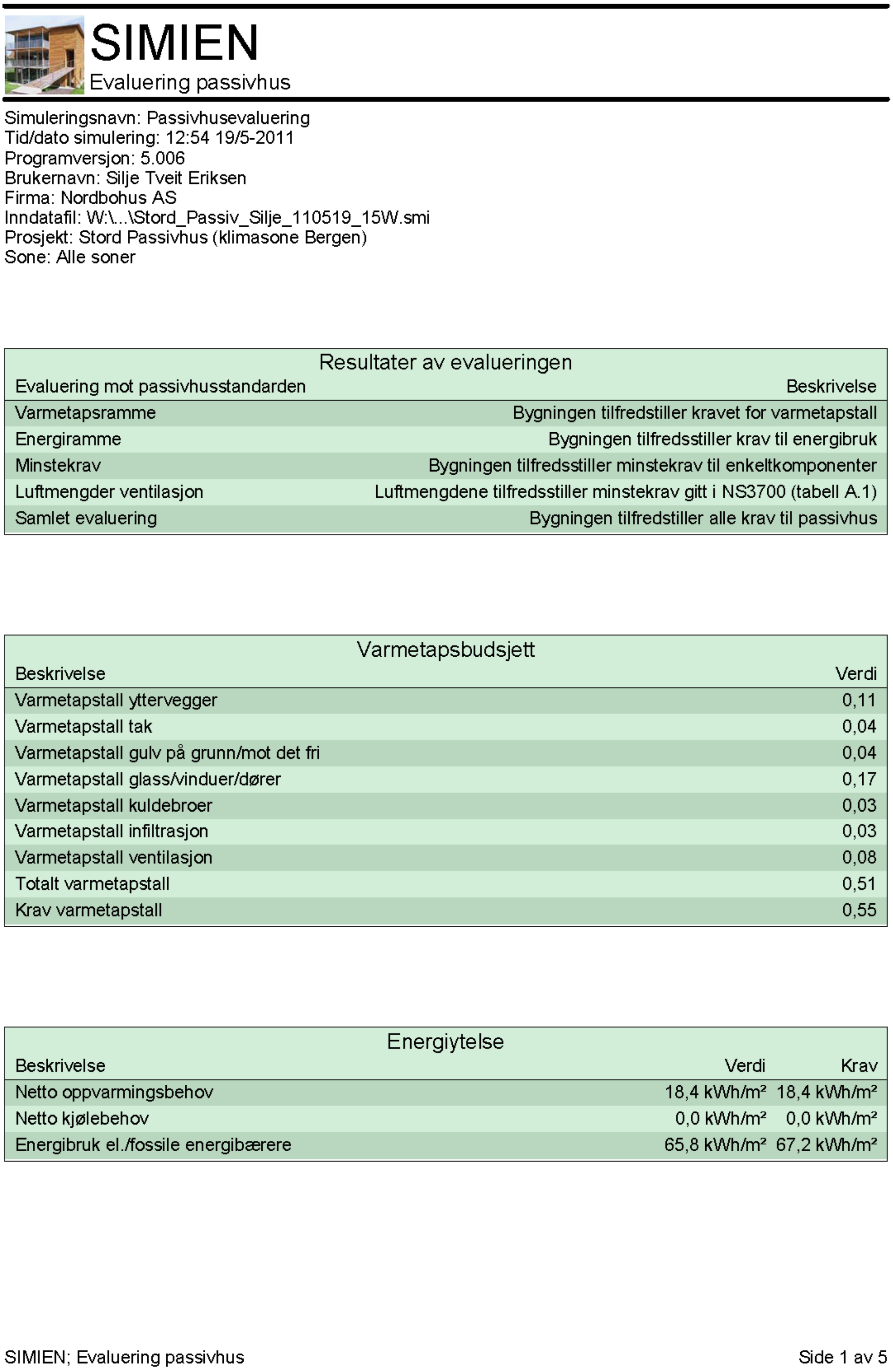


Figure B-1: Network for the water depletion impact category

Appendix C Passive house simulation to NS3700:2010



SIMIEN

Evaluering passivhus

Simuleringsnavn: Passivhusevaluering
Tid/dato simulering: 12:54 19/5-2011
Programversjon: 5.006
Brukernavn: Silje Tveit Eriksen
Firma: Nordbohus AS
Inndatafil: W:\...\Stord_Passiv_Silje_110519_15W.smi
Prosjekt: Stord Passivhus (klimasone Bergen)
Sone: Alle soner

Resultater av evalueringen

Evaluering mot passivhusstandarden	Beskrivelse
Varmetapsramme	Bygningen tilfredstiller kravet for varmetapstall
Energiramme	Bygningen tilfredsstiller krav til energibruk
Minstekrav	Bygningen tilfredsstiller minstekrav til enkeltkomponenter
Luftmengder ventilasjon	Luftmengdene tilfredsstiller minstekrav gitt i NS3700 (tabell A.1)
Samlet evaluering	Bygningen tilfredstiller alle krav til passivhus

Varmetapsbudsjett

Beskrivelse	Verdi
Varmetapstall yttervegger	0,11
Varmetapstall tak	0,04
Varmetapstall gulv på grunn/mot det fri	0,04
Varmetapstall glass/vinduer/dører	0,17
Varmetapstall kuldebroer	0,03
Varmetapstall infiltrasjon	0,03
Varmetapstall ventilasjon	0,08
Totalt varmetapstall	0,51
Krav varmetapstall	0,55

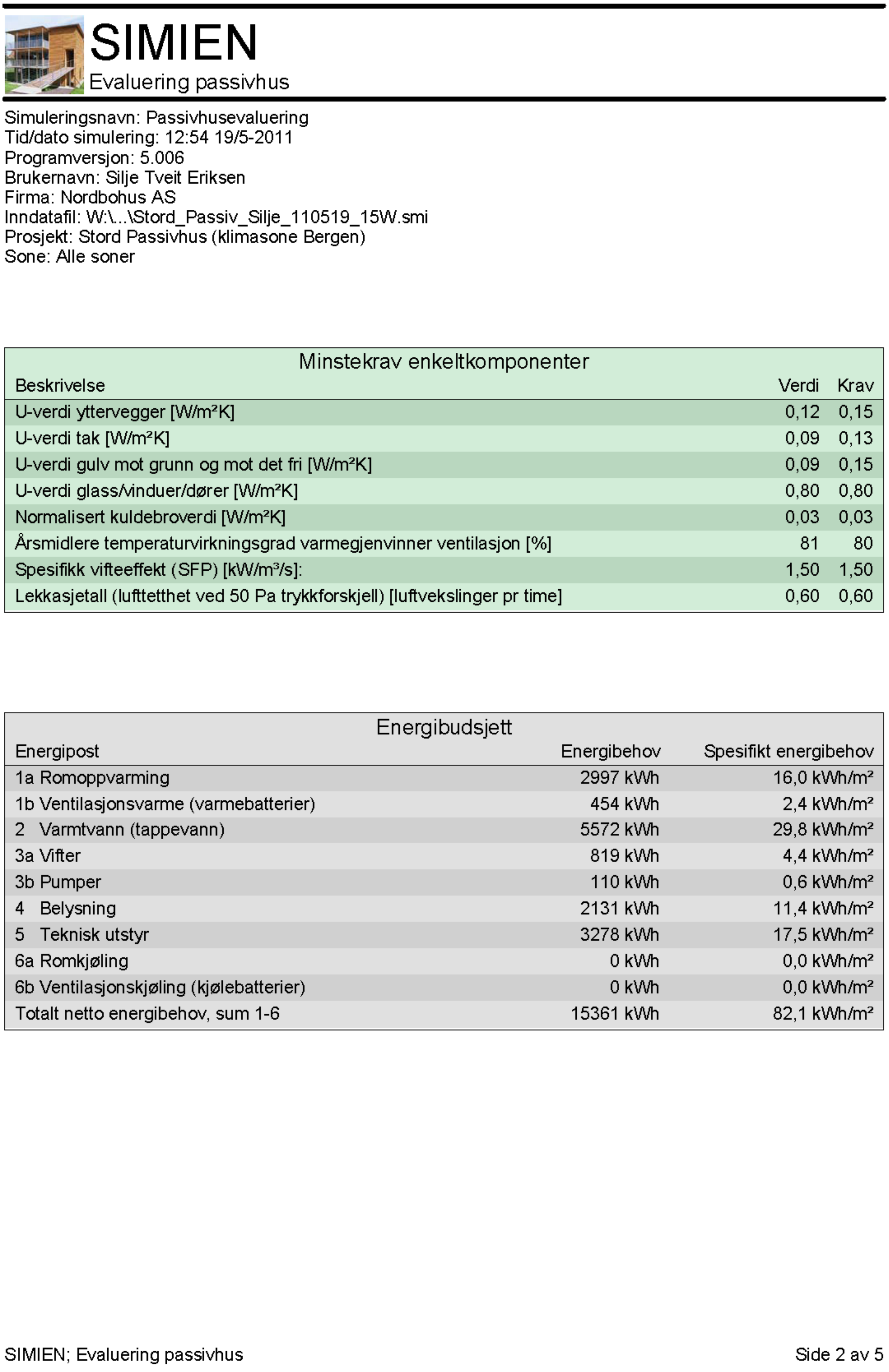
Energiytelse

Beskrivelse	Verdi	Krav
Netto oppvarmingsbehov	18,4 kWh/m^2	18,4 kWh/m^2
Netto kjølebehov	0,0 kWh/m^2	0,0 kWh/m^2
Energibruk el./fossile energibærere	65,8 kWh/m^2	67,2 kWh/m^2

SIMIEN; Evaluering passivhus Side 1 av 5

Figure C-1: Simulation of the technical elements for the passive house to NS3700:2010, calculated by SIMIEN

Figure C-1 continues:



SIMIEN

Evaluering passivhus

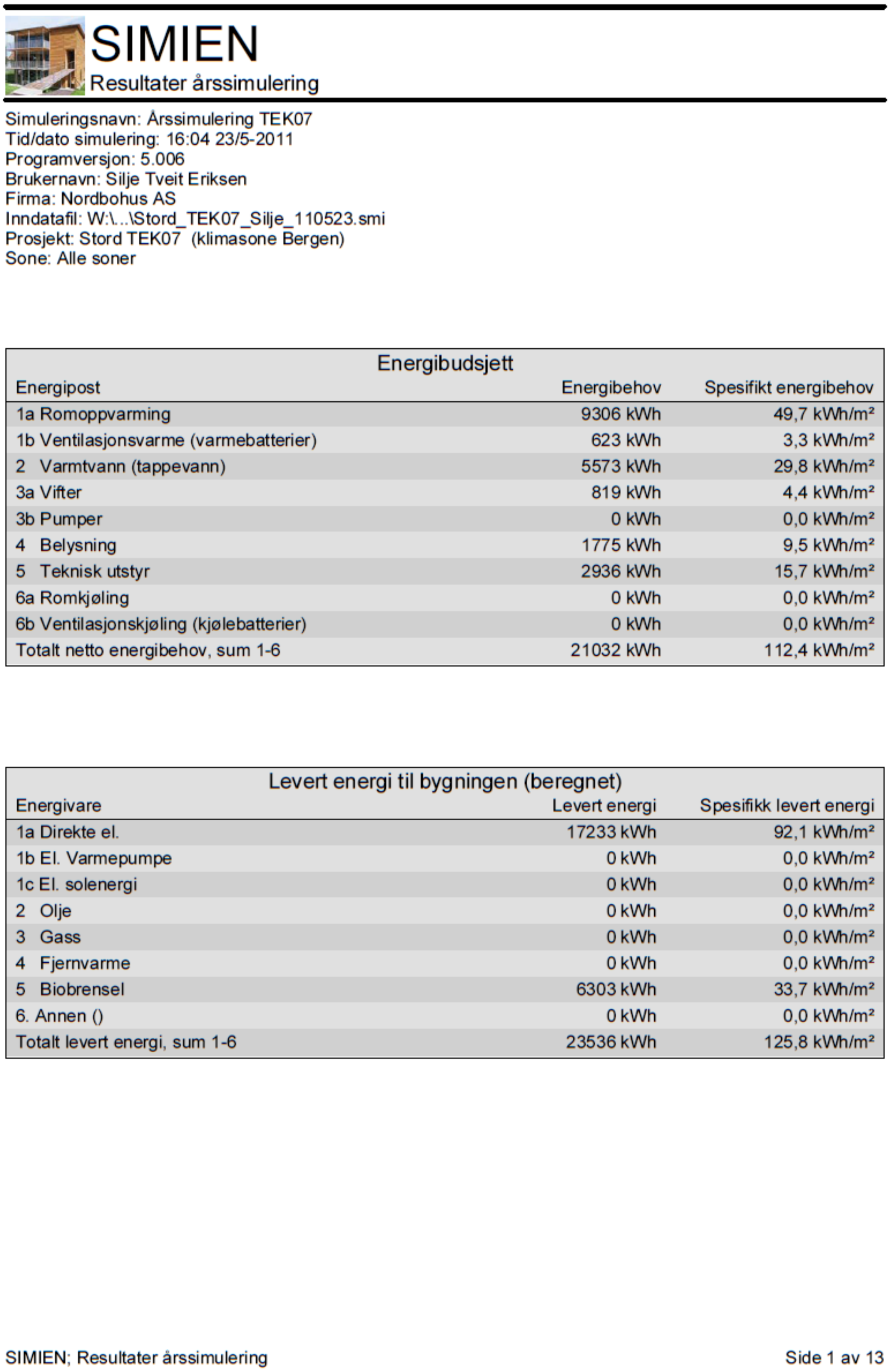
Simuleringsnavn: Passivhusevaluering
Tid/dato simulering: 12:54 19/5-2011
Programversjon: 5.006
Brukernavn: Silje Tveit Eriksen
Firma: Nordbohus AS
Inndatafil: W:\...\Stord_Passiv_Silje_110519_15W.smi
Prosjekt: Stord Passivhus (klimasone Bergen)
Sone: Alle soner

Minstekrav enkeltkomponenter		
Beskrivelse	Verdi	Krav
U-verdi yttervegger [W/m²K]	0,12	0,15
U-verdi tak [W/m²K]	0,09	0,13
U-verdi gulv mot grunn og mot det fri [W/m²K]	0,09	0,15
U-verdi glass/vinduer/dører [W/m²K]	0,80	0,80
Normalisert kuldebroverdi [W/m²K]	0,03	0,03
Årsmidlere temperaturvirkningsgrad varmegjenvinner ventilasjon [%]	81	80
Spesifikk vifteeffekt (SFP) [kW/m³/s]:	1,50	1,50
Lekkasjetall (lufttetthet ved 50 Pa trykkforskjell) [luftvekslinger pr time]	0,60	0,60

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	2997 kWh	16,0 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	454 kWh	2,4 kWh/m²
2 Varmtvann (tappevann)	5572 kWh	29,8 kWh/m²
3a Vifter	819 kWh	4,4 kWh/m²
3b Pumper	110 kWh	0,6 kWh/m²
4 Belysning	2131 kWh	11,4 kWh/m²
5 Teknisk utstyr	3278 kWh	17,5 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	0 kWh	0,0 kWh/m²
Totalt netto energibehov, sum 1-6	15361 kWh	82,1 kWh/m²

Appendix D Energy requirements for the houses

D-1: The TEK07 house



SIMIEN

Resultater årssimulering

Simuleringsnavn: Årssimulering TEK07
Tid/dato simulering: 16:04 23/5-2011
Programversjon: 5.006
Brukernavn: Silje Tveit Eriksen
Firma: Nordbohus AS
Inndatafil: W:\...\Stord_TEK07_Silje_110523.smi
Prosjekt: Stord TEK07 (klimasone Bergen)
Sone: Alle soner

Energibudsjett

Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	9306 kWh	49,7 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	623 kWh	3,3 kWh/m²
2 Varmtvann (tappevann)	5573 kWh	29,8 kWh/m²
3a Vifter	819 kWh	4,4 kWh/m²
3b Pumper	0 kWh	0,0 kWh/m²
4 Belysning	1775 kWh	9,5 kWh/m²
5 Teknisk utstyr	2936 kWh	15,7 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	0 kWh	0,0 kWh/m²
Totalt netto energibehov, sum 1-6	21032 kWh	112,4 kWh/m²

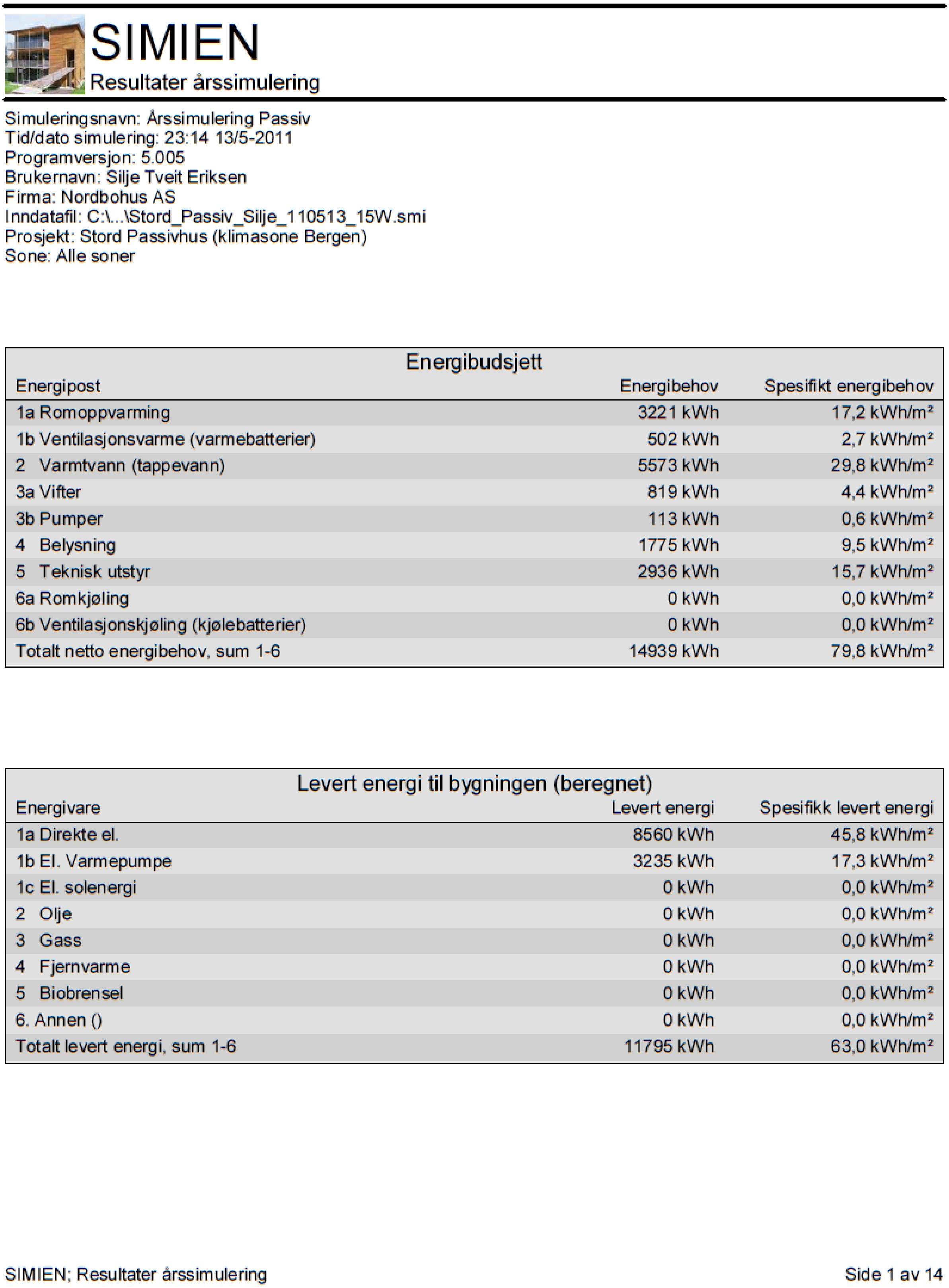
Levert energi til bygningen (beregnet)

Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	17233 kWh	92,1 kWh/m²
1b El. Varmepumpe	0 kWh	0,0 kWh/m²
1c El. solenergi	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	6303 kWh	33,7 kWh/m²
6. Annen ()	0 kWh	0,0 kWh/m²
Totalt levert energi, sum 1-6	23536 kWh	125,8 kWh/m²

SIMIEN; Resultater årssimulering Side 1 av 13

Figure D-1: Total energy requirements for the TEK07 house, calculated by SIMIEN

D-2: The passive house



SIMIEN

Resultater årssimulering

Simuleringsnavn: Årssimulering Passiv
Tid/dato simulering: 23:14 13/5-2011
Programversjon: 5.005
Brukernavn: Silje Tveit Eriksen
Firma: Nordbohus AS
Inndatafil: C:\...\Stord_Passiv_Silje_110513_15W.smi
Prosjekt: Stord Passivhus (klimasone Bergen)
Sone: Alle soner

Energibudsjett

Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	3221 kWh	17,2 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	502 kWh	2,7 kWh/m²
2 Varmtvann (tappevann)	5573 kWh	29,8 kWh/m²
3a Vifter	819 kWh	4,4 kWh/m²
3b Pumper	113 kWh	0,6 kWh/m²
4 Belysning	1775 kWh	9,5 kWh/m²
5 Teknisk utstyr	2936 kWh	15,7 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	0 kWh	0,0 kWh/m²
Totalt netto energibehov, sum 1-6	14939 kWh	79,8 kWh/m²

Levert energi til bygningen (beregnet)

Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	8560 kWh	45,8 kWh/m²
1b El. Varmepumpe	3235 kWh	17,3 kWh/m²
1c El. solenergi	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen ()	0 kWh	0,0 kWh/m²
Totalt levert energi, sum 1-6	11795 kWh	63,0 kWh/m²

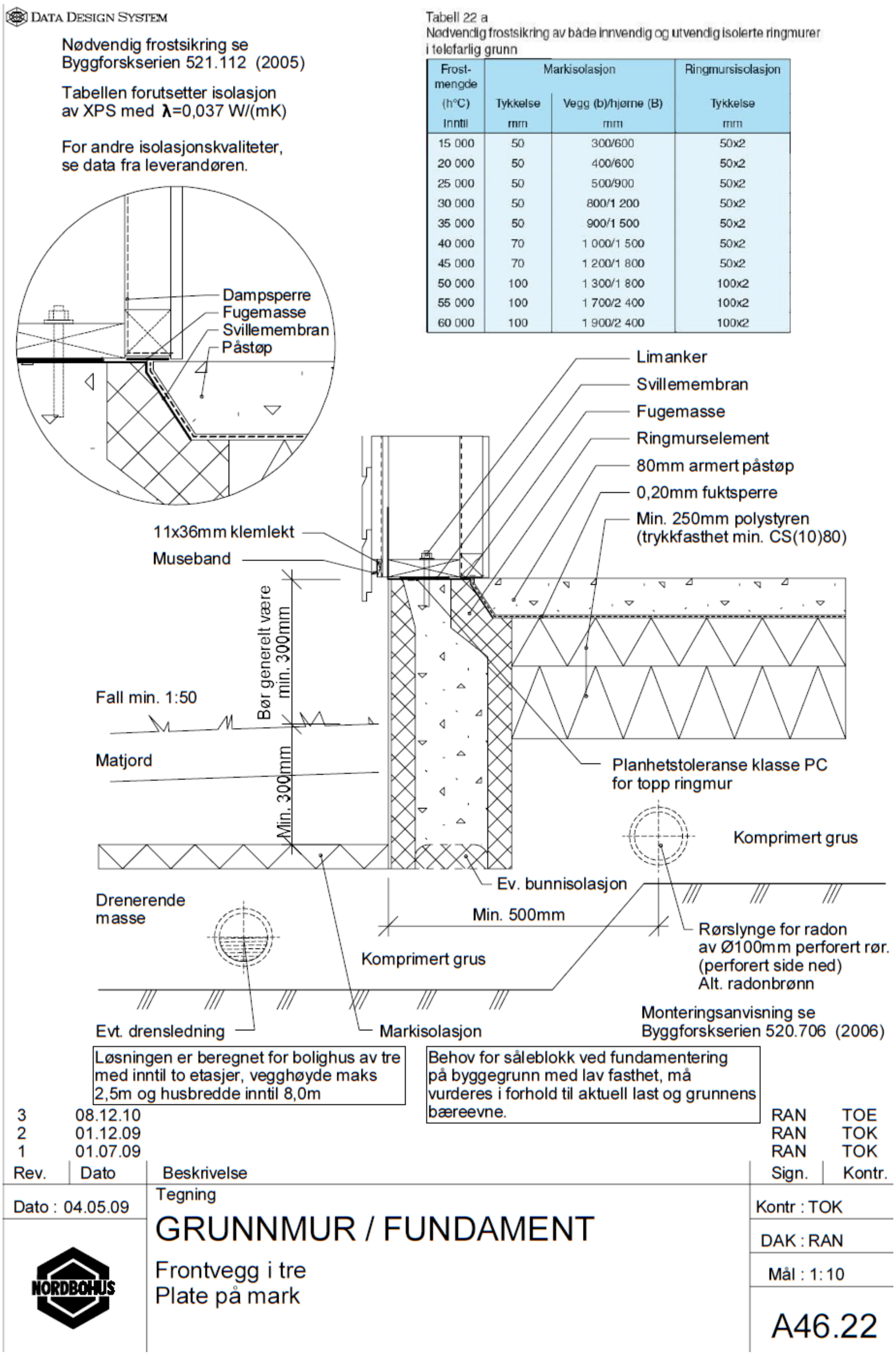
SIMIEN; Resultater årssimulering

Side 1 av 14

Figure D-2: Total energy requirements for the passive house, calculated by SIMIEN

Appendix E Technical drawings for the building elements

E-1: Foundation TEK07



Nødvendig frostsikring se Byggforskserien 521.112 (2005)

Tabellen forutsetter isolasjon av XPS med λ=0,037 W/(mK)

For andre isolasjonskvaliteter, se data fra leverandøren.

Tabell 22 a
Nødvendig frostsikring av både innvendig og utvendig isolerte ringmurer i telefarlig grunn

Frost-mengde	Markisolasjon		Ringmursisolasjon
(h°C)	Tykkelse	Vegg (b)/hjørne (B)	Tykkelse
Inntil	mm	mm	mm
15 000	50	300/600	50x2
20 000	50	400/600	50x2
25 000	50	500/900	50x2
30 000	50	800/1 200	50x2
35 000	50	900/1 500	50x2
40 000	70	1 000/1 500	50x2
45 000	70	1 200/1 800	50x2
50 000	100	1 300/1 800	100x2
55 000	100	1 700/2 400	100x2
60 000	100	1 900/2 400	100x2

Monteringsanvisning se Byggforskserien 520.706 (2006)

Løsningen er beregnet for bolighus av tre med inntil to etasjer, vegghøyde maks 2,5m og husbredde inntil 8,0m

Behov for såleblokk ved fundamentering på byggegrunn med lav fasthet, må vurderes i forhold til aktuell last og grunnens bæreevne.

Rev.	Dato	Beskrivelse	Sign.	Kontr.
3	08.12.10		RAN	TOE
2	01.12.09		RAN	TOK
1	01.07.09		RAN	TOK

Dato : 04.05.09

Tegning
GRUNNMUR / FUNDAMENT
Frontvegg i tre
Plate på mark

Kontr : TOK
DAK : RAN
Mål : 1:10
A46.22

Figure E-1: Technical drawing of the TEK07 foundation

E-2: Foundation and outer wall passive house

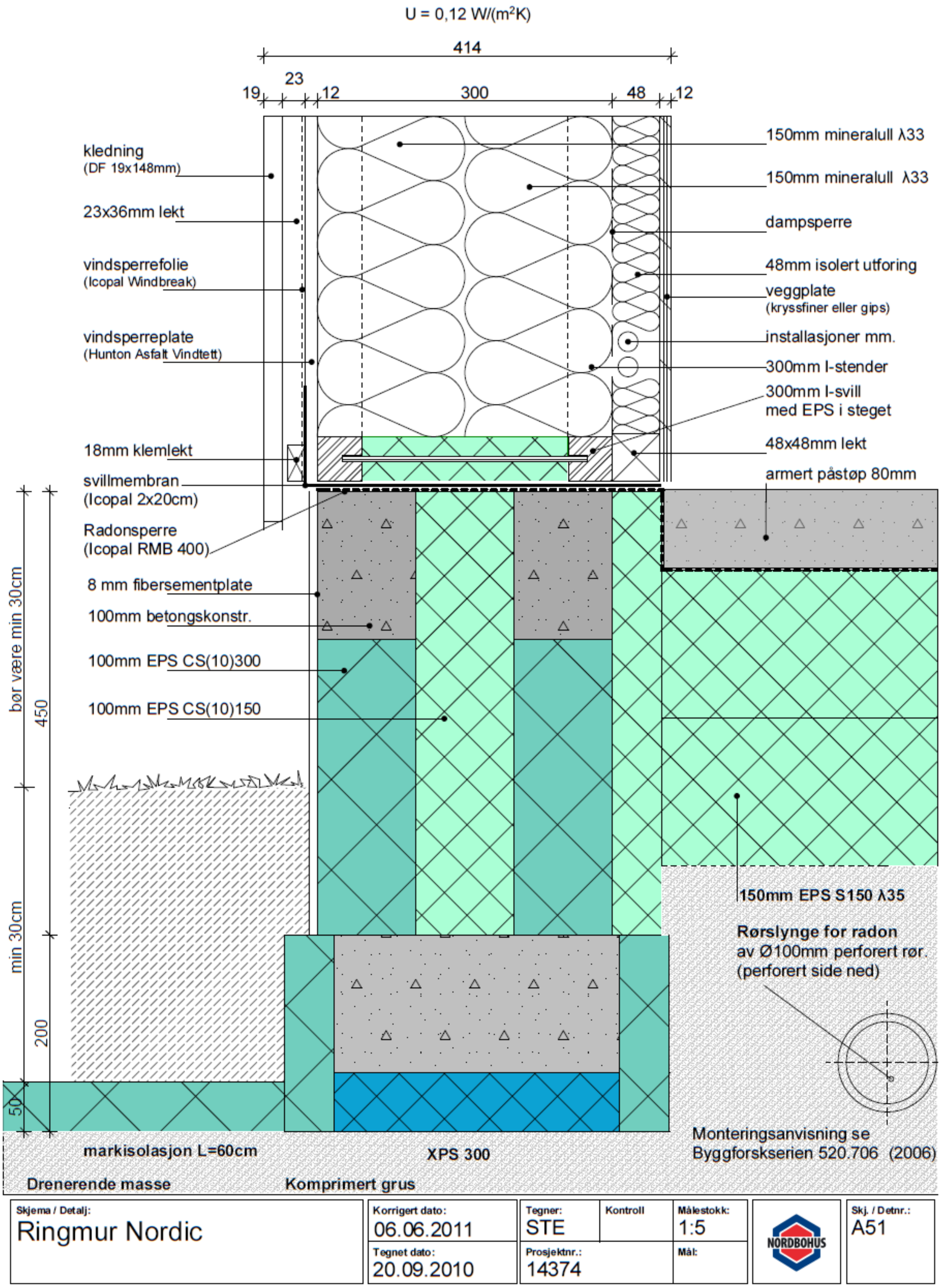


Figure E-2: Technical drawing of the passive house foundation and outer wall

E-3: 1st level floor, TEK07 and passive house; outside wall TEK07

DATA DESIGN SYSTEM

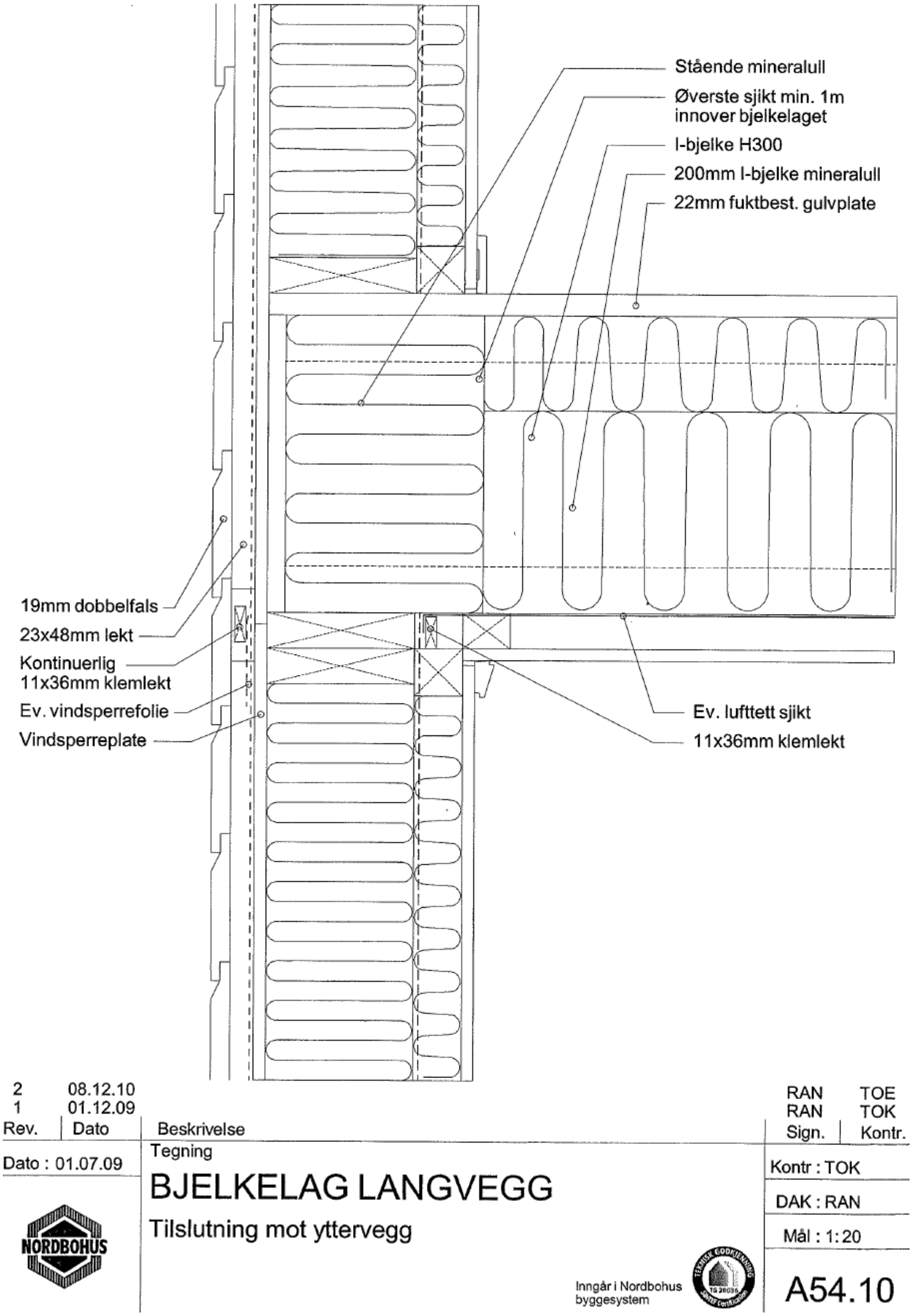
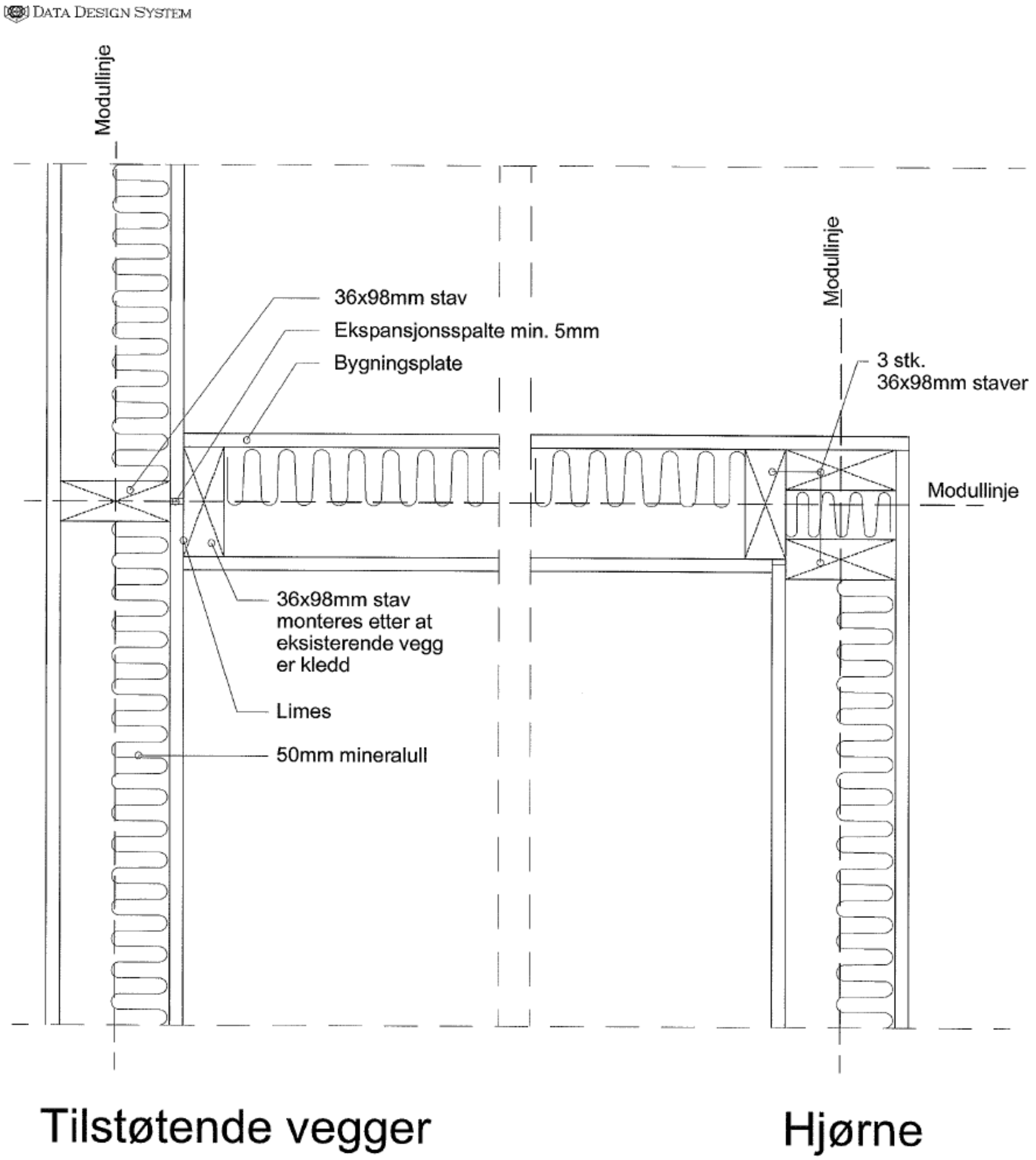


Figure E-3: Technical drawing of the 1st level floor for both TEK07 and passive house; outside wall TEK07

E-4: Inner wall, TEK07 and passive house



Rev.	Dato	Beskrivelse	Sign.	Kontr.
Dato : 01.07.09		Tegning INNVENDIGE VEGGER Lettvegg av tre Horisontalsnitt Inngår i Nordbohus byggesystem	Kontr : TOK DAK : RAN Mål : 1:5 A82.20	

Figure E-4: Technical drawing of the inner wall for both TEK07 and passive house

E-5: Roof for TEK07 and passive house

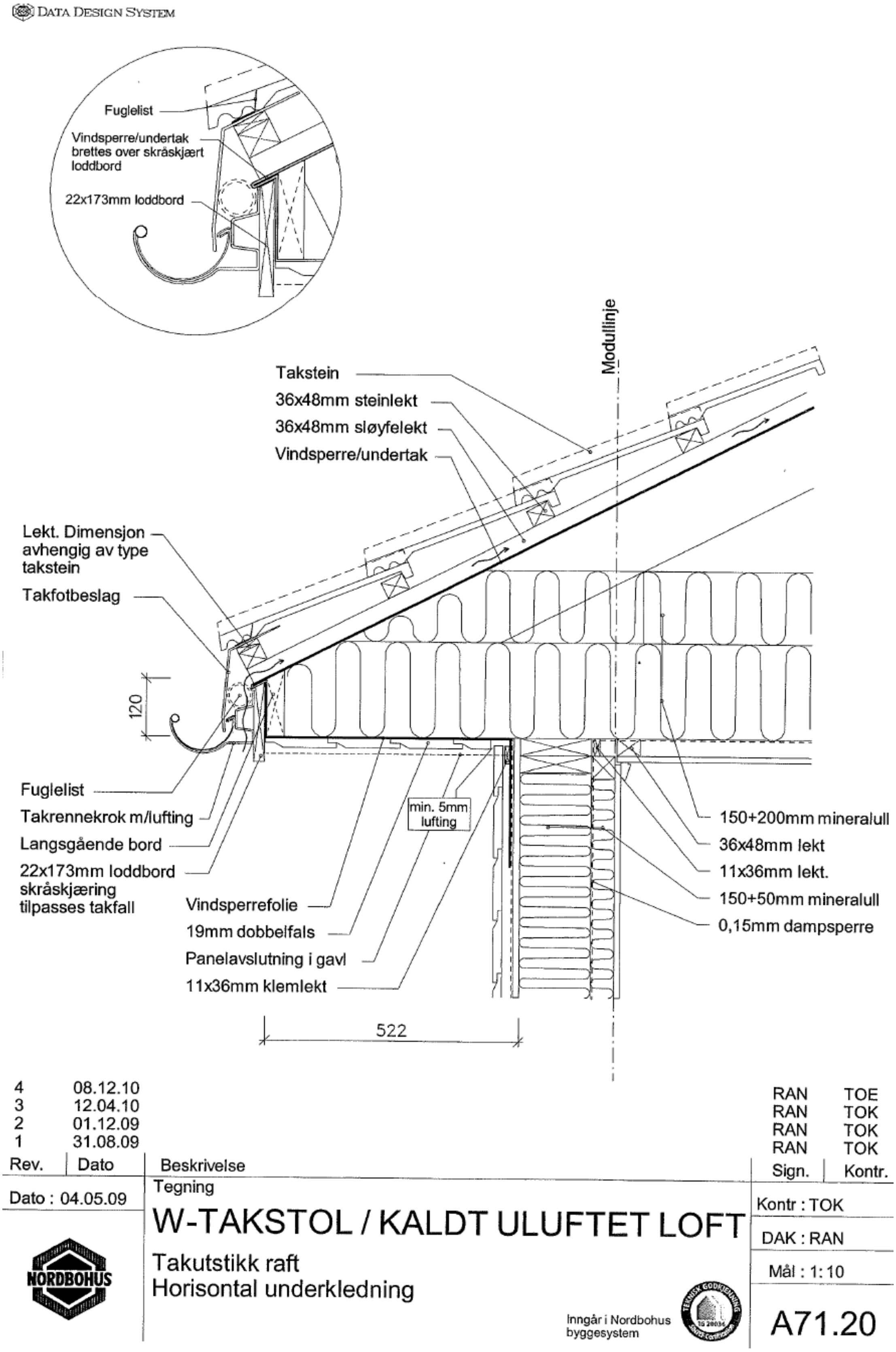


Figure E-5: Technical drawing of the roof for TEK07 and passive house

Appendix F Complete inventory list

Groundwork and foundation	*Used in house*		*Waste during construction*		
Material	*TEK07*	*Passive*	*TEK07*	*Passive*	*Unit*
Foundation wall					
Polystyrene foam slab, at plant/RER /Nordel	47,5	139	4,75	13,9	Kg
Reinforcing steel, at plant/RER/Nordel, 100% recycled	57,5	224	5,75	22,4	kg
Concrete, normal, at plant/CH /Nordel	2,8	2,1	0,28	0,21	m^3
Fiber cement facing tile, at plant/CH /UCTE	71,9	71,9	7,19	7,19	kg
Polystyrene, extruded (XPS), at plant/RER /Nordel	34,8	41,8	3,48	4,18	kg
Sill membrane: 80% bitumen, 20% polypropylene					
Polybutadiene, at plant/RER /UCTE	20,6	50,0	2,28	5,57	kg
Polypropylene, granulate, at plant/RER /UCTE	5,14	12,5	0,57	1,39	kg
Extrusion, plastic film/RER /UCTE	5,14	12,5	0,57	1,39	kg
Foundation footing					
Polystyrene foam slab, at plant/RER /Nordel	21,1	33,7	2,11	3,37	Kg
Polystyrene, extruded (XPS), at plant/RER /Nordel	25,1	25,1	2,51	2,51	kg
Reinforcing steel, at plant/RER/Nordel, 100% recycled	57,5	67,4	5,75	6,74	kg
Concrete, normal, at plant/CH /Nordel	1,77	1,77	0,18	0,18	m^3
Gravel and drainage					
Gravel, crushed at mine/CH /Nordel	164	182	-	-	ton
Polyethylene, HDPE, granulate, at plant/RER /UCTE	68,1	68,1	6,81	6,81	kg
Extrusion, plastic pipes/UCTE	68,1	68,1	-	-	kg

Construction	*Used in house*		*Waste during construction*		
Material	*TEK07*	*Passive*	*TEK07*	*Passive*	*Unit*
Construction					
Glue, for wood products, at plant, Norway	12,8	12,8	-	-	kg
Steel, low-alloyed, at plant/RER U	205	205	-	-	kg
Wire drawing, steel/RER U	205	205	-	-	kg
Chemical anchor; 83 % steel bolt, 17% chemicals					
Steel, low-alloyed, at plant/RER U	5,73	5,73	-	-	kg
Polyester resin, unsaturated, at plant/RER U	1,17	1,17	-	-	kg
Energy for dryer and tools					
Electricity, medium voltage, prod NORDEL, at grid	8874	10494	-	-	kWh
Machines used					
Diesel, burned in building machine, 43,3 MJ/kg	356	403	-	-	kg

Floors	*Used in house*		*Waste during construction*		
Material	*TEK07*	*Passive*	*TEK07*	*Passive*	*Unit*
Ground level floor					
Polystyrene foam slab, at plant/RER /Nordel	595	826	59,5	82,6	kg
Polyethylene, LDPE, granulate, at plant/RER /UCTE	46,2	46,2	4,62	4,62	kg
Extrusion, plastic film/RER /UCTE	46,2	46,2	4,62	4,62	kg
Polybutadiene, at plant/RER /UCTE	2,4	2,4	0,24	0,24	kg
Sealing tape, aluminum/PE, 50mm wide, at plant/RER U	61,4	61,4	6,86	6,86	m
Reinforcing steel, at plant/RER/Nordel, 100% recycled	333	333	33,3	33,3	kg
Concrete, normal, at plant/CH /Nordel	7,60	7,60	0,76	0,76	m^3
1. level floor					
Forestia particle board, floor use	1620	1620	180	180	kg
Timber, planed, at plant, MIKADO/Nordel	437	437	48,6	48,6	kg
Isolation, type 37, Nordel	24,8	24,8	-	-	m^3
I-Beam, at plant, 300mm, MIKADO/Nordel	220	220	24,4	24,4	m
Gypsum plaster board, at plant/CH /Nordel	806	806	89,6	89,6	kg
Forestia particle board, floor use (end wall I-beam)	145	145	16,1	16,1	kg
Laminated wood, at plant, Norway/Nordel	150	150	16,6	16,6	kg
Staircase					
Laminated wood, at plant, Norway/Nordel	134	134	13,4	13,4	kg
Timber, planed, at plant, MIKADO/Nordel	146	146	14,6	14,6	kg
Acrylic varnish, 87,5 % in H2O, at plant/RER /Nordel	4,84	4,84	0,48	0,48	kg
Alkyd paint, white, 60 % in H2O, at plant/RER /Nordel	6,62	6,62	0,66	0,66	kg

Walls	*Used in house*		*Waste during construction*		
Material	*TEK07*	*Passive*	*TEK07*	*Passive*	*Unit*
Outer wall					
Wood cladding: Timber, planed, at plant, MIKADO/Nordel	3201	3201	356	356	kg
Timber, planed, at plant, MIKADO/Nordel	3476	2766	386	307	kg
Polypropylene, granulate, at plant/RER /UCTE	19,8	19,8	2,21	2,21	kg
Extrusion, plastic film/RER /UCTE	19,8	19,8	2,21	2,21	kg
Hundtolitt asfalt, 12mmm Nordel	288	288	28,8	28,8	m^2
I-Beam, at plant, 300mm, MIKADO/Nordel	-	506	-	56,3	m
Isolation, type 37, Nordel	33,3	-	-	-	m^3
Isolation, type 33, Nordel	-	57,2	-	-	m^3
Vapor barrier, X-15 Isola/Nordel	217	217	24,2	24,2	m^2
Forestia particle board, wall use	1736	1736	193	193	kg
Sealing tape, aluminum/PE, 50mm wide, at plant/RER U	118	349	13,0	38,8	m
Bitumen sealing, at plant/RER /UCTE	-	15,5		1,55	kg
Mouse band, aluzinc					
Aluminum, production mix, at plant/Nordel	15,8	15,8	-	-	kg
Zinc, primary, at regional storage/RER /UCTE	13	13	-	-	kg
Sheet rolling, steel/RER /UCTE	28,8	28,8	-	-	kg
Inner wall					
Forestia particle board, wall use	1739	1739	193	193	kg
Isolation, type 37, Nordel	6,26	6,26	-	-	m^3
Timber, planed, at plant, MIKADO/Nordel	1536	1536	171	171	kg

Roof	*Used in house*		*Waste during construction*		
Material	*TEK07*	*Passive*	*TEK07*	*Passive*	*Unit*
Outer roof					
Roof tile, at plant/RER / Nordel	6038	6038	-	-	kg
Timber, planed, at plant, MIKADO/Nordel	801	801	89,0	89,0	kg
Wind and water barrier, under roof, Ventex Supra	166	166	18,5	18,5	m^2
Polyethylene, HDPE, granulate, at plant/RER /UCTE	28,0	28,0	-	-	kg
Injection moulding/RER /UCTE	28,0	28,0	-	-	kg
Bitumen sealing, at plant/RER /UCTE	1,08	5,04	0,12	0,56	kg
Roof truss					
Timber, planed, at plant, MIKADO/Nordel	1683	1683	-	-	kg
Steel, low-alloyed, at plant/RER U	48,1	48,1	-	-	kg
Sheet rolling, steel/RER /UCTE	48,1	48,1	-	-	kg
Ceiling					
Isolation, type 37, Nordel	36,7	42,5	-	-	m^3
Timber, planed, at plant, MIKADO/Nordel	339	339	37,8	37,8	kg
Vapor barrier, non reflective	101	-	11,3	-	m^2
Vapor barrier, reflective	-	135	-	15	m^2
Gypsum plaster board, at plant/CH /Nordel	806	806	89,6	89,6	kg
Steel, low-alloyed, at plant/RER U	107	107	-	-	kg
Sheet rolling, steel/RER /UCTe	107	107	-	-	kg
Rain gutter					
Steel, low-alloyed, at plant/RER U	208	208	-	-	kg
Sheet rolling, steel/RER /UCTE	208	208	-	-	kg
Zinc coating, steel/RER /UCTE	13,4	13,4	-	-	m^2
Powder coating, steel/RER /UCTE	26,7	26,7	-	-	m^2

Windows and doors	*Used in house*		*Waste during construction*		
Material	*TEK07*	*Passive*	*TEK07*	*Passive*	*Unit*
Windows					
Complete window with aluminum cladding, U1,2	16	-	-	-	p
Complete window with aluminum cladding, U0,8	-	16	-	-	p
Forestia particle board, wall use	233	393	23,3	39,3	kg
Alkyd paint, white, 60 % in H2O, at plant/RER U/Nordel	16	26,2	1,6	2,6	kg
Outer doors					
Complete outer door, with frame and lining, U1,0	2	-	-	-	p
Complete outer door, with frame and lining, U0,8	-	2	-	-	p
Inner doors					
Forestia particle board, wall use	110	110	2,24	2,24	kg
Laminated wood, at plant, Norway/Nordel	180	180	-	-	kg
Corrugated board, mixed fibre, single wall, at plant/RER U	20,0	20,0	-	-	kg
Door lock, EPD/Nordel	12	12	-	-	p
Alkyd paint, white, 60 % in H2O, at plant/RER U/Nordel	20,0	20,0	-	-	kg

Electricity and plumbing	*Used in house*		*Waste during construction*		
Material	*TEK07*	*Passive*	*TEK07*	*Passive*	*Unit*
Electricity					
Fusebox	**1**	**1**			**P**
Steel, low-alloyed, at plant/RER U	15	15	-	-	kg/p
Sheet rolling, steel/RER /UCTE	15	15	-	-	kg/p
Powder coating, steel/RER /UCTE	1,4	1,4	-	-	m^2/p
Power point (outlets) + HDPE wall box	**87**	**87**			**p**
Plugs, inlet and outlet, for computer cable, at plant/GLO /UCTE	2	2	-	-	p/p
Polyethylene, HDPE, granulate, at plant/RER	0,11	0,11	-	-	kg/p
Blow moulding/RER /UCTE	0,11	0,11	-	-	kg/p
PVC electrical conduit, 16mm	**350**	**350**	**35**	**35**	**M**
Polyvinylchloride, suspension polymerized, at plant/RER U	0,0598	0,0598			kg/m
Extrusion, plastic pipes/UCTE	0,0598	0,0598			kg/m
Electrical cable, 3*2,5/2,5/Nordel	**350**	**350**	**35**	**35**	**m**
Cable, without plugs, at plant/Nordel	3	3			m/m
Cable, three-conductor cable, at plant/GLO U	5	5			m
Plumbing					
Polyethylene, HDPE, granulate, at plant/RER /UCTE	8,06	8,06	0,81	0,81	kg
Polyvinylchloride, suspension polymerized, at plant/RER U	6,9	6,9	0,69	0,69	Kg
Polypropylene, granulate, at plant/RER /UCTE	27,6	27,6	2,76	2,76	kg
Extrusion, plastic pipes/UCTE	42,6	42,6	4,26	4,26	kg

Surface finish

	Used in house		*Waste during construction*		
Material	*TEK07*	*Passive*	*TEK07*	*Passive*	*Unit*
1 coat outdoor paint, wall					
Alkyd paint, white, 60 % in solvent, at plant/RER/Nordel	34	34	3,4	3,4	kg
1 coat indoor paint, wall					
Alkyd paint, white, 60 % in H2O, at plant/RER/Nordel	57,4	57,4	6,5	6,5	kg
1 coat indoor paint, ceiling					
Alkyd paint, white, 60 % in H2O, at plant/RER/Nordel	24,5	24,5	2,5	2,5	kg
1 complete cover of floors, parquet					
Three layered laminated board, at plant/RER/Nordel	161	161	16,1	16,1	m^2
Acrylic varnish, 87,5% in H2O, at plant/RER/Nordel	102	102	10,2	10,2	kg
Complete bathroom					
Litexplate	**60,6**	**60,6**	**6,73**	**6,73**	**kg**
Polystyrene, extruded (XPS), at plant/RER /Nordel	0,36	0,36			kg/kg
Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/RER U/Nordel	0,64	0,64	-	-	Kg/kg
Polypropylene, granulate, at plant/RER U/UCTE	5,76	5,76	0,64	0,64	kg
Extrusion, plastic film/UCTE	5,76	5,76	0,64	0,64	kg
Bitumen sealing, at plant/RER U/UCTE	17,3	17,3	1,92	1,92	kg
Ceramic tiles, at regional storage/CH U/UCTE	985	985	109	109	kg
Adhesive mortar, at plant/CH U/UCTE	288	288	31,9	31,9	kg
Timber, planed, at plant, MIKADO/Nordel, paneling	413	413	45,9	45,9	kg

Waste processes

Production process	*Waste process*
Acrylic varnish, 87,5 % in H2O, at plant/RER U/Nordel	Disposal, paint,0% water, to municipal incineration/CH U
Adhesive mortar, at plant/CH U/UCTE	Disposal, building, cement (in concrete) and mortar, to sorting plant/CH U
Alkyd paint, white, 60 % in H2O, at plant/RER U/Nordel	Disposal, paint,0% water, to municipal incineration/CH U
Alkyd paint, white, 60 % in solvent, at plant/RER	Disposal, paint,0% water, to municipal incineration/CH U
Aluminum, production mix, at plant/Nordel	Disposal, aluminum, 0% water, to municipal incineration/CH U
Bitumen sealing, at plant/RER U/UCTE	Disposal, rubber, unspecified, 0% water, to municipal incineration/CH U
Cable, three-conductor cable, at plant/GLO U	50% Disposal, copper, 0% water, to municipal incineration/CH U
Cable, without plugs, at plant/Nordel	50% Disposal, copper, 0% water, to municipal incineration/CH U
Ceramic tiles, at regional storage/CH U/UCTE	Disposal, building, brick, to sorting plant/CH U
Concrete, normal, at plant/CH U/Nordel	Disposal, building, concrete, not reinforced, to sorting plant/CH U
Corrugated board, mixed fibre, single wall, at plant/RER U	Disposal, packaging cardboard, 19,6% water, to municipal incineration/CH U
Door lock, EPD/Nordel	Disposal, steel, 0% water, to municipal incineration/CH U
Fibre cement facing tile, at plant/CH U/UCTE	Disposal, cement-fibre slab, 0% water, to municipal incineration/CH U
Forestia particle board, wall use	Disposal, wood untreated, 20% water, to municipal incineration/CH U
Forestia particle board, floor use	Disposal, wood untreated, 20% water, to municipal incineration/CH U
Isolation, type 37 and type 33, Nordel	Disposal, building, mineral wool, to sorting plant/CH U
Glue, for wood products, at plant, Norway	Disposal, plastics, mixture, 15,3% water, to municipal incineration/CH U
Gravel, crushed at mine/CH U/Nordel	-
Gypsum plaster board, at plant/CH U/Nordel	Disposal, building, plaster board, gypsum plaster, to final disposal/CH U
Hundtolitt asfalt, 12mmm Nordel	Disposal, bitumen sheet, 15,9% water, to municipal incineration/CH U
I-Beam, at plant, 300mm, MIKADO/Nordel	Disposal, wood untreated, 20% water, to municipal incineration/CH U
Kledningsbord	Disposal, wood untreated, 20% water, to municipal incineration/CH U
Laminated wood, at plant, Norway/Nordel	Disposal, wood untreated, 20% water, to municipal incineration/CH U
Litexplate	36% - Disposal, expanded polystyrene, 5% water, to municipal incineration/CH U 64% - Disposal, plastics, mixture, 15,3% water, to municipal incineration/CH U
Plugs, inlet and outlet, for computer cable, at plant/GLO U/UCTE	Disposal, wire plastic, 3,55% water, to municipal incineration/CH U

Three layered laminated board, at plant/RER/Nordel	Disposal, wood untreated, 20% water, to municipal incineration/CH U
Polybutadiene, at plant/RER U/UCTE	Disposal, rubber, unspecified, 0% water, to municipal incineration/CH U
Polyester resin, unsaturated, at plant/RER U	Disposal, plastics, mixture, 15,3% water, to municipal incineration/CH U
Polyethylene, HDPE, granulate, at plant/RER U/UCTE	Disposal, polyethylene, 0,4% water, to municipal incineration/CH U
Polyethylene, LDPE, granulate, at plant/RER U/UCTE	Disposal, polyethylene, 0,4% water, to municipal incineration/CH U
Polypropylene, granulate, at plant/RER U/UCTE	Disposal, polypropylene, 15.9% water, to municipal incineration/CH U
Polystyrene foam slab, at plant/RER U/Nordel	Disposal, expanded polystyrene, 5% water, to municipal incineration/CH U
Polystyrene, extruded (XPS), at plant/RER U/Nordel	Disposal, expanded polystyrene, 5% water, to municipal incineration/CH U
Polyvinylchloride, suspension polymerized, at plant/RER U	Disposal, polyvinylchloride, 0,2% water, to municipal incineration/CH U
Reinforcing steel, at plant/RER/Nordel, 100% recycled	Disposal, building, reinforcement steel, to sorting plant/CH U
Roof tile, at plant/RER U/ Nordel	Disposal, building, brick, to sorting plant/CH U
Sealing tape, aluminum/PE, 50mm wide, at plant/RER U	50% Disposal, polyethylene, 0,4% water, to municipal incineration/CH U 50% Disposal, aluminum, 0% water, to municipal incineration/CH U
Steel, low-alloyed, at plant/RER U, in wood	Disposal, steel, 0% water, to municipal incineration/CH U
Steel, low-alloyed, at plant/RER U, Larger parts	Disposal, building, reinforcement steel, to sorting plant/CH U
Timber, planed, at plant, MIKADO/Nordel	Disposal, wood untreated, 20% water, to municipal incineration/CH U
Timber, planed, at plant, MIKADO/Nordel, paneling	Disposal, wood untreated, 20% water, to municipal incineration/CH U
Vapor barrier, Reflective	70% - Disposal, polyethylene, 0,4% water, to municipal incineration/CH U 30% - Disposal, aluminum, 0% water, to municipal incineration/CH U
Vapor barrier, X-15 Isola	Disposal, polyethylene, 0,4% water, to municipal incineration/CH U
Wind and water barrier, under roof, Ventex Supra	60% Disposal, polyurethane, 0,2% water, to municipal incineration/CH U 30% Disposal, polypropylene, 15.9% water, to municipal incineration/CH U 10% Disposal, rubber, unspecified, 0% water, to municipal incineration/CH U
Windows , U1,2	Complete window, aluminum cladding, U.1,2 (E.O.L)
Windows U 0,8	Complete window, aluminum cladding, U.0,8 (E.O.L)
Zinc, primary, at regional storage/RER U/UCTE	Disposal, aluminum, 0% water, to municipal incineration/CH U

Appendix G Particleboard production at Foresitas Braskereidfoss

The resources and waste for particle board production in Norway is from Byggma Foresitas plant Braskereidfoss (Forestia, 2009). Weighted inputs and outputs, Table G-1 and Table G-2, are calculated pr m3 produced fiber board. According to allocation principles in the Mikado project, no energy for sawmill and process heat is allocated the wood chips, hence no impacts from wood chips production.

Table G-1: Resources required for particle board production

Resources	*2007*	*2008*	*2009*	*Weighted average, pr m3 particleboard*	
Total production	*315162*	*261267*	*204434 m3*	***260288***	*m3*
Timber, rough saw	7401	0	9647 m3	**0,037**	m3
Wood chips	489946	402577	306468 m3	**1,536**	m3
Resin	29748	24530	21579 ton	**97,40**	kg
Hardener	1101	979	886 ton	**3,828**	kg
Additive	2863	2598	2560 ton	**10,46**	kg
Electrical energy	52,5	35,7	34,8 GWh	**158,9**	kWh
Light fuel oil	4,25	3,42	4,2 GWh	**15,87**	kWh
Wood chip burned in furnace	284	241	216 GWh	**953,4**	kWh
Water	190818	177331	182249 m3	**0,724**	m3
Lubrication oil	14653	9650	10325 liter	**0,037**	kg

Table G-2 Waste from particle board production

Waste	*2007*	*2008*	*2009*	*Weighted average, pr m3 particleboard*	
Bio waste	2,06	0,42	2,2 ton	**0,008**	kg
Plastic	4,66	5,64	6,3 ton	**0,023**	kg
Cardboard	43,2	41,29	41,57 ton	**0,166**	kg
Paper	7,9	3,65	6,37 ton	**0,025**	kg
Wood waste	60000	55000	50000 ton	**213,5**	kg
Iron	128,14	60,34	47,34 ton	**0,327**	kg
PVC	497,24	308,82	120,84 ton	**1,317**	kg
Big Bag	2,5	2,62	3,38 ton	**0,012**	kg
EE waste	1,73	4,08	8,96 ton	**0,032**	kg
Residual waste	106,9	113,81	89,54 ton	**0,403**	kg
Special waste	4,89	7,85	6,75 ton	**0,027**	kg
Combustion ash	1358,84	531,46	1300 ton	**4,766**	kg

It is assumed an average transport distance of 200 km for all inputs and outputs. For the wall particle board *urea formaldehyde resin (UF*) is used and for the floor particle board *melamine urea formaldehyde (MUF)* is used, assuming the same resin weight.

It is assumed a Nordel electricity mix for the production. The hardener is ammonium nitrate, 50% of the additive is ammonia and 50% paraffin wax. All waste except steel, EE waste and wood ash are sent to a municipal incineration plant with necessary exhaust pipe purification system.

Density of 1m3 fiberboard is 700 kg/m^3. (Forestia, 2010). The factory at Braskereidfoss produces many different types of boards, but it is assumed no difference in the production due to lack of data. With the given density of 700 kg/m^3 and 9% resin content (Forestia, 2010), the weighted average of 97,40 kg resin/m^3 is replaced with this exact demand, 63 kg resin/m^3 (9% of 700kg).

Table G-3: Life Cycle Impact Assessment for production of 1m^3 particle board, wall (UF) and floor (MUF) type

Impact category	*Forestia particle board, wall (UF)*	*Forestia particle board, floor (MUF)*	*Unit*
CC	273	330	kg CO2 eq
HT	179	185	kg 1,4-DB eq
POF	1,01	1,13	kg NMVOC
PMF	0,61	0,72	kg PM10 eq
TA	1,23	1,59	kg SO2 eq
FE	0,01	0,01	kg P eq
ME	0,33	0,38	kg N eq
TET	0,61	0,62	kg 1,4-DB eq
FET	1,03	1,11	kg 1,4-DB eq
MET	1,31	1,47	kg 1,4-DB eq
MD	23,8	29,8	kg Fe eq
CED	10,4	11,4	GJ eq

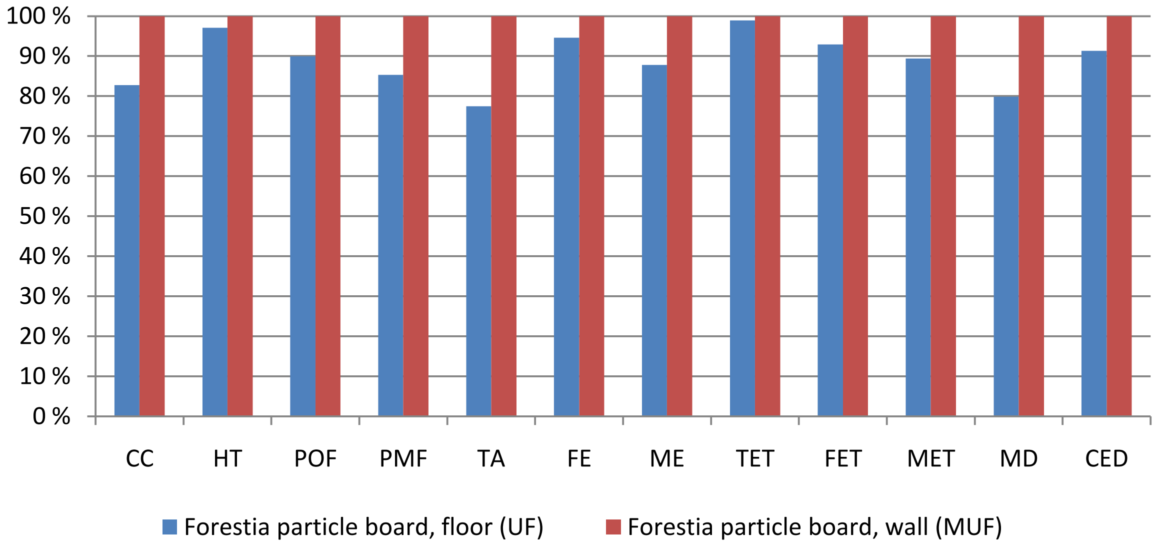


Figure G-1: Difference in the Life Cycle Impact Assessment for 1m^3 particle board

Table G-3 and figure g-1 shows the total impacts for producing 1 m^3 of the different boards. Resin production is 60% of CC impacts for UF and 70% for MUF, while around 30%-60% for the other impact categories.

Appendix H LCA, cradle to gate, outer and inner door production.

Outer doors

An outer door from Trenor, type Vikna without window, is analyzed to get material data (figure h-1). The door consists of a door leaf, door frame, lining, paint and hardware. (Trenor, 2010b)

U value outer door: 0,94 W/m^{2}K

For a passive house door, with U value requirements of 0,8 W/m^{2}K, it is assumed the same components as the Vikna door, but with a total thickness of 100 mm (increased from 53 mm).

Trioving (2009) has made an EPD for door locks. This is used as door hardware for all doors. All material data presented in table h-1 and table h-2 are for one door.

Table H-1: Material requirement for a TEK07 and passive house outer door

Door leaf	*TEK07 door*		*Passive house door*	
Particle board	13,6	kg	18,9	kg
Frame, laminated wood	5,74	kg	11,5	kg
Aluminum sheet	10,2	kg	10,2	kg
XPS	2,81	kg	5,62	Kg
Door frame				
Frame, laminated wood	11,0	kg	17,2	kg
Aluminum sheet	0,40	kg	0,80	kg
Lining, paint and hardware				
Lining	12,58	kg	22,14	kg
Paint	2,80	kg	3,14	kg
Hardware	1	p	1	p

Inner door

An inner door from Trenor, type Sandvik without window, is analyzed to get material data. (Trenor, 2010a). It is assumed the same door type for both the TEK07 house and passive house.

Table H-2: Material requirement for a TEK07 and passive house inner door

Door leaf		
Particle board	7,94	kg
Frame, laminated wood	2,77	kg
Cardboard, honeycomb	1,82	kg
Door frame		
Frame, laminated wood	11,0	kg
Lining, paint and hardware		
Lining	2,06	kg
Paint	1,82	kg
Hardware	1	p

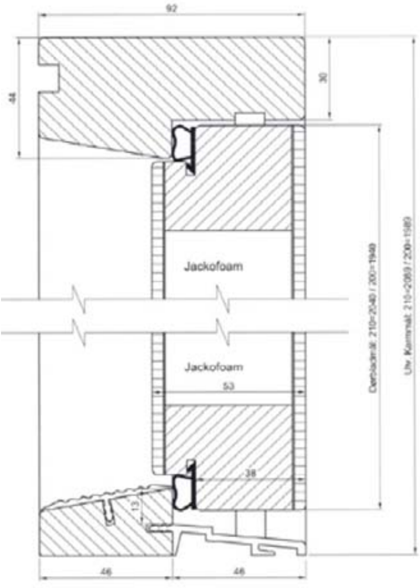


Figure H-1: Analyzed outer door from Trenor (2010b).

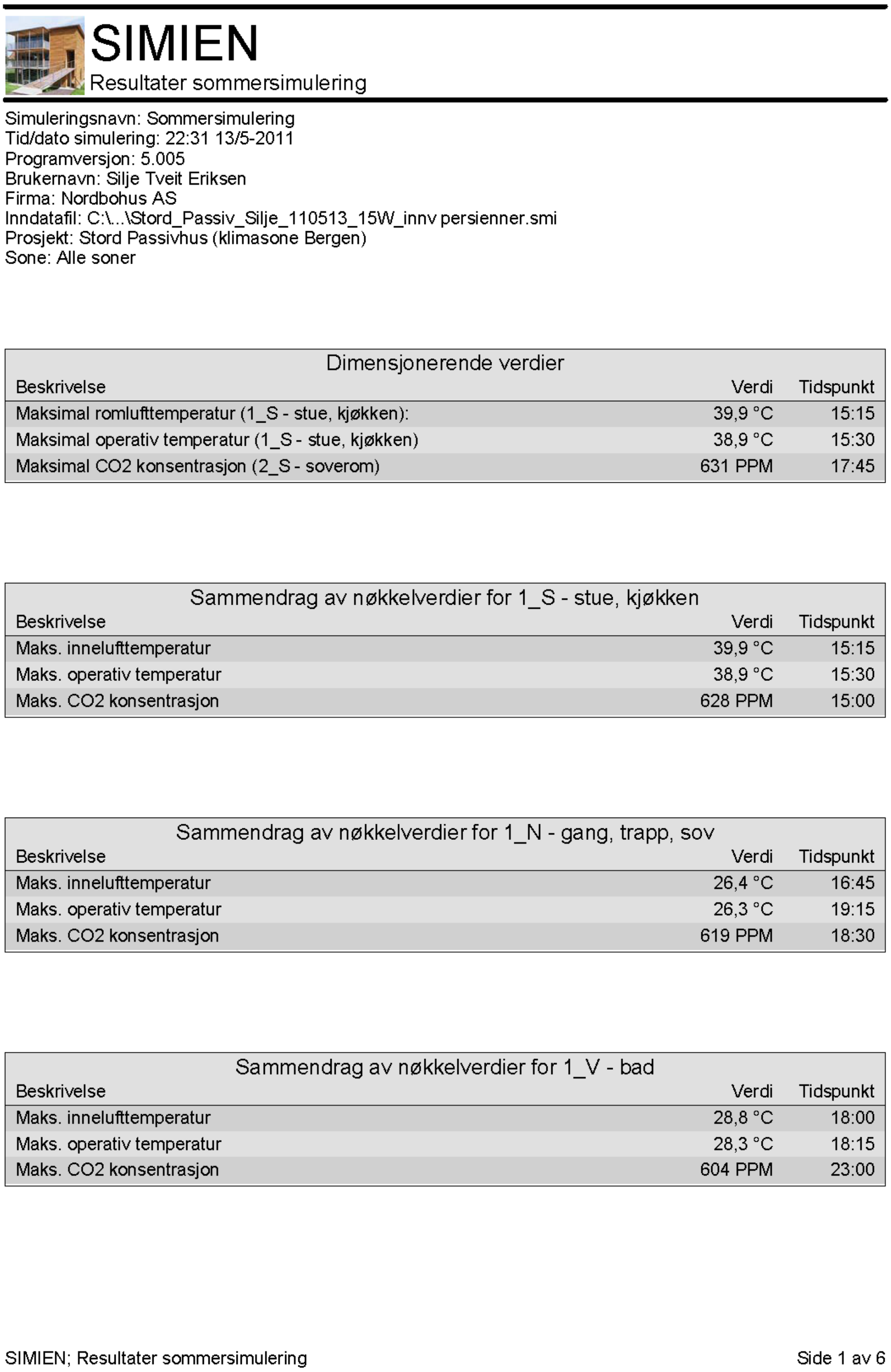
Table H-3 presents the impact assessment for the door materials. The numbered presented here are cradle to gate. There is not taken into account any sealing products between the door leaf and frame. Electricity requirements and waste from production is neither included. The lining is adjusted the different wall and frame thicknesses. 10% cutting waste from lining is included, as waste during construction.

Table H-3: Impact assessment for the different doors

Impact category	*Outer door, TEK07*	*Outer door, passive house*	*Inner door*	*Unit*
CC	139	183	17,2	kg CO_2 eq
HT	37,3	45,3	13,0	kg 1,4-DB eq
POF	0,43	0,55	0,11	kg NMVOC
PMF	0,28	0,33	0,06	kg PM_{10} eq
TA	0,52	0,64	0,12	kg SO_2 eq
FE	0,01	0,01	0,001	kg P eq
ME	0,13	0,16	0,04	kg N eq
TET	0,09	0,12	0,03	kg 1,4-DB eq
FET	0,67	0,75	0,11	kg 1,4-DB eq
MET	0,85	0,92	0,19	kg 1,4-DB eq
MD	29,9	31,3	17,7	kg Fe eq
CED	2,65	3,35	0,40	GJ eq

Appendix I Summer simulations for the passive house

I-1: Summer simulation for the passive house, interior shading



SIMIEN

Resultater sommersimulering

Simuleringsnavn: Sommersimulering
Tid/dato simulering: 22:31 13/5-2011
Programversjon: 5.005
Brukernavn: Silje Tveit Eriksen
Firma: Nordbohus AS
Inndatafil: C:\..\Stord_Passiv_Silje_110513_15W_innv persienner.smi
Prosjekt: Stord Passivhus (klimasone Bergen)
Sone: Alle soner

Dimensjonerende verdier

Beskrivelse	Verdi	Tidspunkt
Maksimal romlufttemperatur (1_S - stue, kjøkken):	39,9 °C	15:15
Maksimal operativ temperatur (1_S - stue, kjøkken)	38,9 °C	15:30
Maksimal CO2 konsentrasjon (2_S - soverom)	631 PPM	17:45

Sammendrag av nøkkelverdier for 1_S - stue, kjøkken

Beskrivelse	Verdi	Tidspunkt
Maks. innelufttemperatur	39,9 °C	15:15
Maks. operativ temperatur	38,9 °C	15:30
Maks. CO2 konsentrasjon	628 PPM	15:00

Sammendrag av nøkkelverdier for 1_N - gang, trapp, sov

Beskrivelse	Verdi	Tidspunkt
Maks. innelufttemperatur	26,4 °C	16:45
Maks. operativ temperatur	26,3 °C	19:15
Maks. CO2 konsentrasjon	619 PPM	18:30

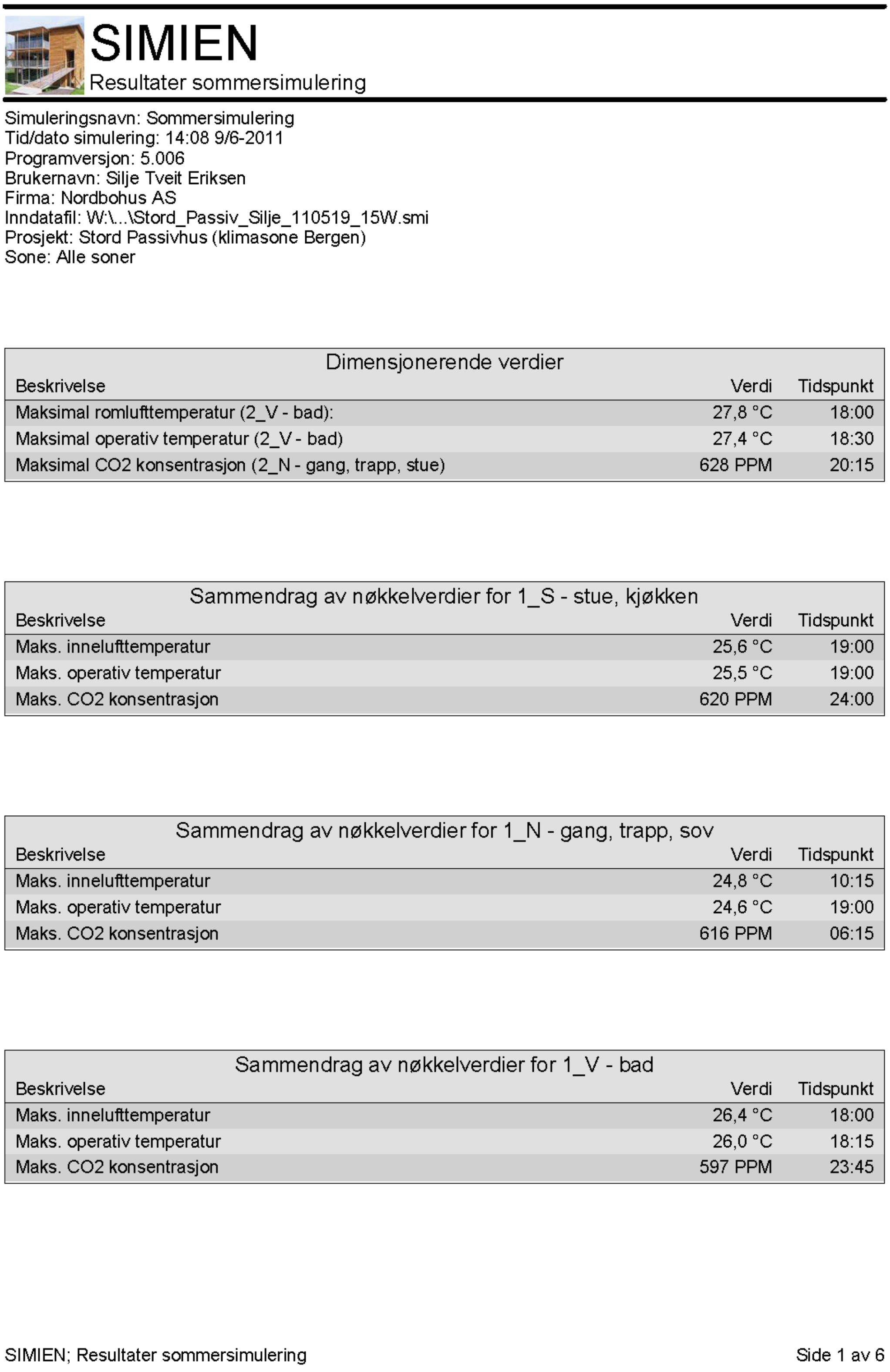
Sammendrag av nøkkelverdier for 1_V - bad

Beskrivelse	Verdi	Tidspunkt
Maks. innelufttemperatur	28,8 °C	18:00
Maks. operativ temperatur	28,3 °C	18:15
Maks. CO2 konsentrasjon	604 PPM	23:00

SIMIEN; Resultater sommersimulering Side 1 av 6

I-1: Summer temperature simulation of the passive house with interior shading

I-2: Summer simulation for the passive house, exterior screens



SIMIEN

Resultater sommersimulering

Simuleringsnavn: Sommersimulering
Tid/dato simulering: 14:08 9/6-2011
Programversjon: 5.006
Brukernavn: Silje Tveit Eriksen
Firma: Nordbohus AS
Inndatafil: W:\...\Stord_Passiv_Silje_110519_15W.smi
Prosjekt: Stord Passivhus (klimasone Bergen)
Sone: Alle soner

Dimensjonerende verdier

Beskrivelse	Verdi	Tidspunkt
Maksimal romlufttemperatur (2_V - bad):	27,8 °C	18:00
Maksimal operativ temperatur (2_V - bad)	27,4 °C	18:30
Maksimal CO2 konsentrasjon (2_N - gang, trapp, stue)	628 PPM	20:15

Sammendrag av nøkkelverdier for 1_S - stue, kjøkken

Beskrivelse	Verdi	Tidspunkt
Maks. innelufttemperatur	25,6 °C	19:00
Maks. operativ temperatur	25,5 °C	19:00
Maks. CO2 konsentrasjon	620 PPM	24:00

Sammendrag av nøkkelverdier for 1_N - gang, trapp, sov

Beskrivelse	Verdi	Tidspunkt
Maks. innelufttemperatur	24,8 °C	10:15
Maks. operativ temperatur	24,6 °C	19:00
Maks. CO2 konsentrasjon	616 PPM	06:15

Sammendrag av nøkkelverdier for 1_V - bad

Beskrivelse	Verdi	Tidspunkt
Maks. innelufttemperatur	26,4 °C	18:00
Maks. operativ temperatur	26,0 °C	18:15
Maks. CO2 konsentrasjon	597 PPM	23:45

SIMIEN; Resultater sommersimulering   Side 1 av 6

I-2: Summer temperature simulation of the passive house with exterior screens

Appendix J Temperature gradients and dew point calculation.

It is assumed an inside temperature of 20°C and 50% relative humidity.
Two outdoor temperatures are used, Stord normal minimum (1,2°C) and Stord normal annual average (7,4°C).

Temperature gradients for the TEK07- and Passive- house outside walls.

The following calculations are from Fourier's Law for heat conduction:

(1) Thermal conductivity, k = [W/(mK)]
(2) Thermal transmittance, U value= k/[thickness of material in meter] = [W/m^2K]
(3) Thermal resistance, R value = 1/[U value] = [m^2K/W]

Table J-1: Calculated thermal transmittance for the TEK07 and Passive house building walls

Element	λ [W/(mK)]	*Thickness TEK 07 [mm]*	*U value [W/m2K]*	*R value* [m^2K/W]	*Thickness passive [mm]*	*U value [W/m2K]*	*R value* [m^2K/W]
Wood covering	0,11[A]	12	9,17	0,11	12	9,17	0,11
Isolation A37	0,037[B]	200	0,19	5,41	-	-	-
Isolation X33	0,033[B]	-	-	-	350	0,09	10,61
Wind break	0,05[C]	12	4,17	0,24	12	4,17	0,24
Air layer, 5°C	0,024[A]	23	1,04	0,96	23	1,04	0,96
Wood covering	0,11[A]	19	5,79	0,17	19	5,79	0,17

A:(Haynes, 2011), B: (Glava, 2011), C: (Byggforsk, 2004)

Table J-1 presents the U and R values for the different wall materials, from interior to exterior side of the wall. The respective temperature gradients for the different elements are calculated in table j-2-B.

Temperature change across a component, assuming steady state parallel heat flow conditions (Scheuneman, 1982):

(4) $\Delta T = R/R_T * \Delta T_T$

Where:

ΔT - temperature change across a component
R - thermal resistance of the component
R_T - total thermal resistance of all components
ΔT_T - total temperature change from interior to exterior

Table J-2: Temperature gradients for the wall, T1 = interior of element, T2 = exterior of element

	TEK07 house				*Passive house*			
Outside temp	*1,2 °C*		*7,4 °C*		*1,2 °C*		*7,4 °C*	
Element	*T1*	*T2*	*T1*	*T2*	*T1*	*T2*	*T1*	*T2*
Wood covering	20,0	19,7	20,0	19,8	20,0	19,8	20,0	19,9
Isolation	19,7	4,9	19,8	9,9	19,8	3,3	19,9	8,8
Wind break	4,9	4,3	9,9	9,5	3,3	3,0	8,8	8,6
Air layer, 5°C	4,3	1,7	9,5	7,7	3,0	1,5	8,6	7,6
Wood covering	1,7	1,2	7,7	7,4	1,5	1,2	7,6	7,4

Dew point calculations, based on the Magnus-Tetens formula (Barenbrug, 1974):

(5) $T_d\ (T,RH) = (b\alpha(T,RH)\ /\ (a-\alpha(T,RH)$

Where:

α(T,RH)	ln (RH) + (aT/(b+T)	
a	17,27	
b	237,7	
RH	Relative Humidity	= 0,01<RH<1,00
T	Temperature in °C	= 0°C<T<60°C

For given conditions, the calculated dew point is

T_d = 9,25 °C

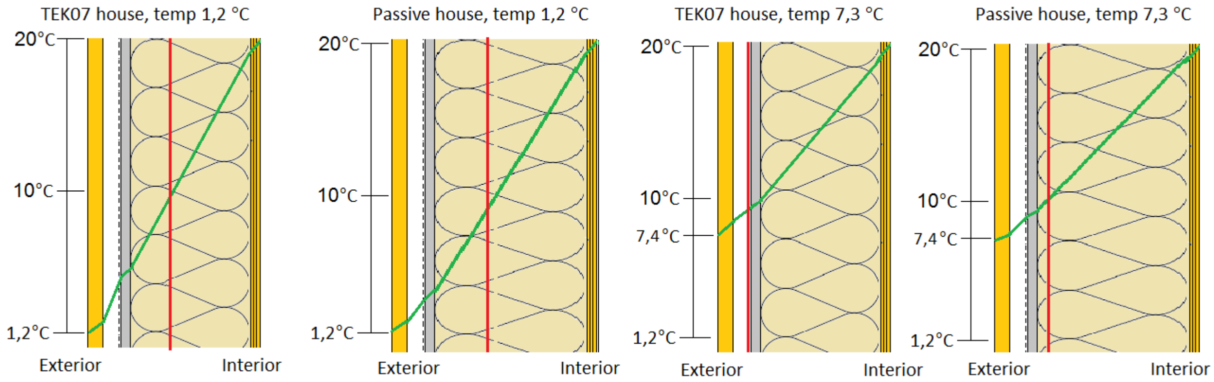


Figure J-1: Temperature gradient (green) and dew point (red : 9,25°C) for the different walls and outside temperatures.

Appendix K Impact calculations for different heating systems

Total energy needs for the Stord houses:

	TEK07 [kWh]	*Passive house [kWh]*
Space heating and ventilation heat	9929	3723
Warm water	5573	5573
Fans, pumps, lights and technical equipment	5530	5643
Total	21032	14939

All impacts are pr m^2 for 50 years.

All energy calculations for heat pumps and solar system and system efficiencies is from NS 3031:2010

Climate change impacts from Nordel, low voltage: 0,212 kg CO_2 eq/kWh. (Ecoinvent, 2007),

System efficiency (NS, 3031:2010):

Air-to-air heat pump:	2,16
Air-to-water heat pump:	2,08
Solar heat system, water:	10,0
Solar heat system, space heat and water:	9,03

TEK07 house

Scenario 1, 40% wood heat

It is assumed the Stord TEK07 house uses a new stow with 70% efficiency.

CO_2 factor wood: 0,077 kg CO_2 eq/kWh heat energy delivered

Wood energy needed: (9929+5573) * 0,4 = 6201 kWh

CO_2 eq wood combustion: **128 kg CO_2 eq**

Scenario 2, 65% of space heat from air to air heat pump

40% total heat for space heat and warm water = 6200 kWh

65% of space heat = 6454 kWh

65% of space heating covered from heat pump > 40% alternative heat requirements.

Needed electricity for heat pump: (9929*0,65)/2,16 = 2988 kWh

CO_2 heat pump: **170 kg CO_2 eq**

Scenario 3, 50% warm water solar heat, 60% wood energy

Needed electricity for solar heat: (5573*0,5)/10,0 = 279 kWh

CO_2 heat pump: **16 kg CO_2 eq**

Wood energy needed: (9929) * 0,6 = 5957 kWh

CO_2 eq wood combustion: **123 kg CO_2 eq**

Passive house

Scenario 1, 80% space heat and 70% warm water heat pump

Needed electricity for solar heat: ((3723*0,8)/2,08)+((5573*0,7)/2,08) = 3307 kWh

CO_2 heat pump: **188 kg CO_2 eq**

Scenario 2, 50% warm water solar heat

Needed electricity for solar heat: (5573*0,5)/10,0 = 279 kWh

CO_2 heat pump: **16 kg CO_2 eq**

Scenario 3, 50% space heat and warm water solar heat

Needed electricity for solar heat: ((3723*0,5)/9,03)+((5573*0,5)/9,03) = 515 kWh

CO_2 heat pump: **29 kg CO_2 eq**