NTNU – Trondheim
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Life Cycle Assessment of a new School Building designed according to the Passive House Standard

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Master in Industrial Ecology
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MASTER THESIS

for

Student Rachel Spiegel
Spring 2014

Life Cycle Assessment of a new School Building designed according to the Passive House Standard
Miljøvurdering av et nytt skolebygg etter passiv hus standard

Background and objective
New technological solutions such as heat-recovery ventilation systems and a better understanding of insulation allows for the construction of buildings that require very little energy for heating or cooling. Under normal weather conditions, the off-heat of humans and equipment and the recovered heat suffices to heat buildings, no active heating is required. Such buildings are called "passive house", based on a translation of the original German word. Formal standards have been issued in several countries to define what is meant by passive house, specifying performance of both building components and buildings as such. In Norway, it is a declared objective to successively tighten the technical standards and requirements for new buildings to meet the passive house standard. Also, many landlords choose to erect passive house buildings, as this has become an easily communicable benchmark for good environmental performance.

Highly energy efficient building shells and especially solutions that require the active management of energy (integrated energy production; energy recovery) are themselves energy demanding in their construction and operation. The push towards higher operational energy efficiency hence raises the question of the trade-off between up-front investment in equipment and reduced energy consumption during operations. This trade-off can only properly be understood using a life cycle assessment. In recent years, a number of LCAs of highly efficient buildings and passive houses has been published, focussing on residential buildings. There has been less focus on public buildings.

The objective of this thesis is to provide a comparative life cycle assessment of a school built as a passive house in compliance with the passive house standard (NS3701 – Norsk passivhusstandard for yrkesbygninger) and compare it to the same school built in compliance with the TEK10 standard (Byggteknisk forskrift – TEK10) to establish the difference in life cycle performance for the two standards. The candidate will have access to relevant project data from Hjellnes Consult AS for two possible cases; Grefsen U3 and/or Stasjonsfjellet Skole.

The following tasks are to be considered:
1. Review of relevant existing LCA studies and data sources.
2. Establishment of an inventory of building elements and their dimensions based on the design of the building.
3. Understanding the energy system and energy use of the building.
4. Development of a life cycle inventory for the construction and operation of the building.
5. Life cycle impact assessment

6. Analysis and interpretation of the LCA results.

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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.

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

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

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

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

Department of Energy and Process Engineering, 14. January 2014

Olav Bolland
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Academic Supervisor

Research Advisors: Bjørn-Yngve Kinzler Eriksen, Hjellnes Consult, Oslo
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Preface

This thesis was written in the spring of 2014 and submitted in partial requirement for the degree of Master of Science in Industrial Ecology. The problem statement was formulated by the Industrial Ecology Program at the Norwegian University of Science and Technology (NTNU) and Hjellnes Consult AS.

Acknowledgements

Without the help from my supervisor Edgar Hertwich this thesis would not have been possible. Changing the thesis subject from fall to spring left me at a disadvantage, and his contribution of relevant data was essential. I am grateful to Bjørn-Yngve Kinzler Eriksen and Jeanette Bøe of Hjellnes Consult, who provided an introduction to SimaPro, answered my questions throughout the semester, and guided me through technical drawings. Thank you to Jens Kristian Holmen for helping me with LaTeX and the formatting of figures and tables.

To my fellow classmates at Industrial Ecology, thank you for making the past two years such a worthwhile experience.

Abstract

Two life cycle assessments are conducted for the comparison of the construction and use of a school built after the Norwegian building code, TEK10, and a passive school built after the Norwegian Standard NS 3701.

Data from Environmental Product Declarations (EPDs) and ecoinvent is used. The NORDEL electricity mix is used for Norwegian production and electricity consumption. SimaPro 8.0 is used to process the data, and the ReCiPe method, hierarchist midpoint version 1.06 is used for the impact assessment. The largest environmental impacts from the production of building materials is from concrete, insulation, and cladding. Comparing the LCA results of the passive house school to the same school built to standard reveals a 16% reduction in climate change impacts. The environmental impacts associated with the use phase are lower for the passive school relative to the standard school.

The total life cycle climate change impacts per m^2 useful floor area is 1.2 tons CO_2 eq for the passive school and 1.46 tons CO_2 eq for the TEK10 school. The delivered energy for electricity and heating for the passive school was estimated to be 44 kWh/m^2, and the cumulative energy consumption for the passive house is 27 GJ eq per m^2, and is 9% lower than the energy demand of the TEK10 school over the same lifetime. Share of impacts from construction, waste, and maintenance were significant including 32% of climate change emissions, 55% of terrestrial acidification and 46% of particulate matter formation.

The overall conclusion is that it is environmentally beneficial to build and operate a passive school compared to a school following the TEK10 building standard.

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June 16, 2014

Chapter 1

Introduction

In 1987 the Brundtland report defined sustainable development as, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [9]. In order to see sustainable development in action, business as usual will be unsuitable. A tool to put sustainability into practice is to map the environmental damages associated with everyday activities, and assess what changes must be made to lessen their burden. Educational services are an essential part of modern society, and schools are needed in order to carry out these services. The objective of this study is to assess the environmental costs and benefits of building a school to the passive house standard.

Buildings are complex industrial products with a long service lifetime. There are already many efforts to control and manage the quality of buildings (building codes, product standards, automated ventilation and lighting), but holistic approaches have played a minor role, especially in the design stage. However, it is precisely the design phase that allows the greatest opportunities for choosing benefits with the potential to last for decades. The environmental impact of a building starts with upstream processes, which include the mining of materials and fuels, transportation, and the production, manufacturing and packaging of building materials and components. In order to achieve low energy use in operation, a tight building envelope is needed that usually contributes to energy use via embodied energy. The embodied energy plays an important role in the potential environmental damages.

This study is a contribution to the growing movement in Norway to construct buildings with a low environmental impact. The thesis is broken up into a literature review, methodology, inventory analysis, impact analysis, interpretation, and conclusion.

Chapter 2

Literature Review

The intention behind this literature review is to provide the theoretical basis of life cycle assessment and its role in the construction industry. Trends and challenges in building life cycle assessment are discussed in order to provide a context of the challenges faced in the later analyses. Benchmarks both within Norway and internationally are pinpointed in order to contextualize this study. Since a project related to the thesis was not performed, a detailed literature review of all aspects of the inventory and impact analysis was performed.

2.1 Life Cycle Assessment

Life cycle assessment (LCA) is a process whereby the material and energy flows of a product system are quantified and evaluated. LCA studies generally consist of four phases: goal and scope definition, life cycle inventory (LCI), impact assessment, and interpretation of results. The goal and scope defines the purposes, audiences, and system boundaries. The LCI involves data collection and calculations to quantify material and energy inputs and outputs of a system. The impact assessment evaluates the significance of potential environmental impacts based on the LCI. Environmental impacts in general include emissions and waste into the environment, and the consumption of resources like land and materials. Figure 2.1 shows that each phase requires interpretation before proceeding to the next to ensure high quality results [26, 60, 64].

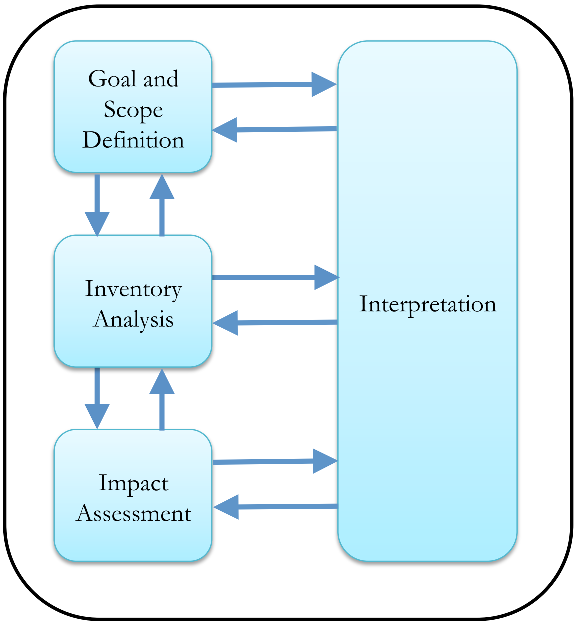


Figure 2.1: LCA framework based on ISO 14040 [13]

In the 1990s a standard definition of LCA was agreed upon through workshops and the publication of several handbooks and scientific papers. The Society of Environmental Toxicology and Chemistry (SETAC) started playing a leading and coordinating role by bringing LCA practitioners together and harmonizing LCA framework, methodology, and terminology, resulting in the SETAC Code of Practice. From 1994 the International Organization for Standardization (ISO) became involved as well, harmonizing methods and procedures even further through the ISO 14040 standard series, first published in 1997. The standards created a general methodological framework, which made it easier to compare different LCAs. Even with agreement on the framework, ISO never aimed at defining exact methods by stating "there is no single method for conducting LCA". The European Union identified LCA as the best framework for assessing the potential environmental impacts of products and established the European Platform on LCA (EPLCA) in 2003. The EPLCA has facilitated the development of the European reference Life Cycle Database (ELCD) and the International reference Life Cycle Data System (ILCD) Handbook, which both conform to the ISO 14040 series [10, 12].

In the impact assessment, midpoint or endpoint environmental indicators are chosen as seen in Figure 2.2. Midpoints make the decision process more complicated, because it leads to many different impact categories which makes the drawing of conclusions with the obtained results complex. The endpoint indicators are based on the damage-oriented approach, aimed at evaluating the environmental consequences with reference to wider areas of concern, such as human health and ecosystem quality. Endpoints involve both physical and social aspects and have a weaker scientific basis. They introduce subjective value choices and uncertainty and there is less international consensus on them. ISO 14040 recommends using midpoint indicators and that is what is used in this analysis [10].

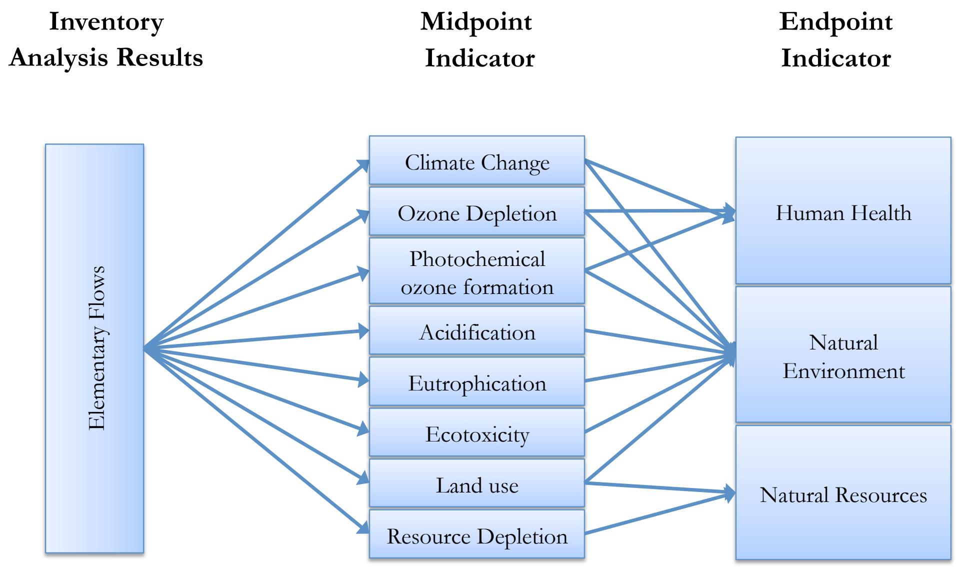


Figure 2.2: Midpoint and endpoint indicators in LCA

Interest in LCA from government and industry has increased markedly since the beginning of the 21st century. An indication of its growing importance is the emergence of Environmental Product Declarations (EPDs). An EPD is a set of quantified environmental data for a product with pre-set categories of parameters based on the ISO 14040 series. This system makes it easier for designers to choose eco-friendly products or materials.

BS EN 15804 provides a core set of Product Category Rules (PCRs) for the Europe-wide generation of EPD for construction products. PCRs define the methods for the collection of data, the calculation of environmental impact, and how the information should be presented. PCRs define how LCA should be conducted for a particular product category, as well as the specifications for the Environmental Product Declaration (EPD), thereby standardizing the methodology and enabling products within that category to be compared to each other. By defining the specific rules for collecting, analyzing and reporting data on a given product type, PCRs ensure manufacturers present their products in a harmonized way and ensure purchasers a reliable basis for comparing product performance data. PCRs should comply with all relevant ISO standards, include open consultation and input from all interested parties, be based on at least one LCA from the relevant product category, be harmonized across different EPD programs, and be reviewed by an expert or panel with knowledge of LCA methodology and experience in the relevant sector [3].

EPDs are verifiable, accurate, non-misleading environment information created by manufacturers in the building and construction industry in order to clearly outline the environmental performance of their products. EPDs in Norway are published as cradle to gate, cradle to gate with options, or cradle to grave [48].

2.2 LCA in the Building Sector

LCA was introduced to the construction industry in the 1980s and was marked by diverging methods, approaches, terminologies and results. There was a clear lack of scientific discussion and the technique was often used for market claims with doubtful results, which prevented LCA from becoming a generally accepted and applied analytical tool. In the last decade, there has been some effort to rectify LCA's misuse and introduce consensus. In 2003, SETAC published a state-of-the-art report 'Life-Cycle Assessment in Building and Construction', highlighting the differences between the general approach of LCA and LCAs of buildings. Standardization was continued by ISO and the European Committee for Standardization (CEN). ISO published four standards describing a framework for investigating sustainability of buildings and the implementation of EPDs. CEN is developing standards for assessing the economic, environmental, and social aspects for both new and existing construction projects. Since these standards are very recent, few studies have been executed according to them.

Life cycle analyses of whole buildings are essential to identify and evaluate how key design parameters will influence a building's environmental performance. Compared to other products, buildings are more difficult to evaluate because they are material dense, have complex functions, and temporally dynamic due to limited service life of building components and changing user requirements. Thus many LCA studies are not directly comparable because of varying system boundaries, functional units, and assumptions.

Impacts are highly inter-dependent in each phase of a building's lifetime. The selection of construction materials can decrease the heating requirement, but might also increase the embodied energy, transport-related impacts, or affect the service lifetime of the whole building. Figure 3 illustrates the environmental inputs and outputs during a building's lifetime.

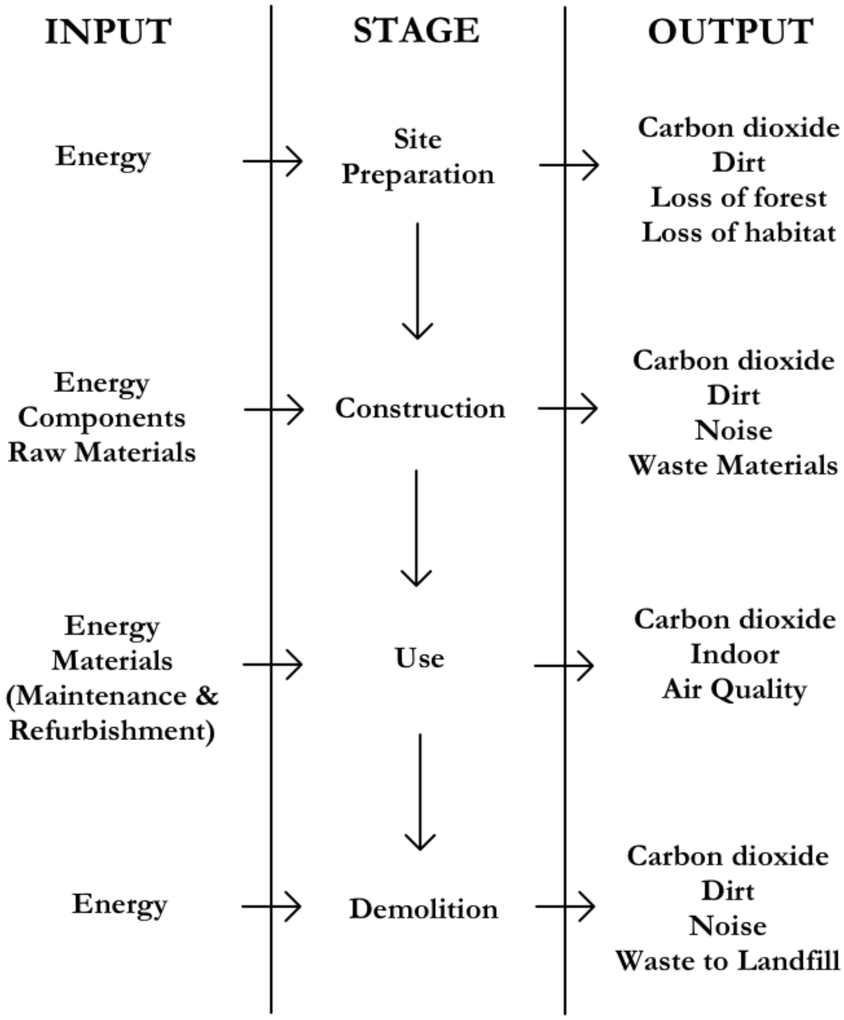


Figure 2.3: Environmental impact of a building through its lifetime [32]

Construction-related software tools and databases provide standardized assessment models and inventory data to aid these analyses. The spectrum ranges from from individual product assessments to whole building assessment and rating systems. Trusty and Horst [73] suggest three main levels for LCA related tools.

1. Level 1 focuses on individual products or simple assemblies and includes tools such as SimaPro and GaBi

2. Level 2 includes whole-building decision support tools like Athena Eco-Calculator and LCA in Sustainable Architecture

3. Level 3 covers whole-building assessment systems and frameworks, such as the BREEAM and LEED rating systems

It is advantageous to utilize complementary tools, even those in the same classification level [73].

Evaluation of environmental impacts of construction and buildings involves more than the simple aggregation of individual product and material assessments. Previous building LCAs have been based on either generalized building information or only addressed certain subsets of the total building such as structural materials or embodied energy. Consequently, recent studies have attempted to assess complete buildings, building systems, and construction processes so that differences that might arise between results from a complete inventory LCA of a building and the results from a partial LCA can be avoided.

Uncertainty in building LCA calculations manifests in multiple ways:

1. The long lifespan of the entire building (50-100 years) and consequently a lower predictability of uncertainty variables

2. A shorter lifespan of some elements and components

3. The use of many different materials and processes

4. The unique character of each building

5. The varying distances to factories e.g., German timber used in Norwegian buildings

6. The evolution of functions over time because of maintenance and retrofitting

7. The long lifespan and dependence of user behavior thereby requiring more assumptions, resulting in larger uncertainties, potentially influencing the credibility of the results [10].

Huijbregts et al. [37] expressed concern regarding various uncertainties related to LCA and presented a methodology to quantify parameters, scenarios, and model uncertainty simultaneously. The study considered uncertainties arising from variations in functional units, system boundaries, allocation methods, product life span, impact categories, and scenario uncertainty through temporal and geographic heterogeneity as scenario uncertainty. Model uncertainties arise from lack of data, steady state assumptions, ignoring nonlinearities in processes, overlooking interactions among pollutants, and not taking into account the sensitivity of the receiving environment. The authors used a Monte Carlo simulation to quantify parameter uncertainty and applied various decision settings for quantification of scenario and model uncertainty. The authors suggested improvements to the proposed methodology through a more systematic analysis of scenario and model uncertainty and recommended development of LCI databases with built-in spatial and uncertainty information [10, 12].

2.3 SimaPro

SimaPro is the world's leading LCA software among industry, research institutes, and consultants in more than 80 countries. It is used to model and analyze complex product life cycles in a systematic and transparent way, following the ISO 14040 series recommendations. All results can be traced back to their origin with a few mouse clicks. You can easily zoom into the "hotspots" or the area of attention. All datasets are harmonized regarding structure, nomenclature and fit well with the life cycle impact assessment methods. [21, 30, 59]

The ecoinvent Center is the world's leading supplier of robust and transparent life cycle inventory (LCI) data. ecoinvent v3 is the main database in SimaPro and contains over

10,000 processes. The impact assessment method of choice for this study is ReCiPe, which has 18 impact categories at the midpoint (problem oriented) level and three endpoint (damage oriented) categories. [59].

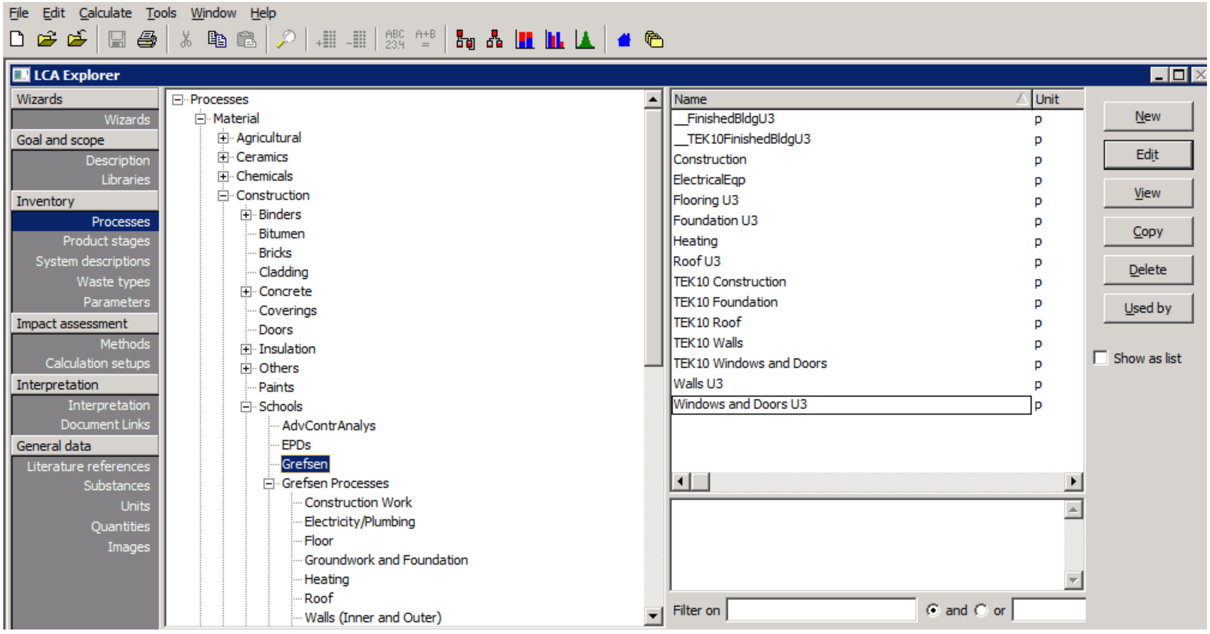


Figure 2.4: The school assembly within SimaPro

SimaPro is a material-level LCA tool. As shown in Figure 2.4, products are defined in an assembly, which contains a list of materials and production processes, as well as transportation processes. Assemblies do not contain environmental data and instead link production processes that contain such data. Once you define a product assembly, SimaPro can immediately calculate the inventory (LCI) results. This is a list of all raw material extractions and emissions that occur in the production of the assembly and the materials and processes that link to it. SimaPro allows you to specify the results as one table or per emission, so that one can look more closely at one (like CO_2). Although the inventory results are detailed, it is not easy to interpret long lists of substances, so a user can define the impacts by midpoint or endpoint indicators as defined by the ISO 14044 series.

2.4 Passive House

The Passive House is the world's leading standard in energy efficient construction. The concept was originally developed by Professor Bo Adamson and Dr. Wolfgang Feist at the Passive House Institute in Germany in the 1980s; the first passive house was built in Darmstadt-Kranichstein in 1990. A passive house has a very low energy consumption compared to conventional houses and its design is based on the goal of reducing heat loss to an absolute minimum; common features are shown in Figure 2.5. It is named so because it adopts the most passive measures to reduce energy demand, such as extra insulation, exemplary airtightness and heat recovery. The main requirement for passive structures after the German standard is that the annual heating requirement does not exceed 15 kWh/m^2 year. With the average heating load of standard buildings in Central

Europe being approximately 100 kWh/m^2, energy saved on heating is 85% compared to conventional standards of new dwellings. The Passive House Institute characterizes different climate conditions based on a color code for Europe (see Appendix 10.1). Technical solutions and architectural standard were developed for each of these locations. A global definition of the Passive House Standard, applicable for all climates has been developed. As of 2014 there are 50,000 residential and non-residential passive buildings in existence worldwide, and over 5,500 certified according to strict Passive House Institute criteria [22, 40, 54, 65, 70].

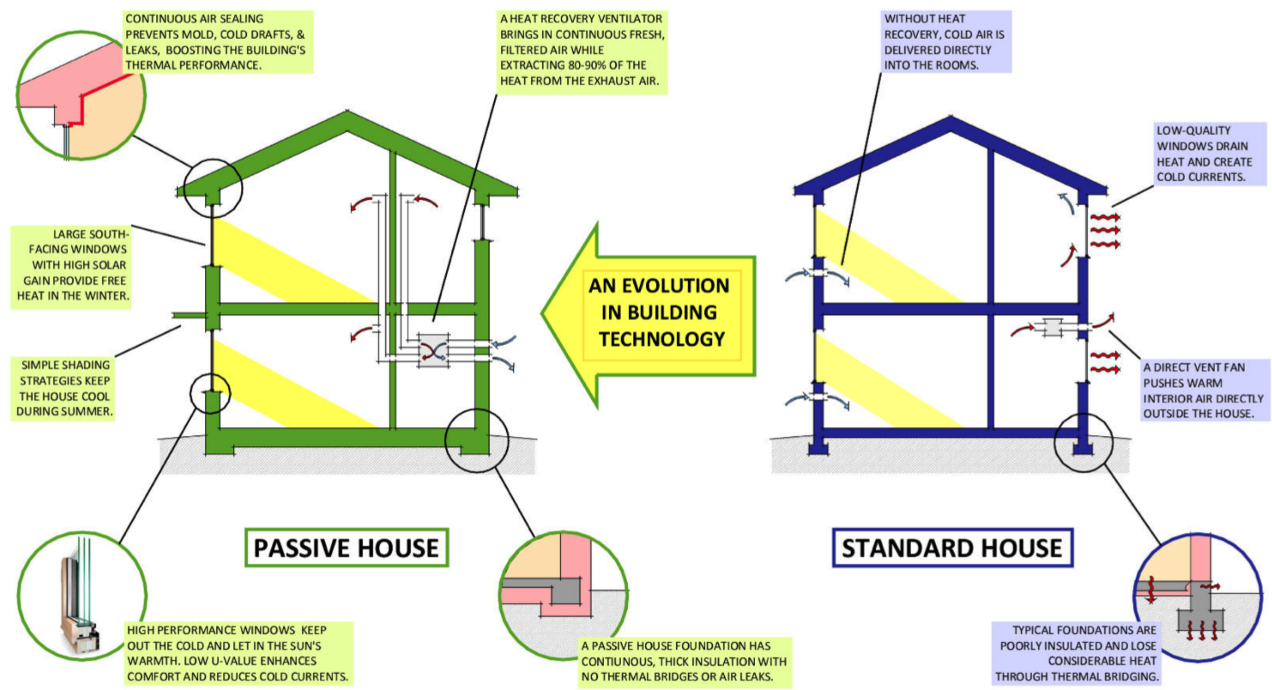


Figure 2.5: Common Passive House Features [2]

The Passive House Institute performed an extensive research project on passive schools in Germany using studies, simulations, measurements, and evaluations of several passive house standard schools. The result is that most of the criteria of passive standard housing can also be used for schools. As in housing, it is assumed that it is possible to cover heating by heating ventilation air. In schools there are considerably higher air changes (and internal loads) in operation time and the power requirement is not a significant limitation as in housing (it is essential that it is sufficient to heat the classrooms before classes begin in the morning, there a much lower need than in homes). During operating time there are major differences between homes and schools, but over time the internal loads and airflow values are comparable. This is considered as a contributing factor for the maximum heating demand of 15 kWh/m^2/year to also be used as a criterion for schools [19,24].

Although it is possible to heat with ventilation air in passive schools, it is generally not recommended in the report. The benefits are only present if groups of rooms share a reheating register. This becomes less beneficial with myriad uses. Many of the evaluated projects had therefore heated with a few centrally located radiators. One of the results is that heavy building elements (thicker walls, more insulation throughout) are used to a greater advantage in schools than in residential buildings [19].

2.5 Norwegian Context

Key features of the Norwegian energy policy in buildings is to ensure that consumption does not increase, but remain stable at about 80 TWh until 2020 through regulation and retrofitting. The target for 2040 is to reduce the annual energy supply to the operation of buildings by 40 TWh compared to the current level [43, 54].

Norway's affiliation with the European Union through the EEA Agreement means that EU Directives providing guidelines for the formulating of national regulations in the construction and connected disciplines also apply to Norway. Norwegian building authorities are thus under obligation to include the EU regulations in Norway's legislation and regulations, as well as practice them in accordance with their intention. Norway has agreed to do this to avoid technical trade blockage across the national borders.

Norway is legislating in line with the EU Renewable Energy Directive, setting targets of a 20% reduction in greenhouse gas emissions, 20% renewable energy and 20% energy efficiency by 2020 (the so-called 202020 - Targets for 2020) [54].

The Ministry of Local Government and Regional Development (KRD) is the central building authority, whereas the responsibility for overview planning is placed under the Ministry of the Environment. The SINTEF Building and Infrastructure journal 'Byggforsk kunnskapssystemer' is published by SINTEF Byggforsk (BKS). The journal series is the most complete source of technical journals on construction and the solutions satisfy the functional requirements of Norwegian building code. The Norwegian Building Authority (DiBK) recommends the use of Byggforskserien to document a building project [11].

NS 3701 sets general requirements for heat loss, heating demand, cooling demand and energy demand for lighting. It sets the absolute minimum for building elements, components, technical systems and leakage rates. NS 3701 must be paired with calculations - putting together a building with passive components does not necessarily mean that the whole meets the passive house criteria. There is no minimum U-value of roofs, walls and floors but there are requirements for heat loss in the whole building as a whole (via transmission and infiltration). NS 3701 requires that the energy need is calculated using climate data for the place where the building is erected. NS 3701 requires the fulfillment of thermal comfort must be documented with calculation at design outdoor temperature summer conditions [44].

The Planning and Building Act is central to all land management and construction in Norway. Technical regulations included in the Planning and Building Act (TEK) are routinely revised and contain general requirements regarding the buildings' function and services, with only a few detailed provisions. It is up to the customer and contractor to prove that the selected solutions meet the requirements of the regulations. The technical regulations of TEK state that the manufacturer must ensure that the goods' properties have been documented before they are sold or applied in structures. The current revision is TEK 2010, or TEK10, which came into effect in July of that year. The passive house standard includes 11 building categories from TEK10 [61].

The argument from Norwegian construction experts is that the original German standard has not been made for the Nordic climate, and that the requirements for insulation would be unmanageable if an absolute limit of 15 kWh/m^2 year should be applied. Norwegian lawmakers modified the standards by distinguishing between residential and commercial buildings, the building's size and annual mean temperature. In Norway the passive standard for residential buildings NS3700 was established in April 2010. Like the German standard, it requires that heating demand not exceed 15 kWh/m^2 per year for buildings larger than 250 m^2, with permission given to higher heating for homes in cold climates (labelled as low-energy buildings). NS 3701 is the standard for non-residential buildings. Both standards establish requirements according to area, type of building and climate.

Table 2.1 shows the upper limits for energy use and U-values under NS 3701 compared to TEK10. The minimum requirement for the U-value of windows applies as average for all windows / window fields in the building.

Table 2.1: Key minimum requirements for passive and TEK10 school buildings [19, 53]

	NS 3701	TEK10
Annual energy requirement	120 kWh/m^2	120 kWh/m^2
Maximum annual heating requirement	15 kWh/m^2/year	
Maximum annual cooling requirement	0 kWh/m^2/year	
Maximum CO_2 Emissions	20 kg/m^2/year	
U-Value outer walls	$\leq$ 0.15 W/(m^2 K)	$\leq$ 0.18 W/(m^2 K)
U-value floor	$\leq$ 0.15 W/(m^2 K)	$\leq$ 0.15 W/(m^2 K)
U-value roof	$\leq$ 0.13 W/(m^2 K)	$\leq$ 0.13 W/(m^2 K)
U-value windows	$\leq$ 0.80 W/(m^2 K)	$\leq$ 1.20 W/(m^2 K)
U-value doors	$\leq$ 0.80 W/(m^2 K)	$\leq$ 1.20 W/(m^2 K)
Normalized thermal bridge	$\leq$ 0.03 W/(m^2 K)	$\leq$ 0.06 W/(m^2 K)
Efficiency heat exchanger	$\geq$ 80%	$\geq$ 80%
SFP factor ventilation systems	$\leq$1.5 kW/(m^3/s)	$\leq$2.0 kW/(m^3/s)
Leakage rate at 50 Pa	$\leq$ 0.60 h^{-1}	$\leq$ 1.50 h^{-1}

The main difference between a passive house and a building constructed to TEK10 is the amount of insulation and precision. To build a passive house correctly, a high degree of accuracy by architects, consulting engineers, and builders is required. A passive house has higher costs because it can take longer to construct and some of its components, like windows with lower U-vales, are more expensive [45].

Electricity Mix

Electricity is used in the production of the different materials and in the operation of the schools. Emissions from electricity generation must be included in the LCA. Norway is a part of a Nordic electricity exchange NordPool [77]. The breakdown of the NORDEL electricity mix in Table 2.2 is taken from Grann [29], which reflected the energy mix in 2009.

Table 2.2: NORDEL Electricity Mix [29]

Electricity source	Denmark	Finland	Norway	Sweden	Total Share
Hard Coal	45.7%	19.1%	0	0.7%	9%
Oil	4.0%	0.7%	0%	1.3%	1.1%
Natural Gas	24.5%	14.8%	0.3%	0.5%	6%
Hydropower	0.1%	17.9%	98.5%	40.1%	48.1%
Wind Power	17.2%	0.1%	0.3%	0.6%	2.1%
Cogen Wood, Allocation Exergy	4.5%	11.8%	0.3%	4.4%	4.8%
Cogen with Biogas engine, Allocation Exergy	0.6%	0%	-	0.1%	0.1%
Peat	-	7.6%	-	0.5%	1.8%
Industrial Gas	-	0.6%	0%	0.5%	0.4%
Nuclear	-	26.7%	-	50.5%	25.6%
NORDEL Production share	10.2%	21.6%	29%	39.3%	

SIMIEN

SIMIEN is a Norwegian simulation program for calculating energy and power consumption and indoor air quality in buildings. It evaluates inputted parameters against building codes and energy labeling, calculates energy needs, validates indoor air quality, and determines the needed size of heating systems, ventilation and space cooling. A useful output is the calculation of net energy consumption and the energy supplied to the building over a year, with duration curves for heating and cooling (see Section 10.5 to see the types of outputs SIMIEN produces). The building is evaluated against the design requirements (TEK10) and passive and low energy criteria and design codes (NS 3700/NS 3701). It evaluates the energy measures, energy limits and minimum.

2.6 The EE-TC-IAC Dilemma

In school buildings, classrooms are the most used functional space, occupy the largest area, and host the largest part of daily activities and occupants. One of the dominant features of a classroom is its high occupancy density, which results in very large values of the internal heat sources as well as of the internal emissions of body odors, water vapor and CO_2, causing an increasing concern for the indoor air quality for students.

School buildings are allotted one of the lowest CO_2 emissions and energy use for heating and cooling in the Norwegian building code. Energy conscious design of school buildings should address the energy efficiency-thermal comfort-indoor air quality dilemma (EE-TC-IAQ). This is the phenomenon where either improving the thermal comfort or indoor air quality will hinder goals for energy efficiency. Previous studies have argued that conventional LCA overlooks important indoor environmental problems that affect human health. There are currently no tools to include indoor climate issues as an impact category in LCA due to methodological differences in LCA, materials emissions assessment (MEA), and indoor climate assessment (ICA) [7, 12, 80].

Extensive natural or controlled ventilation, intended to remove internally generated contaminants without active heating or cooling, is rarely sufficient for required thermal comfort conditions. Most of the literature concerned with energy performance of school buildings is devoted not to indoor thermal conditions, but to savings via specific features such as utilization of solar energy and construction features such as thermal insulation and heating, ventilation, and air conditioning (HVAC) performance. When modeling energy use, assumptions about thermal comfort, indoor air quality, occupancy, internal loads, and architectural features are case-specific and thus make it hard for comparison [7].

Jonsson [42], Hellweg [34], and Assefa [5] all argue that conventional LCA overlooks important indoor environmental problems, focusing on energy use over other impacts. The studies concluded that human health effects during the operation phase need to be considered in environmental analysis more routinely. Zeiler et al. [80] measured relative humidity, temperature, and CO_2-concentrations and performed surveys of perceived comfort of two zero emission schools and two traditional schools over two years in wintertime. The zero emission buildings did not have a satisfactory IAQ, implying the standard for IAQ must be improved upon.

2.7 International Context

Buildings play a major role in the consumption of energy and materials all over the world. The construction industry has depleted two-fifths of global raw stone, grail, and sand, one-fourth of virgin wood. Worldwide it consumes 40% of total energy and 16% of fresh water annually. The building sector accounts for 50% of the European Union's final energy consumption. The European Roadmap to 2050 plans to reduce greenhouse gas emissions 80-95% below 1990 levels. Over the next decade, an estimated $500 billion USD must be invested annually in low-carbon technologies for the building sector to make to conform to the EU [18].

Cabeza et al. [12] summarized and organized the literature on life cycle assessment (LCA), life cycle energy analysis (LCEA) and life cycle cost analysis (LCCA) in the building sector. They focused on studies carried out for environmental evaluation of buildings and building-related industries and sectors including construction products, construction systems and individual buildings. The review shows that most LCAs and LCEAs are carried out for buildings that have been designed and constructed as low energy buildings, with few studies on traditional buildings. Most studies were from developed countries, primarily North America and Europe, with no studies from Africa and only one from South America. The functional unit is not mentioned in all studies; usually those performing a LCA or LCEA of whole buildings do not identify it; in addition there is no agreement from the overview on the functional unit to be considered. Half the studies considered a 50 year service lifetime, the others choosing a lifetime anywhere from 25-100 years.

Table 2.3: Previous School Building LCA Studies

	Current study (2014)	Scheuer et al. [64] (2003)	Dimoudi et al. [17] (2008)	Varun et al. [75] (2012)	Bilec et al. [72] (2013)
Building Purpose	School building	University building	Average school building	University building	University Building
System Boundaries	Construction, Use	All phases	Use	Construction, Use	Construction
Location	Norway	USA	Greece	India	USA
Lifetime	50	75	N/A	50	50
Total Area (m^2)	494	7300	275	3960	2262
Floors	3	6	2	3	3

In this paper, the main focus lies on LCAs of entire school buildings. This way the contribution to the total impact of different products, processes and life cycle stages becomes more clear and environmental hotspots can be identified. The results reveal more about building concepts in general and less about the chosen materials. In these cases, the entire building is the functional unit, but with great differences in building properties, size, location, impact methods, etc. Therefore results are not directly comparable with the example studies in Table 2.3, but still trends can be identified.

Materials

The combination of a large number of materials and products in one building makes LCA data collection far more challenging than for most single product applications. Each material has its own distinct life cycle and interacts as part of an assembly or system. Moreover, production processes for a component of a building are much less standardized than most single products because of the unique character of each building. There is limited quantitative information about the environmental impacts of the production and manufacturing of construction materials, or the actual process of construction and demolition, making environmental assessments of the building industry challenging

The earliest building energy consumption accounting only considered the direct energy consumption in the construction and operation process of buildings. Along with the introduction of the life cycle concept, some researchers began to consider the indirect energy consumption which occurred during material production where major indirect energy consumption is caused. By tracing some key inputs into a material, such as energy sources of the electricity used or the extraction processes for the raw materials, a larger system boundary is achieved.

Embodied energy is the energy utilized during the manufacturing phase of the building. It is the energy content of all the materials used in the building and technical installations, and energy incurred at the time of erection/construction and renovation of the building. Energy content of materials refers to the energy used to acquire raw materials (excavation), manufacture and transport to the building site.

Han et al. [31] quantified the embodied energy consumption for two multi-building projects in Beijing, China using a hybrid method of process and input-output analysis. The accuracy of the assessment depended upon the Bill of Quantities (BOQ), which quantifies the work of all the inputs to construction by documenting the quantity and price of each item and then assigning each item to a production sector, where a corresponding embodied energy intensity was found in the input output database. Steel products accounted for more than 30% of the overall embodied energy consumption of construction followed by concrete products like cement and plaster.

Blengini and Carlo [8] found a large materials-related impact for a passive home with a 70 year lifetime in Italy. Materials in the building envelope had the highest relative contribution, with maintenance operations also playing a major role. However, there was a need for more reliable data on the actual service duration of several materials. The analysis stated that there is no single item or aspect that dominates the life cycle impacts, but several are equally important in determining the overall sustainability of the home. The authors recognize the many case-specific features of the study, like the locally adopted construction techniques, the behavioral pattern of Italian citizens, site-specific climate conditions, local regulations and the Italian energy mix. Thus they concluded that the results should not be generalized.

Scheuer et al. [64] analyzed a university building in Michigan, USA with a lifetime of 75 years. Construction materials were responsible for 94% of the life cycle embodied energy (the rest being energy embodied in replacement materials). The largest contributors were steel, cement and sand used in the excavation, foundation, and structure. This was due to their large mass and not necessarily the energy used in their production. Aluminium, mostly used for window frames, was also significant because of its energy intensity. The study concluded that if all other parameters are kept constant, replacing conventional building material by low-carbon emitting material improves environmental performance significantly.

Dutil et al. [20] outlined the history behind the methodological thinking for zero emission and passive buildings. The study critiques the guidelines for the design of sustainable building practices and the LCA in practice. Weaknesses were found through unsteady environmental indicators over time, the need to differentiate between primary and secondary energy consumption, and the need for more post-occupancy evaluation to determined achieved thermal comfort.

Energy

The energy performance of buildings is a major concern for the European Union in the attempt to meet the Kyoto commitment. As a result, the European Directive 2002/91/EC on the Energy Performance of Buildings was formed and since its implementation the number of passive and low energy non-residential buildings has increased significantly [76].

As of 2011, typical annual heating use for European school buildings was reported as 31 kWh/m^2 in Greece, 96 kWh/m^2 for Ireland, 192 kWh/m^2 for Slovenia, 157 kWh/m^2 for the UK, and 197 $kWh/m^2/year$ in Flanders [4, 35]. The average annual energy consumption of 15 schools in Argentina was 123 kWh/m^2 while 87% of the primary and secondary schools were characterized as low emission buildings. According to the Natural Resources Canada, the average annual energy consumption of schools in Canada was 472 kWh/m^2, and there are examples of low energy buildings like a 2300 m^2 school with actual energy consumption of 72 kWh/m^2. As of 2009 the yearly net winter heat requirement for a standard building in Italy was 110 kWh/m^2 [35].

Thewes et al. [71] reviewed the energy consumption of 68 Luxembourg schools built between 1996-2011, representing the first cohort of buildings constructed to a thermal energy requirement. It was found that energy consumption varied substantially depending on the building's technical installations (ventilation, lighting systems). Almost all schools constructed after 2005 consumed less than 100 kWh/m^2 and often less than 50 kWh/m^2 thermal energy. Of all buildings analyzed, the lowest one was a very airtight, low-energy school with low U-values. The decrease in thermal end energy consumption after 2005 was due to a new regulation becoming effective, providing financial support to construct new public passive and low-energy buildings. The author found that passive and low-energy schools saved an average primary energy of only 17–37% compared to standard buildings and had a higher electricity consumption. The study concluded that passive or low-energy buildings had a smaller positive environmental impact than thought, though new building design led to the most energy-efficient school buildings to consume 50% less primary energy than the mean value of all new school buildings.

The space heating demand of buildings has decreased by improved insulation, reduced air leakage and by heat recovery from ventilation air. Even with gains through material choices and building design, the actual amount of energy used in buildings is often different from the calculated or expected energy use. The difference depends on the final realization of the construction and the technical installations, the actual weather conditions, and the utilization of the technical installations that affect interior temperature and ventilation rate [4]. In a study by Hirst and Goeltz [36] of the difference between the calculated and actual energy use, an energy audit was performed on North American homes and it was found that on average only two-thirds of the expected energy saving was actually realized.

Scheuer et al. [64] measured the primary energy consumption for heating, cooling, ventilation, lighting and water consumption. The primary energy intensity over the buildings life cycle was calculated to be 316 GJ/m^2. Production of materials and transportation to the site accounted for 2.2% of life cycle energy consumption, while HVAC and electricity alone accounted for 94.4%. Building demolition and transportation of waste, accounts for only 0.2% of life cycle primary energy consumption. Results showed that the optimization of the operation phase should be emphasized during the design.

Sartori and Hestnes [63] performed a literature survey of 60 cases from nine countries regarding buildings' life cycle energy use. Case studies on buildings built according to different design criteria (conventional, low energy and zero energy), and holding all other conditions constant, showed that low energy buildings induced both a net benefit in total life cycle energy demand and an increase in the embodied energy. s

In order to achieve a better understanding of the interplay between embodied and operating energy and its effect on the total energy needs, Winther and Hestnes [79] compared five versions of the same dwelling with different insulation levels, different ventilation strategies, and different energy saving equipment in Norwegian conditions. They found that in the long run the operational energy is more important than the embodied energy. Feist [12] compared a passive solar and a zero energy dwelling and found that the former achieved a lower total energy use per m^2 during its lifetime. The latter was equipped with advanced technical installations, causing its embodied energy to be so high that it exceeded life cycle energy use of its counterpart.

Despite these historical cases, from most of the available literature, one can conclude that the operational phase contributes more than 80-85% share in the total life cycle energy of building. Therefore, future efforts should be focused on reducing the operational phase, even at some cost to other less significant phases [12, 20, 67].

Chapter 3

Methods

In this section the characteristics of the case study are introduced. The compiled life cycle inventory necessary to carry out the LCA is described. The chosen environmental indicators are presented.

3.1 Case Description

Grefsen U3 was a high school that is being rehabilitated to become an elementary school for 420 students. The existing buildings on site will be rehabilitated, and a new building will be added. The construction and operation of the new building, Building 6, is the focus of this study. In order to analyze the school building in the Norwegian context, data from another school project with similar goals was used. Stasjonsfjellet School is also located in Oslo and Hjellnes Consult took part in both projects. Both schools are to be rehabilitated to the passive house standard [28].

Weather Characteristics

The school buildings are located in Oslo, Norway. The landscape, weather conditions, and environment are essential conditions in the basic planning and development of the buildings. The Norwegian Meteorological Institute is responsible for obtaining average weather values. Table 3.1 describes weather conditions factored into energy calculation for Oslo [61]. The outdoor design temperature is defined as a location's lowest mean temperature for three continuous days over a 30 year period and is the starting point to calculate the thermal power needed for a building.

Table 3.1: Weather Characteristics for Oslo

Annual mean temperature (°C)	6.3
Annual mean solar radiation (W/m^2)	110
Annual mean wind speed (m/s)	2.2
Number of days with snow covered ground	102
Outdoor design temperature (°C)	-20

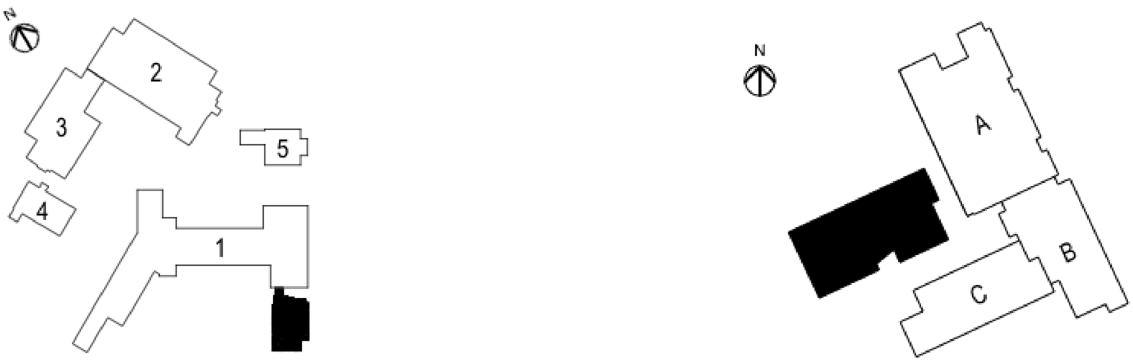
Site Characteristics

Table 3.2 compares the dimensions of the two schools in regards to floor area, and area of walls, windows, and doors. As Figure 3.1 shows, both schools are located in the same city so many of the same design considerations regarding weather, materials, and transportation apply.

Table 3.2: Site Characteristics

	Grefsen U3	Stasjonsfjellet
Total Floor Area	494 m^2	629 m^2
External Wall Area	611 m^2	205 m^2
Windows and Doors Area	69.5 m^2	117 m^2

Figure 3.1: Locations of the two schools



(a) Grefsen (b) Stasjonsfjellet

Figure 3.2: Building Orientation

In Figure 3.2 it can be seen that both buildings of focus (marked in black) are a part of a larger school complex. The new building at Stajsonsfjellet (Building D) is much larger than Building 6, and has many more functions as it included more classrooms and has hallways, bathrooms, and office space. Both new buildings are part of a larger rehabilitation project; Grefsen U3 began rehabilitation in August 2012 and is planned to be finished in the fall of 2014, while Stasjonsfjellet rehabilitation began in 2010 and also will finish in the fall of 2014.

3.2 System Boundaries

The flow sheet of the system (see Figure 3.3) is created to give an overview of how the various life cycle stages interact. In this study, the construction and use of the building is modeled. End of life management is not considered because of the lack of information and transportation is included in all categories [69].

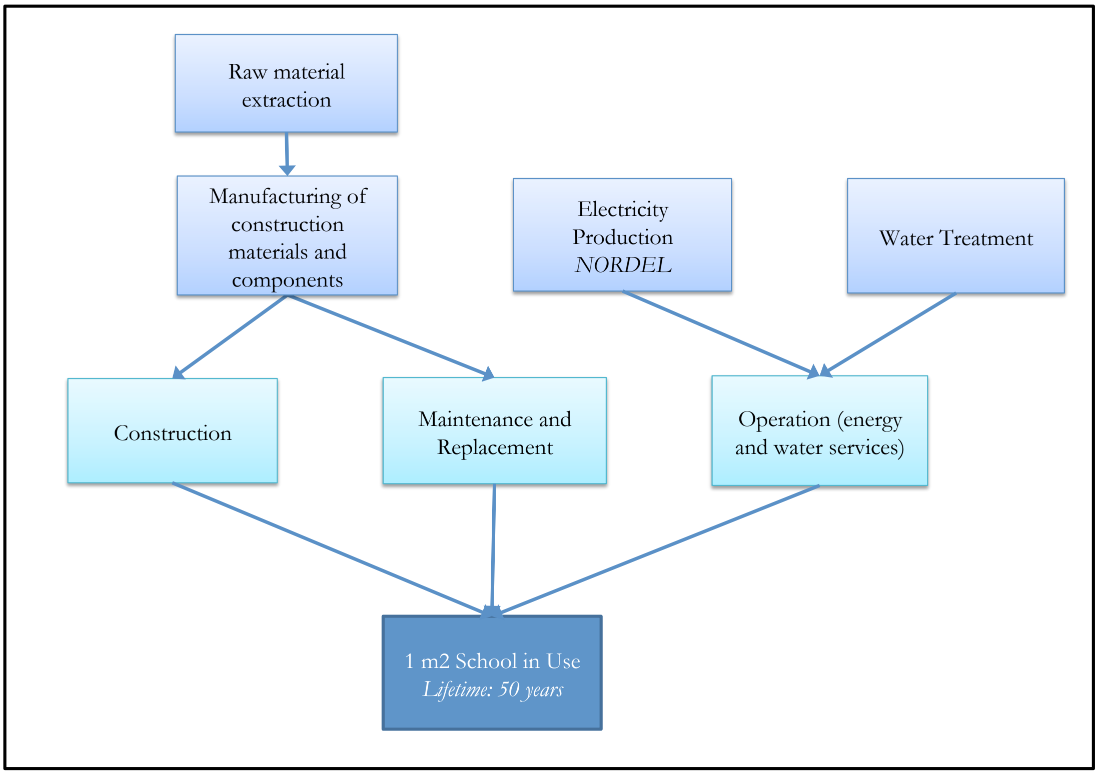


Figure 3.3: System Boundaries

3.3 Functional Unit

The functional unit was chosen so that the buildings are comparable over the same lifetime and providing the same service. The functional unit is defined as:

> *50 years of 1 m^2 utilized floor space (BRA) of the school building, including the construction, maintenance, and operational energy.*

The functional unit is used for both LCAs. The presentation of results on a per square meter utilized floor space basis, enabling comparison to other studies.

3.4 Data Sources

Material inventory data was obtained through the project documents of each school, including estimates, plans, and specifications provided by Hjellnes Consult. Materials were allocated to a representative LCI unit process within SimaPro 8.0, with preference first given to the ecoinvent v3 database. If a unit process was not available from the EPDs, another process from ecoinvent was selected based on the best possible information of the unit process description, boundary considerations, and installed product use.

Bodil Motzke, an environmental consultant from Undervisningsbygg Oslo KF, provided EPDs for the Stasjonsfjellet school project. Undervisningsbygg is now in the final stage of calculating the greenhouse gas emissions from the materials used at Stasjonsfjellet. For Grefsen U3 no calculations of greenhouse gases were done nor were EPDs collected for the materials because the project started up before this process became standard procedure in Norway [47].

All the materials listed in Table 3.3 had EPDs available for use in modeling of Grefsen school. It is marked with an X where an EPD was applied from the Stasjonsfjellet project to Grefsen and where new EPDs were collected. If a product had a lifetime that was not according to the functional unit, its data was adjusted to reflect a 50 year lifetime. For comparability to LCA data in SimaPro a sensitivity analysis is performed in Section 5.3. The reliability and consistency of EPDs are discussed in Chapter 6 and 7.

Table 3.3: EPDs used in both schools

EPD	**Manufacturer**	**Unit**	**Stasjonsfjellet**	**Grefsen**
Concrete	Unicon	1 m^3	X	X
Ceiling Tiles	Gyptone	1 m^3		X
Door Lock	TrioVing	1 unit		X
Fireboard 15mm	Gyproc	1 m^2	X	X
Insulation	Rockwool	1 m^2	X	X
Iso3 Board	Moelven	1 m	X	X
Linoleum Flooring	ERFMI	1 m^2	X	X
Masonry Mortar	Weber	1 kg	X	
Mineral Wool	Glava	1 m^2	X	X
Moisture Barrier	Icopal	1 m^2		X
Plasterboard 12.5mm	Gyproc	1 m^2	X	X
Hard Plasterboard 13mm	Norgips	1 m^2	X	X
Plasterboard 13mm	Norgips	1 m^2	X	X
Planed Structural Timber	Treindustrien	1 m^3	X	
Roofing	Isola	1 m^2		X
Sheathing Board 9.5mm	Gyproc	1 m^2	X	X
Standard Gluelam Beam	Moelven	1 m^3	X	X
Steel Beam w/ Polyetenduk	Norgips	1 lm	X	X
Steel Beam	Norgips	1 lm	X	X
Roofing/Wind Barrier	Hunton	1 m^2		X

3.5 Environmental Indicators

The following energy and environmental indicators were adopted in accordance with the EPDs:

- Global warming potential, GWP, in kg CO_2 equivalents, 100 years.
- Depletion potential of the stratospheric ozone layer, ODP, in kg CFC-11 equivalents, 20 years.
- Acidification potential of land and water sources, AP, in kg SO_2 equivalents.
- Eutrophication potential, EP in kg PO_4 equivalents.
- Formation potential of tropospheric ozone photochemical oxidants, POCP, in kg C_2H_4 equivalents.
- Abiotic depletion potential for non-fossil fuels, ADP, in Sb equivalents [50].

Not all EPDs included ADP in their reports, so it was included when listed.

EPDs also included an energy impact in megajoules (MJ) (see Appendix 10.5). Since the EPDs had various ways of listing the energy mix used, all energy in EPDs were modeled using the NORDEL electricity mix.

Chapter 4

Life Cycle Inventory Analysis

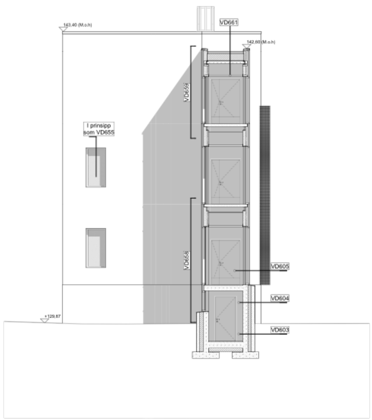
In this section the inventory of materials is described and categorized according to building component. This includes energy used on site, the foundation, flooring, roof, walls (inner and outer), windows and doors, waste during construction, and transportation to site. The inventory was built within SimaPro 8.0 using information from the EPDs and processes within the software. The architectural drawings were made by Heggelund and Koxvold [33]. To build the assembly within SimaPro, the structure from Dahlstrøm [15] was used as a framework.

4.1 Construction phase

Energy used in construction equipment

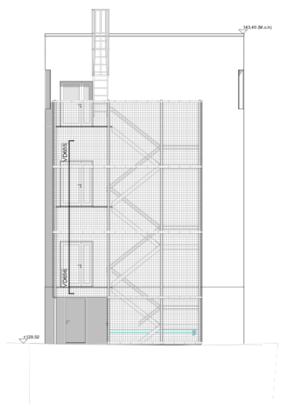
No information about the type of equipment, the number of workers, the tools needed, or the energy requirements of the equipment was available for the study. The best available data from Dahlstrøm [15] was adapted to this study. Based on that study it is assumed an excavator and crane were used. An air compressor, saw, and other electrical tools like screwdrivers and drills are used. The machinery was assumed to burn diesel gas and the energy for tools was electricity. The transportation of workers to site and the hours they worked were not included.

Facade

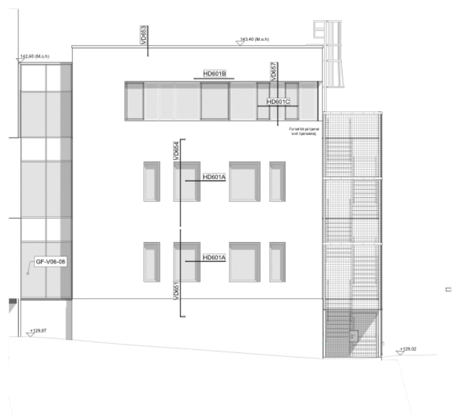


Facade North

Facade East



Facade South



Facade West

(a) Technical Drawing

(b)

Figure 4.1: Architectural Drawings and Picture, Facade

Figure 4.1 displays the information available for the facade of the building. It was unknown if paint was used, and since not other information was obtained it was not included in the model.

Foundation

Figure 4.2 presents the technical drawing from Hjellnes of the foundation wall. Details from the drawings and notes of these documents were used to compile the elements of the foundation in Table 4.1.

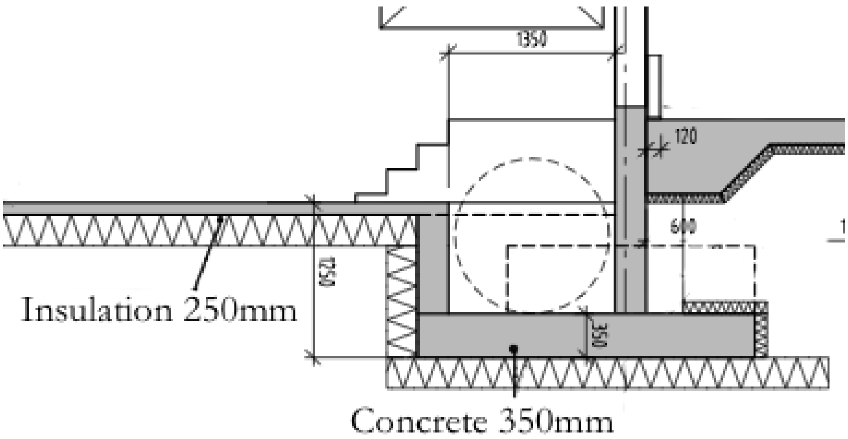


Figure 4.2: Technical Drawing of Foundation

Table 4.1: Material quantities in the foundation

Component	Material	Quantity	Unit
Foundation	Concrete	37.5	m^3
	Insulation	23	m^3
	Steel Beams	164	lm
	Moisture Barrier	4.8	kg
	Crushed Stone	8530	kg

EPDs were used for the concrete and moisture barrier, and the rest were ecoinvent processes “polystyrene, extruded (XPS), at plant; gravel”, “crushed, at mine”; “reinforcing steel, at plant”, and “extrusion, plastic film”.

Flooring

Table 4.2 lists the elements in the flooring that was drawn in Figure 4.3. Concrete was modeled using an EPD and its weight was calculated using a density of 2400 kg/m^3 (see Appendix 10.3). The wood element was labeled Massivtre’ in the architectural drawings.

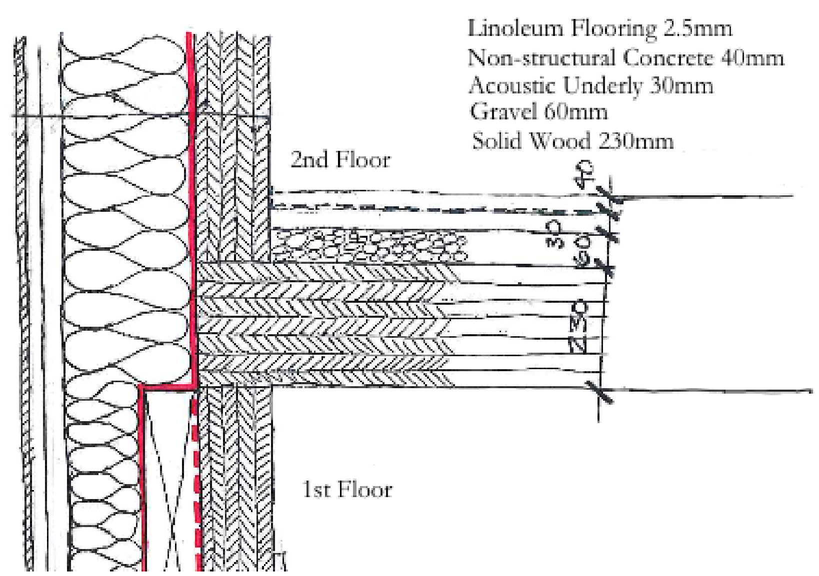


Figure 4.3: Architectural Drawing of Flooring

The emergency exit was a Plannja Combideck, made of steel and aluminum. The dimensions and weight of the stairwell was calculated using technical drawings from the engineering department at Hjellnes and information from data sheets from the manufacturer. The emergency exit was assumed to have steel railings on the staircases and both were assumed to be the process “steel, low-alloyed, at plant”. The walkway and fencing were modeled using “galvanized steel sheet, at plant” and “aluminum sheet, semi finished’ since no EPDs were available.

Table 4.2: Material quantities in the floors

Component	Material	Quantity	Unit
First Floor	Linoleum Flooring	103	m^2
	Concrete	26	m^3
	Concrete slabs	2.1	m^3
Second and Third Floors	Linoleum Flooring	207	m^2
	Crushed Stone	16146	kg
	Acoustic Plates	207	m^2
	Gravel	8.3	m^3
	Solid wood	47.6	m^3
Stairwell	Steel walkway	144	kg
	Chain link fencing	80	m^2
	Steel steps	16	m^2
	Aluminium railing	55	kg

Roofing

The roof (see Table reftab:roof) consists of an outer roofing, plywood, structural timber, fireproof insulation, regular insulation, and a wind barrier. EPDs were available for most elements, and the OSB board was represented by “oriented strand board, at plant” and the plywood “plywood, outer use, at plant”.

Table 4.3: Material quantities in the roof

Component	Material	Quantity	Unit
Roof	Isola Roofing	120	m^2
	Plywood	4	m^3
	Gluelam Beams	9.6	m^3
	Mineral Wool	120	m^2
	Insulation	120	m^2
	OSB	120	m^2
	Wind Barrier	120	m^2

The roofing system materials were estimated using architectural and technical drawings. The exterior roofing was made by Isola, the insulation rock wool and Glava for the mineral wool, and Hunton made the under roofing. The area it covers was estimated by the information in SIMIEN and manual calculations. The parapet, which refers to the crowning element surrounding the top of the roof, was not inventoried because of lack of information in the drawings. No information on the roof gutters was found in the drawings, so it was used they were made of aluminum with no surface finish. The required length was calculated manually and its weight found on the Plannja website [57]. The method for processing the aluminum is assumed to be sheet rolling.

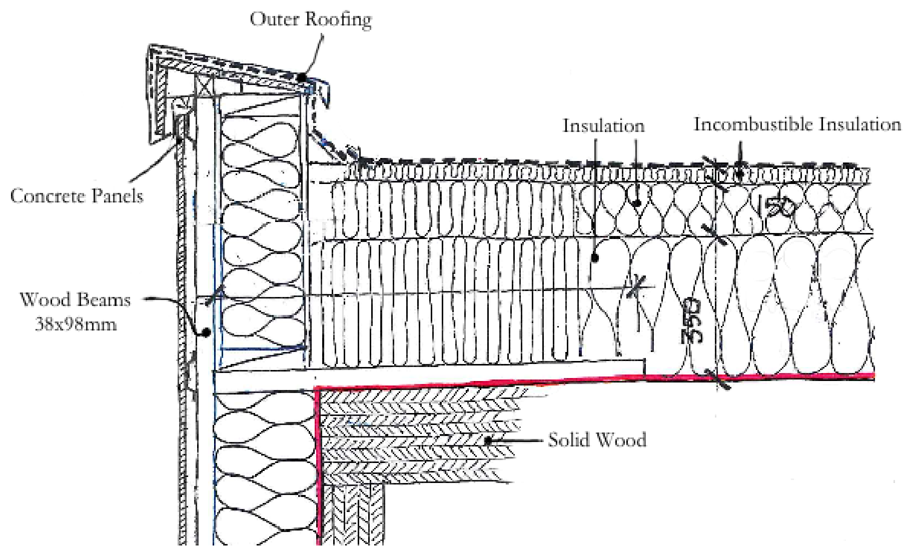


Figure 4.4: Architectural Drawing of Roof

Exterior Walls

The material quantities used in the exterior walls is presented in Table 4.4 and were estimated using the drawing in Figure 4.5.

Table 4.4: Material quantities in the exterior walls

Component	Material	Quantity	Unit
External Wall	Exterior Cladding	432	m^2
	Metal perforated sheet	16	m^3
	Gravel	4	kg
	Gluelam Beams	62.73	m^3
	Vapor Barrier	432	m^2
	Insulation	401.46	m^2
	Iso 3 Beam	67.2	m

The exterior wall composed 89% of the outer surface. The outermost element, Weber Aquapanels, was modeled using the process "fibre cement facing tile, small format, at plant". Gravel was used around the openings for the doors, and it was modeled using the process "gravel, crushed, at mine".

The load supporting structure for the school was solid wood (massivtre). The wooden studs were manufactured by Moelven in Norway. The material inventory for the exterior wall system is provided in Table 4.4. It was assumed that the beams in the walls for both buildings had 600 mm spacing, which is common in the construction industry.

A rough estimate for the total surface area of external walls requiring moisture barrier and wind barrier was estimated manually. This involved measuring the total area of external walls and subtracting the (estimated) fraction of exterior wall area covered by windows. The vapor barrier is assumed to be made of polyethylene with a density of 0.5 kg/m^2 [38].

Interior Walls

The material quantities used in the interior walls is shown in Table 4.5 and were estimated from the architectural drawings. The inside of the building on each floor has a classroom and a meeting room, with the basement completely open. The total manually calculated area of the inner walls, 143 m^2, is just 23% of the area of the exterior walls.

Table 4.5: Material quantities in the inner walls

Component	Material	Quantity	Unit
Interior Wall	Hard Plasterboard	247	m^2
	Plasterboard	247	m^2
	Steel Beams	88	lm
	Insulation	143	m^2

EPDs were used for all elements of the inner walls. Both plasterboards were from the manufacture Gyproc, the steel beams Norgips, and the Insulation Rockwool. The hard

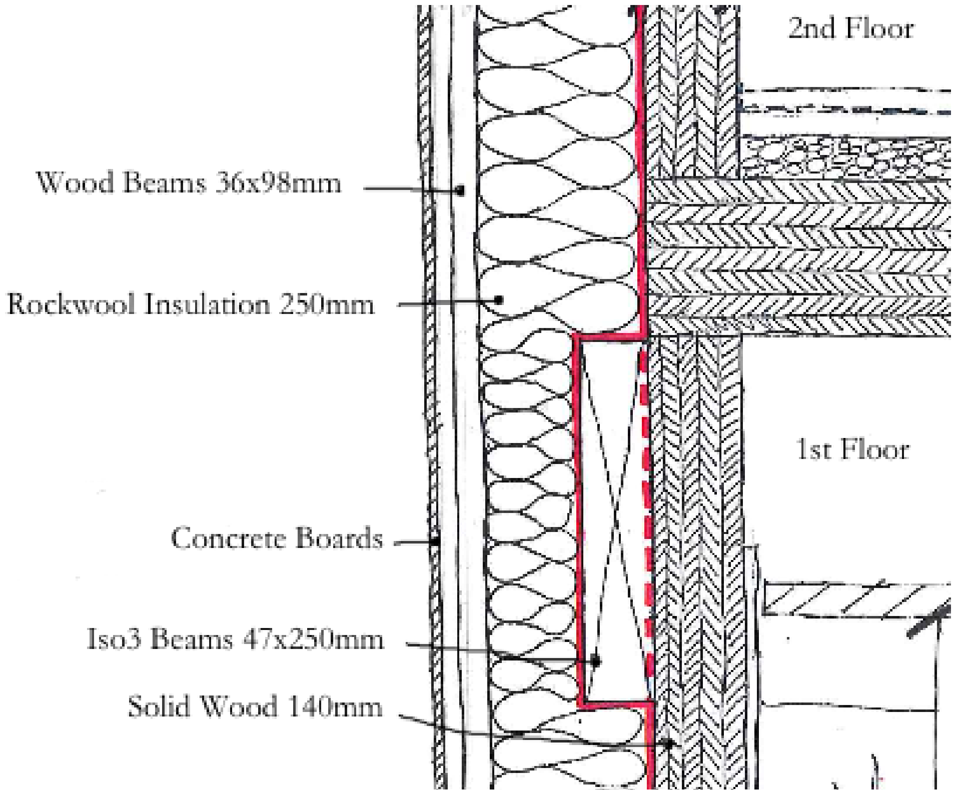


Figure 4.5: Architectural Drawing of Outer Wall

and standard plasterboard were layered on either side of the insulation and beams. See Table 3.3 and Appendix 10.3 to see the characteristics and densities of the elements.

Windows and doors

Figure 4.6 shows the best available information for the overall window design. Windows were adapted from Dahlstrøm [15], who analyzed a 1230 x 1480mm passive house standard window. Since these were not the exact dimensions of the average window at Grefsen (1200 x 1400mm), the reference windows were simply scaled down.

Figure 4.6: Architectural Drawing of Outer Wall

Windows covered 11% of the outer surface and the functional unit for each was one window or door with a U-value of 0.8 cradle to grave. EPDs were found for door leaves and locks for Grefsen, and the frame was assumed to be wood and a process for it found in SimaPro. The 11 doors were made with glass and aluminum. Due to a lack of inventory data on aluminum framed doors, they were created in SimaPro using information from Dahlstrøm and EPDs. The doors are assumed to come from a Norwegian producer, Nordic Dørfabrikk.

Waste During Construction (WDC)

In the present study, waste generated during construction has been assumed to amount to 10% of total materials in line with Melvær [46]. Since there is no information on exact quantities of materials this was applied to all elements in construction. All waste is assumed to be transported to a waste treatment plant located 50km from Grefsen U3 in line with the Product Category Rules about construction [50].

Transport

In SimaPro transport of materials to the site is assumed to be done by a "20-28 ton lorry, fleet average". Materials with EPDs used the production location referenced, and for materials where it was not known production closest to Oslo was assumed. Distance estimations were made using Google maps. According to NPCRs transport from the site to product warehouses in Norway must be included in EPDs and for Norwegian manufacturers this is set to at least 50km [50]. Appendix 10.4 lists the transport distances for all the materials used in the study.

4.2 Use phase

Energy System

Under NS 3701 it is required for heating systems of passive houses to get a significant share of its energy source from non electric and non-fossil energy. This can be district heating systems, heat pumps, pellet/wood/bio-stoves, or a biogas system [53]. Primary energy use for Grefsen was electricity and heat generated from a heat pump. The heat pump accounted for 90% of the space heating, none of the water heating, and 90% of the ventilation heating. Direct electricity accounts for 10% of the space heating, 100% of the hot water and ventilation cooling. Of the delivered energy 28% came from the heat pump and 82% from direct electricity. The heat pump generates more energy than is delivered to it. See Appendix 10.2 to see the technical drawing of the heating system for the entire Grefsen U3 school.

COWI AS is responsible for the energy calculations and information from their work was used to input data into SIMIEN to model the both schools. The total net energy required for both is presented in Table 4.6.

Table 4.6: Energy budget by installation

Energy budget	Passive (kWh/m^2/y)	TEK10 (kWh/m^2/y)
1a Space Heating	14.7	33.6
1b Ventilation Heat (thermal batteries)	4.7	5.3
2 Hot water (tap water)	10.1	10.1
3a Fans	4.5	4.4
3b Pumps	1.5	1.8
4 Lighting	10.6	10.6
5 Technical Equipment	7.1	7.1
6a Space Cooling	0.0	0.0
6b Ventilation Cooling	3.4	3.4
7 Total Net Energy	56.6	76.3

Electricity

The annual energy consumption for the passive house was simulated in the program SIMIEN. See Chapter 10 for the monthly energy needs for the passive standard buildings. The electricity was modeled in SimaPro using the NORDEL mix, medium voltage.

The annual simulated energy requirements for TEK10 is based on the NS 3031, while the passive house is based on NS 3701. The simulated net required energy as presented is not the same as delivered electrical energy and the difference is presented in Table 4.7 while Figure 4.7 shows the breakdown of energy by installation. The passive school will have a much lower expected space heating requirement because of its tight building envelope. It is possible that the delivered energy and energy need are different because in both models the heat pump covers the difference in energy need internally.

Table 4.7: Total Energy requirements, TEK10 vs. Passive

	Annual Delivered Energy	Annual Energy need
Passive	21652 kWh	27592 kWh
	43.8 kWh/m^2	56.6 kWh/m^2
TEK10	37689 kWh	26595 kWh
	76.3 kWh/m^2	53.8 kWh/m^2

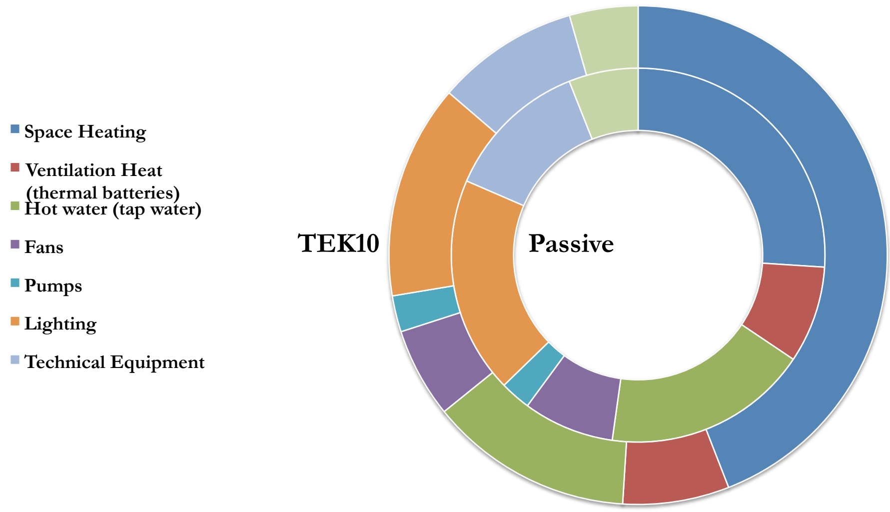


Figure 4.7: Yearly energy impacts

Maintenance

The maintenance of the products listed in Table 4.8 were modeled within SimaPro. Furniture, interior decoration, electronic equipment and other furnishing are not included in the study because of lack of information in the architectural and technical drawings.

Table 4.8: Description of maintenance by building element

Element	**Lifetime (year)**	**Lifecycle (n)**	**Elements replaced**
Doors	30	2	Door leaf
Flooring	30	2	All
Heat Pump	20	3	All
Roof	30	2	Top level roofing, rain gutter, roof guard
Windows	30	2	All

Chapter 5

Life Cycle Impact Assessment

This chapter presents two life cycle assessments of Grefsen U3 for the comparison of the construction and use of the school built after the Norwegian building code, TEK10, and the passive standard built after the Norwegian Standard NS 3701. The total impacts are presented and aggregated into four categories: Construction (year 0), Waste During Construction (year 0), Maintenance (years 1-50), and Operation (years 1-50). Normalization is used through this section as it is an interpretation aid to better understand the relative magnitude of an impact. Each midpoint impact category has its own units and measures different damages, so it is not possible to compare them directly.

5.1 Life Cycle Results

Midpoint Indicators

The total impacts for constructing, maintaining, and operating both schools are shown in Table 5.1. The total impacts and impacts per functional unit, m^2 of useful floor area, are presented side by side. The passive school over its lifetime has a climate change impact of 594 tons CO_2 equivalents (eq) and the TEK10 school 724 ton CO_2 eq. The passive house saves 130 tons CO_2 over the lifetime of 50 years compared to building the same school to building code, which is equivalent to 7.3 kg CO_2 eq per day.

The total life cycle climate change impacts per m^2 useful floor area is 1.2 tons CO_2 eq for the passive school and 1.46 tons CO_2 eq for the TEK10 school. The cumulative energy consumption for the passive house is 27 GJ eq per m^2, and is 9 % lower than the energy demand of the TEK10 school over the same lifetime. The energy demand for the passive house is 152 kWh/m^2/year and the TEK10 school 168 kWh/m^2/year.

Table 5.1: Life cycle impacts for the passive and TEK10 schools

	Total		**Per m^2 floor**		
	Passive	TEK10	Passive	TEK10	Unit
Climate Change (CC)	593901	723974	1202	1465.5	kg CO_2 eq
Ozone Depletion (ODP)	2.6	2.64	0.005	0.005	kg CFC-11 eq
Human Toxicity (HT)	180520	217431	365.4	440	kg 1.4-DB eq
Photochemical oxidant formation (POCP)	850	1005	1.7	2	kg NMVOC eq
Particulate matter formation (PMF)	578.5	670	1.2	1.3	kg PM10 eq
Terrestrial acidification (TA)	1240.5	1423	2.5	2.9	kg SO_2 eq
Freshwater eutrophication (FE)	70	90.5	0.1	0.2	kg P eq
Marine eutrophication (ME)	40	49	0.1	0.1	kg N eq
Terrestrial ecotoxicity (TECO)	276	330	0.6	0.7	kg 1.4-DB eq
Freshwater ecotoxicity (FECO)	2466.5	2887	5	5.8	kg 1.4-DB eq
Marine ecotoxicity (MECO)	2488	2963	5	6	kg 1.4-DB eq
Metal depletion (MD)	20861	26650	42	54	kg Fe eq
Cumulative energy demand (CED)	13510	15911	27.4	32.2	GJ eq

Figure 5.1 shows the life cycle impacts for Grefsen U3 over a 50 year lifetime. Impacts are distributed among Construction, Waste during Construction (WDC), Maintenance, and Operation. Operation accounts for roughly 59% of climate change, 32% from Construction, 6% from Maintenance, and 2% from WDC for the passive house school. The TEK10 school climate change impact was 65% for operation, 26% for Construction, 6% for Maintenance, and 2% for WDC. The passive school has a higher material input than the TEK10 school and therefore the Construction phase is a larger share of impacts. When the Operation phase is excluded, Construction accounts for 78% of the passive school impact, WDC 6%, and Maintenance 16%.

The TEK10 school has a much larger impact during Operation than the passive school. Seeing as the Construction phase has a smaller relative impact, it can be concluded that it is worthwhile to invest the material and precision that is required for passive house standard in order to reduce climate change emissions over the building's lifetime.

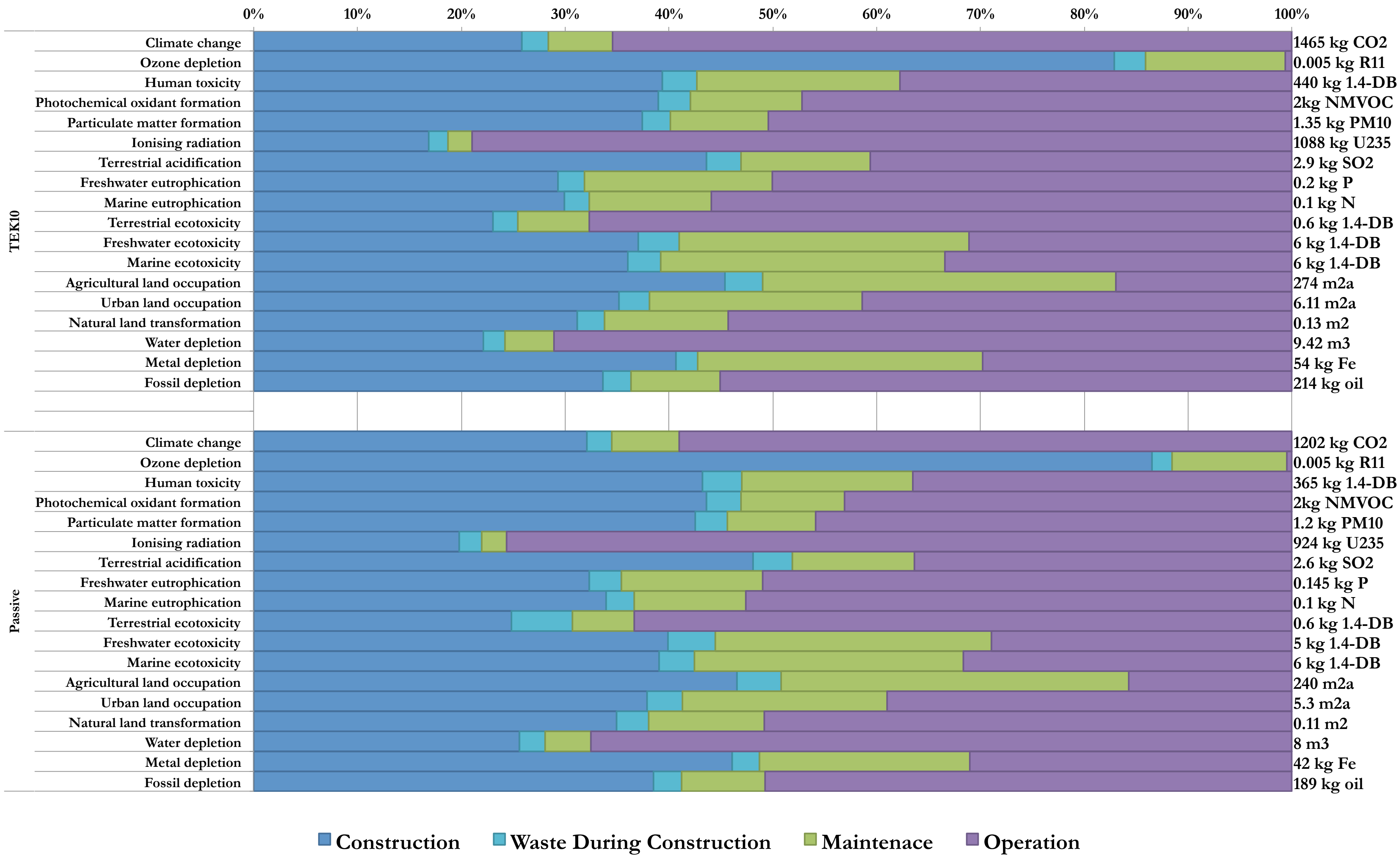


Figure 5.1: All impacts of the building system, normalized. The magnitude of impacts on the right are per m^2.

Figure 5.2 compares the lifecycle impacts for the categories used in EPDs; the EPDs all used the same impact assessment methods. The passive school has higher climate change impacts in the Construction phase for all impacts, the highest being in the freshwater eutrophication impact with a difference of 11%. To see a breakdown of impacts in each Construction category see Appendix refsec:construction. The TEK10 school has a larger impact in Operation almost all categories, varying from a 4% difference in human toxicity impacts to a 29% difference in freshwater eutrophication. The WDC and Maintenance have nearly similar impacts.

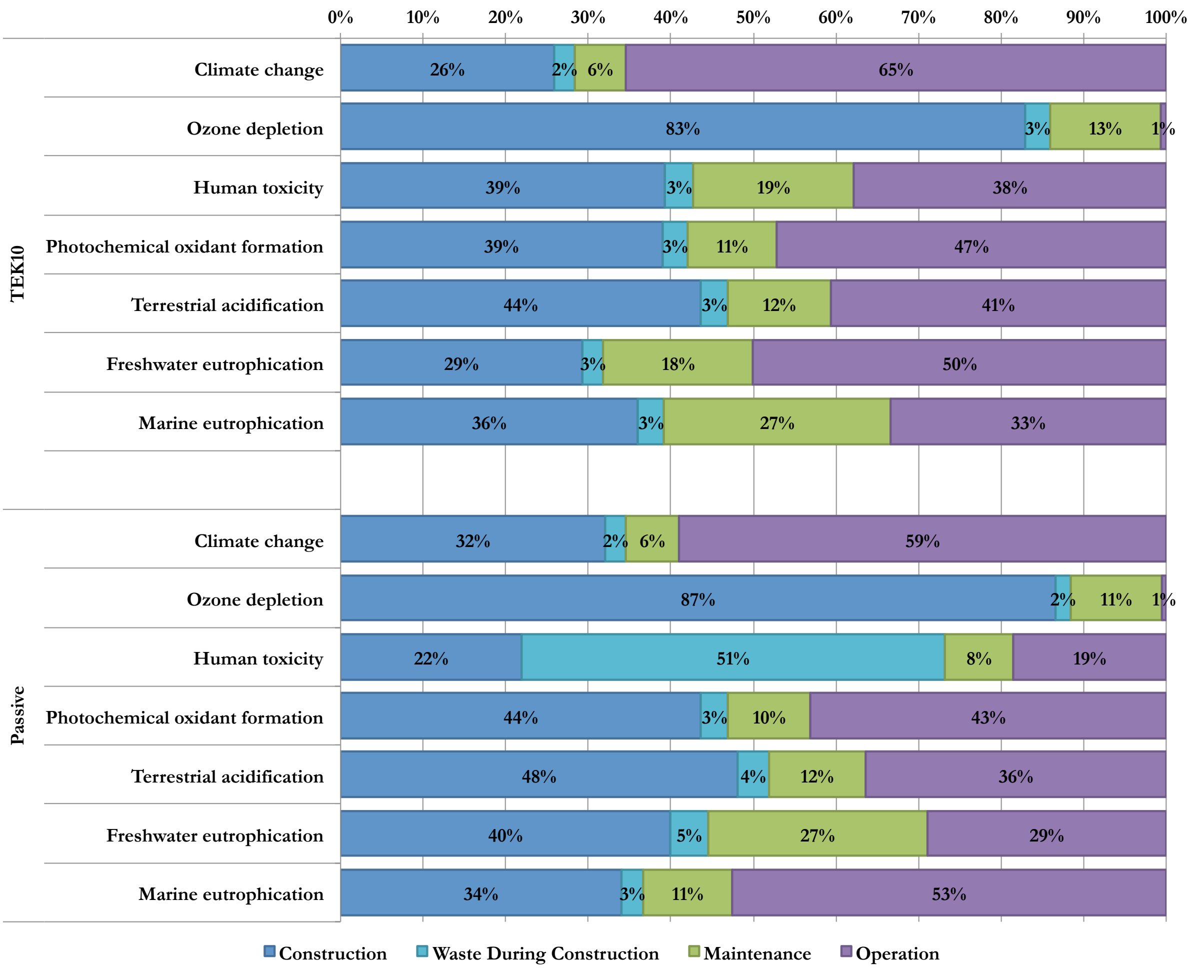


Figure 5.2: Select impacts of the building system, normalized

Annual Impacts

Figure 5.3 presents the yearly climate change impacts, per year (kg CO_2/m^2/year) and accumulated through the lifetime of the two scenarios (kg CO_2/m^2). The highest impacts occur during construction; 29% of impacts for the passive house and 22% for the TEK10 house occur in year 0. The passive house has 21 kg more CO_2 eq higher impacts during the first year because of the extra material and energy used in the building envelope. Each year the TEK10 school has 5 kg more CO_2 eq than the passive school. In year 3, the TEK10 has a higher accumulated impact. Over the entire lifetime, the passive school has an average impact of 22 kg CO_2/m^2/year and the TEK10 school 27 kg CO_2/m^2/year.

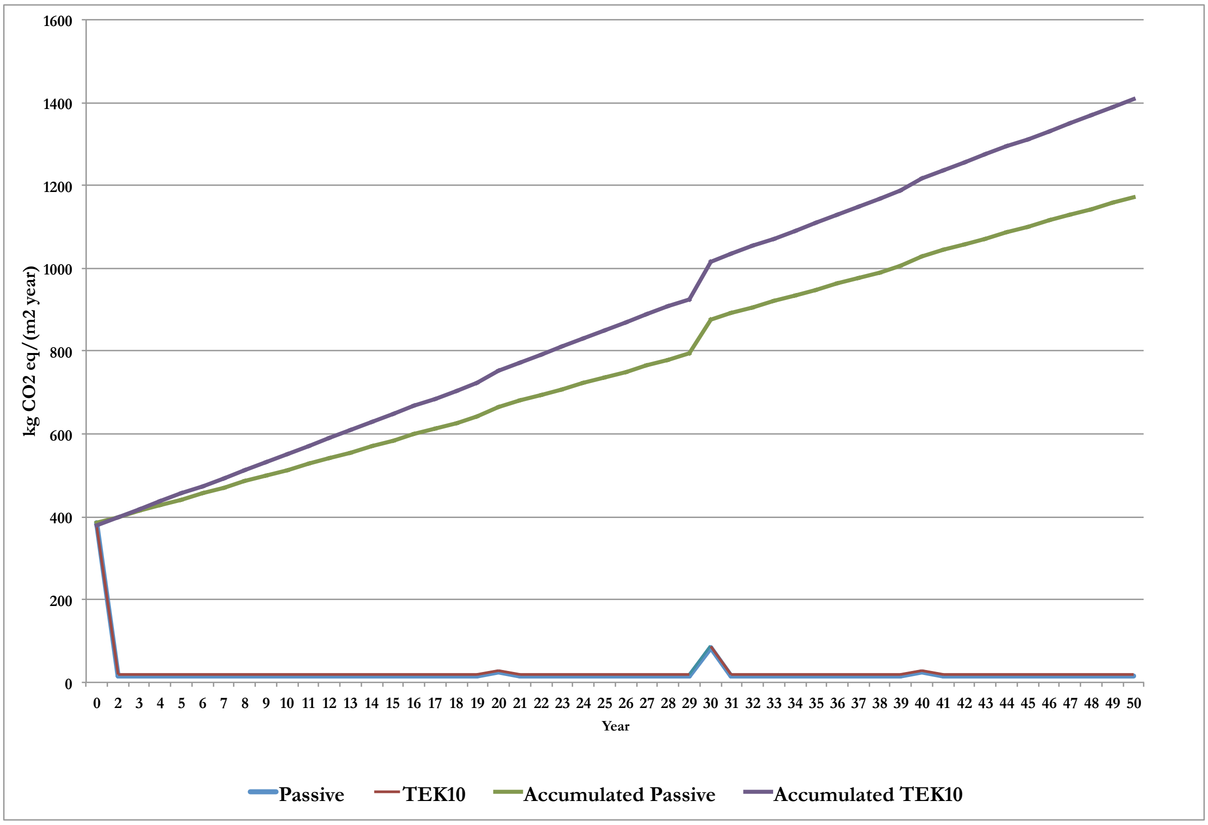


Figure 5.3: Annual and accumulated climate change impacts over time

Another way to look at the annual impacts is that in year 0, the passive school has an embodied energy of 114 kWh/m^2 and the TEK10 school 105 kWh/m^2. With an operational energy use of 4 and 5 kWh/m^2 respectively for each school, it takes 30 years for the passive school and 20 for the TEK10 school to surpass the initial embodied energy inputted.

Endpoint Indicator

As discussed in Chapter 2.1, an endpoint indicator is a straightforward way to present results. The three endpoint categories are normalized, weighted, and aggregated into a single score endpoint indicator is provided in Figure 5.4. To make better sense of the endpoint impact, Figure 2.2 from the Literature Review can help to understand that the endpoint indicator is divided into three categories:

1. Human Health, expressed as the number of years of life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALYs) and its unit is years.

2. Ecosystems, expressed as the loss of species over a certain area, during a year.

3. Resources surplus costs, expressed as the surplus costs of future resource production over an infinitive timeframe (assuming constant annual production), considering a 3% discount rate. The unit is $2000 USD.

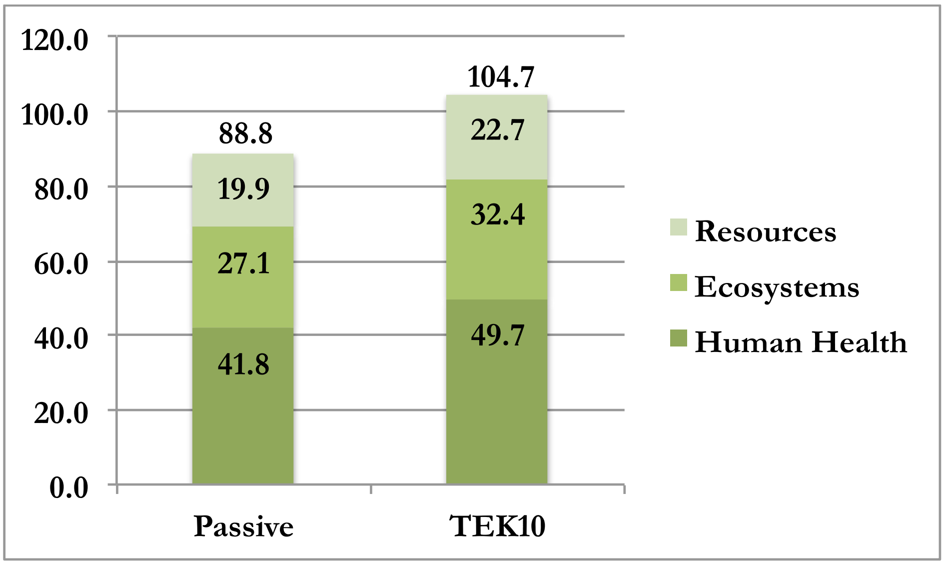


Figure 5.4: Endpoint indicator, Passive vs TEK10

Figure 5.5 further desegregates the endpoint indicator for the three categories. DALYs are made up of climate change affecting human health, human toxicity, particulate matter formation, and ionizing radiation. Species per year impact is calculated using climate change affecting ecosystems, terrestrial ecotoxicity, land occupied by agricultural activity, land occupied by people, and land transformed for human use. Although it is part of the category, the passive school had no impact on species per year through impacts to terrestrial acidification, freshwater eutrophication, or freshwater and marine ecotoxicity so it was not included in Figure 5.5. Economic damage was entire due to fossil depletion with no contribution from metal depletion.

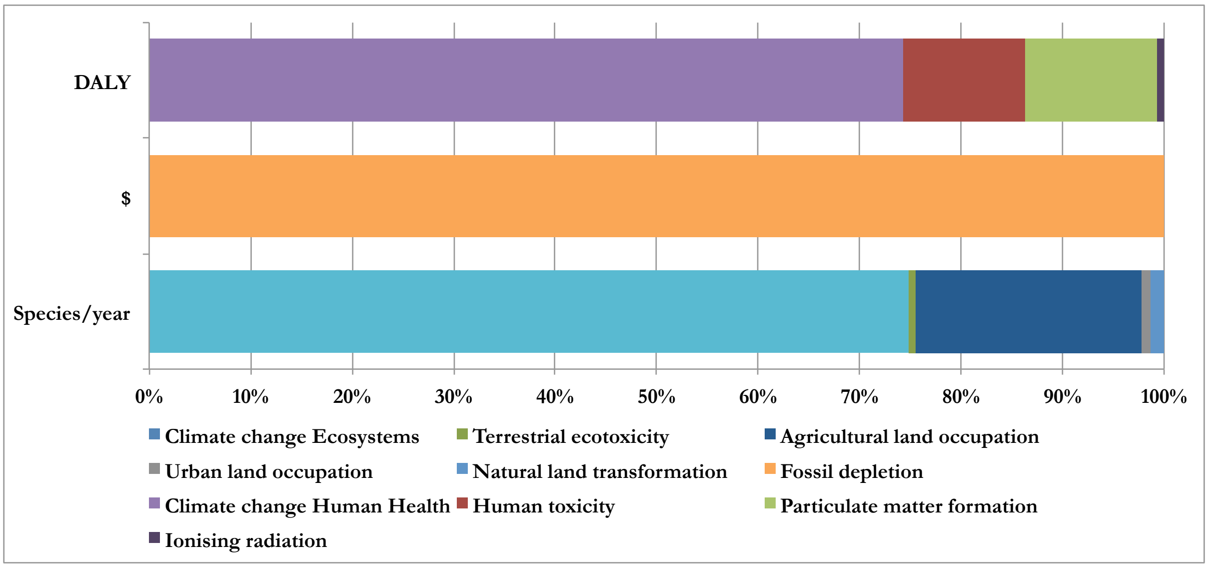


Figure 5.5: Endpoint indicator per damage for the passive school

Primary Energy Use versus Embodied Energy

Primary energy use was assessed using the Cumulative Energy Demand (CED) v1.08 method in SimaPro. The aim of primary energy assessments are to understand how energy use is used throughout the supply chain taking into account both direct and indirect energy use [29].

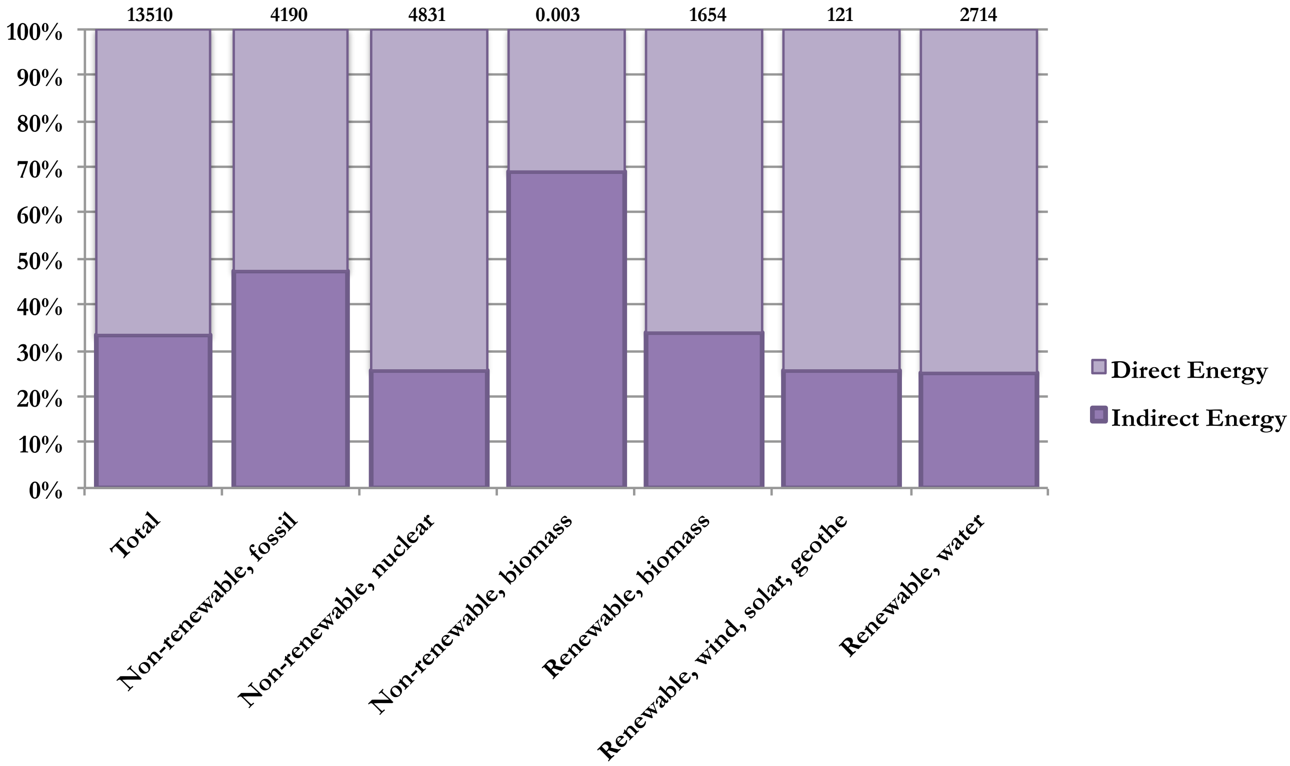


Figure 5.6: Direct and indirect energy use for Grefsen U3 per resource. The magnitude of impacts are expressed in GJ.

In Figure 5.6 direct energy is that which is used in Operation, and indirect that used in Construction, WDC, and Maintenance. When all energy is accumulated, direct energy accounts for 67% of the lifecycle energy use in the passive school. This is in line with Figure 5.1; Operation dominates impacts in the passive school.

The fossil fuel impact is due to contributions from hard coal from the Western EU, offshore natural gas produced in Norway and Russia, and peat from NORDEL. For impacts from nuclear energy, uranium from North American sources is a large contributor. For the biomass impact, the construction was a large contribution to the domination of the category. The Leca blocks used the basement wall and the Weber Aquapanels and Rockwool in the outer walls were the large contributors. Electricity from an offshore wind power plant accounted for 97% of the direct energy impact for Renewable, wind, solar, and geothermal. The direct energy impact from Renewable, water consists of electricity from hydropower sources from Europe in general, followed by Finland and Switzerland.

5.2 Advanced Contribution Analysis

In order to better understand which processes and stressors contribute to the various impact categories, an advanced contribution analysis has been performed. This will pinpoint which processes must be of focus in order to improve upon the environmental impacts of the passive school. The ReCiPe, hierarchist, midpoint method v1.06 was used. The processes and stressors with the highest impact were traced in SimaPro and studied more closely. The operation phase dominates the impacts and it is excluded from this analysis so the non-electrical impacts can be studied. Where impacts from both schools from substances are very similar, the percentage breakdown is combined.

Each table shows the relative contribution of each processes and stressors in each impact category. For stressors, the compartment to which the stressor is released (air, water, soil) is shown.

Climate Change

Table 5.2: Relative contributions to climate change

Process		**Contribution**	
		Passive	TEK10
Concrete		22%	17%
Hard coal, burned in power plant		13%	13%
Polystyrene, extruded (XPS), HFC-134a blown, at plant		9%	7%
Gyptone Ceiling Tiles		6%	7%
Stressors	**Compartment**		
Carbon dioxide, fossil	Air	50%	49%
Carbon Dioxide	Air	25%	29%

We see in Table 5.2 that concrete has the largest share of climate change emissions in both the passive (22%) and TEK10 (17%) schools. This is due to the large relative share in which it is used; it accounts for 60% of the building envelope of the passive school. The hard coal is used in the production of the fuel used in the lorry that goes to and from the construction site. The extra insulation needed for the passive standard school is evident in Table 5.2.

Photochemical Oxidant Formation

Table 5.3: Relative contributions to photochemical oxidant formation

Process	**Contribution**	
	Passive	TEK10
Diesel, burned in building machine	10%	9%
Polystyrene, expandable, at plant	10%	8 %
Electricity, at cogen	9%	9%
Concrete	7%	9 %
Standard Gluelam beam	7%	6%
Hard Coal, burned in power plant	5%	5%
Clinker, at plant	3%	3%
Stressors	**Compartment**	
Nitrogen Oxides	Air	67%
Non-methane volatile organic compounds (NMVOC)	Air	14%
Sulfur Dioxide	Air	8%

We see in Table 5.3 that elements in the construction energy, transportation, and construction are the largest contributors to POCP. The electricity and diesel were the largest contributor to Nitrogen oxides, the polystyrene used in the windows to the NMVOCs, and the gluelam beam to the sulfur dioxide.

Ozone Depletion

Table 5.4: Relative contributions to ozone depletion

Process		**Contribution**	
		Passive	TEK10
Gyptone Ceiling Tiles		78%	80%
Refrigerant R134a, at plant		21%	19.5%
Stressors	**Compartment**		
Methane, trichlorofluoro-, CFC-11	Air	78%	80%
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	21%	19%

Although ozone depleting material is illegal in many countries, construction products still contribute to this impact and are reported in the EPDs [51]. Presented in Table 5.4 is the ozone depletion impact, which was affected mostly by the ceiling tiles, which is one of many EPDs were the stressor methane was used as the equivalent impact. The next impact, refrigerant, is used in the heat pump and also is the largest contributor to the other dominant stressor, ethane.

Terrestrial Acidification

Table 5.5: Relative contributions to terrestrial acidification

Process	**Contribution**	
	Passive	TEK10
Linoleum Flooring	20%	19%
Standard Gluelam beam	8%	8%
Concrete	7%	5%
Flat glass, uncoated, at plant	6%	6%
Polystyrene, expandable, at plant	6%	5%
Stressors	**Compartment**	
Sulfur dioxide	Air	68%
Nitrogen oxides	Air	25%

Terrestrial acidification in Table 5.5 was dominated by the flooring from the European manufacturing association ERFMI. A possible explanation for its large share of impacts is that it needed to be replaced while the other products listed did not. Acidification impacts in the EPDs were accounted for using sulfur dioxide, thus it is the largest stressor with 68% of the impact.

Freshwater Eutrophication

Table 5.6: Relative contributions to freshwater eutrophication

Process	**Contribution**	
	Passive	TEK10
Disposal, spoil from coal mining, in landfill	42%	41%
Disposal, spoil from lignite mining, in surface landfill	29%	31%
Disposal, sulfidic tailings, off-site	13%	13%
Stressors	**Compartment**	
Phosphate	Water	94%
Phosphorus	Water	5%

Table 5.6 shows the main contributors to freshwater eutrophication were from disposal of fuels that were used in the production of insulation, plastics, and windows. This disposal accounted for 84% of the passive school impacts and 85% of the TEK10 school impacts.

Phosphate and Phosphorus account for 99% of the stressors associated with freshwater eutrophication. As the EPDs listed their impacts in Phosphate equivalents, this makes sense.

Human Toxicity

Table 5.7: Relative contributions to abiotic depletion potential

Process	**Contribution**	
	Passive	TEK10
Gyproc Plasterboard 12.5mm	53%	51%
Disposal, spoil from coal mining, in surface landfill	8%	8%
Disposal, sulfidic tailings, off-site	8%	8%
Disposal, wood ash mixture, pure	5%	5%
Stressors	**Compartment**	
Antinomy	Air	50%
Manganese	Water	21%
Phosphorus	Soil	7%

Table 5.7 illustrates the elements with the highest impact on human toxicity account for 74% of impacts for the passive school and 72% of impacts for the TEK10 school. Wood ash impacts are because of the incineration of wood, both from the furnace used in timber production and the end of life treatment of wood products. The EPD for plasterboard included the Antinomy (Sb) impacts per m^2 (see Appendix 10.7), therefore this element was the highest contributor to both projects. The plasterboard was used in the same amounts for both the passive and TEK10 schools.

5.3 Sensitivity Analysis

A sensitivity analysis is performed to see how the model changes when different parameters are set.

Different Electricity Mixes

The electricity mix for all EPDs and energy used for operation are changed to Norwegian (NO) and European (RER) for comparison. All electricity mixes account for the transmission network and direct SF6-emissions to air and are at a medium voltage. The NORDEL network has a capacity of 345 TWh, the RER mix 291 TWh, and NO mix 107 TWh. In Figure 5.7 all impacts are normalized to the passive school using the NORDEL electricity mix for each impact category.

Almost all ecoinvent processes refer to European average technology (termed 'RER' in ecoinvent). The European electricity mix (RER) includes the EU27 and Norway and Switzerland and assumptions about the transmission data are based on Swiss data. The largest contributors to the RER's climate change impact was hard coal and lignite burned in Germany followed by hard coal burned in Spain and Poland.

As of 2012 the Norwegian electricity mix had hydropower as its main energy source (96%). A share of about 2% of the electricity is imported from Denmark, Finland, the Netherlands, Russia and Sweden [41]. Natural gas from the NORDEL mix was also large contributor to the climate change impact. The impacts in every category are consequently much less when using the NO mix. As shown in Figure 5.7, the climate change impact was reduced by 43% for the passive house, 64% of the freshwater eutrophication, and the ecotoxicity on average 75%. The renewable natural of the NO mix means that the fossil depletion impact was reduced by 76% and the water depletion impact by 87%.

As to whether Norway should consider switching its local power source from NORDEL to NO, the problem formulation considered by Dahlstrøm [15] is relevant. If the school and the surrounding area is the only recipient of the hydropower energy, it means the electricity production and consumption is nearly emission free. However, the hydropower plan can sometimes producer more or less energy than the area needs, and hence connection to the national grid is needed to cover the school's need. If the hydropower plant is only producing for Grefsen's region, then less electricity from the hydropower plant is available on the national grid and more electricity must be generated elsewhere, probably with an environmental burden. Thus there is no difference between consuming the local NO mix or getting power from the national grid that uses the NORDEL mix. The goal for the future of the electricity mix should be to have a lower energy need for buildings and use the highest share of renewable energy as possible.

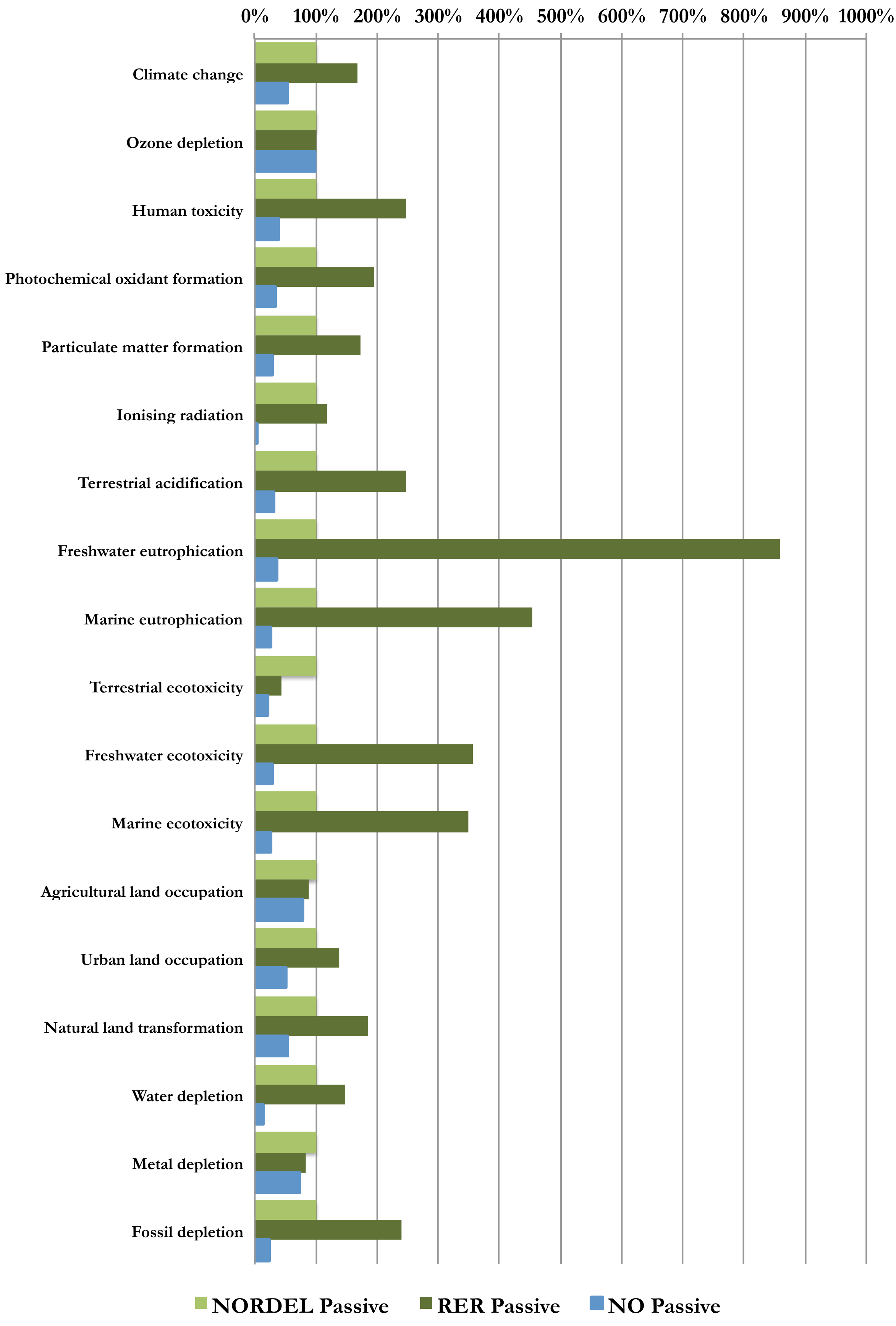


Figure 5.7: Different electricity mixes normalized to NORDEL

Using Only ecoinvent Processes

Currently EPDs in Norway are not integrated into SimaPro. As a result, the manual input of each EPD can possibly affect the output from SimaPro. To test this, nearly all products in the two models were inputted as ecoinvent processes. No similar processes were found for Iso3 studs, Windows with the correct U-value, or linoleum flooring, so the EPDs were used.

We see in Figure 5.8 the ecoinvent passive and TEK10 schools normalized to the original passive and TEK10 schools. The most dramatic differences occur in agricultural and urban land occupation as well as natural land transformation. The EPDs do not have information on these impacts, and thus a much better sense of the ecosystem damages occurring with the minerals, timber, and metal used in the school are available using ecoinvent processes. There is a large reduction in ozone depletion, 68% for the passive school and 72% for the TEK10 school. Since the EPDs had specific ODP impact included, the ecoinvent processes do not accurately reflect the actual impacts. The same can be said for the climate change impact, where ecoinvent processes resulted in a 13% in impacts for the passive schools and 11% for the TEK10 school. There is almost no difference (+/-2%) in the ecotoxicity categories, and the water and metal depletion.

There are advantages to using only ecoinvent processes. The ecoinvent database has detailed upstream processes, by-products, and wastes associated with a given construction product. The benefit of switching all products used in the building to ecoinvent is to increase the credibility and acceptance of the results since ecoinvent is used worldwide. However, many important products used in the school like flooring and passive standard windows are unavailable in the current ecoinvent database, so a trade-off must be made for every product modeled in the program.

In the interest of improving the application of LCA of schools in Norway, it can be concluded that is better to use Norwegian products rather than use ecoinvent processes. Another possibility is to change processes within ecoinvent to reflect Norwegian conditions so that a more robust supply chain is reflected in the LCA and there is less room for error. Bribián et al. [39] argues that it is important to extend and harmonize the existing inventory databases of construction materials to the characteristics of the construction industries in each country. Ultimately, as it is said by ecoinvent itself, their datasets are intended as background data for LCA studies where case-specific foreground data is supplied by the LCA practitioner.

Uncertainty

There are two types of uncertainty, the uncertainty of the data and of the methodology [58]. The data used in this study and the uncertainty associated with it will be discussed in this section.

The existence of uncertainties in input data and modeling is often mentioned as a crucial drawback to a clear interpretation of LCA results. In the models for Grefsen U3, assumptions were made in each component and this affects the accuracy of results. This was due to a lack of a bill of quantities that would specify how much material was used in the construction as well as given better detail for information like technical equipment, the heating and ventilation system, and tools and energy used in excavation and construction.

Building Envelope

Since no bill of quantities was available, the makeup of the building envelope was discerned from architectural and technical drawings. By manually calculating the amount of needed material smaller elements were most likely overlooked. For some elements of the building, like cladding and the heating system, substitutes for what may have actually been used in the building were found since information on them was unavailable. Accordingly there is is a fair amount of uncertainty about the completeness of the accounting of the building envelope.

Functional Unit

According to ISO 14044, systems should be compared using the same functional unit and equivalent methodological considerations, such as performance, system boundary, data quality, allocation procedures, decision rules on evaluating inputs, and outputs and impact assessment [26]. This study chose m^2 of useful floor area, but as Forsberg [27] points out it does not take into considering inner climate, even if IAQ is a difficult quality to measure quantitatively. As each study is a case-by-case analysis, uncertainty is brought in even when a certain functional unit is chosen.

Energy Mix

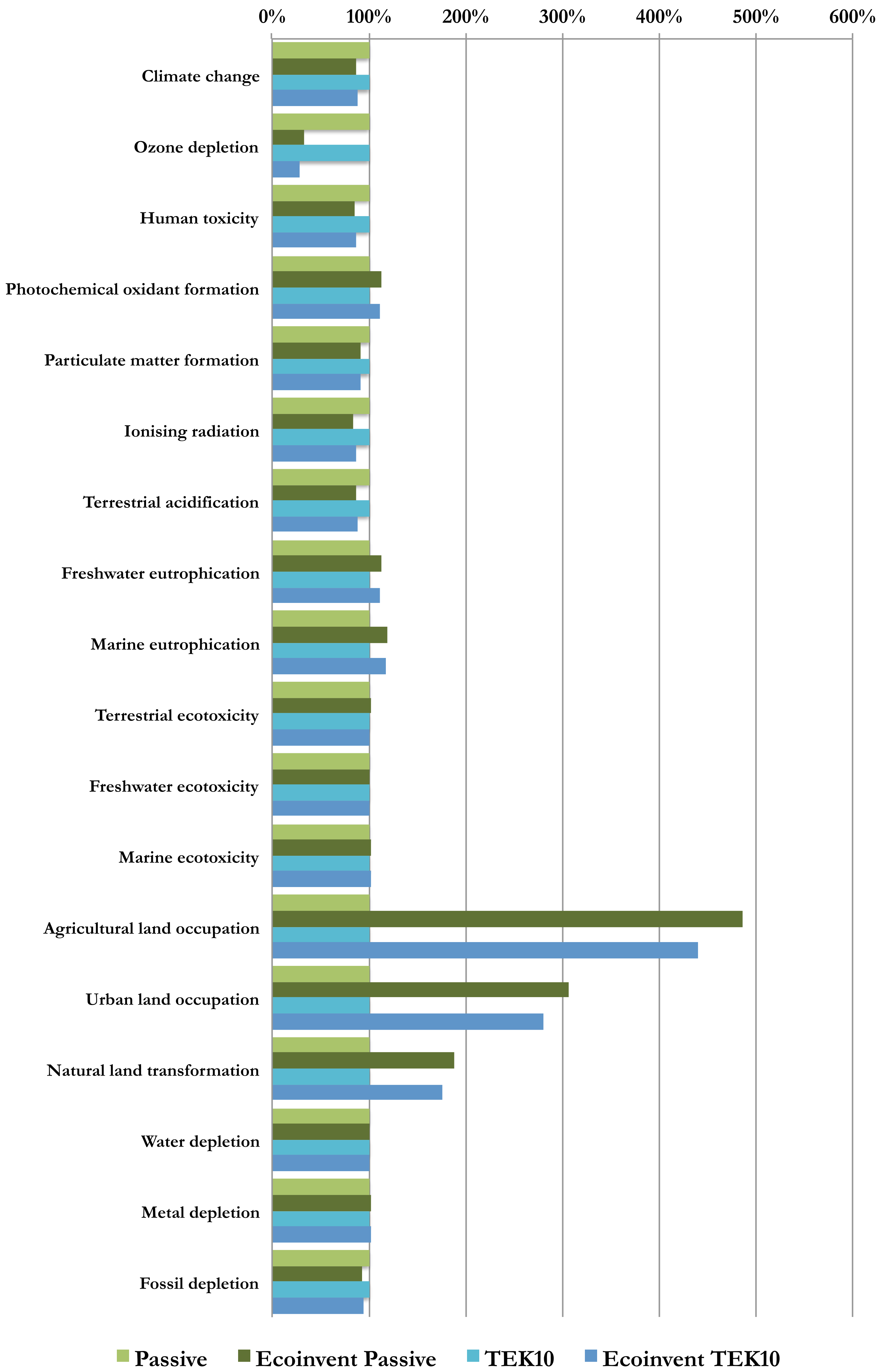
With information from technical drawings of the heating system (see Appendix 10.2, information from COWI to build the SIMIEN models, and many options for the electricity mixes in SimaPro, the energy system and operational energy in the building is fairly certain.

Transportation

Transport distances were estimated based on assumed production locations, the given locations in ecoinvent, or from information from the EPDs. Although uncertainty has been reduced by research on probable production locations, there is still significant uncertainty involved.

Comparison

Through research little information was available about previous LCA studies of schools in Norway. Relevants theses by other Industrial Ecology students were referenced [15,29,46] for framework and interpretation, but those studies focused respectively on a home, an apartment complex, and a much larger university hospital building. With different user needs, locations, and system boundaries, comparison to them is ill-advised.


0%
100%
200%
300%
400%
500%
600%
Climate change
Ozone depletion
Human toxicity
Photochemical oxidant formation
Particulate matter formation
Ionising radiation
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Agricultural land occupation
Urban land occupation
Natural land transformation
Water depletion
Metal depletion
Fossil depletion
Passive
Ecoinvent Passive
TEK10
Ecoinvent TEK10

Chapter 6

Interpretation

It is difficult and sometimes unfitting to compare LCA results to others as discussed in Section 2.2. However, trends can be identified overall in the building sector to further the use of LCA of non-residential buildings in Norway.

The heat energy requirement is calculated with SIMIEN and does not fully take into account the high uncertainty related to people's habits. Therefore it would be interesting after a few years to compare simulated data with field measurements [8]. This would involve expanding the current study to become a dynamic LCA (DLCA), which has recently been written about by Collinge [14] to evaluate tradeoffs of energy saving scenarios and indoor air quality.

Modeling within SimaPro presented many challenges. The software was not immediately understandable, and guidance from Hjellnes was required in order to build the model. When defining a product, the amount had to be one if it were to be counted higher up in the assembly, as shown in Figure 6.1.

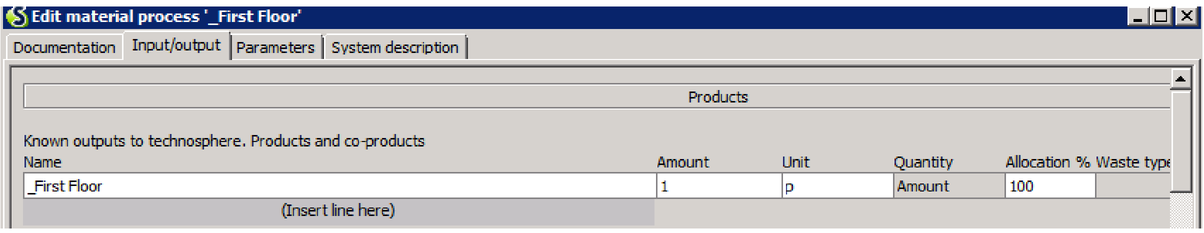


Figure 6.1: Input of a product or component into SimaPro

The program does not have processes that are in compliance with low energy and passive standards. Consequently components like windows must be researched and built manually within the system, and this case-by-case input makes comparisons difficult and increases the risk for calculation error. The processes available in ecoinvent did not always exactly reflect reality for building products. There are no processes that are similar enough to linoleum flooring and ceiling tiles, so these products must be built within SimaPro by hand and thus data from higher up the supply chain is not as accurate as ecoinvent processes. In SimaPro, if an input was to be changed, like changing from NORDEL to NO electricity mix, all products that used that input had to be manually changed. This tedious task allowed for human error if one product was passed over accidentally.

Without national statistics about the life cycle impacts of materials and energy use of schools, a robust comparison is not possible. However, it is recorded that the average school building built after 2000 uses 150 kWh/m^2/year in the operational phase [66]. Grefsen U3 built after the passive house standard uses 63% less energy at 56.6 kWh/m^2/year and the school built to TEK10 a 50% relative reduction at 76.3 kWh/m^2/year. The cumulative energy demand of the building is 27 GJ/m^2 - this is lower than Scheuer, where the university building required 316 GJ/m^2 [64].

As discussed in the literature review, TEK10 and NS 3701 are differentiated by the amount of insulation and precision needed in construction. Most of the components of the building were similar for the models. The largest differentiation came about through infiltration losses, the normalized thermal bridges in the buildings, and the U-values for windows and doors.

The Norwegian EPDs are inconsistent and they completeness of the data changes from manufacturer to manufacturer. Thus it was challenging to input the data manually into SimaPro. Although both systems (EPD and SimaPro) are maintained by a validation and review system, they are not yet integrated for the Norwegian context and there are no guidelines to how to apply EPDs to SimaPro individually. The next big industry trend should be the ability to upload product EPDS into any LCA software.

The simulation program SIMIEN provided a detailed analysis of the energy system. It took into account weather characteristics, orientation, the components in the building envelope and their U-values, infiltration, ventilation, hours of operation, and compared the simulated results against both NS 3031 and NS 3701 within the program. It would be ideal if SIMIEN could be integrated with SimaPro to better depict the carbon emissions associated with different electricity mixes, since in SIMIEN this is not adjustable.

Chapter 7

Limitations and Future Work

The limitations for this study were very similar to those faced in Grann [29]. Limitations included the uncertainty due to the lack of a bill of quantities, human error, manual calculation, and product supplier uncertainty. The composition of all components were assessed using architectural and technical drawings and literature search. Human error manifests through for example, manual calculation of material quantities and the hand-written explanation of building elements in the architectural drawing. For example, in one drawing the thickness of insulation was mislabeled. The material densities applied in this study have been taken from EPDs or generic sources and this adds uncertainty into the model. Transport distances were estimated since the actual supplier for various products was unknown. An inventory was compiled using EPDs and regional producers to the Oslo market. However, this is not necessarily correct because other factors like price, design, quality, or functionality could be a more important factor in choosing suppliers. With some products, like concrete, these factors are not as important, so this assumption varies across products [29].

The variation among EPDs in level of detail introduced uncertainty. The systems for describing products in governed by PCRs, but not all EPDs used in the building were alike. In Appendix 10.7 two current EPDs from different product categories are included for reference. The Gyproc Plasterboard EPD lists energy by primary, renewable, and non-renewable, while the Glava EPD provides better detail on its source, and thus better modeling of its impact in the Norwegian context. Breakdown of impacts during each phase of the Glava product allow for transparency and changes if needed.

There is the possibility of future work with this study both with the methodology and the scope of this subject. It would be interesting to pair this study with a life cycle costing (LCC) of the two buildings with the energy use and impacts results to see if the extra material and precision required for the passive school would mean higher costs over its lifetime. This assessment used a process-based accounting method for materials and energy. The input–output analysis method was not used, and a further study can make use of input-output analysis to identify if there were truncation errors and provide sensitivity analysis of the material energy intensity. Input-output analysis could also provide hotspots in construction, use, and disposal on the national level for school buildings and could be a tool in educational infrastructure planning.

The simulation program, SimaPro, is best suited for LCA of product systems. It was chosen in this study due to its availability, and a future study in which the example school is analyzed using the Level II or III programs as described in Section 2.2 would be useful. One of the biggest improvements this could have on the current study is the integration of the materials LCI and thermal performance of the school. This will be important for future school building designers who would be able to link LCA directly to an architectural drawing program.

In all, the results of this LCA provide a critical look at the common tools to perform environmental impact assessment in Norway. It contributes to investigating the life cycle impacts of educational services and can be used to correlate indoor air quality and building design.

Chapter 8

Conclusion

An ideal building would be inexpensive to build, last forever with modest maintenance, but return completely to the earth when abandoned [6]. This environmentally idealistic vision has not been achieved yet and work to map the environmental damages related to buildings must continue. In order to do that, LCA must be commonly recognized as the definitive method of determining the relative environmental merits of building designs.

This thesis contributes to the growing body of literature for LCA of public buildings in Norway. The cumulative energy consumption for the passive school is 27 GJ eq per m^2, and is 11% lower than the energy demand of the TEK10 school over the same lifetime. Put in another way, the lifecycle energy consumption of 150 $kWh/m^2/year$ over a 50 year lifetime, and was found to be in line with results for school buildings presented in the literature. The energy use from the operation phase of the building had the highest impacts for most of the indicators.

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Chapter 9

Glossary

Declared unit: Quantity of a building product for use as a reference unit in an EPD, based on LCA, for the expression of environmental information needed in information modules. Example: Mass (kg), Volume (m^3)

Demolition energy: Energy required at the end of the buildings" service life to demolish it and to transport the material to landfill sites and/or recycling plants.

Direct energy: Direct energy is consumed in various on-site and off-site operations like construction, prefabrication, transportation and administration.

Dynamic LCA (DLCA): An approach to LCA which explicitly incorporates dynamic process modeling in the context of temporal and spatial variations in the surrounding industrial and environmental systems.

Eco-material: An ecological building material/product is a material/product with no heavy negative environmental impact and with no negative health impact.

Embodied energy: Energy content of all the materials used in the building and technical installations, and energy incurred at the time of new construction and renovation of the building.

End-use energy: Energy measured at the final use level. Feedstock energy: Heat of combustion of raw material inputs, such as wood or plastics, to a system. Generally expressed as gross calorific value.

Function unit: Quantified performance of a product system for a building product for use as a reference unit in a LCA.

Indirect energy: Indirect energy is mostly used during the manufacturing of building materials, in the main process, upstream processes and downstream processes and during renovation, refurbishment, and demolition.

Indoor climate assessment (ICA): Addresses the indoor climate in non-industrial buildings with a focus on health effects on the building occupants.

Initial embodied energy: The sum of the energy embodied in all the material used in the construction phase, including technical installations.

International reference life cycle data system (ILCD): ILCD consists of the ILCD Handbook and the ILCD Data Network. It provides governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments.

Life cycle assessment (LCA): Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life cycle cost (LCC): The total discounted dollar cost of owning, operating, maintaining, and disposing of a building or a building system over a period of time.

Life cycle cost analysis (LCCA): An economic evaluation technique that determines the total cost of owning and operating a facility over a period of time.

Life cycle inventory (LCI): Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life cycle impact assessment (LCIA): Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life cycle interpretation: Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Low-energy building or simply low-energy: Refers to a building built according to special design criteria aimed at minimizing the building's operating energy.

Materials Emissions Assessment (MEA): Analysis of emissions that may affect human health (primarily VOCs) from building materials during the use phase.

Operating energy: Energy required for maintaining thermal comfort and day-to-day maintenance of a building. Energy for HVAC (heating, ventilation and air conditioning), domestic hot water, lighting, and for running appliances.

Passive house: A type of low-energy building; design is oriented to make maximum exploitation of passive technologies (eventually adopting also some active solar technology).

Primary energy: Energy measured at the natural resource level. It is the energy used to produce the end-use energy, including extraction, transformation and distribution losses.

Product category: Group of building products that can fulfill equivalent functions.

Recurring embodied energy: The sum of the energy embodied in the material used in the rehabilitation and maintenance phases.

Reference service life: Service life of a building product that is known or expected under particular set, i.e. a reference set, of in-use conditions and that may form the basis of estimating the service life under other in-use conditions. Applied in the functional unit.

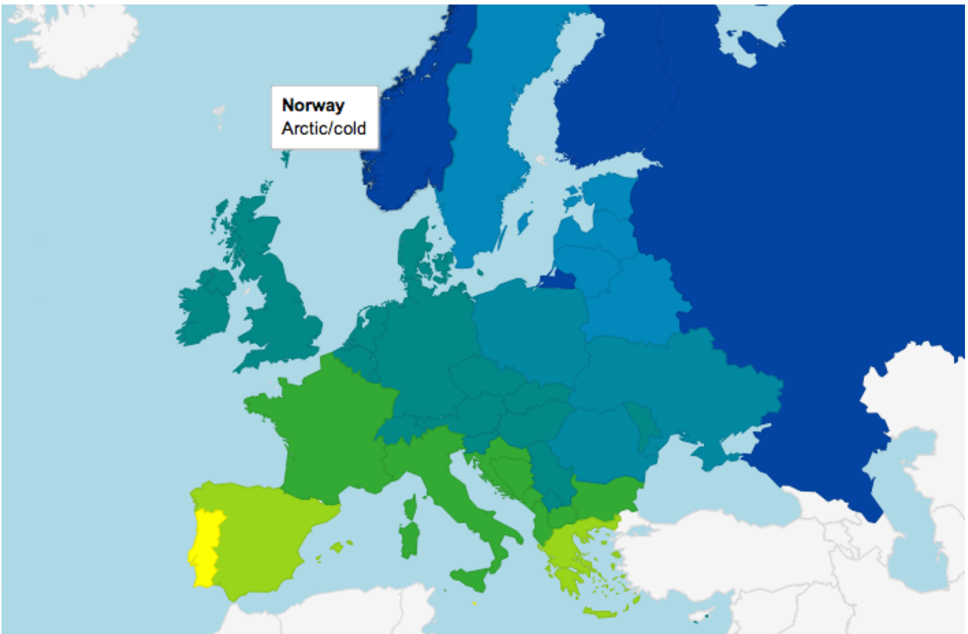
Total embodied energy: The sum of both initial and recurring embodied energies.

Total energy: The sum of all the energy used by a building during its life cycle (total embodied energy plus operating energy multiplied by lifetime).
[12, 14, 25, 42, 50, 63]

Chapter 10

Appendix

10.1 Passive House Weather Criteria



(a) Regional Context

Climate zone	Regions	Building envelope				Building services					Example buildigs
		Exterior wall insulation with λ value of ca. 0.035 W/(m·K)	Glazing	Window frame	Shading	Heating installation	Cooling strategy	Ventilation concept	Domestic hot water system	Renewables	
Arctic	Finnmark, Møre og Romsdal, Nordland, Nord-Trøndelag, Sør-Trøndelag, Troms, Murmansk Region, Norrbotten County	39 cm	Quadruple insulated glazing or double vacuum glazing	Highly insulated, narrow face width, phA class	Roof overhang, interior shading device	Supply air heating is possible	Night ventilation	With heat and humidity recovery, not direct electric frost protection	Boiler or compact unit (ventilation, dhw boiler, heating/cooling in one unit)	Photovoltaic solar panels as much as possible	
Cold	Akershus, Aust-Agder, Buskerud, Hedmark, Hordaland, Oppland, Oslo, Østfold, Rogaland, Sogn og Fjordane, Telemark, Vest-Agder, Vestfold	29 cm	High performance triple or quadruple insulated glazing	Highly insulated, narrow face width, phA class	Roof overhang, interior shading device	Supply air heating is possible	Night ventilation	With heat and humidity recovery, not direct electric frost protection	Boiler or compact unit (ventilation, dhw boiler, heating/cooling in one unit)	Photovoltaic solar panels as much as possible	Example project 1060

(b) Conditions in Norway

Figure 10.1: Climate Conditions for Passive House Standard in N

10.2 Heating System

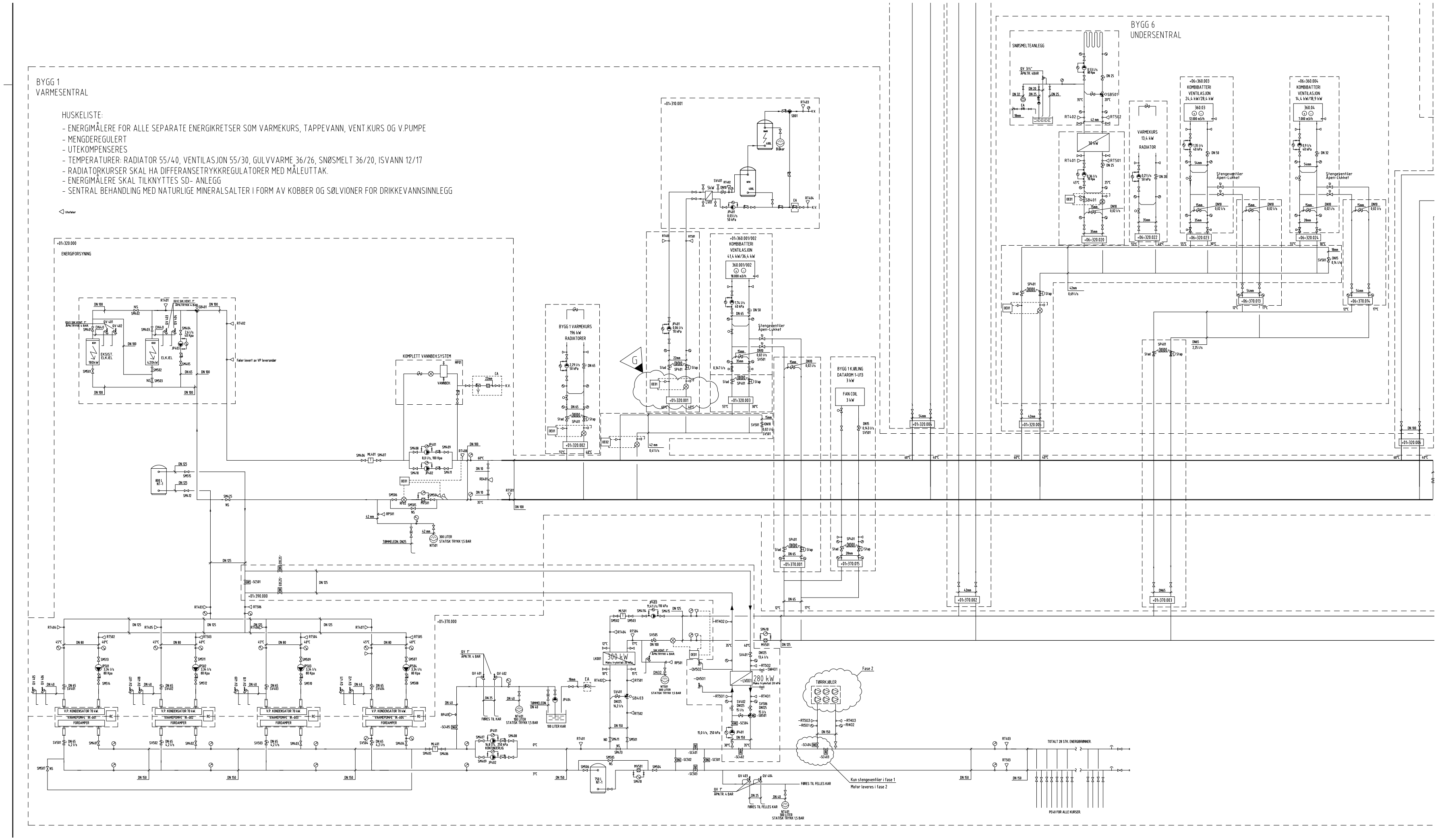


Figure 10.2: Heat Pumps for Building Complex (left) and heating system for Building (right)

10.3 Material Densities

Material	Unit	Weight	Source
Wood			
Plywood	kg/m^2	5.5	Norebo [1]
Gluelam Beams	kg/m^3	470	EPD Moelven
OSB Board	kg/m^3	620	Norebo
Ceiling tiles	kg/m^3	330	EPD Gyptone
Acoustic Barrier	kg/m^2	9	Rockwool [62]
Metals			
Steel handrails	kg/m	3.85	Steelway [68]
Steel Beams	kg/m	0.66	EPD Norgips
Metal Walkway	kg/m^2	8.9	Plannja [56]
Steel Steps	kg/m^2	42	Weland [78]
Minerals			
Concrete	kg/m^3	2400	Unicon [74]
Crushed Stone	kg/m^3	1300	Hamar Pukk og Grus [52]
Concrete Slabs/Screed/Påstøp	kg/m^3	1800	Flowcrete [23]
Fiber cement facing tile	kg/m^2	16	Norgips [49]
Other Materials			
Under Roofing/Wind Barrier	kg/m^2	10.2	EPD Hunton
Linoleum Flooring	kg/m^2	2.9	EPD ERFMI
Mineral Wool	kg/m^3	16.5	EPD Glava
Moisture Barrier	kg/m^2	0.5	EPD Icopal
Insulation	kg/m^3	29	EPD Rockwool
Top Roofing	kg/m^2	4.7	EPD Isola

10.4 Transportation Distances

Material	Supplier	Producer Location	Value (in km)	Mode	Source
Concrete	Unicon	Sjursøya	11	Lorry	EPD
Leca Blocks	Weber	Oslo	6	Lorry	Assumed
Ceiling Tiles	Gyptone	Askim	61	Lorry	EPD
Fireboard 15mm	Gyproc	Fredrikstad	100	Lorry	EPD
Plasterboard 12.5mm	Gyproc				
Sheathing Board 9.5mm	Gyproc				
Insulation	Rockwool	Moss	65	Lorry	EPD
Heat Pump	SGP	Olso	19.1	Lorry	Assumed
Iso3 Board	Moelven	Oslo	6	Lorry	Assumed
Standard Gluelam Beam	Moelven				
Linoleum Flooring	ERFMI				
Mineral Wool	Glava	Askim	61	Lorry	EPD
Moisture Barrier	Icopal	Oslo	17	Lorry	Website [38]
Hard Plasterboard 13mm	Norgips	Sävsjö, Sweden	465	Lorry	EPD
Plasterboard 13mm	Norgips				
Steel Beam	Norgips				
Steel Steps/Railing	Plannja	Frogner	26	Lorry	Assumed
Plywood	Treindustrien	Oslo	11.6	Lorry	The Sawmill Database [16]
Planed Structural Timber	Treindustrien				
Roofing	Isola	Porsgrunn	161	Lorry	EPD
Roofing/Wind Barrier	Hunton	Gjøvik	136	Lorry	EPD
Windows	Nordan	Moi	454	Lorry	Dahlstrøm [15]
Glass Facade	Sto	Linköping, Sweden	438	Lorry	Email [55]

10.5 SIMIEN Models

SIMIEN

Resultater årssimulering

Simuleringsnavn: ÅrssimuleringGrefsenPassive
Tid/dato simulering: 13:12 3/6-2014
Programversjon: 5.014
Brukernavn: Student
Firma: Undervisningslisens
Inndatafil: C:\Users\jenskrho\Downloads\Grefsen - Nybygg - Passive.smi
Prosjekt: Grefsen nybygg
Sone: Grefsen

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	7275 kWh	14,7 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	2342 kWh	4,7 kWh/m²
2 Varmtvann (tappevann)	4979 kWh	10,1 kWh/m²
3a Vifter	2201 kWh	4,5 kWh/m²
3b Pumper	741 kWh	1,5 kWh/m²
4 Belysning	5240 kWh	10,6 kWh/m²
5 Teknisk utstyr	3494 kWh	7,1 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	1679 kWh	3,4 kWh/m²
Totalt netto energibehov, sum 1-6	27952 kWh	56,6 kWh/m²

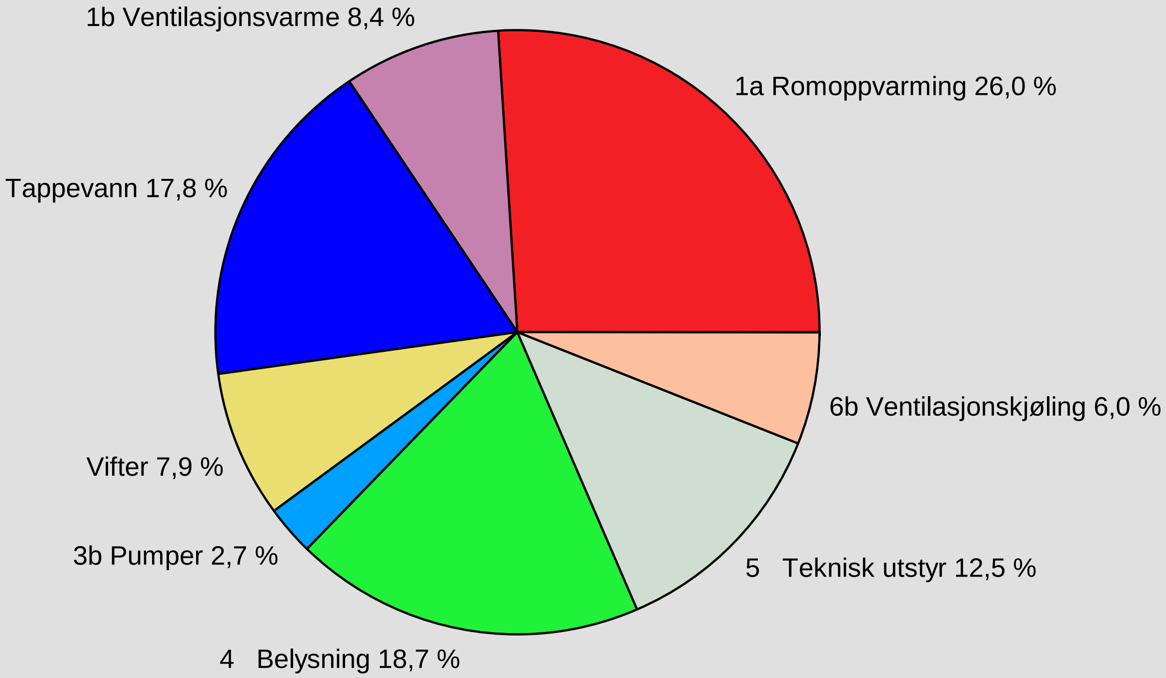
Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	17738 kWh	35,9 kWh/m²
1b El. Varmepumpe	3830 kWh	7,8 kWh/m²
1c El. solenergi	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
Annen energikilde	84 kWh	0,2 kWh/m²
Totalt levert energi, sum 1-6	21652 kWh	43,8 kWh/m²

SIMIEN

Resultater årssimulering

Simuleringsnavn: ÅrssimuleringGrefsenPassive
Tid/dato simulering: 13:12 3/6-2014
Programversjon: 5.014
Brukernavn: Student
Firma: Undervisningslisens
Inndatafil: C:\Users\jenskrho\Downloads\Grefsen - Nybygg - Passive.smi
Prosjekt: Grefsen nybygg
Sone: Grefsen

Årlig energibudsjett

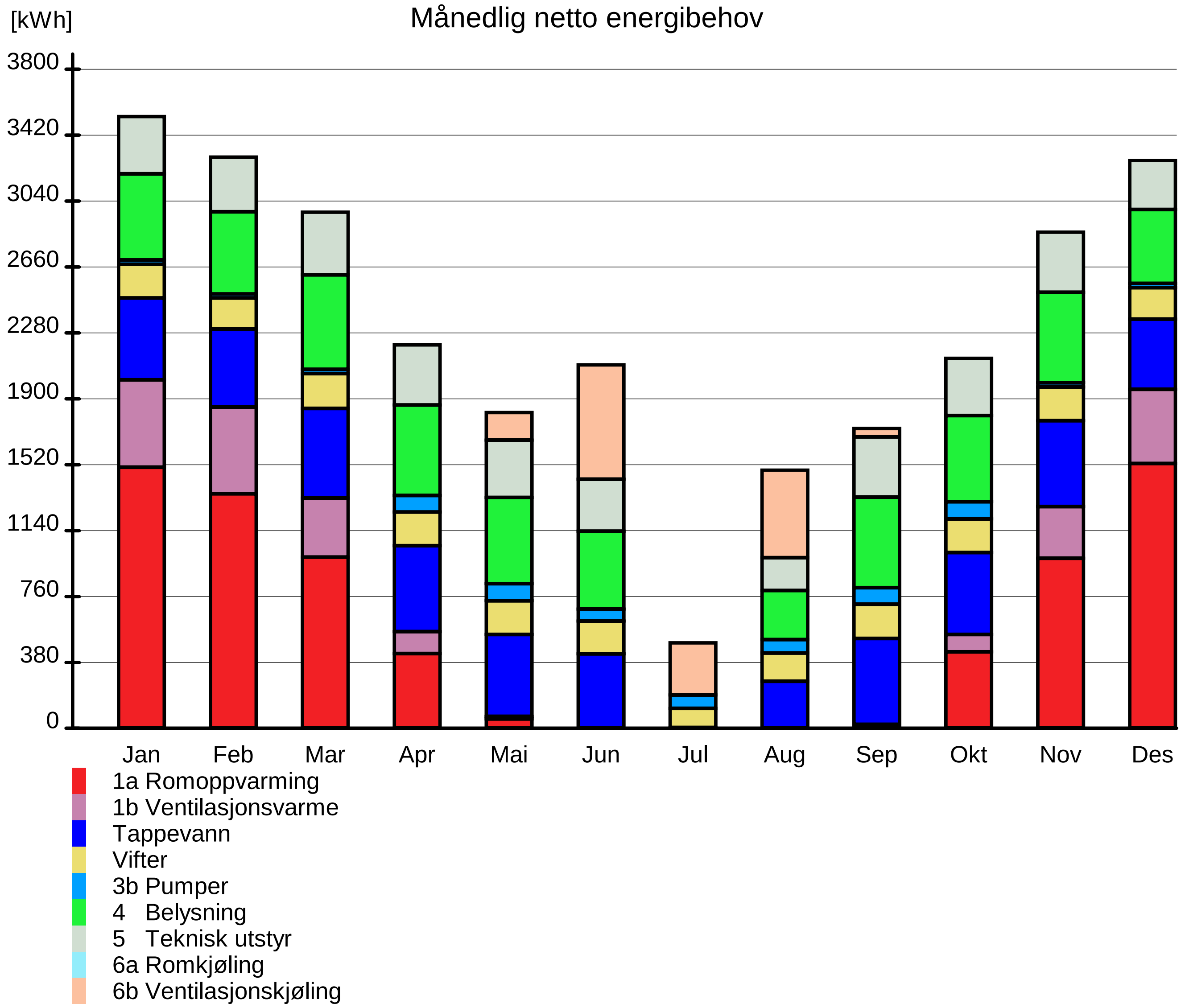


1a Romoppvarming	7275 kWh
1b Ventilasjonsvarme (varmebatterier)	2342 kWh
2 Varmtvann (tappevann)	4979 kWh
3a Vifter	2201 kWh
3b Pumper	741 kWh
4 Belysning	5240 kWh
5 Teknisk utstyr	3494 kWh
6a Romkjøling	0 kWh
6b Ventilasjonskjøling (kjølebatterier)	1679 kWh
Totalt netto energibehov, sum 1-6	27952 kWh

SIMIEN

Resultater årssimulering

Simuleringsnavn: ÅrssimuleringGrefsenPassive
Tid/dato simulering: 13:12 3/6-2014
Programversjon: 5.014
Brukernavn: Student
Firma: Undervisningslisens
Inndatafil: C:\Users\jenskrho\Downloads\Grefsen - Nybygg - Passive.smi
Prosjekt: Grefsen nybygg
Sone: Grefsen



SIMIEN

Resultater årssimulering

Simuleringsnavn: ÅrssimuleringGrefsenTEK10
Tid/dato simulering: 18:38 30/5-2014
Programversjon: 5.014
Brukernavn: Student
Firma: Undervisningslisens
Inndatafil: C:\Users\jenskrho\Downloads\Grefsen - Nybygg -TEK10.smi
Prosjekt: Stasjonsfjellet nybygg
Sone: Grefsen

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	16615 kWh	33,6 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	2603 kWh	5,3 kWh/m²
2 Varmtvann (tappevann)	4979 kWh	10,1 kWh/m²
3a Vifter	2197 kWh	4,4 kWh/m²
3b Pumper	886 kWh	1,8 kWh/m²
4 Belysning	5240 kWh	10,6 kWh/m²
5 Teknisk utstyr	3494 kWh	7,1 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	1675 kWh	3,4 kWh/m²
Totalt netto energibehov, sum 1-6	37689 kWh	76,3 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	18858 kWh	38,2 kWh/m²
1b El. Varmepumpe	7653 kWh	15,5 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
Annen energikilde	84 kWh	0,2 kWh/m²
Totalt levert energi, sum 1-6	26595 kWh	53,8 kWh/m²

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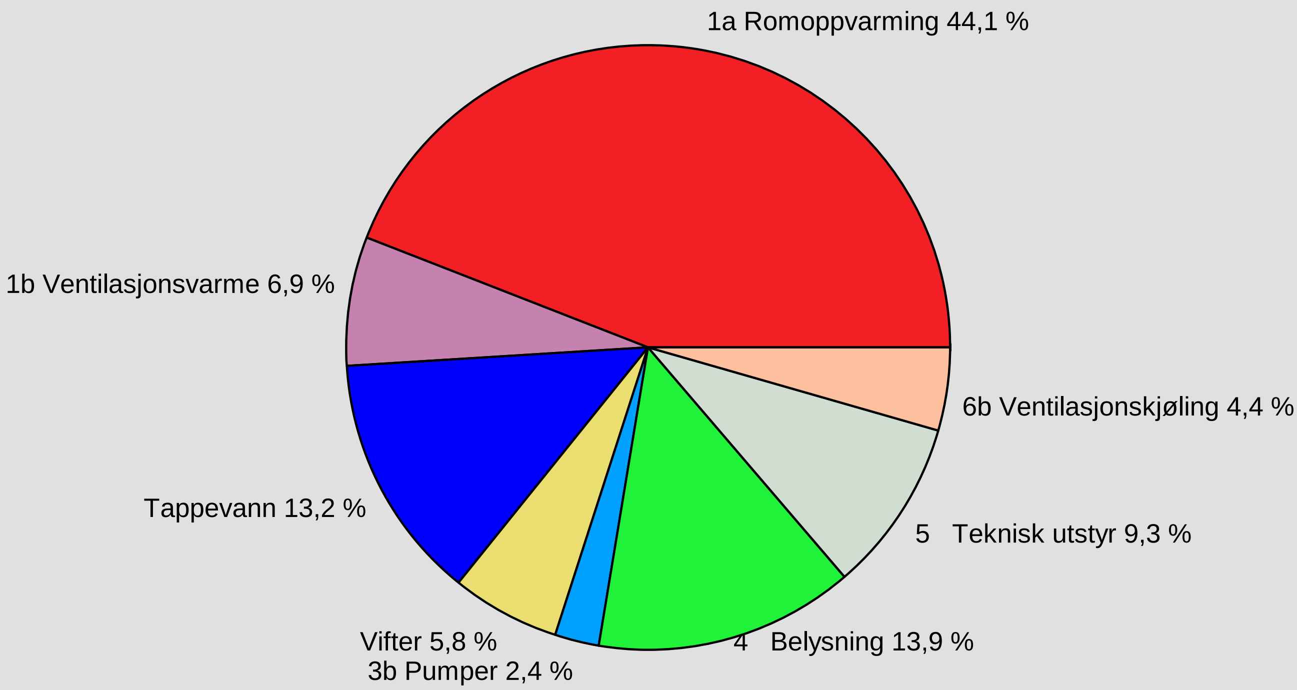
Inndatafil: C:\Users\jenskrho\Downloads\Grefsen - Nybygg -TEK10.smi
Prosjekt: Stasjonsfjellet nybygg
Sone: Grefsen

Årlig energibudsjett



1a Romoppvarming	16615 kWh
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2 Varmtvann (tappevann)	4979 kWh
3a Vifter	2197 kWh
3b Pumper	886 kWh
4 Belysning	5240 kWh
5 Teknisk utstyr	3494 kWh
6a Romkjøling	0 kWh
6b Ventilasjonskjøling (kjølebatterier)	1675 kWh
Totalt netto energibehov, sum 1-6	37689 kWh

SIMIEN

Resultater årssimulering

Simuleringsnavn: ÅrssimuleringGrefsenTEK10
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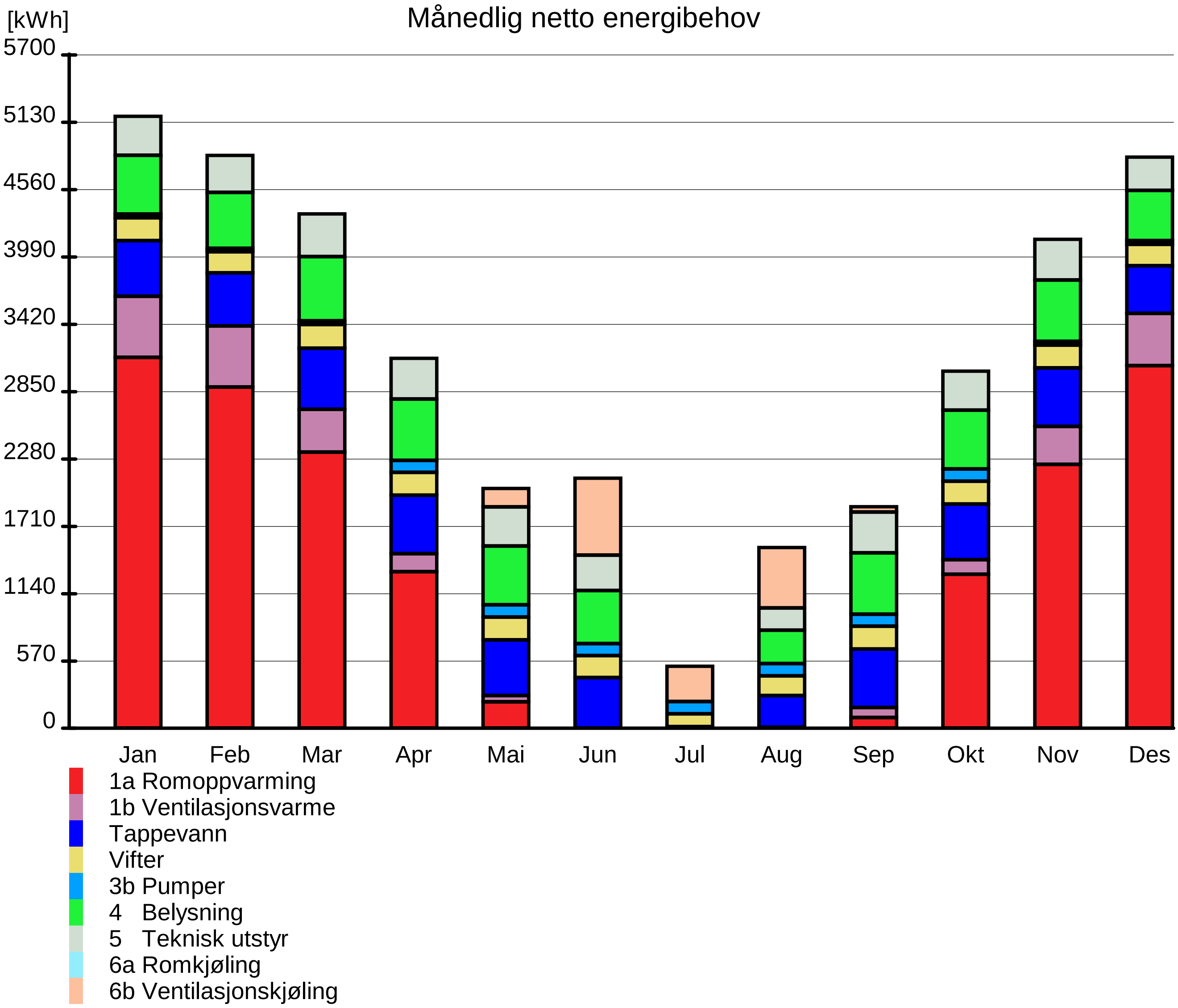
Prosjekt: Stasjonsfjellet nybygg
Sone: Grefsen



10.6 Relative Construction Impacts

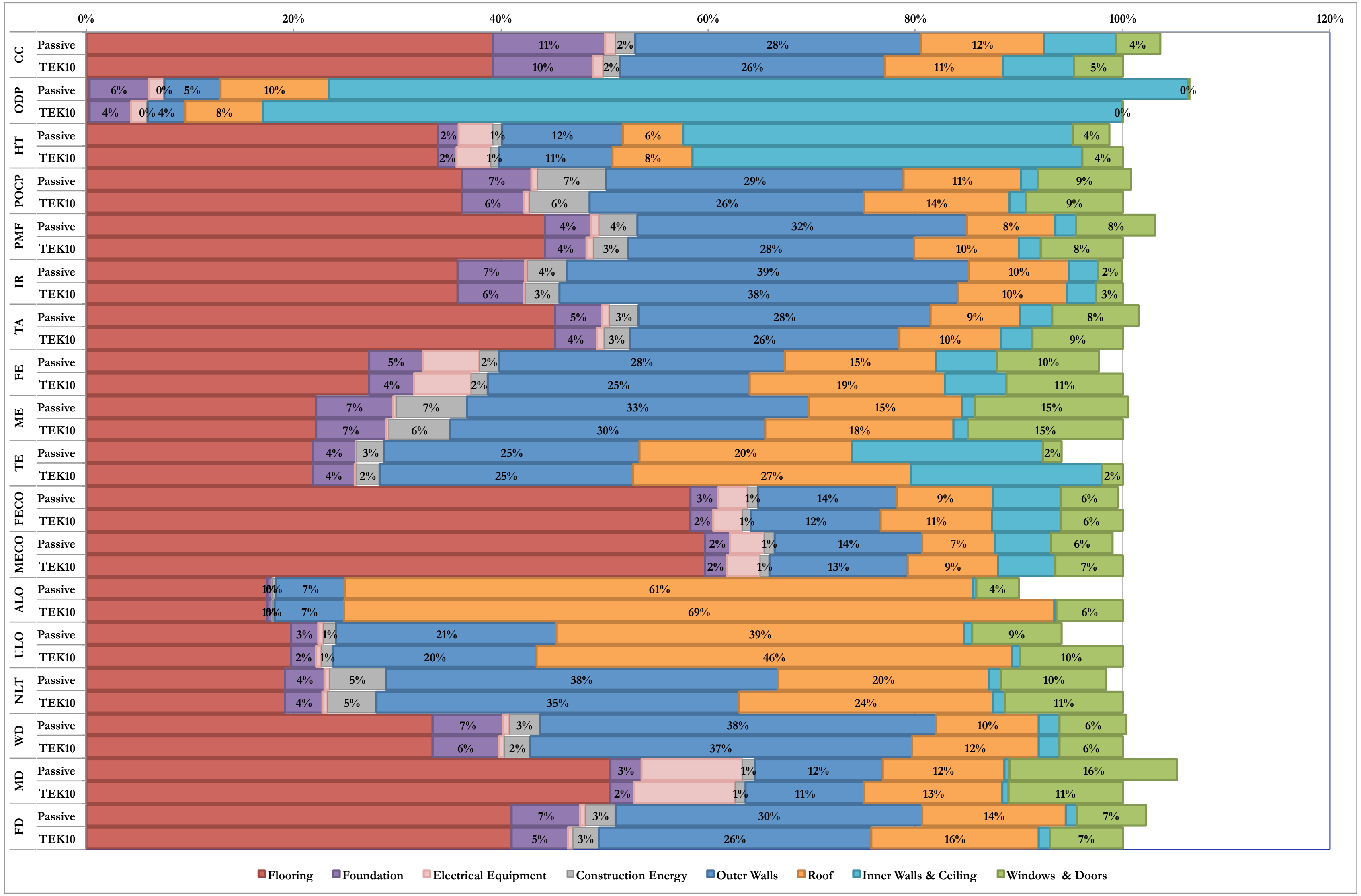


Figure 10.3: Construction impacts of the passive school relative to the TEK10 impact

10.7 Examples of EPDs

Gyproc SAINT-GOBAIN

Gyproc Plasterboard 12,5 mm, GN13

NEPD NO: 223E

Approved according to ISO14025, §8.1.4: 11.11.2011
Valid until: 11.11.2016

Sverre Fossdal

Verification of data:
Independent verification of data and other environmental information has been carried out by Senior Research Scientist Anne Rønning in accordance with ISO14025, §8.1.3

Anne Rønning

Declaration compiled by:
Vikki Holme and Jon Gjerlow

PCR:
NPCR010 Building boards

About EPD:
EPDs from program operators other than the Norwegian EPD Foundation may not be comparable

A critical review has been carried out by Michaël Medard (Saint-Gobain) in accordance with ISO 14044 clause 6

Manufacturer:
Gyproc AS
Habornveien 59, 1630 Gamle Fredrikstad, Norway
Organisation no. NO 951699403
ISO 14001: NS-EN-ISO 14001:2004 Certificate 008
EMAS: EMAS Registered
Place of manufacture: Fredrikstad, Norway
Market area: Norway

Contact person: Jon A. Gjerløw
Telephone: +69357500
Fax: +4769357501
e-mail: jon.gjerlow@saint-gobain.com

Product information:

Scope:	Cradle to grave
Year of study:	2010
Expected service life of building:	60 years
Service life of product:	60 years
Thickness:	12,5 mm
Functional unit (FU):	m^2 installed plasterboard with expected service life of 60 years

Product description:
Gyproc plasterboards consist of an aerated gypsum core encased in, and firmly bonded to, strong paper liners. The Gyproc GN 13 Normal plasterboard contains a glass-fibre reinforced core with added dimension stabilizing minerals. Gyproc GN 13 Normal is used as cladding for internal walls and ceilings, and can be used in all types of buildings. Suitable for most applications where normal fire, structural and acoustic levels are specified. The plasterboards have tapered long edges and short edges sawn straight.

Product specification:

Material	Part %	Quantity (kg/FU)
Gypsum	95.2	8.57
Paper liner	3.9	0.35
Additives	0.9	0.08
SUM	100	9

Environmental Indicators:

Climate Change – Global Warming	2,66	kg CO2 equiv.
Energy use	45,7	MJ
Recycled materials	33	%
Indoor air classification (Classification according to EN 15251:2007)	M1	

2 Representative environmental impacts of plasterboard GN13 in relation with NPCR 010

All these impacts are reported or calculated in accordance with NPCR 010 §8.2 and § 9.4 of the Saint-Gobain PCR and the data below are derived from the process of life cycle analysis. The units of reference are defined by NPCR 010 §5.1 and the totals per functional unit (FU) are related to the Typical Life Time (TLT) of the product i.e. 60 years.

N^o	Flow	Units	Production	Transport	Implementation	Utilisation	End of life	Total per FU
1	Consumption of energy resources:							
	Total primary energy	MJ	41.57	2.14	1.79	0.00	0.2138	45.7
	Renewable energy	MJ	4.38	0.0050	0.3694	0.00	0.0006	4.75
	Non-renewable energy	MJ	37.20	2.13	1.42	0.00	0.2132	41.0
2	Resource depletion (ADP)	kg antimony equivalent (Sb)	0.0160	0.0010	0.0005	0.00	0.0001	0.0177
3	Water consumption	Litre	9.52	0.1665	0.7804	0.00	0.0202	10.5
4	Solid waste:							
	Recovered waste (total)	kg	0.0549	4.730E-07	0.0265	0.00	5.790E-08	0.081
	Eliminated waste:							
	Dangerous waste	kg	0.0440	4.171E-05	0.0005	0.00	5.103E-06	0.0446
	Non dangerous waste	kg	0.0304	4.050E-05	0.4931	0.00	9.00	9.5
	Inert waste	kg	1.4321	7.067E-05	0.0419	0.00	8.641E-06	1.474
	Radioactive waste	kg	2.277E-05	2.795E-05	5.595E-06	0.00	3.421E-06	0.000060
5	Climate change	kg CO_2 equivalent	2.39	0.17	0.08	0.00	0.02	2.66
6	Atmospheric acidification	kg SO_2 equivalent	0.0112	0.0016	0.0003	0.00	0.0001	0.0133
7	Air pollution	m^3	130.69	16.80	6.30	0.00	1.74	156
8	Water pollution	m^3	1.06	0.1832	0.4947	0.00	0.6717	2.41
9	Destruction of stratospheric ozone layer	N/A	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]
10	Formation of photochemical ozone	kg ethylene equivalent	0.0009	0.0002	4.182E-05	0.00	2.232E-05	0.00120
Another indicator (non-standard NF P01-010)								
11	Eutrophication	g PO_4^{3-} equivalent	0.98	0.0021	0.0430	0.00	0.5874	1.61016

Electricity model: Production of electricity in Norway (2004), predefined in TEAM (CO_2 factor: 1.03954 g/MJ).

See "Guide to Reading" Note 1

Environmental Product Declaration ISO 14025

epd-norge.no The Norwegian EPD Foundation

Glava glass wool

NEPD nr.: 221E ver 2

Approved according to ISO 14025:2006, 8.1.4
Approved: 11.01.2013
Valid until: 11.01.2018

Verification leader:
Sverre Fossdal

Verification Internal External X

Independent verification of data has been carried out by Marte Renaas, Rambøll in accordance with EN ISO 14025:2010, 8.1.3

Marte Reenaas

The declaration has been prepared by
Thale Plesser, SINTEF Building and Infrastructure

Thale Plesser

Manufacturer
Glava AS, www.glava.no
Addr.: Nybråtveien 2, 1801 Askim, Norway
Phone: +47 69 81 84 00 E-mail: post@glava.no
Org.nr.: NO-912 008 754
ISO 14001-certified: Yes
Contact person: John A. Bakke, +47 951 47 820

About EPD
EPD from other program operators than the Norwegian EPD Foundation may not be comparable.

PCR
PCR for insulation material, NPCR 012:2012

Environmental indicato	*Cradle to gate*		*Cradle to grave*	
Global warming	0,74	kg CO_2-eq./DU	0,76	kg CO_2-eq./FU
Energy consumption	18,9	MJ/DU	19,5	MJ/FU
Amount of renew. energy	24,3	%	23,6	%
Indoor air	TVOC < 0,8 µg/(m^2 h)			
Chemicals	The finsihed product contains no chemicals on the REACH candidate list or the Norwegian priority list.			

Scope and expected marked area

Declared unit (DU): 1m^2 glass wool insulation insulation material with a thickness that gives a declared thermal resistance of R = 1 m^2 K/W. This is achieved by using a product with a thickness of 35 mm, a λ_D of 0,0035 W/mK and a density of 16,5 kg/m^3.

Expected service life: Set equal to the reference service life of the building, i.e. 60 years. The service life of the product is >> 60 years.

Scope: The declaration is cradle to grave.

Year of study: 2012.

Year of data: Production and emission data for Glava AS at Askim in 2011.

Expected market area: Norway.

Product description

The insulation is mainly manufactured from recycled glass (75%). The product is used to insulate against cold, heat, fire and sound. They can be used in buildings, industrial installations, road, rail and marine constructions. The glass wool is elastic and can be compressed to 1/5 of the volume in use.

Product specification

Composition of the final product Table 1

Material	Part [weight]	Per DU
Silicate glass	95,0 %	0,589 kg
Hardened, urea modified phenol formaldehyde resin	4,4 %	0,027 kg
Dust binding oil	0,6 %	0,004 kg
SUM	100 %	0,62 kg

Energy and resources

Primary energy

Table 3. Energy consumption specified for the different energy carrier and life cycle stages

	Unit	Raw materials A1	Transport A2	Production A3	Total A1-A3	Transport A4	Installation A5	Total A4-A5
Non-renewable primary energy								
Fossil	MJ	5,11	0,526	3,73	9,37	0,328	0	0,328
Nuclear	MJ	0,568	0,032	4,35	4,95	1,90E-02	0	1,90E-02
Non-renewable, biomass	MJ	2,87E-06	1,48E-06	4,21E-06	0,00	9,80E-07	0	9,80E-07
Renewable primary energy								
Renewable, biomass	MJ	0,037	1,04E-03	1,96	2,00	6,07E-04	0	6,07E-04
Wind, solar, geothermal	MJ	0,010	3,04E-04	0,106	0,12	1,51E-04	0	1,51E-04
Water	MJ	0,084	5,46E-03	2,40	2,49	3,39E-03	0	3,39E-03

CO_2 factor for the production in Norway is 189 g CO_2 equivalents per kWh (NORDEL for 2007)

Table 4. Energy consumption specified for the different energy carrier and life cycle stages

	Unit	Use stage B1-B7	Demolition C1	Transport C2	Waste processing C3	Disposal C4	C1-C4
Non-renewable primary energy							
Fossil	MJ	0	0	0,041	0	0,190	0,231
Nuclear	MJ	0	0	2,36E-03	0	7,02E-03	9,38E-03
Non-renewable, biomass	MJ	0	0	1,22E-07	0	3,09E-07	4,31E-07
Renewable primary energy							
Renewable, biomass	MJ	0	0	7,59E-05	0	2,42E-04	3,18E-04
Wind, solar, geothermal	MJ	0	0	1,89E-05	0	5,86E-05	7,75E-05
Water	MJ	0	0	4,24E-04	0	1,16E-03	1,58E-03

Table 5. Energy used as raw materials. Product stage and construction process stage.

Parameter	Unit	Raw materials A1	Transport A2	Production A3	Total A1-A3	Transport A4	Installation A5	Total A4-A5
Use of renewable primary energy excluding renewable primary energy resources used as raw materials	MJ	0,100	5,93E-03	3,24	3,35	3,92E-03	0	3,92E-03
Use of renewable primary energy resources used as raw materials	MJ	0,031	8,76E-04	1,23	1,26	2,28E-04	0	2,28E-04
Total use of renewable primary energy resources	MJ	0,131	6,80E-03	4,47	4,61	4,15E-03	0	4,15E-03
Use of non renewable primary energy excluding non renewable primary energy resources used as raw materials*	MJ	Not calculated	Not calculated	Not calculated	Not calculated	Not calculated	Not calculated	Not calculated
Use of non renewable primary energy resources used as raw materials*	MJ	Not calculated	Not calculated	Not calculated	Not calculated	Not calculated	Not calculated	Not calculated
Total use of non-renewable primary energy resources	MJ	5,68	0,558	8,08	14,32	0,347	0	3,47E-01

*non renewable primary energy used as raw material is not calculated because it cannot be separated from non renewable primary energy used as energy.

Emissions and environmental impacts

Table 9. Environmental impacts.

Indicator	Unit	Raw materials A1	Transport A2	Production A3	Total A1-A3	Transport A4	Installation A5	Total A4-A5
Global warming potential	kg CO_2 eq.	0,236	0,034	0,467	0,737	0,021	0	0,021
Ozone layer depletion potential	kg CFC-11 eq.	2,01E-08	7,05E-06	1,52E-08	7,09E-06	3,35E-09	0	3,35E-09
Acidification potential for soil and water	kg SO_2 eq.	7,49E-04	2,24E-04	2,97E-03	3,94E-03	1,03E-04	0	1,03E-04
Eutrophication potential	kg $(PO_4)^{3-}$ eq.	3,84E-04	4,70E-05	8,04E-04	1,24E-03	2,68E-05	0	2,68E-05
Photochemical ozone creation potential	kg C_2H_4 eq.	8,13E-05	7,05E-06	1,05E-04	1,93E-04	3,22E-06	0	3,22E-06
Abiotic depletion potential for non fossil resources	kg Sb eq.	9,12E-05	1,47E-07	1,73E-06	9,31E-05	1,00E-07	0	1,00E-07
Abiotic depletion potential for fossil resources	MJ	5,11	0,526	3,73	9,37	0,328	0	0,328

Table 10. Environmental impacts.

Indicator	Unit	Use stage B1-B7	Demolition C1	Transport C2	Waste processing C3	Disposal C4	Total C1-C4
Global warming potential	kg CO_2 eq.	0	0	2,67E-03	0	4,10E-03	6,77E-03
Ozone layer depletion potential	kg CFC-11 eq.	0	0	4,18E-10	0	1,23E-09	1,65E-09
Acidification potential for soil and water	kg SO_2 eq.	0	0	1,29E-05	0	2,44E-05	3,73E-05
Eutrophication potential	kg $(PO_4)^{3-}$ eq.	0	0	3,35E-06	0	5,95E-06	9,30E-06
Photochemical ozone creation potential	kg C_2H_4 eq.	0	0	4,03E-07	0	8,46E-09	4,11E-07
Abiotic depletion potential for non fossil resources	kg Sb eq.	0	0	1,25E-08	0	2,11E-06	2,12E-06
Abiotic depletion potential for fossil resources	MJ eq.	0	0	0,041	0	0,110	0,151

Output flows and waste

Table 11. Output flows through the life cycle

Parameter	Unit	Raw materials A1	Transport A2	Production A3	Total A1-A3	Transport A4	Installation A5	Total A4-A5
Hazardous waste disposed	kg	8,29E-06	0	3,69E-07	8,66E-06	0	0	0
Non hazardous waste disposed	kg	1,74E-02	0	3,02E-05	1,74E-02	0	0	0
Radioactive waste disposed	kg	0	0	0	0	0	0	0

Table 12. Output flows through the life cycle

Parameter	Unit	Use stage B1-B7	Demolition C1	Transport C2	Waste processing C3	Disposal C4	Total C1-C4
Hazardous waste disposed	kg	0	0	0	0	0	0
Non hazardous waste disposed	kg	0	0	0	0	0,578	0,587
Radioactive waste disposed	kg	0	0	0	0	0	0