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Abstract:
The study was part of an ongoing research project “ZEB Shoebox modeling and development of a CO_2 accounting method” being conducted in the ZEB centre whose objective is to investigate the impact on emissions of different envelope and energy supply system combinations for a simple office building. The focus of the thesis was on the GHGs emissions related to operational and embodied energy of the ZEB Shoebox Office model, using the Norwegian online programme called Klimagassregnskap. Designing a ZEB Shoebox model with reduced energy demand was the initial step for developing the reference building. Starting from this reference case, two scenarios were defined focusing on the operational and embodied energy, respectively. In the first scenario the emissions from different renewable energy supply options were calculated with different methods (Klimagassregnskap among the others) while in the second, the embodied emission accounting for various structural solutions was performed using Klimagassregnskap. The results of the first scenario indicated that the energy generation on the building footprint (solar thermal and PV) is the optimal energy supply in terms of GHGs emissions and delivered energy. While the findings of the second scenario showed that the service life of the materials in the envelope and internal partitions has a higher impact on the embodied emission than the choice of structural materials. Moreover, the results showed that Klimagassregnskap suffers from a lack of transparency in emissions calculation and in the inputs used for defining the emission factors. Therefore further improvements are needed for a more accurate assessment of the future ZEB buildings environmental impact.

Keywords:

1. Zero Emission Building (ZEB)
2. Operational energy
3. Embodied carbon
4. Klimagassregnskap

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Emissions accounting for ZEB shoebox office model:

Strategies for optimizing the operational energy supply

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Strategies for reducing the embodied carbon from a life cycle perspective

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Master thesis

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The strength is in unity

Preface

The report represents a joint Master Thesis, conducted the last semester in the MSc Sustainable Architecture programme, class of 2012. The work has been carried out at the Faculty of Architecture and Fine Arts at the Norwegian University of Science and Technology, NTNU, in Trondheim, Norway.

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Abstract

Buildings consume approximately 40% of the world's primary energy use and contribute up to 24% of global green house gas emissions. An energy consuming as well as producing building, denoted as zero energy and zero emission building (ZEB), can be seen as a solution in respect to energy efficiency and environmental impact. However, a clear and agreed definition of Zero Emission Building is yet to be achieved, both internationally and in Norway. Nevertheless, national research programmes, such as Centre on Zero Emission Building (ZEB), started to focus on investigating and developing the ZEB concept.

The study was part of an ongoing research project "ZEB Shoebox modeling and development of a CO_2 accounting method" being conducted in the ZEB centre whose objective is to investigate the impact on emissions of different envelope and energy supply system combinations for a simple office building. The focus of the thesis was on the GHGs emissions related to operational and embodied energy of the ZEB Shoebox Office model, using the Norwegian online programme called Klimagassregnskap.

Designing a ZEB Shoebox model with reduced energy demand was the initial step for developing the reference building. Starting from this reference case, two scenarios were defined focusing on the operational and embodied energy, respectively. In the first scenario the emissions from different renewable energy supply options were calculated with different methods (Klimagassregnskap among the others) while in the second, the embodied emission accounting for various structural solutions was performed using Klimagassregnskap. The results of the first scenario indicated that the energy generation on the building footprint (solar thermal and PV) is the optimal energy supply in terms of GHGs emissions and delivered energy. While the findings of the second scenario showed that the service life of the materials in the envelope and internal partitions has a higher impact on the embodied emission than the choice of structural materials. Moreover, the results showed that Klimagassregnskap suffers from a lack of transparency in emissions calculation and in the inputs used for defining the emission factors. Therefore further improvements are needed for a more accurate assessment of the future ZEB buildings environmental impact.

Table of contents

Abbreviations and acronyms

CHP Combined heat and power

COP Coefficient of performance

HVAC Heating, ventilation and air conditioning

DHW Domestic hot water

NEPD Credible, standardized and internationally valid Norwegian Environmental Product Declarations for products and services

PHPP The Passive House Planning Package is a spreadsheet tool for designing Passive Houses, includes calculation of energy balance and U values, designing windows, ventilation system, estimating heating demand and designing heating and DHW supply.

PV Photovoltaic system

Glossary

Base case: ZEB Shoebox model built after TEK10 standards.

Building life time: The life time of buildings is the limiting term of the buildings during which it maintains the required operating qualities.

CO2 equivalent: metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential / metric for global warming potential (which mainly includes CO2 but also CH4, N2O, and other gases).

Cradle to gate: An assessment of a partial product life cycle from resource extraction (cradle) to the factory gate (before it is transported to the consumer). The use phase and disposal phase of the product are omitted in this case.

Cradle to grave: The full Life Cycle Assessment from resource extraction (cradle) to use phase and disposal phase (grave).

*Ecotect: B*uilding performance analysis software.

Embodied carbon: Embodied carbon can be defined as the amount of carbon released from material extraction, transport, manufacturing, and related activities.

Embodied energy: The sum of all the energy needed to manufacture a good. Generally expressed in term of primary energy.

Emission factor: Measure of the average amount of a specific pollutant or material discharged into the atmosphere by a specific process, fuel, equipment or source. It is expressed as number of kilograms of particulate per ton of the material or fuel.

End use energy: Energy measured at the final use level.

Klimagassregnskap: Free, web-based and holistic model for GHG calculations for buildings.

Life-cycle assessment (LCA): Technique for assessing the environmental aspects and impacts associated with a product, or service, in a life cycle perspective.
Life-cycle energy (LCE): Life cycle energy of the building is the sum of the all the energies incurred in its life cycle.

Operational energy: the amount of energy that is consumed by a building to satisfy the demand for heating, cooling, ventilation, lighting, equipment, and appliances.

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.

Reference building: ZEB Shoebox model built after Norwegian passive house standard used as a starting point for the two scenarios.

Simien: Dynamic building simulation software incorporating the Norwegian calculation procedures NS3031.

SINTEF : Iindependent multidisciplinary research organisation in Scandinavia.

SINTEF Byggforsk: International research institute, consulting in architecture, construction physics, management etc.

1. Introduction

In an environmental context, the building industry is often referred to as “the 40% sector”. 40% of all use of materials and products are related to buildings. Worldwide buildings account for about ~ 40% of all primary energy use. Moreover, the sector contributes up to 24% of global green house gas emissions (GHG) (Jones et al., 2009). It is evident that the building sector provides a great potential for energy savings and deep emission cuts. In fact, this constantly drives research towards the development of innovative energy efficient building design. In this respect, the new concept of a building that balances consumption of energy with production of energy from renewable sources (therefore the name Zero Energy Building – ZEB) can be seen as a realistic and valid contribution to the decrease of the energy consumption in the building sector (Marszal, 2012). However, a formal, comprehensive and consistent framework that considers all the relevant aspects characterizing ZEBs, allowing each country to define a consistent ZEB definition is still missing (Sartori et al., 2012). Considerable research has been carried out on this subject since 2006 when Torcellini et al. (Torcellini et al., 2006) introduced the issue:

“Despite the excitement over the phrase “zero energy”, we lack a common definition, or even a common understanding, of what it means. (…) A zero energy building can be defined in several ways, depending on the boundary and the metric. Different definitions may be appropriate, depending on the project goals and the values of the design team and building owner. (…) Four commonly used definitions are: net zero site energy, net zero source energy, net zero energy costs, and net zero energy emissions. (…)

***Net Zero Site Energy**: A site ZEB produces at least as much energy as it uses in a year, when accounted for at the site.*

***Net Zero Source Energy**: A source ZEB produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building’s total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.*

***Net Zero Energy Costs**: In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.*

***Net Zero Energy Emissions**: A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources."*

Despite the different definitions and a lack of common understanding, the ZEB concept has very quickly gained attention, both internationally and in Norway (Marszal, 2012). In the course of the past few years a consistent number of research programmes started to investigate and develop methods and technical solutions for zero energy buildings as well as zero emission buildings. In SINTEF, the largest independent multidisciplinary research organisation in Scandinavia, the department of Energy Efficiency is today working on concepts of zero-emissions houses and energy efficiency measures which could significantly reduce GHGs emissions. Furthermore the Research Centre on Zero Emission Buildings (ZEB), one of eight new national Centres for Environment-friendly Energy Research (FME), is developing solutions for existing and new buildings, residential, commercial and public owned, in order to develop concepts strategies for buildings with zero GHGs emissions associated with their construction, operation, and demolition (Sartori et al., 2010).

In this respect, the Norwegian government and policy makers have set a milestone on the path towards "zero" or nearly "zero" goal for 2020, which was set in May 2010 from the European Parliament and the Council of the European Union by adopting the recast of the Directive on Energy Performance of Building – EPBD (EU, 2010, Marszal, 2012).Current building regulations and the proposal for a future scenario in Norway are here summarized (Table 1) and described in the following part.

Table 1. Current building code in Norway and proposed scenario towards ZEB (Direktoratet for byggkvalitet, 2012).

Current building regulations	2015	2020
2010 - TEK10 120 kWh/m2 residenatial house 150 Wh/m2 office buiding (final energy)	Proposal: Passive house standards for all new buildings	Proposal: Nearly ZEB

1.1 TEK10 Standard

A building built after the TEK 10 standard, is one that meets the minimum requirements in the building code regulations currently in force in Norway. It defines several requirements, such as, maximum energy need (120 kWh/m^2 for dwellings, 150 kWh/m^2 for office buildings), the U-value of the external wall, floors, roof and windows, amongst others. The regulations require that a significant portion (from 40% to 60% depending on the area of the building) of the net heat demand must be met by renewable sources rather than electrical and fossil energy (Government and Regional Development, 2010). The technical regulation came into force from the 1st July 2010 replacing the previous regulations TEK 07. For the transition period of one year it was possible to choose which code to follow. The main differences from the TEK 07 is the increase of the heat exchanger efficiency form 70% to 80%. The technical requirements such as U-values remained the same.

1.2 Passive House Standard

A passive house is "*a building in which thermal comfort [EN ISO 7730] can be guaranteed by post-heating or post-cooling the fresh-air mass flow required for a good indoor air quality.*" (Feist, 2007). The concept was developed in May 1988 in Germany where most of the Passivhaus structures where built in these 20 years. The concept has also been successfully implemented in other countries like Austria, Sweden, Denmark and Norway. The main feature of a passive house is the significant reduction in the yearly heating demand which should not exceed 15 kWh/m^2. In Norway, due to differences in climate, design solutions and construction policy, an adaptation of the German passive house concept was necessary. A Norwegian standard for passive and low energy residential buildings was approved in April 2010 (NS 3700:2010 Criteria for passive houses and low energy houses - Residential buildings) will enter into force in 2015 (Standard Norge, 2003). The standard was designed solely for buildings with residential purposes, such as detached house, two to four family houses etc. The maximum yearly heating demand depends on the useful floor area and the local annual mean temperature, e.g. 15 kWh/m^2 for sites where the annual mean temperature is at least 6.3 °C, or higher demand for buildings below 250 m^2 and situated in colder regions in the country. There is also a minimum requirement for delivered energy provided by resources other than electricity or fossil fuels.

The standards mentioned above are solely referring to residential buildings, however a proposal or "temporary standard" for passive house commercial buildings – based on SINTEF Prosjektrapport

42 (prNS 3701), has been developed in Norway in collaboration with ENOVA (Norwegian public enterprise owned by the Ministry of Petroleum and Energy) and SINTEF Research Organization (Dokka et al., 2009). It is based on the principles of NS 3700:2010 and it sets the requirements for net heating demand (15-25 kWh/m^2 depending on the building type) and cooling demand (0-20 kWh/m^2 depending on the building type), heat loss values and specifies requirement for maximum allowable CO_2 emissions calculated from the total delivered energy (for office building ≥ 25 kg of CO_2eq/m^{2}year). In addition the standard gives guidelines for internal heat gains and air flow values, based on what is today considered the best available technology. The term 'commercial building' encompasses eleven building categories, such as kindergartens, offices, schools, universities among others (Dokka et al., 2009).

1.3 ZEB shoebox models and proposal for ZEB values

The ZEB Centre focuses on investigating and implementing the ZEB concept in several pilot projects. In fact a group of researchers, from the ZEB centre (including Prof. Aoife Houlihan Wiberg), together with NTNU and SINTEF are working on several generic concepts called "shoebox" models for office and residential building typologies. The impact of the building's form and location in relation to different building envelope and energy supply system combinations in terms of GHGs emissions will also be examined (Houlihan Wiberg and Hestnes, 2010). Several sensitivity analysis of different combinations will be conducted to assess the impact on emissions. In this respect the performance values for the envelope have been revised and significantly improved from the one in NS 3700:2010 and prNS 3701. Moreover, Prof. Aoife Houlihan Wiberg is developing a CO_2 accounting method using data from the Swiss material database "Ecoinvent" (Althaus & Ökobilanzdaten Bauteilkatalog). The decision to use this database is based on the outcome of prior research, during which other databases have been also analysed including the Norwegian database Klimagassregnskap (Version 3.0) (Houlihan Wiberg and Hestnes, 2010).

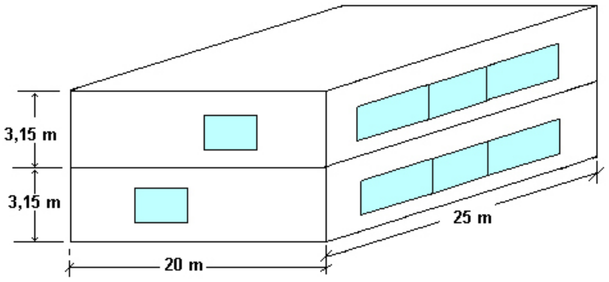

Fig. 1 Preliminary ZEB Shoebox model – office building (ZEB, 2010).

1.4 Aim and research questions

The thesis is part of above described research work in ZEB centre. The aim of this study is to account for the GHGs emissions from a life-cycle perspective using the Norwegian tool Klimagassregnskap (Statsbygg/Civitas, 2007), for the ZEB shoebox office model. The emissions for the model will be calculated using three different standards or performance values, i.e. TEK10 (Base case), Passive house Norwegian Standard NS 3700:2010 (first variant of the Base case) and finally ZEB shoebox model values (second variant). This allows a comparison of the base case and two variants in order to choose the optimal one which will be further analysed and modified in the two scenarios. A secondary aim is to evaluate the implications of alternative design options in order to achieve a Zero Emission Building in terms of energy supply (first scenario) and construction materials (second scenario). Hence the main research questions are:

- Whether there is an optimal energy supply solution that covers energy demand with renewable resources aiming to achieve ZEB.

- How different structural solutions, materials and their service life affect the embodied emissions in progress towards ZEB over a lifetime?

Since the GHGs emissions accounting tool (Klimagassregnskap in this case) is crucial for achieving the Zero Emission Building concept, the thesis work carries out also an analysis about the advantages and limitations of the tool.

1.4.1 Scope and limitations

The Base case ZEB shoebox office model, built after TEK10 standard, represents the starting point of the research project. The standard corresponds to current minimum requirements in Norway.

The proposed ZEB requirements for the ZEB shoebox models are still under development. The available values refer solely to the building components. At the time of the writing, certain information was missing (e.g. energy demand, specific fan power factor - SFP factor, heat recovery efficiency, air flow rate) which affected the scope of the research that can be conducted.

2. Literature review

2.1 Climate change and the building sector

Climate change is defined in the Article 1 of the United Nations Framework Convention on Climate Change (UNFCCC) as “a change which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods” (UN, 1992).

The atmosphere is made up of various gases, some of which act as a protective shield for the Earth. The so called greenhouse gases (GHGs) absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth’s surface, the atmosphere and clouds. This property causes the greenhouse effect (from here the name for the gases). Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases (Metz, 2007). Due to human activities and industries, the concentration of these gases is rising, particularly carbon dioxide (CO_2), has been steadily rising since the past century. According to the scientific community, this increase will cause severe impacts on ecosystems and our society over the next 100 years.

In response to the threat of climate change, the Kyoto Protocol was adopted in December 1997. Under the Protocol, industrialised countries and the European community have a legally binding commitment to reduce the emissions from three GHGs (carbon dioxide, nitrous oxide, methane) and three of other gases (perfluorocarbons PFC, hydrofluorocarbons - HFC, and sulphur hexafluoride – SF_6) produced by them, by at least 5% compared to 1990 levels by the period 2008 - 2012. Furthermore recognizing that developed countries are principally responsible for the current high levels of GHGs emissions in the atmosphere as a result of more than 150 years of industrial activity, the Protocol places a heavier burden on developed nations under the principle of “common but differentiated responsibilities” (UN, 1992).

Norway’s total emissions of greenhouse gases, measured as CO_2 equivalents, were ~ 54.8 million tonnes in 2003 (see Fig. 2), ca. 12 tonnes per capita, which is higher than in the rest of Europe.

These emissions rose by about 9% in the period 1990-2003. The main factors behind the growth are CO_2 emissions from the rapidly developing petroleum sector (Norwegian ministry of environment, 2005).

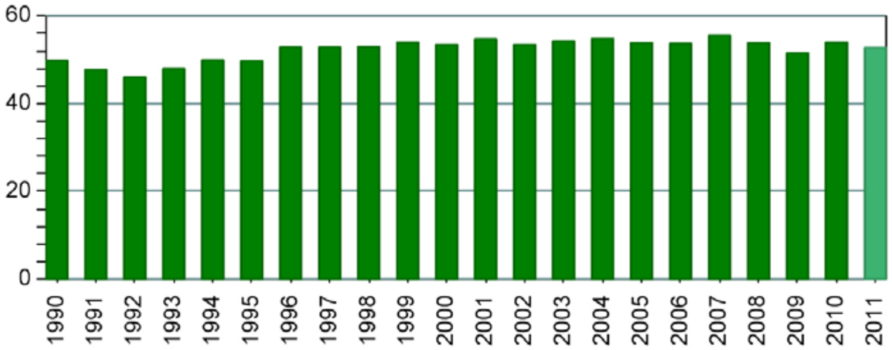

Fig. 2. Greenhouse gases emissions in Norway for the years 1990-2011 (preliminary value) in million tonnes CO_2 equivalents (Norwegian ministry of environment, 2009).

Accordingly, it is expected a long-term trend of a significant rise in total emissions unless substantial measures are taken. In this respect the Norwegian government has ratified the Kyoto Protocol on 30 May 2002, and it entered into force on 16 February 2005. Under the Protocol, Norway is committed to ensuring that its greenhouse gases emissions do not exceed the 1990-level by more than 1% in the period 2008-2012 (UN, 1992). Furthermore, according to the Government's White Paper on the climate situation (White paper no. 34 - 2006-2007, Norwegian climate policy), a more ambitious target has been set: reduce greenhouse gases emissions to 9% below the 1990 level in the period 2008–2012. To do this, average annual emissions in 2008–2012 must be reduced to 45.2 million tonnes, as compared with 49.7 million tonnes in 1990. As part of an ambitious global climate agreement, in January 2008 Norwegian government went a step further and declared a goal of achieving emission cuts of 30% by 2020 (approximately two thirds of these emissions reductions will be implemented nationally) and being carbon neutral by 2030 (Norwegian ministry of environment, 2009).

Effective actions for achieving the ambitious goals are necessary in all economic sectors, in particular those that are responsible for a high percent of the GHGs emissions. Hence, key sectors required to make a significant contribution to the mitigation efforts. In this respect the building sector in Norway is the one of the largest single contributors to the production of the GHGs (24%). Yet it offers the largest share (29%) of cost-effective opportunities for GHGs mitigation among all other sectors (Fig. 3) (Metz, 2007).

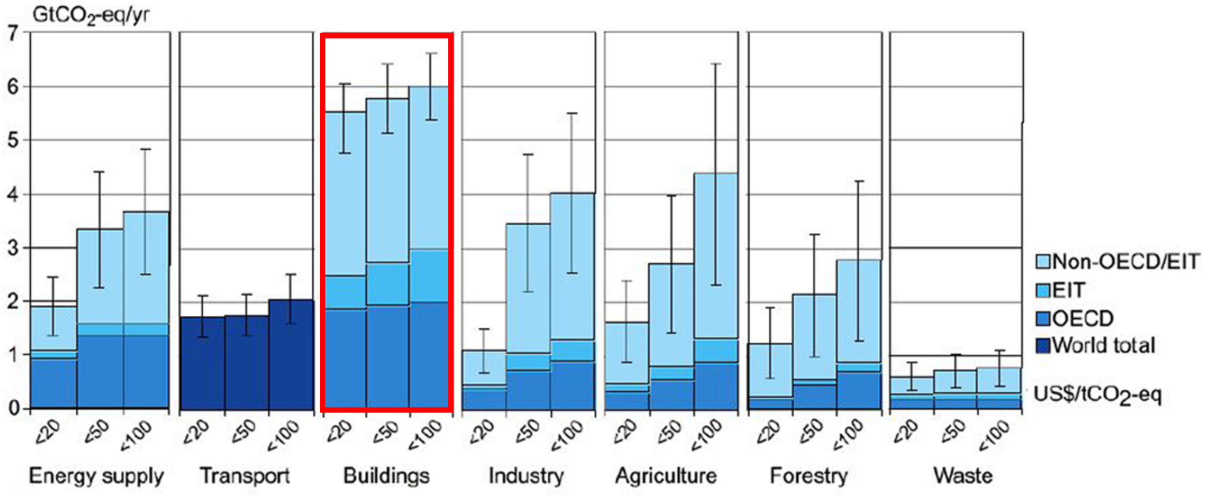

Fig. 3. Estimated sectoral economic potential for global mitigation for different regions as a function of carbon price (US$/tCO$_2$-eq) in 2030. The highest potential lies in the building and agriculture sectors (Metz, 2007).

In this regard, improving energy efficiency in new and existing buildings can lead to a substantial reduction in GHGs emissions and constitute one of the main measures to enforce (Metz, 2007). The evaluation of energy use in buildings during their life cycle is needed to identify phases of largest energy use and consequently to implement strategies for its reduction and efficient design solutions (Ramesh et al., 2010).

2.2 Life-cycle energy use in buildings

Buildings demand energy in their life cycle, both directly and indirectly. Directly for their construction, operation (operational energy), rehabilitation and eventually demolition and indirectly through the production of the materials they are made of (embodied energy) (Sartori and Hestnes, 2007). As this demand occur in different stages of the building life cycle, it is useful to divide them into four distinct categories of energy use:

- Energy to initially produce the building (Initial embodied energy).
- Energy required to refurbish and maintain the building over its effective life (Recurring embodied energy).
- Energy to operate the building, i.e. the energy required to heat, cool, ventilate and light the interior spaces and to power equipment and other services (Operational energy).
- Energy to demolish and dispose of the building at the end of its effective life (Cole and Kernan, 1996).

2.2.1 Embodied energy

Embodied energy is the energy utilized during the manufacturing phase of the building. It represents the energy content of all the materials and technical installations used in the building, as well as energy incurred at the time of construction and renovation/maintenance of the building. The energy content of materials refers to the energy used to acquire raw materials (extraction), manufacture and transport to the building site (Ramesh et al., 2010). Therefore the more processes a product goes through, the higher its embodied energy will be. As it is rather difficult to recover the embodied energy during the lifetime of the building, the choices of materials and construction methods play an important role when reducing the amount of energy embodied in the structure (Newton and Westaway, 1999).

As mentioned above, embodied energy is divided in two: initial embodied energy and recurring embodied energy which is described below.

Initial embodied energy

The initial embodied energy is the energy used to produce the building, therefore it is the sum of the energy embodied in all materials used in the construction phase, including building services (Sartori and Hestnes, 2007). It does not include the energy associated with maintaining, repairing and replacing materials and components over the lifetime of the building (i.e. recurring embodied energy), hence the importance of using the designation initial. The embodied energy in the building envelope, structure, building services and finishes (relatively small share) is the most significant component of the total initial embodied energy (Chen et al., 2001, Cole and Kernan, 1996).

Recurring embodied energy

The recurring embodied energy is the energy used to maintain, repair, restore, refurbish or replace materials, components or systems during the life of the building. The building services, interior finishes and components are the most significant categories of recurring embodied energy. The finishes and components, which represent only a relatively small share of the embodied energy initially, typically account for the highest increase in recurring embodied energy (Cole and Kernan, 1996). It is worth noting that with the recent improvements in technologies for manufacturing materials, the recurring energy intensities has been relatively reduced increasing the opportunity for selection of efficient materials and components (Chen et al., 2001).

2.2.1.1 Embodied carbon

Embodied energy is usually quoted in MJ or GJ units of energy, however it can also be expressed in terms of the CO_2 equivalent associated with the embodied energy, defining the term embodied carbon. In the pursuit of carbon neutrality and zero emission buildings, embodied carbon is likely to become one of the key metrics to address in whole-life building sustainability. Hence the importance of understanding the relation between embodied energy and embodied carbon (Ayaz and Yang, 2009).

The relationship between embodied energy and carbon emissions is important to understand and is determined by (1) the primary energy utilised to drive the material processing and the efficiency (e.g. an aluminium product extracted with hydro power will have very little embodied carbon but a huge energy use) (Haynes, 2010) and (2) the emissions or sequestration of CO_2 during the material processing (for example cement emits about half of its embodied carbon because of an inherent chemical process unrelated to energy use; in contrast, timber sequesters carbon during its growth) (Ayaz and Yang, 2009). A summary of the differences between embodied energy and embodied carbon is given in the Table 2 below.

Table 2. Summary of the differences between embodied energy and embodied carbon (Ayaz and Yang, 2009).

Embodied Energy	**Embodied Carbon**
Energy used to:	CO2 eq. resulting from:
Extract raw materials	Embodied energy use (each energy expenditure has its own mix of fuel types)
Manufacture	
Transport	Chemical reactions
Construction	Sequestration (CO_2 absorbed)
Maintenance and repair	

2.2.1.2 System boundaries

The system boundary determines which unit processes shall be included within a whole life cycle of the building's materials. Therefore clearly defined boundaries are important to draw useful conclusions on the embodied energy or embodied carbon of a building (Newton and Westaway, 1999) . Ideally, the boundaries would be set from the extraction of raw materials until the end of the product lifetime – disposal phase (including energy/emissions from manufacturing, transport, operation, maintenance, etc.), known as "Cradle-to-Grave". It has become common practice though to specify the embodied energy/carbon as “Cradle-to-Gate”, which includes all energy/emissions (in primary form) required to deliver the product to the gate of the factory or “Cradle-to-Site”, which includes all energy/emissions consumed until the product has reached the point of use (i.e. building site) (Hammond and Jones, 2008). Furthermore there is also a specific kind of Cradle-to-Grave assessment, where the end-of-life disposal step for the product is a recycling process, called “Cradle-to-Cradle” (Kotaji et al., 2003).

2.2.2 Operational energy

Energy used in buildings during their operational phase for maintaining comfort conditions and day-to-day maintenance of the buildings. It is the energy for HVAC (heating, ventilation and air conditioning), domestic hot water, lighting and for running appliances (Ramesh et al., 2010). It might be expressed either in terms of end-use or primary energy.

Design of low energy buildings directly addresses the target of reducing operational energy. This is done by means of both passive measures such as providing higher insulation on external walls and roof, better performing windows, reduction of infiltration losses and ventilation air heat recovery from exhaust air, or active measures such as heat pumps coupled with air or ground/water heat sources, solar thermal collectors, building integrated solar photovoltaic panels, biomass burners etc. (Sartori and Hestnes, 2007). Operational energy and the measures for reducing it differ considerably with the level of comfort required, climatic conditions, efficiency of the building and its systems and operating schedules (Cole and Kernan, 1996).

2.2.2.1 Operational carbon

Operational energy is usually quoted in kWh or kWh/m^2. However, as for the embodied energy, it can also be expressed in terms of the CO_2 equivalent associated with GHGs emissions from the energy use to operate the building, defining the term operational carbon.

The amount of emissions related to energy use varies depending on fuel type: fossil fuel-derived energy will produce high carbon emissions, while on-site renewable energy may produce zero. In this way, operational energy and carbon are roughly proportional for a given fuel mix (Ayaz and Yang, 2009). A summary of the differences between operational energy and operational carbon is given in the Table 3 below.

Table 3. Summary of the differences between operational energy and operational carbon (Ayaz and Yang, 2009).

Operational Energy	**Operational Carbon**
Electricity, steam and natural gas used to: Oprate building (HVAC, DHW, lighting, appliances etc.)	CO_2 eq. resulting from: Operational energy use, whole building uses a mix of fuel types

2.2.3 Demolition energy

At the end of buildings' service life, energy is required to demolish the building and transporting the waste material to landfill sites and/or recycling plants (Ramesh et al., 2010). However, different studies show that the demolition and disposal energy is negligible or settled at approximately 1-3% of the total life cycle energy need (Cole and Kernan, 1996). Moreover this component is very difficult to assess due to difficulty in predicting the useful life of a building, the methods of demolition and the energy implications of materials and/or component re-use and/or recycling at a future date (Yohanis and Norton, 2002). This might explain the disregard of the demolition energy from the building's life cycle energy in most of the literature and case studies. Different studies show that the demolition and disposal energy is negligible and difficult to assess, therefore most of the literature does not consider this category as part of the building life cycle (Sartori and Hestnes, 2007).

2.2.4 Energy as a function of building life cycle

The graph shown in Fig. 4 gives an overview of the different energy use during the building life time. The initial embodied energy increases from zero to a maximum during the construction phase. During this phase there is no operational energy requirement since the building is not occupied. Any energy requirement associated with construction work is assumed to be part of the initial embodied energy. Throughout the operation phase, the increase in embodied energy is due to the replacement, refurbishment and maintenance of the internal partitions and doors, finishes and building services (so called recurring embodied energy) (Yohanis and Norton, 2002). It is worth noting that the end of life phase (demolition and dispose energy) is not included in the building life as represented on the x-axis of the graph.

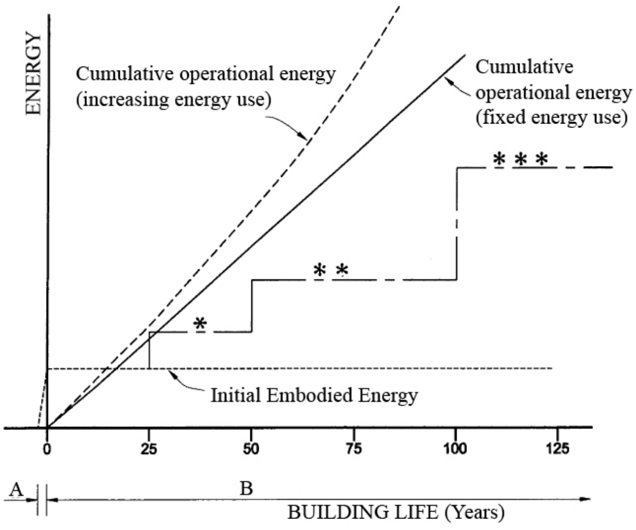

*Fig. 4. Operational and embodied energy as a function of building life. * Initial embodied energy plus recurring embodied energy over 25 years*, 50 years**, and 100 years**. A, Construction phase; B, Operation phase (Yohanis and Norton, 2002).*

2.2.5 Embodied vs. operational energy

Until recently, it was understood that operational energy represented by far the largest share (80-90%) in the life cycle energy use of buildings followed by embodied energy (10-20%). Yet, the increased awareness of the sustainability issues related to energy processes together with an increasing energy demand from the building sector have lead to the need of more energy efficient design solutions and tighter building regulations (Sartori and Hestnes, 2007). Indeed, with the improvements in construction standards such as air-tightness and increased insulation, buildings are becoming more energy efficient. Moreover the use of low and zero carbon energy supply on-site, such as PV panels and solar thermal hot water systems, further reduces the operational energy. In terms of the total life-cycle energy of the building, the embodied energy (and embodied carbon) is becoming more important due to an increased use of materials, and especially of energy intensive materials, both in the building envelope and in the technical installations (Sartori and Hestnes, 2007). For the conventional building embodied energy is ca. 10% of the total over its life, whereas for the low energy building the embodied energy is 30-40% (in some case studies up to 50%) of the total (Newton and Westaway, 1999).Given the above becomes evident that the benefit of reducing operational energy (i.e. higher energy efficiency of building and its appliances) is, to a large extent or completely, counterbalanced by similar increases in the embodied energy (Sartori and Hestnes, 2007).

2.2.6 Life – cycle assessment (LCA) in buildings

As mentioned before buildings demand energy in all their life cycle stages right from the cradle to the grave.The life cycle stages of a building are: production of materials, transport of materials to the site, construction, operational energy use, maintenance and replacements, demolition, waste treatment (Kotaji et al., 2003). In order to provide better understanding and better estimation of the environmental impacts during all the phases, holistic assessment methods have been developed, including Life Cycle Assessment (LCA). The Life-Cycle Assessment for buildings is carried out in following steps: goal and scope definition (choice of functional unit from the perspective of the performance concept, description of building), inventory analysis (buildings life cycle phases description, system boundaries-service life), impact assessment (e.g. carbon footprint, water use, resource depletion, etc.), interpretation of the results (Kotaji et al., 2003). Given the above becomes evident that the Life-Cycle Analysis can be used as a method for the assessment of emissions from a building. To do this, the CO_2 emission factor for materials and energy sources has to be calculated or extracted from existing databases (likewise based on LCA method).

2.3 Zero Energy Building (ZEB) definitions

There are many definitions of ZEB found in literature. However, they all have their particularities and often lack a holistic outline of the ZEB understanding (Marszal, 2012).

Conceptually, the Zero Energy Building can be described as a building with significantly reduced energy demand and the remaining energy offset by production from renewable energy sources (Marszal, 2012). Therefore, it is implicit from the definition that there is a focus on buildings that are connected to an energy infrastructure and not on autonomous buildings. In this respect the term Net ZEB (also called on-grid ZEB) can be used to refer to buildings that are connected to the energy infrastructure or energy grid. The wording “Net” underlines the fact that there is a balance between energy taken from and supplied back to the energy grids over a period of time, nominally a year (Sartori et al., 2012). On the other hand, the term ZEB is more general and may also include autonomous buildings, not connected to any energy grid (also called off-grid). All the energy demands are offset by means of renewable energy technologies and energy storage system for periods with peak loads. The need for large storage capacity, oversized renewable energy producing systems, energy losses due to storing or converting energy, and backup generator are the main reasons why the autonomous ZEBs did not gain international attention in favour of Net ZEB

(Marszal, 2012). However, this Net ZEB definition does not consider all the relevant aspects characterising this building concept and a more detailed description is necessary.

2.3.1 The main Net ZEB aspects

When designing a Net ZEB several aspects have to be evaluated and some explicit choice made. The Table 4 gives an overview of the main criteria and different sub-criteria that needs to be taken into account when characterizing Net ZEBs. Evaluation of the criteria and selection of the related options becomes a methodology for elaborating Net ZEB definitions in a systematic, comprehensive and consistent way (Sartori et al., 2012).

Table 4. Main criteria and different sub-criteria of Net ZEB (based on Sartori et al., 2012).

Criteria	Characteristics
Net ZEB balance:	Refers to the balance between delivered/import energy and exported energy equals to zero over a period of time ($\text{export} - \text{import} = 0$).
- Balancing period	Annual balance, seasonal or monthly, entire building's life cycle.
Unit of balance	Four main types of units may be considered: final energy, primary energy (kWh), energy cost, and carbon emissions related to energy use (CO_2eq).
- Weighting system	Converts the physical units of different energy carriers into a uniform unit (primary energy, CO_2), allowing the evaluation of the entire energy chain.
Type of energy use	Defines which energy uses are considered for the Net ZEB balance: operational energy uses typically include heating, cooling, ventilation, domestic hot water, fixed lighting. Embodied energy in material and technical installations may be considered to broaden the scope of Net ZEB as environmental friendly and sustainable building.
Renewable energy supply options	Sets a hierarchy of renewable energy supply options: on-site supply options (PV, solar thermal, CHP, etc.); off-site supply options (import of biofuel for CHP, purchase of green electricity etc.).
Building system boundary	Necessary for identifying what energy flows cross the boundary.
- Physical boundary	Determines whether renewable supply options are ‘on-site’ or ‘off-site; can encompass a single building or a group of buildings.
Requirements	Refers to minimum energy efficient requirements and perspective requirements (properties of envelope components).
Temporal energy match characteristics	
- Load matching	Defines the ability to match the building's own load. The load match index can express the seasonal unbalance of energy exchanged with a grid.
- Grid interactions	Defines some indicators (e.g. grid interaction index) which can evaluate the impact on the energy carrier exchange between the building and energy grid

Moreover Sartori et al. developed the sketch shown in Fig. 5 which gives a schematic overview of the relevant aspects in a Net ZEB and illustrate the connection between buildings and energy grids (Sartori et al., 2012). Relevant terms are then explained.

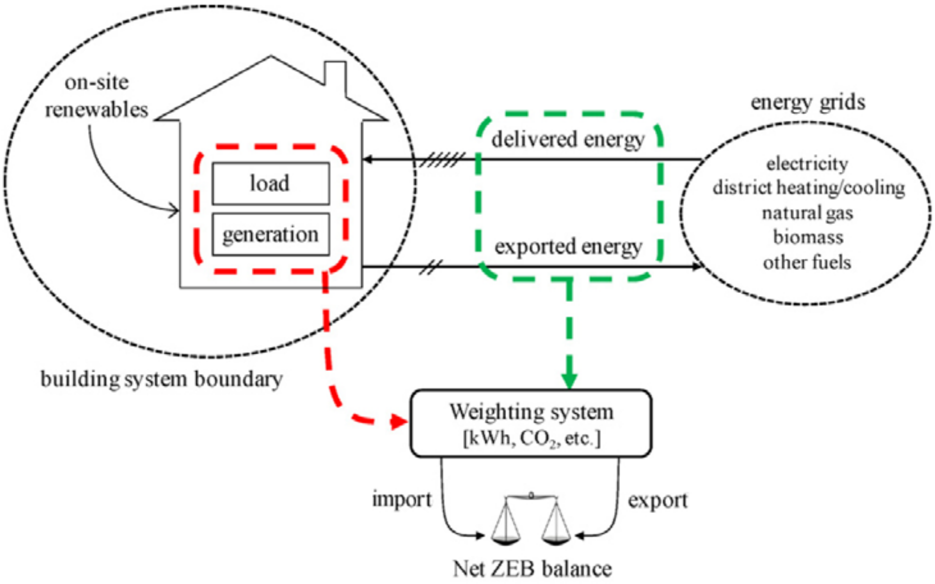

Fig. 5. Sketch of connection between buildings and energy grids showing relevant aspects of a Net ZEB (Sartori et al., 2012).

Building system boundary: the boundary at which to compare energy flows in and out the system (physical boundary).

Delivered energy (import): energy flowing from the grids to buildings – imported by the building, specified per each energy carrier in (kWh/y) or (kWh/m^{2}y).

Exported energy (export): Energy flowing from buildings to the grids, specified per each energy carrier in (kWh/y) or (kWh/m^{2}y).

Load: building’s energy demand, specified per each energy carrier (kWh/y) or (kWh/m^{2}y).

Generation: building’s energy generation, specified per each energy carrier (kWh/y) or (kWh/m^{2}y).

It is evident that the key feature of the Net ZEB concept is the balance condition, which is satisfied when delivered or import energy meets or exceeds exported energy over a period of time, the choice of the unit of balance, weighting system and the renewable energy supply options.

2.3.1.1 Net ZEB balance

The Net ZEB balance is calculated as in Eq. 1:

$$\text{Net ZEB balance}: \quad |\text{export}| - |\text{import}|^{*} = 0 \qquad \textit{(Eq.1)}$$

*Absolute values are used simply to avoid confusion on whether supply or demand is consider as positive.

It is worth noting that the appropriate balancing period (annual, seasonal, monthly or entire building's life cycle) over which to calculate the balance represent an important aspect when aiming to satisfy the condition mentioned above (Eq.1).

The Net ZEB balance can be also represented graphically as in Fig. 6, plotting the delivered energy on the x-axis and the feed-in energy on the y-axis. The pathway to a Net ZEB is given by the balance of two actions:

(1) reduce energy demand (x-axis) by means of energy efficiency measures;
(2) generate electricity as well as thermal energy by means of energy supply options to get enough credits (y-axis) to achieve the balance.

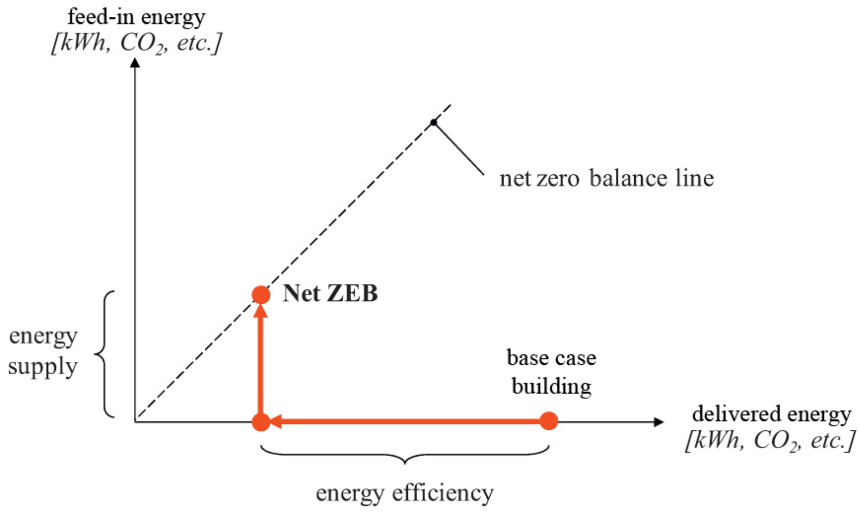

Fig. 6. Graphical representation of the pathway to ZEB (Sartori et al., 2012).

Unit of balance and weighting system

Torcellini et al. (2006) considered four main units of balance that can be applied in the Net ZEB definition: final/delivered energy, primary energy, energy cost and CO_2 equivalent emissions. Therefore, they propose four different Net ZEB definitions (see also introduction): Net site ZEB, Net source ZEB, Net cost ZEB and Net emissions ZEB, respectively (Torcellini et al., 2006). Various reasons may influence the choice of a specific unit of balance, e.g. project goals, intention of investor, concern about climate change and reducing GHGs emissions. Moreover it is worth noting that the choice of the unit will influence the relative value of energy carriers, hence affecting the evaluation of the optimal carriers and influencing the required (electricity) generation capacity (Sartori et al., 2012).

The balance calculated in delivered energy (Net site ZEB definition) is the easiest to fulfil and is the most acknowledge unit among the others. However, it has two major drawbacks: firstly, conversion and transportation losses are not accounted and secondly the quality of different kinds of energy is fully neglected (Marszal et al., 2011). Therefore most frequent applied unit is the primary energy (Net source ZEB definition) as it accounts the quality of energy carriers in the so called primary energy conversion factor. The factor is a multiplicative coefficient converting values from delivered energy to primary energy and varies depending on energy carriers and countries (Sartori and Hestnes, 2007). Although, in common praxis the buildings are evaluated and certified based on energy performance rather than on emissions, the balance can be also calculated on basis of CO_2 emissions equivalent (Net emissions ZEB) (Marszal et al., 2011). As for the primary energy, a conversion factor for carbon equivalent emissions is necessary in order to calculate the direct correspondence between energy and emissions. The Table 5 gives an overview of the CO_2 – factors for some energy carriers developed in Norway.

Table 5. Conversion factors for carbon equivalent as applied in current building design practice in Norway (Sartori et al., 2012).

Energy carreir	CO2 factors (g/kWh)	Sources
Electricity	395 132	NS 3700 (2010) ZEB centre *
Natural gas	211	NS 3700 (2010)
Oil	284	NS 3700 (2010)
Biofuels (solid)	14	NS 3700 (2010)
District heating	231	NS 3700 (2010)

* ZEB centre proposal: European mix scenario for nearly carbon-free grid towards 2050, for average years 2010-2060.

It must be noted that the quantification of proper conversion factors is a rather challenging task, in particular for electricity and thermal networks (district heating) as several aspects have to be taken into account, e.g. the mix of energy sources within certain geographical boundaries (international, national, regional or local), average or marginal production, present or expected future values and so on. Different conversion factors are possible according to the scope and assumptions of the analysis (Sartori et al., 2012).

2.3.1.2 Renewable energy supply options

A Net ZEB definition may set mandatory requirements on energy supply. In Torcellini et al. (2006) a hierarchy of supply options is proposed as a pathway for design of Net ZEBs, where on-site supply options, e.g. PV and wind, are prioritised over off-site supply options, e.g. import of biofuel for cogeneration or purchase of green electricity. Alternatively, energy supply options may be categorized in different ways. In this respect, Marszal et al. (2011) graphically represented the possible renewable energy supply options suggested in different energy calculation methodologies, see Fig. 7. Nevertheless, the authors emphasized that the graph should not be seen as a “hierarchy” of renewable supply options, therefore no option is understood as preferable. The five options (I–V) are ordered following the location of the energy supply option with respect to the building (Marszal et al., 2011).

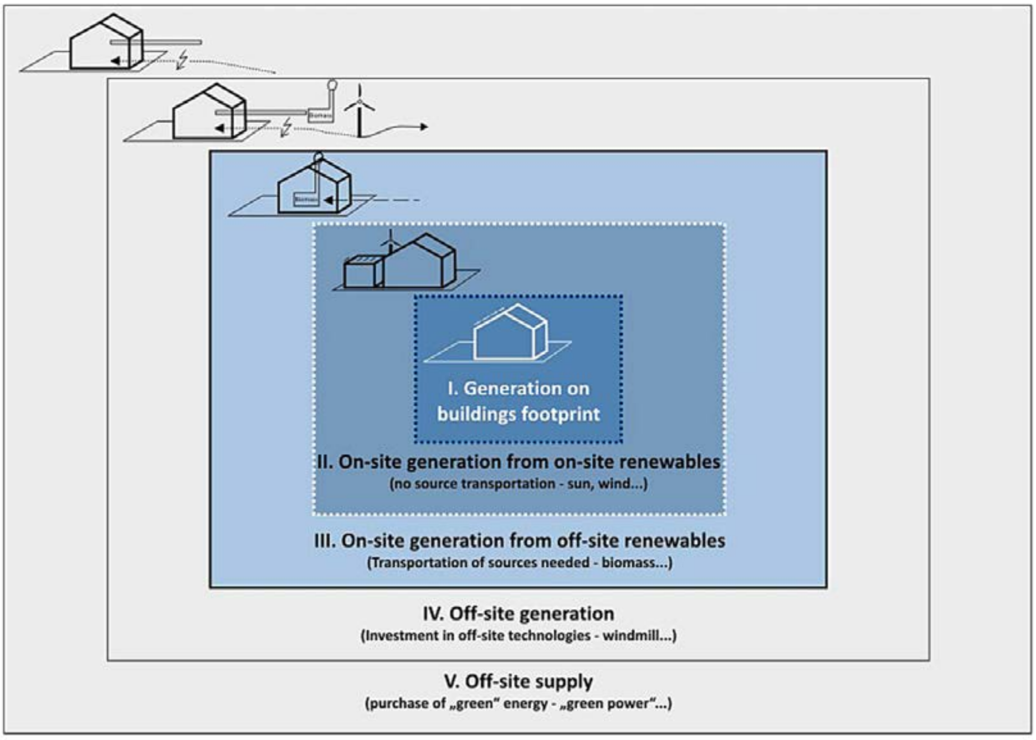

Fig. 7. Overview of possible renewable supply options (Marszal et al., 2011).

2.3.2 Zero emission buildings

Although a clear and agreed definition of Zero Emission Building (ZEB) is yet to be achieved, both internationally and in Norway, the key concept of balance is clearly explained by Sartori et al., (2010):

“In a Zero Emissions Building the balance is achieved not directly on the energy demand and generation but on the associated carbon equivalent (CO_2eq.) emissions. The energy imported (delivered) from the grids into the building is accountable for certain emissions. The export of renewable energy from the building to the grids is accountable for avoiding similar emissions by other (non-renewable) energy producers connected to the same energy grids.” (Sartori et al., 2010).

As mentioned above, more energy efficient and energy producing building are likely to use more materials and technical installations. In this respect, an alternative definition has been proposed:

“The main concept of a zero emission building is that renewable energy sources produced or transformed at the building site have to compensate for CO2 emissions from operation of the building and for production, transport and demolition of all the building materials and components during the life cycle of the building.” (Houlihan Wiberg and Hestnes, 2010).

3. Methodology

3.1 Overview

For achieving the aim of the thesis a literature review of the environmental assessment methods and emissions calculation tools has been carried out. LCA method and the tool employing it - Klimagassregnskap was chosen in order to account the GHGs emissions for ZEB Shoebox office model. The study is divided into four steps.

(1) First step was to design the given model in more detail in order to develop the *Base case*. This was done by means of local climate analysis, energy and thermal envelope performance simulations and choice of available energy supply systems. The GHGs emissions were then calculated in Klimagassregnskap.

(2) In the next step two variants of the *Base case* with alternative performance requirements were developed (Variant Passive house standards and Variant ZEB values). Energy and thermal envelope performance were simulated and the GHGs emissions were obtained in Klimagassregnskap.

Then, the results from the first and second step were analyzed and compared in order to define the optimal *Reference building* for the development of two scenarios.

(3) At last the two scenarios were defined: first scenario is focusing on alternatives for energy supply (carried out by Elisabetta Caharija), while the second one is looking at minimizing the embodied carbon of different structural solutions (carried out by Nigar Zeynalova). GHGs emissions of the alternative design options for both scenarios were then calculated in order to identify the optimal choices for achieving a Zero Emission Building.

3.2 Klimagassregnskap assessment tool

Klimagassregnskap Versions 3 is a Norwegian, online and free-access GHGs emissions calculation tool based on the life-cycle analysis method (Selvig et al., 2011). Using this tool the study evaluates the possibility of achieving a zero emission building conceived for Norwegian conditions and location, according to national standards. However, the tool has some limitations such as reliability of the emission factors and others that will be further discussed. In this respect it is important to consider these limitations when analysing the results.

Klimagassregnskap consists of four modules and covers emissions from production of materials used in the building, energy use in the construction phase and transport of materials to the building site, energy for use heating and cooling in connection with operation/use of the building and energy use for transport in connection with operation/use of the building (Selvig and Cervenka, 2008). Other stages, such as the demolition and the disposal of the building are not included.Table 6 gives an overview of the four modules.

Table 6. Overview of the modules in Klimgagassregnskap .

Module	Description	Additional phases
Materials	Life cycle embodied emissions from materials used in the building	Early / Planned
Construction	Life-cycle emissions during construction and transport of materials	
Stationary energy	Life cycle emissions from operational energy use	Early / Planned
Transport	Life-cycle emissions from the transport of the users during operation of the building	

The third version of Klimagassregnskap allows the possibility to choose Early or Planned design phase for calculating the emissions of materials and stationary energy. The early phase module enables an easy estimation of GHGs emissions in the first stages of the design (Statsbygg/Civitas, 2007). It might be observed that the planned phase gives more accurate results as it has a wide range of choices.

Given that the modules can be used independently, the scenarios in the second part of the thesis (development of the scenarios) are mainly focusing on two modules: operational energy use (planned phase) and material (early and planned). Yet when looking at overall emissions (Base case, variants and Reference building) the transport module, which represents a significant aspect, is included in order to obtain more realistic results. Lastly emissions of the construction phase are not calculated, as the module requires information unavailable at the design stage of ZEB shoebox project.

3.2.1 Calculation method in Klimagassregnskap

The calculation tool has been designed in such a way that the emissions from the various different parts are calculated separately and the results are also summed up across the modules (Selvig and Cervenka, 2008).

The basic principle for the calculations is:

Input factor/activity x *emissions factor* (CO_2, CH_4, N_2O etc.) = *greenhouse gas emission* (CO_2 equiv.)

The *input factor / activity* is a litre of fuel, a litre of heating oil, a kilogram of steel, a square metre of timber outside wall, the number of vehicle kilometres driven by lorry, energy need / use per square metre, etc. The *emissions factors* for stationary energy consumption and transport are taken from national emissions accounts based on international sources. Emissions factors for materials have been calculated from a number of different references and are mean figures for European production, given as CO_2 equivalent per tonne of basic material. The system boundary used for the data is “Cradle-to-Gate” (Houlihan Wiberg, 2011). Concerning the CO_2-factor for electricity Klimagassregnskap offers a choice of three different factors. These are called EU reference (395 g/kWh), ZEB 2-degree target (132 g/kWh) and 0 level (Statsbygg/Civitas, 2007).

3.3 Base case

ZEB Concept Office Building - the original ZEB model

ZEB Shoebox office building is a generic model currently under development in ZEB Research centre. The building is 25 by 20 meters in plan and has 2 stories with the height 3,15 m each. Building's footprint and total floor area is 500 m^2 and 1000 m^2, respectively. The model has a simplified floor plan identical for both stories. The structural system of the building is comprised of concrete slabs, supported by concrete pad foundations and beams. Several solutions for Norwegian climate and approved by SINTEF Byggforskserien (Byggforsk, 2010) are given as guidelines for building components (APPENDIX 1).

Location and site analysis

The location of the model is chosen in order to apply a holistic bioclimatic design and obtain accurate emissions accounting. After a screening, it was decided to choose Brøset area as it is planned to be developed into carbon neutral neighbourhood. The area is located at four kilometers from city centre of Trondheim, offering a good connection and availability of public transport which can reduce transport emissions by 60 -70% (Selvig et al., 2011). Moreover the site has a good solar access due to topography (low vegetation and small scale buildings). The building is oriented towards south for taking advantage of passive solar heating and daylighting. Once the climatic conditions have been established, design strategies for achieving/avoiding heat gains and providing adequate daylighting and shading have been analyzed in Ecotect.

Development to TEK 10 standard

The base case was designed to fulfill the TEK10 requirements. The layering and choice of materials is based on the solutions from SINTEF Byggforskserien (Byggforsk, 2010) in compliance with current Norwegian Standard. The U-values of the thermal envelope have been estimated in PHPP tool (APPENDIX 2). The concrete structure is insulated externally (100 mm) and internally (45 mm) with glass wool. Additionally the light timber frame walls contain 250 mm insulation between studs and joints. The compact concrete roof has the external insulation of 250 mm. The precast concrete floor slab has an underlying insulation of 250 mm. Additionally wing insulation (thickness 100 mm) is used as frost protection. The overall thermal bridge value is assumed to be 0,06 W/mK (Byggforsk, 2010). Technical drawings for building elements were produced based on the information and materials given from the ZEB centre (APPENDIX 3).

Energy demand and supply systems

The energy supply system is basic and available on site with potential for future improvement. Electricity is supplied by the grid, while heating and domestic hot water demands are covered by district heating as Brøset lies within its concession area. The energy demand is performed according to the Norwegian calculation procedure NS 3031:2007 (Standard Norge, 2007) using the software SIMIEN.

GHGs emissions accounting in *Klimagassregnskap*

The quantities of the chosen materials were input in the accounting tool. Moreover, the results obtained in SIMIEN are used as an input for the stationary energy module in Klimagassregnskap. After first screening and discussion with the supervisor the value from the ZEB centre was chosen as electricity factor (132 g/kWh).

3.4 Stepwise upgrade towards ZEB

According to Sartori et al. (2010) the first main step in the pathway to a ZEB consists of reducing energy demand by means of energy efficiency measures (see Fig. 6). Therefore a stepwise upgrade in the thermal envelope and consequently improvement of the energy performance of the Base case – TEK10 Shoebox office model was carried out in order to enable the choice of the optimal reference building for the two scenarios. Two variants were chosen: the first corresponds to the Passive house standards prNS 3701 – Variant Passive house, the second corresponds to the ZEB values – Variant ZEB. The design, the energy supply and the electricity factor (ZEB target) were not changed in order to enable further comparison of *Base case* and the two variants.

Fig. 1 Stepwise upgrade towards ZEB.

The Table 7 provides an overview of the minimum performance requirements of building envelope and technical systems.

Table 7. Main parameters for the three cases. minimum performance requirements (Government and Regional Development, 2010, Standard Norge 2003, Houlihan Wiberg and Hestnes, 2010).

	Unit	**TEK10***	**prNS 3701****	**ZEB values**
U-value outer wall	W/(m^{2}K)	0.18	0.15	0.09
U-value roof	W/(m^{2}K)	0.13	0.13	0.09
U-value floor	W/(m^{2}K)	0.15	0.15	0.07
U-value window and door	W/(m^{2}K)	1.2	0.8	0.65
Thermal bridge value	W/(mK)	0.06	0.03	0.02
Air tightness n50	ach	1.5	0.6	0.3
Heat recovery ventilation	%	80	80	-
Specific fan power (SFP)	kW/m^3/s	2	1.5	-
Air flow rate during operation	m^3/hm^2	10	6	-
Air flow rate outside operation	m^3/hm^2	3	1	-

* For TEK10 the maximum energy need is set to 150 kWh/m^2 for office building.

** In Passive house standard prNS 3701 the heating demand is set to 15kWh/m^2.

Moreover the calculations follow the same procedure: determination of U-values in *PHPP* excel tool to analyse the improvement of the thermal envelope performance by adding more insulation, energy simulation in *SIMIEN* to see the reduction in energy demand and GHGs emissions accounting in *Klimagassregnskap.*

3.4.1 Variant Passive house

In order to fulfill the heating demand requirement the thermal envelope is improved. The insulation of the external wall is increased to 150 mm and extra 50 mm glass wool is added to the floor on the ground. Thermal bridge has been assumed to be reduced to 0,03 W/mK through additional insulation measures (e.g. insulating pad foundation) (Byggforsk, 2010).

3.4.2 Variant ZEB

The low U-values are achieved by increasing amount of insulation. The external wall has 250 mm of glass wool. The insulation of the floor on the ground is increased to 450 mm. And extra 150 mm of glass wool is added to the roof.

The choice of the optimal *Reference building* was made comparing and analyzing the results from the Base case and the two variants.

3.5 Two scenarios

3.5.1 Scenario 1 - Strategies for optimizing the operational energy supply

(Elisabetta Caharija)

Given the information above becomes evident that the energy supply system will affect significantly the way buildings are designed to achieve the Zero Emission Building goal. In this respect the scenario represents an estimation of the potential renewable energy supply options for accomplishing that target. The study is divided into several steps. First, a more detailed energy budget was calculated for the Reference building with a division of energy need into heat and electricity. This allowed to determine five different options for renewable energy supply. The components in each option were sized to generate renewable energy, which covers the building's consumption on the annual basis. Table 8 gives an overview of the options and the renewable energy system components.

Table 8. Renewable energy supply options determined for the scenario.

	Energy supply system		
	DHW	Heating	Rest
Reference building	DH	DH	EL Grid
Option 1	ST	ST	$PV_{(grid)}$
Option 2	ST + CHP	CHP	$PV_{(grid)}$+ CHP
Option 3	CHP	CHP	$PV_{(grid)}$ + CHP
Option 4	HP	HP	$PV_{(grid)}$
Option 5	HP	HP	$WT_{(grid)}$

DH – district heating, EL grid - electricity grid, ST – solar thermal system, PV – photovoltaic, grid – interaction with the grid, CHP – combined heat and power, HP – heat pump, WT – wind turbines.

In fact, it was here assumed that the output of the solar collectors has similar monthly distribution as the PV system, since both systems are exposed to the same solar radiations throughout the year. Flat plate solar collectors (FPC) was chosen as it can be integrated in the building façade. PV system simulation tool PVSyst v5.56 was used to calculate the expected annual performance of the PV system for electricity production (APPENDIX 4). Mono-crystalline silicon PV modules were modeled with 30° tilt on the flat roof of the building. The solar thermal system was estimated according to the results of the PV simulation (APPENDIX 5). A micro Stirling biomass CHP was selected as supply system component for the second and third option. This technology has good potential due to its ability to attain high efficiency and fuel flexibility (renewable energy sources like solid biomass) (NTNU and SINTEF, 2007). Ground-source heat pump was chosen among other systems as it can achieve a high energy efficiency and COP (3.5-4) due to the relatively high and stable heat source temperature (NTNU and SINTEF, 2007). The COP of 3.5 was here chosen for the two options (4 and 5). Furthermore, the relation between different system's efficiencies and GHGs emissions was then analysed and compared. Lastly the wind turbine system was estimated according to local climate analysis (APPENDIX 6). It was here assumed that the turbines are located in the Brøset area, close to the building's site.

The efficiencies of technologies applied in the analysis were chosen (see Table 9) and the delivered energy for each option was afterwards calculated.

Table 9. Supply systems efficiency according to NS 3031:2007 (Standard Norge, 2007).

Technologies	Efficiency factor
Photovoltaic	100
Solar thermal	8.55
MiCHP biomass	0.84
Boiler biomass	0.84
Heat pump	3.5 (COP)
Wind turbine	100
Grid electricity	0.98

As it is in the purpose of this study to analyze which is the optimal solution for achieving ZEB, the GHGs emissions for each option were calculated. This is done by means of three different methods: spreadsheet-based calculation (performed according to the Norwegian procedure NS 3031:2007 in Excel), SIMIEN software and Klimagassregnskap – stationary energy module (planned phase) (Statsbygg/Civitas, 2007). The use of multiple methods allows to compare different approaches for achieving the balance in the zero emissions building.

The following options hold through the work presented in this scenario: the GHGs are accounted for one year; the accounting is limited to operational energy, hence no embodied energy is considered. Moreover, emissions factors for the energy systems were chosen for each method (see Table 10). In SIMIEN, the default factors were used when available, alternatively they were input manually from other sources. As mentioned before in Klimagassregnskap has its default values, just the electricity factor can be chosen. There must be noted that there is no national agreement on the CO_2 factors and thus there is a great uncertainty in these figures (Haase and Novakovic, 2010). Moreover is not clear how they were calculated and what they encompass.

Table 10. CO2 factors for different energy sources (Dokka et al., 2009, Haase and Novakovic, 2010).

	CO2-factor (g/kWh)		
Energy system	Excel	SIMIEN	Klimagassregnskap
Electricity from the grid	395[a]	395*	395**
Solar thermal system	51[b]	51 [b]	0
PV system	130[b]	395*	0
Wind turbine	20[b]	20[b]	0
Biofuel	14[a]	14*	0
Heat pump	395[a]	395*	74

[a] taken from (Dokka et al., 2009).
[b] taken from (Haase and Novakovic, 2010).
*SIMIEN default values (based on NS 3700:2010)
** European mix was here chosen in order to enable the comparison among the different calculation methods.

Finally a comparison of results obtained from different methods and analysis of saved GHGs emissions in the renewable energy supply options gives a basis of possible solutions for achieving a Zero Emission Building.

3.5.2 Scenario 2 - Strategies for reducing the embodied carbon from a life cycle perspective

(Nigar Zeynalova)

The scenario determines the influence of different structural solutions on total embodied emissions and how the results are affected by change in service life of materials.

The procedure of investigation consists of following steps:

1. Development of the steel and timber alternatives of the reference building. The initial concrete reference building was used as a basis for defining steel and timber solutions. Due to the scope and limitations of study, the design of the two alternatives involved certain simplifications. The objective was to use as much of the target material as possible, both in the structure and finishes. However, steel building also contains certain amounts of concrete, as it is rare for structural systems to be composed of a single material. Similarly, concrete is one of the construction materials used in timber building.

Steel building The structure consists of a steel beams and columns supporting composite concrete slabs with steel profiles. The external and internal walls are comprised of lightweight steel framing. The cladding of the facades is made of steel sheets. The solutions from Byggforskserien (Byggforsk, 2010) were used as a guideline to dimension steel beams, columns and internal steel frame walls (APPENDIX 7).

Timber building The timber columns are located in the same position and have similar sizes to the ones in the concrete building. Light weight timber framed walls are placed in the spaces between the structural columns. The floors and roof are of massive wood.

2. Assessment of emissions of three buildings in Klimagassregnskap materials module. The calculation was performed in the early and planned phase, respectively, in order to estimate the sensitivity to materials choices- if they are reflected in the resulting emissions. Eventually, the phase enabling more accurate emission accounting is chosen to be consistently used in the scenario.

3. Comparison of three solutions in terms of emissions and their distribution (based on the results of one phase).Which led to determination of the components contributing the most to the emissions. Additionally sensitivity tests were carried out to identify materials that constitute the most emissions in the components.

4. Analysis of the effect of service life on the emissions. Emissions were calculated for all three buildings first with 60 and then 100 years life time assigned to all the components. Afterwards comparison of the results obtained with default lifespans and increased lifespans is carried out.The influence of extended life times on the components and materials with relatively high emissions is studied in more detail. The structural components and insulation in Klimagassregnskap are expected to last the entire lifespan of the building, which is 60 years. The list of materials with life spans below 60 years is given in the Table 11.

Table 11. Service life times of various components and materials in Klimgagassregnskap (based on (Selvig et al., 2011).

Component	Elements and materials	Concrete building	Steel building	Timber building	Service life*
External wall	External timber cladding	✓		✓	30
	External steel cladding		✓		30
	Aluminium windows	✓	✓	✓	25
	Internal timber cladding	✓	✓	✓	20
Internal wall	Steel frame wall		✓		30
	Aluminium profiles	✓	✓	✓	15
	Glazing	✓	✓	✓	15
Floor	Laminated parquet	✓	✓	✓	25
Roof	Wind barrier	✓	✓	✓	30
	Vapour barrier	✓	✓	✓	30

*****Klimagassregnskap default values

5. Finally, based on the comparative analysis of the outcomes of above mentioned steps an optimum structural solution in regards to emissions is defined.

4. Results and discussion

The following section presents the results of all the analysis done in the thesis project. The results are organised in chapters following the steps of the methodology.

4.1 Base case

Results of daylight and shading simulations (Ecotect)

The results of daylight and shading simulations and their consequences on the design of the building are here presented. The daylight factors of 5% and 4,5% are achieved for first and second floor respectively (APPENDIX 8). The results are obtained for the facades with varying amount, distribution and transparencies of glazing. The fully glazed South facade and the translucent internal partitions allow light to penetrate deeper into the plan and ensure adequate daylight levels. The analysis of the solar exposure proves shading to be a sensitive variable for the South facade. For the optimal shading conditions a combination of external shading elements (vertical, horizontal overhangs, venetian blinds) is added to the facade. As a result the South facade is shaded 70-80% of the time on June 21st (APPENDIX 9). The balcony along the South facade functions as an overhang, providing shading and protection against overheating in summer. However, balcony can be a potential thermal bridge, therefore a solution which avoids this effect is taken from Løvåshagen dwelling development (APPENDIX 10) (Houlihan Wiberg, 2011). The visualization of the final design is given in Fig. 9.

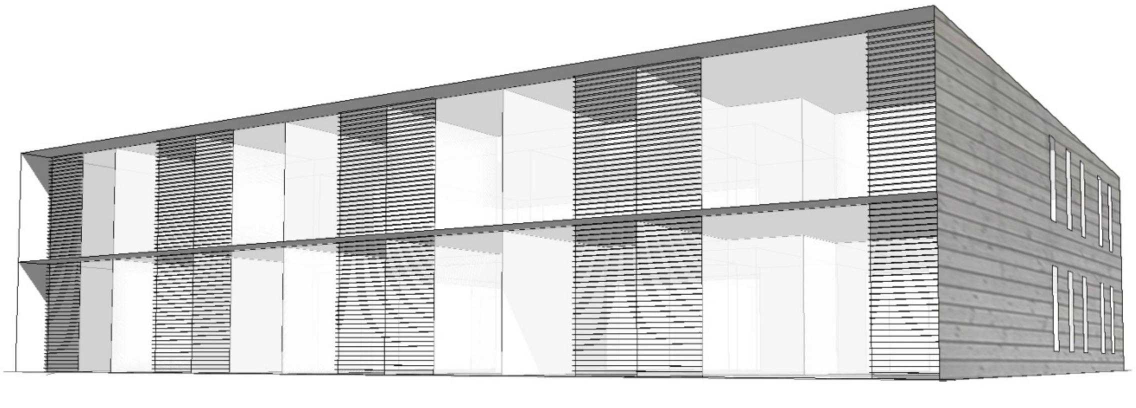

Fig. 9. Final design of ZEB Shoebox model – office building (ZEB,2011).

Results of energy performance calculations (Simien)

The main outcomes of the energy performance simulations are described below. The input data used for calculations is summarized in the APPENDIX 11. The total energy demand is 100,4 kWh/m²year, which is significantly lower than the 150 kWh/m^2 required in TEK 10.The results show the typical values for office building where 68% of operational energy use is electricity specific. Moreover the domestic hot water comprises only 7% of the total demands. The cooling demand (very little after all passive measures were applied) was here assumed to be met through natural ventilation. Its effect is estimated in Summer simulation (the windows are assumed to be open and infiltration rates increased).

Results of emissions calculation (Klimagassregnskap)

The overall emissions are shown in the Fig. 10. The results are based on the planned phase calculation. As can be seen in the breakdown, emissions are almost equally distributed over three modules - the difference of approximately 5 % is considered marginal. The 71% of energy use emissions comes from electricity delivered by the grid (Fig. 11). The result corresponds to the large share of electricity in total energy demands of the building.

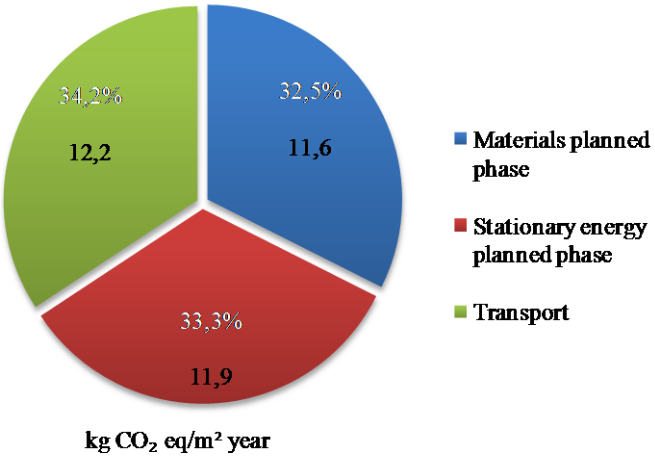

Fig. 10. Overall GHG emissions from materials, stationary energy, transport (Base case).

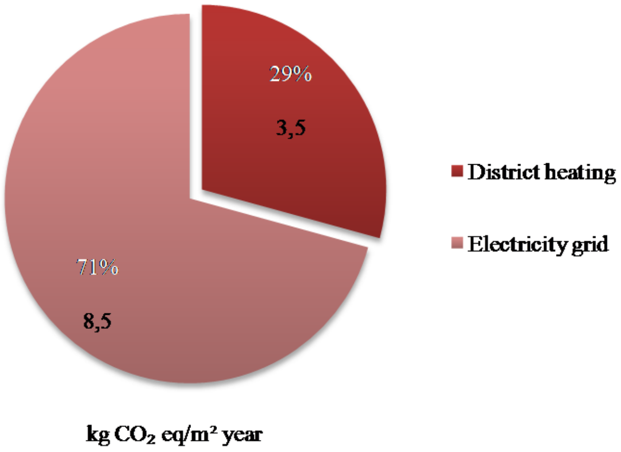

Fig. 11. GHG emissions from stationary energy with division to district heating and electricity grid (Base case).

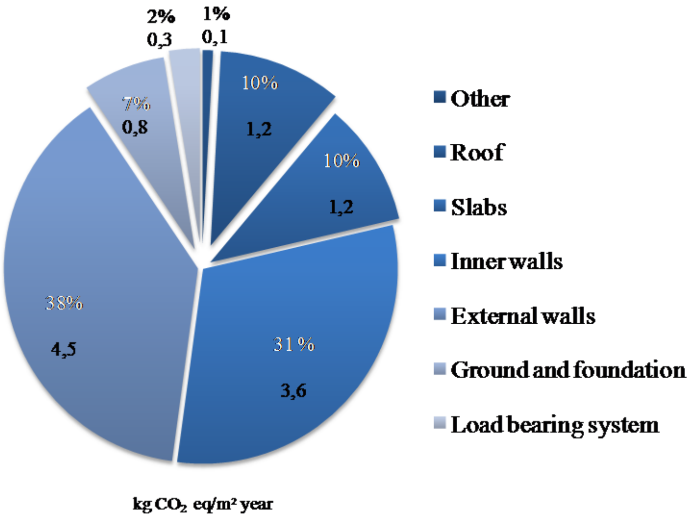

Fig. 12. GHG emissions from materials segregated into building components (Base case).

According to the Fig. 10 ~32,5% of the total emissions are attributed to materials. Looking at the distribution of the emissions in components, it is evident that the external walls are responsible for the most emissions ~38 % of total. Moreover inner walls have substantial share in the emissions ~ 31 %. The concrete structure (foundations, load bearing system, slabs and roof) constitutes the rest 29 % of the emissions.

4.2 Two variants

4.2.1 Variant Passive house

Results of energy performance calculations (Simien)

Simulations show that the total energy demand has decreased by 21% (79,4 kWh/m²year) as a result of the improvement measures. The heating demand is significantly reduced from 25,5 kWh/m^2year in the Base case to 14 kWh/m²year.

Results of emissions calculation (Klimagassregnskap)

It can be observed from the Fig. 14 that improved energy performance has a pronounced effect on the emissions from stationary energy use. The emissions reduce by 26 % as a consequence of minimized energy demands. For materials the relation is inverse - upgrade of the thermal envelope results in the 6 % increase in the emissions. The influence of additional insulation is visible in Fig. 15, the external wall accounts now for 5 kg CO_2 eq/m²year. Overall the share of materials in total emissions has risen to 36%.

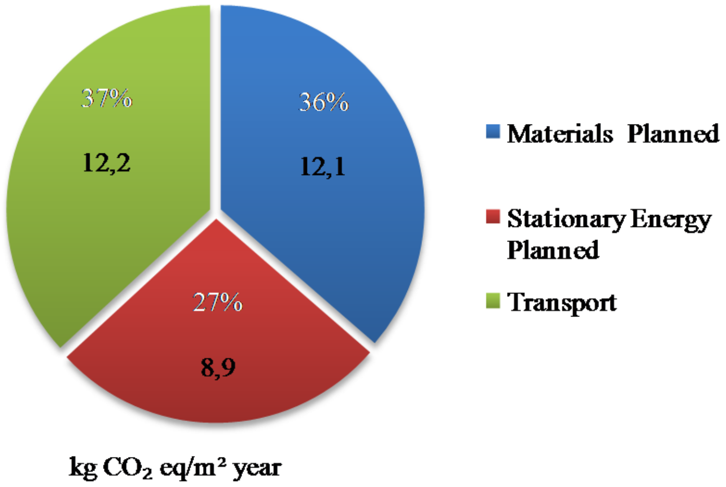

Fig. 13. Overall GHG emissions from materials, stationary energy, transport (Variant Passive House).

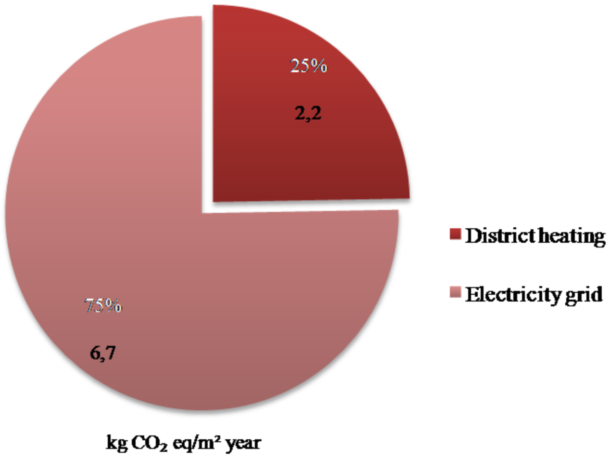

Fig. 14. GHG emissions from stationary energy with division to district heating and electricity grid (Variant Passive House).

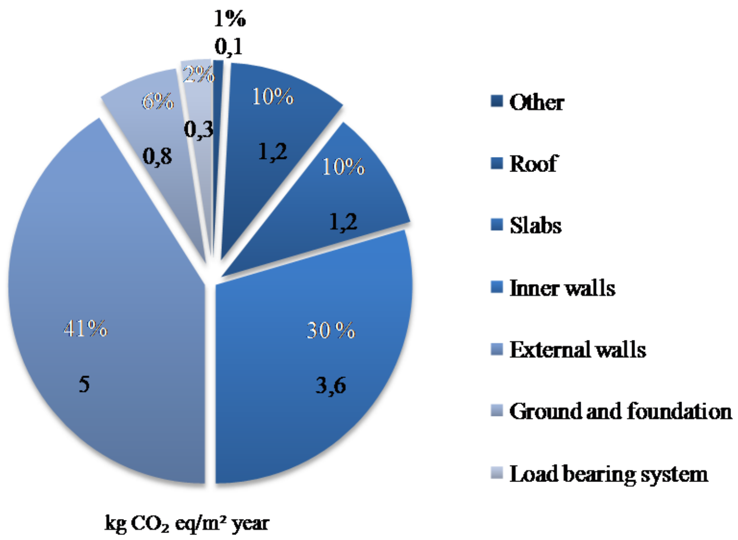

Fig. 15. GHG emissions from materials segregated into building components(Variant Passive House).

4.2.2 Variant ZEB

Results of energy performance calculations (Simien)

Obtained results demonstrate that despite the significant improvement of U-values total energy demand decreased only by 5 % (75,8 kWh/m^{2}y). The heating demand is decreased by one fifth compared to first variant.

Results of emissions calculation (Klimagassregnskap)

According to the Fig. 16, second variant achieves only a slight change in the overall emissions. However the emissions from materials rise by 1kg CO_2 eq/m²year from the 12,1 kg CO_2 eq/m²year in the first variant. Fig. 18 demonstrates that additional insulation in the external wall has approximately same effect on the emissions as in the first variant ~8%. increase. Consequently materials constitute 39 % of total emissions.

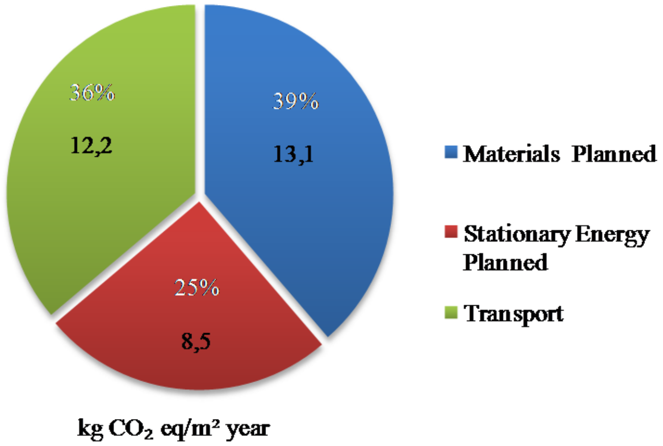

Fig. 16. Overall GHG emissions from materials, stationary energy, transport (Variant ZEB).

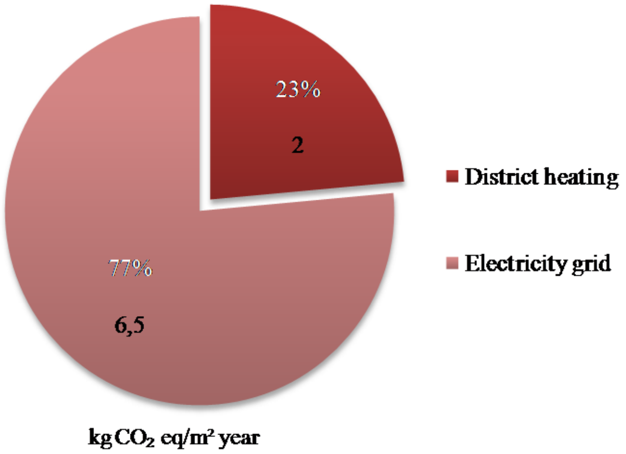

Fig. 17. GHG emissions from stationary energy with division to district heating and electricity grid (Variant ZEB).

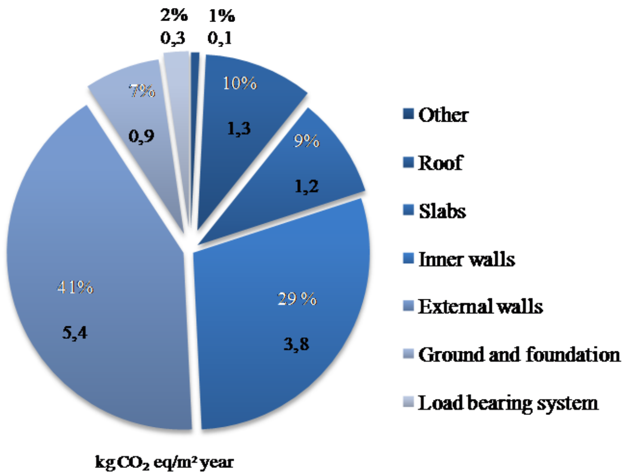

Fig. 18. GHG emissions from materials segregated into building components (Variant ZEB).

4.3 Comparison of the results in the stepwise upgrade

Thermal performance.

The extent of the efficiency of insulation measures applied in two variants has been estimated in PHPP tool. The graph below shows the U values as a function of insulation thickness (Fig. 19). The values are obtained for the external wall. As can be seen from the curve the effect of insulation on U value diminishes with each addition. The first 100 mm increase in thickness achieves 38% improvement of U value. The subsequent 100 mm increase contributes to 26 % improvement. This implies that very low U values of ZEB require substantial amounts of insulation, which might not be feasible from the point of view of embodied emissions.

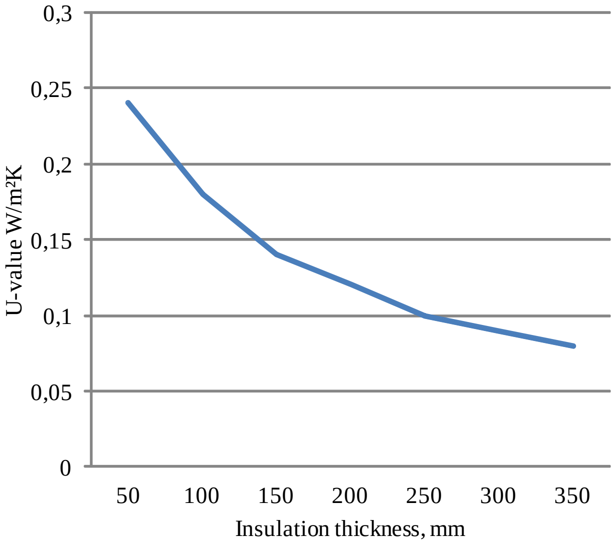

Fig. 19. U values as a function of insulation thickness.

Energy performance and emissions

The effectiveness of applying higher performance requirements is analyzed in regards to total energy demands , emissions from energy use and materials. According to the Fig. 20 the first step (from TEK 10 to Passive house) achieves the most significant reduction in energy needs - 21 % compared to Base case. Further improvement of U values (Variant ZEB) reduces the demands only by 5 % below the first variant's level.

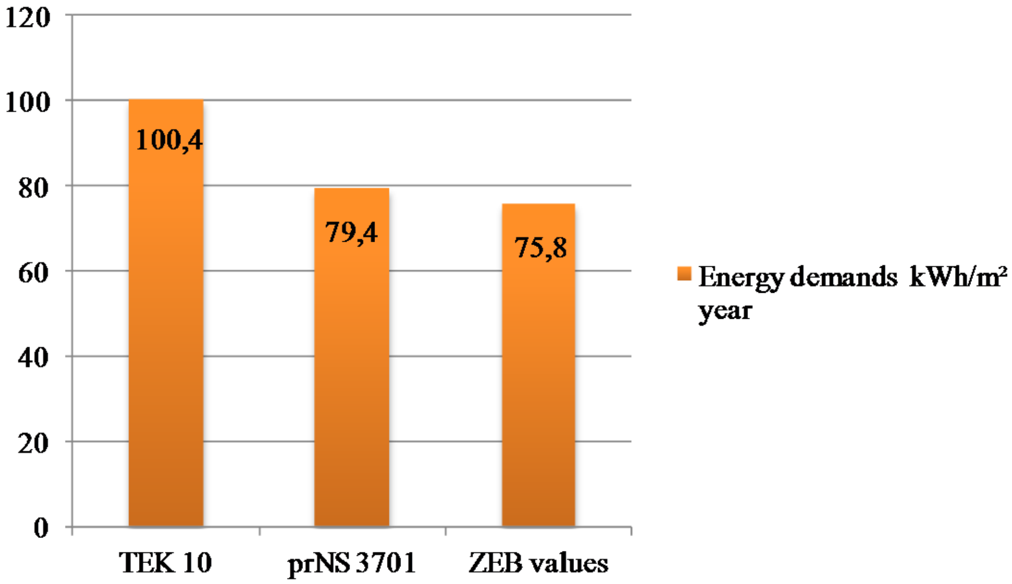

Fig. 20. Annual energy demands of Base case and two Variants.

It can be observed from the Figs. 20 and 21 that notable decrease in operational energy emissions of Passive house variant results from highly reduced energy consumption.The next step (ZEB) achieves marginal decrease of emissions ~ 5% , due to reduction of energy use being negligible.

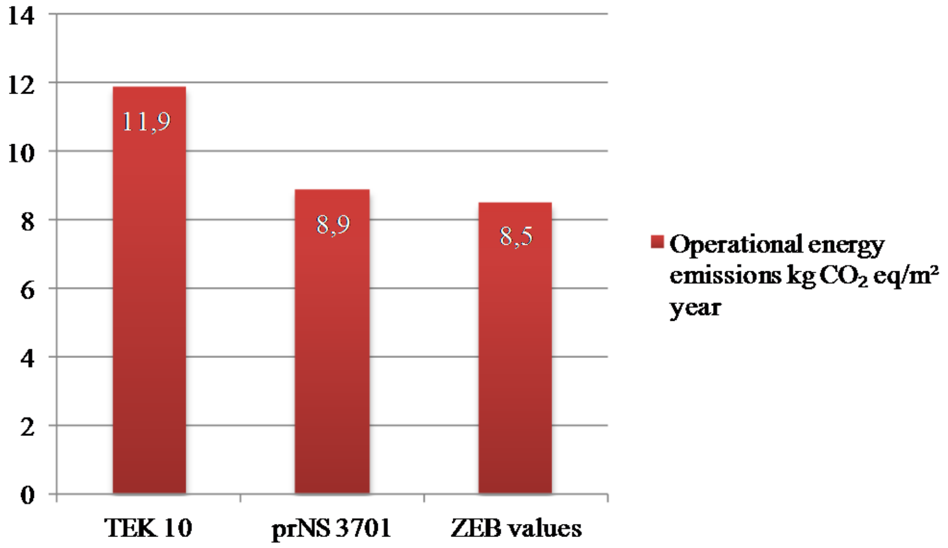

Fig. 21. Annual operational energy emissions of Base case and two Variants.

The emissions accounted for the Base case and its two variants illustrate the relation of improved thermal envelope with the increase in emissions from materials. As can be seen from the Fig. 22 the Passive House variant has a lower contribution to emissions than ZEB variant. While first step results in 5 % increase, the following step (ZEB value) is responsible for ~ 10 % rise in the embodied emissions.

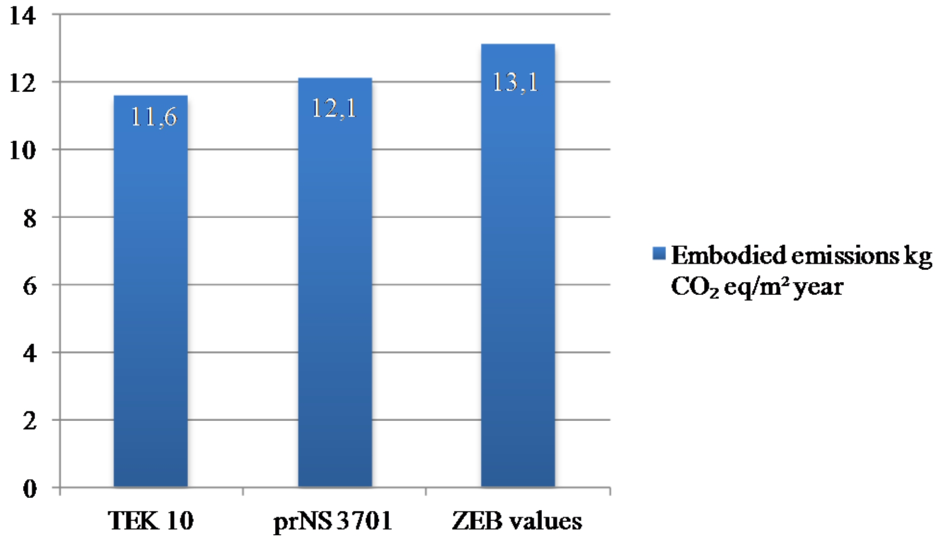

Fig. 22. Annual embodied emissions of Base case and two Variants.

4.4 Determination of optimum performance requirement (*Reference building*)

The two variants of the Base case have been analyzed in order to define the reference building. Which will be a common starting point for the development of the two scenarios with aim of balancing emissions from energy use and minimizing embodied emissions, respectively.

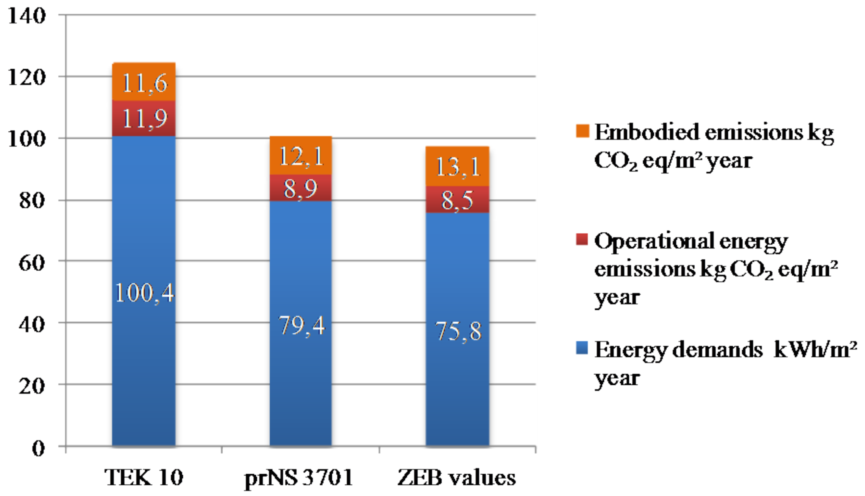

Fig. 23. Annual energy demand, operational and embodied emissions of Base case and two Variants.

The Fig. 23 depicts the overall effect of the stepwise improvement on the energy consumption, operational and embodied emissions. The first variant allows the largest reduction in energy demands and operational energy emissions ,with low contribution to the embodied emissions. The application of ZEB values has considerably less impact on all three aspects. As a result of the above mentioned Passive house has been chosen a reference building for further development.

4.5 Discussion of the main results

The calculated emissions show that increased energy efficiency is not enough for achieving zero emission balance. The results demonstrate that the choice of energy supply might have a significant impact on the emissions as most of the operational energy emissions come from electricity use. The operational energy use has a significant share in the overall emissions, therefore next step is to use a more efficient energy supply system. Another aspect that has high potential in emission reduction is the choice of the materials. As the share of embodied emissions increases it is important to determine the influence of the different construction materials on the emissions.

4.6 Strategies for optimizing the operational energy supply

4.6.1 Energy budget

As mention before the *Reference building* requires 79.4 kWh/(m^{2}year). Here the results of a detailed calculation of the energy use in the building are presented. Assumptions about operation time (according to NS 3031 for office building – 12hours*5days*52weeks) and installed power (operation time*energy demand kWh/m^{2}year) were made. The Table 12 gives an overview of the energy budget, while the Fig. 24 depicts the monthly distribution of the demand.

Table 12. Energy budget for the Reference building.

Category	Installed power (in W/m²)	Operation time (h/y)	Energy demand (kWh/(m²y)	(kWh/y)
Space heating			6.0	5035.0
Ventilation heating	2.56	3120	8.0	6788.0
Domestic hot water	2.37	3120	7.4	6241.0
Fans and pumps	2.02	3120	6.3	5384.0
Equipment	9.58	3120	29.9	25236.0
Lighting	6.99	3120	21.8	18360.0
Cooling	-		0	0.0*
Total energy demand			**79.4**	**67044.0**

* Cooling demand was assumed to be zero.

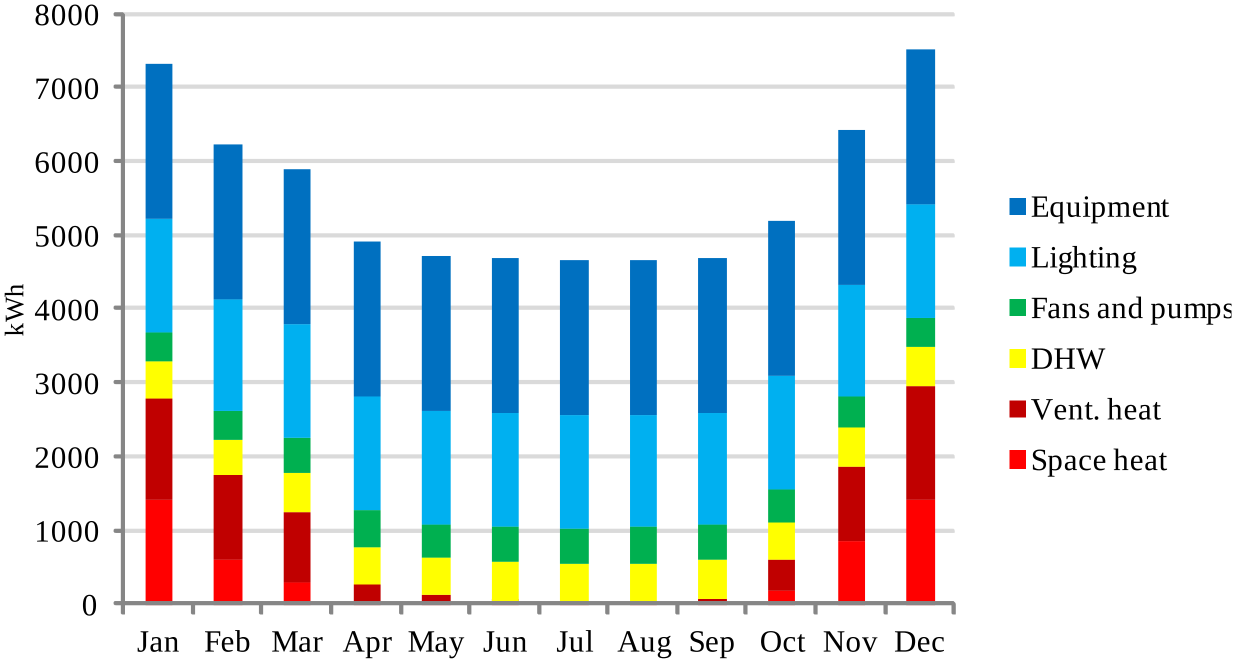

Fig. 24. Monthly total energy demand distribution.

The energy budget was then divided into need for heat and electricity. Table 13 gives the sum for heating and electricity. Here, space and ventilation heating and warm water was assumed to be heat while electricity use was assumed for fans and pumps, technical equipment and lighting (assuming a heating system that is not based on electricity). The *Reference building* has an annual energy budget of 67044 kWh. This can be divided into 18064 kWh heat (27% of the total budget) and 48980 kWh electricity (73% of the total budget).

Table 13. Annual energy budget for heat and electricity.

Category	Electricity (kWh/y)	Heating (kWh/y)
Space heating		5035.0
Ventilation heating		6788.0
Domestic hot water		6241.0
Fans and pumps	5384.0	
Equipment	25236.0	
Lighting	18360.0	
Total energy demand	**48980.0** (73%)	**18064.0** (27%)
	Total	**67044**

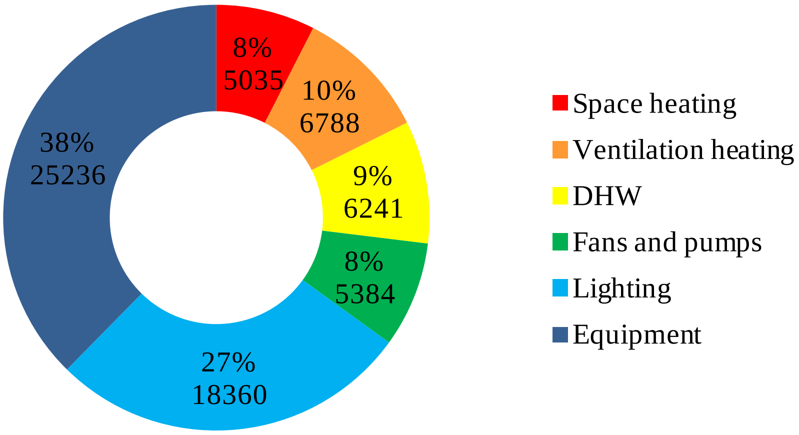

Fig. 25. Total energy demand per category and share of each component (kWh/y).

The results presented until here show that electricity (fans and pumps, technical equipment and lighting) has the highest share in the energy budget and is constant throughout the year, as it is the trend for office buildings. With these energy budget figures it is possible to estimate alternatives renewable energy supply systems, the specific delivered energy and consequently calculate the GHGs emissions.

4.6.2 Renewable energy supply options

Option 1 (Solar thermal and PV)

Building with solar thermal and photovoltaic installations. Solar thermal panels are sized to meet the DHW demand and the heat demand while the PV panels are sized to meet electricity demand.

The results (also plotted as in graphs in order to give a visual understanding - see APPENDIX 12) show that there is a significant seasonal unbalance between delivered heat from the solar thermal system and the building's heat demand (heating and DHW). One solution would be to use a seasonal heat storage system that enables to shift some of the supplied heat to the winter when is needed (Haase and Novakovic, 2010). Estimations were made and calculations showed that 80 m^3 of adsorption seasonal storage tanks are necessary for covering building's heating and DHW demand in winter (APPENDIX 13). This will have implications on the design of the building as additional space for the tanks is needed. Another solution for covering the mismatch might be to feed the excess heat into Trondheim district heating network and take it back in the winter months.

Likewise the solar thermal system, the PV electricity production is subject to seasonal mismatch. Therefore, the building has to rely on the electricity grid for covering the power demand in winter and feeding in the generated surplus in summer.

The above considerations bring to the conclusion that when using energy carriers with a poor correlation between building's energy demand and energy generation, the building's ability to interact with the grid becomes crucial and has to be addressed.

Option 2 (Solar Thermal, biomass micro CHP and PV)

Building with solar thermal and photovoltaic installations and a micro Stirling biomass CHP. Solar thermal panels are sized to meet the 70% of DHW demand, the rest is covered from the micro CHP. The micro CHP runs with heat demand as priority (70%) with electricity production as by product (30%). The rest is covered by PV installations.

The results (APPENDIX 14) show that the micro CHP is covering most of the heating demand in winter. However, as the solar thermal system is covering most of the DHW demand, especially in summer, a micro CHP with lower heat power can be used in order to meet the remaining heating demand. In this respect a micro CHP with power heat of 4.5 kW (total energy output ~ 16000 kWh) was chosen for this option. The system is sized to cover 35% of the peak heat demand. Hence the need of using an additional conventional biomass boiler during the hours with peak heat load (winter months) in order to optimize the yearly heat production (for additional explanation see

APPENDIX 15). Furthermore, when designing the building is important to keep present that biomass requires a storage space. As in the previous option, the PV panels are covering most of the electricity demand, therefore the building has to rely on the electricity grid for the seasonal balancing. It is worth noting that the amount of electricity taken from the grid during the winter months is slightly lower due to the power production of the micro CHP.

Option 3 (Biomass micro CHP and PV)

Building with a micro Stirling biomass CHP and photovoltaic installations. The micro CHP runs with heat demand as priority (70%), covering also the DHW demand, with electricity production as by product (30%). The rest is covered by PV installations. The results (APPENDIX 16) are similar as the previous option. The main difference lies in the fact that the micro CHP has to cover the whole heating demand, hence the importance of using a system with higher power heat – 6.5 kW was chosen for this option (total energy output ~ 23000 kWh). The system is sized to cover 50% of the peak heat demand, an additional conventional biomass boiler during the hours with peak heat load is needed.

Option 4 (Heat pump and PV)

Building with a ground source heat pump and photovoltaic installations. PV panels are sized to meet corresponding electricity demand. The results (APPENDIX 17) show that the heating and domestic hot water demands are covered by the ground source heat pump which is sized to supply 100% of the peak heat demand. Once again, PV panels are covering most of the electricity demand, therefore the building has to rely on the electricity grid for the seasonal balancing.

Option 5 (Heat pump and wind turbines)

Building with wind turbines and a ground source heat pump (APPENDIX 18). The wind turbines are sized to meet the electricity demand in first instance. A surplus of production was then considered to be feed back into the grid. Otherwise it could supply the future Brøset carbon neutral neighbourhood with renewable energy. It is worth noting, however, that wind is considered as unreliable source of energy as its velocity can often changes dramatically. As a result, the power output can swing wildly over the course of a single day.

The results for the heating demand mirror the results from the previous option as the same supply system has been chosen.

4.6.2.1 Delivered energy

After the energy budget was estimated and the renewable supply options with the specific efficiencies (Table 9 in methodology) were chosen, the delivered energy was calculated for each alternative. Results are reported in the Fig. 26.

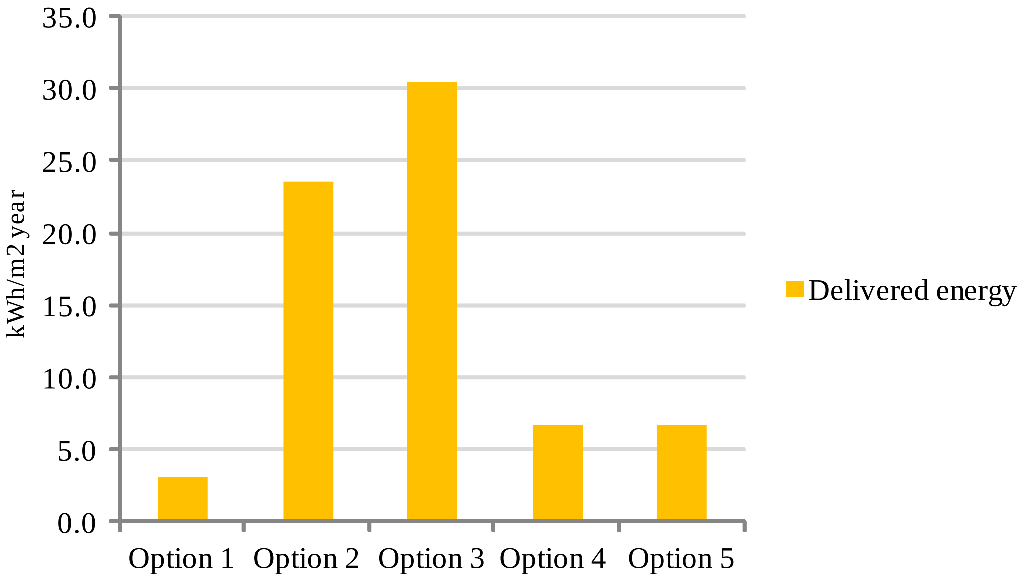

Fig. 26. Delivered energy of different supply options.

It can be seen that options 2 and 3 result in higher overall delivered energy due to the fact that the biofuel micro CHP has a low efficiency factor . The highest delivered energy is needed for option 3 (biomass micro CHP and PV) as the micro CHP is covering the entire heating demand which implies a higher power heat. The first option has the lowest value as solar thermal and PV systems have a relatively high efficiency factor compared to others. It can be concluded that the delivered energy increases due to the diminishing efficiencies and vice versa.

4.6.3 Analysis and comparison

GHGs emissions calculation

The GHGs emissions of the operational energy (i.e. operational carbon) were calculated using the three methods. In all of them the emissions are calculated based on the delivered energy with the following formula: *Delivered energy* $* \ CO_2$ *factor [CO2eq]*

The results are presented in Table 14 and Fig. 27, where the methods have been sorted in the order they were performed. The spreadsheet-based calculation method is called “Excel” for an easier and better understanding.

Table 14. Total annual operational carbon for the reference building and all the renewable energy supply options calculated with three methods.

	CO2 emissions (kg CO2-eq/m²year)		
	Excel	Simien	Klimagass.
Reference building	29.3	28.8	17.5
Option 1	-3.2	0.4	0
Option 2	-2.9	0.5	0
Option 3	-2.8	0.6	0
Option 4	-0.9	2.6	1.5
Option 5	-5.6	2.4	1.5

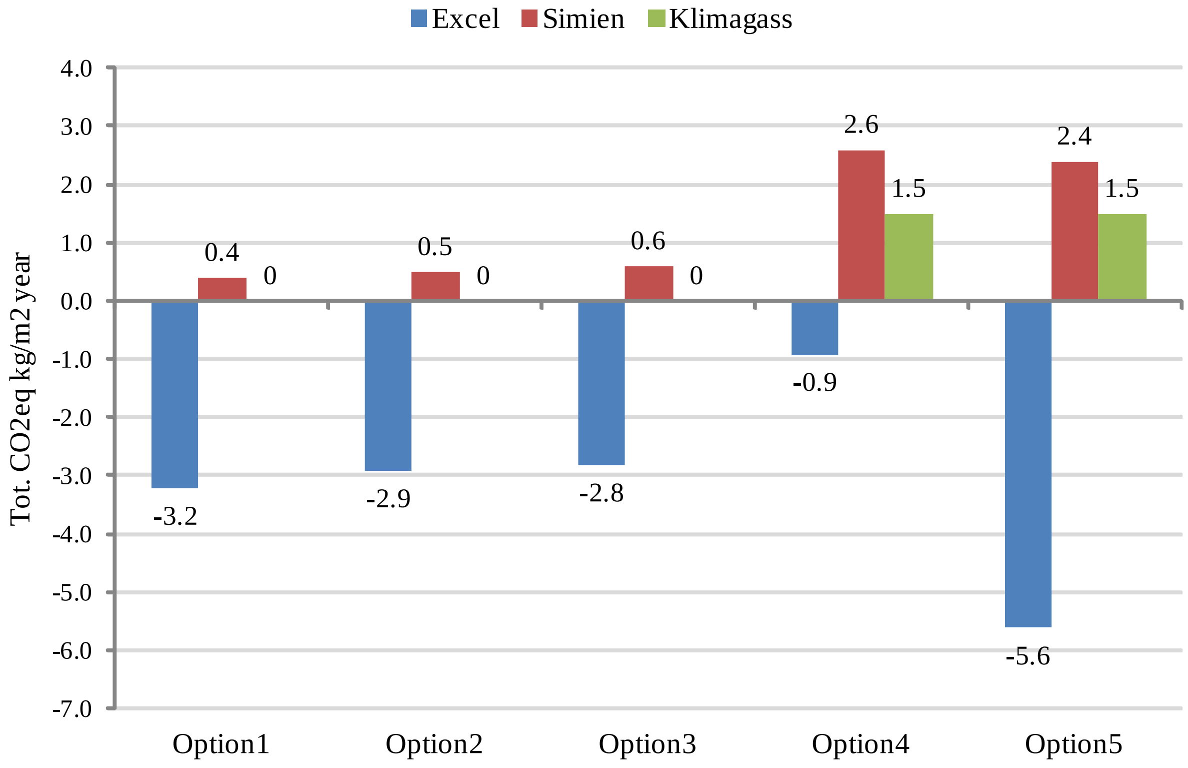

Fig. 27. Overview of the total operational carbon of the five energy supply options.

The results show that all the supply options significantly reduce the GHGs emissions from operational energy, independently of which calculation method was used. However, the graph present some singularities.

It should firstly be noticed that the values obtained with spreadsheet-based calculation (APPENDIX 19) are negative in all the options. This is due to the fact that the method is taking into account the interaction with the electricity grid. In order to satisfy the condition of ZEB balance (here calculated by means of physical units of CO_2eq.), the carbon equivalent emissions associated with energy feed into the grid have to be considered. Therefore, becomes evident that the interaction is crucial for achieving the zero emission goal. On the other hand the values obtained in Simien and Klimagassregnskap are positive (or zero, which will be discussed further in this section) in all the options as is not possible to include a surplus of the building's energy production in the calculation process. Therefore, the interaction with the grid is not taken into account. It is worth noting, however, that the spreadsheet-based calculation and Simien follow the same trend (increasing or decreasing trend) as the calculation in both cases are based on the Norwegian calculation procedure NS 3031 (Standard Norge, 2007).

In the second instance, it is worth focusing the attention on the use of different CO_2 factors which causes divergences in the values. In the first three options the CO_2 factor for solar thermal and biofuel (used for micro CHP) used in Excel and Simien is relatively low compared to others energy carriers, which results in low GHGs emissions. In Klimagassregnskap the same systems has a CO_2 factor of 0. It was here assumed that the tool considers on-site renewable energy supply, i.e. sun, biomass and wind systems, as carbon emissions free (without taking into account the embodied energy of the technologies). However, it is not clear which inputs are used in the calculation of the emission factor. In the fourth and fifth option the high CO_2 factor of the heat pump significantly influences the emissions. However, in the last option, for Excel and Simien, it can be noticed that a supply system with wind turbines can help to minimize emissions as the it has low CO_2 factor. Once again in Klimagassregnskap the PV and wind system is consider as carbon neutral supply system, therefore the emission are solely due to the heat pump.

Delivered energy and GHGs emissions

The interplay between the delivered energy and GHGs emissions in the second and third option was here analysed and discussed. As it can be seen in the Fig. 26 the use of biofuel results in a higher amount of delivered energy, while the emissions in the two options are reduced (Fig. 27) due to the low CO_2 factor. It has been argued that renewable energy resources like biomass and biofuels with low GHG emissions are not necessarily equally environmental friendly as they are limited and its availability varies significantly with the geographical area (Sartori et al., 2010). Hence, the importance of not overemphasizing the benefit of these resources. An option for the ZEB definition could be to account for some sort of environmental credits that are defined with a broader scope than just GHG emissions, i.e. environmental cost analysis (Sartori et al., 2010).

COP and GHGs emissions

In order to achieve a better understanding of the interplay between the heat pump's coefficient of performance (COP) and GHGs emissions and its repercussions on the total CO_2eq of the energy supply options, different COPs were analysed and compared. As mentioned before increase in efficiency of the supply system implies the reduction of the delivered energy. Consequently the emissions decrease. The results are shown in Figs. 28 and 29, for the fourth and fifth option, respectively.

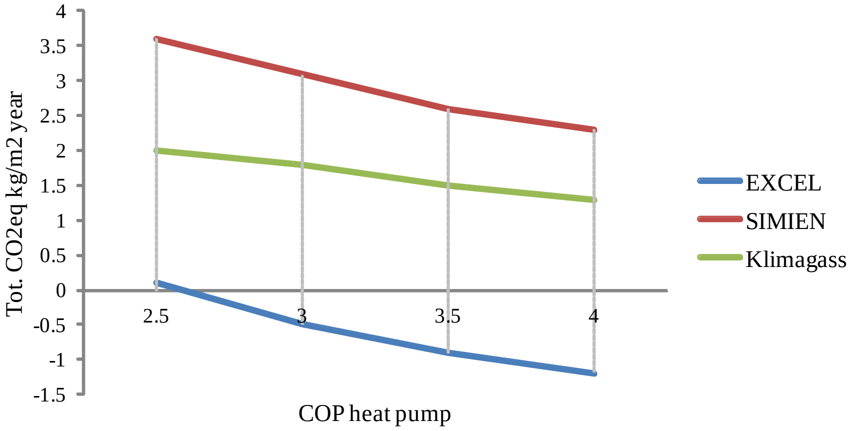

Fig. 28. Total CO_2eq. versus COP of the heat pump for the fourth option (heat pump + PV).

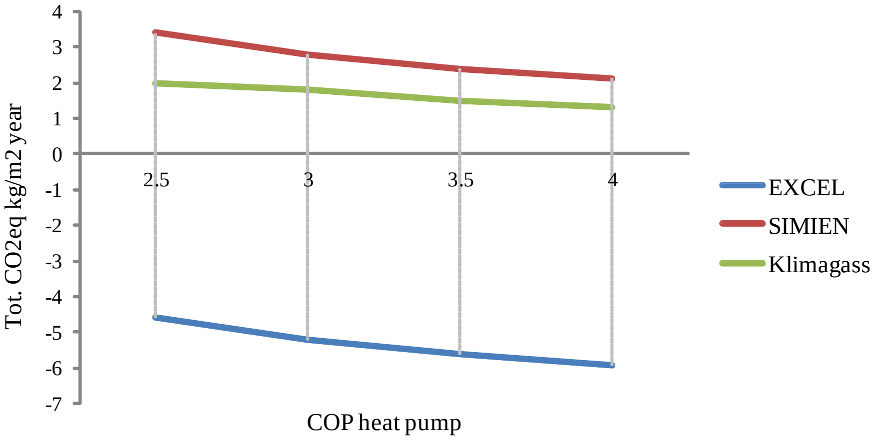

Fig. 29. Total CO_2eq. versus COP of the heat pump for the fifth option (heat pump + wind turbines).

The graphs show how, in both options, the higher COP results in less total emissions. It is worth noting that in both options the trends of the curve are about the same for all the three methods, meaning that there is a steady decrease of the emissions. However, it might be observed that in the fourth option the slope is more pronounced. It was here assumed that in the option with PV (4th option), the COP of the heat pump is an important factor to take into account when decreasing the emissions, while in the fifth option the emissions are already low because of the wind energy supply. Therefore, higher COP is not actually needed as there will be no significant reduction in the emissions.

4.6.4 Evaluation and conclusion

The section presents a comparison of the results from various energy supply options and address the research question.

Table 15. Comparison of five renewable supply options according to different criteria.

Supply option	Energy label	Delivered energy*	CO2eq emissions*			On-site / off-site supply options**
			Excel	Simien	Klimagass	
Option 1	A	1	2	1	1	I (grid)
Option 2	A	4	3	2	1	III + I (PV) (grid)
Option 3	A	5	4	3	1	III + I (PV) (grid)
Option 4	A	2	5	5	2	II + I (PV) (grid)
Option 5	A	3	1	4	2	II (grid)

* 1= best
** Based on the graph of different possible renewable supply options developed by Marszal et al., (2011).
Grid – interaction with the electricity grid.

According to the Norwegian labelling system for the energy performance of buildings all the options analysed reach A, which the most energy efficient class (delivered energy less than 84 kWh/m2 year). It can be argued that when pursuing the goal of zero energy or zero emissions building this labelling may not help to make the optimal decision for a building's energy reduction. It is therefore important that the ZEB definition set mandatory minimum requirements on energy efficiency (Sartori et al., 2012).

Moreover, the ZEB definition may define a hierarchy of renewable supply options. Typically, the distinction is made between 'on-site' and 'off-site' supply options (Marszal et al., 2011). The division made in the above analysis is based on the graphical representation developed by Marszal et al., (2011). In this respect the Option 1 (solar thermal and PV system) is generating all the energy needed on the building footprint, therefore is labelled as I alternative. According to Torecellini et al. (2006) priority should be given to this option. Options 4 (heat pump and PV) and 5 (heat pump and wind turbine) are labelled as II alternative as they use renewable energy sources available at the site of the building ('on-site generation from on-site renewable'). Options 2 and 3 are categorized as III alternative - 'on-site generation from off-site renewable' as the sources to run the biomass micro CHP have to be transported from off-site. It should be noticed, however, that there are uncertainties in renewable supply options with regards to the biomass/biofuel CHP as in some cases is seen as on-site (focus on the actual location of the electricity generation) and in another as off-site renewable supply (focus of the fuel's origin) (Marszal et al., 2011).

The Option 1, to which should be given priority in terms of 'on-site' and 'off-site' hierarchy, presents also the lowest GHGs emissions in Simien and Klimagassregnskap, as well as the least delivered energy. In the spreadsheet-based calculation (Excel) the lowest emissions were estimated for the Option 5 (heat pump and wind turbines). However, it was here assumed that the first option is more feasible than the last one, due to reliability of the energy supply, availability of the technologies and their easier implementation in an urban area.

To sum up the Option 1 may represents an optimal solution on the pathway to a ZEB. This solution is closely followed by the Option 4 and 5. However, all the renewable energy supply options presented and analysed here can be considered acceptable in terms of energy and environment.

Nevertheless, it is worth noting that other important parameters of energy supply selection should be taken into account, including embodied energy/carbon of the technical installations and the cost-attractiveness of the systems . The embodied energy/carbon of the building services represents one of the most significant components of total embodied energy (Cole and Kernan, 1996). Hence, the importance of including the aspect in the analysis so that it broadens the scope of Net ZEBs as environmental friendly and sustainable buildings (Sartori et al., 2012). Moreover the cost-attractiveness of different systems is playing an important role in the energy supply selection, as it is often an obstacle when investing money in environmental or climate friendly products (Marszal, 2012). To sum up the next step of the scenario could be to focus on investigating these parameters and analyze the implications they have on the energy supply selection.

4.7 Strategies for reducing the embodied carbon from a life cycle perspective

4.7.1 Analysis of the accuracy of the early and planned phase calculations

Comparison of buildings component's emissions calculated in two phases

Figs. 30, 31 and 32 show the embodied emissions segregated into six building components with the subdivision into early and planned phase for concrete, steel and timber building, respectively. It is worth noting that the difference between emissions in early and planned phase remains similar for certain components in all three buildings. Two trends can be observed in the results - components with higher emissions in the early phase and the ones with increased emissions in planned phase.

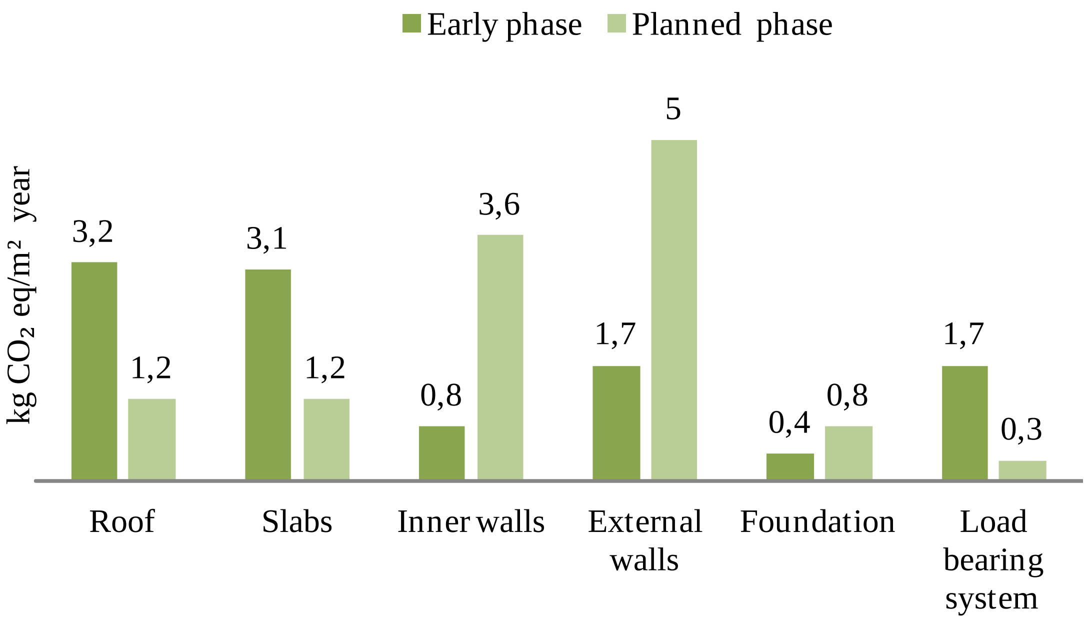

Fig. 30. Embodied emissions distributed over building component from early and planned phase calculation (Reference concrete building).

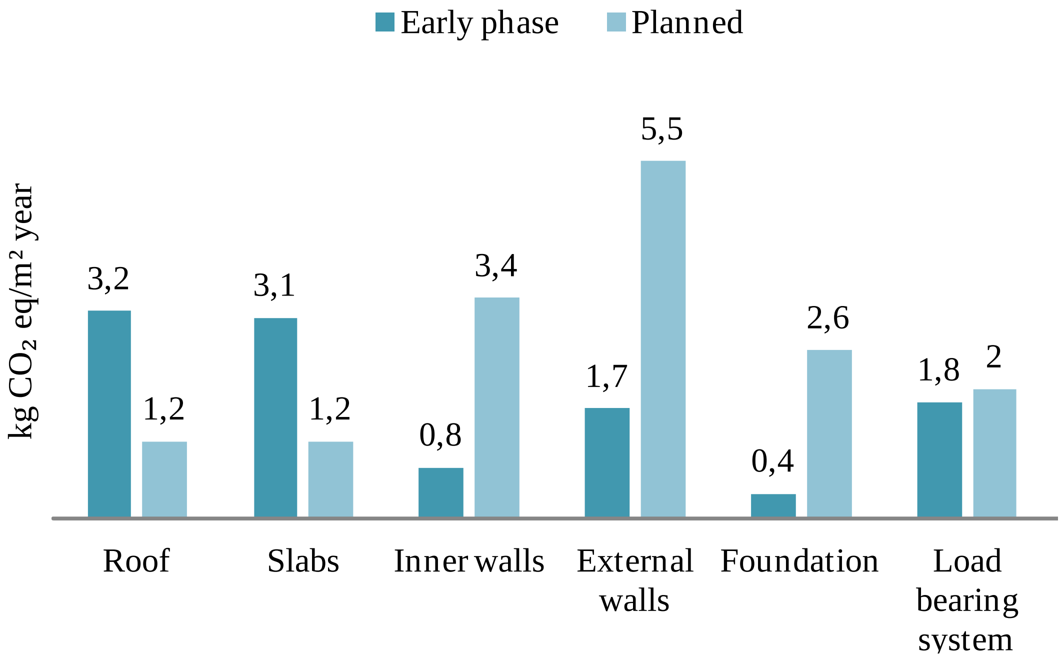

Fig. 31. Embodied emissions distributed over building component from early and planned phase calculation (Steel building).

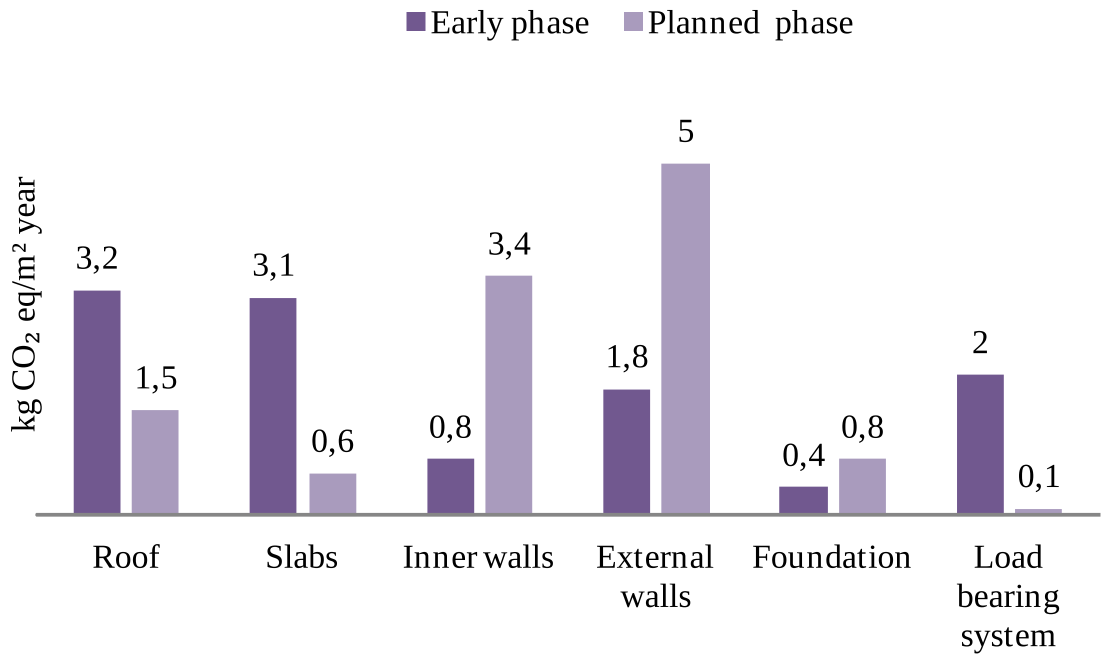

Fig. 32. Embodied emissions distributed over building component from early and planned phase calculation (Timber building).

The graphs demonstrate that in both concrete and steel building the slabs and roof contribute to emissions 2,5 times more in early phase than in planned (Figs. 30 and 31). The discrepancy in the values is due to the fact that early calculation uses default thickness of concrete slab as well as predefined amount and type of insulation(EPS), which has substantially higher emissions than the glass wool used in planned phase calculation. Moreover, Fig. 30 shows that load bearing system is responsible for approximately 5 times higher emissions in the early phase. The difference arises from unavailability of choice of concrete columns and beams in early phase calculation (only steel and timber is available). The above described limitations are assumed to be a reason for increased emissions in the 3 components (roof, slabs, load bearing system).It can be stated that early phase calculation leads to a certain degree of overestimation of the emissions.

However the opposite relation can be observed for internal and external walls. According to the Figs. 30, 31 and 32 external walls have 3 times lower emissions in the early calculation. The substantial difference results from restrictions in the early phase - layering of the wall and insulation are predefined. Additionally there is no possibility to choose the window frames and the default thickness of glass cannot be modified. The planned phase, on the other hand allows to define the materials closest possible to the actual design .The emissions for external wall are calculated with the exact amounts of insulation used and the large areas of triple glazed windows with aluminium frames are taken into account. Therefore the share of the external wall in the emissions is much higher in planned than in early phase. In all 3 buildings inner walls amount for 4 times more emissions in planned calculation. This is due to the fact that glazed surfaces and aluminium profiles in the internal partitions are not considered in calculation, due to limited choice of materials in early phase. Same applies for steel frame interior walls.
Concluding the comparison it can be noted that on a component level early phase calculation results in either underestimation or overestimation of the emissions depending on the component studied.

<u>Comparison of the buildings overall emissions in two phases and determination of optimum phase</u>

Fig. 33 depicts variation in the emissions from early to planned phase. The graph shows that change of structure from concrete to steel and eventually to timber is practically not reflected in the results of early phase ,with difference of less than 4 %. However, a more pronounced effect can be observed when the structural materials are changed in the planned phase. As can be seen from Fig. 33 the emissions of the concrete reference building increase by 10 % when calculated in the planned phase. The most evident change in values is in steel solution, with emissions 31 % higher than in early phase. Thus it can be argued that planned phase is better suited for assessing the effect of changes in materials on the emissions. The early phase calculation on the other hand gives a rather narrow range of standardized results according to building's typology and size. The conclusion can be drawn that for the aim of the study and for obtaining more realistic emissions planned phase calculation should be preferably used.

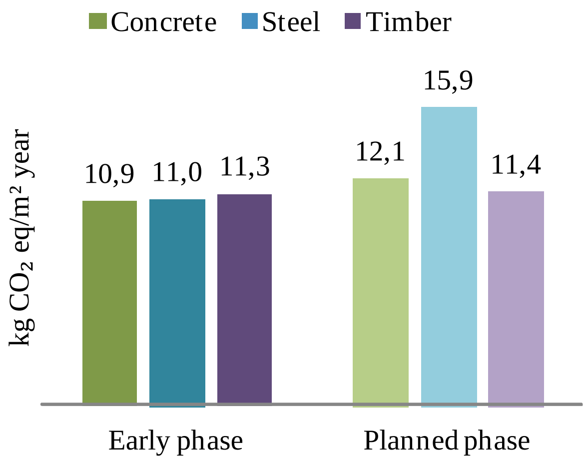

Fig. 33. Embodied emissions of Concrete, Steel and Timber building calculated in early and planned phase.

4.7.2 Analysis of embodied emissions of the three structural solutions

Distribution of emissions in the buildings components

The embodied emissions subdivided into six building components (roof, slabs, inner walls, external walls, foundations, load bearing system) are shown in the Fig. 34. The external walls represent dominant proportion of the total emissions-constituting 41, 35 and 44% for the concrete, steel and timber building. The inner wall is the component responsible for the second largest emissions with 30 % in the concrete and timber, and 22% in the steel building. The lowest contribution is from the load bearing system (columns and beams) - 3 an 1 % for concrete and timber building, respectively.The exception is steel building where columns and beams account 11 % of emissions, due to steel being a highly emission intensive material. Moreover foundations in the steel building are standing out from the general emissions distribution pattern ,being the third significant contributor to the emissions -roughly 17 %.

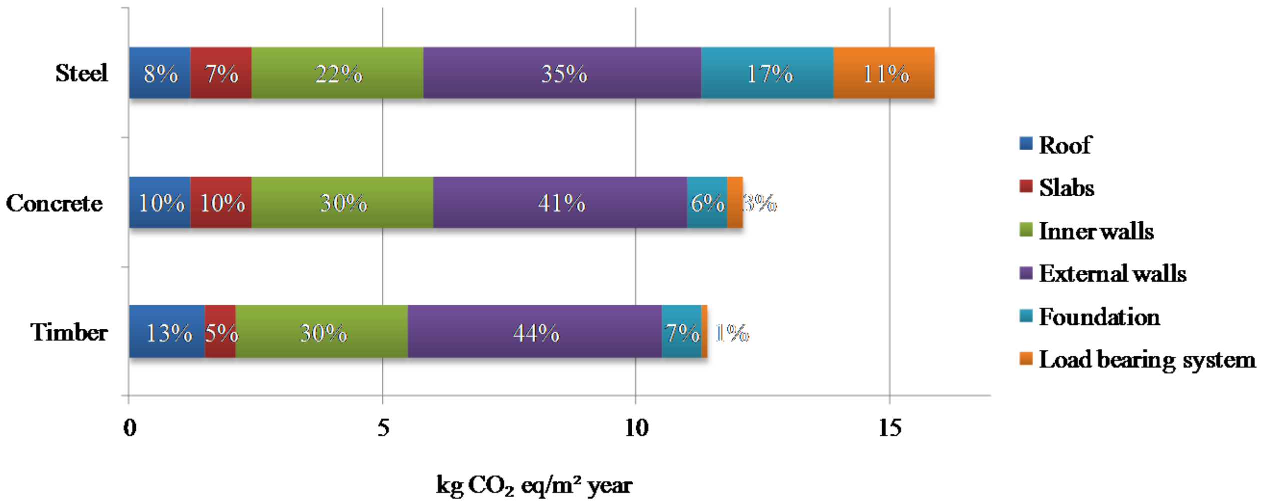

Fig. 34. Percentage distribution of embodied emissions in components of Concrete, Steel and Timber building.

Identification of materials contributing to high emissions in the components (sensitivity tests)

The investigation of the materials responsible for the most emissions in the components (external and internal walls) is presented in the Figs. 35, 36 and 37. As there is no possibility to obtain the breakdown of the emissions in the materials in Klimagassregnskap, sensitivity tests were carried out in order to indicate the materials with the most significant impact on the emissions. The modifications were introduced to the steel building, as it has the highest emissions of the three structural solutions. It was assumed that the most emissions in the external and internal walls come from glazing. Thus the first sensitivity test was performed by accounting emissions with exclusion of glazed areas (windows, internal partitions). The results confirmed the initial assumption. According to the Fig. 36 emissions from the external wall reduced by 84 %, for the internal walls however the effect was less significant- emission were minimized by 42%. Consequently the proportion of the external and internal walls in the total embodied emissions decreased from 35 and 22 % to approximately to 5 and 1 %.After proving glazing to be a major contributor to the emissions it was important to determine the effect of substituting aluminium windows with the timber windows. Comparison of the emissions of external wall before and after changing the window frame material demonstrated that emissions reduced by more than half (Fig. 37). However, the reduction is not as dramatic as the one achieved in the first sensitivity test. Based on the obtained results, glass and aluminium can be identified as the most emission intensive materials in the external and internal walls.

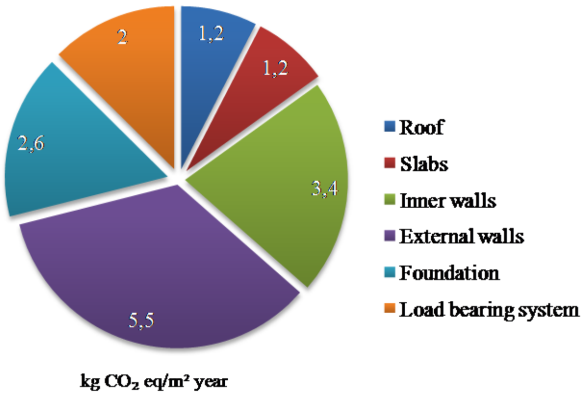

Fig. 35. Distribution of embodied emissions in components (aluminium windows).

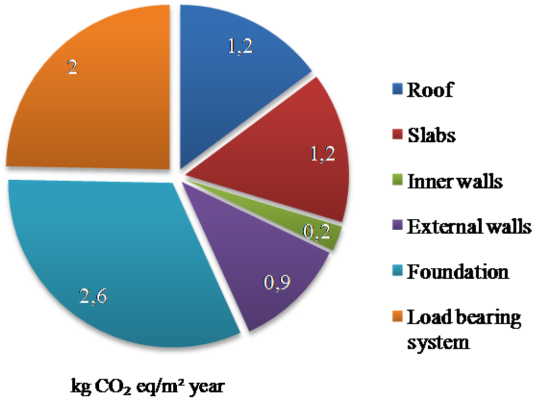

Fig. 36. Distribution of embodied emissions in components (no glazing).

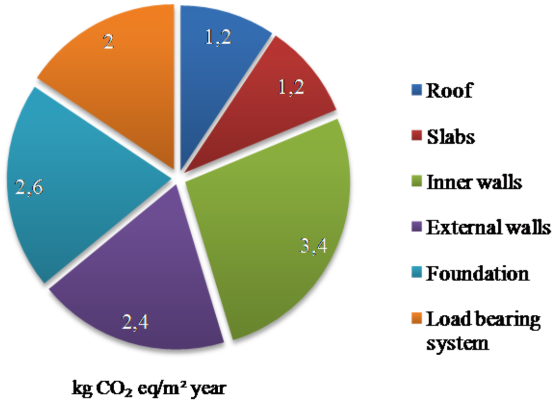

Fig. 37. Distribution of embodied emissions in components (timber windows).

4.7.3 Analysis of the impacts of extended service lives on emissions

Comparison of total embodied emissions of 3 buildings in relation to changed lifetimes

Fig. 38 demonstrates how total embodied emissions of the concrete, steel and timber building change with varying length of lifetimes (default,60 and 100 years).As has been mentioned previously in Methodology default values in Klimagassregnskap imply 60 years lifetime for structural materials and insulation and life span below 60 years for certain envelope materials and interior partitions and components (see also Table 11).

It can observed from the graph extension of the initial service lives of all the components to 60 years results in a decrease of emissions by 41, 36 and 49 % for the concrete, steel and timber building, respectively (Fig. 38). As can be seen from the results the first increase in lifetime has less pronounced on the steel building compared to others. This is due to large share of emissions being attributed to the steel structure (load bearing system),which has default service life of 60 years, therefore no change in lifetime is introduced. The subsequent change in lifetime to 100 years has an approximately equal impact on the emissions of 3 buildings, with reduction ranging from 41 to 39 %. From the results above it can be concluded that 40 years of additional service life have almost the same or even slightly diminished effect on the emissions compared to the first change of lifetime to 60 years. This is due to the fact that during the whole service life of the building substantial emissions result from substituting materials and elements with service lives not corresponding to building's lifetime. Therefore matching service lives of all the components with building's service life achieves the most significant decrease in the emissions.

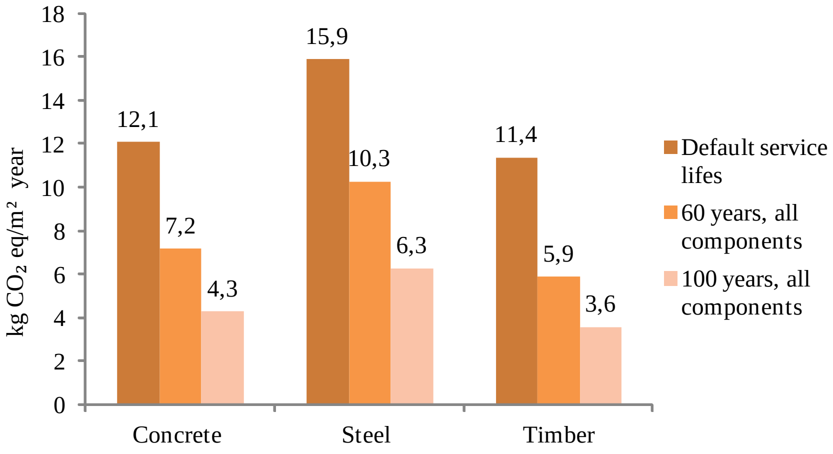

Fig. 38. Embodied emissions of Concrete, Steel and Timber building calculated with 3 service life options.

Comparison of the effect of changed lifetimes on components level

Based on the observations above, it is worth to analyse the change in the distribution of the emissions in components with the extended service life.

As can be seen from the graphs below certain similarities can be traced in the results of three buildings. The prolongation of lifetimes from default values to 60 years, results in different proportions of components in total emissions. Moreover Figs. 39, 40 and 41 demonstrate that the emissions remain constant for almost all the components. Exception are external and internal walls with the reduction of emissions by 2 and 3 times, respectively. Accordingly the share of the external wall in the emissions is minimized by approximately 7-9 % percent, for the internal wall decrease is roughly 15 %.

However, an opposite relation can be observed for all three buildings when lifetimes are extended from 60 to 100 years. The proportion of each component in the total emissions remains constant ,on the other hand the emissions in the components are considerably affected by the change in lifetime to 100 years.

It can be concluded that external and internal walls have the highest share in the emissions in all 3 service life options, however the most significant reduction in the respective emissions is achieved when the service life is set to 60 years for all components.

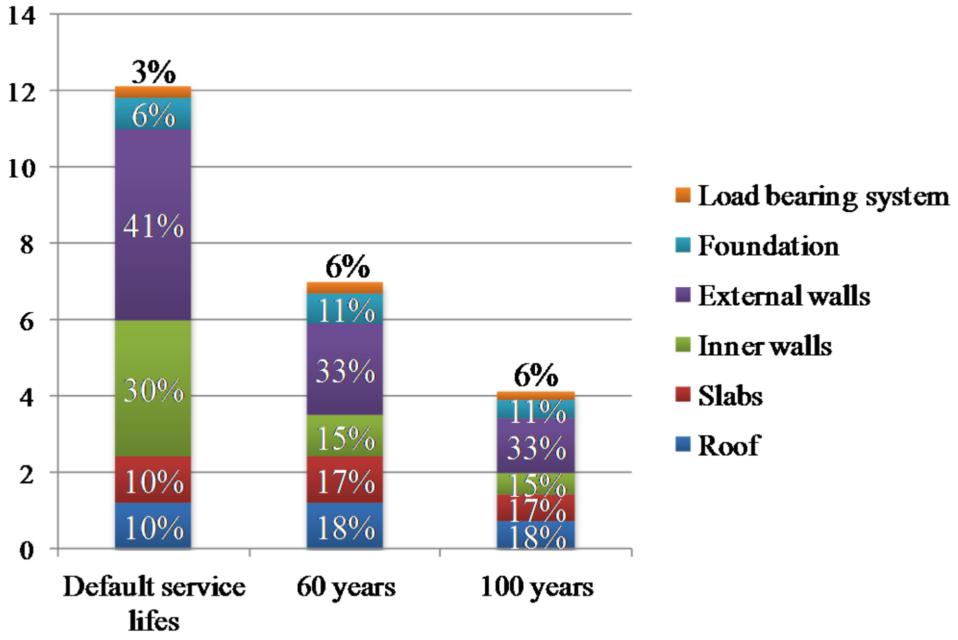

Fig. 39. Proportional distribution of embodied emissions in components (Concrete building).

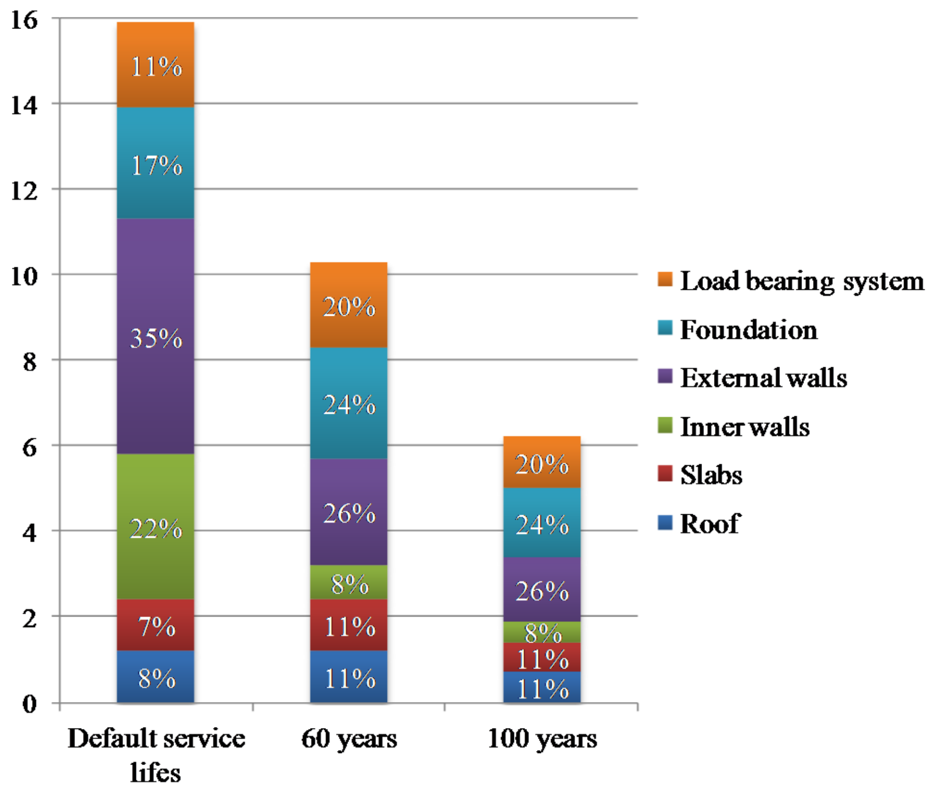

Fig. 40. Proportional distribution of embodied emissions in components (Steel building).

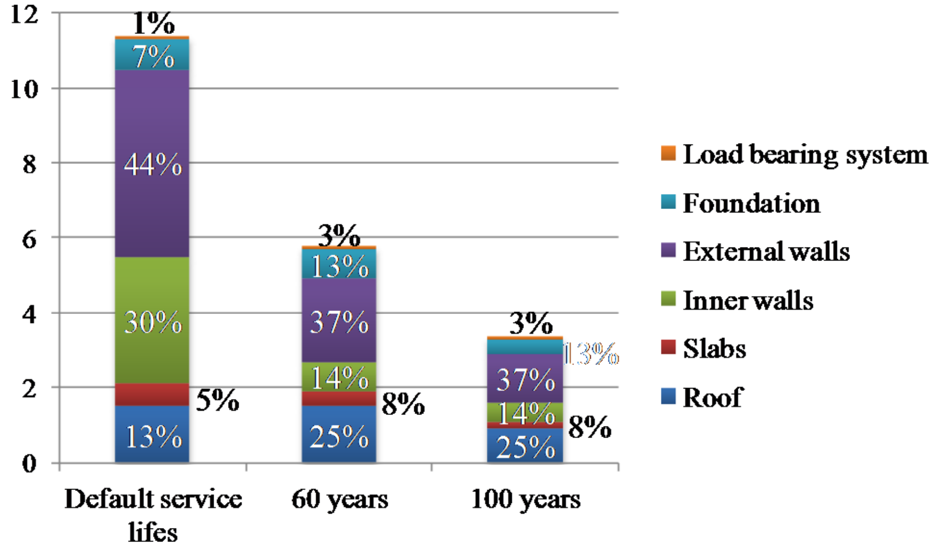

Fig. 41. Proportional distribution of embodied emissions in components (Timber building).

4.7.4 Conclusion on the main results and choice of optimal structural solution

The section provides the comparative analysis of the main results , which answer the research question of the Scenario.

The timber structure has been determined as the solution with lowest contribution to the emissions based on the assessment of the impact of different structural materials and service lives on the life cycle embodied emissions in Klimagassregnskap and subsequent comparative analysis of the results.

As is evident from the Fig. 42 the choice of structural solution can either decrease or increase the embodied emissions. The extent of this influence is relative and can be affected by the chosen calculation method, emissions database used, typology and design of the building. Therefore the results and the implications of the this study are not universally applicable ,but more relevant to the particular case studied. Moreover the determination of the components most responsible for emissions is specific to the building studied and the choices made in the development of the design.

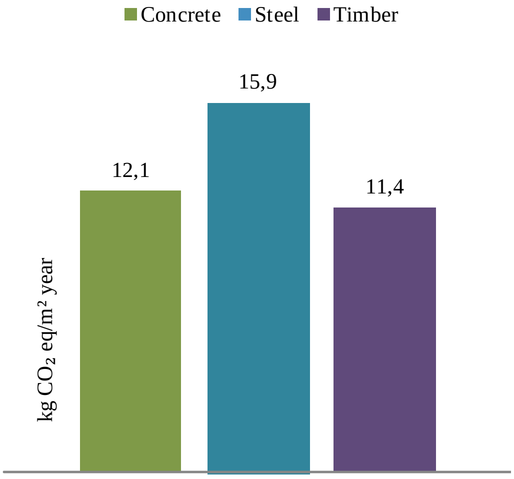

Fig. 42. Embodied emissions of Concrete, Steel and Timber building.

The differences in the embodied emissions of the three structural solutions are shown in the Fig. 42. The emissions of the concrete reference building are slightly higher than that of timber alternative and substantially lower than emissions of the steel building. Proportionally the embodied emissions of the timber solution are almost 1,5 times lower than emissions of the steel structure. The change of the structural material to timber achieves 29 % and 6% lower emissions than steel and concrete structure, respectively. Marginal difference in the emissions of concrete and timber alternatives is assumed to be due to relatively low emission concrete used in Klimagassregnskap database. The difference would have been more pronounced if the sequestration of carbon in the timber would have been taken into account the calculation.

As can be concluded from the Fig. 42 the overall effect of various structural materials on the emissions is relatively moderate. Moreover, summarizing the results of the scenario it should be noted that structural materials are only one of the aspects affecting the emissions. The distribution of the materials in the components shows that building's envelope and interior partitions have a significant impact on the emissions, the effect becomes more pronounced in life cycle perspective. This is due to the fact that on the contrary to structural system, which has the lifetime corresponding to that of the building, materials in the envelope and interior partitions have short life spans and are subject to replacement and maintenance during the building's life cycle .Therefore the optimum solution for minimized embodied emissions should encompass a range of aspects affecting total life cycle emissions.

5. Conclusion

The thesis investigated the influence of various design options on the life cycle emissions of ZEB Shoebox Office model, mainly using Klimagassregnskap GHGs accounting tool. Two independent studies were performed, one focusing on minimizing operational energy emissions, the other on reducing the embodied emissions.

In the first scenario, when looking solely at the results from Klimagassregnskap, the findings suggested three optimum energy supply options with zero operational emissions: (1) Solar thermal and PV; (2) Solar Thermal, biomass micro CHP and PV, (3) Biomass micro CHP and PV. It is worth noting that the first option has the lowest emissions when calculated with other methods. Moreover, the energy needed is generated on the building footprint, hence it may represent an optimal solution on the pathway to ZEB. However, the reliability of the results is questionable due to low transparency of the calculation process and unavailability to trace the source of CO_2 factors (0 for all the three options) used for energy supply systems.

The results of the second scenario showed that timber is as an optimum structural solution with relatively low emissions compared to concrete and steel. However the service life of the materials in the envelope and internal partitions has a higher influence on the embodied emission compared to the choice of structural materials. It is worth noting that the accuracy of these results is affected by limited choice, lack of visibility of the material's emissions distribution and non accessibility of database used in the tool.

For both scenarios the interpretation and comparison of the results with other studies was a rather difficult task to perform due to the lack of researches done on the building's life-cycle emissions. Indeed, in common praxis the buildings are evaluated and certified based on energy performance rather than on emissions.

Finally, regarding the usability of Klimagassregnskap, it was observed that the tool suffers from a lack of transparency in emissions calculation and in the inputs used for defining the emission factors. Therefore further improvements are needed for a more accurate assessment of the future ZEB buildings environmental impact.

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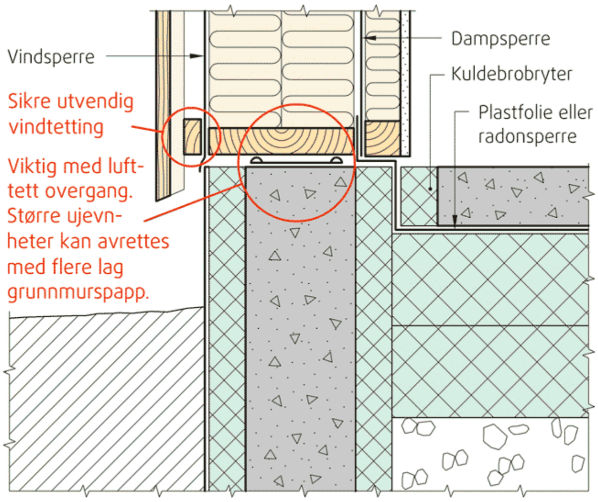
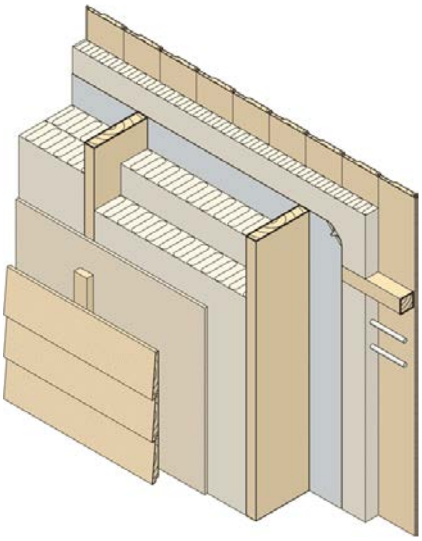
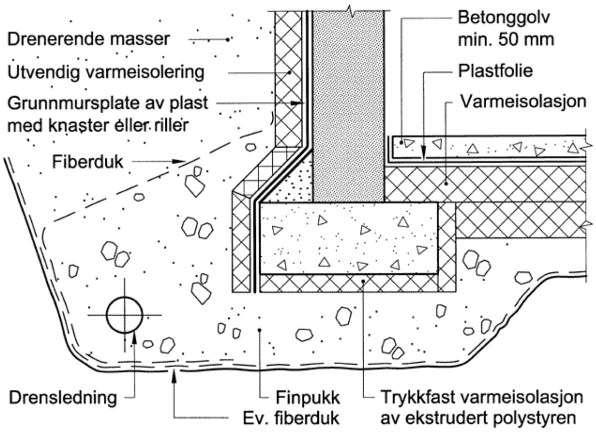
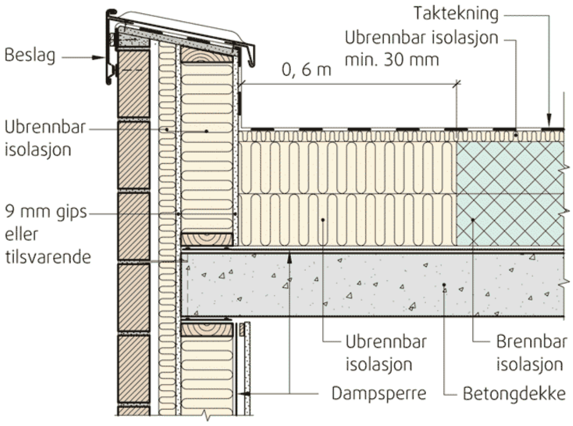
Appendix

APPENDIX 1. Byggforskserien solutions

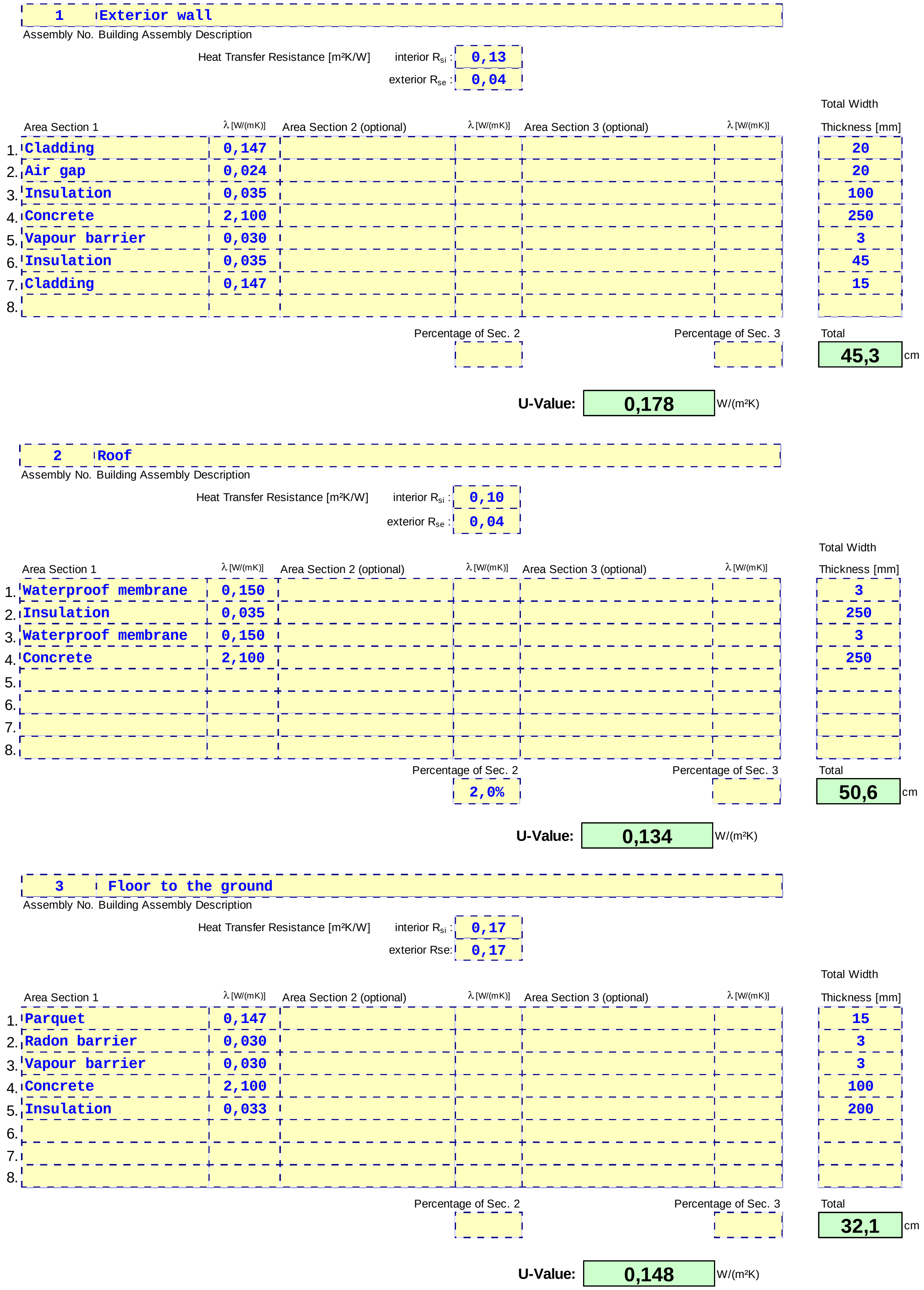








APPENDIX 2. PHPP U-values of building elements



Assembly No.	Building Assembly Description
1	Exterior wall

Heat Transfer Resistance [m²K/W] interior R_{si} : 0,13

exterior R_{se} : 0,04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.	Cladding	0,147					20
2.	Air gap	0,024					20
3.	Insulation	0,035					100
4.	Concrete	2,100					250
5.	Vapour barrier	0,030					3
6.	Insulation	0,035					45
7.	Cladding	0,147					15
8.							

Percentage of Sec. 2:

Percentage of Sec. 3:

Total 45,3 cm

U-Value: 0,178 W/(m²K)

Assembly No.	Building Assembly Description
2	Roof

Heat Transfer Resistance [m²K/W] interior R_{si} : 0,10

exterior R_{se} : 0,04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.	Waterproof membrane	0,150					3
2.	Insulation	0,035					250
3.	Waterproof membrane	0,150					3
4.	Concrete	2,100					250
5.							
6.							
7.							
8.							

Percentage of Sec. 2: 2,0%

Percentage of Sec. 3:

Total 50,6 cm

U-Value: 0,134 W/(m²K)

Assembly No.	Building Assembly Description
3	Floor to the ground

Heat Transfer Resistance [m²K/W] interior R_{si} : 0,17

exterior Rse: 0,17

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.	Parquet	0,147					15
2.	Radon barrier	0,030					3
3.	Vapour barrier	0,030					3
4.	Concrete	2,100					100
5.	Insulation	0,033					200
6.							
7.							
8.							

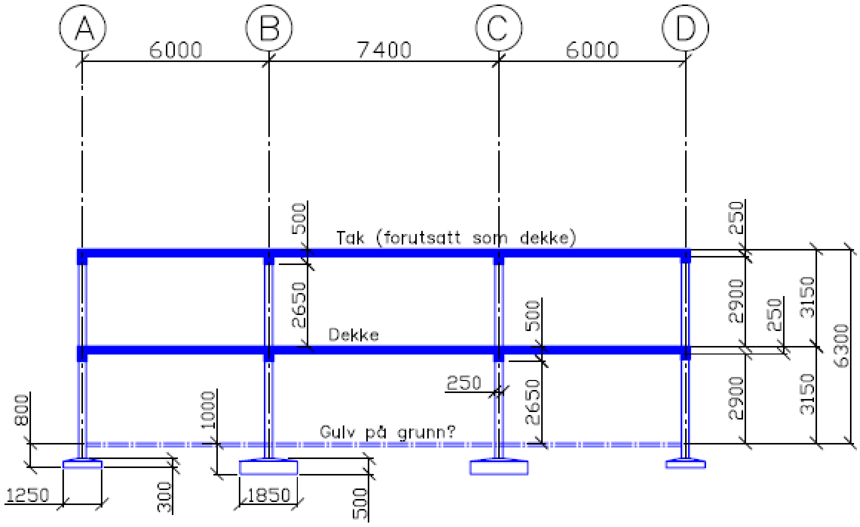
Percentage of Sec. 2:

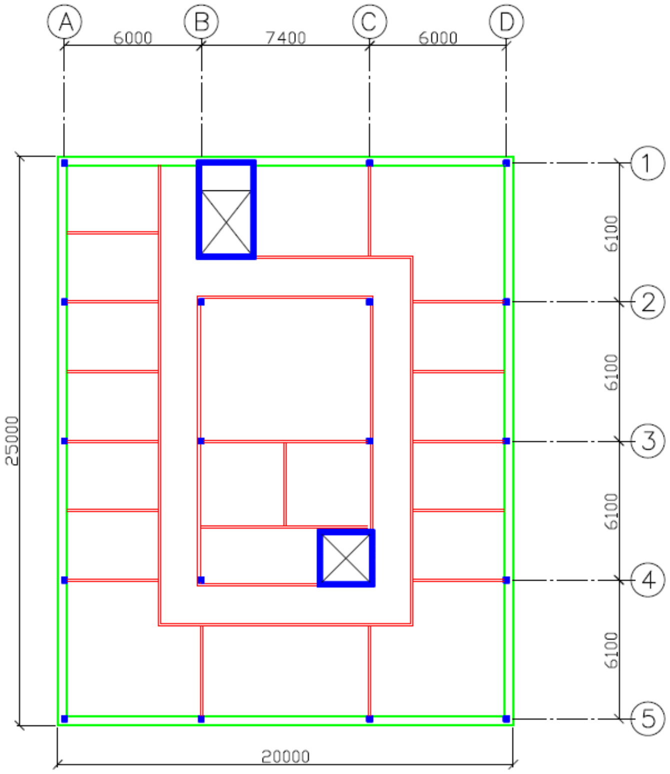
Percentage of Sec. 3:

Total 32,1 cm

U-Value: 0,148 W/(m²K)

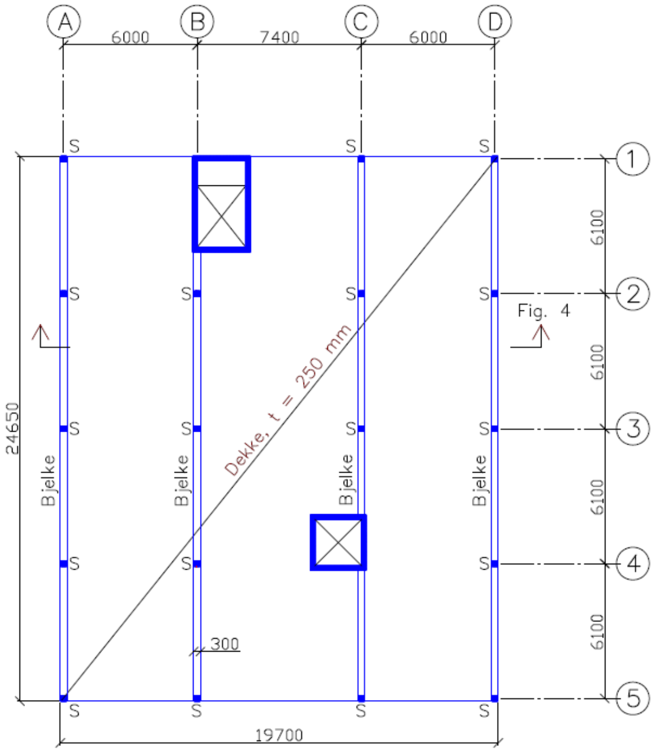
APPENDIX 3. ZEB Concepts - Office building, drawings provided by ZEB Research centre.



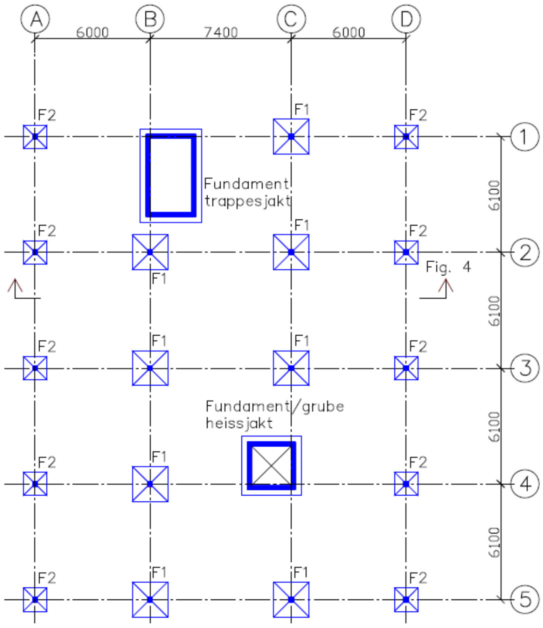


Figur 1
Forutsatt planløsning

🟩 ”Klimaskjerm”
🟥 ”Lette” konstruksjoner (vegger)
🟦 Betongkonstruksjoner

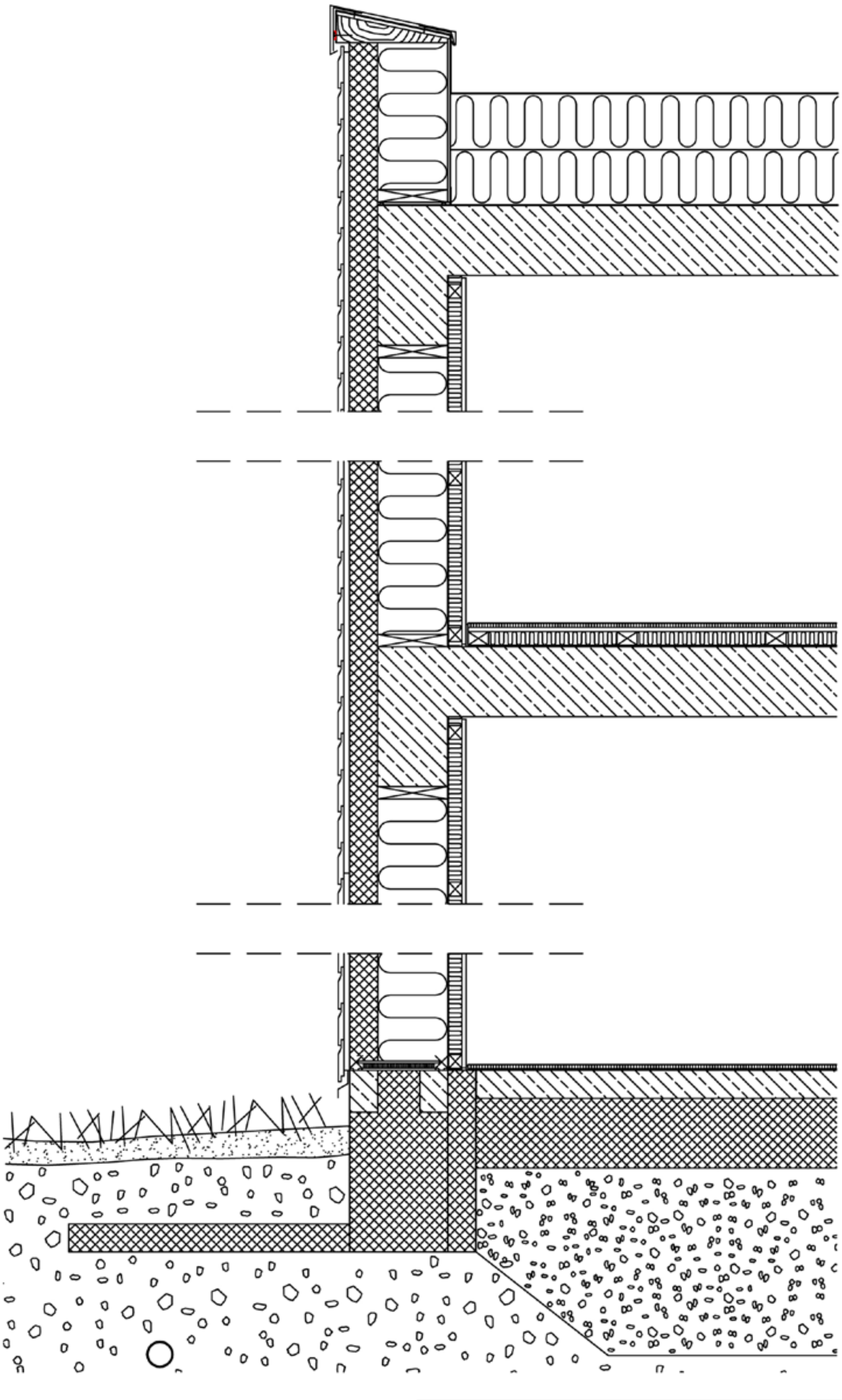


Figur 2
Speilprojeksjon dekke
Illustrasjon bæresystem
– S = Søyler 250 x 250
– Bjelke b x h = 300 x 250
(tot. h inkl. dekke = 500 mm)



Figur 3
Fundamentplan
– F1: Fund. 1850 x 1850 x 500
– F2: Fund. 1250 x 1250 x 300

The detailed section drawn by the authors of the thesis



Norwegian University of Science and Technology
Faculty of Architecture and Fine Arts

Master Thesis - MSc Sustainable architecture
NTNU, Trondheim

Drawing n. 1

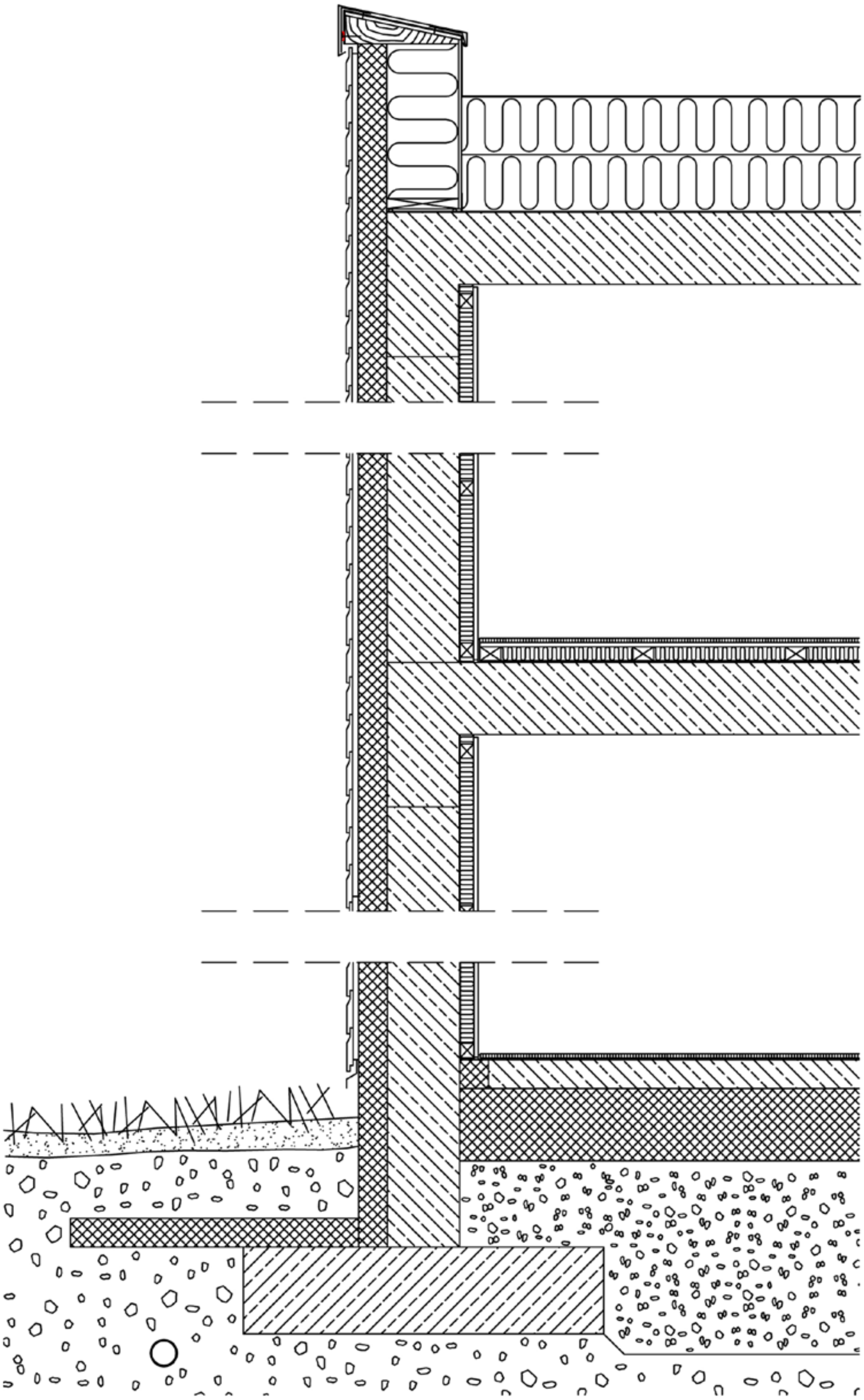
Emissions accounting for ZEB shoebox office mode

Date: 03.06.2012

Vertical longitudinal section

Scale: 1:20

Elisabetta Cabarija Nigar Zeynalova



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NTNU, Trondheim

Drawing n. 2

Emissions accounting for ZEB shoebox office mode

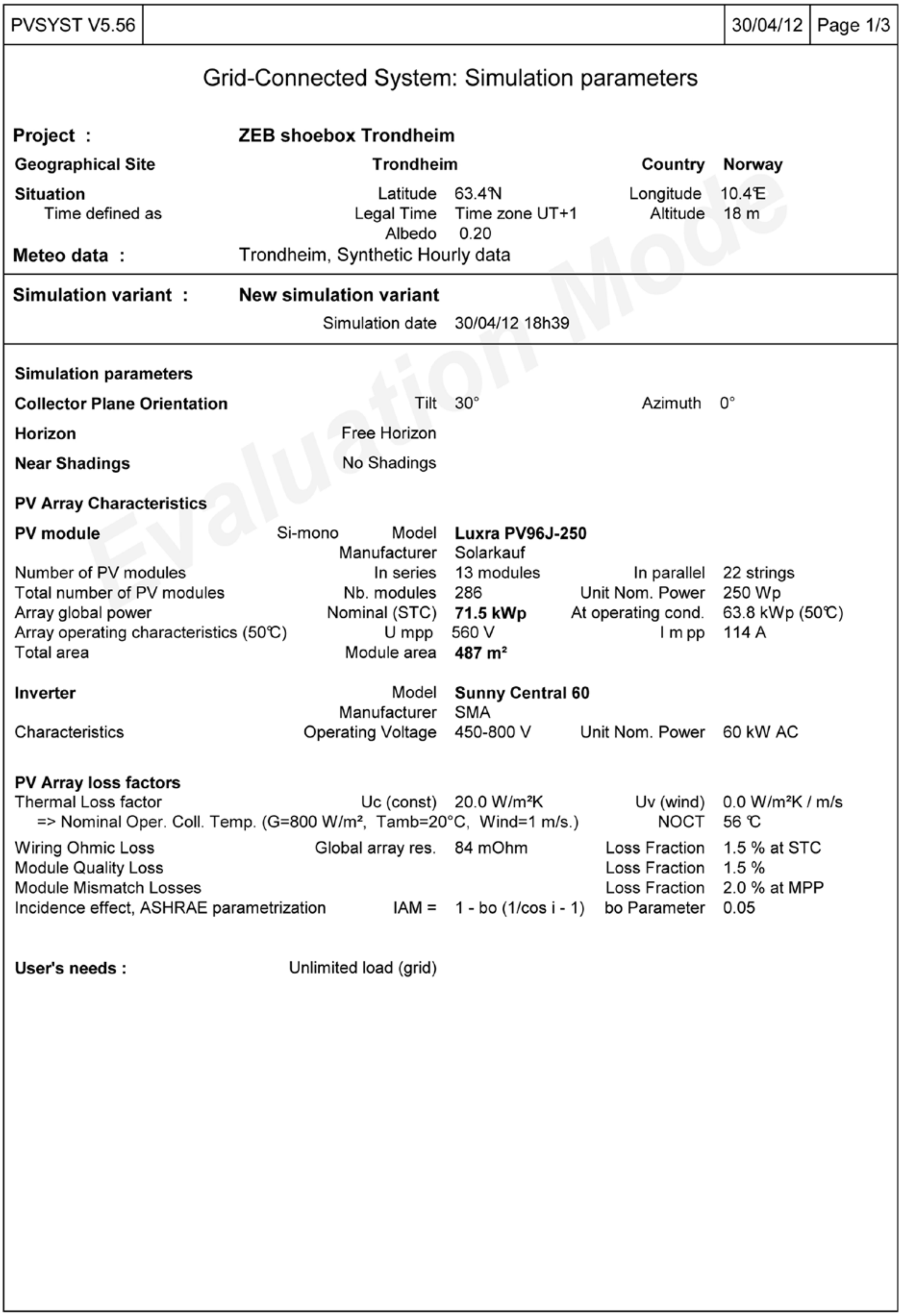
Date: 03.06.2012

Vertical longitudinal section

Scale: 1:20

Elisabetta Caharija Nigar Zeynalova

APPENDIX 4. PV simulation in PVsyst v5.56



PVSYST V5.56		30/04/12	Page 1/3

Grid-Connected System: Simulation parameters

Project :	**ZEB shoebox Trondheim**			
Geographical Site	**Trondheim**		**Country**	**Norway**
Situation	Latitude	63.4°N	Longitude	10.4°E
Time defined as	Legal Time	Time zone UT+1	Altitude	18 m
	Albedo	0.20		
Meteo data :	Trondheim, Synthetic Hourly data			

Simulation variant :	**New simulation variant**			
	Simulation date	30/04/12 18h39		

Simulation parameters

Collector Plane Orientation	Tilt	30°	Azimuth	0°
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module Si-mono	Model	**Luxra PV96J-250**		
	Manufacturer	Solarkauf		
Number of PV modules	In series	13 modules	In parallel	22 strings
Total number of PV modules	Nb. modules	286	Unit Nom. Power	250 Wp
Array global power	Nominal (STC)	**71.5 kWp**	At operating cond.	63.8 kWp (50°C)
Array operating characteristics (50°C)	U mpp	560 V	I m pp	114 A
Total area	Module area	**487 m²**		

Inverter	Model	**Sunny Central 60**		
	Manufacturer	SMA		
Characteristics	Operating Voltage	450-800 V	Unit Nom. Power	60 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	84 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.5 %
Module Mismatch Losses			Loss Fraction	2.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

User's needs : Unlimited load (grid)

Grid-Connected System: Main results

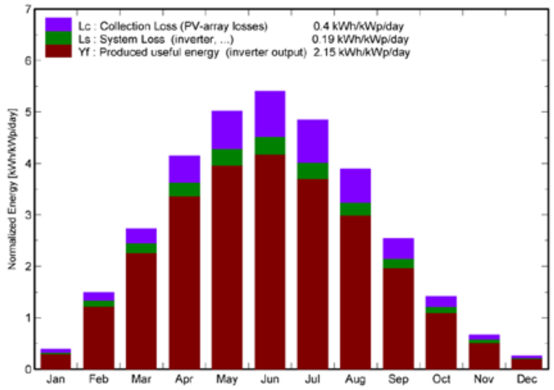
Project : **ZEB shoebox Trondheim**

Simulation variant : **New simulation variant**

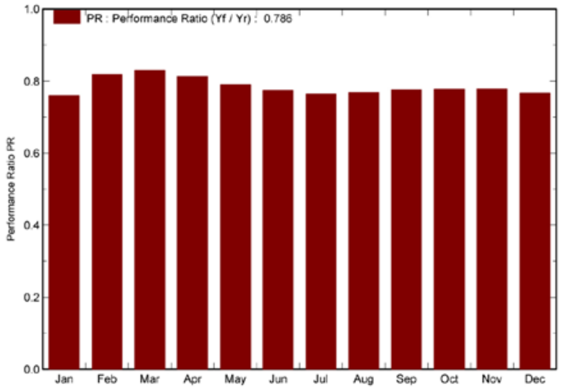
Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	Luxra PV96J-250	Pnom	250 Wp
PV Array	Nb. of modules	286	Pnom total	**71.5 kWp**
Inverter	Model	Sunny Central 60	Pnom	60.0 kW ac
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**56.1 MWh/year**	Specific prod.	785 kWh/kWp/year
	Performance Ratio PR	78.6 %		

Normalized productions (per installed kWp): Nominal power 71.5 kWp



Performance Ratio PR

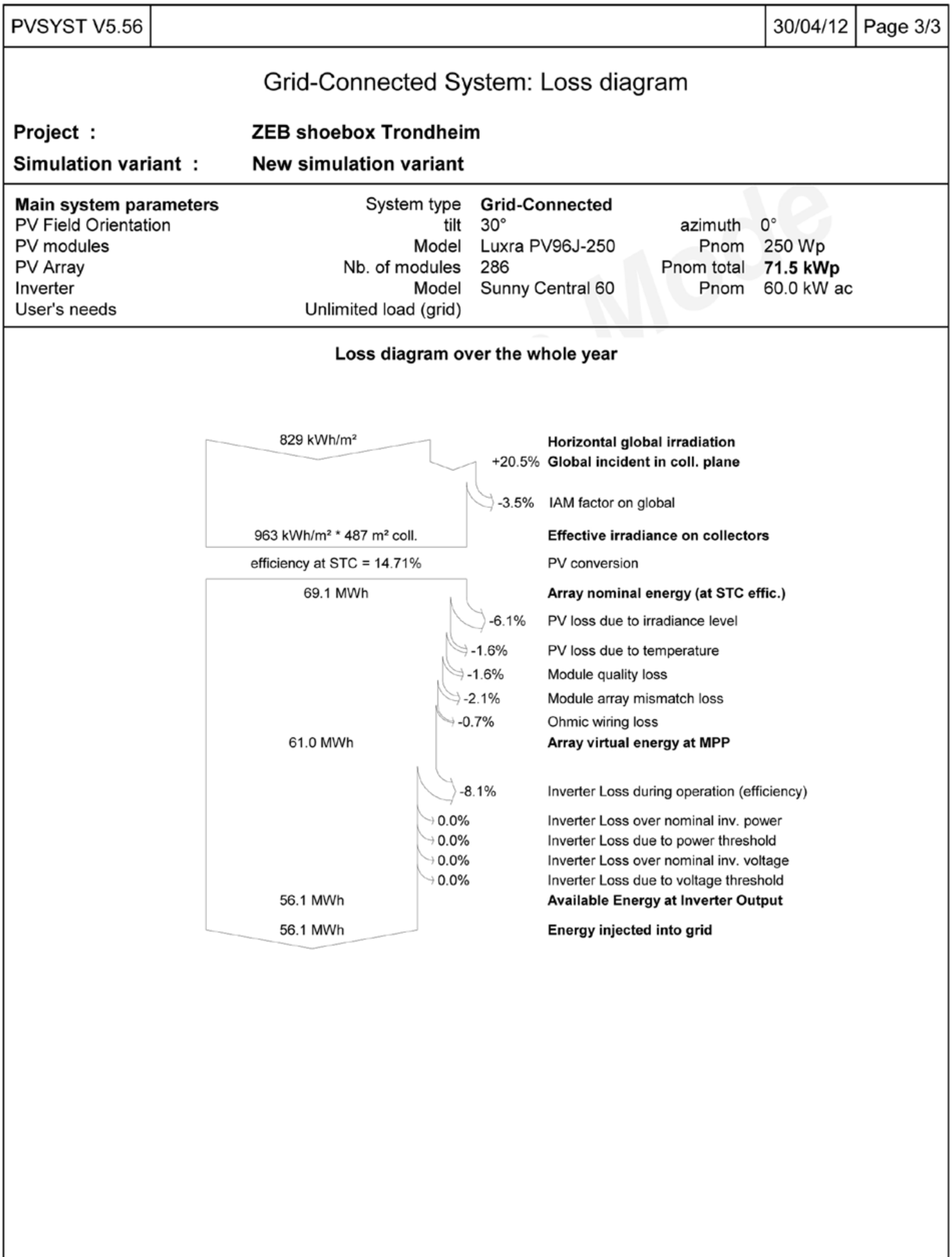


New simulation variant

Balances and main results

	GlobHor kWh/m²	**T Amb** °C	**GlobInc** kWh/m²	**GlobEff** kWh/m²	**EArray** MWh	**E_Grid** MWh	**EffArrR** %	**EffSysR** %
January	4.7	-2.30	12.0	11.5	0.735	0.649	12.61	11.13
February	20.4	-1.90	41.8	40.2	2.680	2.448	13.15	12.01
March	56.7	-0.20	84.8	81.7	5.448	5.025	13.18	12.16
April	100.5	4.60	124.2	119.8	7.799	7.219	12.88	11.92
May	143.5	8.70	155.3	150.1	9.505	8.781	12.55	11.60
June	156.9	12.60	161.9	156.3	9.703	8.952	12.30	11.34
July	144.2	15.20	150.1	145.0	8.913	8.205	12.18	11.22
August	107.0	14.90	120.7	116.4	7.198	6.627	12.23	11.26
September	58.5	11.30	76.3	73.5	4.623	4.228	12.44	11.38
October	26.7	6.00	43.9	42.2	2.704	2.440	12.65	11.41
November	7.7	1.00	19.9	19.1	1.240	1.107	12.79	11.42
December	2.1	-2.20	8.0	7.7	0.494	0.441	12.61	11.25
Year	829.0	5.69	998.9	963.5	61.041	56.122	12.54	11.53

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
	GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area



PVSYST V5.56		30/04/12	Page 3/3

Grid-Connected System: Loss diagram

Project : **ZEB shoebox Trondheim**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	Luxra PV96J-250	Pnom	250 Wp
PV Array	Nb. of modules	286	Pnom total	**71.5 kWp**
Inverter	Model	Sunny Central 60	Pnom	60.0 kW ac
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

829 kWh/m²		**Horizontal global irradiation**
	+20.5%	**Global incident in coll. plane**
	-3.5%	IAM factor on global
963 kWh/m² * 487 m² coll.		**Effective irradiance on collectors**
efficiency at STC = 14.71%		PV conversion
69.1 MWh		**Array nominal energy (at STC effic.)**
	-6.1%	PV loss due to irradiance level
	-1.6%	PV loss due to temperature
	-1.6%	Module quality loss
	-2.1%	Module array mismatch loss
	-0.7%	Ohmic wiring loss
61.0 MWh		**Array virtual energy at MPP**
	-8.1%	Inverter Loss during operation (efficiency)
	0.0%	Inverter Loss over nominal inv. power
	0.0%	Inverter Loss due to power threshold
	0.0%	Inverter Loss over nominal inv. voltage
	0.0%	Inverter Loss due to voltage threshold
56.1 MWh		**Available Energy at Inverter Output**
56.1 MWh		**Energy injected into grid**

APPENDIX 5. Solar thermal system – estimation

PV production	56122 kWh/y
DHW demand covered by solar thermal	6241 kWh/y
Ratio PV production to DHW demand	~ 9

Monthly solar thermal production:

Production = PV production (monthly) * 9

	PV	Solar thermal
Jan	649	72
Feb	2448	272
Mar	5025	559
Apr	7219	803
May	8781	976
Jun	8952	995
Jul	8205	912
Aug	6627	737
Sep	4228	470
Oct	2440	271
Nov	1107	123
Dec	441	49
Total	**56122**	**6241**

It was here assumed that every square meter of the collector deliver 400 kWh per year (average).

In the option 1 the solar thermal system has to cover the whole heating demand (18064 kWh/y), therefore:

18064/400 = 45m2 of solar collector

In the option 2 the solar thermal system has to cover part of the DHW demand (4419 kWh/y), therefore:

4419/400 = 11m2 of solar collector

APPENDIX 6. Wind turbines estimation

Wind speed values for each months were taken from Weather tool in Ecotect and Dview climate analysis tool.

Formula given by Prof. Matthias Haase has been used to calculate the power of the wind turbine (power law) $P = \frac{1}{2} * v^3 * \rho * A$

Where:

v is 5 m/s average yearly wind speed in Trondheim.

ρ is 1,269 kg/ m^3 - mass density for Trondheim average temperature of 5°

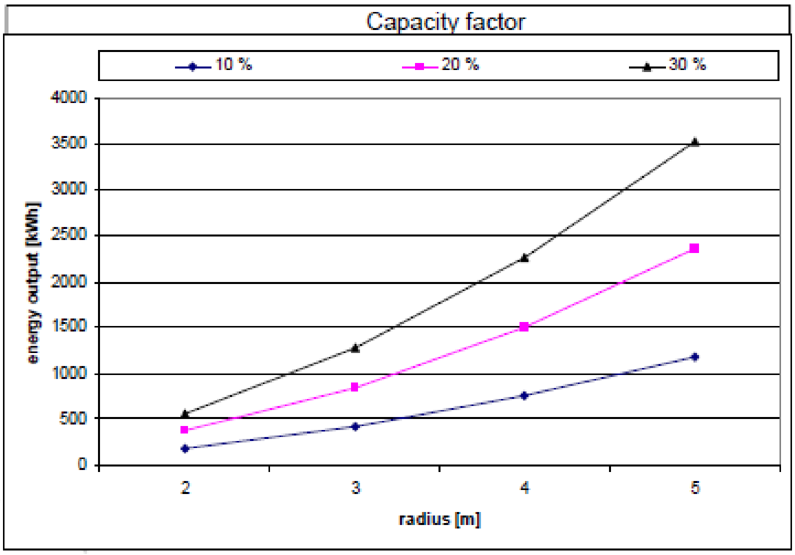
A is 63 m^2 area

Result of the calculation: P = 5 kW -the power of the wind turbine needed.

Selection of the product:

15m high – 5 m radius wind turbine (10000 – 25000 kWh per year of electricity).

The maximum capacity factor - 30 % was chosen according to the graph developed by Prof. Haase



In order to calculate the yearly production of a wind turbine the following formula was used:

$P = Capacity * 8760\ (hrs\ in\ a\ year) * Power$

capacity (%)	power (kW)	production (kWh/y)
0.3	5	13140

The result was multiplied by 5 to get the production of 5 wind turbines:

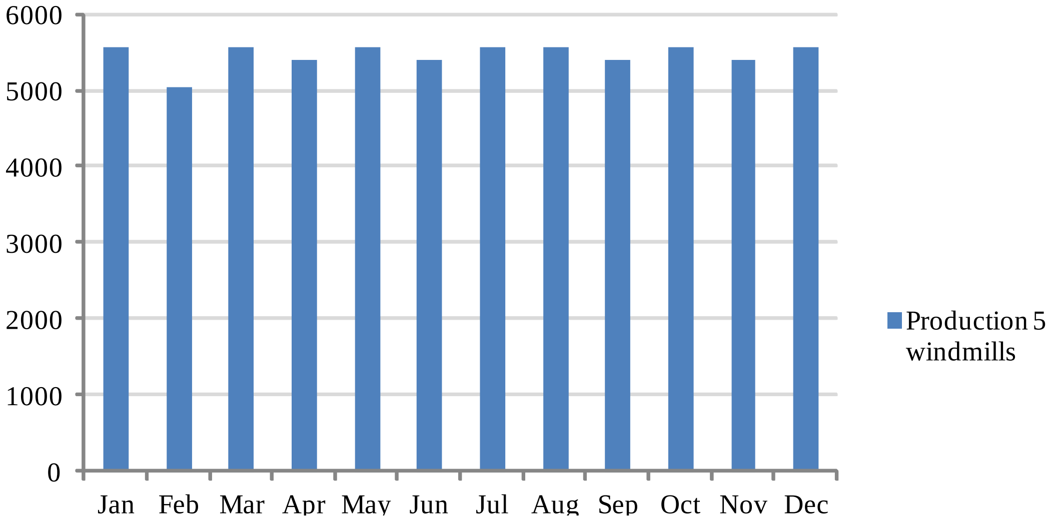
*13140 * 5 = 65700 kWh/year*

To calculate the monthly production of the 5 windmills the following formula was used:

*P = Capacity * hrs (in a month) * Power*

In order to have more realistic production for each month, the wind speeds used in calculation were assumed to be higher in winter and slightly lower in summer months.

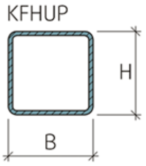
	wind speed m/s	days month	hr months	production 5 WM
Jan	5	31	744	5580
Feb	5	28	672	5040
Mar	5	31	744	5580
Apr	3	30	720	5400
May	4	31	744	5580
Jun	5	30	720	5400
Jul	5	31	744	5580
Aug	3	31	744	5580
Sep	4	30	720	5400
Oct	5	31	744	5580
Nov	5	30	720	5400
Dec	5	31	744	5580
			Total	**65700**



APPENDIX 7. Byggforskserien solutions for steel structure

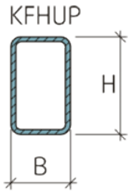
Steel columns

Dimensions (mm) H × W × t, 250 × 250 × 10



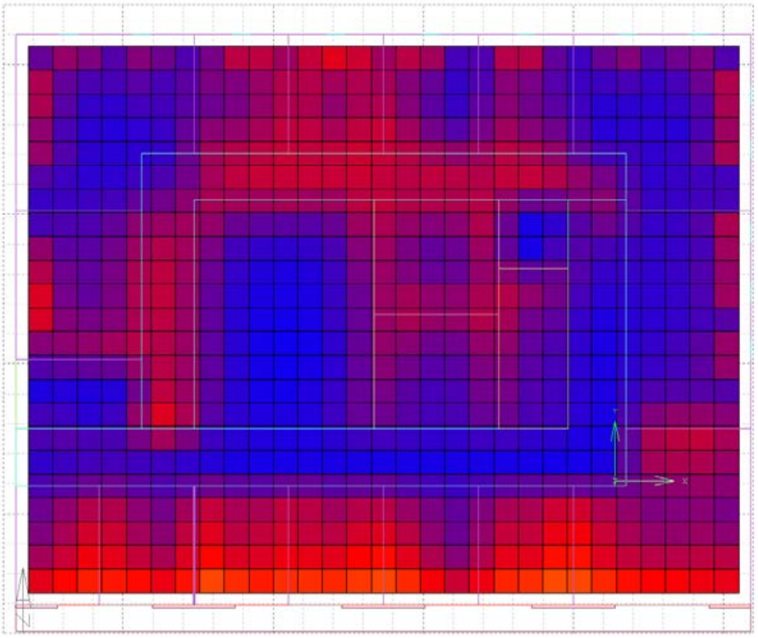
Steel beams

Dimensions (mm) H × W × t, 300 × 200 × 6.3

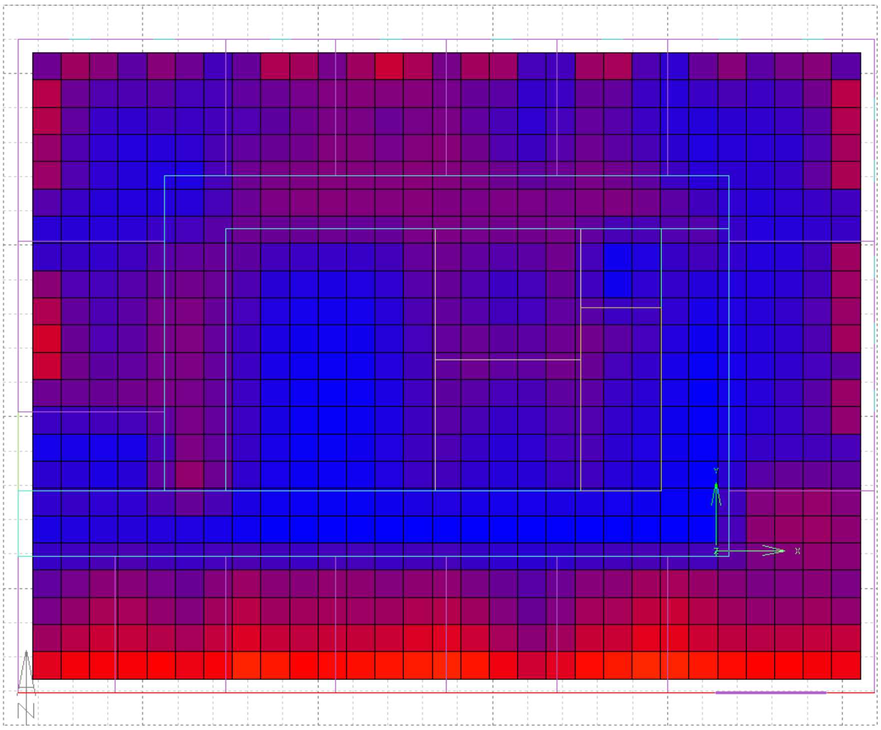


APPENDIX 8. Daylight analysis in Ecotect

First floor, daylight factor 5 %

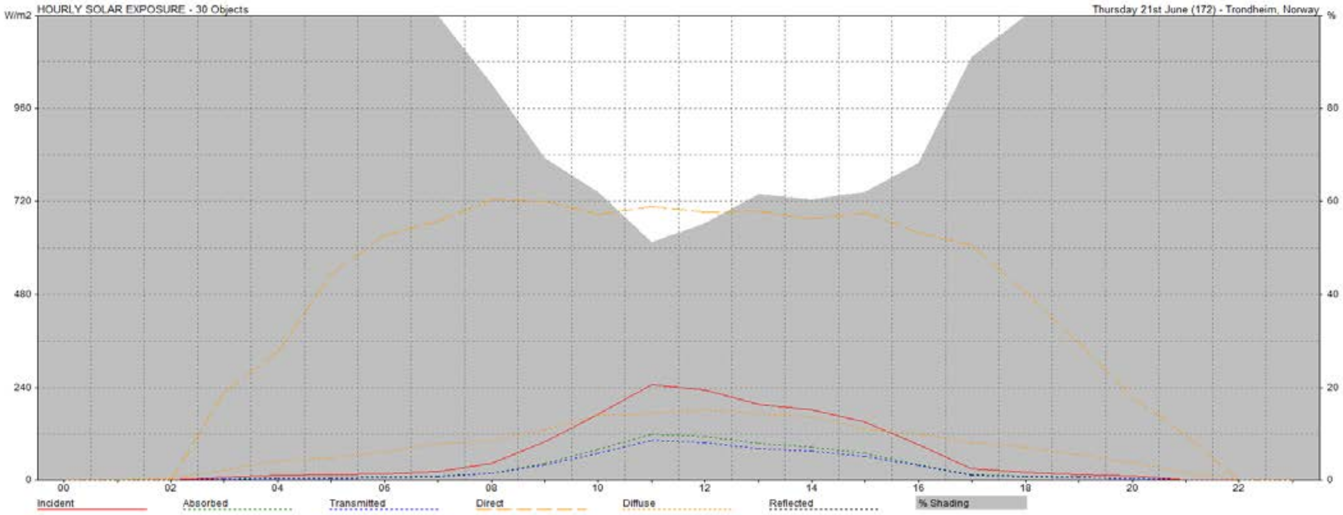


Second floor, daylight factor 4,5 %



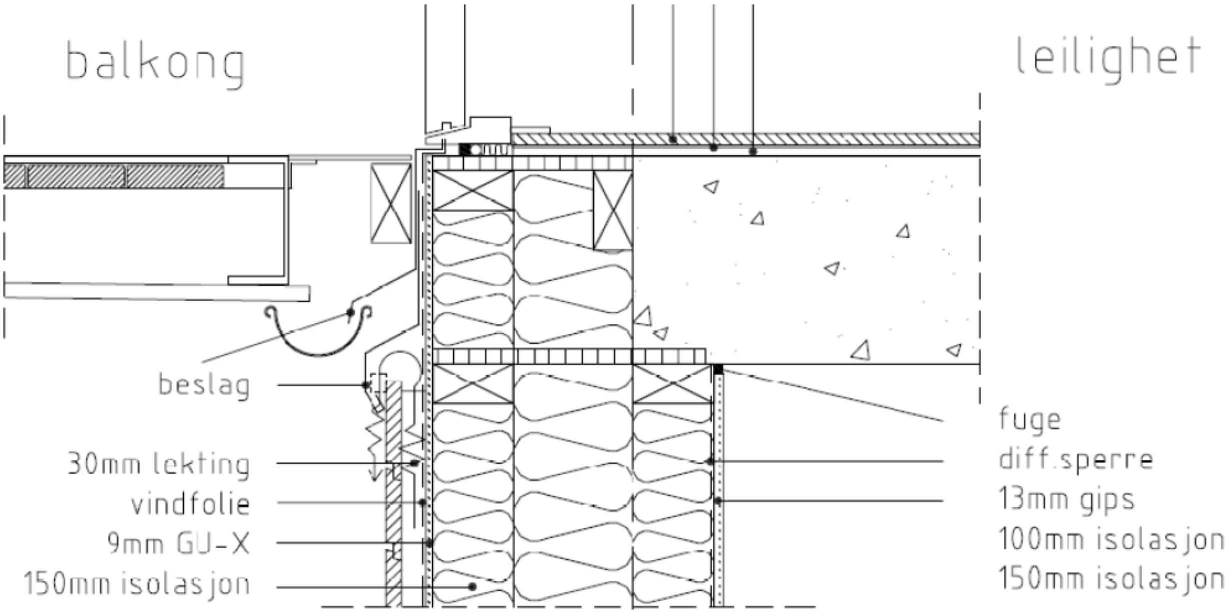
APPENDIX 9. Solar exposure analysis in Ecotect

Shading conditions of the South facade on 21st of June



APPENDIX 10. Balcony solution from Løvåshagen dwelling development

Detail: external wall - balcony



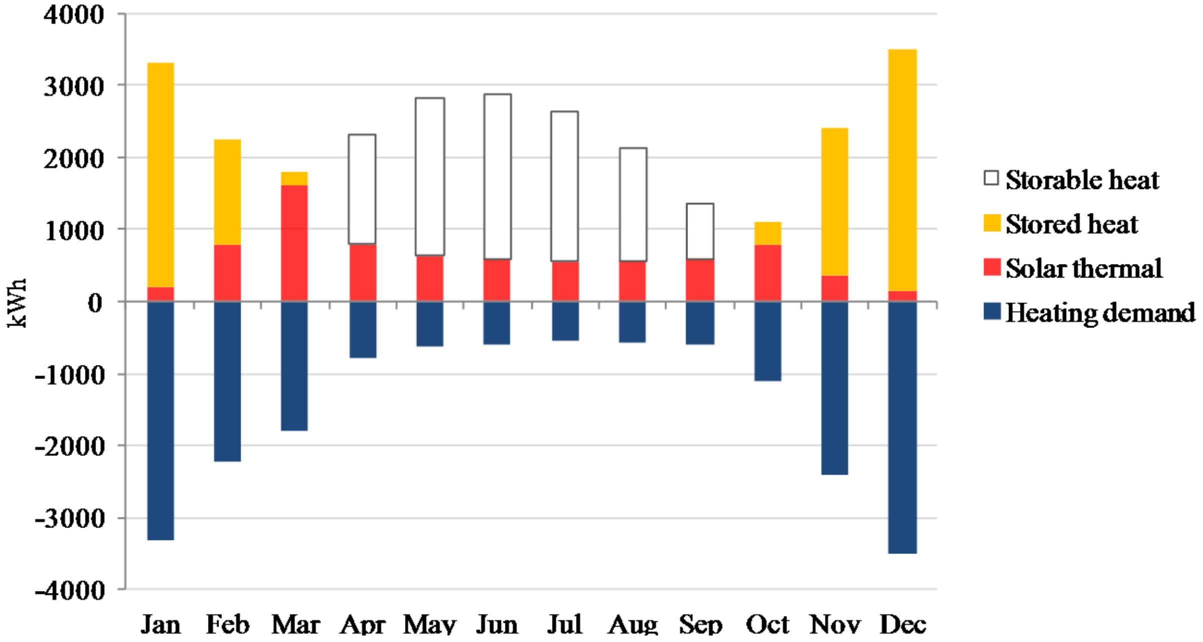
Source: Løvåshagen: Norges første lavblokkprosjekt med passivhusstandard. Tor Helge Dokka, SINTEF Byggforsk.

APPENDIX 11. Input parameters for Simien

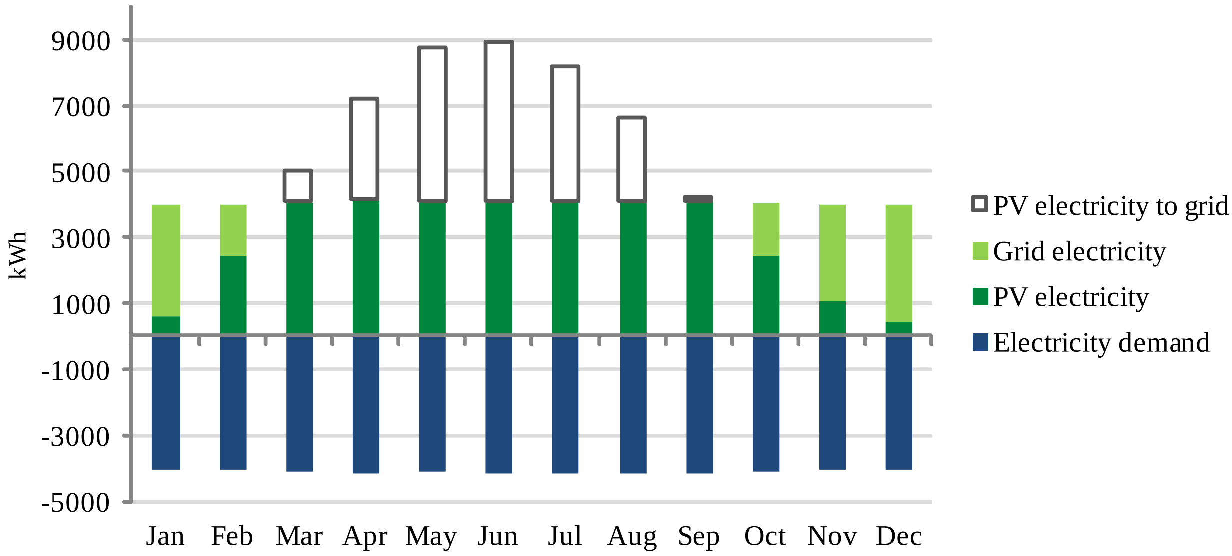
Category	Data
Location	Trondheim (latitude 63.30"N, longitude 10.22"E)
Building type	Office building
Floor areas	Total heated floor area = 844 m²
Dimensions	25 m × 20 m ; areas: external walls = 479 m² ; roof = 394 m² ; floor = 422 m²;
	windows and doors = 169 m² ; window -to- floor ratio = 20 %
Occupancy	Mon. to Fri.-0700 to 1900 hr, Sat. and Sun. Closed
Construction	External walls U-value: 0.18 W/m² K (TEK 10)
	Roof U-value: 0.13 W/m² K (TEK 10)
	Ground floor U-value : 0.15 W/m² K (TEK 10)
	Windows: 3 layers , 1 energy glass coating
	U-value: 1.2 W/m²K; glazing factor: 1; g-value: 0.45
	Solar shading system: venetian blinds, outside, light color, automatic
	(closes when radiation on window > 200W/m2)
HVAC design	Internal gains (TEK 10): persons = 4 W/m² ;
	lighting = 8 W/m²; equipment = 11 W/m²
	Heating set point Operative temperature 21°C during operating hours
	(19°C outside operating hours)
	Cooling set point Operative temperature 24°C (off outside operating hours)
	Ventilation system: Minimum airflow rate 7.0 m3/hm²;
	maximum airflow rate 10.0 m3/hm²
	VAV system
	SFP = 2 kW/(m3/s) (TEK 10)
	Heating operating hours 0700 hr to 1900 hr

APPENDIX 12. Option 1 – Solar thermal and PV

Heating demand



Electricity demand



APPENDIX 13. Heat storage

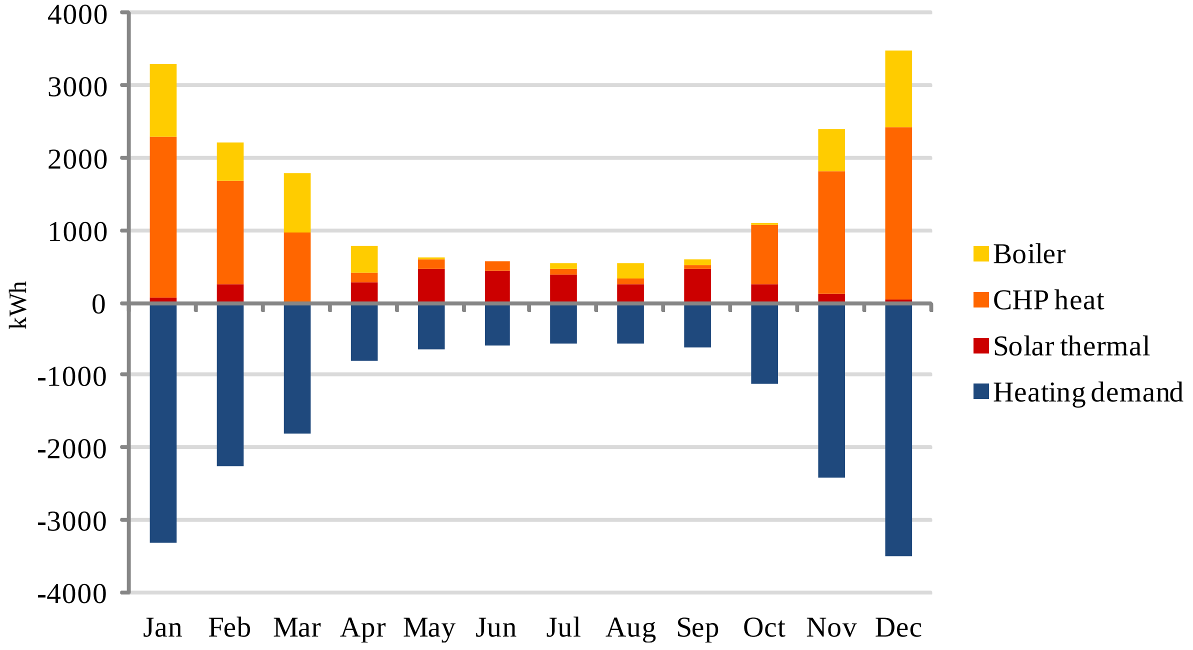
Type of the storage tank chosen - adsorption long-term heat storage. Technology has been tested in the " Solar house Freiburg" , Fraunhofer-Institute for Solar Energy Systems ISE.

Energy density 135 kwH/m^3 (energy density is a term used for the amount of energy stored in a given system or region of space per unit volume).

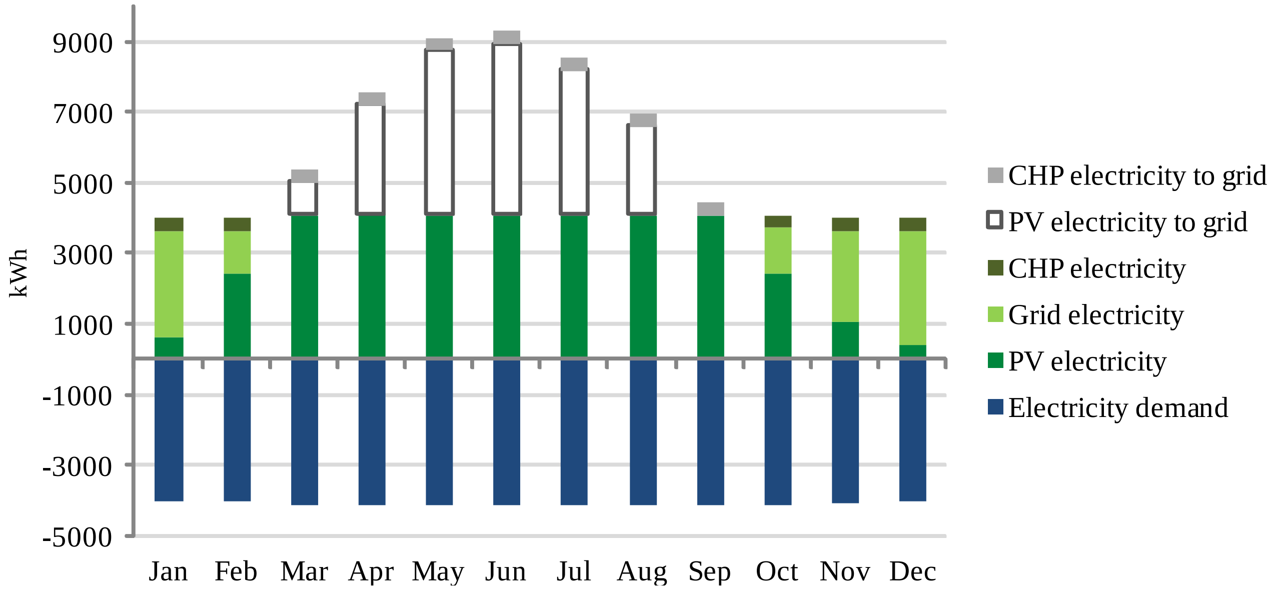
Heat that needs to be stored 10500 kWh per year.
10500/135 = ~ 80 m^3
80 m^3 of adsorption seasonal storage tank to cover both heating and DHW demand in winter.

APPENDIX 14. Option 2 - Solar Thermal, biomass micro CHP and PV

Heating demand



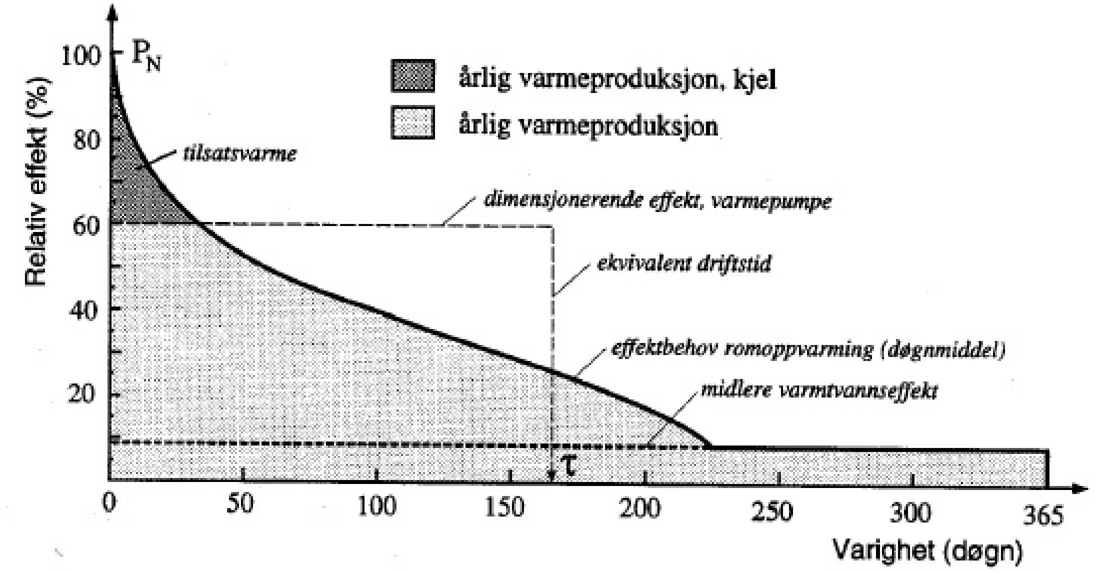
Electricity demand



APPENDIX 15. Base load and peak load demand

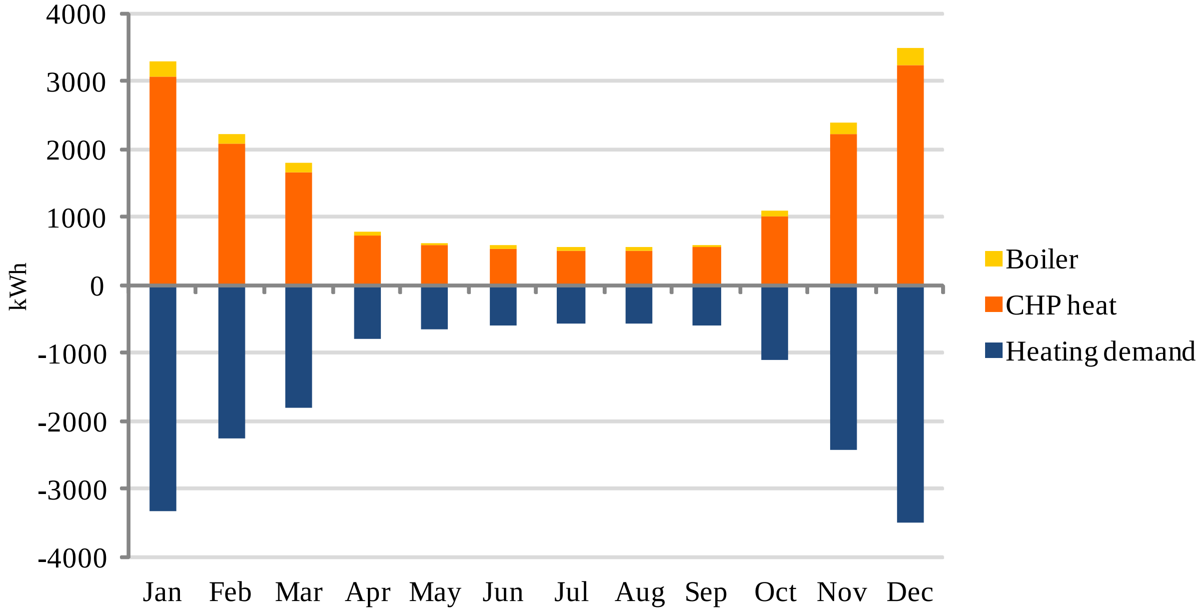
The principle of dividing the heating demand into base load and peak load for sizing the heating system is taken from the "Energy management in buildings". The peak load is a demand that occurs on the coldest day of the year. The rest of the heating demands constitute the base load. The optimal heating power for the system should be from 30–70 % of peak power demand at the design outdoor temperature. Then the base load or approximately 90–95 % of the heating demand will be covered for the building all year around.

The principle has been applied for calculating the optimal heating power of the biomass micro CHP. The micro CHP has been sized to manage demands during long operating time (base load), therefore it meets only a proportion of the peak power demand on the coldest day of the year (see graph below). In the coldest periods the peaks are met by biomass boiler. This has been done in order to not over dimension the CHP, which might result in poor operating conditions and poor economy.

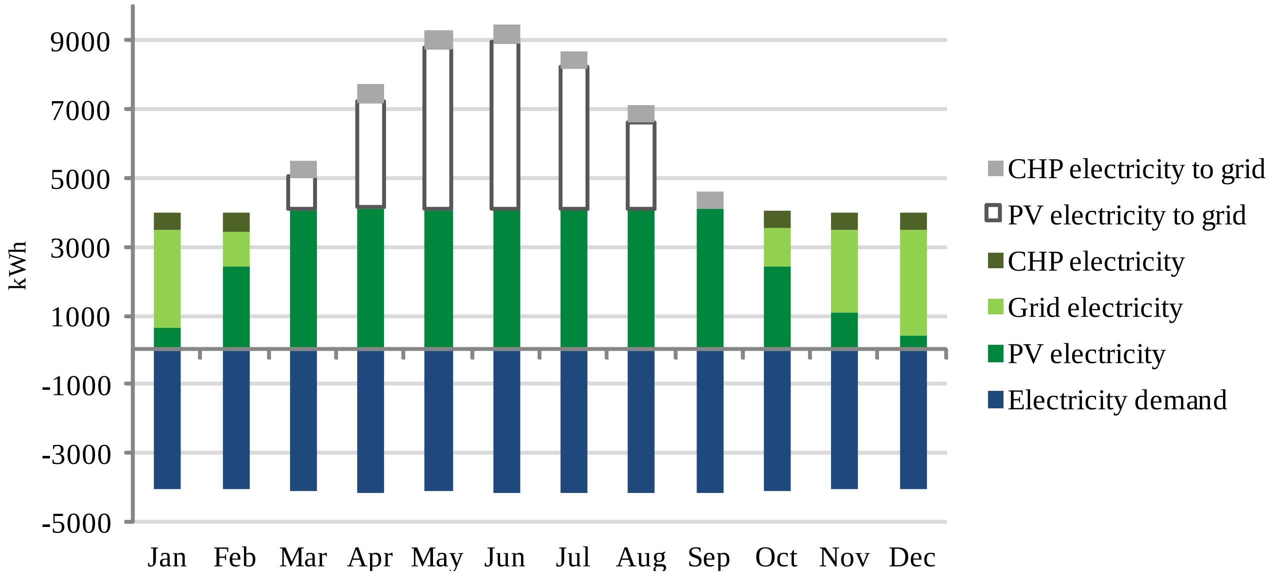


APPENDIX 16. Option 3 - Biomass micro CHP and PV

Heating demand

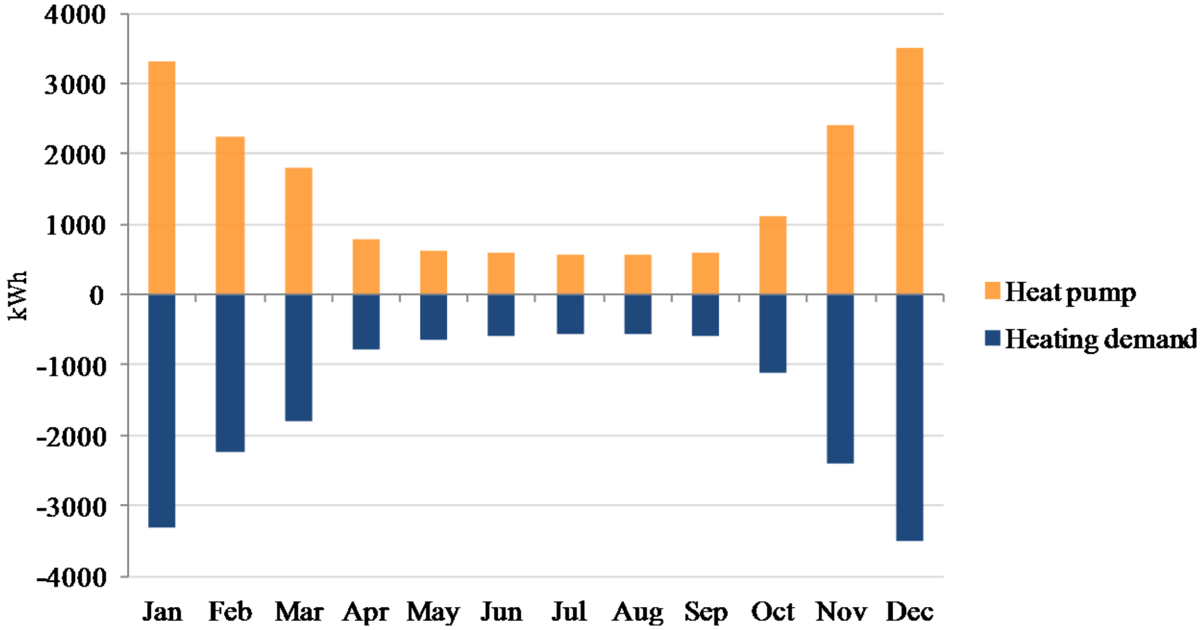


Electricity demand

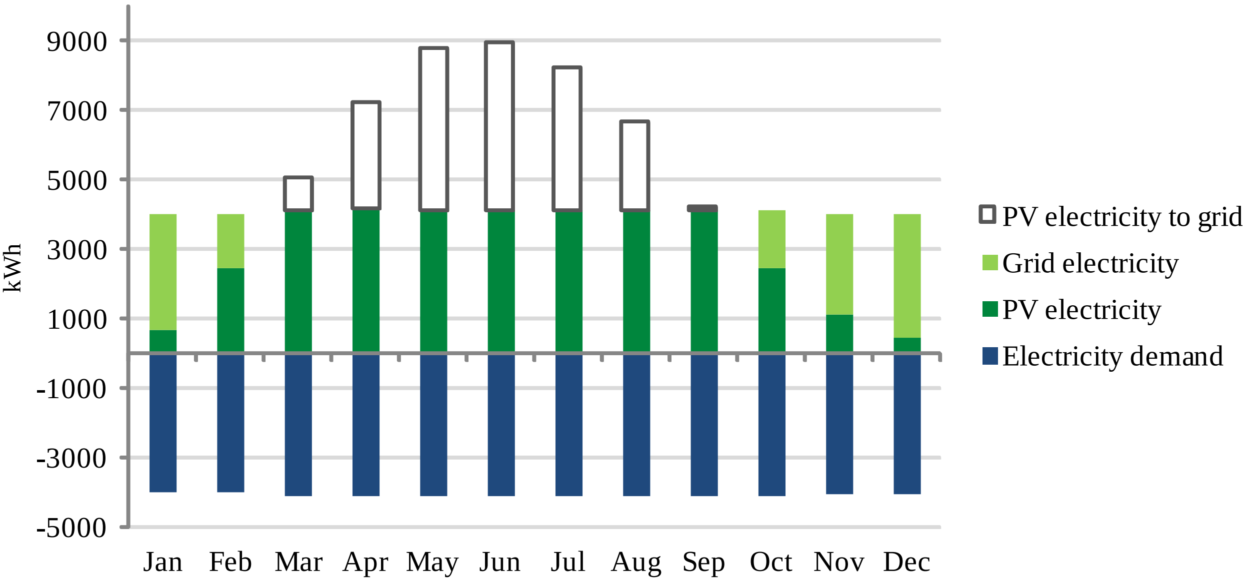


APPENDIX 17. Option 4 - Heat pump and PV

Heating demand

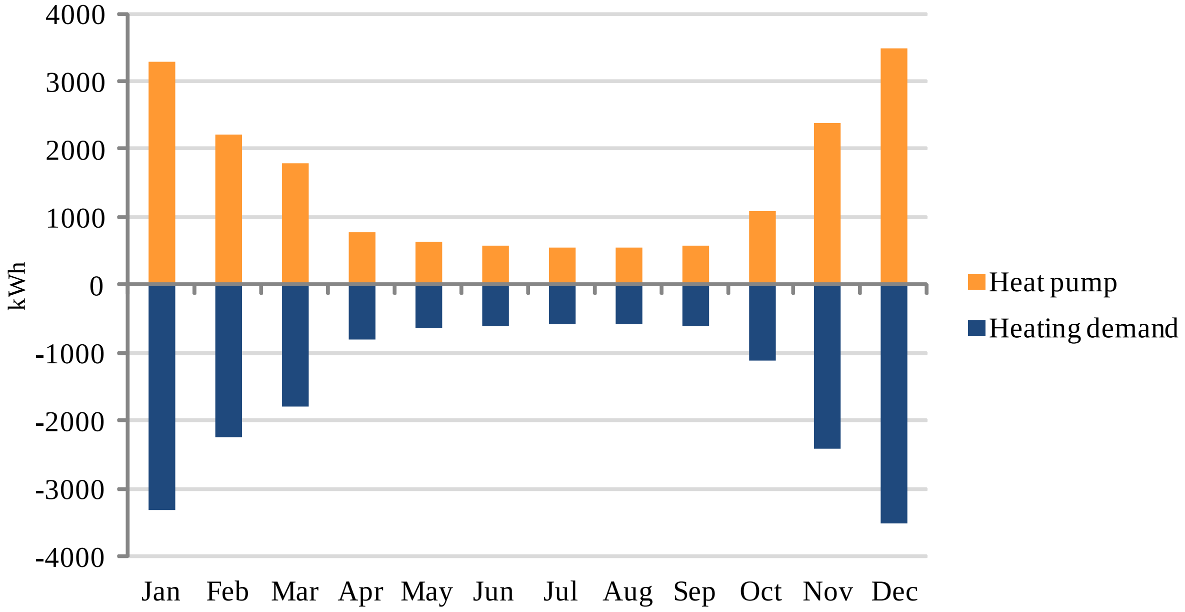


Electricity demand

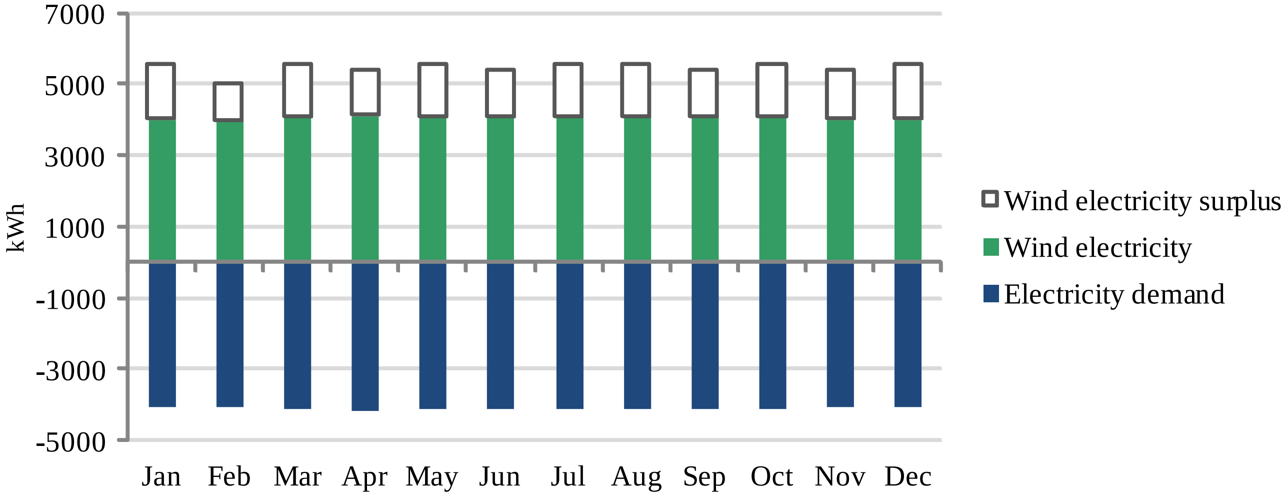


APPENDIX 18. Option 5 - Heat pump and wind turbines

Heating demand



Electricity demand



APPENDIX 19. GHGs emissions - spreadsheet-based calculation (performed according to the Norwegian procedure NS 3031 – 2007 in Excel)

Option 1

	energy supply	fraction	efficiency	delivered energy		fraction	CO2 factor	CO2 emissions	
	(kWh/a)	(%)		(kWh/a)	(kWh/m^{2}a)	(%)	(g/kWh)	(kg)	(kg/m^2)
electricity									
monocristalline PV	56122.0	114.58%	100.0	561.22	0.7	-8.34%	130.0	73.0	0.1
grid	-7142.0	-14.6%	1.0	-7287.8	-8.6	108.3%	395.0	-2878.7	-3.4
total electricity	48980.0	100.0%		-6726.5	-8.0	100.0%		-2805.7	-3.3
heating									
solar thermal	18064.0	100.0%	8.6	2112.7	2.5	100.0%	51.0	107.8	0.1
total heating	18064.0	100.0%		2112.7	2.5	100.0%		107.8	0.1
total	67044.0			-4613.8	-5.5			-2698.0	-3.2

Option2

	energy supply	fraction	efficiency	delivered energy		fraction	CO2 factor	CO2 emissions	
	(kWh/a)	(%)		(kWh/a)	(kWh/m^{2}a)	(%)	(g/kWh)	(kg)	(kg/m^2)
electricity									
monocristalline PV	56122.0	114.58%	100.0	561.22	0.7	-36.51%	130.0	73.0	0.1
biomass CHP (30%)	4359.0	8.90%	0.8	5189.3	6.1	-337.57%	14.0	72.7	0.1
grid	-7142.0	-14.6%	1.0	-7287.8	-8.6	474.1%	395.0	-2878.7	-3.4
total electricity	48980.0	100.0%		-1537.2	-1.8	100.0%		-2733.1	-3.2
heating									
biomass CHP (70%)	9801	82.9%	0.84	11667.9	13.8	82.9%	14.0	163.35	0.2
biomass boiler	2022	17.1%	0.84	2407.1	2.9	17.1%	14.0	33.7	0.0
total heating	11823.0	100.0%		14075.0	16.7	100.0%		197.1	0.2
DHW									
solar thermal	4419.0	70.8%	8.6	516.8	0.6	19.2%	51.0	26.4	0.0
biomass CHP (70%)	1822.0	29.2%	0.84	2169.0	2.6	80.8%	14.0	30.4	0.0
total DHW	6241.0	100.0%		2685.9	3.2	100.0%		56.7	0.1
total	67044.0			15223.6	18.0			-2479.3	-2.9

Option 3

	energy supply	fraction	efficiency	delivered energy		fraction	CO2 factor	CO2 emissions	
	(kWh/a)	(%)		(kWh/a)	(kWh/m²a)	(%)	(g/kWh)	(kg)	(kg/m²)
electricity									
monocristalline PV	56122.0	114.58%	100.0	561.22	0.7	73.00%	130.0	73.0	0.1
biomass CHP (30%)	6296.1	12.85%	0.8	7495.4	8.9	974.91%	14.0	104.9	0.1
grid	-7142.0	-14.6%	1.0	-7287.8	-8.6	-947.9%	395.0	-2878.7	-3.4
total electricity	48980.0	100.0%		768.8	0.9	100.0%		-2700.8	-3.2
heating									
biomass CHP (70%)	10548.5	89.2%	0.84	12557.7	14.9	89.2%	14.0	175.8	0.2
biomass boiler	1274.5	10.8%	0.84	1517.3	1.8	10.8%	14.0	21.2	0.0
total heating	11823.0	100.0%		14075.0	16.7	100.0%		197.1	0.2
DHW									
biomass CHP (70%)	6241.0	100.0%	0.84	7429.8	8.8	100.0%	14.0	104.0	0.1
total DHW	6241.0	100.0%		7429.8	8.8	100.0%		104.0	0.1
total	67044.0			22273.6	26.4			-2399.7	-2.8

Option 4

	energy supply	fraction	efficiency	delivered energy		fraction	CO2 factor	CO2 emissions	
	(kWh/a)	(%)		(kWh/a)	(kWh/m²a)	(%)	(g/kWh)	(kg)	(kg/m²)
electricity									
monocristalline PV	56122.0	114.58%	100.0	561.22	0.7	-8.34%	130.0	73.0	0.1
grid	-7142.0	-14.6%	1.0	-7287.8	-8.6	108.3%	395.0	-2878.7	-3.4
total electricity	48980.0	100.0%		-6726.5	-8.0	100.0%		-2805.7	-3.3
heating									
heat pump ground-s.	18064.0	100.0%	3.5	5161.1	6.1	100.0%	395.0	2038.7	2.4
total heating	18064.0	100.0%		5161.1	6.1	100.0%		2038.7	2.4
total	67044.0			-1565.4	-1.9			-767.1	-0.9

Option 5

	energy supply	fraction	efficiency	delivered energy		fraction	CO2 factor	CO2 emissions	
	(kWh/a)	(%)		(kWh/a)	(kWh/m²a)	(%)	(g/kWh)	(kg)	(kg/m²)
electricity									
windmills	65700.0	134.14%	100.0	657.0	0.8	-4.01%	20.0	13.1	0.0
grid	-16720.0	-34.1%	1.0	-17061.2	-20.2	104.0%	395.0	-6739.2	-8.0
total electricity	48980.0	100.0%		-16404.2	-19.4	100.0%		-6726.0	-8.0
heating									
heat pump ground-s.	18064.0	100.0%	3.5	5161.1	6.1	100.0%	395.0	2038.7	2.4
total heating	18064.0	100.0%		5161.1	6.1	100.0%		2038.7	2.4
total	67044.0			-11243.1	-13.3			-4687.4	-5.6