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Carbon Footprint Calculation of an AEH-technology Residential House from Cradle to Grave

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This thesis presents the carbon footprint calculation of a Finnish active energy house (AEH), which uses a range of innovative energy saving technologies. The calculation is made for all the stages of the 50-year life-cycle from cradle to grave.

The results of the study take into account footprints of all materials production, materials transportation to the site, commissioning and demolition phases with all the waste and its transportation to waste treatment facilities and also the 50-year operation cycle of the house.

As the house is mostly made of wood and wood-based materials, their carbon storage capacity is used as a benefit so that the CO_2 emissions from wooden structures for a 50-year life cycle decrease by one half. The other benefit of the wooden structure shows during the final disposal phase, as the structures can be used in waste-to-energy plants to produce energy. The energy is allocated for the energy use during the whole life cycle. Due to special construction arrangements, the electricity need for the house is extremely low. Thus when the bioenergy form the final phase is being considered, the energy use is not only evened out, but also energy is left in excess.

According to the results, the mass of the whole house structure is 83.6 tones and the net carbon footprint for all the materials is 24 tons of CO_2-eq. Due to the fact that most of the structure is wood-based, carbon uptake was accounted for 50 years, resulting in the final carbon footprint of the structure being reduced to 13 tons of CO_2-eq. Three sources of emissions were considered in the calculations: transportation, contruction+demolition+renovations and construction waste. Transportation was found to be the biggest emission cause resulting in 0.9 tons of CO_2-eq. Footprints of construction waste and building activities seemed to be minor sources of emissions, being 0.3 and 0.2 tons of CO_2-eq, respectively. When it comes to electricity demand for the whole 50-year life cycle, the emissions from electricity production were calculated to be 15.8 tons CO_2-eq. When energy that can be produced from the house materials after demolition was allocated to the electricity demand calculation, the result was a benefit of -5 tons CO_2-eq. The possibility of recycling some of the materials also gave a benefit of 0.546 tons CO_2-eq. After taking all the emissions and uptakes into account, the final result for the amount of GHG emitted for the life cycle of the active house from cradle to grave was 8.7 tons of CO_2-eq, which is 20 times less than the carbon footprint of a standard house.

Keywords	Cradle-to-grave, Carbon footprint, Net Zero Energy Building

Table of contents

List of figures 4

List of Tables 5

Abbreviations 6

Units 7

1 Chapter 1. Literature research 8

- 1.1 Introduction 8
- 1.2 Energy saving technologies 10
  - 1.2.1 Passive design 10
  - 1.2.2 Insulation 11
  - 1.2.3 Thermal bridges 12
  - 1.2.4 Residential heating and cooling 13
  - 1.2.5 Ventilation 16
  - 1.2.6 Windows 16
  - 1.2.7 Daylight planning 17
  - 1.2.8 Own electricity production 18
  - 1.2.9 Carbon neutrality 19
- 1.3 Case study practicalities 20

2 Chapter 2. Case study 24

- 2.1 Introduction 24
- 2.2 Goal and scope 25
- 2.3 Basic information about the house 26
- 2.4 Cradle-to-gate 27
  - 2.4.1 Carbon stock 28
- 2.5 Transportation to the building site 29
- 2.6 Commissioning 30
  - 2.6.1 Construction waste 30

2.7 50 year operation 31
  2.7.1 Renovations 33
2.8 Demolishing 33
2.9 Transportation of waste 33
2.10 Final disposal 33
2.11 Discussion 34
2.11.1 Uncertainty and limitations 34
2.12 Results 35
2.13 Sensitivity analysis 37
  2.13.1 Scenario 1. Electricity demand. 37
  2.13.2 Scenario 2. Heating/cooling demand. 39
  2.13.3 Scenario 3. Distant transportation. 40
  2.13.4 Discussion 40
3 Optimi 360 42
4 Conclusion 45
5 References 47
Appendices 51

List of figures

Figure 1. Concept of passive design. 11
Figure 2. Left: Conventional wall structure with a thermal bridge... 13
Figure 3. Air channel from the ground.. 21
Figure 4. Mantle ventilation.. 22
Figure 5. New window technology. 22
Figure 6. Energy center.. 23
Figure 7. Steps for calculating carbon footprint.. 24
Figure 8. Process map of the life-cycle. 25
Figure 9. Southern and Eastern views of the house.. 26
Figure 10. Floor plan of the house.. 27
Figure 11. Comparison with other types of houses. 36
Figure 12. Relation between rising electricity demand and total carbon footprint. 38
Figure 13. Relation between rising heating/cooling demand and total carbon footprint. 39
Figure 14. Relation between growing transportation distance and total carbon footprint. 40
Figure 15. Results by 360 Optimi: mass of structure and carbon footprint of different phases. 43
Figure 16. Carbon footprint division between different life-cycle stages. 44

List of Tables

Table 1. Mass of structure, carbon footprint, carbon footprint with carbon stock. 29
Table 2. Transportation of materials to the building site. 30
Table 3. Construction waste fractions, recyclable and energy waste... 31
Table 4. Transportation of construction waste. 31
Table 5. Electricity need for 50-year operation: 1. Net 2. With allocations due to energy from waste. 32
Table 6. Transportation of waste after demolition. 33
Table 7. Study results. 35
Table 8. Emission generation with a 40% greater electricity demand, 50 years. 38
Table 9.Comparison of manually calculated results with software outcome. 44

Abbreviations

ACH	Air changes per hour
AEH	Active energy house
BREEAM	Building Research Establishment Environmental Assessment Methodology
CDD	Cooling degree days
CHP	Combined heat and power plant
COP	Coefficient of performance
CPFA	Carbon footprint analysis
EPBD	DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings
ER	Energy rating
EU	European Union
GHG	Greenhouse gas
HDD	Heating degree days
HRV	Heat recovery ventilation
IEA	International Energy Agency
ILCD	Life Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
nZEB	Net Zero Energy Building
OPEC	Organization of Petroleum Importing Countries
PAS	Publicly available specification
PCM	Phase change materials
PV	Photovoltaic
RSI	Resistance, Systeme International
SHGC	Solar heat gain coefficient
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compound
VT	Visible transmittance
VTT	Technical Research Centre of Finland
WTEPP	Waste-to-energy power plant

Units

℃	Degree Centigrade
CO_2eq	Carbon dioxide equivalent
g	Gram
g/tkm^2	Gram per ton per kilometer
h	Hour
kg	Kilogram
km	Kilometer
kW	Kilo Watt
kWh	Kilo Watt hour
KWh/m^2	Kilo Watt hour per meter cubed
m	Meter
m^2	Meter squared
m^3	Meter cubed
min	Minute
MJ	Megajoules
mm	Millimeter
MWha	Megawatt annually
t	Tones
W/m^2 K	Watts per meter squared kelvin

1 Chapter 1. Literature research

The following chapter will introduce the concept of net zero energy buildings, active house and passive house and give the overview of technology and methods used in buildings to achieve the needed energy targets. It will prepare a theoretical base for the case study in terms of energy consumption and its influence on the overall carbon footprint of a building. The chapter is based on literature sources and a case study. Although some measures for larger residential and office buildings are mentioned in the chapter, the main focus is single-family/terraced residential houses.

1.1 Introduction

Building industry in one of the most energy intensive industries in the world. According to the International Energy Agency in 2006 (IEA), buildings use “40 percent of primary energy consumed globally, accounting for roughly a quarter of the world’s greenhouse gas emissions. Commercial buildings comprise one third of this total” (Kubba, 2009, p. 2). Greenhouse gas emissions account for the climate change, which is nowadays growing into a huge environmental, economic and even social problem. Here the Kyoto Protocol, 1997 (extending the 1992 United Nations Framework Convention on Climate Change (UNFCCC)) should be mentioned. It set a target of reducing greenhouse gas emissions and is now ratified by 192 Parties. But the concept of a green building is much older than the Protocol due to economic reasons. At least in the USA, the movement of green building started in the mid-1970s with the oil embargo by OPEC (the Organization of Petroleum Importing Countries) (Kleer and Burke, 2009, p. 34). This lead to an increase in design of highly insulated buildings to reduce the needs for heating and cooling and, therefore, the costs. And later this trend became the key point of the green building movement in terms of energy conservation.

Nowadays the concept of green building being “less bad” economically and environmentally as transformed into the second concept of “sustainable design and construction” being a “good” building and “integrating the principles of economic, social and ecological sustainability” (Kleer and Burke, 2009, p. 44).

Here the term “carbon neutral” comes into existence. “Carbon neutral” is the nirvana of sustainability. It is a complete cradle-to-gate analysis of all embodied energy in the making of an object, the use and recycling of that product so it can be used again instead of becoming waste” (Kleer and Burke, 2009, p. 44).

Hence, when it comes to the main principles, sustainable building must meet the following criteria:

- Tackle site-demolition issues and construction-and-packaging-waste issues, as well as waste generated by the users of the building;
- strive for efficiency in a broad area of resource use;
- minimize the impact of mining and harvesting for materials production and provide measures for replenishing natural resources;
- reduce soil, water and energy use during materials manufacture, building construction and occupant use;
- plan for low embodied energy during shipment;
- proceed logically, as the chain of materials’ production is traced;
- conserve and design for the efficiency of energy consumed by powering mechanical systems for heating and cooling, lighting and plug loads” (Kleer and Burke, 2009, p. 33-34).

The first step towards carbon neutrality is ZEB, a (net) zero energy building. There are many existing definitions for nZEB, the following one is the most official ad presented in the Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (EPBD). The directive sets a goal of reducing, by 2020, the overall greenhouse gas emissions by at least 20% below 1990 levels.

According to the directive, “nearly zero-energy building’ means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” (Directive 2010/31/EU). Annex I mentions a range of measures for a high energy performance, which will be discussed in the next chapter. When it comes to implementation, “interpreting the implementation of measures and methods of calculation are lest to the member states” (Harvey, 2006, p. 13).

Here it needs to be mentioned that we are sometimes using another term for a net zero energy building, which is “passive house”. What is more, a term “active house” is present in the name for the technology of our case study. The term means a plus-energy building: a building with a surplus energy production; renewable sources within the building produce more energy than it consumes over a year.

1.2 Energy saving technologies

A good building model uses integrated design, consisting of several aspects that need to be taken into consideration: structure, material data, fluid dynamics, geographic location, electrical plumbing, lighting, energy and environmental design (Ganguly, 2013, p. 13). The following passages will describe sustainable solutions for such an integrated designs.

1.2.1 Passive design

For every building there is a balance-point temperature, when a comfortable indoor temperature is reached for a certain outdoor temperature without any additional heating or cooling. Passive houses aim for a maximum indoor/outdoor temperature difference at the balance point, using, for example, proper insulation, high-performance windows (Kleer and Burke, 2009, p. 82). For every country there are specific “comfort” values for indoor temperature, humidity and air change rate, these factors combined influence each other. In the climate of central Europe, for instance, the interior temperature of a passive house doesn’t fall below 10 °C without any heating (Voss and Musall, 2011, p. 18).

Another way of defining passive design is “the use of architecture to harvest free energy from the environment” (Hootman, 2012, p. 185), for example, natural heating, cooling, ventilation and lighting. This means that “the traditional active systems are not employed and that the passive strategies alone are enough to satisfy the needs of building occupants” (Hootman, 2012, p. 185). A schematic concept of passive design can be seen in Figure 1.

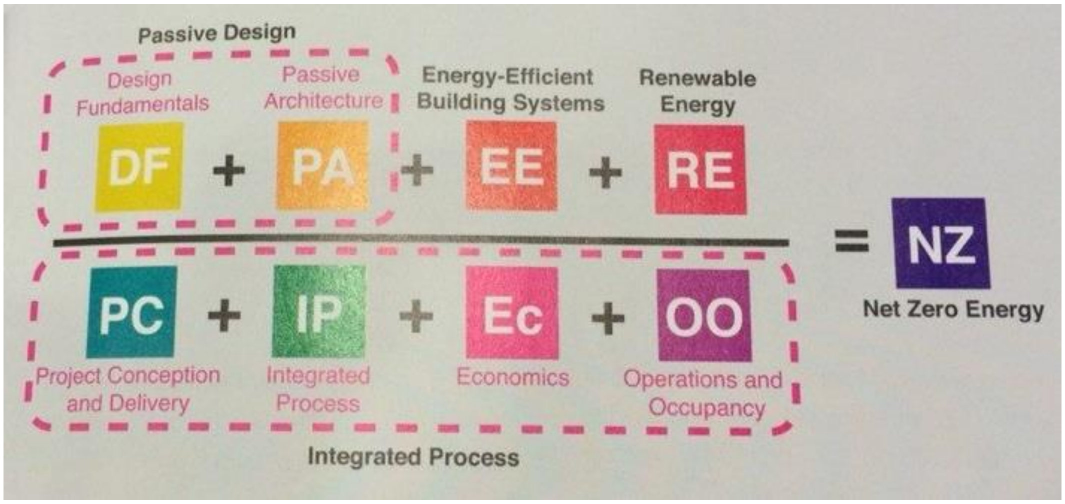


Figure 1. Concept of passive design. (Hootman, 2012).

In a passive house air leakages are minimized, the standard leakage rate of air is 0.2 air changes per hour (ACH), 50 Pa. This is done with a super-insulated structure (U<0.15), high performance windows and doors $0.6<U<1.0$ W/m^2 K (Mumovic and Santamouris, 2009, p. 71-72).

1.2.2 Insulation

Insulation is designed to limit heat transfer between the building envelope and the outdoor air. There is a number of insulation materials, produced in different shapes. The most common are fiberglass (sold in rolls), paper fiber insulation (blown in), rigid insulation (foam-like substance like extruded polystyrene) and foamed-in-place insulation like the mixture of isocyanate and polyol that comes from an injection gun. Any type of insulation limits the air movement, which creates a hinder to heat-loss by convection. The measure of insulation performance is the R value, heat resistance. There is another type of insulation, reflective insulation. It is usually made from shiny metals; this type of insulation reflects the heat back to its source, like a mirror (Kleer and Burke, 2009, p. 107-108).
Insulation plays an important role in the moisture control of a building.

The most insulated houses in the world have wall RSI (resistance, Systeme International) values of 5-7 and roof RSI values of 7-10. High levels of insulation can be combined with appropriate framing systems so that the use of wood and wood waste is minimized (Harvey, 2006, p. 58). For a wooden framing spray-on cellulose insulation is a good solution, as it fills the voids completely and has a 10-

15% higher insulation value compared to insulation batts. Moreover, it is preferred not only for its efficiency but also due to its environmental friendliness with negligible embodied energy and absence of halocarbons (Harvey, 2006, p. 61).

Phase change materials (PCM) in the form of micro-encapsulated paraffins can be added to mineral insulation materials of walls and ceilings to improve their heat storage capacity. This material absorbs heat at 21-22 °C while melting and gives it back during solidification. Salt hydrates have an even better heat storage capacity (Voss and Musall, 2011, p. 18). There is a range of salt hydrates working in the temperature interval from 18.5 to 116 °C (Abhat, 1983, p. 318) so they should be chosen in accordance with the objective. Still and additional heating system is needed to reach a comfortable dwelling temperature ex. at night.

Insulation for the attic is an important measure to significantly improve the insulation efficiency, as all the warm air moves up towards the roof. Studies have shown that the most significant heat losses occur through roofs, also good roof/attic insulation is beneficial for cooling, as roofs tend to heat up more than any other part of a building.

Green roofs have been used for centuries to protect homes. “Eco-roofs are aesthetically pleasing, add insulation, reduce outside noise, protect the roof from destructive ultraviolet radiation, filter pollution from rainwater and absorb much of the water that could otherwise create runoff problems” (Koones, 2010, p. 55). These roofs provide a layer of vegetation in soil, placed over a waterproof membrane supported by wood framing (Koones, 2010, p. 55).

Double-skin façade technology can also be used for insulating purposes. A double-skin façade is a “façade with an inner and outer wall separated by an air space that is not actively heated or cooled” (Harvey, 2006, p. 91). A similar technology is used for the case study building in the second chapter of the report. There are many types of such constructions. Usually they are two separate glass walls (may be double or triple glazed) with operable windows. In the case study, though, the walls are not made of glass.

1.2.3 Thermal bridges

More conductive elements let the heat flow from hot to cold more eagerly, and if they are placed across a building’s envelope, they contribute to heat loss. Such paths are called “thermal bridges”. A “failure to eliminate these bridges creates the conditions for interstitial condensation forming deep within the construction and lead to potentially serious issues of mold growth and rot” (Adele, 2011, p. 32). For a better R value of the insulation and less moisture problems, thermal bridges should be minimized. Figure 2 below shows a comparison between a conventional wall with a thermal bridge and a high performance wall without the thermal bridge. Breaking the thermal bridge was done by replacing ordinary plywood with rigid foam having a better insulating performance. Red arrows represent the heat inside the house, whereas orange arrows show the heat flow form the building to the outside. Figure 2 clearly shows that less heat escapes through a high performance wall structure than through a conventional wall.

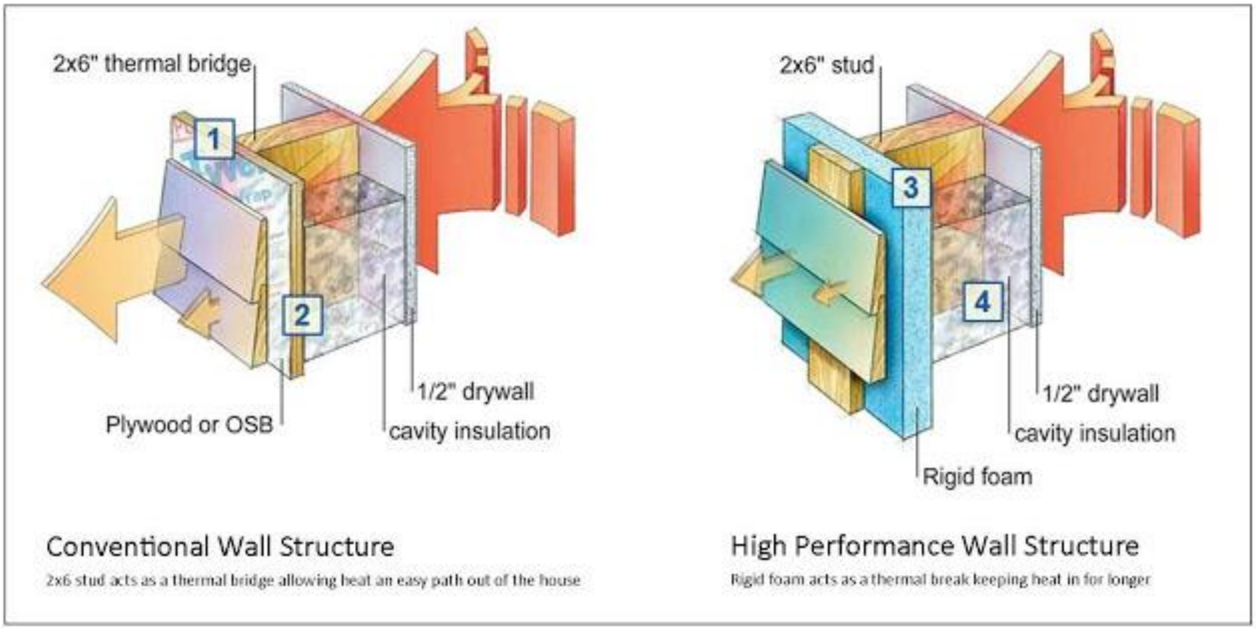


Figure 2. Left: Conventional wall structure with a thermal bridge. Right: High performance wall structure with a thermal brake. (Mcgar, 2014).

1.2.4 Residential heating and cooling

The need for residential heating and cooling depends on the climate; therefore, the terms heating degree days (HDD) cooling degree days (CDD) (Harvey, 2006) have been introduced to make comparisons numerical.

Good insulation of the building envelope provide a good start for energy efficiency; during mild temperatures this measure could be enough for a comfortable indoor climate; but during more extreme temperatures additional heating/cooling is needed.

Heating can be provided with basically three main principles: hot air, hot water or electric heating.

Warm air is delivered to the living space through ducts. Compared to water heating systems, air heating is more problematic due to possible duct losses. Also a large temperature difference between the air inside and outside the duct leads to efficiency losses. Therefore, ducts need to be well sealed and well insulated.

Hot water runs through radiators or, in some designs, through pipes in the floor. In heating systems, which involve combustion of fuel, special sealed ventilation should be provided to make sure no contaminants enter the indoor air and to prevent carbon monoxide poisoning. Wood-burning stoves running on harvested cuttings from forests could be a good renewable solution (Mumovic and Santamouris, 2009, p. 64). For a sustainable building, the heating system should be properly sized to maximize the efficiency.

Solar thermal collectors could be one solution to help the major heating system. Solar air and water pre-heating systems are also available to decrease the heating demand. Ground heat exchangers have the same working principle and can be used for air/water pre-heating/cooling. Hot water storage with thermo-chemical substances (zeolites) even more effective than common ones. Hot water storages in combination with heat pumps (Voss and Musall, 2011, p. 19-20) are also more effective than conventional ones.

Electric heating systems (electric furnaces, radiant floor systems,) are fully dependent on the electricity price and availability; hence, they are not the first priority when more “natural” heating ways are available.

Nevertheless, electric heat pumps have shown being quite effective. There are several types of such appliances. For instance, air-sourced heat pumps (can also provide cooling) are good for climates where outdoor temperature does not fall below freezing. Thus, the COP of such a device would be stably 3-3.5 within a temperature range of -3 to +10°C. In milder climates, it can reach 4.

Ground source or geothermal heat pumps are more suitable for cold climates. This type of heat pump uses vertically or horizontally (depending on the ground temperatures) placed tubing with refrigerant, and works in a heating or cooling cycle. In cold climates, the depth of the boreholes can be large, which would make the installation costly. Geothermal heat pumps can reduce energy consumption by 44% compared to air-source heat pumps and 72% compared to standard electric heating. The COP can range from 3 to 6 during the coldest periods (Carmichael).

Here not only heating but also control mechanisms need to be mentioned. Thermostats (manual of programmed) are one way of optimizing energy use and reducing the costs.

When it comes to cooling, shading is the best known practice. Simple ventilation and ground heat exchanger pre-cooing are much cheaper than air conditioning and work well in hot dry climates and hot climates with normal humidity. Moreover, opening the window at night is an easy and effective solution. In hot and dry climates, evaporative cooling is applied. In hot and humid climates, passive cooling techniques are the most limited; therefore, air conditioning is used more frequently (Kleer and Burke, 2009, p. 114-119).

Thermal zoning is one important aspect that could save energy for heating and cooling. It “refers to the strategic arrangement of spaces to take advantage of the thermal synergies and qualities of spaces, and their relationships to other spaces” (Hootman, 2012, p. 178). For instance, some spaces can afford a wider range of thermal comfort, while some have tighter requirements; some spaces, like kitchen, have high internal heat gains and in colder climates these spaces could be placed on the northern perimeter of the house (Hootman, 2012, p. 178-180).

In order to make carbon reduction in a building more effective, all the heating/cooling equipment needs to have high efficiency ratings and to be properly sized; variable volume air systems, for example, can be used to respond the changing demands. To reduce heating/cooling energy usage, energy storage and desiccant dehumidification can be considered (Mumovic and Santamouris, 2009, p. 64). Thermal energy storages have several options: chemical reactions (collecting heat to excite a reversible endothermic chemical reaction), thermo-chemical (sorption) processes (storing energy by using it to break the bonding of water with a relevant substance (desorption), evaporate one of the products, and condense it for future use). The heat is recuperated by re-evaporating the condensed product and re-bonding it (sorption) with the other substance.), latent storage with phase change materials and sensible storage storing heat as internal energy in a solid or liquid medium like water (Pinel et al, 2011).

1.2.5 Ventilation

A tight building envelope of a passive house requires ventilation, which would give thermal comfort and a sufficient air quality. It needs to be designed in a way that it does not impair air quality or the building structure by providing a sufficient number of inlets and outlets. If the amount of inlets if not sufficient, back drafting can occur. This means that the air from the outlets can flow back with all the contaminants, ex. kitchen exhaust. The more advanced type of ventilation is installed, the more complicated control system is required.

For energy saving purposes, ventilation with heat recovery (HRV) can be installed, ex. run-around loops, cross-flow heat exchangers, heat pipes, heat wheels. It uses the temperature of exhaust air to warm up incoming air. The system saves up to 4/5 of the energy, which otherwise would have been lost (Kleer and Burke, 2009, p. 114). Heat recovery can also use other fluid streams such as used hot water. Heat recovery ventilation is feasible for buildings which are relatively air tight (below 5 $m^3/(h\ m^2)$ at 50Pa) and suffer from excess relative humidity. It can be used in all types of buildings, but it should be kept in mind that the feasibility of the HRV unit fully depends on its sizing, so it is recommended not to oversize the unit.

1.2.6 Windows

Most of the passive houses built nowadays use triple-glazed windows. The three key values for choosing a window (ready combination of glass, frame and else) are its U-value, solar heat gain coefficient (SHGC) and visible transmittance (VT). The U-value represents the heat loss through the window; in cold climates, the lowest possible U-value is recommended, whereas in hot climates just low U-values are permissible. Solar heat gain coefficient is the amount of solar radiation after the window compared to the amount of radiation before the window; this value is more important for hot climate conditions and not shaded windows. The term visible transmittance (VT) represents the percentage of visible light that is transmitted to the interior. It includes the impact of the frame, which is not transparent to light.

Window frame materials and glazing play an important role in the overall insulation of the building envelope. For instance, aluminum frames act like thermal bridges and therefore cannot be used in cold climates; wooden frames perform well thermally, but require more maintenance than other materials; vinyl frames require practically no maintenance, but are less stable dimensionally and have questionable environmental impacts; window frames of fiberglass have low maintenance requirements, good dimensional stability and thermal performance; hybrid frames, which take the advantages from different materials, are also available on the market.

When it comes to glazing, in modern houses three or four (in colder climates) panes of sealed glass are used. To improve window performance, inert gases like argon or krypton fill the air gap between the panes, as inert gasses are less conductive. E-coatings (ex. thin metallic coating) are sometimes applied for the window glass to improve U and SHGC values (Kleer and Burke, 2009, p. 109-114).
Vacuum windows are another solution to completely eliminate conductive and any convective heat transfer, although not through the pillars. Anyway, a 6 mm thick vacuum glazing might have a U value half that of a conventional double-glazed window (Harvey, 2006, p. 65-66).

As it has been mentioned earlier, passive solar heating is one of the energy saving solutions for cold climates. The Canadian Standards Association has even developed an index called *energy rating (ER)* for windows that combines the effect of solar heat gain and non-solar heat loss. According to the ratings, high performance windows not facing the north can become a good source of heat for the coldest days, when the temperature is low and pressure high, resulting in sunshine (Harvey, 2006, p. 81-82).

1.2.7 Daylight planning

Among the factors that affect a building's design, natural specialties play the leading role. They include such factors as geographical position, climatic conditions and landscape. Lighting is one of them. Research has shown that exposure to daylight has a positive effect on human health, mental abilities and work efficiency and even school test results (Kleer and Burke, 2009, p. 80). Moreover, daylight planning techniques in buildings are an opportunity to reduce energy for lighting, and that is an essential feature for an energy saving house.

So it is possible to design a house in a way, where day lighting is maximized, by merging architecture, materials and equipment. So from the point of view of architecture, the house needs no be placed along the east-west axis with sources of day-light from more than one side; window dimensions should be chosen in proportion with a particular room's depth. The design should maximize light and minimize heat gains. This is normally done by avoiding direct sunlight (glare) and creating solutions for diffuse light. Preferring diffuse light is also due to visual comfort. Here it should be said that design solution differ greatly in cold and hot climates, so while windows in hot climates would be preferably shaded (or electrochromic/thermochromic windows used) all the time, direct sunlight and heat gains would not be a problem and would even be desirable for cold climates in winter. So in cold climates window shading could be done seasonally. Also taking into account the fact that the sun shines at lower angles during the winter, louvers could be used all the year round. As for technical appliances for lighting, their goal is to optimize artificial lighting loads. There several ways for doing it. For instance, daylight sensors that trigger artificial lighting, when the daylight level drops to a certain amount, could be installed together with sensors, that switch off the light when daylight is enough. Another solution for artificial lighting economy would be dimming techniques either guided or prescheduled. Moreover, movement sensors would also be a good solution for electricity economy when the room is empty. Even color and textures that either reflect or absorb light could partly be a path to energy saving (Kleer and Burke, 2009, p. 80-82).

A handbook of sustainable building design and engineering also advises to design narrow buildings, “maximize the amount of daylight entering the building by providing windows with a view of the sky zenith”, “use light shelves to ‘bounce’ daylight deeper into the occupied space” and “
where possible, use clerestory, light pipes and roof glazing systems”. It is also stated that “buildings with small glazing ratios will produce significantly more carbon than buildings with larger glazing ratios” (Mumovic and Santamouris, 2009, p. 64-66).

1.2.8 Own electricity production

Earlier heat pumps and thermal solar collectors have already been mentioned as a way of heating/cooling optimization.

The following passage is dedicated to mostly electricity production. For zero energy buildings, this electricity should be enough to cover the building’s own needs, and as for plus energy buildings, the additional electricity produced can be fed to the grid.

Electricity can be generated from the sun using photovoltaic (PV) cells with additional electrical connections and a battery backup. To improve the orientation of the modules to the sun, mounting hardware can be used (Kleer and Burke, 2009, p. 119-120). Of course, climatic conditions and the

amount of sunlight need to be taken into consideration when PV is being considered. For instance, in Finland it would not be feasible to rely only on PV as there is almost no sunlight 4 months a year.
Small residential turbines for electricity production are also available on the market. "To generate power, the average autonomous house needs only one small wind generator, 5 m or less in diameter. On a 30 m high tower, this turbine can provide enough power to supplement solar power on cloudy days" (A guide to sustainable architecture, p. 7). Of course, all the installations should be made according to the weather characteristics and in line with the local legislation.

Micro-combined heat and power plants (CHP), although expensive, could provide both electricity and heat to an individual home or a small community. "Current technologies for these systems are capable of providing the same comfort levels in a home as a traditional boiler, while at the same time reducing carbon dioxide emissions by about 1.5 tons per year (around 25 per cent)" (Mumovic and Santamouris, 2009, p. 70-71). This number could be applied to fuels as residuals and waste, while biomass fuels would produce nearly no fossil CO_2.
Nevertheless, Voss and Musal (Voss and Musall, 2011, p. 20) claim that a self-sufficient power supply should be implemented only if necessary because smaller power systems suffer from lower efficiency and cause more costs than a centralized stable power supply. However, with own production, the end user avoids, for example, transfer losses (7% in Finland). Furthermore, in high capacity rate wind conditions, wind turbines can have same electricity production efficiency than condensing nuclear power.

1.2.9 Carbon neutrality

Carbon emissions have been separated into two subclasses: regulated (from fixed building services) and unregulated (caused by the dwellers, e.g. cooking and electrical appliances) (Cotterel and Dadeby, 2012 p. 64). The following passage will focus on regulated emissions. Unregulated ones could be minimized by A energy class appliances and responsible use.

The energy performance of buildings directive does not focus on building materials used in construction, as the focus on use of low-impact materials would discourage mainstream builders. But there is no reason to use non-natural materials. On the contrary, environmental friendly materials would help to achieve carbon neutrality and environmental performance. Embodied energy of material is one of the main material properties from this point of view. It is the sum of all the energy inputs required for the production of the material. High-embodied energy products like steel result in a higher carbon footprint, so the use of such materials should be reasonable. For instance, there are “added values” like improved performance, structural strength, space saving or aesthetic benefits that high-embodied energy might bring. Natural materials can also bring added values.

Some practical ways to reduce embodied energy, offered by the Passivhaus Handbook, are as follows: recycling of materials whenever possible, retrofitting and extending rather than demolishing, use of locally sourced materials, avoidance of over-engineered solutions (like steelwork and concrete foundations), use of assemblies that can be dismantled rather than destroyed, build once-build well approach (Cotterel and Dadeby, 2012 p. 61-63). The benefit of natural materials lies not only in low-embodied energy but also in carbon sequestration and in the ability of many materials to help regulating internal humidity levels and improve air quality by absorbing VOCs (ex. caused by off-gassing of paints) (Cotterel and Dadeby, 2012 p. 64). One example of this would be a timber frame. It is a simple construction, which does not require additional machinery and therefore additional energy to assemble; it is a carbon storage and “many of today’s timber frames use standing dead wood, and wood that has been purchased from managed forests” (Koones, 2010, p. 15) that makes it even more beneficial. When a building is disassembled its timber frame can be reused or used for bioenergy production. Also a well-built log house could be an even better choice. It does not have moisture problems, and its thick walls are excellent heat insulators. So when it comes to a single-family house, log could be a better alternative than structures with layered walls, which have more artificial materials and can have moisture problems. However, a log house needs a bigger investment.

According to a study made in Finland (Ruuska and Häkkinen, 2012, p. 81), increasing the wood fraction in new construction and refurbishments is highly beneficial: firstly, it reduces the overall amount of annually used construction materials (12% reduce in construction material use in a 22% share wooden construction) and secondly, the amount of annually emitted GHG fall significantly (13% reduction in GHG in a 22% share wooden construction).

1.3 Case study practicalities

In this section energy solutions for the case study building will be shown and commented. Yet no description of the building, its dimensions and materials will be presented before the second chapter.

This is done for the integrity of the second chapter, not to digress on energy efficiency solutions when only their performance value is needed.

According to the standards, the overall energy use for all domestic appliances is 120 KWh/m^2, and the energy for space heating is limited to 40 kWh/m^2 (Rode and Eriksen, 2013, p.3). In the case study building, the construction of the building provides a remarkable 0 kWh/m^2 for space heating and 40 KWh/m^2 for all electricity use. Figures below show the innovations applied in the active energy house (AEH) technology.

Figure 3 below shows an air pre-heating/cooling geothermal system, which consists of an underground pipe at a depth of 2,0-2,5 meters. The more stable ground temperature provides cooling of air during summer and heating during winter. There is also a water-collecting system for condensate. The pre-heated/cooled air is then transferred to the hollow channel between the air-tight mantle and the facade, preventing outdoor air from directly influencing the mantle.

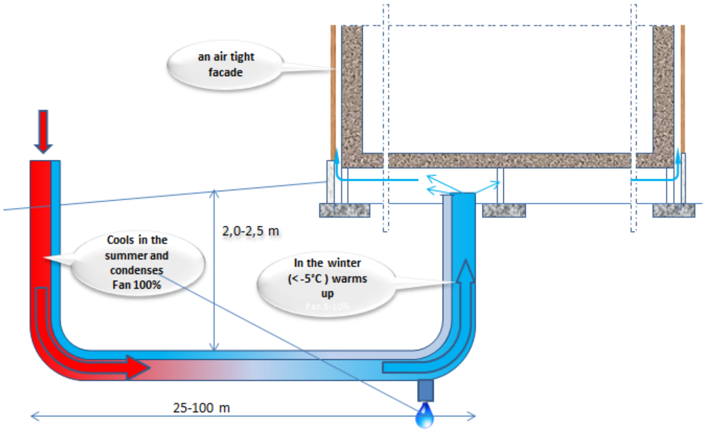


Figure 3. Air channel from the ground. Source: AEH technology commercial presentation.

Figure 4. emphasizes the building's air tightness and shows the possibilities of passive solar heating. Air tight and properly insulated roof is one of the most important solutions, as hot air rises and heat can escape from a poorly insulated roof in winter; or, as the roof is the most heated part of the house in summer, lack of insulation could lead to overheating. Ventilation with heat recovery is also shown in the picture. A more detailed outline of the ventilation system can be found in the picture on the right.

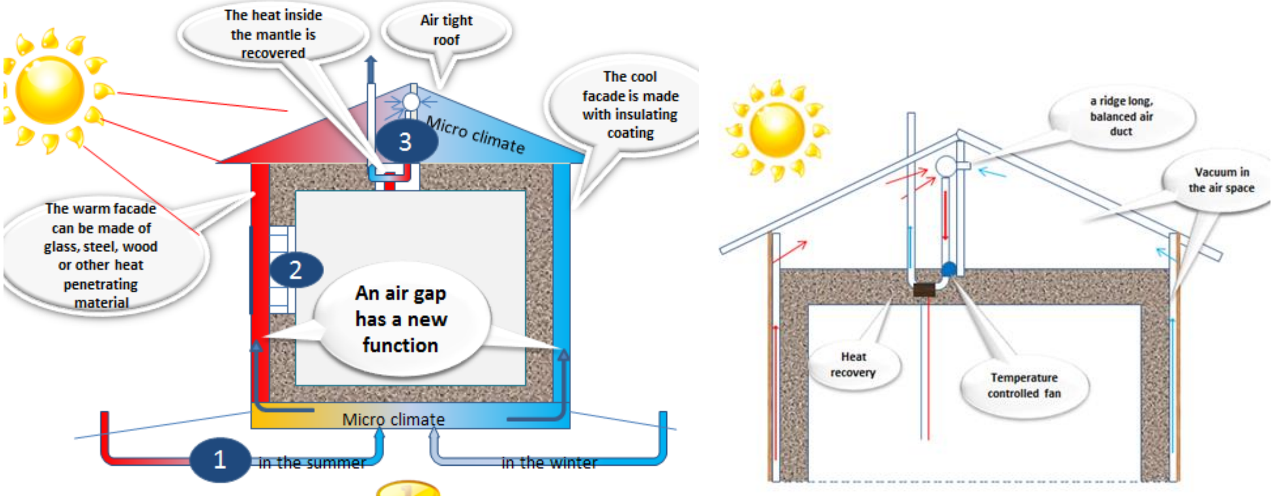


Figure 4. Mantle ventilation. Source: AEH technology commercial presentation.

Window design is different from common design. It is illustrated in Figure 5. Firstly, there is an “outer window” in line with the façade, which does not let snow and rain inside the air gap. This outer glass does not fog up because of the air circulating inside the air gap. And secondly, there is a blind only on the latter half of the window. This is done for shading in the summer, when the sun is high up in the sky. The blind blocks direct sunlight and the uncovered part of the window allow light to come inside. In winter, when the sun’s angle is low, there is no need for shading. The U-value of the window is suitable for a passive house.

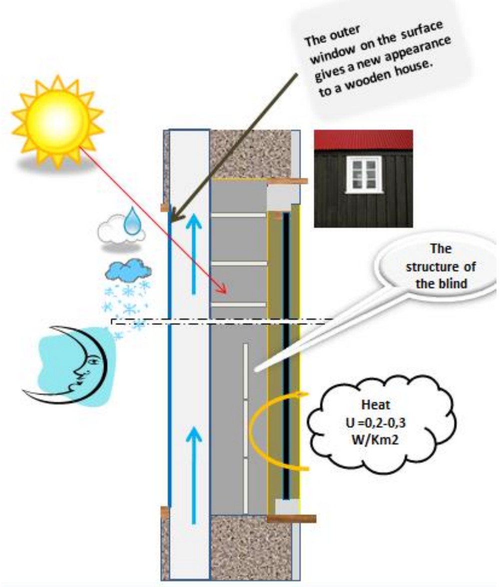


Figure 5. New window technology. Source: AEH technology commercial presentation.

Figure 6 below shows a possible solution for extra heating with a heat pump, water heating or an “energy center” that would control energy use in the house.

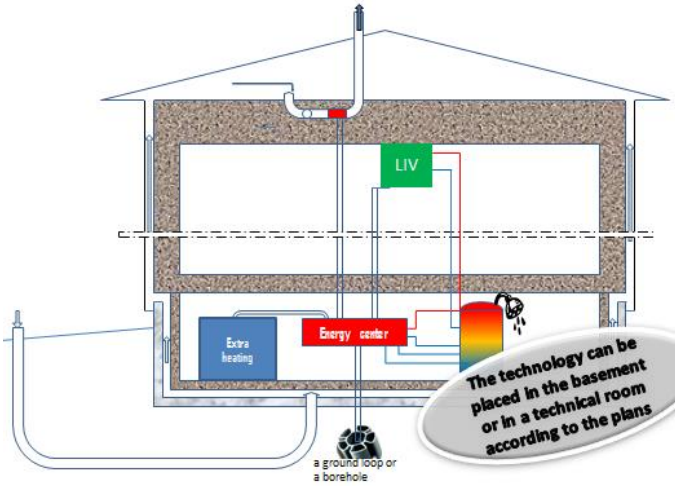


Figure 6. Energy center. Source: AEH technology commercial presentation.

2 Chapter 2. Case study

2.1 Introduction

Carbon footprint is expressed in terms of CO_2eq and represents the sum of emissions of GHG (as CO_2 fossil, CH4 and N2O). Carbon footprint data is covered by a complete LCA. So Life Cycle Assessment (tool used to determine and evaluate the environmental loadings and impacts of a particular product/process, including the effects associated with process upstream in the supply chain (Crawford, 2011, p. 38)) approach was used as the main principle of the case study; however, some specific steps were omitted due to the fact that the goal of the research was reduced to only the carbon footprint calculation.

The following sequence of sections and chapters will explain the carbon footprint calculation procedure, starting with the scope of the study and system boundaries. The main 5 steps of a carbon footprint calculation, according to the Guide to PAS 2050 (Guide to PAS 2050, 2008, p. 10), can be seen in Figure 7. The chapters are placed in the order of life cycle stages. At the end of the report there is a chapter, discussing the results. Figures for properties of different materials can be found in Appendix 1.

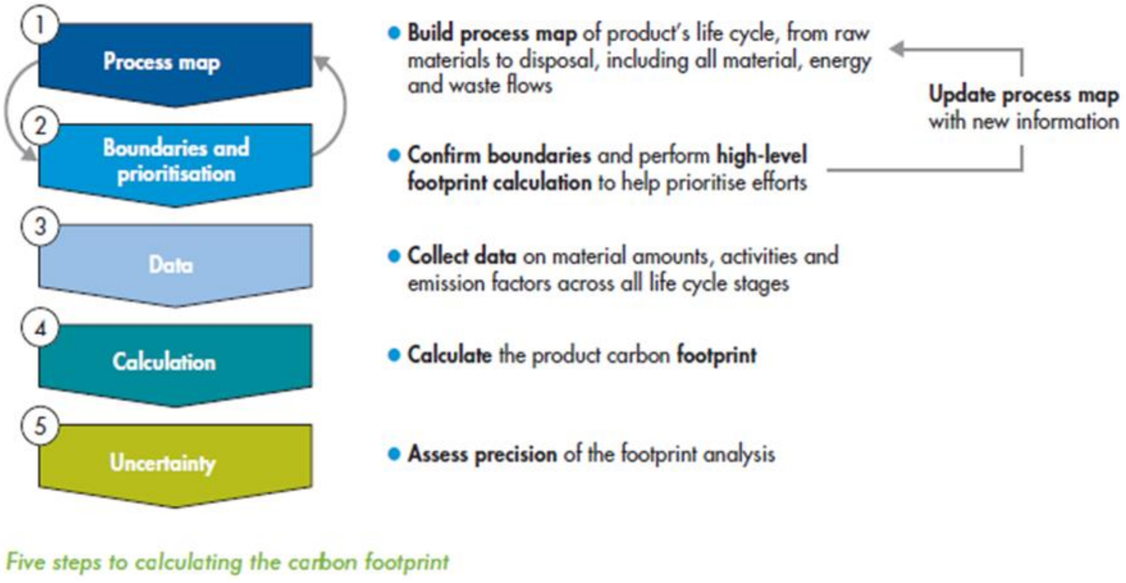


Figure 7. Steps for calculating carbon footprint. (Guide to PAS 2050)

2.2 Goal and scope

The goal of the thesis was to perform a complete carbon footprint analysis (CFPA) of the full life cycle form cradle to grave for the innovative active energy house. This full analysis included calculations for every stage of the life cycle including materials' production, transportations, commissioning and demolition, operation and maintenance for 50 years and final disposal. A process map of the life cycle can be found in Figure 8. Each step of the life cycle is described in a separate section below.

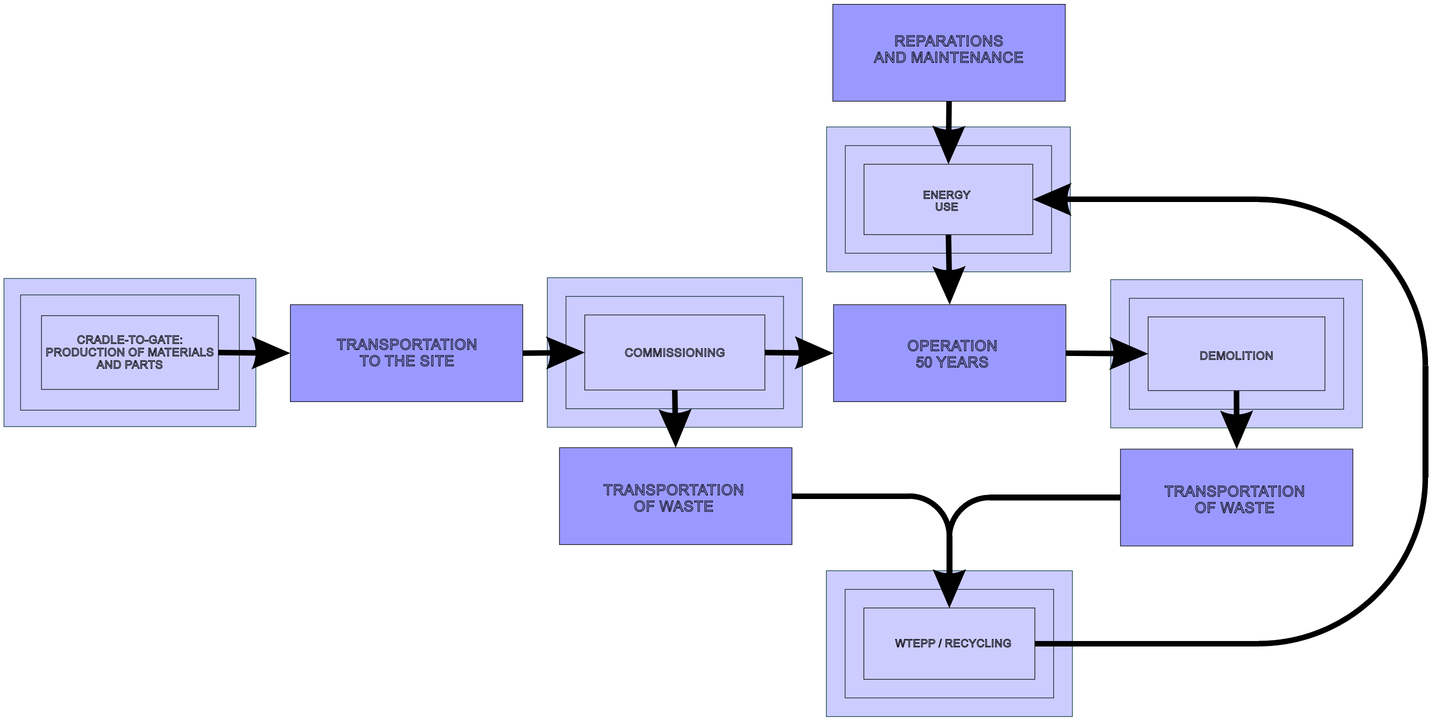


Figure 8. Process map of the lifecycle.

The scope of the study sets system boundaries and a functional unit. A functional unit is "quantified performance of a product system for use as a reference unit in a life cycle assessment study" (ISO 14040: 1997, p. 2). In this thesis, the functional unit was a building, existing for 50 years.

A system boundary is an "interface between a product system and the environment or other product systems" (ISO 14040: 1997, p. 3). As it can be seen in Figure 7, the system boundaries were set from a cradle-to-gate material production to the final disposal of demolition waste. Here it should be mentioned that no materials' carbon footprint was calculated manually, as that data is widely available for common construction materials. In this thesis, the source of data was mainly VTT, Technical Research Centre of Finland (Ruuska, 2013(1)), (VTT, 2013).

2.3 Basic information about the house

The basic layout of the house is presented in Figure 9. It can be seen that the Southern view has a significant window area, at the same time the Northern façade minimizes the area of windows, following the daylight strategy and optimizing heat transfer. According to the data given by the manufacturer, a number of energy saving innovative technologies, mentioned earlier, is used in the house resulting in about a zero need for external heating and an extremely low electricity need (lighting, heat pump and appliances) of 40 KWh/m^2.

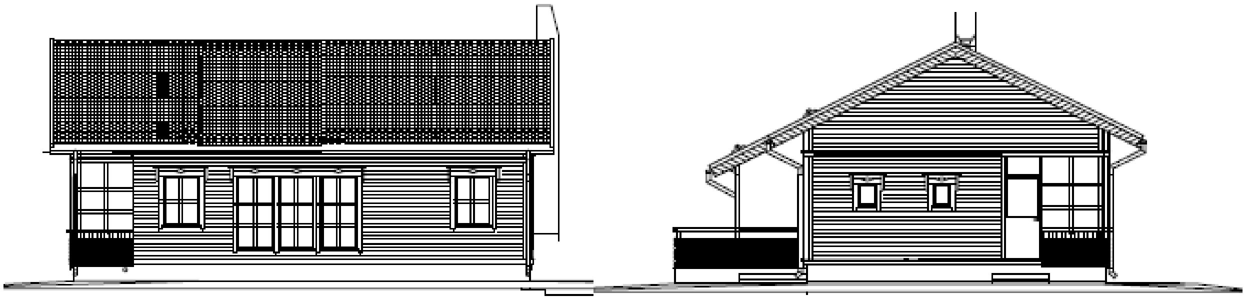


Figure 9. Southern and Eastern views of the house. Source: AEH technology working materials.

The floor plan of the house (see Figure 10) show a floor area of almost 83 m^2. This gives a 3.3 MWh/a electricity need for the whole house.

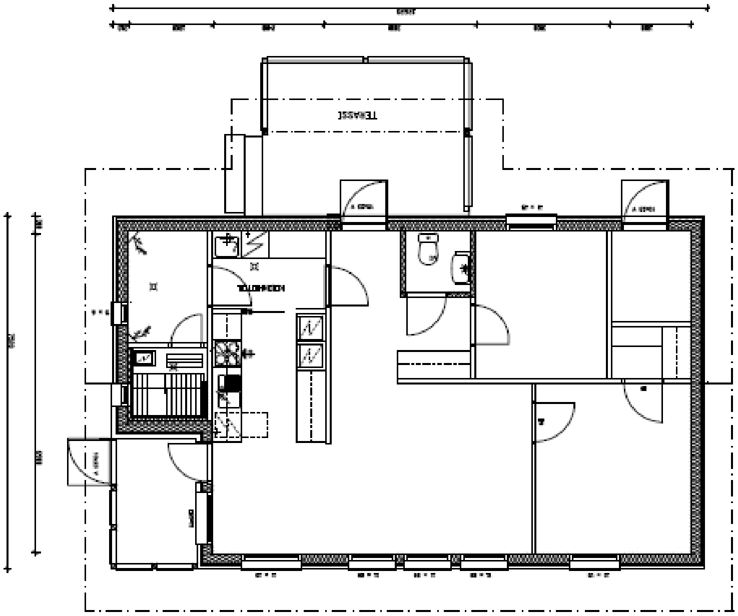


Figure 10. Floor plan of the house. Source: AEH technology working materials.

The setup and materials of the main structural elements and also the mass of each part can be found in Table 1 bin the following section.

2.4 Cradle-to-gate

This section presents how the carbon footprint of all the building materials, i.e. the GHG emissions of the building from cradle to gate, was calculated. The calculations were performed using the following formula:
*Emission = material mass * emission factor*

As the emission factors of all the needed materials have already been calculated and are available in open online sources provided by VTT and material manufacturers, the thesis used that data. The data can be found in Appendix 1. The factors already include transportation of raw materials and production. As it can be deducted from the formula above, masses of different materials should be also known. Table 1 below shows masses of different house structures and their carbon footprint. The mass of the house is calculated to be 84 tons and the carbon footprint is 24 tons of CO_2 equivalent. As most of the structures are made of wood, stored carbon can be taken into account as a benefit in the calculation as follows.

2.4.1 Carbon stock

There are several existing strategies of accessing carbon credits for products. Some of them are described below.

- **ISO/TS 14067:2013**

The ISO technical specification fines the term *carbon storage* as "carbon removed from the atmosphere and stored as carbon in a *product*"; nevertheless, no credits are given for storing carbon.

- **ILCD Handbook (European Commission, 2010)**

According to the ILCD handbook, the temporary removal of carbon dioxide from the atmosphere of both fossil and biogenic origins can be calculated in the same manner with the following formula:

Credits = Carbon content (CO_2eq) Length of storage (years) / -0.01 kg (kg CO_2eq/kg CO_2eq*years)*

The formula shows that, for a 50-year lifetime, the overall emission is reduced by half and, for a period of 100 years, it becomes zero.

- **PAS (Publicly available specification) 2050:2011**

The lifetime of the house is stated to be 50 years; thus, according to PAS 2050, credits for carbon storage can be subtracted from the overall footprint during the 100-year period following the product formation period, where part of the product is biogenic carbon. The amount of credits can be calculated with the following formula:

*Credits = Length of storage (years)/100*Carbon content CO_2eq*

Hence, in the calculation made this thesis, half of the carbon content of the product could be subtracted from the carbon footprint as credits were similar to those of the previous method. The carbon footprint with the stock taken into account can be also seen in Table 1 for easier comparison.

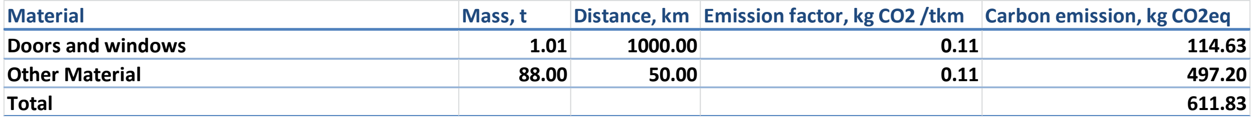
Table 1. Mass of structure, carbon footprint, carbon footprint with carbon stock.

Walls	Mass, kg	Carbon footprint, kg CO2eq	Carbon footprint-carbon uptake, kg CO2eq
Outer walls			
Insulation board	489.70	200.78	-166.50
Coniferous plywood	750.87	450.52	75.09
k600 22*100	280.33	5.61	-151.38
Intello (vapor barrier)	14.96	20.95	20.95
k600 50*150	955.67	19.11	-516.06
k600 50*50	30.45	0.61	-16.44
Selluvilla	714.15	171.40	-271.38
Insulation board	489.70	200.78	-166.50
Air gap			
Intello (vapor barrier)	14.96	20.95	20.95
Heat-treated wood	1632.34	190.44	-1637.78
Basement wall			
Laminated veneer lumber	367.67	239.26	-119.60
k900 50*100	66.19	1.32	-35.74
Selluvilla	84.59	20.30	-32.14
Laminated veneer lumber	367.67	239.26	-119.60
Finnfoam	60.90	0.00	0.00
Mortar/plaster	0.91	0.33	0.33
Inner walls	**18428.00**	**12899.60**	**12899.60**
Total	**24749.06**	**14681.21**	**9783.79**
Floor			
Heat-treated wood panel	1138.83	132.86	-504.88
Filler	3416.49	1229.94	1229.94
Coniferous plywood	873.10	523.86	87.31
50*200	1223.68	24.47	-660.79
Selluvilla	854.12	204.99	-324.57
Insulation board	7117.68	2918.25	2918.25
32*100	1390.39	27.81	-750.81
Air gap			
Macadam	37557.62	375.58	375.58
Filter fabric	10.44	23.70	23.70
Total	**53582.35**	**5461.45**	**2393.72**
Roof			
Roof			
Roofing sheet	320.00	576.00	576.00
Rib 32*100	40.96	73.73	73.73
Plywood	522.24	365.57	57.45
Lath	870.40	609.28	95.74
Insulation			
Selluvilla	1708.24	409.98	-649.13
Intello	10.44	14.61	14.61
Roof support	197.20	3.94	-106.49
Inner layer	571.49	11.43	-308.60
Total	**4240.97**	**2064.54**	**-246.69**
Doors	**550.00**	**1100.00**	**646.25**
Windows	**464.40**	**624.38**	**501.98**
Total	**83586.78**	**23931.58**	**13079.06**

2.5 Transportation to the building site

This section describes GHG emissions from transportation of all the materials to the building site. Here it was assumed that windows and doors would be transported from Sweden, whereas all the other material would come from Finland. For the transportation within Finland, a distance of 50 kilometers was used, for transporting from Sweden, the used distance was 1000 km. All the materials were assumed to be transported with freight lorries, 9 tones load, and emission factor 113 g/tkm for a 50% load (LIPASTO-database). A summary of the transport emission calculations can be be found in Table 2. The mass of structure in these calculations was not 83.586 tones, but 89,215 tons due to the future losses in construction, see chapter 'Commissioning'. As the transportation would be made with commercial transport, only one-way transportation with 50% load was calculated. The way back would very likely to be used for some other commercial transportation by the companies.

Table 2. Transportation of materials to the building site.



Material	Mass, t	Distance, km	Emission factor, kg CO2 /tkm	Carbon emission, kg CO2eq
Doors and windows	**1.01**	**1000.00**	**0.11**	**114.63**
Other Material	**88.00**	**50.00**	**0.11**	**497.20**
Total				**611.83**

2.6 Commissioning

This section will describe the construction phase emissions, amounts of construction waste and benefits from waste-to energy production.

As wooden frame houses are quite easy and fast to construct, compared to traditional houses, so no special energy intensive equipment is required. Also it was assumed that the construction phase would take place in summer, so no extra energy for heating is involved. Basically, electricity is needed, but it would be included into the operation phase. Transportation of workers to the site, their working clothes and equipment were excluded from the calculations. In conclusion, carbon footprint of the commissioning and demolition phases was considered to be 1% of the 50 years operation emission amount.

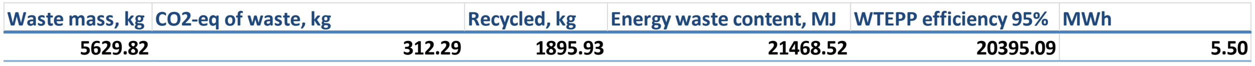
2.6.1 Construction waste

This section discusses the impact of material waste during construction phase and its impacts on the results presented in the previous chapter. The material waste adds to the total material needs of a building, therefore increasing the environmental impacts of the building.

The waste fractions, recyclable waste and energy waste, are presented in Table 3. Following the case study of T148, it was decided that the amount of construction waste would be 5%. This amount would raise the total amount of material and therefore increase its environmental impact. After construction, the waste would be transported to a waste treatment facility.

Although the building's frame could be theoretically reused in construction, in Finland, it would require a thorough testing in one of the special laboratories, which would cause additional costs (Hradil, 2012, p 42). Hence, the wooden waste was assumed to be used in a waste-to energy plant, and the energy was therefore allocated to the electricity need of the house. In this case, the carbon storage capacity of wood could not be applied.

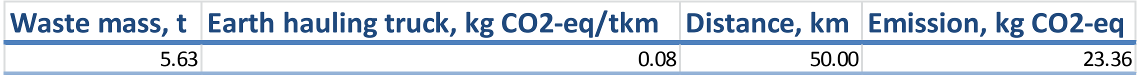
Table 3. Construction waste fractions, recyclable and energy waste.



Waste mass, kg	CO2-eq of waste, kg	Recycled, kg	Energy waste content, MJ	WTEPP efficiency 95%	MWh
5629.82	312.29	1895.93	21468.52	20395.09	5.50

Anyhow, emissions for waste transportation should be also considered. Assuming a distance of 50 km, the construction waste was estimated to be taken off site with earth-hauling trucks (50% load), with emissions of 83g/tkm (VTT Technical Research Centre of Finland, 2012). The resulting emission can be found in Table 4.

Table 4. Transportation of construction waste.



Waste mass, t	Earth hauling truck, kg CO2-eq/tkm	Distance, km	Emission, kg CO2-eq
5.63	0.08	50.00	23.36

2.7 50 year operation

In this section, all emissions produced during the 50-year lifetime are described. The overall annual electricity consumption including everything would be 40KWh/m^2, and for the floor area of 82.8m^2 it would mean 3.3 MWh annually. To calculate the electricity need and the emissions arising from electricity production for 50 years, it is needed to consider different emission standards, set by the

Finnish and EU legislation. The results of the calculations are given in Table 5; all the data was obtained from the Finnish Climate and energy strategy (by Finnish Ministry of Employment and Economy). For different periods in future, different emission factors were introduced taking into account the goal of increasing the share of renewable energy and therefore decreasing the emission factor.

As the house structure is mainly wood and some other combustible materials it could be used as an energy source in a waste-to-energy plant after being demolished at the end of its 50-year life cycle. So the energy produced could be allocated to the energy need of the house during its lifetime. Therefore GHG removals should also be allocated to the system. The total energy content of combustible structures is 816546 MJ, and considering a WTEPP with a 95% efficiency, it would become 775718 MJ (215 MWh). Here we also need to take into account 5.5 MWh from waste, obtained during the construction phase. To allocate the energy, it was divided equally for the whole period of 50 years, resulting in 4.41 MWha. This gave an extra 1.11 MWha, so the removals could be also calculated, see Table 5.

Table 5. Electricity need for 50-year operation: 1. Net 2. With allocations due to energy from waste.

Year	**2015-2019**	**2020-2029**	**2030-2065**	**Total, kg CO2-eq, 50 years**
Emission factor, electricity (kg CO2-equ/MWh)	243.00	230.00	36.00	
Energy need, 40KWh/m2*82.8m2 = 3.3MWh/a	16.50	33.00	115.50	
Kg CO2-eq, for a stated period	**4009.50**	**7590.00**	**4158.00**	**15757.50**
Reduction - 1.11 MWh/a	-5.55	-11.10	-38.85	
Kg CO2-eq, for a stated period	**-1348.65**	**-2553.00**	**-1398.60**	**-5300.25**

So firstly, the emissions from operation were calculated directly, for a 50 year period and electricity consumption of 3.3 MWh/a. There were three different emission factors for 3 periods of time in future, so it was also considered. So the net emissions from operation are 15.8 tons of CO2eq. This number was not considered in the final overall carbon footprint, because bioenergy from the waste-to-energy process the wooden structure after demolition covers those energy needs and even more. The calculation of the benefits from the waste-to-energy process can be found in the same table. It was done in a similar way to the first calculation with only difference in the energy need, which was now -1.1 MWh/a, resulting in 5 tons of CO2eq in excess.

2.7.1 Renovations

Renovations and maintenance needs were to be minimal. So they were assumed to be equal to 0.5% of the whole GHG emissions for the 50 years of operation.

2.8 Demolishing

The transportation calculations were simplified by assuming that the lifetime material balance of the building site would equal zero. In other words, all the materials used as building materials would also exit the site as waste. As in the commissioning phase, we assume that the carbon footprint of the stage would be 1%, as disassembling is a more correct word for demolishing a frame house.

2.9 Transportation of waste

The waste after disassembling the house is taken out from the site with earth-hauling trucks with max 19t load (VTT Technical Research Centre of Finland, 2012). In this thesis both empty driving and full driving were calculated for a distance of 50 km, one way. For the whole amount of waste, 3 trucks were calculated with full load, 1 with half-load and 4 empty loads, see Table 6.

Table 6. Transportation of waste after demolition.

Waste mass, t	Earth hauling truck (50%) kg/tkm	Full load (19t)	Empty load kg/km (4)	Distance, km	Emission, kg CO2-eq
61.66					
57.00		**0.05**		**50.00**	**133.95**
4.66	**0.08**			**50.00**	**57.98**
0.00			**0.67**	**50.00**	**134.80**
Total					**326.73**

2.10 Final disposal

This section describes the benefits that arise in the case of recycling and using the waste in a WTEPP, and shows how those benefits are allocated to the whole carbon footprint value.

Most of the structure consists of materials good for producing energy; thus, they were assumed to be taken to a waste-to-energy power plant, as it has already been mentioned before. Other materials such as glass and steel would be recycled, and macadam could be reused. No material is landfilled. Recyclable material inputs can be accounted for by the closed-loop approximation method (PAS2050), and that would reduce the carbon footprint of the material.

A closed loop approach can therefore be applied for the recycling of steel; this also follows ISO 14044:2006 section 4.3.4.3, which describes the allocation procedures for closed loop material recycling (World Steel Association, 2011). According to this study, the recycling benefit of 1 kg steel is -0.4 kg CO_2/eq. If this number was used for the roof structure and also for the steel waste during the commissioning phase, the recycling benefit would be – 151.6 kg CO_2-eq.

For glass the same closed-loop strategy is used, meaning that the material does not experience significant losses in quality when recycled. According to HSY (Dahlbo et al, 2011), 741 kg of CO_2 eq/ton waste glass is an environmental benefit of glass recycling. This results in – 206.7 kg CO_2/eq. Macadam was assumed to be simply reused in road construction, so the emissions for macadam production could be reduced by one half, following the PAS2050 strategy for calculating benefits form reuse.

2.11 Discussion

In some similar case studies, side streams of wood production and the energy produced form them is also allocated to the ”bioenergy production from structural waste” to reduce the carbon footprint. However, in this thesis such allocation will not be used as energy production from side streams would be more likely used in small-scale boilers on site, in wood production facilities for heat.

2.11.1 Uncertainty and limitations

Although the results of the calculation are presented in a certain way in the report, some interpretation restrictions must be kept in mind. First of all, some uncertainties might be considered due to the unknown geographical position. This means that the active house is still a project, and knowing its address could change the results for transportation emissions as the calculations made in this thesis used pure assumptions. Moreover, geographical position could also change heating requirements and therefore electricity consumption figures. Hence, it is suggested that some of the results should be reconsidered when the place for the building is finally chosen.

If the house is mainly operating with heat pump, outdoor temperature might also have a large effect on the carbon footprint.

2.12 Results

The results of the thesis show a remarkably low number for the carbon footprint of the house. If the result is compared to those of other studies (Ruuska, 2013), it is 20-25 times lower.

Table 7 below shows emission sources from the main process stages of the lifecycle. It can be clearly seen that the main source of carbon reduction comes from the low energy demand, due to special innovative equipment. Therefore, bioenergy produced from wooden waste after house demolition not only covers the need but also is in excess. Thus, the emissions from those two stages combined result in a negative value.

Table 7. Study results.

Emission source	kg CO2-eq
Structure	**13079.06**
Construction waste	**312.29**
Transportation	**961.92**
Operation (not accounted)	**15757.50**
Construction, delomition, rennovations	**236.36**
Operation with benefits from incineration	**-5300.25**
Benefits from recycling	**-546.09**
Total	8743.29

To conclude, it should be said that this thesis has shown the environmental benefits of the AEH technology are almost 20 times lower GHG emissions compared to those of a log house and around 28 times lower compared to those of a standard house, see Figure 11.

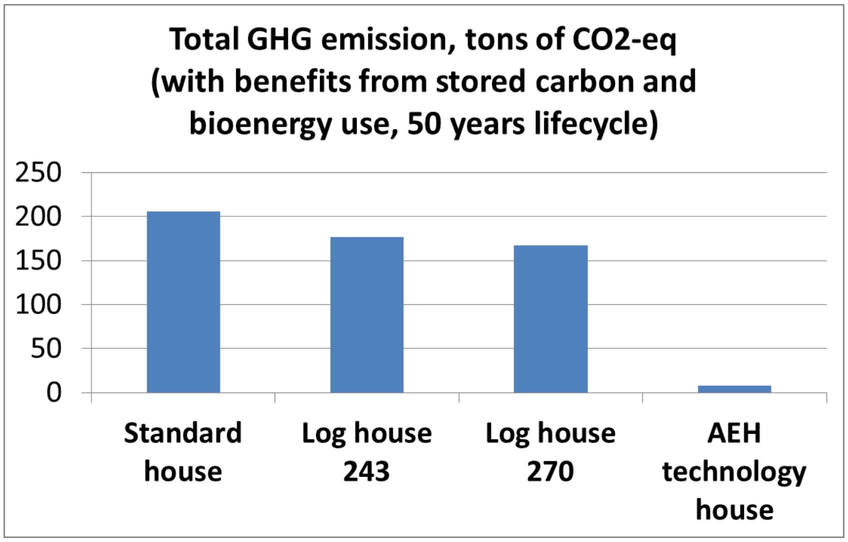


Figure 11. Comparison of the active energy house with other types of houses (Ruuska, 2013)

The life-cycle approach has been important for the carbon footprint analysis, because it has clearly shown the phases benefiting a lower carbon footprint. For instance, recent studies suggest that “the energy embodied in constructing buildings can be equivalent to the energy required for their operation over their life” (Crawford, 2011, p. 74). And it can be clearly seen from the results of this thesis that the construction and demolition energy accounts only for 1.5% of the energy used for the operation of the studied building due to a simple structure. Thus, this approach could be used to optimize any product’s performance, and it clearly shows that “reduction in impacts at one point does not create greater impacts at another point in the life cycle” (Crawford, 2011, p. 75), meaning that an eco-friendly design can be reached by combining measures.

Using the life-cycle approach, it was deducted that the combination of a well-insulated frame and energy capturing and saving equipment makes the energy need for the house quite low. Also a frame structured house is easy and fast to construct; therefore, no energy-intensive equipment is needed. More than that, the wooden structure together with paper-fiber insulation plays an important role: firstly, it is the carbon storage capacity and, secondly, the possibility to turn the waste into bioenergy. All these factors result in a remarkably low carbon footprint of the active house for a 50 years life cycle from cradle to grave.

2.13 Sensitivity analysis

Due to all the assumptions, uncertainty and limitations, the results of the study cannot just be used outside the context. Therefore, several scenarios need to be considered. First of all, let us define the data, which is certain and would remain constant throughout the different scenarios. All the material data (density and carbon footprint) was obtained from external certified sources, so the mass of structure, its carbon footprint and stored carbon will remain constant. As for the construction waste, the used 10% is a common number for such buildings, so it also stays the same. The chosen construction, demolition and renovation figures are also common for such structures delete too, it is informal, regardless of the location or any other factors.

Secondly, let us decide upon the data that could be changed significantly due to circumstances. The value of annual electricity requirement was obtained from the building's manufacturer, and the calculation behind that value is unknown to us. Due to this value, results of our carbon footprint calculation showed a 20 times difference between the AEH house and a standard house, we need to verify the sensitivity the carbon footprint results of this thesis were 20 times lower for the AEH house than for a standard house; therefore, it is necessary to verify the sensitivity. What is more, it was not known where the house would be located, and where the materials would be taken from, so the transport emissions could also be varying. Also, the heating demand information received from the manufacturer had no explanation behind it and was equal to zero. That number might change because of different outdoor temperatures in different locations and heating demand would be varying.

Hence, 3 scenarios with varying electricity and heat demands and various transportation differences are considered below.

2.13.1 Scenario 1. Electricity demand.

According to the manufacturer, the electricity demand for the whole house was 40 KWh/m2, resulting in 3.3 MWh/a for the area of 83 m^2. This number is extremely low, even compared to the passive house standard upper limit of 120 KWh/m^2, mentioned in Chapter 1 (Case study practicalities), which is 3 times higher. Let us observe how a 40 % increase in electricity demand will influence the overall carbon footprint.

Table 8 shows how much CO_2 would be emitted with the electricity need of 4.62 KWh/m^2, taking different emission factors into consideration. With a 40% increase in the electricity, the carbon footprint of house operation increases by 40% from 15.75 to 22 tons CO_2eq proportionally.

As the wooden structure can be used for energy production after the building's demolition, it gives a benefit of -4.41 MWh/a resulting in the electricity need of only 0.21 MWh/a. This gives another value for carbon footprint with benefits from incineration. With the increase in energy demand, this figure grows 120% from -5 to 1 ton CO_2eq.

Table 8. Emission generation with a 40% greater electricity demand, 50 years.

Year	2015-2019	2020-2029	2030-2065	Total, kg CO2-eq, 50 years
Emission factor, electricity (kg CO2-equ/MWh)	243.00	230.00	36.00	
Energy need, 120 KWh/m2*82.8m2 = 4.62 MWh/a	23.10	46.20	161.70	
Kg CO2-eq, for a stated period	**5613.30**	**10626.00**	**5821.20**	**22060.50**
With reduction = 0.21 MWh/a	1.05	2.10	7.35	
Kg CO2-eq, for a stated period	**255.15**	**483.00**	**264.60**	**1002.75**

The final result of the overall carbon footprint changed from 8 to 15 tons CO_2eq. So with a 40% greater heating demand, the overall footprint increases by 73%. This gives a dependence between the percentage of electricity increase and the total increase in the carbon footprint that could be seen in Figure 12. It can be clearly seen that the footprint is increasing faster with greater values of electricity demand.

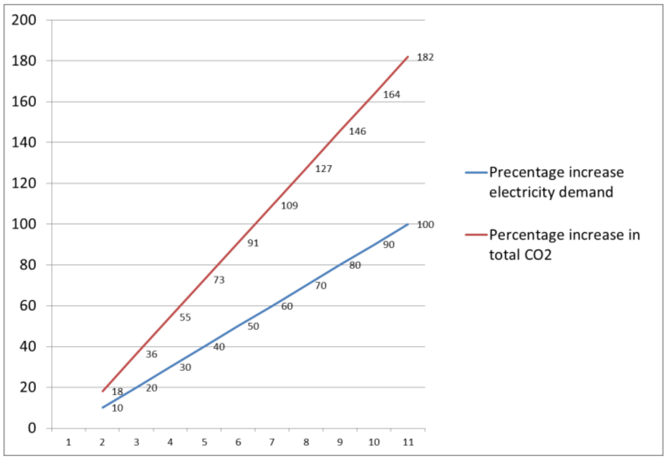


Figure 12. Relation between rising electricity demand and total carbon footprint.

2.13.2 Scenario 2. Heating/cooling demand.

The building’s heating demand is stated to be zero by the manufacturer. However, depending on the location and temperature, this figure could become different. Here it is important to find how crucially a changing heating demand would influence the final carbon footprint of the house. The heating demand for a passive house does not exceed 40 kWh/m^2, according to the standard mentioned in Chapter 1 (Case study practicalities). So 40 kWh/m^2 was considered the upper limit for the calculation that would account for both heating and cooling all the year round. Here it should be mentioned that equipment efficiency plays the most important role here, giving an opportunity to decrease this number.

Same emission factors for electricity were used in this calculation as previously, giving 15757.5 kg CO_2eq for 50 years of heating and cooling the house with a limit value of 40 kWh/m^2. This would give an increase of 180 % for the overall carbon footprint.

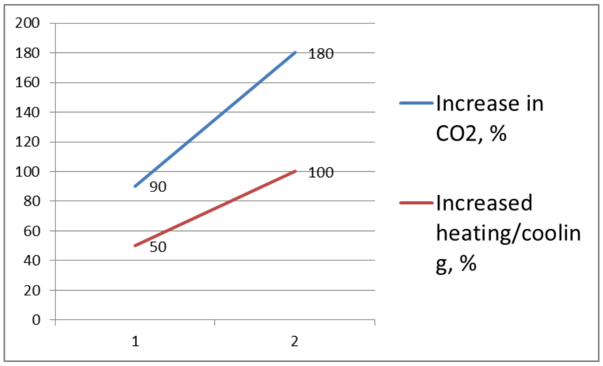


Figure 13. Relation between rising heating/cooling demand and total carbon footprint.

Figure 13 shows the relation between increased heating/cooling demand and growing total carbon footprint. Total carbon footprint is increasing more rapidly in relation with the heating/cooling. This makes this parameter quite sensitive for the calculation.

2.13.3 Scenario 3. Distant transportation.

The needs for transportation of materials to the building site and waste to the disposal facilities fully depend on the location of the building. As the exact place has not been set yet, the calculations made are only an approximation and need to be examined for sensitivity. So with a 40% increase of all the transportation routes, 1.3 CO_2eq are emitted in comparison to 0.96, clearly giving a 40% increase. The relation between growing distance by percent and growing percentage of the overall carbon footprint can be seen in Figure 14. This parameter shows very little influence on the overall result; therefore, location is not being sensitive. It is clearly because transportation makes up only 2% of the final result.

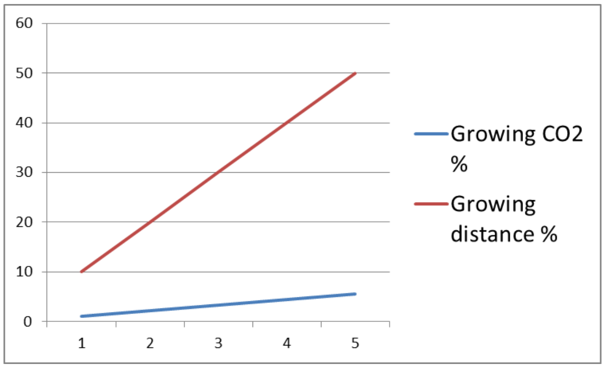


Figure 14. Relation between growing transportation distance and total carbon footprint.

2.13.4 Discussion

We have observed the influence of three changing parameters in three scenarios: increased electricity, heating/cooling demand and longer transportation differences. The results show that transportation emission is not a sensitive parameter for the overall result, being only 2% of the overall carbon footprint. Operation of the house accounts for 52% and therefore has a great influence on the results. It has been proved by scenarios 1 and 2. Electricity use is quite an important parameter that increases carbon footprint rapidly, regardless of the fact that it has a reduction due to biomass incineration. The demand for heating/cooling can also affect the results drastically if the house is designed inadequately to climatic conditions and suffers from bad insulation or inefficient equipment.

3 Optimi 360

This chapter contains an overview of a software that which helps to calculate the carbon footprint of buildings, and an attempt to compare the results of the calculation done by hand and the calculation with the software. As a matter of license issues, the calculation with the software could not be completed for exactly the same house, some parameters have been changed, so a significant uncertainty in the results should be considered.

360 optimi is a modern life-cycle CO_2 and cost calculating software. It is meant to optimize a project's life-cycle efficiency, create variants of designs and in that way gain (Leadership in Energy and Environmental Design LEED) and Building Research Establishment Environmental Assessment Methodology (BREEAM) credits. The software complies with standards, as well as with LEED&BREEAM (Bionova Ltd.). Therefore, the program focuses mainly on larger buildings, such as residential blocks, schools, offices, commercial buildings etc. But in any case, within a variety of building types, one can also chose a single family house.

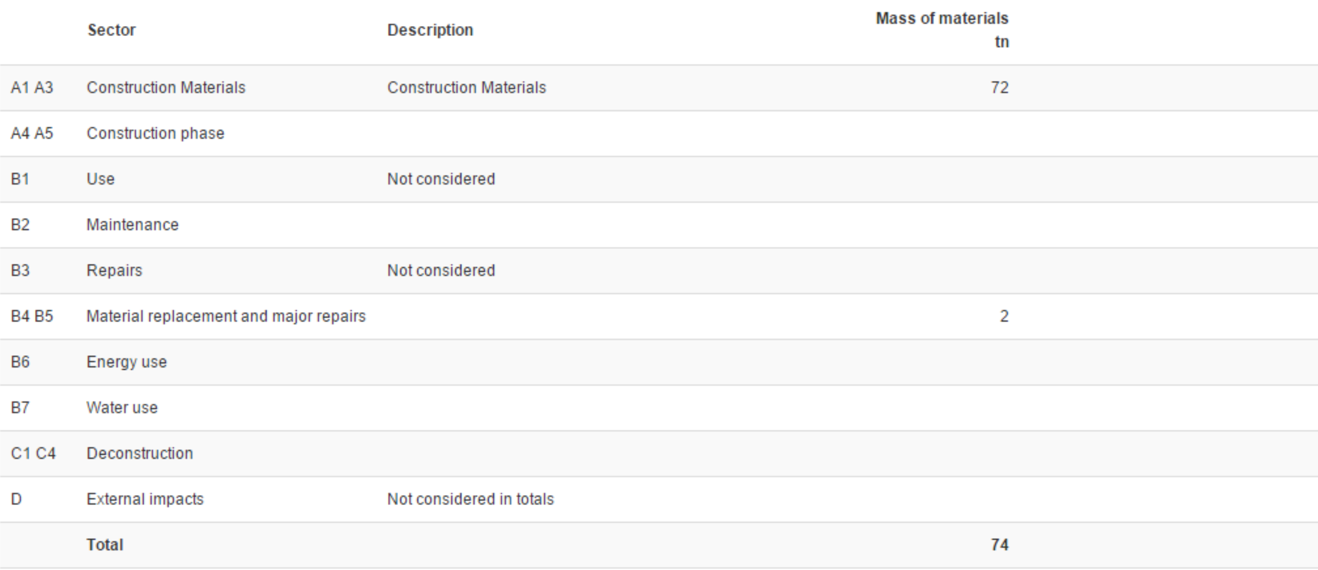
The program offers to calculate life-cycle CO_2 and life-cycle costs. For those calculations, a range of data classes can be inputted. For the life-cycle CO_2, the data classes are *construction materials of buildings, other construction materials in the building plot, energy consumption, building technology and water consumption*. For the life-cycle cost, the building classes are: *building plot and construction phase costs, operating costs, energy consumption, discount factors* and *water consumption.*

Due to this thesis' specific interest towards CO_2 only these calculations are discussed in more detail . For the modified active house only "construction materials of buildings" and "energy consumption", as water consumption was not known and building technology did not require machinery.

The *construction materials of buildings* data class was divided into the following subclasses: *foundation, structural frame, facade, internal space elements and surfaces*, and *supporting buildings* at the same building plot. For each part of building materials can be added from a long list. For some materials, thicknesses can be specified; for others, default values (not shown) are used. These default values are one reason why it can be hard to compare the results with a manual calculation. For the active energy house studied in this thesis, not all of the materials could be matched with those on the program's list, so the closest ones were used. For instance, wood fiber insulation was used instead of Selluvilla (paper fiber insulation), as it has the ability of carbon uptake, for example, cross laminated timber sheet instead of laminated veneer lumber and timber lining instead of heat treated wood. For some of the materials, mass can be defined, for some – volume or area; material densities are there by default and cannot be seen. For doors and windows, one just needs to enter the area, door type and type of glazing for windows.

The "energy consumption" data class consists of consumption of grid electricity (green electricity with certified origin can be chosen), fuel demand for stationary units, consumption of district heating, consumption of district cooling and exported energy.

Calculation results are given in Figure 10.

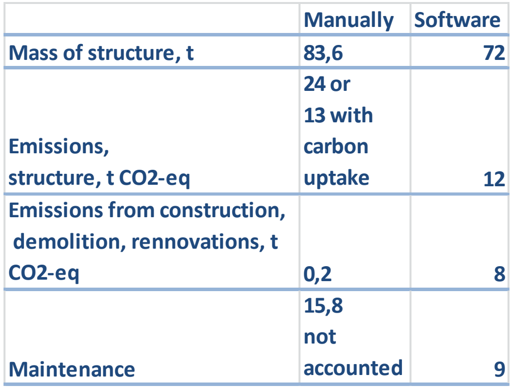


	Sector	Description	Mass of materials tn
A1 A3	Construction Materials	Construction Materials	72
A4 A5	Construction phase		
B1	Use	Not considered	
B2	Maintenance		
B3	Repairs	Not considered	
B4 B5	Material replacement and major repairs		2
B6	Energy use		
B7	Water use		
C1 C4	Deconstruction		
D	External impacts	Not considered in totals	
	Total		**74**

Figure 15. Results by 360 Optimi: mass of structure and carbon footprint of different phases.

If the results are compared with the manual part of the calculation, it can be seen that the mass of structure from the manual calculation is almost 12 tons larger, being 83.6 tons and the footprint form the manual calculation (excluding carbon uptake) is 12 tons higher, being 24 tons CO_2-eq, demonstrated in Table 8 below. With carbon uptake the numbers match almost perfectly. It is an interesting result, as the building's dimensions for 360 optimi have been enlarged by about 7 %. Probably different results come from different material properties used in the calculations. For instance, doors and windows could lead to a great difference, as the default thicknesses of materials. Moreover, it should be kept in mind that some of the materials used in the software calculation were not exactly the materials used in the building.

Table 9.Comparison of manually calculated results with software outcome.



	Manually	Software
Mass of structure, t	83,6	72
Emissions, structure, t CO2-eq	24 or 13 with carbon uptake	12
Emissions from construction, demolition, rennovations, t CO2-eq	0,2	8
Maintenance	15,8 not accounted	9

As it can also be seen in Table 8, the software accounts more for construction and demolition, as in in the calculations, manual assembling and disassembling of a simple frame construction was considered. The division between different stages can be seen in Figure 11.

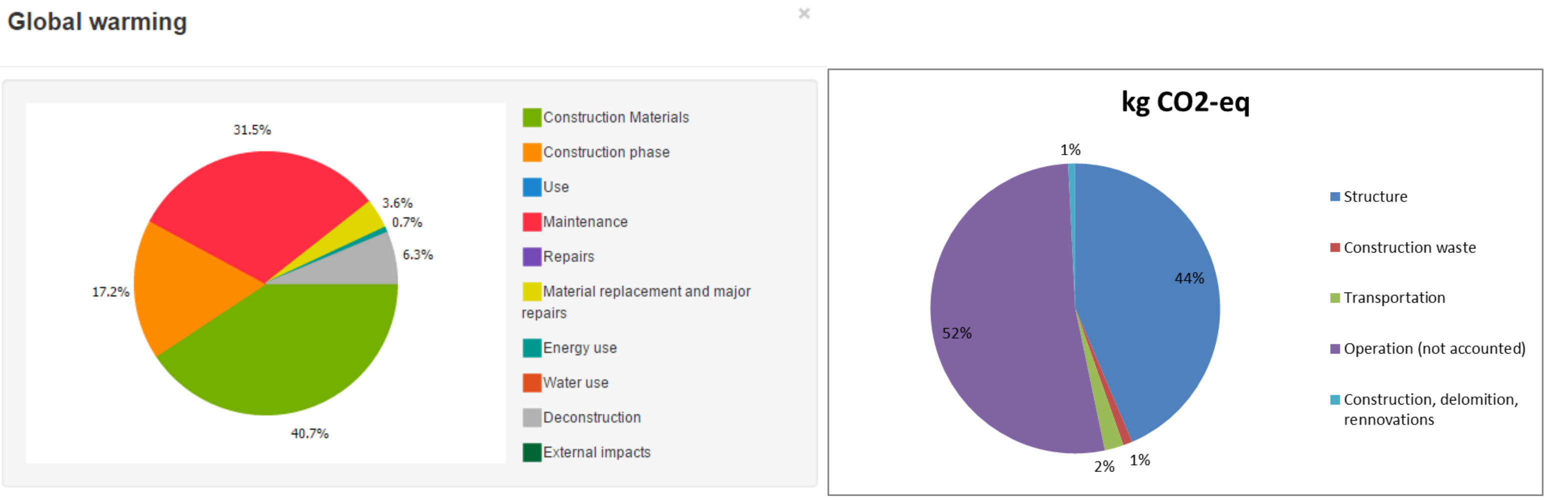


Figure 16. Carbon footprint division between different life-cycle stages. Left: software, right: manual calculation.

In the end, it should be said that 360 optimi is a fast and helpful tool to calculate carbon footprint, for commercial building it is priceless, but there are some aspects, such as benefits form recycling or final disposal, transportation and allocations that still would need to be calculated manually (or with other software) to make the picture complete.

4 Conclusion

Construction of energy saving houses is one of the modern trends due to the economic and environmental benefits. The concept of net zero energy buildings has been introduced to European legislation and, therefore, shows the future track for the whole building industry. So it is highly important to understand the technology which makes a nZEB and the benefits it brings.

The active energy house technology has been one example of an energy saving house with a tendency towards carbon neutrality. A range of energy saving technologies makes the heating and electricity demands for the building much lower than those of a standard building . The technologies include proper thermal insulation with layered walls, double façade, roof insulation, high performance windows with shading, ventilation with heat recovery and pre-heating/cooling of inlet air, a daylight planning strategy and an energy center to control all the heating/cooling devices and appliances.

The aim of this thesis was to calculate the carbon footprint of an active energy house and determine whether it is beneficial for the environment or not in comparison with standard houses. Several common measures for carbon neutrality were applied in the building: less materials with high embodied energy, more wood (carbon storage plus assures less material use), recyclable and reusable materials, simple structure (easy to assemble and dismantle) and locally produced materials.

The carbon footprint calculation was made for the building from cradle to grave, including CF of all of the materials, their transportation to the cite, assembling, operation of the house for 50 years, dismantling, transportation of waste and final disposal. According to the strategy presented in the standards, the carbon stored in the wooden structure for 50 years reduced the overall CF of all the wooden parts by one half. After dismantling, all the wooden waste was incinerated to produce bioenergy with a zero fossil carbon emission. The amount of electricity produced was enough to cover all the energy needs of the house for 50 years. The simple structure of the house made it possible to assemble and dismantle the building without extra heavy machinery or extra energy needs. Materials like steel and macadam were recycled and reused in other construction so there was no need for landfill disposal.

The results of the calculation show that the amount of GHG emitted for the life cycle of the active energy house from cradle to grave is 8.7 tons of CO_2-eq, which is 20 times lower than carbon footprint of a standard house. The main benefit comes from the remarkably low energy need for the house, which proves the advantage of energy saving technologies in buildings. Anyhow, this number needs to be carefully examined because it has shown to be very sensitive for the overall result.

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Appendices

Appendix 1.

Material properties

Material	Carbon content kg/kg	GHG-emissions, kg/kg CO2-eq	Energy content MJ/kg
Insulation board	1.50	0.41	20.00
Coniferous plywood	1.00	0.60	20.00
Pine	1.12	0.02	18.20
Intello (vapor barrier)	0.00	1.40	43.60
Selluvilla	1.24	0.24	13.50
Heat-treated wood (birch)	1.12	0.12	20.00
Laminated veneer lumber	1.95	0.65	20.00
Finnfoam	0.00	0.00	43.00
Mortar/plaster	0.00	0.36	0.00
Filler	0.00	0.36	0.00
Macadam	0.00	0.01	0.00
Steel	0.00	1.80	0.00
Plywood (birch)	1.18	0.70	21.00
Glass	0.00	1.23	0.00