ZEB Project report 24 – 2015

Marianne Rose Inman and Aoife Houlihan Wiberg

Life Cycle GHG Emissions of Material Use in the Living Laboratory

ZEB The Research Centre on Zero Emission Buildings

SINTEF Academic Press

Marianne Rose Inman and Aoife Houlihan Wiberg

Life Cycle GHG Emissions of Material Use in the Living Laboratory

ZEB Project report 24 – 2015

ZEB Project report no 24
Marianne Rose Inman[1] and Aoife Houlihan Wiberg[1]
Life Cycle GHG Emissions of Material Use in the Living Laboratory

Keywords:
design drivers, embodied emissions materials, design process, net zero emission buildings

Illustration on front page:
Katrine Peck Sze Lim/NTNU

ISSN 1893-157X (online)
ISSN 1893-1561
ISBN 978-82-536-1481-6 (pdf)
ISBN 978-82-536-1482-3 (printed)

20 copies printed by AIT AS e-dit
Content: 100 g Scandia
Cover: 240 g Trucard

Norwegian University of Science and Technology [1)]
N-7491 Trondheim
Tel: +47 73 59 50 00
www.ntnu.no
www.zeb.no

SINTEF Building and Infrastructure Trondheim [2)]
Høgskoleringen 7 b, POBox 4760 Sluppen, N-7465 Trondheim
Tel: +47 73 59 30 00
www.sintef.no/byggforsk
www.zeb.no

SINTEF Academic Press
c/o SINTEF Building and Infrastructure Oslo
Forskningsveien 3 B, POBox 124 Blindern, N-0314 Oslo
Tel: +47 73 59 30 00, Fax: +47 22 69 94 38
www.sintef.no/byggforsk
www.sintefbok.no

Acknowledgement

This report has been written within the *Research Centre on Zero Emission Buildings* (ZEB). The authors gratefully acknowledge the support from the Research Council of Norway, BNL – Federation of construction industries, Brødrene Dahl, ByBo, DiBK – Norwegian Building Authority, Caverion Norge AS, DuPont, Entra, Forsvarsbygg, Glava, Husbanken, Isola, Multiconsult, NorDan, Norsk Teknologi, Protan, SAPA Building Systems, Skanska, Snøhetta, Statsbygg, Sør-Trøndelag Fylkeskommune, and Weber.

Abstract

This report documents the design and construction of the ZEB Living Laboratory in Trondheim; with a view to better understand the implication of design choices on embodied material emissions. Accordingly, the material inventory in terms of the building envelope, building services, and energy supply system are presented in-depth. The embodied material emission results are presented for each building component category, and highlight important design drivers for the reduction of embodied material emissions in the construction of buildings. A material emission balance is also presented.

Compared to previous ZEB projects, the results show relatively high emissions, with total emissions of 23.5kgCO_{2eq}/m^2/yr, whereby 12.1kgCO_{2eq}/m^2/yr originate from the production phase (A1 – A3). There are multiple reasons for this. Firstly, a more comprehensive material inventory was available for the Living Laboratory at an 'as built' stage. The system boundary includes more life cycle stages (A1 – A3, A4, A5 and B4). Furthermore, the building is not a typical residential building but a test laboratory.

The results demonstrate that the choice of insulation material is a key design driver in lowering embodied material emissions, and that even state-of-the-art insulation materials, with typically high embodied emission factors, can be applied in a sensitive and effective way for low total embodied emissions. The results demonstrate that when half the quantity of concrete is used in the strip foundation design, then embodied emissions are significantly reduced. The foundation design may also be further optimised through specifying low carbon concrete. Another design driver is identified in the timber superstructure, which has a relatively low contribution to total embodied emissions, despite its large volume. It is suspected that a corresponding concrete and steel structure will not only weigh more, but also result in a two-fold increase in emissions. The results demonstrate that approximately half of all embodied emissions originate from the outer roof and PV system. This is because of the roof profile and building adapted PV system used, and highlights an area for further optimisation.

The findings show that the reference service lifetime (RSL) of materials can greatly affect the distribution of emissions across life cycle phases, whereby a short RSL has higher embodied emissions in the replacement phase (B4), and a long RSL, in line with the lifetime of the building, has a larger focus on production phase emissions (A1 - A3). The material emission balance also highlights that further measures are required to reduce material emissions and increase on-site renewable energy production, in order to reach a zero emission balance. The sensitivity analysis of the functional unit questions the use of a 60-year building lifetime, when the Living Laboratory is a temporary building. It is therefore recommended that the end-of-life (EOL) life cycle phases are considered in more detail, in order to optimise the demountability and recyclability of the building, instead of the durability of materials.

In conclusion, it was found that these results provide useful approximations for embodied material emission calculations, when a detailed material inventory may not be available. It also highlights methodological and design considerations when carrying out a life cycle assessment of a building. Furthermore, the Living Laboratory provides alternative solutions for low embodied emission design.

Contents

1. Introduction

1.1 Background

Previously, the Research Centre on Zero Emission Buildings (ZEB) carried out two simplified concept studies in late autumn 2011, with the goal of achieving a ZEB-OM ambition level (defined in Section 1.4). In the beginning of 2012, it was decided to develop these concepts into more realistic building models; one of the concept studies was an office building, (Dokka et al., 2013b) whilst the other was a single-family house. (Houlihan Wiberg et al., 2013) The two ZEB concepts were designed to 'provide a benchmark for Nordic conditions (i.e. cold climate) and [as] a starting point for comparison' of embodied emissions. (Georges et al., 2015)

The Living Laboratory is one of the first ZEB pilot studies to be built and tested. This report builds upon the embodied emission methodology developed by the Research Centre on Zero Emission Buildings, and applies it to the real case of the Living Laboratory situated in Trondheim; with a view to better understand the implication of design choices on embodied material emissions. The Living Lab is an experimental facility that utilises state-of-the-art materials and innovative technical equipment. It will be tested and occupied by researchers, students and professors from the Norwegian University of Science and Technology (NTNU).

1.2 Goal and Scope

The main goal of this work is to complete realistic simulations and calculations of the embodied material emissions for the Living Laboratory. Through completing these calculations, important design drivers for low embodied emission design shall be revealed, as well as outlining what level of performance is necessary for components in a Zero Emission Building according to the current ZEB definition outlined in Section 1.4. Accordingly, a material embodied emission balance shall also be presented.

1.3 Tools and Methods Used

The material inventory has been calculated manually, from architect's drawings and product literature. Generic life cycle inventory data has been accessed via SimaPro Analyst version 8.0.5, and uses datasets from EcoInvent version 3. (PRé, 2015) (EcoInvent Centre, 2010) All of the calculations have been structured in MS Excel according to NS 3451 Table of Building Elements. (NS3451, 2009) The building elements covered in this report have been split into three sections, namely; building envelope, building services and energy supply system. Each section will be described in-depth, and broken down into its relevant building components, sub-components and materials. Table 1.1 gives an overview of this framework, whereby the number in brackets corresponds to the 2-digit building part number in the Table of Building Elements standard.

Table 1.1 Table of Building Elements Framework in terms of the Living Lab (NS3451, 2009)

Section	Component
Building Envelope	Groundwork and Foundations (21) Superstructure (22) Outer Walls (23) Inner Walls (24) Floor Structure (25) Outer Roof (26) Fixed Inventory (27) Stairs, Balconies etc. (28)
Building Services	Sanitary (31) Heating (32) Ventilation and Air Conditioning (36) Lighting (44) Other Services: Appliances (39)
Energy Supply System	Other Electric Power: Photovoltaic (49)

1.4 ZEB Definition and Ambition Level

For the purposes of this report, the Living Lab has a ZEB-OM ambition level, with a particular focus upon 'M' - materials. The ZEB-OM ambition level is defined as: *'Emissions relating to all operational energy (O) use plus embodied emissions from the materials (M) and technical installations shall be compensated for with on-site renewable energy generation.' (Dokka et al., 2013c)*

As both of the concept studies mentioned previously were theoretical, the material inventory used for embodied material emission calculations was limited. Both case studies relied upon traditional building solutions, with no form of material optimisation. The results of the two case studies showed that the ZEB-OM ambition level could not be achieved, and that innovative and alternative solutions were required to reduce total embodied material emissions.

In contrast, the Living Lab is one of the first ZEB pilot studies to be built, and provides a more detailed material inventory for analysis. Although the materials used have not been optimised in terms of embodied material emissions, the building incorporates innovative, state-of-the-art materials and technology to drive down emissions relating to the operational phase. In contrast, this report focuses upon the emissions relating to material use. Operational energy use (B6) is not considered.

The definition for 'M - materials' was initially outlined to cover emissions relating to the production phase and replacement phase of building construction materials, according to life cycle stages A1 - A3 and B4; as prescribed in EN15978 (2011). However, this definition was developed further to include:

'…all the building construction materials, such as the foundation, load-bearing systems, outer and inner walls, façade systems, windows and doors, flooring systems, stairs and technical units (such as electrical cabling, ventilation and heating systems and energy-producing units). Materials used for interior furnishings like wardrobe closets or kitchen cabinets do not have to be included, nor do water sewage and lighting systems.' (Kristjansdottir et al., 2014)

Accordingly, the Living Lab's material inventory covers those building components listed above. It also encompasses other building parts, such as; interior furnishings, lighting and sanitary ware, whereby inventory information was available, thus providing a more comprehensive material inventory. For this report, material emissions relating to transport to site (A4) and construction (A5) are also included. Replacement emissions (B4) also include transportation of the replacement materials to site (A4). A full description of the system boundary is provided in Section 3.1.2.

1.5 Structure of Report

Chapter 2 of this report describes the building used in this analysis; focusing upon the building envelope, building services and energy supply system. Chapter 3 outlines the embodied emission methodology used for calculations. Chapter 4 presents the results, whilst Chapter 5 discusses these results. Chapter 6 draws preliminary conclusions and recommendations for further research.

2. Building Description

The Living Laboratory is a single storey, temporary, multi-purpose demonstration experimental facility. The building is characterised by a detached, single-family house typology, which represents over 52% of the Norwegian building stock. (SSB, 2013)

Previous MSc. students originally designed the Living Laboratory as a prefabricated modular construction, as part of the solar decathlon competition in 2012. It has since been redesigned as a temporary building located on the university campus at Gløshaugen, Trondheim. The building utilises passive and active design strategies with an emphasis on energy conservation and solar energy exploitation. (Finocchiaro et al., 2014) (Finocchiaro et al., 2012) It should be noted that no material optimisation was implemented during the design phase.

The building is located at latitude 63°4'N and longitude 10°4E'. A site plan and photograph of the building is supplied in Figure 2.1. A morphological analysis of the building shows the following building characteristics: compactness (0.64), porosity (0.006) and slenderness (0.71), whereby 0 is the lowest and 1 is the highest score. (Serra and Coch, 2001) Such characteristics are befitting morphological traits of a bioclimatic house in Norway. (Lechner, 2009) (Olgyay, 1963)

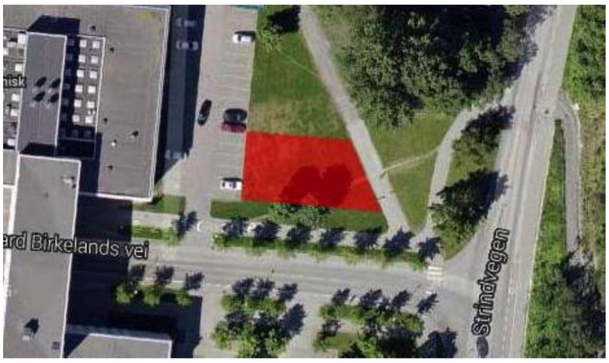


Figure 2.1 Site Plan (Google, 2015) and photograph of the Living Lab by Marianne Inman

The building is of a timber-framed loadbearing structure, with a raised timber floor construction. A more detailed explanation of the building envelope is supplied in Section 2.1.

The building consists of two adjoining rectangular cells approximately 12.5 x 4.1 metres, with elongated facades facing north and south. As can be seen from Figure 2.2, the Living Lab contains two bedrooms, one bathroom, a living area, a kitchen, a study, as well as an entrance hallway and technical room.

The ground floor has a heated floor area (BRA) of 102 m², a gross floor area (BTA) of 132 m², a net floor area (NTA) of 97 m² and a built up area of 219 m². A definition of these areas is supplied in Section 3.1. The total window and door areas are 47.3 m², which gives a window/door to floor area ratio of 46.4%.

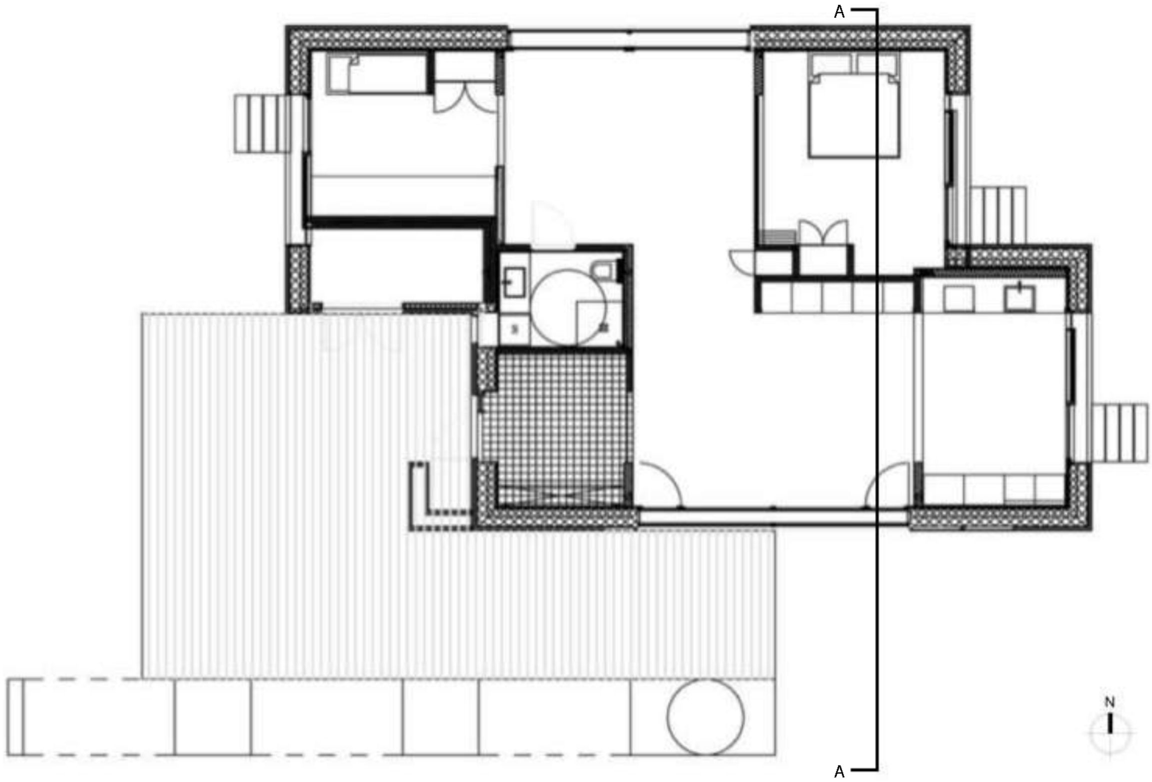


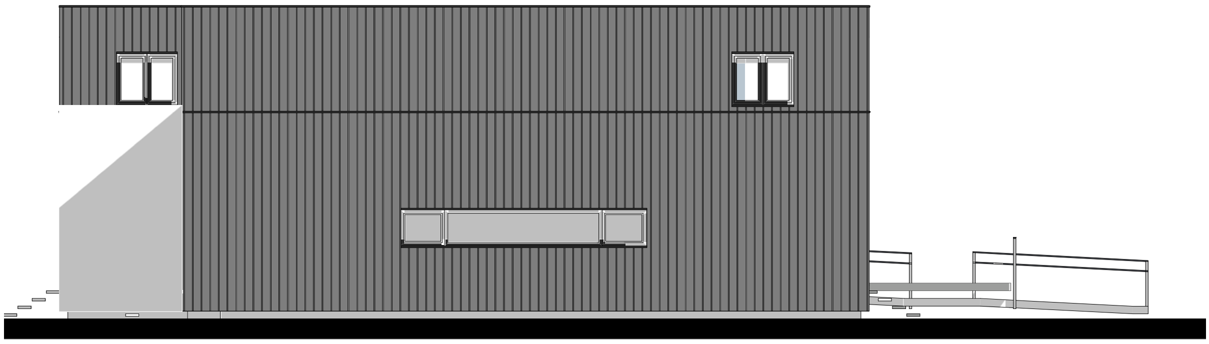
Figure 2.2 Plan of the Living Lab (courtesy of Bergersen Arkitekter AS)

The passive design strategies implemented include a compact form and high-performance building envelope to reduce heat loss, a south orientation to maximise solar gain, with deciduous vegetation to the south for protection from the sun during the summer months, as well as two sloped south-facing roofs. Window openings to the north are reduced in size to avoid heat loss, whilst the main entrance to the west is sheltered from the wind through the use of a faux wall.

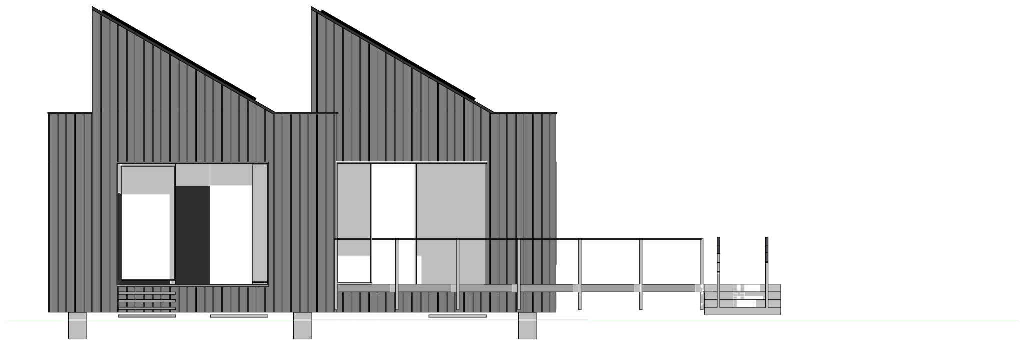
The active design strategies implemented include an in-roof building adapted photovoltaic (BAPV) system, a geothermal heat pump, phase change material (PCM) in the roof, vacuum insulation panels (VIP) in the sliding doors, two solar thermal collectors integrated into the south façade, a double skin south-facing window that acts as a buffer zone, hybrid ventilation with opportunities for cross ventilation, as well as dynamic solar shading to regulate solar gain and solar glare.

It is important to distinguish the difference between a building adapted photovoltaic system and a building integrated photovoltaic system. Building integrated photovoltaic (BIPV) systems are defined as 'a building component used as part of the building envelope…sun protection devices…architectural elements or accessories…and any other architectural element that is necessary for the proper functioning of the building.' (SUPSI, 2013) In contrast, BAPV systems are defined as a photovoltaic system that can be removed without reducing the technical functionality of the building. (Farkas et al., 2013) In-roof systems are a sub-category that falls under BAPV, and are semi-integrated systems that typically use flashings behind and around the modules, to safeguard the technical functionality of the building. (Renusol, 2010) In-roof systems are typically used on existing buildings, however it has also been used on the Living Laboratory to maximise flexibility in the testing of PV solutions.

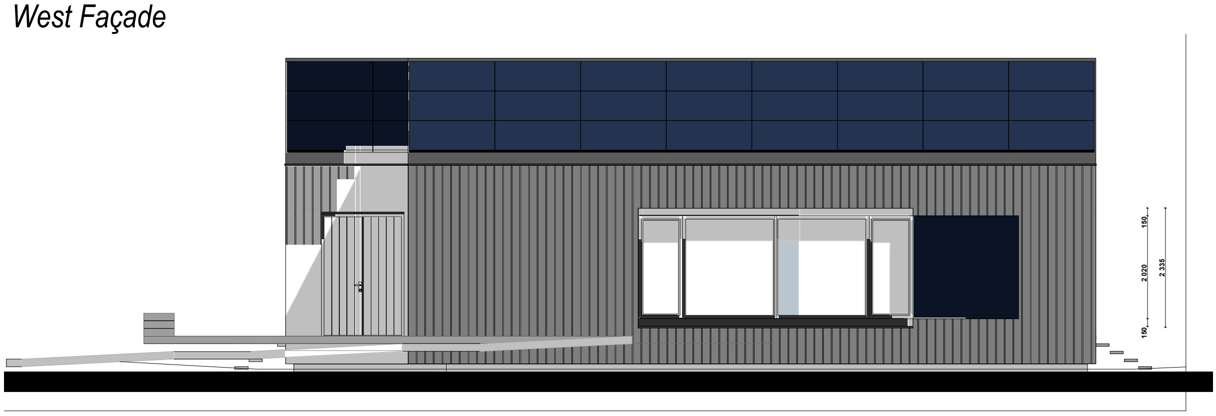
Figure 2.3 depicts the Living Lab in elevation, whilst Figure 2.4 demonstrates in section, how some of the passive and active strategies work together.



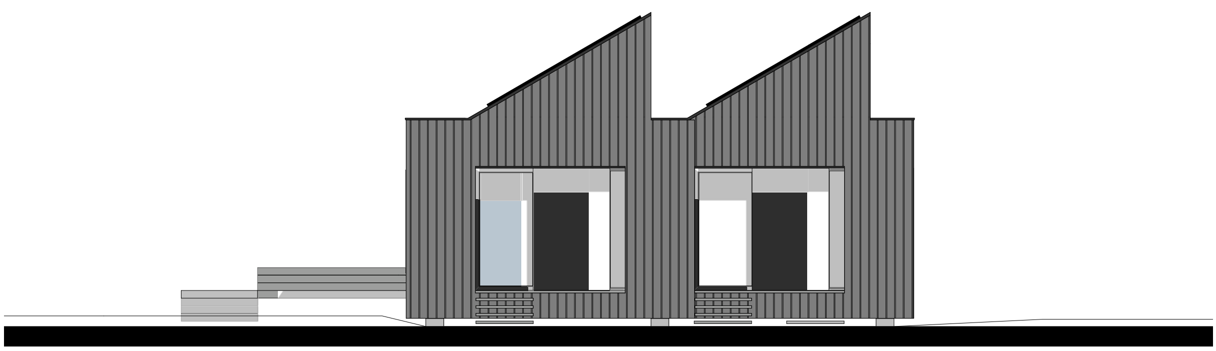
North Façade



West Façade



South Façade



East Façade

Figure 2.3 Elevations of the Living Lab (courtesy of Bergersen Arkitekter AS)

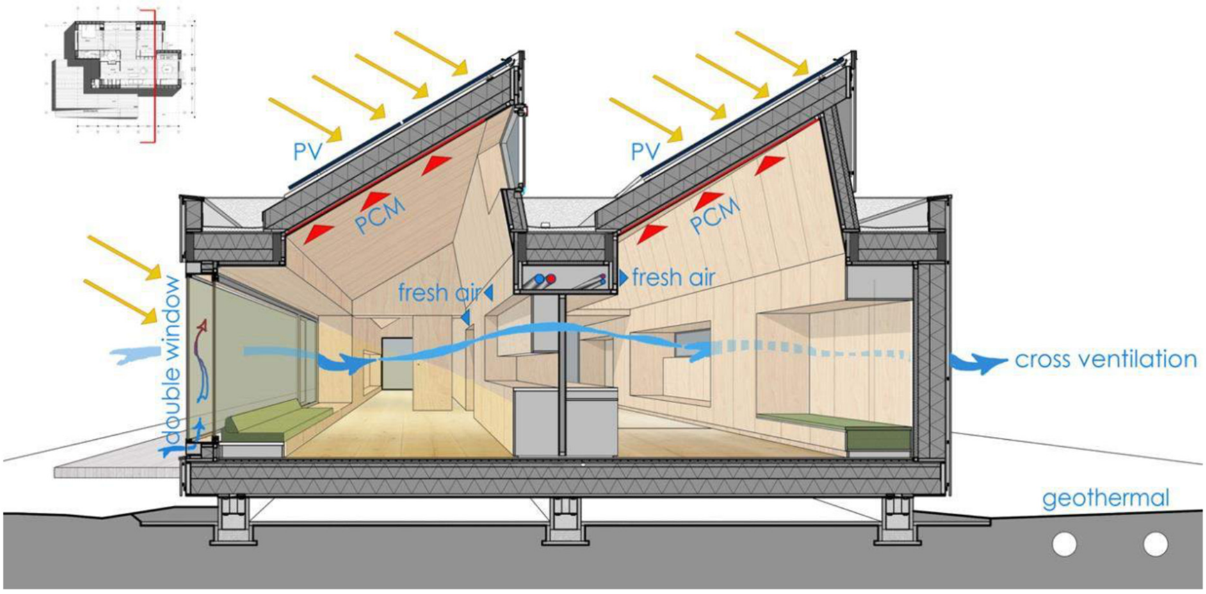


Figure 2.4 Section of the Living Lab (Finocchiaro et al., 2014)

2.1 Building Envelope

Table 2.1 demonstrates the thermal specification of the high-performance building envelope used in the Living Laboratory. To follow is an outline of each of the building component categories, with an overview of the material inventory used in calculations.

Table 2.1 Building Envelope Specification (Finocchiaro et al., 2014)

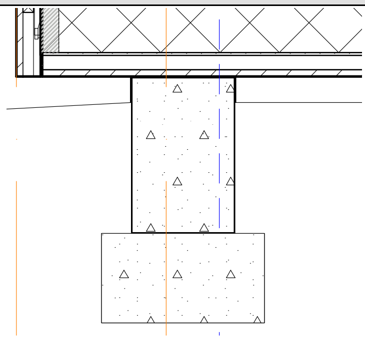
Component	Value	Description
Floor	U = 0.1 W/m²K	Raised timber framed construction, mineral wool insulation, parquet timber flooring
Outer Wall	U = 0.11 W/m²K	Timber framed construction, mineral wool insulation, timber cladding
South Window	U = 0.65 - 0.69 W/m²K*	Triple glazed unit with insulated aluminium frame, double skin
North Window	U = 0.97 W/m²K	Triple glazed unit with insulated aluminium frame, double skin
East and West Doors with VIP	U = 0.8 W/m²K	Aluminium clad timber framed triple glazed units, integrated vacuum insulated panels
Roof	U = 0.1 W/m²K	Timber framed construction, mineral wool insulation, integrated phase change material, in-roof photovoltaic panels
Roof Lights	U = 1.0 W/m²K	Aluminium clad timber frame, triple glazed
Thermal Bridge (normalised)	Ψ = 0.03 W/m²K	Detailed thermal bridge design
Air Tightness	0.3 ACH at 50Pa	Detailed design of a continuous vapour and wind barrier, pressure tested.

*The u-value for the south window varies depending on whether or not the buffer space is ventilated.

2.1.1 Groundwork and Foundations

The foundations were originally designed with a concrete footing for each of the three concrete strip foundations. However, during construction this additional footing was dropped, reducing the amount of concrete by almost half. In addition, extruded polystyrene (XPS) insulation and a timber plinth have been added to the construction. An overview of the material inventory at both the design and construction stage is given in Table 2.2. It should be noted that external landscaping, formwork and metal fasteners have not been included in the inventory. The steel rebar in the reinforced concrete is based on an estimate of 75kg/m^3, as used in the ZEB office concept study. (Dokka et al., 2013b)

Table 2.2 Groundwork and Foundations

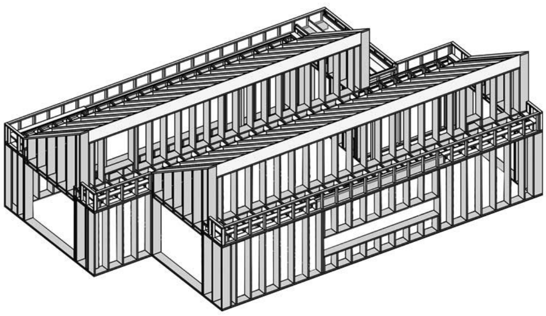
	Construction Detail	Material	Quantity
Design		Concrete Polyvinylchloride (PVC) Aluminium Reinforcing Steel Rebar	16.2 m^3 14.5 kg 9.3 kg 571.2 kg
As Built		Concrete Polyvinylchloride (PVC) Aluminium XPS Insulation Reinforcing Steel Rebar Timber	9.3 m^3 14.5 kg 9.3 kg 166 kg 571.2 kg 0.3 m^3

Detail courtesy of Bergersen Arkitekter AS

2.1.2 Superstructure

The superstructure is characterised predominantly by timber framework. An overview of the material inventory is given in Table 2.3. It should be noted that scaffolding, adhesives, timber treatments, cross-bracing and metal fasteners have not been included in the inventory.

Table 2.3 Superstructure

	Construction Detail	Material	Quantity
As Built		Glue-laminated Timber I-Beam Timber	13.9 m^3 0.5 m^3 1.96 m^3

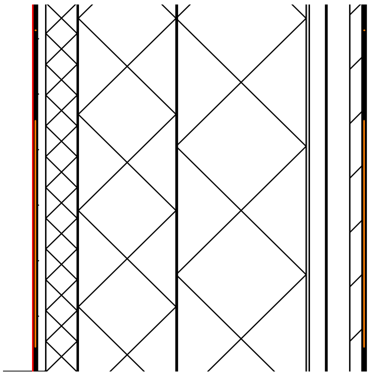
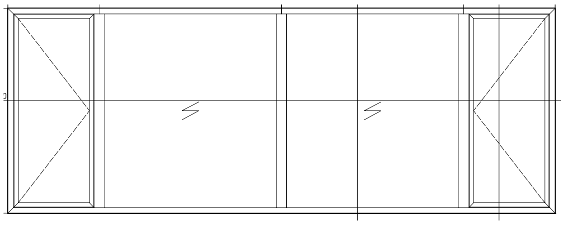
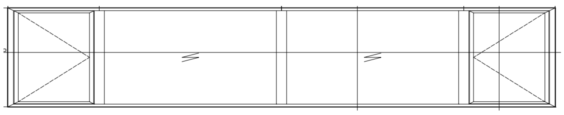
(Optimera, 2014)

2.1.3 Outer Walls

The outer walls consists of 200 + 150 + 50mm mineral wool insulation with a plywood internal finish, a vapour and wind barrier as well as battens, counter-battens and an external timber cladding. There are a number of high performance apertures, as detailed under windows and doors of Table 2.4.

Approximate weights have been stated for the windows and doors, as it concerns sensitive data provided by the manufacturers. It should be noted however that adhesives, some tapes and metal fasteners; as well as handles, lock cylinders, keys and hinges from the door and window components, have not been included in the inventory.

Table 2.4 Outer Walls

	Construction Detail	Material	Quantity
Design		Plywood Mineral Wool Insulation Polyethylene, HDPE Polypropylene Timber Ceramic Tiles (bathroom)	1.3 m^3 435.8 kg 140.9 kg 736.3 kg 4.9 m^3 203.7 kg
Windows	  	South Window - Aluminium - Steel - Glass Fibre Reinforced Plastic - Rubber - Powder Coating - Glass North Window - Aluminium - Steel - Glass Fibre Reinforced Plastic - Rubber - Powder Coating - Glass - ABS - Timber Bathroom Window - Aluminium - Glass Fibre Reinforced Plastic - Glass - Argon - Timber - Sealing Tape	Approx. 660 kg Approx. 196 kg Approx. 38 kg

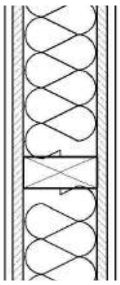
	Construction Detail	Material	Quantity
Doors		Sliding Door x 3 - Aluminium - Glass Fibre Reinforced Plastic - Glass - Argon - Timber - Sealing Tape - Plywood - Vacuum Insulation Panel	Approx. 130 kg
		Entrance Door - Aluminium - Glass Fibre Reinforced Plastic - Glass - Argon - Timber - Sealing Tape - Plywood - Polystyrene - Steel	Approx. 90 kg

Wall detail courtesy of Bergersen Arkitekter AS, window drawings courtesy of SAPA and NORDAN

2.1.4 Inner Walls

The inner walls are characterised by timber stud partitions with mineral wool insulation, a plywood cladding and a timber skirting board. There are also two sliding doors and a door to the bathroom, all of which have been included in the inventory. An overview of the material inventory is given in Table 2.5. It should be noted that adhesives, sealants and metal fasteners have not been included in the inventory.

Table 2.5 Inner Walls

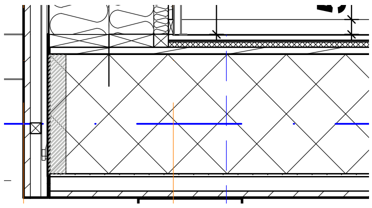
	Construction Detail	Material	Quantity
Design		Plywood Mineral Wool Insulation Timber EPS Insulation	3.97 m^3 187 kg 0.1 m^3 2.6 kg

Detail courtesy of Bergersen Arkitekter AS

2.1.5 Floor Structure

The floor structure is characterised by a raised timber frame construction, with 400mm mineral wool insulation and a timber parquet flooring finish. The construction is raised off the ground, providing a crawl space under the building. In the bathroom, anhydrite screed has been used with a ceramic tile finish. An overview of the material inventory is given in Table 2.6. It should be noted that the under floor heating apparatus is located under 'Heating' and that adhesives, sealants, tapes and metal fasteners have not been included in the material inventory.

Table 2.6 Floor Structure

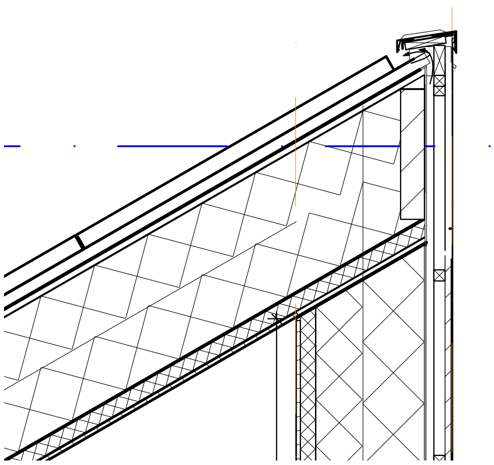
	Construction Detail	Material	Quantity
Design		Chipboard	5.5 m³
		Mineral Wool Insulation	826 kg
		Anhydrite Screed	173 kg
		Polyethylene, HDPE	243 kg
		Timber Parquet Flooring	1.8 m³
		Ceramic Tiles (bathroom)	53 kg

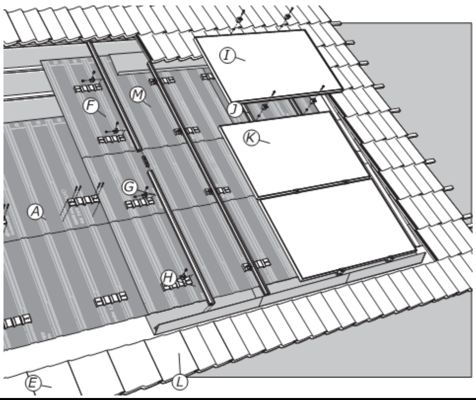
Detail courtesy of Bergersen Arkitekter AS

2.1.6 Outer Roof

The outer roof has a timber frame construction with 250mm EPS insulation in the flat roof areas and 200 + 150 + 50mm mineral wool insulation for the sloped roof areas. Roofing felt has been used in the flat roof, whilst the sloped roofs integrate the in-roof building adapted photovoltaic (BAPV) system (consisting of overlapping polyethylene plates, sealing tape and sealing strips, additional timber battens, aluminium rails and fixings with stainless steel screws). The roof also includes 90m² of phase change material (PCM), a wind and vapour barrier, aluminium flashings, and an internal plywood cladding. Approximate weights have been stated for the four roof lights, as it concerns sensitive data provided by the manufacturer. An overview of the material inventory is given in Table 2.7.

Table 2.7 Outer Roof

	Construction Detail	Material	Quantity
Design		Plywood	4.2 m³
		Mineral Wool Insulation	1210 kg
		Polyethylene, HDPE	653 kg
		Polypropylene	767 kg
		Timber	2.5 m³
		Roofing Felt	221 kg
		EPS Insulation	222 kg
		Chipboard	0.7 m³
		Aluminium	255 kg
		PCM	405 kg

	Construction Detail	Material	Quantity
Roof Lights		Roof Light x 4 - Aluminium - Felt Insulation / Material - Glass - Argon - Steel - Timber	Approx. 48.8 kg
PV Mounting Frame		Aluminium Sealing Tape Sealing Foam Strip Polyethylene Plate Timber Stainless Steel	156.4 kg 106 kg 4.3 kg 224 kg $0.2\ m^3$ 11.3 kg

Detail courtesy of Bergersen Arkitekter AS, photograph from Velux, diagram from Renusol Intersole

It should be noted that adhesives, sealants, some tapes and metal fasteners; as well as handles, lock cylinders, keys, hinges, rubber gaskets, clips, friction springs, filters and rollers for the roof lights, have not been included in the inventory. The BAPV mounting frame has been included in the 'Outer Roof' building component, whilst the photovoltaic modules and balance of systems (BOS) are located under 'Other Electric Power'.

2.1.7 Fixed Inventory

The fixed inventory category includes window seating, cupboards, kitchen units and worktops and consists of 2.3 m^3 plywood and 0.5 m^3 hardwood. The material inventory does not include soft furnishings, loose furniture, adhesives or metal fasteners.

2.1.8 Stairs and Balconies

The stairs and balconies category includes the external timber decking and three timber and stainless steel entrance steps (yet to be installed). It comprises of 21.6 m^3 timber and 1880 kg of stainless steel. The material inventory does not include metal fasteners or railings to decking.

2.2 Building Services

The building services category includes sanitary installations, heating, ventilation and air conditioning, as well as lighting and common household appliances. It should be remembered that, in order to simulate multiple energy scenarios, the technical systems for the Living Laboratory have purposefully been over specified. Any additional technical equipment, control systems, sensors or probes used to document the performance of the Living Lab, have been purposefully left out of the material inventory.

2.2.1 Sanitary

The sanitary component category includes sanitary ceramics (29.9 kg), stainless steel shower, tap and drain covers (1.7 kg) a glass mirror (27.6 kg), a stainless steel kitchen sink (5.5 kg) and kitchen tap (1.5

kg). The material inventory does not include the basin cabinet, shower cabinet, toothbrush holder, soap dispenser, toilet roll holder, shower shelf, towel hooks, toilet brush, or soil vent pipes known to be installed in the building, due to a lack of quantifiable information.

2.2.2 Heating

The heating component category includes under floor heating (UFH), a ground source heat pump, a hot water tank and two solar thermal collectors. The secondary heating system of two panel oven radiators has purposefully been left out of the material inventory, as this would imply a double up of heating systems. Figure 2.5 provides a schematic of how these components interact.

The under floor heating encompasses the entire building footprint, supplying heat to all rooms via PEX pipes (137.8 kg) fastened in polyethylene heat emission plates (85 kg). It should be noted that the UFH central distribution unit, pressure pump, circulation pump, thermostats, heating battery and energy meters are not included in the material inventory due to a lack of available inventory data.

The heat pump is a 3kW ground source heat pump, with co-efficient performance (COP) of 3.69. (Calorex, 2015)

The hot water tank is a 300-litre, stainless steel, triple coil, combi-boiler designed for solar thermal collectors and heat pumps, suitable for a 5-person household. It should be noted that the level vessels, regulators, mixing valves, spiral vent and additional pipework are not included in the material inventory due to a lack of available inventory data.

The two solar thermal collectors (STC) (4.2 m^2) are integrated into the south façade, have a liquid capacity of 1.1 litres, an optical efficiency of 80.2%, and a first order u-value of 3.80 W/m^{2}K. The mounting frame and balance of systems required for the solar thermal collectors are not included in the material inventory due to a lack of available inventory data.

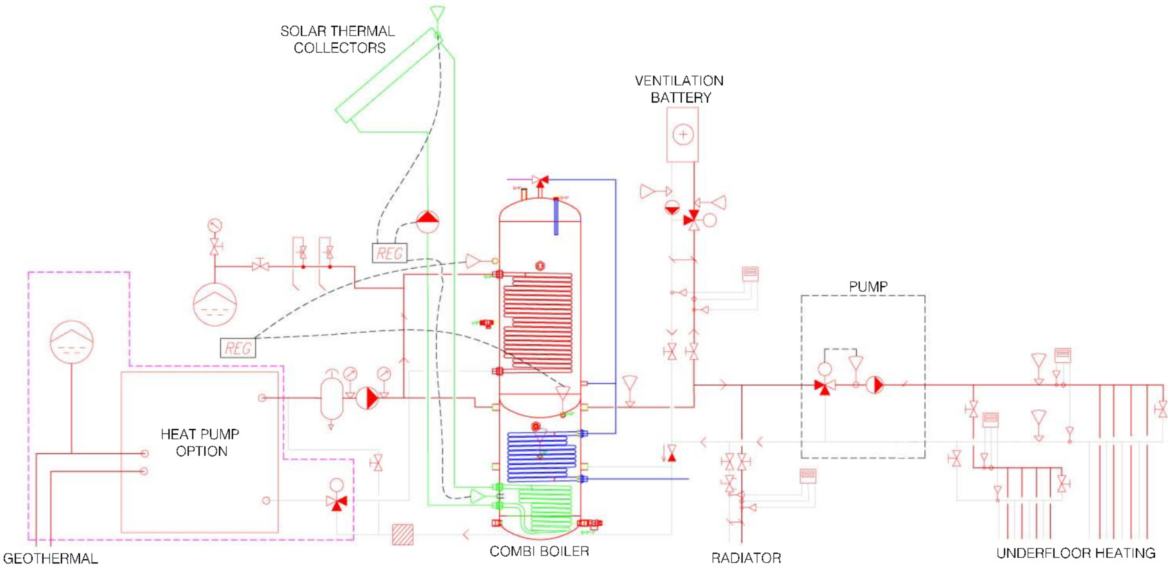


Figure 2.5 Technical Specification for heating and domestic hot water in the Living Lab

2.2.3 Ventilation and Air Conditioning

The air-handling unit (AHU) is placed in the technical room, and is connected to the intake and exhaust grills, fitted to the west façade, via alu/PET flexible duct (3m). The stainless steel ventilation ducts (53.4

kg) run along the central spine of the building, supplying pre-heated fresh air to each of the habitable rooms and technical room through five supply air inlets. Three forced ventilation extracts are installed in the bathroom, kitchen and technical room. An overview of the ventilation plan can be found in Figure 2.6. The ventilation system has a temperature efficiency of 85%, and a specific fan power of 1.0 kW/m^3/s. The material quantities for ducting are based on kg/m estimates, as used in the ZEB single-family house concept study. (Dokka et al., 2013a)

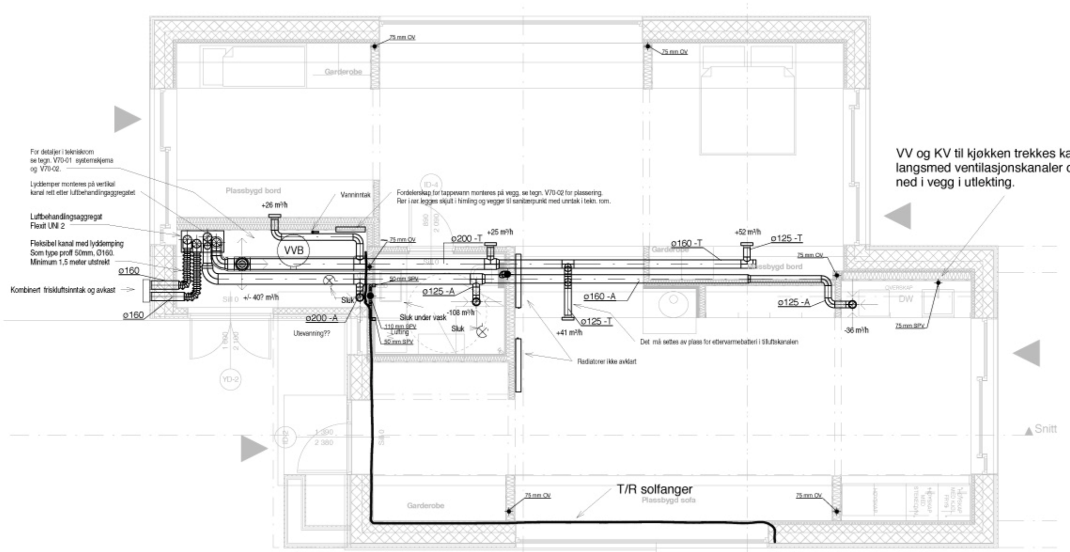


Figure 2.6 Ventilation plan for the Living Laboratory, courtesy of Prosjektutvikling Midt-Norge AS

2.2.4 Lighting

At the time in which the material inventory was assembled, a detailed lighting and electrical plan was not available. Therefore only 23 plug sockets were included in the material inventory. This represents an area for further, more detailed, work. Therefore, it should be noted that the material inventory does not, amongst other things, include LED spotlights, lighting fixtures, wiring, cabling, master controls, light switches or 25A sockets for the white goods.

2.2.5 Other Services: Appliances

Material quantities and transportation modes have been gathered from environmental declarations for a range of white goods, including: a dishwasher, a tumble dryer, a washing machine, a fridge freezer, an oven and a hob. An overview of these white goods can be found in Table 2.8. It should be noted that any other electrical appliances such as TVs, PCs or other kitchen appliances have not been included in the material inventory.

Table 2.8 Energy Efficiency of White Goods

Appliance	Annual Energy Use	Description
Dishwasher	241 kWh	Electrolux dishwasher, energy class A.
Tumble Dryer	177 kWh	Electrolux tumble dryer, energy class A+++
Washing Machine	162 kWh	Electrolux washing machine, energy class A+++.
Fridge Freezer	233 kWh	Electrolux fridge freezer, energy class A++.
Oven	Approx. 230 kWh	Electrolux oven, energy class A.
Hob	-- kWh	Electrolux hob
TOTAL	**1043 kWh**	

Since, detailed material, transport, packaging and energy inventories were available for the Electrolux appliances outlined above, through a series of environmental declarations; embodied emissions relating to these white goods are considered representative and accurate.

2.3 Energy Supply System

The energy supply solution for heating, cooling and electricity is an 'all electric' solution based on:

1. High-efficiency photovoltaic panels on the roof
2. Solar thermal collectors on the south façade (as outlined in Section 2.2.2 Heating)
3. Geothermal heat pump (as outlined in Section 2.2.2 Heating)

2.3.1 Photovoltaic Panels

There are two 3 x 8 south facing arrays integrated into the two south facing sloped roofs of the Living Laboratory, each with an almost optimal tilt of 30 degrees. Each roof has an upper and a lower string of modules. Each poly-crystalline silicon PV module measures 1665 x 991 x 38mm, providing a total coverage of 79.2m^2, with a nominal power efficiency of 15.8% (under standard test conditions) and a total rated power of 12.48kWp. The photovoltaic system is grid connected. (Kristjansdottir et al., Submitted) (REC, 2013) (Solbes, 2013)

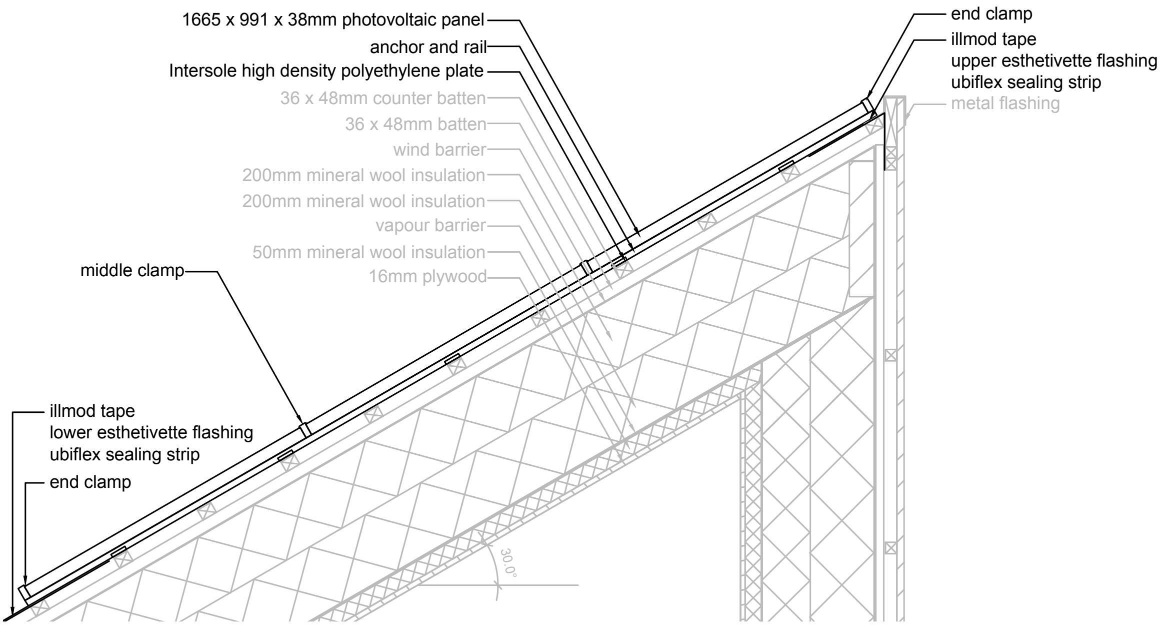


Figure 2.7 Roof section of the BAPV system for the Living Laboratory

The balance of systems (BOS) material inventory includes a Sunny WebBox Ethernet (0.75kg), a SMA RS485 interface (0.18kg), a SMA Sunny SensorBox RS485 (0.5kg), a SMA mounting board, a SMA wind sensor (0.3kg), two SMA Sunny Boy 5000 TL-21 MS Basic Inverters with two MPP trackers for each string (52kg), eight male and female MC4 contacts (0.16kg) and cabling (195m). (Kristjansdottir et al., Submitted) It should be noted that a generic electronic component dataset has been used for each of these components, except for the cabling and mounting board.

Preliminary results show that there is an expected cumulated energy yield of 268,844 kWh for the first 30 years, and an expected cumulated energy yield of 443,685 kWh for the second 30 years, giving a total cumulative energy yield of 712,529 kWh for the 60-year lifetime of the building. When the ZEB emission factor for electricity is used (0.132 $kgCO_{2eq}$/kWh), this equates to 94054 $kgCO_{2eq}$ or 15.4 $kgCO_{2eq}/m^2/yr$ of embodied material emissions saved. (Graabak and Feilberg, 2011) (Georges et al., 2015) (Kristjansdottir et al., Submitted)

3. Embodied Emission Methodology

3.1 Goal and Scope

The goal of these calculations is to estimate, and thus provide an overview, of the materials and components in the Living Laboratory, which contribute the most to embodied CO_{2eq} emissions. The calculations are based on the principals of environmental assessment through life cycle analysis.

The Living Laboratory can be used as a base case, against which further steps to optimise the design, and corresponding impact on emissions, can be compared in further harmonisation work, currently being conducted between the other ZEB pilot projects. Likewise, both the system boundary and functional unit have been defined so that the results of this report are comparable with the other ZEB pilot projects.

3.1.1 Functional Unit

The functional unit has been set to: 'emissions per square metre of heated floor area (BRA) per year of operational building lifetime', so that the results are comparable with the other ZEB pilot projects. The results are normalised according to a heated floor area of $102m^2$ and a building lifetime of 60 years. For transparency, a sensitivity analysis of the functional unit, in terms of definition of area and building lifetime, shall also be presented.

An overview of the Norwegian definition for building areas can be found in Figure 3.1. A functional unit that takes into account heated floor area is comparable in a ZEB energy balance considering operational energy use. (Graabak and Feilberg, 2011) Such a definition prioritises operational energy use, whilst net floor area (NTA) prioritises differences in material use. (Hastings and Wall, 2013) According to NS 3454, gross floor area (BTA) is comparable with life cycle costs (LCC), which gives an economical perspective to the financial cost of global warming. (NS3454, 2013) (Konig et al., 2010)

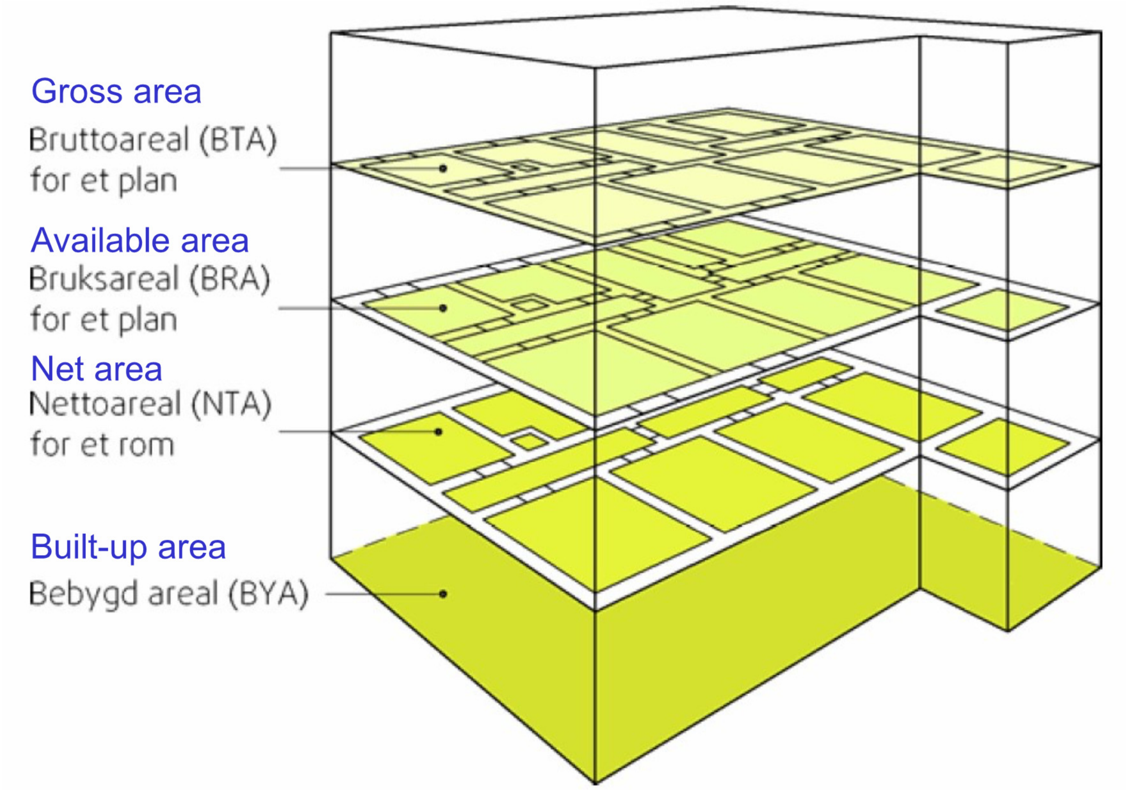


Figure 3.1 Definitions of Area (Norsk Standard, 2012)

It is of interest to study the emissions of the Living Laboratory under a shorter building lifetime, as the building is of a temporary nature, and may be dismantled before its 60-year building lifetime has been reached. It is expected that using a shorter building lifetime of say 30 years will have higher embodied material emissions, as total CO_2 emissions are distributed evenly across a shorter building lifespan. In addition, using a shorter building lifetime means that no benefit is gained from using building materials with long reference service lifetimes (RSL), such as steel, which has an RSL of over 100 years. As a result, a higher proportion of embodied material emissions are expected during the production phase (A1 - A3). Conversely, using a longer building lifetime of say 75 or 100 years should see an overall reduction in embodied emissions, as the environmental burdens are distributed evenly across a longer building lifespan. Furthermore, emissions relating to replacement (B4) will see an increase, as the reference service lifetime of building materials will gain significance.

3.1.2 System Boundary

The boundaries for the analysis are limited to the extraction of raw materials and the manufacture of products and materials needed (A1 - A3), including the transport of goods to site (A4) and their installation into the building (A5). Replacement of new materials over the lifetime of the building has also been included (B4), including the transportation of these new materials to site (A4). The reference service lifetime (RSL) used for the different materials and components are listed in Table 3.2. The reference service lifetimes are based on manufacturer's literature, BKS 700.320 and 700.330, EcoInvent reports and previous ZEB pilot projects.

The different life cycle stages included in the study of the Living Laboratory are shown in Figure 3.2.

A1-3 Product Stage			A4-5 Construction Process Stage		B1-7 Use Stage							C1-4 End of Life				D Next Product System			
A1: Raw Material Supply	A2: Transport to Manufacturer	A3: Manufacturing	A4: Transport to building site	A5: Installation into building	B1: Use	B2: Maintenance (incl. transport)	B3: Repair (incl. transport)	B4: Replacement (incl. transport)	B5: Refurbishment (incl. transport)	B6: Operational energy use	B7: Operational water use	C1: Deconstruction / demolition	C2: Transport to end of life	C3: Waste Processing	C4: Disposal	D1: Reuse	D2: Recovery	D3: Recycling	D4: Exported energy / Potential
x	x	x	x	x				x											

Figure 3.2 System Boundary (NS-EN 15978, 2011)
Note: x indicates modules included in embodied emission calculations for the ZEB Living Laboratory

3.1.3 Electricity Mix

The choice of electricity mix used in the production of materials, for the Living Laboratory, can have a decisive influence on results. The calculations presented here are not based on any one single emission factor for electricity, but is instead based on the EcoInvent database. For example, the concrete data set used in the analysis, is based on a concrete process from Switzerland, using the Swiss electricity mix as an input. The photovoltaic modules use a rest of world (ROW) electricity mix factor, since they are produced in Singapore.

3.2 Material Inventory

The material inventory was calculated manually using the architect's drawings, and has been cross-referenced with product literature and on-site observations. The life cycle GHG emission calculations should be thought of as an iterative process, from design drawings to the as built construction, whereby the most recent and available detail has been used. Assumptions and limitations with regards to the material inventory have already been outlined under the relevant component category in Section 2.

Table 3.1 presents an overview of the EcoInvent processes used for the Living Lab's material inventory, together with the transportation mode and distance travelled. Instead of assuming a standard 500km estimate of distance travelled, places of production and transportation modes have been acquired from the manufacturers, and distances have been calculated using Google Maps and Sea Rates. (Google, 2015) (SeaRates, 2015) The following generic processes were used for the various transportation modes: '*transoceanic freight ship, OCE, tkm*', '*freight, rail, RER, tkm*', '*lorry 16-32t, EURO3, RER, tkm*' and '*lorry 16-32t, EURO5, RER, tkm*'. (EcoInvent Centre, 2010) (PRé, 2015)

It should be noted that the emission factors for two different processes have been adjusted; namely '*heat pump 30kW / RER / unit*' and '*hot water tank, 600l / CH / unit*'. The heat pump's emission factor has been reduced by a factor of 10, so that it is representative of the 3kW heat pump installed, whilst the hot water tank's emission factor has been divided in half so that it corresponds to the 300l hot water tank installed. These adjustments have been made so that the processes are more representative of the products used. The photovoltaic panels are the only dataset to have a rest of world (ROW) electricity mix, since they are the only building component to be produced outside of Europe, in Singapore. All other datasets use either, a European (RER), Swiss (CH) or generic global (GLO) electricity mix.

Table 3.1 EcoInvent datasets used for material processes in the Living Lab's material inventory

Material Input	EcoInvent Process	Distance to Site (km)	Transportation Mode
ABS	Acrylonitrile-butadiene-styrene copolymer / RER / kg	1655	EURO 5, Ship
Air compressor	Air compressor, screw-type compressor, 300kW / RER / unit	2521	EURO 5, Train
Air Handling Unit	Air Distribution housing panel, steel 120m3/h / CH / unit	552	EURO 5
Aluminium	Aluminium, production mix / RER / kg	1891	EURO 5, Ship
Anhydrite Screed	Anhydrite floor, at plant / CH / kg	1673	EURO 5, Ship
Argon	Argon, liquid, at plant / RER / kg	485	EURO 5
Roofing Felt	Bitumen adhesive compound, hot, at plant / RER / kg	378	EURO 5
Sealing Tape	Bitumen seal, alu80, at plant / RER / kg	-	-
Butane	Butane-1,4-diol, at plant / RER / kg	2521	EURO 5, Train
Cable	Cable, three-conductor cable / GLO / m	2164	EURO 5
Ceramic Tile	Ceramic tiles, at regional storage / CH / kg	4261	EURO 5, Ship
Stainless Steel	Chromium steel 18/8, at plant / RER / kg	1456	EURO 5, Ship
Concrete	Concrete, normal, at plant production / CH / m^3	456	EURO 5
Copper	Copper, at regional storage / RER / kg	2521	EURO 5, Train
Electronic Component	Electronic component, unspecified / GLO / kg	2396	EURO 5, Train
PEX pipes	Ethylene, pipeline system, at plant / RER / kg	668	EURO 5
Exhaust outlet	Exhaust air outlet, steel/alu 85x365 / CH / unit	552	EURO 5
Exhaust valve	Exhaust air valve, in-wall housing DN125 / CH / unit	552	EURO 5
VIP	Expanded perlite, at plant / CH / kg	1870	EURO 5, Ship
Glass	Flat glass, coated, at plant / RER / kg	625	EURO 5
STC	Flat plate collector, at plant / CH / m^2	1953	EURO 5, Ship
Flexible Duct	Flexible duct, alu/PET, at plant / RER / m^2	552	EURO 5
Cardboard	Folding boxboard, at plant / RER / kg	2396	EURO 5, Ship
Glass Fibre Reinforced Plastic	Glass fibre reinforced plastic, polyamide injection / RER / kg	650	EURO 5
Mineral Wool Insulation	Glass wool mat, at plant / CH / kg	545	EURO 3
Glulam Timber	Glued laminated timber, indoor / RER / m^3	366	EURO 5

Material Input	EcoInvent Process	Distance to Site (km)	Transportation Mode
Heat Pump	Heat pump, 30kW / RER / unit	2485	EURO 5, Ship, Train
Hot Water Tank	Hot water tank, 600l / CH / unit	556	EURO 5
Paper	Kraft paper, bleached / RER / kg	2396	EURO 5, Train
Chipboard	OSB, at plant / RER / m^3	1413	EURO 5
External Intake	Outside air intake, ss DN370 / RER / unit	552	EURO 5
PCM	Paraffin, at plant / RER / kg	5	EURO 5
Iron	Pig iron, at plant / GLO / kg	2521	EURO 5, Train
Plywood	Plywood, indoor use / RER / m^3	1834	EURO 5, Ship
Plugs	Plugs, inlet and outlet for computer cable / GLO / unit	552	EURO 5
PV	Photovoltaic panel, multi-Si wafer / ROW / m^2	2636	Ship
Vapour barrier, PE Plates	Polyethylene, HDPE / RER / kg	378	EURO 5
Wind barrier	Polypropylene, granulate / RER / kg	378	EURO 5
EPS	Polystyrene, expandable / RER / kg	1891	EURO 5, Ship
XPS	Polystyrene, extruded, CO_2 blown / RER / kg	1891	EURO 5, Ship
PUR, Sealing Foam Strip	Polyurethane, rigid foam / RER / kg	2521	EURO 5, Train
PVC	PVC, at regional storage / RER / kg	650	EURO 5
Powder Coating	Powder coating, alu sheet / RER / m^2	-	-
Reinforcing Steel	Reinforcing steel / RER / kg	1456	EURO 5, Ship
Sanitary Ceramics	Sanitary ceramics, regional storage / CH / kg	4261	EURO 5, Ship
Softwood	Sawn timber, softwood, planed, air dried / RER / m^3	494	EURO 3
Hardwood	Sawn timber, hardwood, planed, air kiln dried / RER / m^3	494	EURO 3
Sealing Tape	Sealing tape, aluPE 50mm / RER / m	-	-
Unalloyed Steel	Steel, converter, unalloyed / RER / kg	1456	EURO 5, Ship
Cardboard	Stone ground wood pulp / RER / kg	2396	EURO 5, Train
Air Inlet	Supply air inlet SS DN75 / RER / unit	552	EURO 5
Rubber	Synthetic rubber / RER / kg	553	EURO 5
Textile	Textile, woven cotton / GLO / kg	492	EURO 5

With regards to installation (A5), material losses of the building materials have been accounted for with a 10% estimate, which is in line with current practice at the Research Centre for Zero Emission Buildings. As a ZEB-COM ambition level is not considered in this report, installation (A5) does not include formwork or scaffolding, metal fasteners, adhesives, sealants or tapes, machinery, tools or on-site energy consumption, labour, on-site water consumption, on-site office or storage facilities, supplementary lighting or security fences used for installing the building products. However, this represents an area for further work.

Table 3.2 refers to the reference service lifetimes (RSL) used for various building parts, components and materials, with a reference below the table to the RSL source. It is has been assumed that the PV panels will be produced 50% better in 30 years' time.

Table 3.2 Reference Service Lifetimes of Building Parts, Components and Materials

Building Part	Building Component	Building Material	Reference Service Lifetime (years)
Groundwork and Foundations			60 [1) 2) 3)]
Superstructure			60 [1) 2) 3)]
		Plasterboard / Plywood	30 [1) 2) 4)]
		Mineral Wool Insulation	60 [1) 2)]
		Timber cladding incl. wind barrier	50 [4)]
Floor Structure			60 [1) 2)]
		EPS Insulation	25 [3)]
		Timber Parquet Flooring	25 [5)]
		Ceramic Tiles	20 [4)]
		Anhydrite Screed	50 [5)]
	Windows (timber and steel)		40 [4)]
	Doors (external)		30 [1) 2) 3) 4) 6) 7)]
	Doors (internal)		40 [4)]
	Roof Lights		40 [5)]
Outer Roof			60 [1) 2)]
		Bituminous Roofing Felt	30 [1) 2)]
		Guttering, flashings	30 [4)]
Stairs and Balconies			60 [1) 2)]
		Stairs (timber)	20 [4)]
		Dishwasher	10 [8)]
		Fridge Freezer	10 [8)]
		Washing Machine	10 [8)]
		Tumble Dryer	15 [9)]
		PE / PEX Pipes	50 [8)]
		Kitchen Tap	15 [8)]
		Hob	15 [9)]
		Oven	15 [9)]
		Basin Mixer	15 [8)]
		Stainless Steel Hot Water Tank	20 [8)]
		Bathtub / Sink / Toilet	50 [8)]
Ventilation and Air Conditioning			60 [1) 2)]
Lighting and Electrical			30 [3)]
		Heat Pump	20 [1) 2)]
	PV System		30 [1) 2) 3) 10)]
		Inverters	15 [11)]
	STC System		25 [10)]

[1)] (Dokka et al., 2013a) [2)] (Dokka et al., 2013b) [3)] Multikomfort, Larvik [4)] (BKS 700.320, 2010)
[5)] Manufacturer's literature [6)] (Dahlstrøm, 2011) [7)] (Ghose, 2012) [8)] (BKS 700.330, 2003) [9)] Estimate
[10)] (Dones et al., 2007) [11)] (Kristjansdottir et al., Submitted)

3.3 Impact Assessment

Generic life cycle inventory data has been accessed from SimaPro Analyst version 8.0.5, and uses datasets from EcoInvent version 3. (PRé, 2015) (EcoInvent Centre, 2010) All the calculations have been structured in MS Excel according to NS 3451 Table of Building Elements. (NS3451, 2009) The IPCC GWP 100 year scenario method has been used, for the impact assessment of the material inventory. (PRé, 2007)

4. Embodied Emission Results

4.1 Results

This section presents the results from the current material inventory for the Living Laboratory. The total carbon dioxide emissions for the functional unit are presented in the last column of Table 4.1 below. The embodied emissions are calculated as 23.5 $kgCO_{2eq}/m^2/yr$, as 1410 $kgCO_{2eq}/m^2$ over a 60-year lifetime, as 2396 $kgCO_{2eq}/yr$ and 143788 $kgCO_{2eq}$ in total for the whole building.

Table 4.1 Carbon Dioxide (eq) emissions from material use in the ZEB Living Laboratory

Life Cycle Stage	$kgCO_{2eq}$	$kgCO_{2eq}/yr$	$kgCO_{2eq}/m^2$ 60 years	$kgCO_{2eq}/m^2/yr$
Initial Material Use (A1 - A3)	74121	1235	727	12.1
Transport to Site (A4)	6188	103	61	1.0
Construction (A5)	7412	124	72	1.2
Replacement (B4)	56067	934	550	9.2
TOTAL	**143788**	**2396**	**1410**	**23.5**

The results shown below in Figure 4.1 show the total emissions per m^2 per year for each life cycle stage; namely, the emissions associated with the initial material use (A1 - A3), transport to site emissions (A4), construction emissions (A5) and material and transport emissions associated with replacements (B4) over an estimated building lifetime of 60 years.

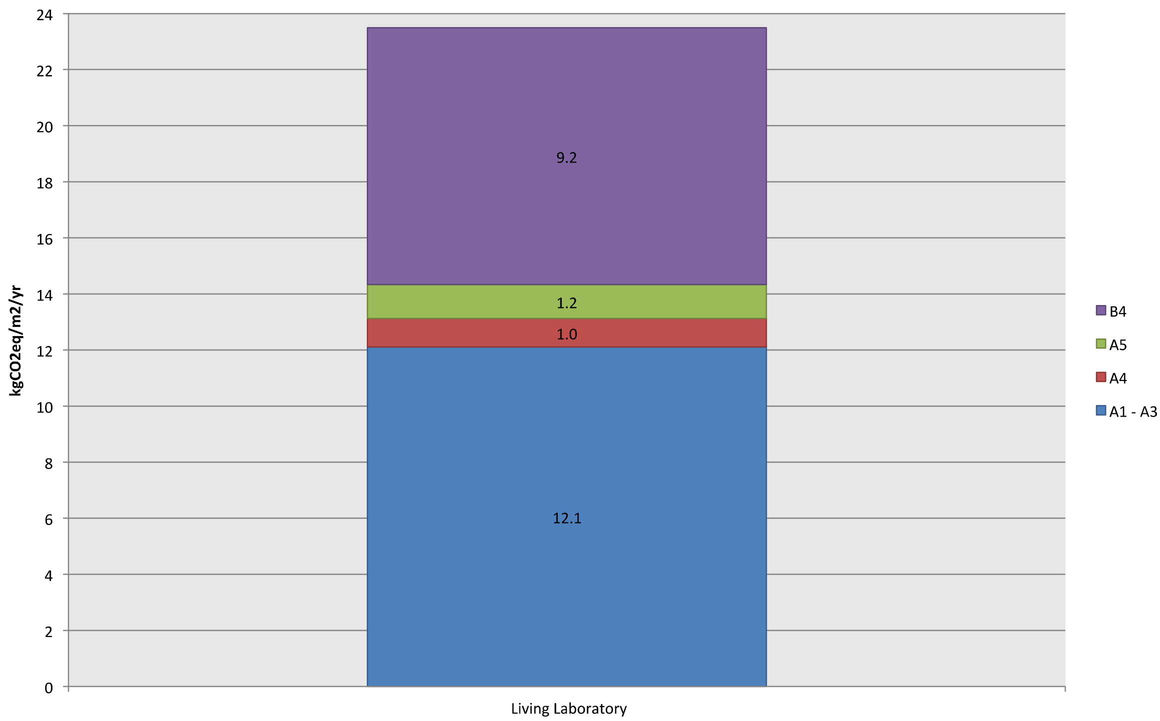


Figure 4.1 Total embodied material emissions of the Living Laboratory, by life cycle stage

The majority of the emissions come from the production (A1 - A3) and replacement (B4) stages, attributing 51.5% and 39.1% of emissions respectively. Transport to site emissions (A4) and construction emissions (A5) account for 4.3% and 5.1% respectively.

Total embodied emissions from the Living Laboratory are considered high when compared to other ZEB projects. The Living Laboratory has total embodied emissions of 23.5 $kgCO_{2eq}/m^2/yr$ in comparison to the ZEB single-family house (SFH) which has 7.2 $kgCO_{2eq}/m^2/yr$. (Dokka et al., 2013a) The same can be seen for production phase emissions (A1 – A3) whereby the two buildings have embodied emissions of 12.1 $kgCO_{2eq}/m^2/yr$ and 5.25 $kgCO_{2eq}/m^2/yr$ respectively. This difference in emissions is explained by the Living Laboratory having a more detailed material inventory and a more comprehensive system boundary than the ZEB SFH. Both of these factors contribute to higher total embodied emissions in the Living Laboratory. In addition, the Living Laboratory has an area of 102m^2, whilst the ZEB SFH has an area of 160m^2. This means that the Living Laboratory has a higher concentration of emissions per m^2 of heated floor area than in the ZEB SFH. However, when the A1-A3 embodied emissions are compared in terms of total $kgCO_{2eq}$, thehe Living Laboratory has 74,121 $kgCO_{2eq}$ whilst the ZEB SFH experiences 50,422 $kgCO_{2eq}$, thus showing a smaller disparity in A1 - A3 embodied emissions

In terms of replacement (B4) the ZEB SFH has 1.95 $kgCO_{2eq}/m^2/yr$, whilst the Living Laboratory has 9.2 $kgCO_{2eq}/m^2/yr$. This difference is explained by the ZEB SFH having an incomplete replacement scenario, whereby only a few building materials were replaced. Transport (A4) and construction (A5) of replaced materials was also excluded. In contrast, the Living Laboratory includes reference service lifetimes (RSL) for every building material and component; furthermore all replaced materials include transport and construction emissions.

The results shall now be presented for each building component, and each building material. It should be noted that the results are presented in $kgCO_{2eq}$. As seen in Figure 4.2, the components that drive the highest emissions are the 'Outer Roof' (23.6%), followed by 'Other Electric: Photovoltaic' (22.7%), 'Outer Walls' (14.8%), 'Stairs and Balconies' (13.1%), 'Other Services: Appliances' (8.2%), 'Groundwork and Foundations' (4.5%) and 'Floor Structure' (3.3%). The components that drive the highest emissions in A1 - A3 are the 'Outer Roof' (26.1%), followed by 'Other Electric: Photovoltaic' (19.6%), 'Outer Walls' (15.1%), 'Stairs and Balconies' (13.9%) and 'Groundwork and Foundations' (5.8%). The majority of emissions arise from the outer roof because of the complex roof form and aluminium flashings, roof lights and over-dimensioned PV mounting frame.

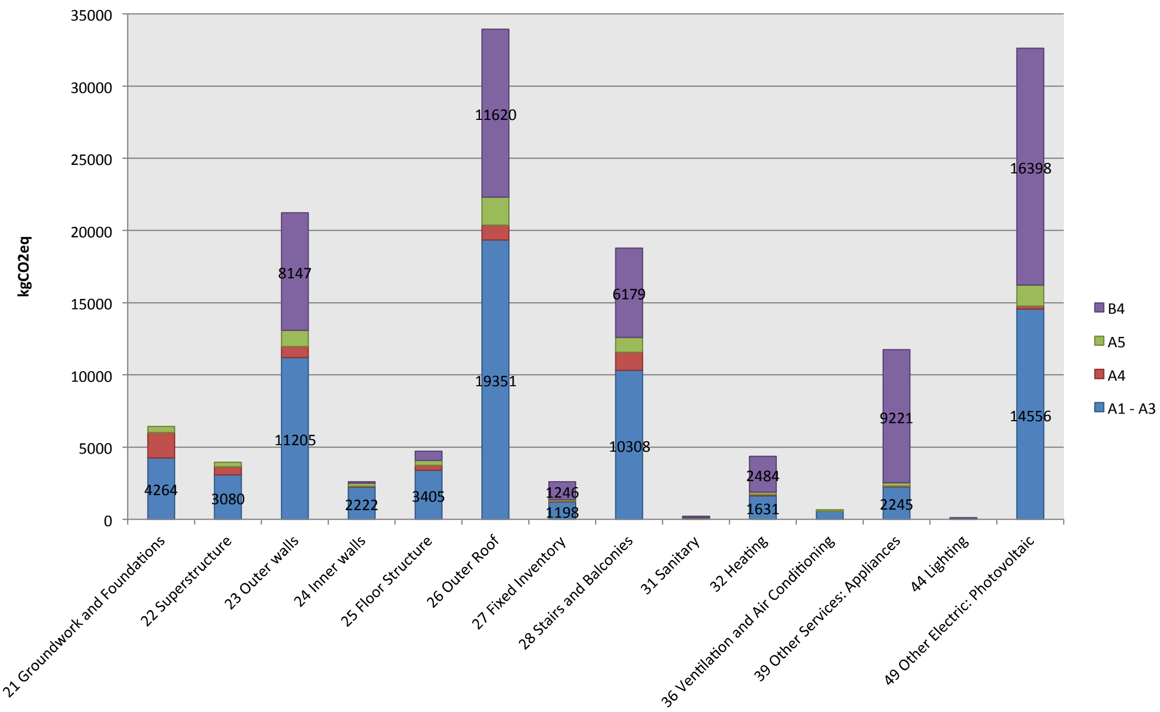


Figure 4.2 Total embodied material emissions of the Living Lab, by component

As seen in Figure 4.3, the materials that drive the highest emissions are ‘timber, cardboard, paper, chipboard, plywood’ (21.8%), followed by ‘electrical components’ (19.5%), ‘metals: aluminium, steel, iron, copper’ (18.9%), ‘photovoltaic panels’ (12.6%), ‘plastics’ (9.5%), ‘textiles’ (6.2%) and ‘concrete, anhydrite, ceramics’ (4.1%). The materials that drive the highest emissions in A1 - A3 are ‘metals: aluminium, steel, iron, copper’ (23.4%) followed by ‘timber, cardboard, paper, chipboard, plywood’ (18.4%), ‘photovoltaic panels’ (15.1%), ‘plastics’ (11.8%) and ‘electrical components’ (9.8%). It is also interesting to note that both the ‘timber, cardboard, paper, chipboard, plywood’ and ‘concrete, anhydrite, ceramics’ material categories have significant emissions from transport to site (A4), with 53.8% and 28.8% of total transport to site (A4) emissions, respectively. Timber experiences high emissions because the building is predominantly of timber construction, similarly some of the wood products have been processed (e.g. plywood processing involves glue additives) which may lead to an increase in embodied emissions compared to unprocessed timber products. A complete breakdown of the 53 different building materials used in the construction of the Living Laboratory is provided in Appendix A.

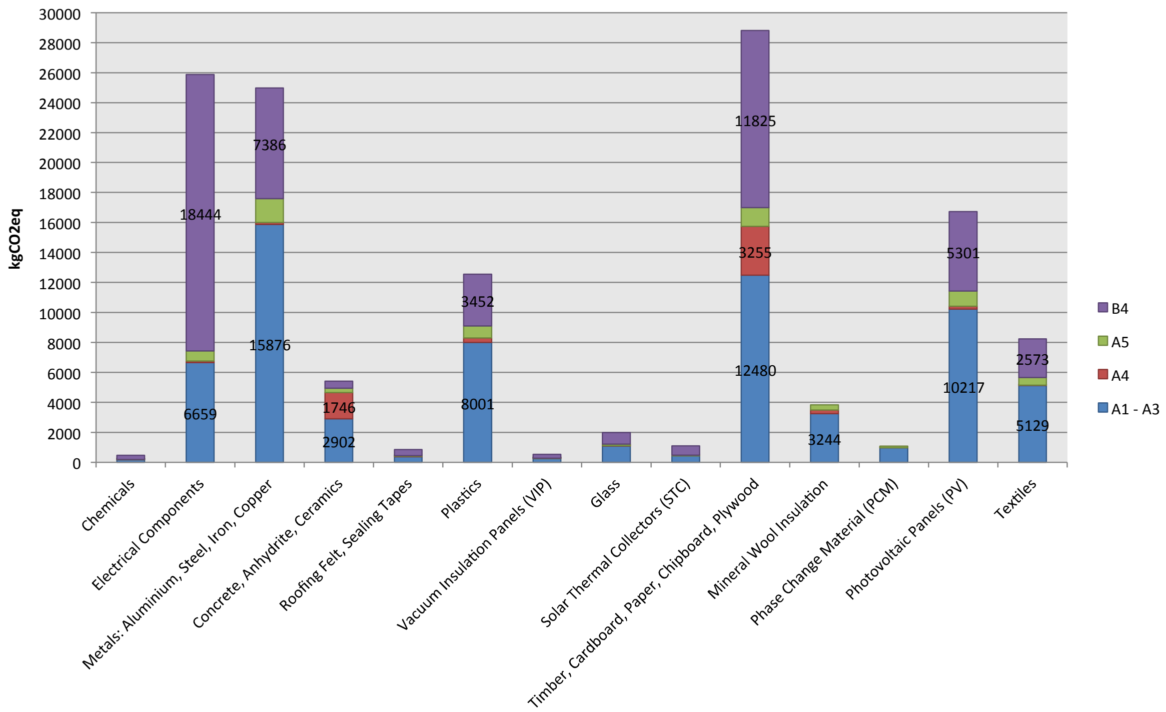


Figure 4.3 Total embodied emissions of the Living Lab, by material

As discussed in Section 3.1.1, the functional unit is sensitive to the definition of building lifetime and area. Given that the Living Laboratory is a temporary building, it is likely that the building lifetime will be shorter than the standard 60-year lifetime specified by the Research Centre for Zero Emission Buildings. For that reason, a sensitivity analysis of the results, with regards to the length of building lifetime, is presented in Figure 4.4, showing material emission results for a 30, 60, 75 and 100-year lifetime. The reference service lifetimes have also been adjusted accordingly.

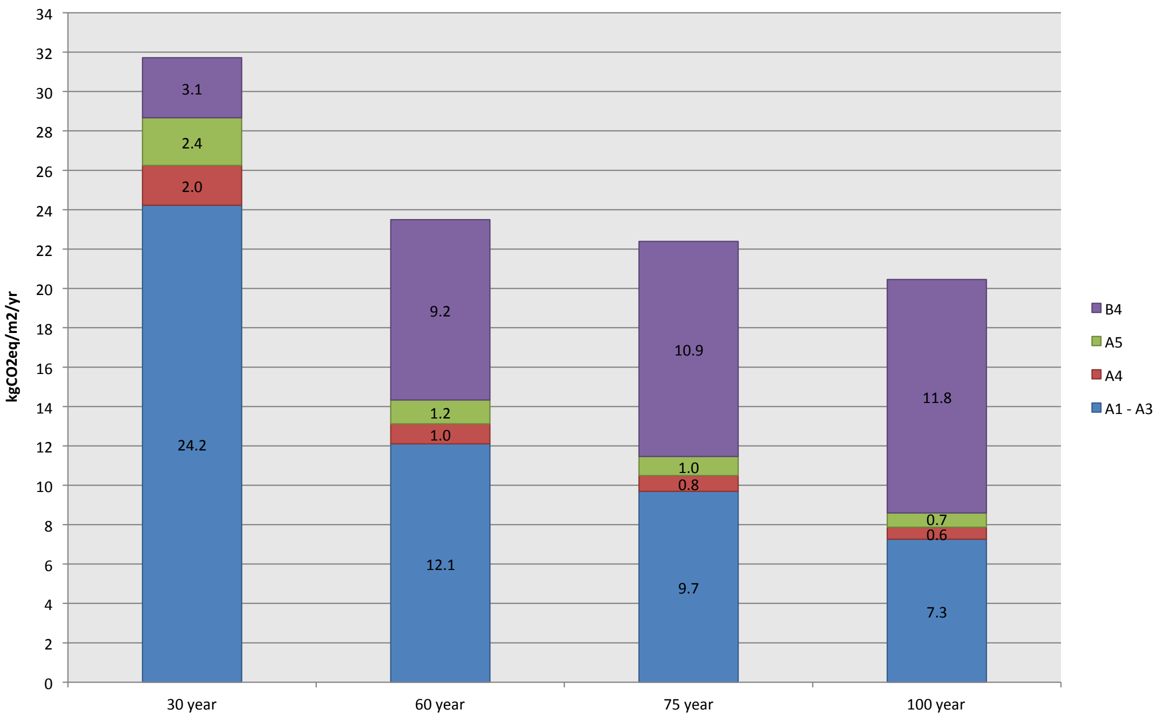


Figure 4.4 Sensitivity analysis of building lifetime

The embodied emissions are calculated as 31.7 $kgCO_{2eq}/m^2/yr$ for a 30-year building lifetime, 23.5 $kgCO_{2eq}/m^2/yr$ for a 60-year building lifetime, 22.4 $kgCO_{2eq}/m^2/yr$ for a 75-year building lifetime and 20.5 $kgCO_{2eq}/m^2/yr$ for a 100-year building lifetime. It is interesting to note that in the 30-year scenario, the majority of emissions (76.3%) originate from the production phase (A1 - A3). This is double the amount of (A1 - A3) material emissions as in the 60-year scenario (51.5%), as the materials are used for half the amount of time. Similarly, in the 75-year and 100-year scenarios, the production phase emissions account for 43.3% and 35.6% of total emissions respectively. In contrast, the replacement (B4) emissions gain significance the longer the building lifetime, contributing 9.8% in the 30-year scenario, 39.1% in the 60-year scenario, 48.7% in the 75-year scenario and 57.6% in the 100-year scenario. As the lifetime of the building increases, so does the replacement of materials. In terms of transport to site (A4) and construction (A5) emissions, the 30-year scenario contributes 6.3% and 7.6% respectively, the 60-year scenario contributes 4.3% and 5.1% respectively, the 75-year scenario contributes 3.5% and 4.5% respectively and the 100-year scenario contributes 2.9% and 3.4% respectively.

Likewise, Figure 4.5 shows a sensitivity analysis of the results, with regards to the definition of area, showing material emission results for the gross floor area (BTA), heated floor area (BRA), net floor area (NTA) and the built-up area (BYA) for the Living Lab, as defined by NS 3940: 2012. (Norsk Standard, 2012)

The embodied emissions are calculated as 18.2 $kgCO_{2eq}/m^2/yr$ in the BTA scenario, 23.5 $kgCO_{2eq}/m^2/yr$ in the BRA scenario, 24.7 $kgCO_{2eq}/m^2/yr$ in the NTA scenario and 10.9 $kgCO_{2eq}/m^2/yr$ in the BYA scenario. It should be noted that the life cycle phase emissions are proportional across the four definitions of area, despite an almost 2-fold variation in total embodied emission results.

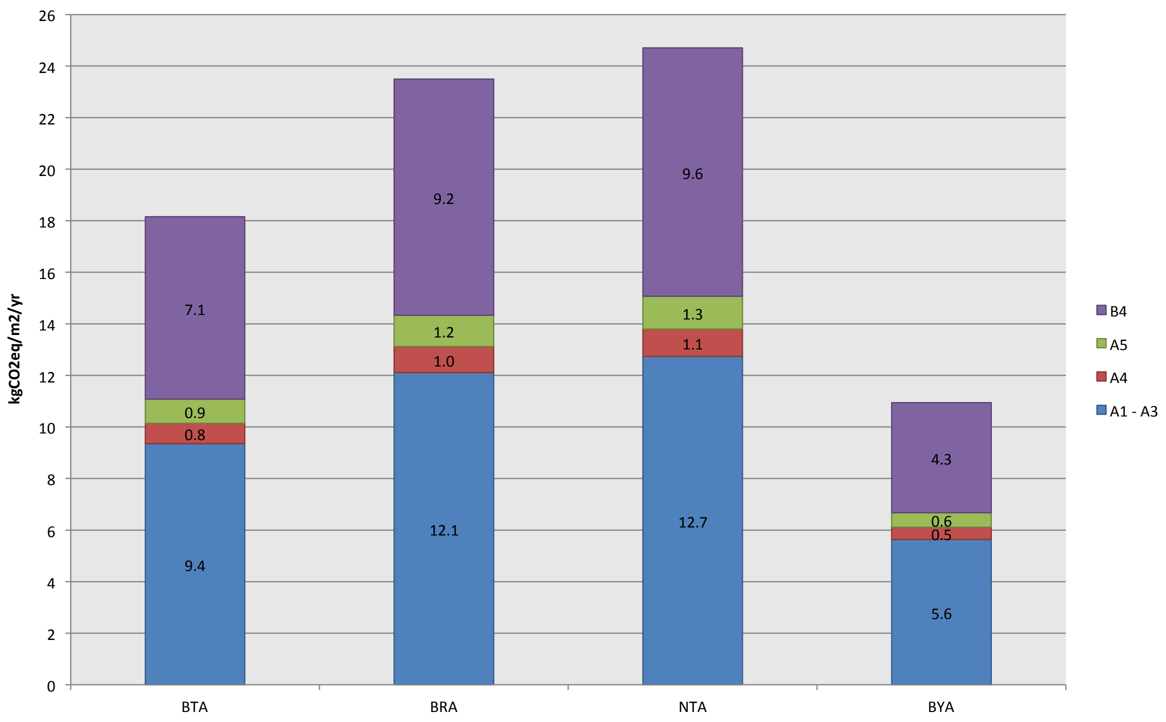


Figure 4.5 Sensitivity analysis of definition of area

4.2 Building Envelope Results

A breakdown of the results for each building component category shall now be presented. The corresponding bar graphs for each building component can be found in Appendix B.

4.2.1 Groundwork and Foundations

The groundwork and foundations are responsible for 5.8% (A1 - A3) and 4.5% (A1 - A3, A4, A5, B4) of total emissions in the building. The A1 - A3 category contributes 66.2% to emissions for this particular building component. Transport emissions to site (A4) contribute almost one third of total emissions (27.1%) for this component. Construction emissions (A5) contribute 6.6% to total emissions for this component.

It was found that concrete is responsible for driving the highest emissions in A1 - A3 (62.4%) for this building component. However there is a 42.3% reduction in the quantity of concrete used between the design and construction phase, which leads to a 20.7% reduction in emissions. It should be noted that the emission factor for concrete is 285 $kgCO_{2eq}/m^3$, and does not consider low carbon concrete. Therefore, replacing normal concrete with a low carbon concrete alternative could, significantly reduce the emissions originating from concrete.

4.2.2 Superstructure

The superstructure is responsible for 4.2% (A1 - A3) and 2.8% (A1 - A3, A4, A5, B4) of total emissions in the building. The A1 - A3 category contributes 78% to emissions for this particular building component. Transport emissions to site (A4) contribute 14.3% to total emissions for this component. Construction emissions (A5) contribute almost 7.8% to total emissions for this component.

Glue laminated timber is responsible for driving the highest emissions in A1 - A3 (92.4%) for this building component. However, it is anticipated that compared to a steel superstructure, the choice of specifying glue laminated timber may result in a 30-50% reduction in emissions. This hypothesis is based on the findings of a previous comparative study between the concrete and steel loadbearing structure used in the ZEB office concept study, and a predominantly wooden alternative loadbearing structure consisting of wood trusses, glue laminated beams and columns which were adapted by Hammersland (2013). The results of the study show that the wooden alternative structure, results in 30% less weight and almost 50% fewer emissions compared to the original concrete and steel ZEB office concept model. Full details of this analysis can be found in Hofmeister et al. (Hofmeister et al., 2015) The wooden alternative in the office concept study is comparable since it has been dimensioned to fulfil the same technical requirements for loadbearing capacity, sound and fire resistance.

4.2.3 Outer Walls

The outer walls are responsible for 15.1% (A1 - A3) and 14.8% (A1 - A3, A4, A5, B4) of total emissions in the building. The A1 - A3 category contributes 52.8% to emissions whilst replacement (B4) contributes 38.4% to total emissions for this particular building component. Transport emissions to site (A4) contribute 3.6% to total emissions for this component. Construction emissions (A5) contribute 5.3% to total emissions for this component.

The outer wall construction comprises of three main parts: the outer wall construction (30.9%), the windows and doors (66.9%) and the VIP (2.2%), responsible for A1 - A3 emissions in this component.

In the outer wall construction for the A1 - A3 system boundary, interestingly it is the wind barrier that drives the highest emissions (12.9%) followed by birch plywood (5.6%), mineral wool insulation (4.7%), cladding with battens and counter batten (3.7%), vapour barrier (2.4%) and ceramic tiles (1.4%).

In the window and door category, for the A1 - A3 system boundary, 21% of emissions come from the aluminium frame windows, and 45.9% from the timber frame window and doors. In the latter category, the majority of emissions originate from the sawn timber (35.2%). In terms of the aluminium frame windows, the aluminium contributes 71.8% of A1 - A3 emissions to the north window, and 44.5% to the south window. Interestingly, 39.6% of A1 - A3 emissions come from the flat glass used in the south window; however glass only contributes 9.7% of A1 - A3 emissions to the north window. This is presumably because the south window has a larger opening area and consists of both inner and outer glazed units.

4.2.4 Inner Walls

The inner walls are responsible for 3% (A1 - A3) and 1.8% (A1 - A3, A4, A5, B4) of total emissions in the building. The A1 - A3 category contributes 87% of emissions for this particular building component. Transport emissions to site (A4) contribute 2.5% to total emissions for this component. Construction emissions (A5) contribute almost 8.7% to total emissions for this component. Replacement emissions (B4) contribute almost 1.8% to total emissions for this component.

Plywood and doors are responsible for driving the highest A1 - A3 emissions (89%) in this component, followed by a 10.3% contribution to emissions from glass wool insulation.

4.2.5 Floor Structure

The floor structure is responsible for 4.6% (A1 - A3) and 3.3% (A1 - A3, A4, A5, B4) of total emissions in the building. The A1 - A3 category contributes 72% of emissions for this particular building component. Transport emissions to site (A4) contribute 7.1% to total emissions for this component. Construction emissions (A5) contribute almost 7.2% to total emissions for this component. Replacement emissions (B4) contribute almost 13.6% to total emissions for this component.

Chipboard (OSB) is responsible for driving the highest A1 - A3 emissions (50.7%) in this component, followed by the glass wool insulation (29%), polyethylene HDPE (13.8%) and timber parquet flooring (4.5%). The contribution of timber parquet flooring is relatively low, which may be due to a number of factors, such as lack of specific (EPD) data. Therefore, a generic timber dataset was used, which does not include other materials or processes used during the manufacture of the flooring. This highlights an area for further work. It should be noted however, that the main driver for replacement emissions derives from this timber parquet flooring, as it accounts for 71.3% of the replacement emissions.

4.2.6 Outer Roof

The outer roof is responsible for 26.1% (A1 - A3) and 23.6% (A1 - A3, A4, A5, B4) of total emissions in the building. The A1 - A3 category contributes 57% and replacement (B4) 34.3% of emissions for this particular building component. Transport emissions to site (A4) contribute 3% to total emissions for this component. Construction emissions (A5) contribute 5.7% to total emissions for this component. These emissions are explained by the breakdown of the outer roof construction. The outer roof construction comprises of four main parts: the outer roof construction (50.8%), Velux windows (33.5%), PV mounting frame (10.7%) and PCM (5%) responsible for A1 - A3 emissions. For the outer roof construction: the aluminium flashing (11.3%) and plywood (10.9%) drive the highest A1 - A3 emissions, followed by the wind barrier (7.8%), glass wool insulation (7.6%) and vapour barrier (6.5%). These high emissions are explained by the use of aluminium in the flashings, PV mounting frame and roof lights.

Interesting the Velux window's blind material and felt insulation accounts for 26.5% of A1 - A3 emissions in this component. Typically, fabrics consume high quantities of water and energy during the production phase which may lead to high emissions. For the PV mounting frame, the aluminium flashing and fixtures account for 6.9% of the emissions followed by polyethylene HDPE with 2.2% emissions. In the PCM, the 2 aluminium sides account for 2.2% of emissions followed by HDPE (1.4%).

4.2.7 Fixed Inventory

The fixed inventory category is responsible for 1.6% (A1 - A3) and 1.8% (A1 - A3, A4, A5, B4) of total emissions in the building. The A1 - A3 category contributes 45.9% and replacement (B4) 47.7% of emissions for this particular building component. Transport emissions to site (A4) contribute 1.9% to total emissions for this component. Construction emissions (A5) contribute almost 5% to total emissions for this component. Plywood is responsible for driving the highest emissions for A1 - A3 (97.3%) in this component, but could be replaced by many other materials e.g. hard wood, plastic, metal, composite materials.

4.2.8 Stairs and Balconies

The stairs and balcony category is responsible for 13.9% (A1 - A3) and 13.1% (A1 - A3, A4, A5, B4) of total emissions in the building. The A1 - A3 category contributes 54.9% and replacement (B4) 32.9% of emissions for this particular building component. Transport emissions to site (A4) contribute 6.7% to total emissions for this component. Construction emissions (A5) contribute almost 5.5% to total emissions for this component. The chromium steel frame for stairs is responsible for driving the highest A1 - A3 emissions at 82% in this component, followed by 17.9% emissions from the Kebony pine steps and decking. The replacement emissions originate from the replacement of Kebony wood used in the pine steps and decking.

4.3 Building Services Results

4.3.1 Sanitary

The sanitary category is responsible for negligible emissions in the A1 - A3 (0.1%) and A1 - A3, A4, A5, B4 (0.1%) total emissions for the building. The A1-A3 category contributes 53.2% and replacement (B4) 38.1% of emissions for this particular building component. Transport emissions to site (A4) contribute 3.4% to total emissions for this component. Construction emissions (A5) contribute 5.3% to total emissions for this component.

The ceramic tiles and mirrors account for driving the highest (A1-A3) emissions in this component with approximately 30% each, followed by the kitchen sink at 24.8%. The sanitary ceramics and kitchen sink have an RSL of 50 years and are replaced 1.2 times during the lifetime of the building. The mirror has an RSL of 40 years and is replaced 1.5 times during the lifetime of the building. The showerheads, drain covers, bathroom and kitchen taps have an RSL of 15 years and are replaced 4 times during the lifetime of the building.

4.3.2 Heating

The heating category is responsible for 2.2% (A1 - A3) and 3.0% (A1 - A3, A4, A5, B4) of total emissions in the building. The A1-A3 category contributes 37.3% and replacement (B4) 56.9% of emissions for this particular building component. Transport emissions to site (A4) contribute 2.1% to total emissions for this component. Construction emissions (A5) contribute 3.7% to total emissions for this component.

The heat pump accounts for driving the highest A1 - A3 (31%) emissions for this component, followed by the solar thermal collectors (26.7%), hot water tank (20%), PEX pipes (12.3%) and heat emission plates (10.1%). The solar thermal collectors have an RSL of 25 years and are replaced 2.4 times, whilst the hot water tank and heat pump have an RSL of 20 years and are replaced 3 times during the lifetime of the building.

4.3.3 Ventilation and Air Conditioning

The ventilation and air-conditioning category is responsible for 0.7% (A1-3) and 0.4% (A1-3, A4, A5, B4) of total emissions in the building. The A1-A3 category contributes 89.8% of emissions for this particular building component. Transport emissions to site (A4) contribute 1.2% to total emissions for this component. Construction emissions (A5) contribute 9% to total emissions for this component.

The steel ventilation ducts are responsible for driving the highest A1 - A3 (43.6%) emissions in this component, followed by the combi-exhaust at 35.8%, the supply grill (10.2%), the air handling unit (5.5%), combi-intake (3%), extractor fan (1.1%) and flexible duct (0.75%). There are no replacement (B4) emissions due to all of the products having a RSL of 60 years.

4.3.4 Lighting

The lighting and electrical category is responsible for 0.01% (A1-3) and 0.01% (A1-3, A4, A5, B4) of total emissions in the building. However, it should be remembered that plug sockets are the only component included in this category, and it is expected that emissions from material use in lighting and electrical could be much higher, and highlights scope for further work. As the product service lifetime is 30 years, they are replaced twice during the lifetime of the building. The A1-A3 category contributes 35.2% and replacement (B4) 48.2% of emissions for this component. Transport emissions to site (A4) contribute 13.1% to total emissions for this component. Construction emissions (A5) contribute 3.5% to total emissions for this component.

4.3.5 Appliances

The other building services category is responsible for 3% (A1 - A3) and 8.2% (A1 - A3, A4, A5, B4) of total emissions in the building. The A1 - A3 category contributes 19.1% and replacement (B4) 78.5% of emissions for this particular building component. Transport emissions to site (A4) contribute 0.5% to total emissions for this component. Construction emissions (A5) contribute 1.9% to total emissions for this component.

The washing machine accounts for driving the highest A1 - A3 emissions at 32.5%, followed by the dishwasher (20.2%), oven (18.8%), fridge freezer (14.7%), tumble dryer (9.7%) and hob (4.2%). The replacement emissions originate from the replacement of white goods, which have a product service lifetime of between 10 - 15 years, and therefore have to be replaced 4 to 6 times during the lifetime of the building.

4.4 Energy Supply System Results

4.4.1 Photovoltaic Panels

The other electric power category is responsible for 19.6% (A1-3) and 22.7% (A1-3, A4, A5, B4) of total emissions in the building. The A1-A3 category contributes 44.6% and replacement (B4) 50.2% to emissions for this component. Transport emissions to site (A4) contribute 0.66% to total emissions for this component. Construction emissions (A5) contribute 4.5% to total emissions for this component.

The PV balance of systems (BOS) accounts for 67.7% of the replacement (B4) emissions, of which the inverters account for 91% of these emissions. The PV replacement (B4) emissions account for 32.3%. The product service lifetime for PV is 30 years, so they are replaced twice during the lifetime of the building. However, it has been assumed that the panels will be produced 50% better in 30 years' time, with half the amount of material emissions per m^2. In contrast, the inverters have a 15-year service lifetime, and are replaced four times during the lifetime of the building.

In contrast, Figure 4.6 presents a material emission balance of the embodied material emissions and on-site energy production from the PV system. The bar graph shows that production emissions (A1 - A3), transport to site emissions (A4) and construction emissions (A5) are covered by the on-site PV energy production, however it also shows that the on-site PV energy production falls short of covering all of the emissions originating from the replacement phase (B4). In this case, the ZEB emission factor for electricity (0.136 $kgCO_{2eq}$/kWh) has been assumed, given a PV cumulative energy yield of approximately 8996 kWh/m^2/yr over a 60-year lifetime per m^2 of module. (Graabak and Feilberg, 2011) (Kristjansdottir et al., Submitted) Essentially, on-site PV energy production counterbalances 94,054 $kgCO_{2eq}$ out of 143,788 $kgCO_{2eq}$ emissions, which equates to 65% of total embodied material emissions (A1 - A3, A4, A5, B4).

In order to compensate for all emissions relating to material use, a total of 121m^2 PV is required, meaning that an additional 42m^2 of PV would need to be installed on-site (this does not account for the additional material emissions from the installation of additional photovoltaic modules and supporting services). It should be noted that this emission balance considers material use only, and does not take into account operational energy use (B6). In addition, a small amount of embodied emissions may also be counterbalanced by the thermal energy production of the solar thermal collectors and heat pump, however this has not been included in the calculations.

Moreover, the choice of electricity mix greatly affects the performance of the PV system in an emission balance. If a European electricity mix had been used instead of the ZEB emission factor, (which is typically much higher and has a higher proportion of fossil fuels in the mix) then the efficiency of on-site energy production from PV would have been much greater in terms of counterbalancing embodied material emissions. However, if the Norwegian electricity mix, (based almost solely on hydropower) had been used, then the efficiency of on-site energy production from PV would not have been so effective in counterbalancing embodied material emissions.

This emission balance highlights that further measures are required to reduce the amount of emissions relating to material use, and to improve the efficiency of energy production from photovoltaic panels or other renewable sources on-site.

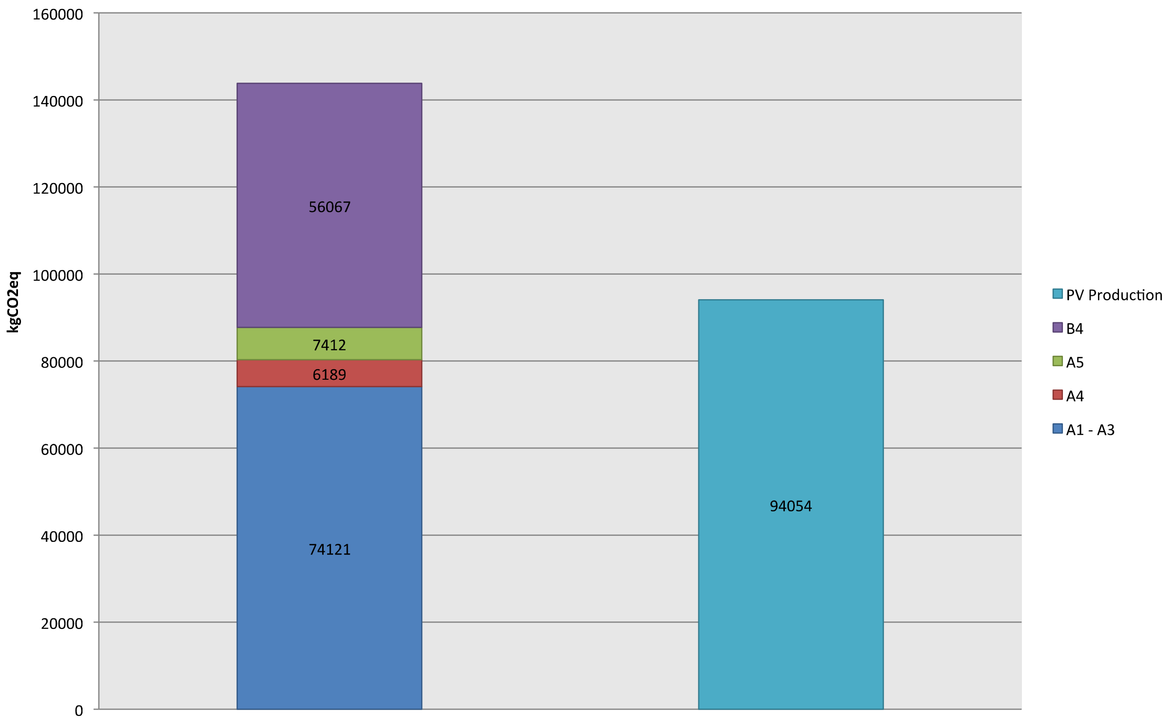


Figure 4.6 Material Emission Balance for the Living Laboratory

5. Discussion and Further Research

The results for the Living Laboratory show that the carbon dioxide emissions are calculated as 1410 $kgCO_{2eq}/m^2$ over a 60-year lifetime, and approximately 23.5 $kgCO_{2eq}/m^2$ per year. It was found that the majority of emissions come from the production phase (A1 - A3) at 51.5%, and from replacement (B4) at 39.1%. Transport to site (A4) emissions account for 4.3% and construction (A5) emissions account for 5.1%.

The results of a sensitivity analysis of the single-family house concept study embodied emission calculations, shows a 20% reduction from 7.2 to 5.8 $kgCO_{2eq}/m^2/yr$ in embodied emissions when product specific data from Norwegian environmental product declarations (EPDs), where available, is used in place of generic data from EcoInvent for those materials driving the highest emissions. Wood was also selected in this sensitivity analysis, to study the benefits of using locally sourced materials using Norwegian EPD data. The results show that this 20% reduction is largely due to the Norwegian EPDs using a much lower emission factor for the Nordel electricity mix, however other factors such as material efficiency, process techniques used, heat energy and other factors can also play a crucial role. (Houlihan Wiberg et al., 2015)

The key components, which drove the highest emissions, were found to be in the building envelope, namely the outer roof category (23.6%), the outer wall (14.8%), the stairs and balconies (13.1%), the groundwork and foundations (4.5%) and the floor structure (3.3%). Other key drivers were found to be from the electric power i.e. PV modules (22.7%), and other services i.e. appliances (8.2%). In the outer roof, the majority of the emissions came from the production phase (57%) compared to the replacement phase (34.3%), whereby the complex roof form together with the PV mounting frame and flashings drove higher embodied emissions. Whereas, in the next highest emitting component, other electric power (PV), half of the emissions came from production and half from replacement. This is due to the RSL of PV being 30 years, compared to the 60-year lifetime of the building. The same pattern was found in the outer wall, with just over half of the emissions coming from production, compared to 38.4% of emissions from the replacement phase. It was interesting to note that the VIP, which is typically identified as a high driver of emissions, was found to be responsible for only 2.2% of emissions, which is largely due to the small quantity used sensitively in the design.

A significant finding was found to be based on the choice of a three-strip foundation design, which reduced foundation emissions by almost one third, compared to the pad foundation design found in the ZEB single-family house (SFH) concept study. (Dokka et al., 2013a) In both cases, the results show that concrete was responsible for approximately 60% of these emissions. In the Living Lab, 16m^3 of concrete was used, whilst 32m^3 was used in the SFH. Essentially, this difference in quantity arises from the types of construction techniques implemented; namely, a raft foundation in the SFH compared to a three-strip foundation in the Living Lab, which uses significantly less concrete than the raft foundation, and has subsequently fewer CO_{2eq} emissions. However, as pointed out earlier, there was also a 42.3% reduction in the quantity of concrete used between the design and construction phases in the Living Lab, which has led to a 20.7% reduction in emissions. This was as a result of an omission, during construction of the concrete pier base, which reduced the amount of concrete from 16m^3 to just 9m^3, thus further reducing embodied emissions. In fact, these emissions could be reduced even further if a low carbon concrete alternative had been used.

Another key design driver for reduced emissions includes the superstructure, which accounts for only 4% of the production phase (A1 - A3) emissions, despite its material volume. This is largely due to the choice of a timber load-bearing structure, namely, glue-laminated timber. A sensitivity analysis of the office concept study found that replacing the original steel and concrete structure with a corresponding timber one resulted in a 30% weight reduction and a 50% reduction in embodied emissions. (Hofmeister et al., 2015) It is anticipated that compared to a concrete and steel superstructure, the choice of specifying glue-laminated timber in the Living Lab has resulted in a similar reduction.

It is worth discussing the integration of photovoltaic panels in the roof, given that the outer roof and other electric power components contribute the most to total embodied emissions (46.3%). It is thought that a less elaborate roof form may save on material emissions, simply because less material is used. It is thought that additional material savings could also be made if the PV system was building integrated instead of building adapted. This would mean that the BIPV system has an integral function to the performance of the building; compared to an in-roof BAPV system that requires a double up of materials to ensure that the building is still watertight after the BAPV system has been removed, as well as additional flashings. Further work could include comparing these two types of systems with a non-integrated PV solution that uses a less-complicated flat roof construction (similar to that used in the SFH concept study). In addition, it was noted that the two-sloped roof design of the Living Lab is subject to shading on the lower string of PVs on the northern most slope. It would be interesting to see how much extra energy could be produced on-site if a one-sloped roof design with no overshadowing was implemented instead.

The stairs and balconies component accounts for 13.9% of total production (A1 - A3) emissions and 13.1% of total emissions (A1 - A3, A4, A5, B4). Of this 13.9%, over half of the emissions originate from the production phase, and 32.9% from the replacement phase. This is because over 80% of the production phase emissions come from the stainless steel frame used, whilst most of the replacement emissions come from the short RSL of Kebony pine (20 years), which therefore needs to be replaced three times during the lifetime of the building.

In general, it was found that components which include a high proportion of materials with long service lifetimes, for example an RSL of 60 years, will have the majority of emissions produced during the production phase (A1 - A3), whereas components using materials with a short service lifetime, of 15 or 20 years, will typically have a higher proportion of emissions originating from the replacement phase (B4). In general, it was found that, for the components used in the building envelope, the transport phase (A4) emissions accounted for, 6.2% of total emissions (although this ranged from 0.5 - 27.1% depending on the location of the factory producing the material) and that the construction phase (A5) typically experienced 5.7% of total emissions.

The results also show that the other services component, which includes appliances and white goods (dishwasher, fridge freezer, washing machine, tumble dryer, hob and oven) accounts for 3% of total production phase emissions (A1 - A3) and 8.2% of total (A1 - A3, A4, A5, B4) emissions. Almost 80% of the emissions for this category come from the replacement phase (B4), due to the short RSL of most of the white goods, ranging from 10 to 15 years, which means they are replaced 4.5 to 6 times during the lifetime of the building. Almost 20% of the emissions come from the production phase (A1 - A3).

The lighting and electrical component contributes negligible emissions (0.01%) to the production phase (A1 - A3) and total emission phase (A1 - A3, A4, A5, B4), as it only represents 23 electrical plug sockets. It can therefore be expected that emissions from this component category are in fact higher and have greater significance, since other electrical components such as cabling and light fittings are missing from the light and electrical material inventory. It also presents scope for further work, once a more detailed material inventory is made available for the lighting and electrical components.

In contrast, the other electric power component, which includes the photovoltaic panels and balance of systems, is responsible for 19.6% of production phase (A1 - A3) emissions and 22.7% of total emissions (A1 - A3, A4, A5, B4) in the building. The A1 - A3 life cycle phase contributes 44.6% to emissions and the replacement phase (B4) is responsible for 50.3% of emissions for this particular component. The PV panels are responsible for 70% of emissions whilst the BOS is responsible for 30% of emissions during the production phase (A1 - A3).

A recent study has shown that the choice of insulation can have significant impacts on emissions. (Schlanbusch et al., 2014) The study showed that mineral wool insulation has relatively low embodied emissions compared to XPS, EPS and VIP. Interestingly, mineral wool insulation has been used extensively throughout the Living Laboratory, contributing just 2.7% to total embodied emissions. Mineral wool insulation has therefore been identified as a key design driver for low embodied emissions.

However, it should be noted that although VIP is associated with high-embodied emissions, a small quantity has been used in the Living Laboratory, in a sensitive way, to improve the thermal performance of the east and west facing windows, contributing 0.4% to total embodied emissions. Similarly, PCM has been used in the outer roof to improve the thermal envelope, contributing 0.7% to total embodied emissions. This demonstrates that state-of-the-art materials with higher embodied emissions can be used sensitively without contributing significantly to embodied material emissions.

The results showed that metals were the third highest contributor to embodied emissions. However, it should be noted that conservative emission factors were used, that only considered primary metal use. This demonstrates the importance of including the whole life cycle (WLC) of materials, as it is very likely that these metals have come from recycled sources and will be recycled at the end of their lives, meaning that a lower, secondary emission factor could be used that accounts for the recycled proportion of metal. For example, in these calculations a primary aluminium dataset was used that has an emission factor of 8.55 $kgCO_{2eq}$/kg of aluminium. If a secondary aluminium dataset were used, then the emission factor would have been reduced to 1.38 $kgCO_{2eq}$/kg. In contrast virgin aluminium has an emission factor of 12.23 $kgCO_{2eq}$/kg. (EcoInvent Centre, 2010)

The emission balance demonstrates that the on-site PV energy production falls short of covering all embodied emissions. The on-site PV energy production counterbalances 94,054 $kgCO_{2eq}$ of 143,788 $kgCO_{2eq}$ emissions, which equates to 65% of total embodied material emissions (A1 - A3, A4, A5, B4). In order to compensate for all emissions relating to material use, a total of 121m^2 PV is required, meaning that an additional 42m^2 of PV would need to be installed on-site. Moreover, the choice of electricity mix greatly affects the performance of the PV system in an emission balance. If a European electricity mix had been used instead of the ZEB emission factor, (which is typically much higher and has a higher proportion of fossil fuels in the mix) then the efficiency of on-site energy production from PV would have been much greater in terms of counterbalancing embodied material emissions. However, if the Norwegian electricity mix, (based almost solely on hydropower) had been used, then the efficiency of on-site energy production from PV would not have been so effective in counterbalancing embodied material emissions. This emission balance highlights that within a Norwegian context further measures are required to reduce the amount of emissions relating to material use, and to improve the efficiency of energy production from PV or other renewable sources on-site.

The functional unit sensitivity analysis demonstrates that the emission results are sensitive to the definition of building lifetime and building area. In order for the results of this report to be comparable with other ZEB pilot projects, a functional unit of 'emissions per square metre of heated floor area (BRA) per year of operational building lifetime' was used, with a BRA of 102m^2 and a building lifetime of 60 years. However, the sensitivity analysis raises the question of whether or not a 60-year lifetime is appropriate for the Living Laboratory, since the building is temporary, and will be dismantled at it's end-of-life (EOL). In these circumstances, there should be more of a focus on the demountability and recyclability of the building, rather than the durability of materials. As an area for further research, it is suggested that the EOL life cycle phases of the Living Lab are considered in more detail, in order to cap emissions arising from demolition.

This body of work also demonstrates that, at the component category level, the results are sensitive to the component classification of materials and that even though total embodied emissions for the building will be the same, this can greatly affect embodied emission results at the component category level. For example, the Living Lab's floor superstructure was placed under the superstructure component category as it contains load-bearing trusses, the floor make-up was placed under the floor structure component category as a raised timber floor construction was used, and the under floor heating was placed under the heating component category. In contrast, the entire single-family house concept study's floor was placed under the groundwork and foundations component category, because a raft foundation was placed directly on the ground. As a result, it is difficult to directly compare emissions arising from these two floor constructions. Likewise, it is also questionable; whether or not, STC or PV systems should be placed under the outer wall or outer roof component categories if they are building integrated, or whether the STC system should be placed under the heating category, and the PV system under the other electrical category. It is recommended that more could be done to resolve the organisation of materials at the building component level.

Further work recommended by Houlihan Wiberg et al. (2015) recommended the calculation of embodied emissions using Norwegian EPD data for other construction materials should be incorporated where available, and that the system boundary should be extended to include end of life emissions. In line with this work, it is recommended that the embodied emission calculations for the Living Lab are simulated again, using Norwegian EPDs wherever possible, so that the results are valid for a Norwegian context, reflecting the impact of using a much lower emission factor for the Nordel electricity mix.

In summary, these results provide useful approximations for embodied material emissions, for use by designers during the early design phase, when a detailed material inventory may not necessarily be available. It also highlights methodological and design considerations when carrying out a life cycle assessment of a building. Furthermore, the Living Laboratory provides alternative solutions for low embodied emission design.

6. Conclusion

This report has documented the design and construction of the ZEB Living Laboratory in terms of its embodied material emissions. Essentially, the results for the Living Laboratory show that carbon dioxide emissions are calculated as 1410 $kgCO_{2eq}/m^2$ over a 60-year lifetime, and approximately 23.5 $kgCO_{2eq}/m^2/yr$. It was found that just over half of these emissions originate from the production phase (A1 - A3) and almost 40% from the replacement phase (B4). The remaining 10% of emissions come from the transport to site (A4) phase (4%) and the construction (A5) phase (5%).

Compared to previous ZEB projects, the results show relatively high emissions, with total emissions of 23.5$kgCO_{2eq}/m^2/yr$, whereby 12.1$kgCO_{2eq}/m^2/yr$ originate from the production phase (A1 – A3). There are multiple reasons for this. Firstly, a more comprehensive material inventory was available for the Living Laboratory at an 'as built' stage. The system boundary includes more life cycle stages (A1 – A3, A4, A5 and B4). Furthermore, the building is not a typical residential building but a test laboratory.

The functional unit sensitivity analysis raises the question of whether or not a 60-year lifetime is appropriate for the Living Laboratory, since the building is temporary, and will be dismantled at its end-of-life (EOL). In these circumstances, there should be more of a focus on the demountability and recyclability of the building, rather than the durability of materials. Moreover, since this is a ZEB demonstration building, it has higher emissions than a normal building of this size, because of the high level of technical equipment and state-of-the-art materials used. However, measures were taken to reduce the double up of emission accounting.

The results are sensitive to the component classification of materials, in order to directly compare emissions between different construction types. Even though total embodied emissions may be the same for two projects, the choice of component classification, of specific materials, may greatly affect the distribution of embodied emission results at the component level.

Further work should include a sensitivity analysis of replacing the generic data with product specific EPD data, in line with the findings of Houlihan Wiberg et al. (2015), which demonstrates a 20% reduction in total embodied emissions from materials when specific Norwegian data is used, where available, in place of generic data from EcoInvent.

As a result of an omission between the design and construction phases of the foundations, there was over a 40% reduction in the quantity of concrete used, which has led to a 20% reduction in emissions. This could be reduced further if a low carbon concrete alternative was used.

Schlanbusch et al. (2014) found that the choice of insulation can have a significant impact on emissions, with mineral wool insulation having relatively low embodied emissions compared to XPS, EPS and VIP. Interestingly, even though mineral wool insulation has been used extensively throughout the Living Laboratory, it contributes just 2.7% to total embodied emissions. Mineral wool insulation has therefore been identified as a key design driver for low embodied emissions. The results show that state-of-the-art materials, such as VIP and PCM, may also be used sensitively and effectively without contributing significantly to embodied material emissions.

Given that the outer roof, PV modules and mounting frame contribute almost half to total embodied emissions, further work could investigate building integrated, instead of building adapted photovoltaic panels on the roof or a less elaborate roof form, which may save on material emissions, simply because less material is used. Further work could include comparing these two types of systems with a non-integrated PV solution that uses a less-complicated flat roof construction (similar to that used on the SFH concept study). In addition, it would be interesting to see how much extra energy could be produced on-site if a one-sloped roof design, with no overshadowing, was implemented instead. The findings demonstrate that an additional 42m^2 of PV would need to be installed on site, in order to compensate for all emissions from material use, when the ZEB emission factor for electricity is used. Moreover, the choice of electricity mix greatly affects the performance of the PV system in a ZEB emission balance.

In general, it was found that components which include a high proportion of materials with long service lifetimes, for example a RSL of 60 years, will have the majority of emissions produced during the production phase, whereas components using materials with short service lifetimes, of 15 or 20 years, will typically have a higher proportion of emissions originating from the replacement phase.

The results also show that appliances and white goods account for approximately 8% of total emissions, whereas almost 80% of these emissions come from the replacement phase, due to the short RSL of the white goods, which means they are replaced 4.5 to 6 times during the lifetime of the building. Almost 20% of these emissions come from the production phase.

Once a more detailed material inventory is made available for lighting and electrical components, it is anticipated that this component will be responsible for driving higher emissions. Currently, it contributes negligible emissions since it only represents 23 plug sockets.

The emissions from the photovoltaic panels and balance of systems (BOS), is responsible for just over one fifth of the total emissions in the building. The production and replacement phase emissions both contribute half to total emissions within this particular component. The PV panels are responsible for over two thirds of the production phase emissions, whilst the balance of systems are responsible for one third of the emissions.

The material emission balance highlights that further measures are required, to reduce the amount of emissions relating to material use, and to improve the efficiency of energy production from photovoltaic panels or other renewable sources on-site.

In conclusion, it was found that material optimisation should be considered at an early stage in the design process, in order to reduce embodied material emissions. These results provide useful approximations for embodied material emissions, for use by designers during the early design phase, when a detailed material inventory may not necessarily be available. Furthermore, the Living Laboratory provides alternative solutions for low embodied emission design.

7. References

BKS 700.320. 2010. *Intervaller for vedlikehold og utskifting av bygningsdeler: middelverdier* [Online]. Oslo: SINTEF Byggforsk. Available: https://bks.byggforsk.no/DocumentView.aspx?documentId=3312&sectionId=2 [Accessed 03.08.2015].

BKS 700.330. 2003. *Levetider for sanitærinstallasjoner i boliger* [Online]. Oslo: SINTEF Byggforsk. Available: http://bks.byggforsk.no/DocumentView.aspx?sectionId=2&documentId=3112 [Accessed 03.08.2015].

CALOREX 2015. Domestic Heat Pumps: Low Carbon Solutions for Heating and Hot Water. *Calorex Heat Pumps Ltd.* Essex.

DAHLSTRØM, O. 2011. *Life Cycle Assessment of a Single-Family Residence Built to Passive House Standard.* Norwegian University of Science and Technology.

DOKKA, T. H., HOULIHAN WIBERG, A., GEORGES, L., MELLEGÅRD, S., TIME, B., HAASE, M., MALTHA, M. & LIEN, A. G. 2013a. *A Zero Emission Concept Analysis of a Single-Family House,* Oslo, ZEB Project Report (9) SINTEF Academic Press.

DOKKA, T. H., KRISTJANSDOTTIR, T., TIME, B., MELLEGÅRD, S., HAASE, M. & TØNNESEN, J. 2013b. *A Zero Emission Concept Analysis of an Office Building,* Oslo, ZEB Project Report (8) SINTEF Academic Press.

DOKKA, T. H., SARTORI, I., THYHOLT, M., LIEN, K. & LINDBERG, K. B. A Norwegian Zero Emission Building Definition. Passivhus Norden 2013, 2013c Gothenberg, Sweden.

DONES, R., BAUER, C., BOLLIGER, R., BURGER, B., HECK, T., RODER, A., PAUL SCHERRER INSTITUT, VILLIGEN, EMMENEGGER, M. F., FRISCHKNECHT, R., JUNGBLUTH, N., TUCHSCHMID, M., ESU-SERVICES LTD. & USTER 2007. *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries,* Dubendorg, Swiss Centre for Life Cycle Inventories.

ECOINVENT CENTRE 2010. *Ecoinvent Data and Reports v.3,* Dubendorf, Switzerland, Swiss Centre for Life Cycle Inventories.

FARKAS, K., MATURI, L., SCOGNAMIGLIO, A., FRONTINI, F., WALL, M., LUNDGREN, M. & ROECKER, C. 2013. Designing Photovoltaic Systems for Architectural Integration: Criteria and Guidelines for Product and System Developers. *In:* SHC, I. (ed.) *Task 41 Solar Energy and Architecture.*

FINOCCHIARO, L., DOKKA, T. H. & GUSTAVSEN, A. +Hytte. A versatile Construction System for Zero Emission Buildings. Zero Energy Mass Custom Homes, 2012 Glasgow.

FINOCCHIARO, L., GOIA, F., GRYNNING, S. & GUSTAVSEN, A. 2014. The ZEB Living Lab: A Multi-Purpose Experimental Facility. *Ghent Expert Meeting.* Ghent Univeristy.

GEORGES, L., HAASE, M., WIBERG, A. H., KRISTJANSDOTTIR, T. & RISHOLT, B. 2015. Life Cycle Emissions Analysis of Two nZEB Concepts. *Building Research and Information,* 43**,** 82-93.

GHOSE, A. 2012. *Life Cycle Assessment of Active House: Sustainability Concepts by Integrating Energy, Environment and Well-Being.* Norges Teknisk- Naturvitenskapelige Universitet.

GOOGLE. 2015. Google Maps. Available: www.google.no/maps/@63.4164935,10.4104202,172m/data=!3m1!1e3 [Accessed 23.02.2015].

GRAABAK, I. & FEILBERG, N. 2011. CO2 Emissions in Differnet Scenarios for Electricity Generation in Europe. Oslo: SINTEF Energy for the Research Centre on Zero Emission Buildings.

HASTINGS, R. S. & WALL, M. 2013. *Sustainable Solar Housing: Volume 1 - Exemplary Buildings and Technologies*, Taylor & Francis.

HOFMEISTER, T. B., KRISTJANSDOTTIR, T., TIME, B. & WIBERG, A. H. 2015. Life Cycle GHG Emissions from a Wooden Load-Bearing Alternative for a ZEB Office Concept. *ZEB Project Report (20).* SINTEF Akademisk Forlag.

HOULIHAN WIBERG, A., DOKKA, T. H., MELLEGÅRD, S., GEORGES, L., TIME, B., HAASE, M. & LIEN, A. 2013. *A Zero Emission Concept Analysis of a Norwegian Single-Family House: A CO2 Accounting Method,* Trondheim, The ZEB Research Centre.

HOULIHAN WIBERG, A., GEORGES, L., FUFA, S. M. & RISHOLT, B. 2015. A Zero Emission Concept Analysis of a Single-Family House: Part 2 Sensitivity Analysis *ZEB Project Report (21).* SINTEF Akademisk Forlag.

KONIG, H., KOHLER, N., KREISSIG, J. & LUTZENDORF, T. 2010. *A Life Cycle Approach to Buildings: Principle Calculations and Design Tools,* Munich, DETAIL.

KRISTJANSDOTTIR, T., FJELDHEIM, H., SELVIG, E., RISHOLT, B., TIME, B., GEORGES, L., DOKKA, T. H., BOURELLE, J., BOHNE, R. & CERVENKA, Z. 2014. *A Norwegian ZEB-Definition Embodied Emissions,* ZEB Project Report (17), SINTEF Academic Press.

KRISTJANSDOTTIR, T., GOOD, C. S., SCHLANBUSCH, R. D. & INMAN, M. R. Submitted. A GHG Emission Balance for Roof Mounted PV Systems Installed in ZEB Residential Pilot Buildings in Norway.

LECHNER, N. 2009. *Heating, Cooling, Lighting : Sustainable Design Methods for Architects,* Hoboken, N.J., Wiley ; Chichester : John Wiley [distributor].

NORSK STANDARD 2012. NS3940: 2012 Areal- og volumberegninger av bygninger. Calculation of areas and volumes of buildings.: Standard Norge.

NS3451 2009. Norsk Standard NS3451: 2009 - Bygningsdelstabell / Table of Building Elements. Standard Norge.

NS3454 2013. *Livssykluskostnader for byggverk: Prinsipper og klassifikasjon,* Oslo, Norsk Standard.

NS-EN 15978 2011. EN ISO 15978: 2011 Sustainability of Construction Works: Assessment of Environmental Performance of Buildings. Calculation Method. International Standards Organisation.

OLGYAY, V. 1963. *Design with Climate: Bioclimatic Approach to Architectural Regionalism,* New Jersey, Princeton University Press.

OPTIMERA 2014. Tegnings- og monteringsveileder: Konstruksjonspakke. Optimera Byggsystemer.

PRÉ 2007. *IPCC 2007 method GWP 100a V.1.02,* Netherlands, PRé.

PRÉ 2015. *SimaPro Analyst LCA Software v. 8.0.5,* Netherlands, PRe.

REC 2013. REC Peak Energy Series. REC Group.

RENUSOL 2010. *Renusol Solar Mounting Systems: Intersole SE in-Roof System,* Germany, Intersole SE.

SCHLANBUSCH, R. D., FUFA, S. M., SØRNES, K. & KRISTJANSDOTTIR, T. 2014. Energi- og klimagassanalyse av isolasjonsmaterialer. Elsevier.

SEARATES. 2015. *Routes Explorer* [Online]. SeaRates. Available: http://www.searates.com/services/routes-explorer/ [Accessed 23.06.2015].

SERRA, R. & COCH, H. 2001. *Arquitectura y energia natural*.

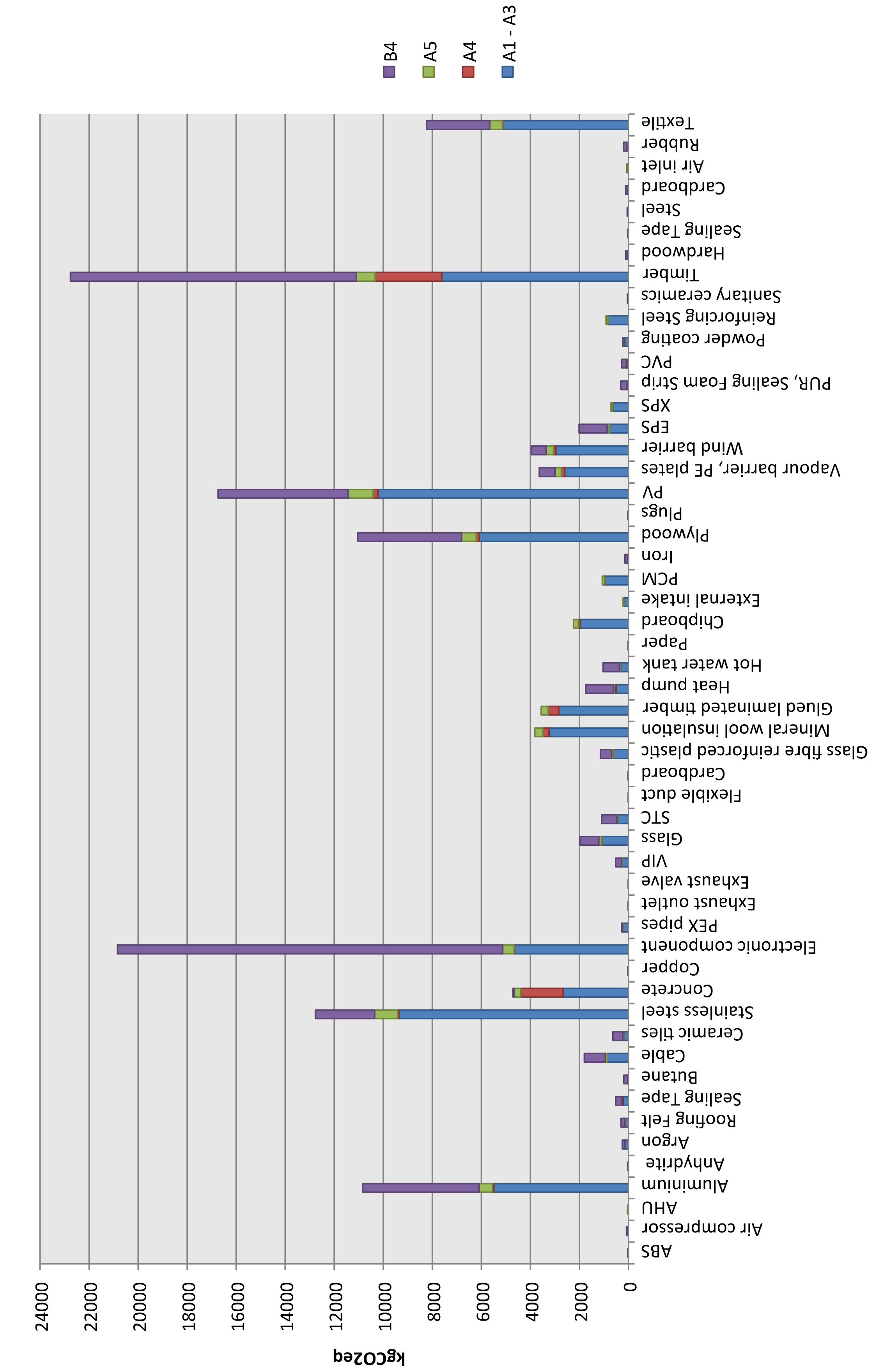
SOLBES 2013. ZEB Living Lab: Takintegrert PV-system. Tilbud for leveranse og installasjon. Narvik.

SSB. 2013. *Boliger, etter bygningstype og år* [Online]. Statistisk Sentralbyrå. Available: www.ssb.no/bygg-bolig-og-eiendom/statistikker/boligstat/aar/2013-07-12#content [Accessed 19.02.2014].

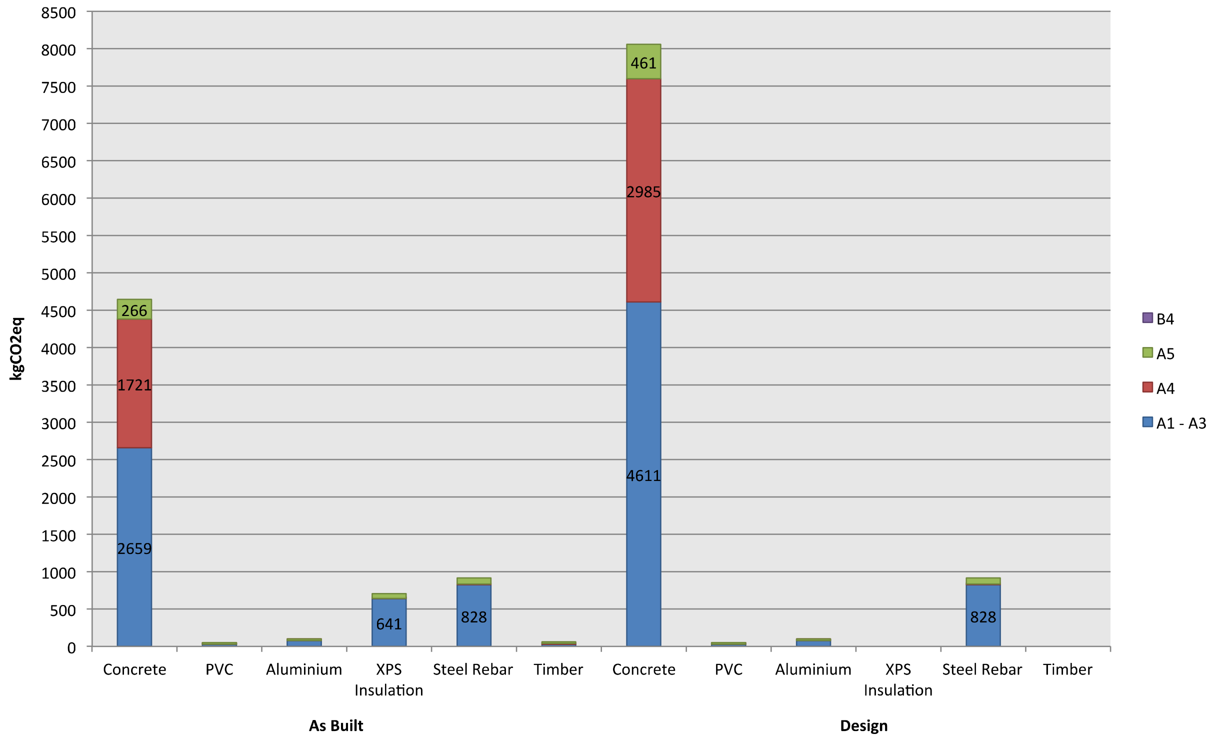
SUPSI. 2013. *Building Integrated Photovoltaic Systems* [Online]. Switzerland: SUPSI/ISAAC. Available: http://www.bipv.ch/index.php/en/about-en-top [Accessed 10.08.2015].

APPENDICES

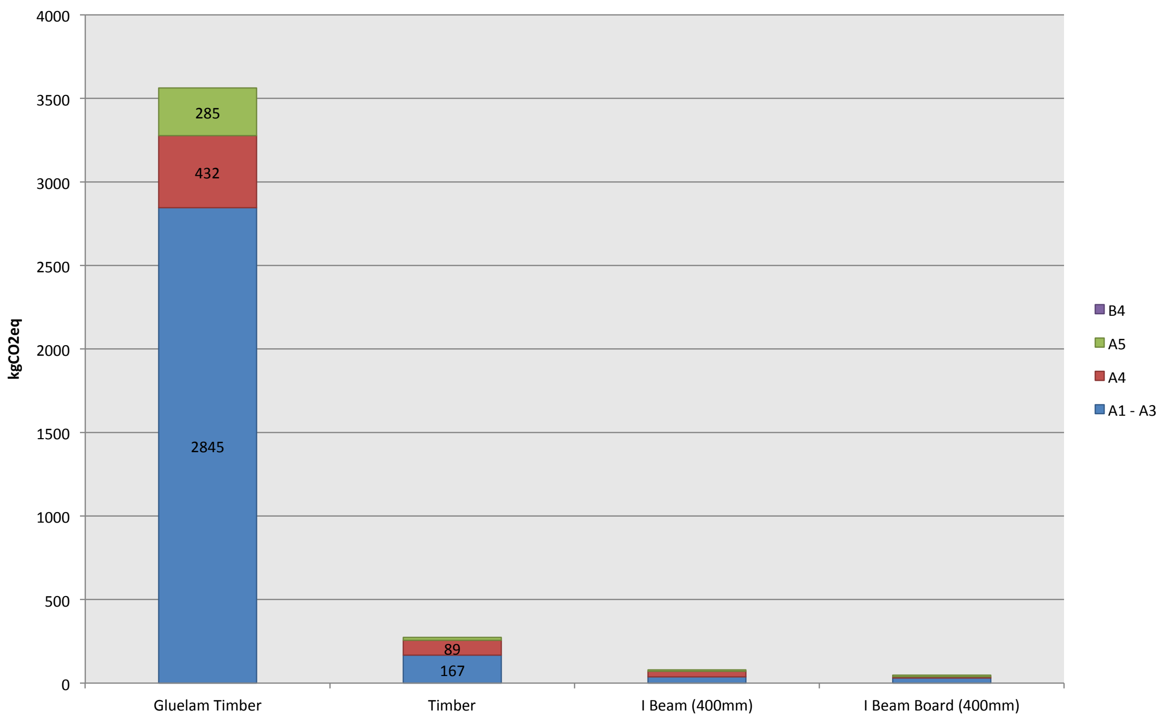
Appendix A: Embodied emission results by material for the Living Laboratory.



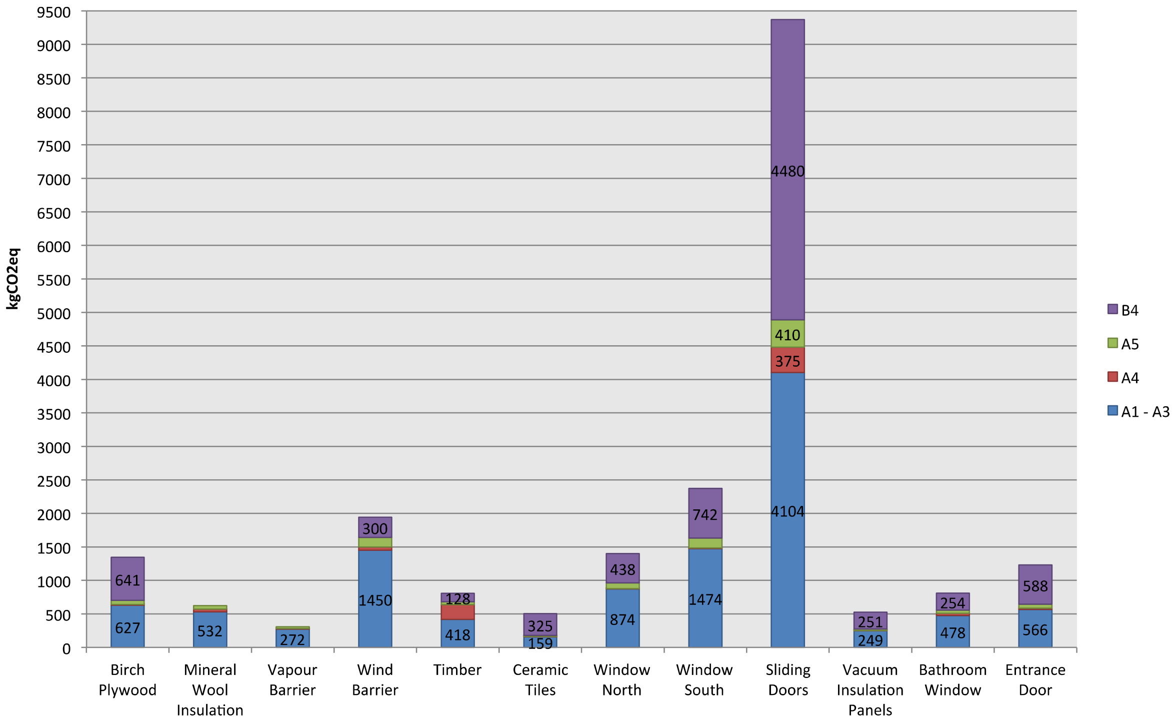
Appendix B.1: Embodied emission results for the groundwork and foundations in the Living Laboratory.



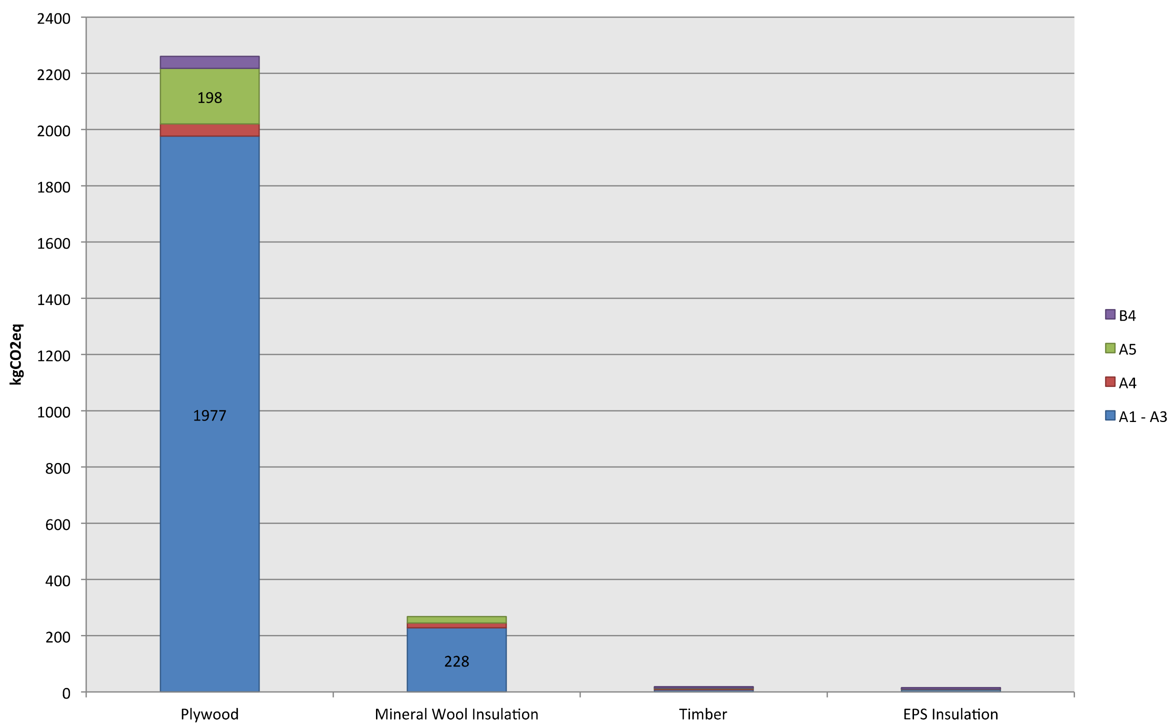
Appendix B.2: Embodied emission results for the superstructure in the Living Laboratory.



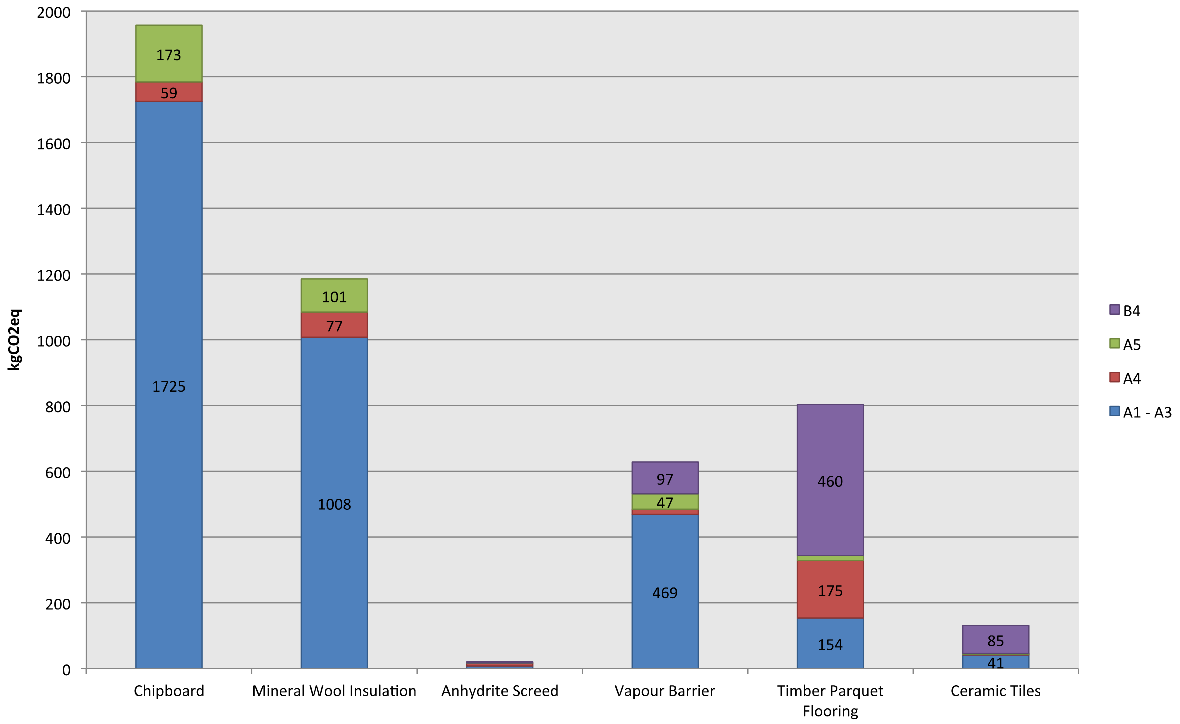
Appendix B.3: Embodied emission results for the outer walls in the Living Laboratory.



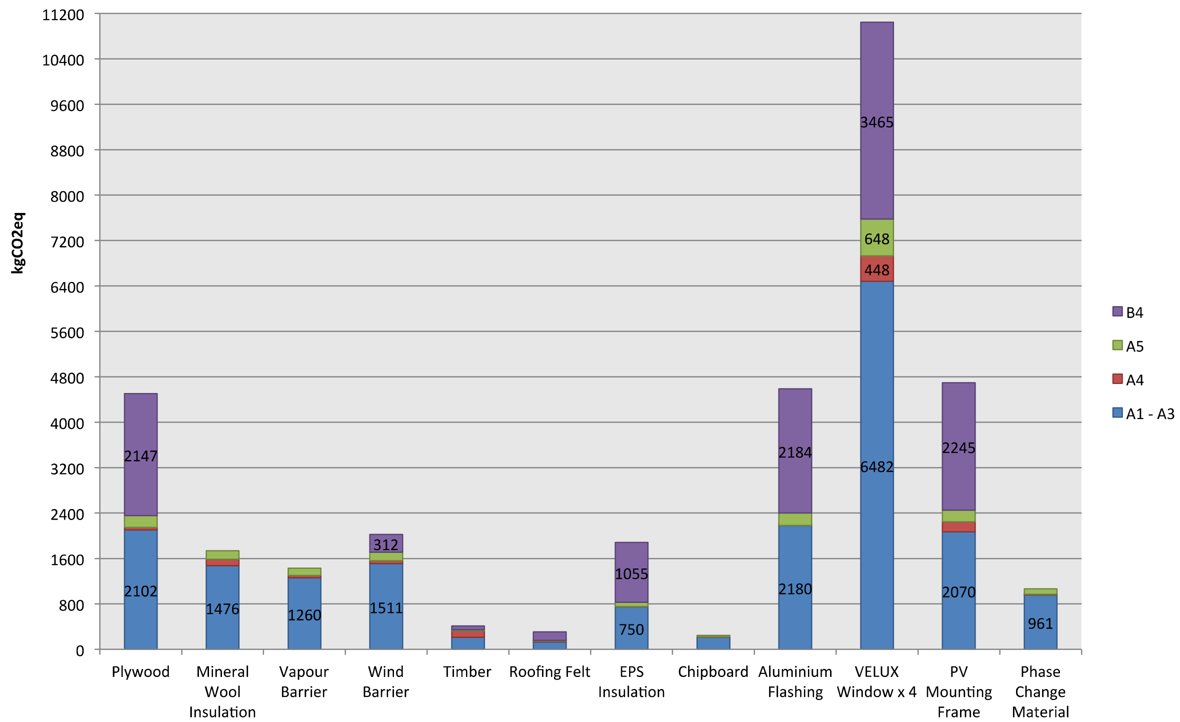
Appendix B.4: Embodied emission results for the inner walls in the Living Laboratory.



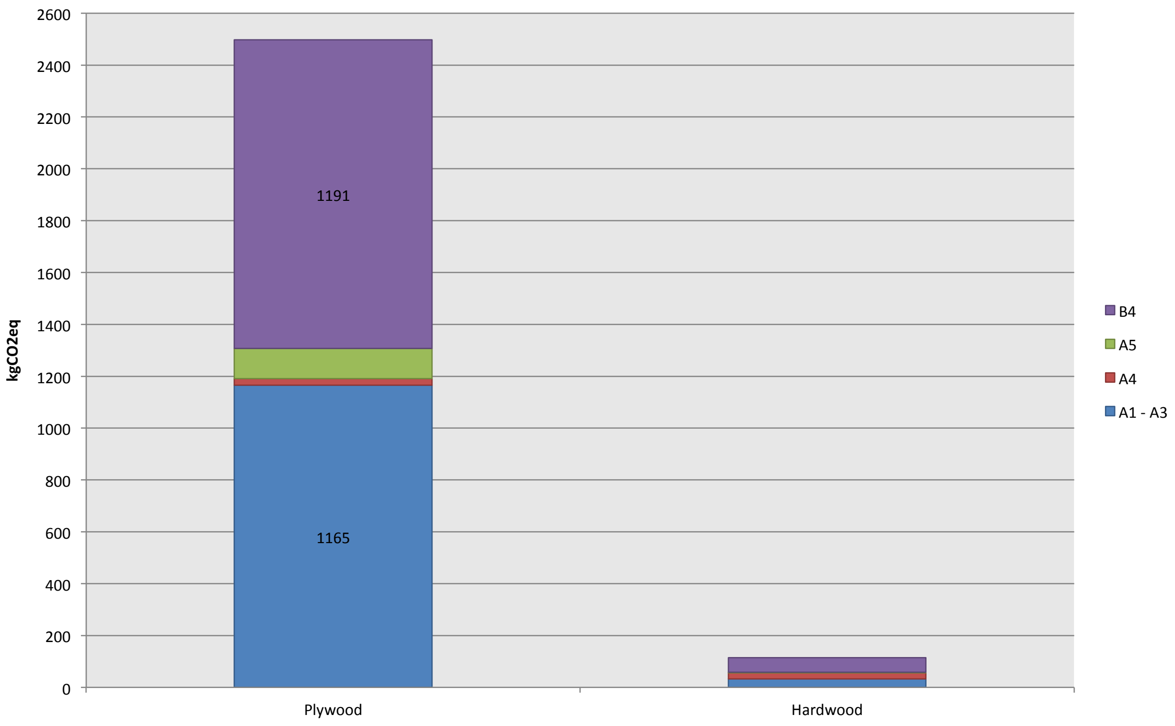
Appendix B.5: Embodied emission results for the floor structure in the Living Laboratory.



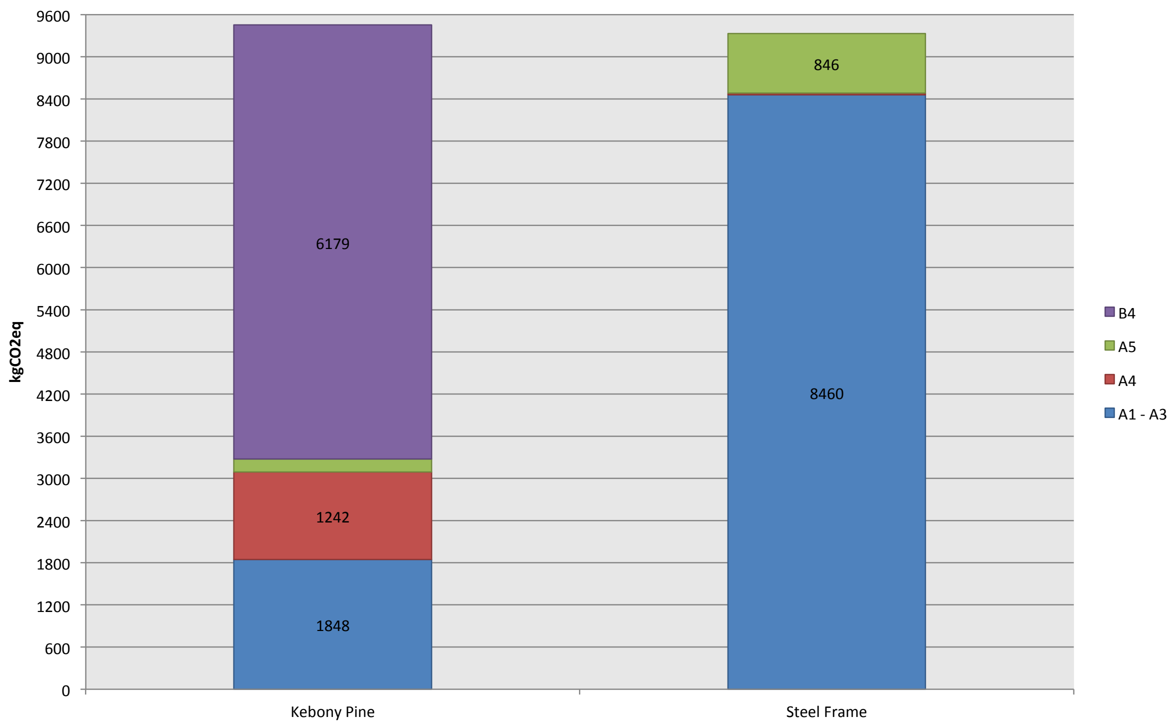
Appendix B.6: Embodied emission results for the outer roof in the Living Laboratory.



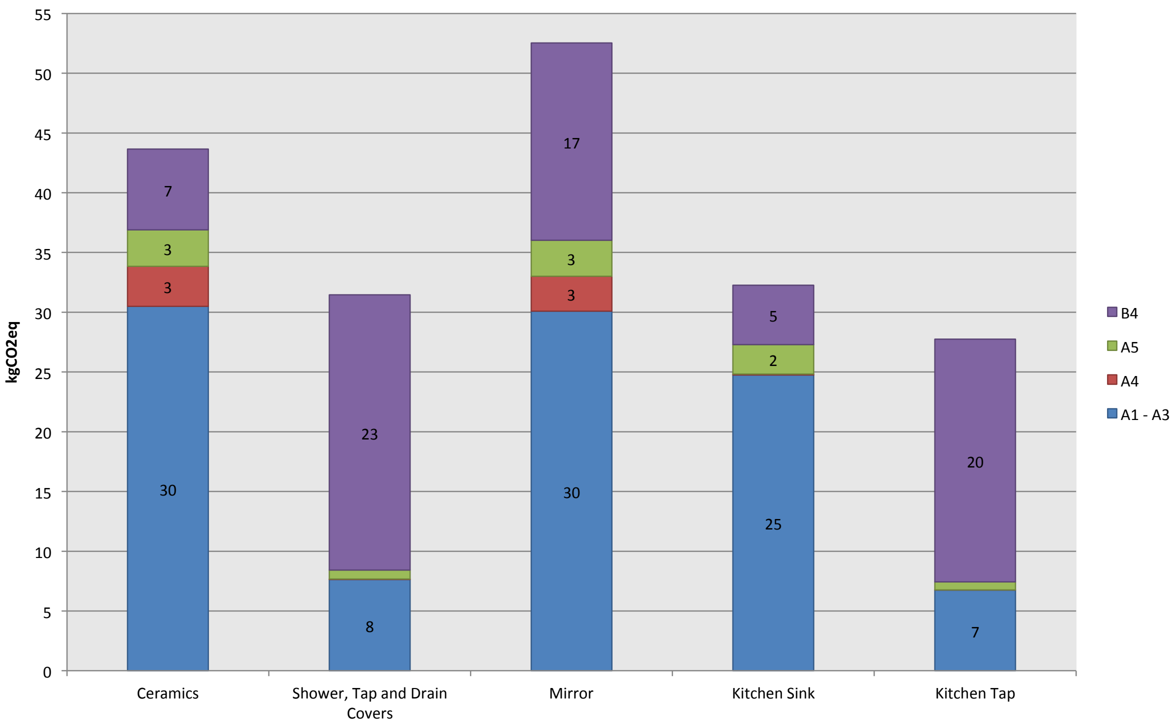
Appendix B.7: Embodied emission results for the fixed inventory in the Living Laboratory.



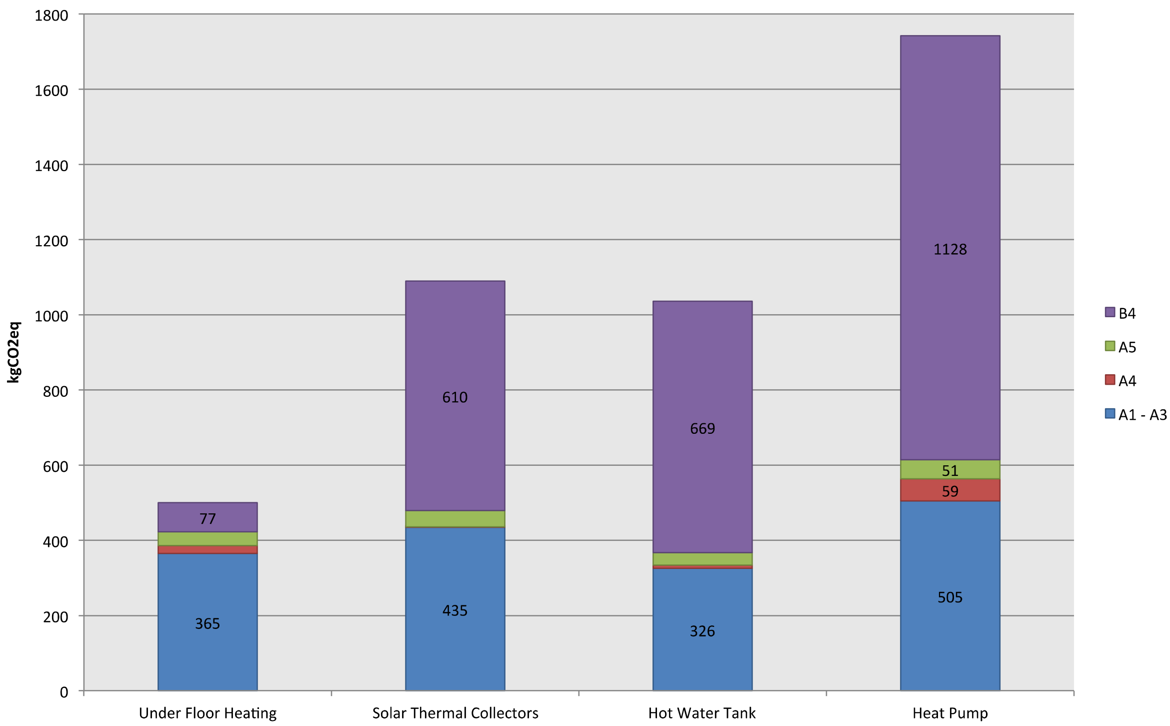
Appendix B.8: Embodied emission results for the stairs and balconies in the Living Laboratory.



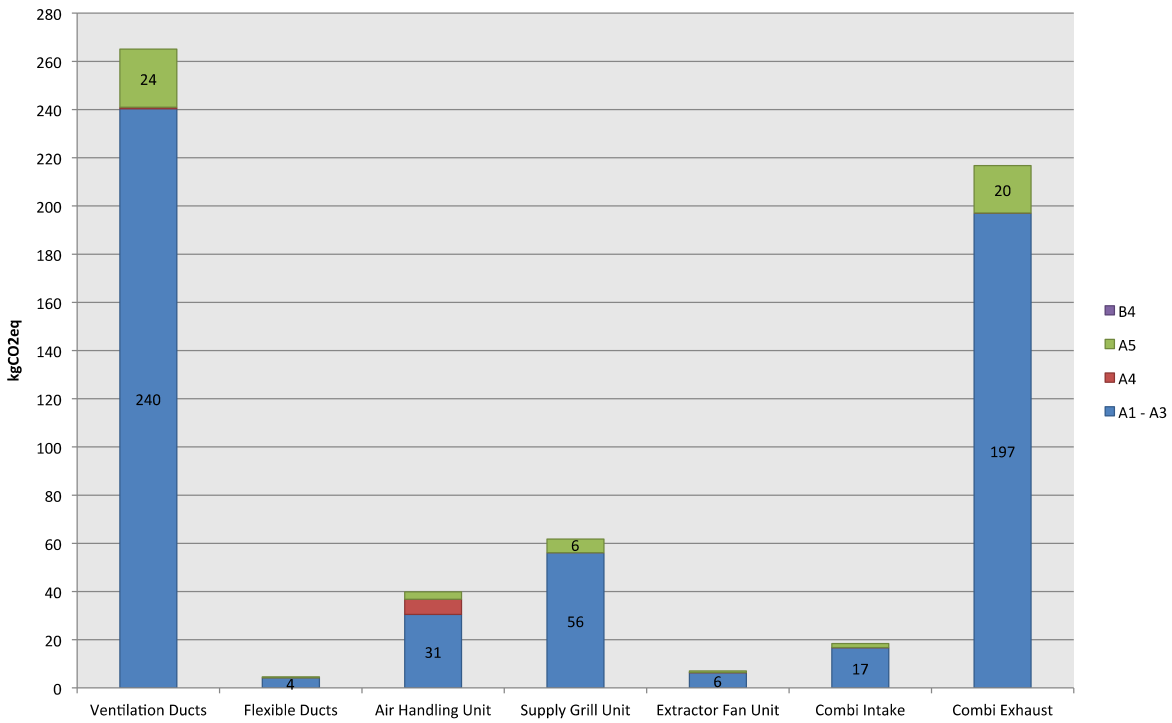
Appendix B.9: Embodied emission results for the sanitary installations in the Living Laboratory.



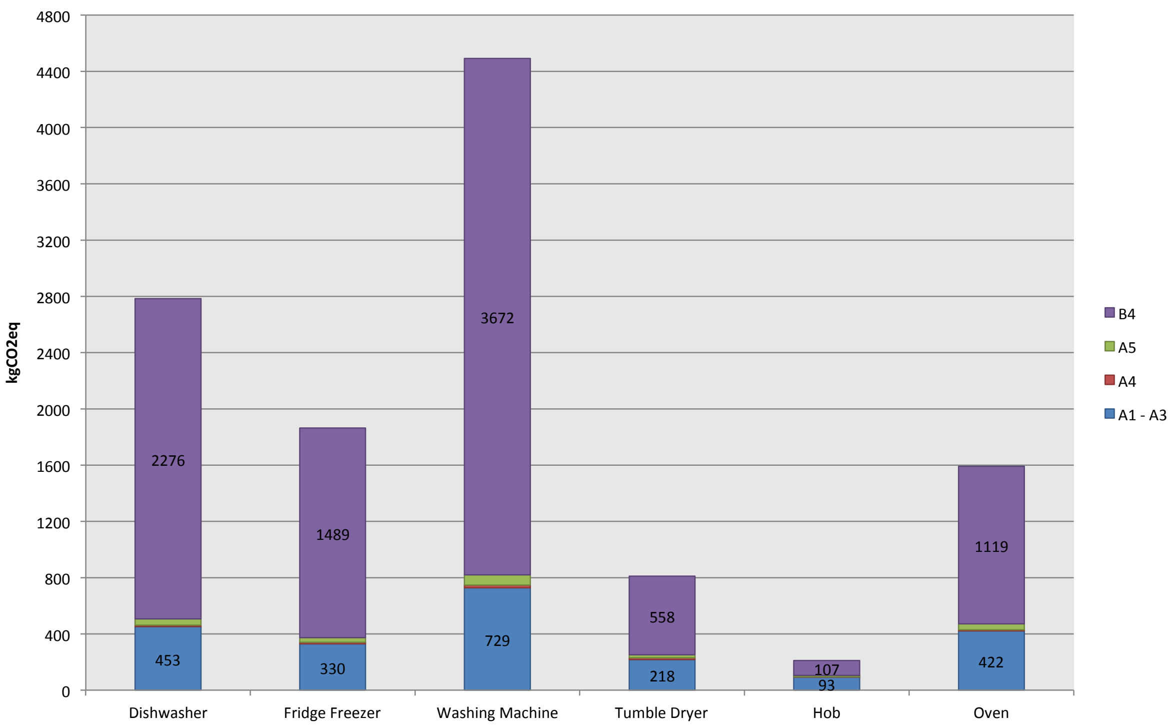
Appendix B.10: Embodied emission results for the heating installations in the Living Laboratory.



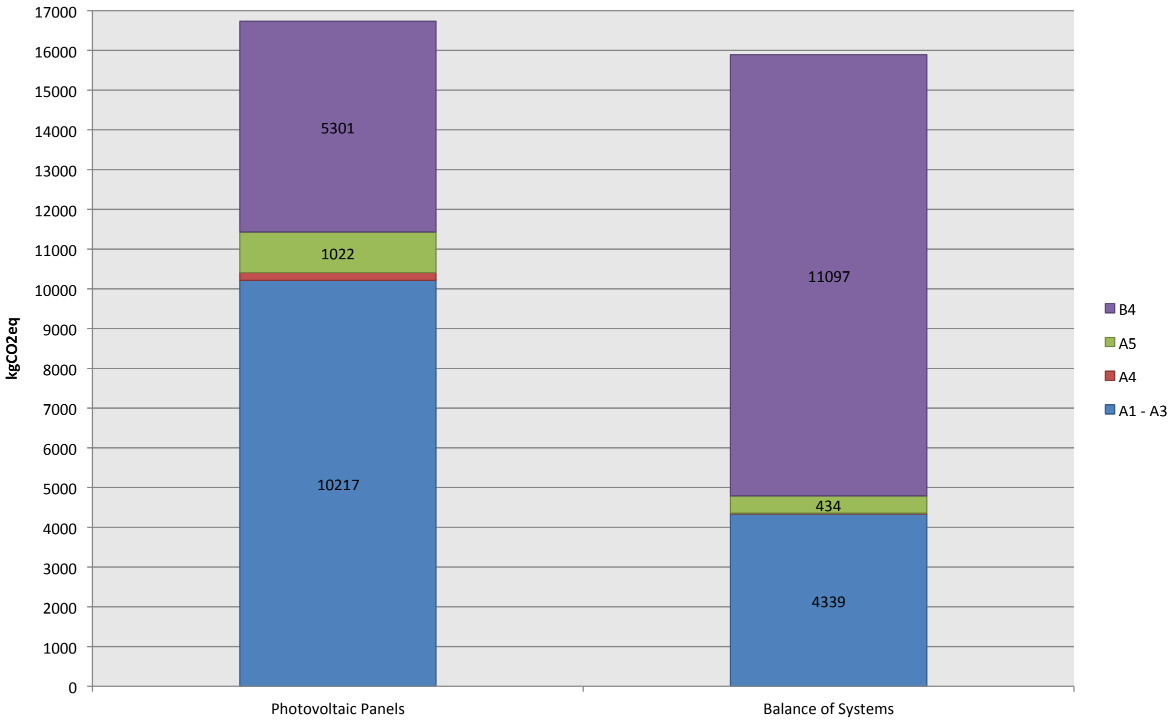
Appendix B.11: Embodied emission results for ventilation and air conditioning in the Living Laboratory.



Appendix B.12: Embodied emission results for the appliances in the Living Laboratory.



Appendix B.13: Embodied emission results for the photovoltaic system in the Living Laboratory.



The Research Centre on Zero emission Buildings (ZEB)
The main objective of ZEB is to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition. The Centre will encompass both residential and commercial buildings, as well as public buildings.

NTNU – Trondheim
Norwegian University of Science and Technology

SINTEF

The Research Centre on
Zero Emission Buildings

Partners

NTNU
www.ntnu.no

SINTEF
www.sintef.no

Skanska
www.skanska.no

Weber
www.weber-norge.no

Isola
www.isola.no

Glava
www.glava.no

Protan
www.protan.no

Hydro Aluminium
www.hydro.com

Caverion Norge
www.caverion.no

ByBo
www.bybo.no

Multiconsult
www.multiconsult.no

Brødrene Dahl
www.dahl.no

Snøhetta
www.snoarc.no

Forsvarsbygg
www.forsvarsbygg.no

Statsbygg
www.statsbygg.no

Husbanken
www.husbanken.no

Byggenæringens Landsforening
www.bnl.no

Norsk Teknologi
www.norskteknologi.no

Direktoratet for byggkvalitet
www.dibk.no

DuPont
www.dupont.com

NorDan AS
www.nordan.no

Enova
www.enova.no

VELUX
www.velux.com

Entra
www.entra.no

www.zeb.no