Master's thesis

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Dynamic analysis of material flows and embodied emissions of the building stock of a zero emission neighbourhood

Case study: Ydalir

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Abstract

The bottom-up approach model developed earlier by Næss et al. (2018) is extended to include the dynamic material flow and embodied emissions from materials during construction, renovation and demolition activities of a neighbourhood in time. The model is then applied to the ZEN pilot project Ydalir in order to estimate the material flows and the associated embodied emissions of the building stock of the neighbourhood for a 60 years timeframe.

In order to achieve that, the model is made up of three parts that consist of: (i) simulating the long-term building stock of the neighbourhood and identifying construction, renovation and demolition over time, (ii) setting up the material inventories that characterize the building stock and determining the emission intensities of those materials, (iii) combining (i) and (ii) to calculate the dynamic material use and embodied emissions for the neighbourhood over time. The neighbourhood is characterized by 15 initial individual archetypes according to type of building, renovation stage and cohort.

The dynamic model of Ydalir indicates that construction and renovation activities mobilize a total of 116 kton of materials with 82.6 kton CO2-eq of embodied emissions between 2019 and 2080. Initial construction being the activity that drives most use of materials and embodied emissions. The major source of embodied emissions are the PV panels that are part of the energy system in the residential buildings, this is due to the high carbon intensity of the system but also its need to be replaced every 30 years. Wood is the second most used material in the neighbourhood, as well as the second most accountable for the neighbourhood's embodied emissions. In terms of material flow, concrete is the dominant material, more than half of the material input to the neighbourhood is concrete.

The sensitivity analysis suggests that variations in renovation rates, material inventories and emission intensities of materials have an effect in the total embodied emissions, with room to reduce embodied emissions. Additionally, the material specifications and emission intensities that are selected in the material categories of concrete, wood, glass and membrane can have a greater impact in the total embodied emissions for the case of Ydalir.

The model is robust because its methodology is thorough, transparent and detailed, yet, the assumptions made and lack of knowledge about the future limit the certainty and accuracy of of the results for Ydalir. Nevertheless, some strategies related to embodied emissions and material flow of the building stock of a neighbourhoods are identified. For instance, using threshold values for the embodied emission intensity of the building stock of a neighbourhood could be implemented as a guideline to design the neighbourhood and control the embodied emissions from the building stock.

Contents

Introduction

2.1 Background

Among the economic activities that contributes buildings are responsible for 18.4% of total GHG emissions (Lucon et al., 2014). Of those, 12% are indirect emissions mainly from the use of electricity, a share that can vary substantially according to the emission factor of the source of energy. At the same time, 32% of global final energy is consumed by buildings.

Mitigation possibilities in terms of energy savings have been identified in the building sector where solutions and technology are ready available (Lucon et al., 2014). Passive house designs lower considerably the energy consumption of a building (Sartori & Hestnes, 2007) and if the house is combined with energy generation from renewable sources, such as solar energy, the remaining need for energy can be balance out. This buildings are known as nearly or net zero energy/emissions buildings (nZEB, ZEB) (Fufa, Schlanbusch, Sørnes, Inman, & Andresen, 2016; Torcellini, Pless, Deru, & Crawley, 2006; Marszal et al., 2011).

The potential of the building sector stands out when compared to other sectors where mitigation strategies are more difficult to achieve (Edenhofer et al., 2014). As a result, policies and efforts have been set to lower energy consumption and emissions from this sector. The European Union has set into place the Energy Performance of Buildings Directive and the Energy Efficiency Directive and has established that by 2020 all new buildings should be constructed to be ZEB.

Buildings are part of a broader context and combined with mobility, open spaces and infrastructure such as water, sewage, telecommunications, heating distribution and electricity distribution networks form the built environment (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015; Anderson, Wulfhorst, & Lang, 2015). This built environment can be looked at multiple scales, from neighbourhood to urban or city scale. Analyzing it is necessary because at this scale sustainability is addressed at a higher and more complex level where different systems and variables overlap. Questions such as: how to design a neighbourhood so that its emissions are reduced towards zero (Næss et al., 2018; Sartori et al., 2017), what parts of the built environment contribute the most to the overall impact and how to integrate the different parts of the neighbourhood so that impacts are reduced, arise.

Answering these questions and start developing solutions that resemble the sustainability goal in the built environment is a huge task and requires studying the different pieces separately and as a set so that greater understanding emerge. In order to do that, the Research Centre of Zero Emission Neighbourhoods (ZEN) aims to create cost effective and resource and energy efficient buildings, technologies and solutions to operate energy flexible neighbourhoods (Bremvåg, Gustavsen, & Hestnes, 2017). The research centre has designated 8 pilot projects and advanced research on the field to reach its goals. Among the studies done, one in particular developed a bottom-up approach model that estimates the dynamic stock, the energy demand and GHG emissions of the building stock of a neighbourhood (Næss et al., 2018).

Big efforts have been concentrated in understanding the energy dimension of buildings, however the knowledge and certainty about the constribution of emissions from production of materials, construction, maintenance and end of life stages of buildings is still limited (Lotteau, Loubet, et al., 2015). Understanding and reducing the emissions from all the stages is necessary to accomplish ZENs, where emissions are the result of use of energy and use of materials from the different parts of the neighbourhood (mobility, buildings and infrastructure).

Investigating the embodied emissions from the materials that are used in the neighbourhood, either in the construction or maintenance of buildings is interesting because once ZEB are implemented, literature suggest that embodied emissions in the buildings are increased (Kristjansdottir et al., 2018; Wiik et al., 2018), compromising the benefits of on-site energy generation. More and more studies are analysing the different parts of the neighbourhood on the whole, adopting a system thinking approach, in order to avoid overlooking and shifting problems.

While analysing a neighbourhood as whole is important, it is also necessary to create a detailed understanding of its parts to be able to combine them together and pinpoint potentials for reductions and improvements. Particularly, analysing the dynamics of the embodied emissions from the building stock of a neighbourhood can be benefitial to identify material flows and parameters that can be optimize to reduce embodied emissions of the stock.

Considering the model developed by (Næss et al., 2018) that estimates the dynamic stock, energy and associated emissions of a neighbourhood. This thesis' goal is to build on that model and create an equal detailed analysis of the material flow and associated emissions of a neighbourhood. Developing a model that adds a detailed material layer can be used to plan the design of a built environment in a way that embodied emissions and measures to mitigate them are also considered.

2.2 Research question

In this master thesis the bottom-up approach model developed earlier by Næss et al. (2018) in the context of the ZEN Research Centre is extended to include the dynamic material flow and embodied emissions from materials during construction, renovation and demolition activities of a neighbourhood in time. The model is then applied to the ZEN pilot project Ydalir in order to estimate the material flows and the associated embodied emissions of the building stock of the neighbourhood for a 60 years timeframe.

Having that in mind the research questions that want to be addressed by this study are the following:

1. What are the materials that contribute the most to total embodied emissions due to construction and maintenance of the building stock in Ydalir?

2. How are the flow and quantity of specific materials in the construction and maintenance of the building stock in Ydalir related to its associated embodied emissions?

3. What are possible strategies to reduce embodied emissions of the building stock in Ydalir?

Literature review

In this chapter important concepts and results found in the literature are reviewed as a framework for the development of this project report. Particularly findings from life cycle studies in buildings and in the built environment are looked at closely.

3.1 Life cycle emissions in buildings

Life cycle emissions in conventional residential buildings are dominated by emissions from the operational phase due to energy use (Rashid & Yusoff, 2015; Heeren et al., 2015). In this phase, energy use can represent from 80% to 95% the total energy a building uses in its whole life time (Sharma et al., 2011; Sartori & Hestnes, 2007). In addition, around 15% is attributed to the embodied energy from the production of materials(Anderson et al., 2015) and only approximately 1% to energy from construction, demolition and transportation stages.

The operational energy is generally dominated by heating, ventilation and air conditioning systems (HVAC) with a contribution between 40% to 60% followed by lightning with a share around 20% to 30% and others such as hot water needs and electrical appliances(Sartori & Hestnes, 2007; Li, Yang, & Lam, 2013). Nevertheless, this results can vary according to the geographical location of the building (Rashid & Yusoff, 2015), since heating requirements are dependent on weather conditions, as well as seasonal changes.

Considering that emissions in conventional buildings are dominated by their energy use, it is common practice to address energy rather than emissions in buildings. This is specially convenient because emissions become determined by the carbon emission factor of the local energy mix, which can vary greatly among regions (Lucon et al., 2014).

Great focus has been concentrated in reducing energy consumption from the operational phase in buildings, as a result low-energy buildings have appeared. This type of buildings achieve a lower energy need in their operation when compared to conventional buildings due to their special design criteria and specifications (Sartori & Hestnes, 2007). These criteria range from: material choices, architectural and structural design, and systems used in the operation of the building for heating, lightning, ventilation, etc (Anderson et al., 2015). In addition, according to the Passivhaus standard these buillddings do not reach more than 120kWh/m^2 of total annual primary energy consumption (Kylili & Fokaides, 2015).

Li et al. (2013) identified 3 types of energy-efficient measures that contribute significantly to reduce energy consumption in a building and that can be implemented either in new buildings or during renovation. These measures comprise building envelopes, internal conditions such as lightning and indoor design and building services systems which include HVAC systems. In terms of building envelopes, the aim is to design them to avoid energy gains in summer and energy losses in winter, key features include thermal insulation, thermal mass, windows and green roofs. Li et al. (2013) points out that buildings with cooling needs require different design solution than those with heating needs and finding the right balance of choices is a key challenge. Besides, Anderson et al. (2015) highlights the influence of choice of materials in thermal properites as well as in thermal performance. Additionally, other aspects such as surface-area-to-volume-radio of buildings have been identified to contribute to energy-efficiency in buildings (Anderson et al., 2015).

Sartori and Hestnes (2007) reviewed different life-cycle assessments of low-energy buildings and found out that the absolute and relative share of embodied energy in this buildings is higher than that of conventional buildings, reporting values that vary between 2% to 38%. This is the direct result of an increased use of materials, including energy intensive ones. On the other hand, when assessing total enegy use, low-energy buildings do display lower total enegy use than conventional buildings (Sartori & Hestnes, 2007), achieving their goal.

3.1.1 Zero emission buildings

In addtion to low-energy buildings, zero energy/emission buildings (ZEB) have also emerged. This are low-energy buildings that are coupled with on-site renewable energy generation in order to balance out their energy consumption or generated emissions, depending on the definition used (Fufa et al., 2016; Kristjansdottir et al., 2018; Torcellini et al., 2006; Marszal et al., 2011).

The Norwegian ZEB research centre chose to define ZEB in terms of its life cycle GHG emissions, where ZEB's aim to accomplish zero GHG emissions from a whole life cycle perspective (Fufa et al., 2016), any extra emissions should be ideally compensated with on-site energy generation. The standard NS-EN15978:2011 is a good reference that delineates the life stages of a building, which include the production stage (A1-A3), the construction stage (A4-A5), the use stage (B1-B7), the end of life (C1-C4) and benefits and loads (D).

The research center recognized the high ambition in their definition and adopted different ambition levels to address the challenge one step at a time (Wiik et al., 2018). In order to define the levels of ambition, the research center used the life stages proposed by the standard mentioned before, where the most ambitious level takes into account all life cycle stages (excluding benefits and loads) and the lowest ambitious level only consider emissions from the operational energy use, figure 3.1 illustrates the 6 ambition levels and the life stages covered by each one.

When compared to low-energy buildings, Kristjansdottir et al. (2018) reported that ZEBs from the research centre have lower emissions from energy use, but at the same time higher embodied emissions, with shares between 55% to 87% the total emissions(Wiik et al., 2018). Due to the high contribution of embodied emissions in this context there

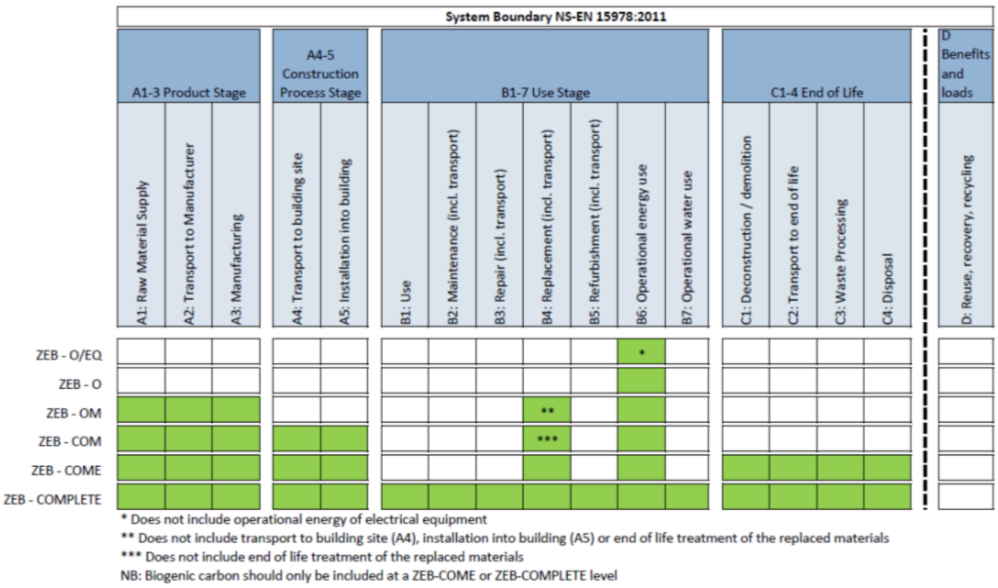


Figure 3.1: ZEB ambition levels and life stages from NS-EN 15978:2011. Image taken from Fufa et al. (2016)

is a need to implement design strategies that focus on reducing embodied emissions (Kristjansdottir et al., 2018; Wiik et al., 2018).

Strategies such as reducing constructed areas and materials used, increasing the use of reused and recycled materials, as well as adopting materials with low embodied carbon emissions, high durability and long service life are suggested by Wiik et al. (2018). Notwithstanding, this study admits that reducing embodied emissions can be difficult due to the complexity of building projects. Other studies suchs as Bribián, Capilla, and Usón (2011) and Augiseau and Barles (2017) also stress the importance of comitting to reuse and recycle materials from buildings in order to close material cycles and reduce their environmental impacts. In order to address this, Bribián et al. (2011) propose that building's designs also consider solutions that facilitate the disassembly of materials at the end of life of the building, for instance by making joints between materials reversible.

The need to lower embodied emissions is also supported by the fact that lowering operational energy and implementing renewable energy generation on-site in buildings is not enough to balance out life-cycle GHG emissions in buildings. Experience from the ZEN research center has shown that projects aiming to reach a ZEB-OM ambition level fall short (Inman & Wiberg, 2015; Hofmeister, Kristjansdottir, Time, Aoife Houlihan Wiberg Tobias Barnes Hofmeister, & Wiberg, 2015; Dokka, Wiberg, et al., 2013; Dokka, Kristjansdottir, et al., 2013; Kristjansdottir et al., 2018). In addition to this, the need to expand the system boundaries and consider integrated solutions, such a energy generation alternatives for multiple buildings and interactions between mobility, infrastructure and buildings have been addressed as the way to go to target zero emission ambitions (Kylili & Fokaides, 2015).

3.2 Life cycle emissions in the built environment

The built environment in simple words is the combination of buildings, transportation and infrastructure systems (Anderson et al., 2015). Lotteau, Loubet, et al. (2015) more precisely distinguish four spheres: (i) buildings, (ii) open spaces, such as roads and green spaces, (iii) networks, such as telecommunication, sewage, heating and electricity distribution, and (iv) mobility.

Studies made at this scale vary in focus and definition. For instance, Anderson et al. (2015) highlight that research in this area concentrates on urban form, density, transportation, infrastructure and consumption. On the other hand, Lotteau, Loubet, et al. (2015) reviewed 14 LCA studies that feature integrated assessments of the built environment at a neighbourhood scale and admit that all the study cases are widely heteregeneous, not only in the definition of the functional units and system boundaries, intrinsic to a LCA assessment, but in the composition and definition of the neighbourhoods.

In order to analyse the built environment, Anderson et al. (2015) indicate that total energy use of a built environment includes embodied and operational energy, attributed to buildings and infrastructure, as well as energy used in transportation and consumption. From a life cycle perspective Lotteau, Loubet, et al. (2015) and Stephan, Crawford, and de Myttenaere (2013) identify a construction phase, which includes material extraction, manufacturing and construction, an operation phase, comprising operation and maintenance, and a deconstruction or end-of-life phase. The contribution in each phase is characterize at either a neighbourhood or building scale. For instance, in the construction phase the contribution is made by buildings and by infrastructure; in the operation phase, mobility, networks operation and public lightning constitute the neighbourhood's contributors, while the building's contribution cover heating, cooling, hot water, appliances, etc.

Literature that assess environmental impacts at a neighbourhood level exist, however Lotteau, Loubet, et al. (2015) and Lausselet, Borgnes, and Brattebø (2018) agree that these studies are still scarce. From 14 LCA studies at a neighbourhood level that Lotteau, Loubet, et al. (2015) reviewed, the following general conclusions were drawn: (i) the major contributors to energy consumption and GHG emissions are buildings and then mobility, (ii) the contribution from the operation of the buildings, mobility and embodied emissions can share same order of magnitude, additionally, (iii) if the neighbourhood displays a high energy efficiency the contribution to energy consumption and GHG emissions from the production phase becomes higher, finally (iv) contributions from the demolition phase are almost negligible.

Figure 3.2 shows the compilation of results from three different LCA studies at a neighbourhood level in terms of contribution from the different parts of the neighbourhood.

The first study, made by Lausselet et al. (2018) was based on a ZEN concept to be developed in Bergen with a total area of 91 891 m2, 695 dwellings and 1340 inhabitants, the analysis is made for a 60 years period. The second study, from Stephan et al. (2013) assess a new suburban neighbourhood in Wyndham, Australia, with a total area destinated to buildings of 43850m^2, and 500 inhabitants/km^2, the analysis period is 100 years.

The third study, developed by Lotteau, Yepez-Salmon, and Salmon (2015) is a case study inspired by urban projects in France and simulates an are of 17300m^2 for 350 inhabitants.

Although the ideas is not to thoroughly compare these three studies, which vary greatly in their definition and specifications. The results illustrate and corroborate the findings by Lotteau, Loubet, et al. (2015). Particularly from figure 3.2a and 3.2c the contribution to CO2 emissions from buildings is evident, and even though the operation of the building dominates emissions, embodied emissions from materials in buildings also have a significant contribution to the neighbourhood's emissions overall. Moreover, scenario 0 and 1 in figure 3.2c contrast the case where high-performance buildings are modeled (scenario 0) against business as usual performance buildings (scenario 1). It can be noticed that embodied emissions become the second major contributor in the scenario with high-performance buildings. From all figures it is also clear the significant role of mobility in the neighbourhood's use of energy and CO_2 emissions. Moreover, Lausselet et al. (2018) and Lotteau, Yepez-Salmon, and Salmon (2015) make the distintion that this contribution is driven by mobility from personal vehicles.

The results of these studies hint to the main contributors and drives of CO_2 emissions at a neighbourhood scale. The results also recognize the importance of considering drivers of embodied, operational and transport energy and emissions together, in order to avoid shifting energy consumption between categories when aiming to reduce energy consumption and emissions. In addition, Lausselet et al. (2018) and Lotteau, Loubet, et al. (2015) point out the importance of considering the temporal aspect in the analysis and include the evolution in time of different parameters such as energy production mix, technology and material's production processes.

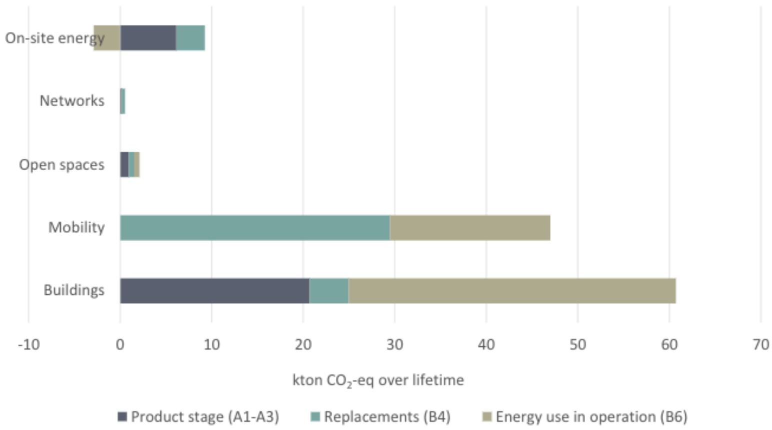
3.2.1 Zero emission neighbourhoods

The ZEN research center is a recent initiative following the ZEB research center which aims to create solutions for buildings and neighbourhoods to reach zero GHG emissions. The center has 8 pilot projects where research can be combined and tested. Projects developed under the ZEN center include the one done by Lausselet et al. (2018) and Næss et al. (2018).

The center defines a neighbourhood as a geographical space that contains buildings, energy systems and infrastructure connected to each other. This neighbourhood has delimited physical boundaries, where energy systems do not need to share the same boundaries from buildings and infrastructure (Sartori et al., 2017).

In addition, the center defines a ZEN as a neighbourhood that during its lifetime induces or creates minimun GHG emissions to the point of reaching close to zero emissions (Sartori et al., 2017). In order to reach such neighbourhoods, its elements such as buildings, infrastructure and almost everything that makes the neighbourhood needs to be designed and produced so that their GHG emissions from a life cycle perspective are low or ideally zero.

Among the aspects that the center recognize as key to reach such goal are emissions, energy, power, economy, mobility, spatial qualities and innovation. In order to assess



(a) LCA result of a neihbourhood by Lausselet et al. (2018).

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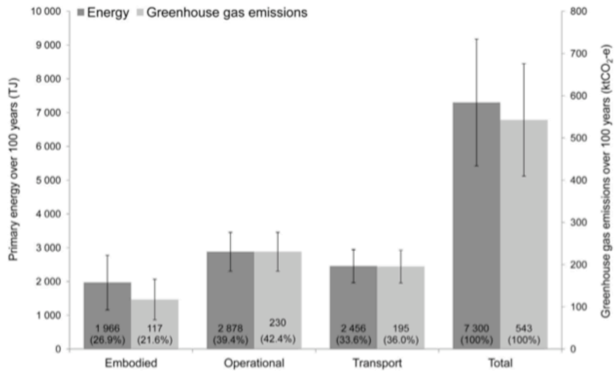

(b) LCA results of a model of a neighbourhood by Lotteau, Yepez-Salmon, and Salmon (2015)

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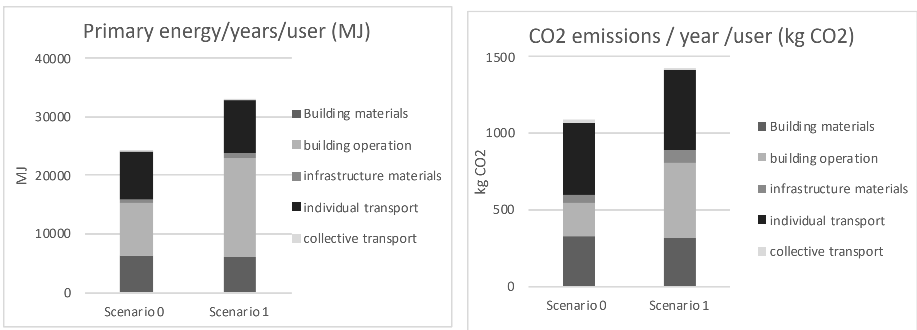

(c) LCA results for a suburban neighbourhood by Stephan et al. (2013).

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Figure 3.2: Illustration of results from 3 LCA studies at a neighbourhood scale

emissions, particularly total GHG emissions and GHG emissions reduction, the center relies on the standards and methodologies: EN15978 (Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method), NS3720 (Method for greenhouse gas calculations for buildings), NS3451 (Table of building elements) and NS 3457-3 (Classification of construction works - Part 3: Building types).

Particularly, EN15978 and NS3720 include guidelines to perform LCA analysis. The idea is to use these guidelines and applied them to the analysis of a neighbourhood. Lausselet et al. (2018) is a good example of how to perform and LCA at a neighbourhood level taking into consideration the rules in this standards, in this study the life cycle analysis is made for each element of the neighbourhood, also the ambition level for each element is initially defined.

On the other hand, the study by Næss et al. (2018) provides high detail in the estimation of energy demand of a neighbourhood. It helps to avoid overestimating the energy demand and associated emissions of a neighbourhood by calculating future energy demand in an hourly basis using coincidental analysis. The precision of the model is desired in order to better couple energy generation from the neighbourhood to the electricity grid, as well as to dimention energy storage needs.

Methodology

A model that calculates the material flow and embodied emissions of the building stock of a neighbourhood over a period of time is developed. The model is applied to the case study of the ZEN Ydalir, Elverum, Norway, and the results are subjected to a sensitivity analysis. In this section, the methodology of the model, application case and sensitivity analyisis are explained.

4.1 Model

The model calculates the long-term dynamic use of material and associated embodied emissions of the building stock of a neighbourhood as a result of the construction, renovation and demolition activities. In order to achieve that, the model is made up of three parts that consist of: (i) simulating the long-term building stock of the neighbourhood and identifying construction, renovation and demolition over time, (ii) setting up the material inventories that characterize the building stock and determining the emission intensities of those materials, (iii) combining (i) and (ii) to calculate the dynamic material use and embodied emissions for the neighbourhood over time.

The following sections describe those parts in detail.

4.1.1 Long-term dynamic building stock

Næss et al. (2018) created a detailed model that assess the development of a neighbourhood's building stock based on construction, renovation and demolition activities over a period of time.

The model is construction driven. For each year, the number of buildings contructed, their floor area type and average heated floor area are initial parameters. A description of the initial stock is also required, this includes the year of construction or cohort, the floor area type, the average heated floor area and the renovation state of the building.

In order to model the renovation and demolition activities, the model can either set when these activities take place for each type of building or it can model the activities by using a probability distribution function (PDF). For the renovation activity, the renovation will follow a Normal distribution where the mean μ is the years, after construction or a previous renovation, a renovation is expected to happen. A building can be renovated multiple times during its lifetime. For the demolition activity, the PDF can either follow a Weibull or Normal distribution and the expected lifetime of the building is the main paramater to the function.

Figure 4.1 illustrates Næss et al. (2018)'s model and the initial parameters required by the model.

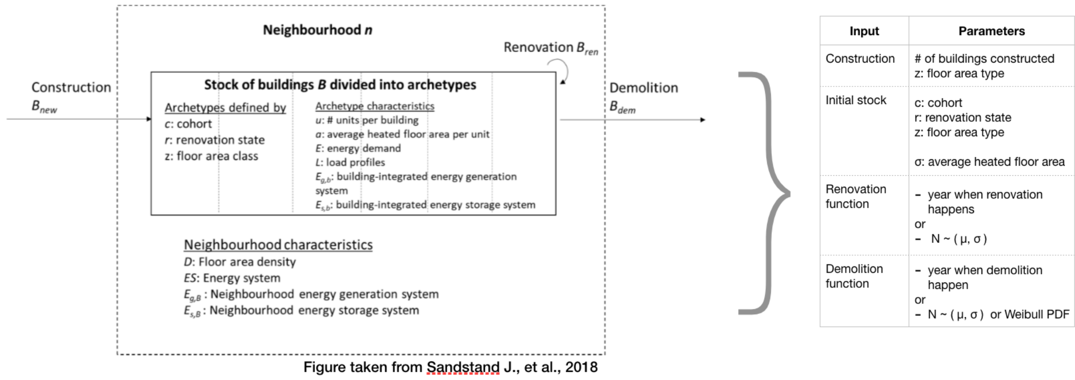


Figure 4.1: Building stock model and initial parameters (Næss et al., 2018)

The initial parameters of the stock model are set on a template in excel and are used by a program developed in Matlab that calculates the building stock over the years. The program simulates the buildings as individual objects and follows their evolution throughout the years.

As an output, the model provides an excel file with a summarized description of the building stock for each year simulated and the complete stock for the final year. In addition, a folder with the complete building stock for each year in .csv files is also created. Each csv file provides the list of all standing buildings in that year with their cohort, floor area type, heated floor area, renovation state, year of construction and a unique building ID. Figure 4.2 illustrates a fragment of one of the csv files.

Building name	Building input ID	Building Matlab ID	Heated floor area	Construction year	Cohort	State	Main floor area type	Actual Year
DD2019-20	100000	99	80	2019	1	1	Single Family House	2020
DD2019-20	100000	100	80	2019	1	1	Single Family House	2020
DD2019-20	100000	101	80	2019	1	1	Single Family House	2020
DD2019-20	100000	102	80	2019	1	1	Single Family House	2020
DD2019-20	100000	103	80	2019	1	1	Single Family House	2020
School	100001	104	6474	2019	1	1	School	2020
Kindergarden	100002	105	2140	2019	1	1	Kindergarden	2020
DD2019-20	100004	106	80	2020	1	1	Single Family House	2020
DD2019-20	100004	107	80	2020	1	1	Single Family House	2020
DD2019-20	100004	108	80	2020	1	1	Single Family House	2020

Figure 4.2: Fragment of information from one of the csv files

4.1.2 Characterize building stock by activities and archetypes

Once the information of the building stock over the years is obtained, the csv files are imported into a database, where the information is organized to determine the floor area in m^2 that is constructed, renovated and demolished each year according to archetypes. An archetype is defined by a cohort, renovation state and floor area type. A scheme of this process is shwon in figure 4.3.

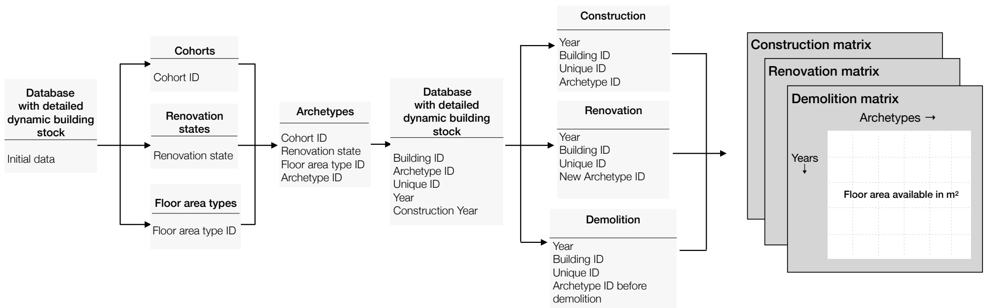


Figure 4.3: Process to obtained the floor area in m^2 for each activity and archetype

Initially, a unique table in the database contains the information of the building stock for all the years modeled. From this data all the cohorts, renovation states and floor area types are gathered and combined to find out all archetypes that manifest in the stock. Each archetype is given an ID.

The initial table is then modified to only include the archetype ID, the building ID which identifies a building each year, the unique ID which does not repeat itself, the year in time and the construction year. From this table, 3 tables, one for each activity (construction, renovation and demolition) are created. The tables are respectively populated with the buildings that are built, renovated or demolished over the years.

In order to do that, the building ID is used to trace the history of the buildings and spot when the activities occur for each of them. For instance, construction occurs the year the building ID appears for the first time, renovation when the archetype of the building changes, due to change in renovation state, and demolition the last year the building appears, exluding the last year of analysis.

When the table for each activity is completed, the number of buildings for each year an archetype are counted and set up in a 2D matrix of dimensions (achetype, year). The matrix of each activity is then multiplied by the floor area in m^2 according to the type of building of the archetype.

4.1.3 Define the material inventory for each archetype and the CO_2 emission intensity of the materials

A material inventory is set up for each of the archetypes identified in the previous section. This inventory includes information about the part of the building where the material is used for, the material specification or description, the amount of material in kg per m^2 and the lifetime of the specific material. The list of building elements from the norwegian standard NS 3451:2009 is used as reference to determine the part of the building, which can be for instance groundwork and foundations, superstructure, outer walls, floor structure, among others.

Initially, the inventory of materials that are required for the construction of the archetypes are defined. Afterwards, the material inventory for the renovation stage is set up based on the lifetime of the material specifications from the construction inventory.

When the material inventory for all the archetypes is defined, a 2D matrix of dimensions (material, archetype) with the corresponding quantities is created.

In addition, a 2D matrix with the cradle-to-gate life cycle emissions intensities for the different material specifications is created. The functional unit for each materials is harmonized to be 1 kg of material. A database such as Ecoinvent or values from Environmental Product Declarations-EPD, among others, can be used to define the emission intensities. The matrix also includes a time scale and emission intensities can be set to vary throughout the years to foresee possible scenarios where decarbonization of the energy mix and/or more efficient production processes take place. This matrix has dimensions (material, year).

4.1.4 Long-term dynamic material use and embodied emissions by activity and archetype

The floor area contained in the 2D matrix (archetype, year) for each activity is then combined with the material inventory (archetype, material) to obtain a 3D matrix with the dynamic total use of material for each activity. The matrix gives the material use according to archetype, material and year. This is illustrated in figure 4.4.

In addition, the total embodied emissions for each year, according to material and archetype, are calculated by multiplying the dynamic material use each year with the emission intensity of the materials the same year, this for all the years modeled. This is also illustrated in figure 4.4.

4.2 Case study: ZEN Ydalir

4.2.1 Dynamic building stock

The model is applied to the early stage planning ZEN project Ydalir located in Elverum, Norway. The analysis covers a timeframe of 60 years starting in 2019.

In order to simulate the dynamics of the building stock in ZEN Ydalir the construction process is set to build a school, a kindergarden and 625 single family houses (SFHs) with a floor area of 6474 m^2 , 2140 m^2 , and 100000 m^2 respectively. The school and kindergarden are built in 2019 while the construction of the SFHs is distributed evenly from 2019 until 2030. According to the year of construction the buildings are identified with one of three cohorts : 2019 to 2020, 2021 to 2025 or 2026 to 2030.

Once a building is constructed it can follow up to two renovation phases before being demolished. These renovation phases concentrate on replacing materials that need to

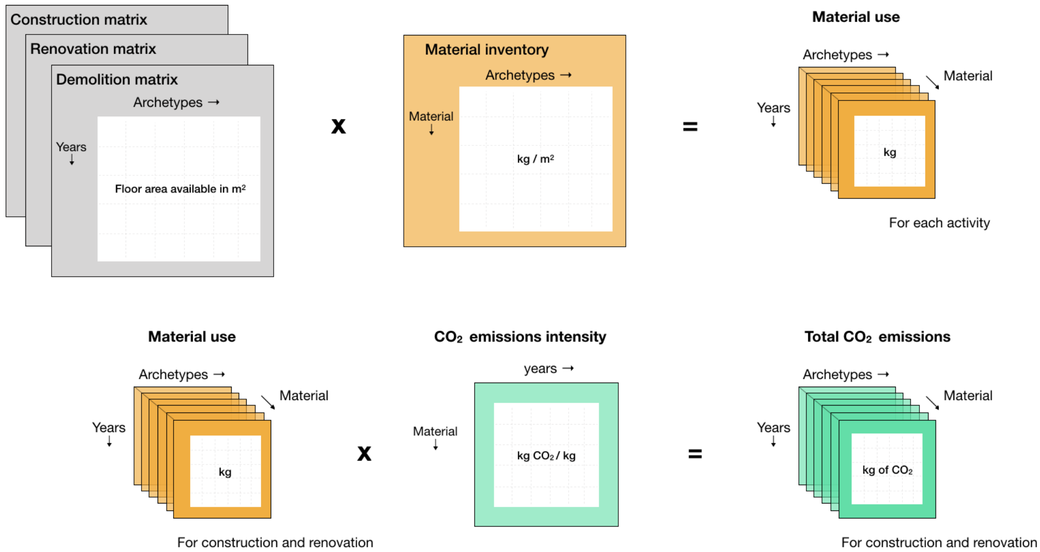


Figure 4.4: Scheme of the model to calculate the dynamic material use and embodied emissions by archetype, material and year

be changed because their lifetime has expired. For a building to go through a second renovation it must have been renovated a first time. The renovation process for both phases is simulated using a Normal probability distribution function according to table 4.1. Once a building is renovated there is a chance it is renovated again according to the same renovation fucntion or it can be demolished. For the residential buildings a mean of 30 years and standard deviation of 5 years is used, while for the school and kindergarden the mean is kept 30 years but the standard deviation is shorten to 2 years. This is because it is assumed that the school and kindergarden will be renovated as a whole and both renovations will happen close in time between each other.

Table 4.1: Probability distribution function used for renovation and demolition for the SFHs, school and kindergarden

Type of building	**Renovation**	**Demolition**
Residential buildings - SFHs	N $\sim$ (30,5)	N $\sim$(60, 5)
Kindergarden, school	N $\sim$ (30, 2)	not demolished

Considering that the timeframe of the analysis is 60 years it is assumed that the school and kindergarden are not demolished. On the other hand, the lifetime of the residential houses are set to follow a normal probability distribution function of 60 years with standard deviation 5 years. This lifetime reflects the technical lifetime of the building refering to the lifetime of materials.

The combinations of cohort, floor area type and renovation state result in 15 different archetypes which are define in 4.2.

Table 4.2: Archetype definition according to cohort, floor area type and renovation state

Cohort	Floor area type	Renovation state	Archetype ID
2019-2020	Kindergarden	Original state	AK1
		First renovation	AK2
		Second renovation	AK3
	School	Original state	AK4
		First renovation	AK5
		Second renovation	AK6
	SFH	Original state	AK7
		First renovation	AK8
		Second renovation	AK9
2021-2025	SFH	Original state	AK10
		First renovation	AK11
		Second renovation	AK12
2026-2030	SFH	Original state	AK13
		First renovation	AK14
		Second renovation	AK15

Archetypes AK1, AK4, AK7, AK10 and AK13 represent the original state of the building and are linked to the construction activity while the remaining archetypes represent buildings that went through either one or two renovation phases and thus are associated with the renovation activity.

Additionally, to mantain the floor area balance and fulfill the living space demand of the neighbourhood an extra archetype appears, AK-new, this archetype has the same properties as AK13 and represent the floor area that needs to be built to make up for the floor area demolished. It is assumed that the amount of floor area constructed of this archetype mirrors the area demolished over time.

4.2.2 Material inventory

The material inventories used follow the structure of the table of elements from the standard NS 3451, specifying the building part, the description of the material and the amount. The school and kindergarden are assembled using as basis the material inventories provided by *Context AS* that analyse the life cycle emissions of these two buildings. These inventories reflect the actual construction of the school and kindergarden in Ydalir and the description of the material include specifications for products found in the market in Norway with an Environmental Product Declaration, EPD. On the other hand, for the residential buildings the inventory of the zero emission SFH concept by Dokka, Wiberg, et al. (2013) is used as reference, the materials in this inventory are initially matched with a material specification from Norwegians EPDs, otherwise materials from processes in the Ecoinvent 3.2 database are used. This SFH house fulfills a ZEB-O ambition level by installing PV panels in its roof, however, the materials and design do not intend to lower embodied emissios. In addition, it is worth noting that only the material inventory from the SFH includes information on the energy and technical systems such as thermal collector, photovolatics, ventilation and heating.

The inventories are harmonized to *kg* as same unit of weight by using the density reported in the EPD for the different material specifications, for the materials matched with an ecoinvent process the density from this database is used instead. The material inventories for the school, kindergarden and SFH are included in the appendices A.2.

In total the inventories acount for 78 different material specifications, which are further classified according to 12 material categories:

Table 4.3: Main material categories

Material categories		
Concrete	Membrane	Others
Energy system	Mineral	Steel
Glass	Insulation from minerals	Technical
Gypsum	Insulation from polystyrenes	Wood

The specifications that are assigned to each category are included in the apprendices A.3.

The classification is made based on the primary material in the material composition of the specification, for instance the category *mineral* includes materials based on aggregates, stone and cement, *membrane* refers to materials used in the membrane which mostly comprise polymers such as polyethylene (PE, HDPE, LDPE) or polypropylen (PP), *other* refers to specification that are difficult to put in one material category like linoleum and rubber floor. Likewise, insulation materials are distinguished between *insulation mineral* and *insulation PS* in concordance to the primary material either mineralwool or glasswool for the first or polyestyrene (extruded or expanded) for the second.

So far, these material inventories represent the material requirement for the construction of the school, kindergarden and SFHs, which is described by archetypes AK1, AK4 and AK7. In order to create the material requirement for the renovation activity of this archetypes (AK2, AK3, AK5, AK6, AK8 and AK9) the lifetime of the materials is considered. The lifetime reported in the EPD or Ecoinvent, as well as the lifetime suggested by Kristjansdottir et al. (2018) is used to determine the specifications that need to be replaced in the renovation process. The material inventory for the renovation includes only materials that need to be replaced, this applies for both renovation phases.

Regarding the SFHs that are part of the second and third cohort (2021 to 2025 and 2026 to 2030) it is assumed that the material inventory is identical to the one from the SFH in the first cohort (2019-2020) for both construction and renovation activities, the same assumption applies for the archetype that replaces demolished buildings AK-new.

4.2.3 Emissions intensities

A matrix with the emissions intensities per unit of weigth for all the material specifications is created in Excel. The emission intensity represent the cradle-to-gate emissions of the materials, that is to say extraction and production phases.

In order to build the baseline scenario, wich intends to depicts a European scenario, the 78 material specifications are matched to a suitable Ecoinvent material process from the database Ecoinvent 3.2 and the emission intensity reported in the database is assigned to the material specification. The emission intensity is harmonized to a functional unit of 1 kg when necessary according to the density reported in the process in Ecoinvent.

Appendices A.3 shows the Ecoinvent process that is assigned to each of the 78 material specifications.

In addition, for the baseline scenario, it is assumed that the emission intensities of materials remain unchanged over time.

4.3 Sensitivity analysis

The sensitivity of the model can be simply expressed using equations 4.1 and 4.2, where the embodied CO_2 emissions of a specific year t are proportional to the the total area A that is constructed and renovated that year, the material intensity m of that area, either renovated or constructed, and the emission intensity of the materials used e. Any change in any of these parameters will have a proportional effect on the embodied emissions. In addition, the total embodied emissions over the simulated period are the sum of the embodied emissions each year, therefore changes over time in A, m or e will also have an effect in the total embodied emissions.

$$CO_2\ emissions_{\,\mathrm{t}} = A \times m \times e \tag{4.1}$$

$$Total\ CO_2\ emissions = \sum_{t=2019}^{2080} CO_2\ emissions_{\,\mathrm{t}} \tag{4.2}$$

While A, m, and e have a proportional effect on the total embodied emissions, each of these variables are influenced by other parameters and it is of interest to investigate how changes in those parameters affect these three general variables.

In order to do that, a local sensitivity method approach is used, in this method one parameter from the baseline scenario is changed while the others remain constant, then the influence of the change in the total embodied emissions is measured. Not all the parameters of the model are subject to a sensitivity analysis because for some of them that would imply a complete change of the boundaries or characteristics of the system initially defined, in this case Ydalir.

Initially, paramaters that influence area A, material intensity per m^2 m and emission intensities e are identified. These parameters are simply described in table 4.4. After identifying parameters in each category, 11 sensitivity scenarios are created. The scenarios are created by trying to touch on parameters that influence different parts of the general model A, m and e. The scenarios are briefly presented in table 4.5 and a description of them follows in the text.

Table 4.4: Description of parameters that influence each part of the model

General variable	**Parameter description**
A	Area built (initial variable) Constructed area: floor area types, cohorts and distribution Renovated area: renovation function, renovation stages Demolished area: demolition function, lifetime of buildings
m	Definition of archetypes Material need in the construction of each archetype Material need in the renovation of each archetype Lifetime of materials
e	Emission intensity of materials Categorization of materials Change of emission intensity over time

The area that is built and renovated over the years A is determined in the first part of the model (the dynamic building stock) by (i) the initial construction, including the amount of area built and its distribution according to floor area types and cohorts, (ii) the renovation function and (iii) the demolition function. From the case study it is certain that a school, a kindergarden and 100000 m^2 of residential buildings will be built by 2030, moreover the floor area of the school and the kindergarden are rather certain, as well as their year of construction (2019). In terms of renovation, it is assumed that renovation follows a normal distribution with a mean of 30 years and standard deviation 5 years, to test the impact of assumptions in renovation, two renovation means are investigated: 20 and 40 years, the standard deviation is kept unchanged. This is done through scenarios *S1-Ren20* and *S2-Ren40*. Additionally, the technical lifetime of the building has been set to follow a normal distribution with mean 60 years and standard deviation 5 years, this assumption is tested in *S3-Con80* and *S4-Con100* by assuming two other different lifetimes: 80 and 100 years respectively, both with a broader standard deviation of 10 years.

The material intensity m per m^2 is determined by the material inventory of the archetypes. The material inventory of the construction of the school and the kindergarden are rather certain, thus this are left untouched. In the case of the residential buildings, the hypothesis of building MFHs instead of SFHS is tested, this is done through scenarios *S5-MFH16* and *S6-MFH32*. In scenario *S5-MFH16*, the MFHs are organized in sets of 16 units of 80 m^2 arrange in 2 stories as displayed in figure 4.5, while for scenario *S5-MFH32* the MFH contain 32 units of the same size and are arrange in 4 stories. The same 100000 m^2 of floor area are constructed, however, the the need for material in the outer walls, roof, as well as PV panel per m^2 changes. The material inventory for the MFHS is based on the initial inventory of the SFH. The relations used to adapt the material inventory

Table 4.5: Sensitivity analysis scenarios

Variable affected	Scenario	Description
A	S1-Ren20	Renovation function is changed to N ∼ (20,5) for all buildings
	S2-Ren40	Renovation function changes to N ∼ (40,5) for all buildings
	S3-Con80	Demolition function changes to N ∼ (80,10) for SFHs
	S4-Con100	Demolition function changes to N ∼ (100,10) for SFHs
m	S5-MFH16	SFHs are replaced by MFHs of 16 units each set
	S6-MFH32	SFHs are replaced by MFHs of 32 units each set
	S7-noPV	SFHs do not have PV panels
e	S8-decrease	Emission intensities decrease 40% from 2019 to 2050
	S9-EPD	Emission intensities are replaced with EPD values
	S10-high	Emission intensities are replaced with highest values *
	S11-low	Emission intensities are replaced with lowest values *

for these two scenarios are presented in table 4.6.

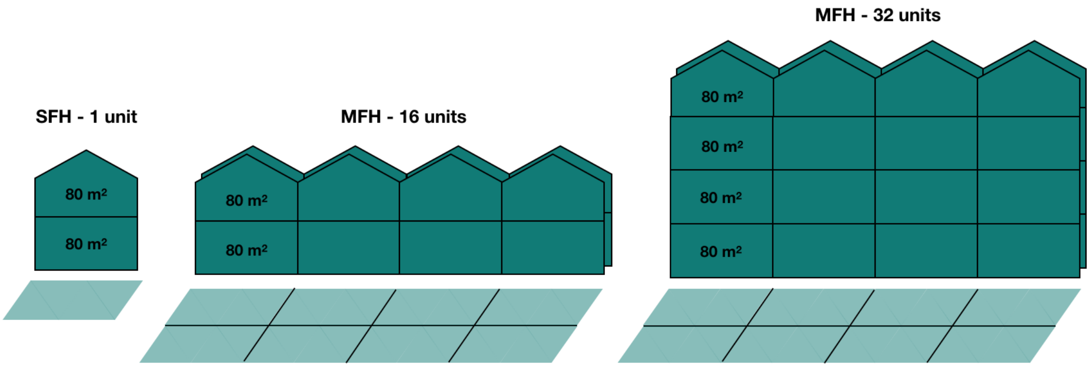


Figure 4.5: Illustration of assumption for MFH-16 and MFH-32 with respect to SFH

In addition, to test the relevance of the PV panels in the material inventory a scenario where residential buildings do not include this element is created, this scenario is identified as *S7-noPV*.

When it comes to the sensitivity of the model relative to the emission intensity of materials e, it is of interest to understand how embodied emissions are affected by changes in emission intensities according to the material category. Results on this can, for example, hint about how deviated total embodied emissions can be due to the uncertainty when pairing emission intensities and material specifications in the material inventories.

In order to evaluate this, the total embodied emissions are calculated when all specifications in one material category adopt one same value while the rest of the specifications in other material categories continue with the baseline case value, this is done for the 12

Table 4.6: MFH-16 and MFH-32 in relation to SFH

	SFH	**MFH-16**	**MFH-32**
Number units	1	16	32
Outer roof factor	1	8	8
Outer walls factor	1	24	48
PV panel factor	1	8	8
Floor area unit	160 m^2	80 m^2	80 m^2
Floor area set	160 m^2	1280 m^2	2560 m^2
Total sets	625	78	39
Total units	625	1250	1250
Total PV panels *	625	625	313

* Assuming 1 roof = 1 panel

material categories. The values that are used followed three different cases: the highest, average and lowest emission intensity value from the material category according to 4.6. The range of emission intensities used included intensities taken from EPD specifications and Ecoinvent processes according appendixes A.3. Intensities that are too high or too low in comparison to the rest of the intensities in the category are not taken into consideration.

Complemenatry to this, scenarios *S10-high* and *S11-low*, test the cumulative effect in which all material categories adopt the highest or lowest emission intensity of the category.

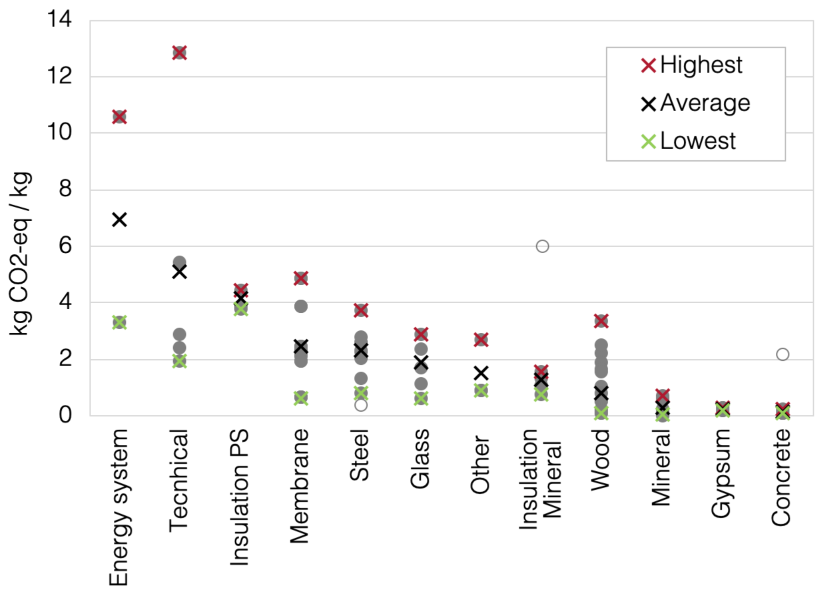


Figure 4.6: Range of emission intensities for the 12 material categories, with the highest, average and lowest values highlighted.

Lastly, 2 other sensitivity scenarios are created in connection with the emission intensity of materials. In scenario *S8-decrease*, the emission intensities from the baseline scenario are assumed to have a linear reduction of 40% until 2050, this reduction is an estimate based on the standard NS 3720-2018 and the scenario for Europe suggested, that assumes that in 2010, 48% of the energy used in Europe came from coal plants and it will be completely replaced by green energy by 2050. On the other hand, in scenario *S9-EPD*, the effect of using emission intensities from EPD specifications instead of Ecoinvent 3.2 processes is investigated.

Results

In this section, the dynamics of the floor area, the material flow and embodied emissions of the building stock of Ydalir are presented and described, followed by the results from the sensitivity analysis.

5.1 Material intensity and embodied emissions by archetype

5.1.1 Material intensity by archetype

The material need per m^2 for each archetype, differentiated in 12 material categories, is presented in the left part of figure 5.1. The amount of material required by the archetypes that constitute the construction activity confirms that this activity has the larger requirement of materials when compared to the material need for the archetypes that identify renovation activities.

Both, the kindergarden and the SFHs, have a similar need for material per m^2 in the construction phase, 743 kg/m^2 and 731 kg/m^2 respectively. The school, on the other hand, has a material requirement of 1024 kg/m^2 , around 1.4 times more than the material needed from the SFH and kindergarden per m^2 . This difference can be explained by the fact that the school has larger area coverage and it is expected to require more materials for the ground and foundation, this is corroborated by the extra need for concrete, wood and minerals such as asphalt depicted in figure 5.1.

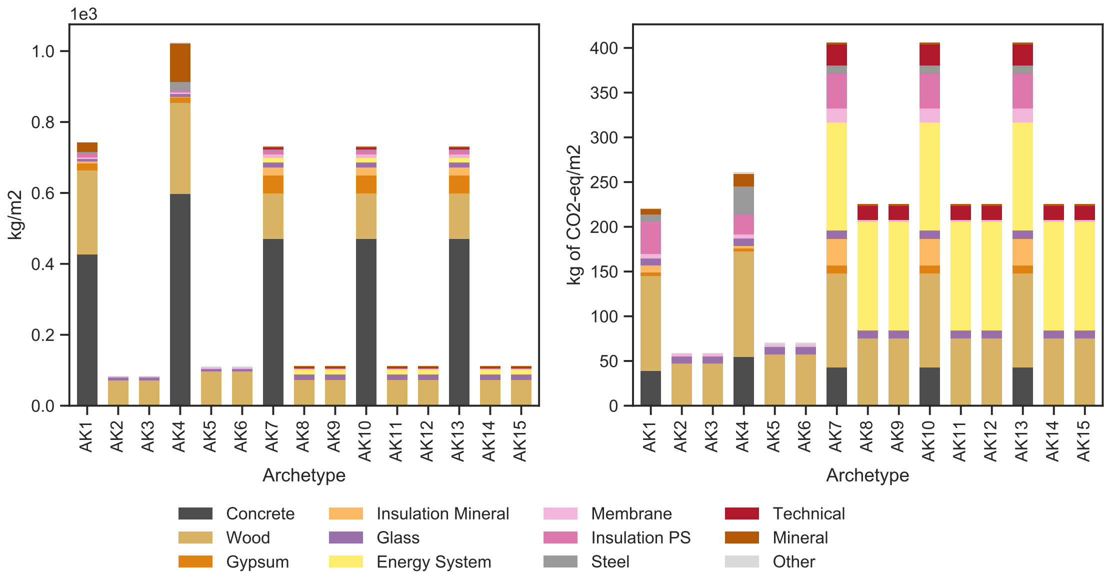


Figure 5.1: Left: Material intensity per m^2 per archetype according to material inventory. Right: Emission intensities per m^2 per archetype based on the material inventory

Concrete is the main material used in the construction process, it constitutes more than 57% of the material needed, 64% for the SFHs. The second most used material in this activity is wood which ranges between 18% for the SFHs, 25% for the school and 32% for the kindergarden. Concrete and wood represent alone between 82% and 89% of the material needed in the construction process of the SFHs, school and kindergarden.

In addition mineral materials are particularly representative for the school, 11%, when compared to the kindergarden and the SFHs, 3.5% and 0.5% respectively. Gypsum represent between 2% to 7% the material used in the construction of the buildings, 2% and 3% for the school and the kindergarden, and 7% for the SFHs. The rest of materials account for around 5% of the total material needed in the construction of the school and kindergarden, while close to 11% for the SFHs. This difference is explained by the contributions of glass, mineral insulation and the energy system, which adds up to 7% of the total material needed in the construction of the SFHs.

The renovation activity has a material requirement of 11% the material used in the construction of the kindergarden and the school, equal to 84 kg/m^2 and 110 kgm^2 respectively. The renovation of the SFHs has a higher need of material, 111 kg/m^2 which represents 15% the material used in construction.

Wood is the main material being replaced in the renovation activity for the three type of buildings. While in the school and kindergarden it represents around 87% of the material replaced, for the SFHs it accounts for 66%. This amount of wood constitutes 30%, 38% and 57% the wood used in the construction of the kindergarden, school and SFHs respectively. The kindergarden and the school also have replacement of glass, membrane and other materials (floor coverings), this constitutes the remaining 13% of material replaced in these buildings. On the other hand, the SFHs have a larger replacement of glass and energy system, accounting for 13% and 11% of the material replaced respectively. In addition, for the SFHs, the remaining 9% of replaced material are membranes, minerals and technical materials.

The material need for the second renovation resembles the material need for the first renovation for all type of buildings and cohorts as depicted in figure 5.1. Additionally, figure 5.1 shows that all SFHs, regardless of cohort, have the same material need per m^2 , as assumed.

5.1.2 Embodied emissions intensity by archetype

The embodied emissions per m^2 for the 15 archetypes is shown in the right part of figure 5.1.

In terms of construction, the kindergarden is the least emission intensive per m^2 with an embodied emission intensity of 221 kg CO_2-eq/m^2 , followed by the school with 261 kg CO_2-eq/m^2 . The SFHs has an intensity 1.8 higher than the kindergarden with 406 kg CO_2-eq/m^2 .

In terms of renovation, the renovation of the kindergarden embodies 58.5 kg CO_2-eq/m^2 , the school 70.5 kg CO_2-eq/m^2 and the SFHs 225.2 kg CO_2-eq/m^2 , the emission per m^2 for the SFHs are more than 3 times higher than those of the school.

The embodied emission per m^2 from the renovation activity of the kindergarden and school represent 27% of the embodied emissions of their construction, while 55% for the SFHs. Overall the embodied emissions per m^2 of the SFHs are higher than those of the school and kindergarden for both construction and renovation activities.

Wood and concrete dominate the embodied emissions per m^2 for the construction of the school and kindergarden. 66% of the embodied emissions in these buildings is due to the extraction and production of these two materials. 48% of emissions in the kindergarden and 45% in the school come from wood, while, 18% and 21%, for the kindergarden and the school, respectively, come from concrete.

In addition, for the kindergarden, insulation from polyestyrene (PS)represents 17% of embodied emissions, 11% from glass, steel and mineral insulation and the remaining 7% of emissions are divided in the remaining materials. Regarding the school, steel is the third material that constributes the most to total embodied emissions per m^2 , 12% of emissions are due to steel, 8% are from materials in the insulation PS category, 5% from mineral materials, 3% from glass and the other 5% is covered by the remaining materials.

Embodied emissions per m^2 from the construction of the SFHs are dominated by the emissions from the materials in the energy system which account for 30% of the total emissions, followed by 25% emissions from wood. Concrete and insulation-PS represent an extra 20%, around 10% each material category. The mineral insulation represents 7% and the materials from the technical system 5%. These 6 materials account for 89% of the embodied emissions per m^2 of the SFH. When the emissions per m^2 are compared to the amount of material needed per m^2 for the SFH, the energy system, the material in the technical system and the insulation PS material are the most emission intensive materials in terms of weight in the SFHs. Even though concrete is highly present in the material need its emission intensity per m^2 is low when compared to other materials.

In terms of embodied emissions per m^2 in the renovation activities for the school and the kindergarden, they are mostly dominated by the emissions from wood materials, which represent 80% to 82% the total emissions. When compared to the amount of wood needed per m^2 the share in the total emissions is lower than that of the share of material. Glass, on the other hand, takes a larger share of emissions when compared to the amount of material, 14% emissions of the kindergarden and 12% of the school. The remaining emissions are due to membrane and other materials.

Embodied emissions for the renovation of the SFHs are large, surpassing even the emission intensity from the construction of the kindergarden. The large embodied emissions in the renovation of the SFHs are the result of the embodied emissions from the energy system, which represent 54% of emissions, wood, which has a share of 33%, the technical system and glass. Minerals and membrane materials also contribute in the emissions from renovation but in a lower proportion. Even though the share of embodied emissions per m^2 for wood represents a lower proportion when compared to the ones from the school and kindergarden, the emissions per m^2 are higher for the SFH, 75 kg CO_2-eq/m^2 in comparison to 57 kg CO_2-eq/m^2 from the school and 47 kg CO_2-eq/m^2 from the kindergarden.

Overall, figure 5.1 shows that embodied emissions per m^2 from the construction and renovation of the archetypes not necessarily resemble the proportion of materials needed. Concrete represents the larger share of material needed in the construction of the archetypes, however is wood and the energy system the materials that contribute the most to the emissions embodied in the archetypes. In the same way, materials that are required in a small amount contribute in a larger proportion to the embodied emissions, one example of that are the insulation materials, almost all the materials have a larger contribution to the embodied emissions with respect to the share in the material requirement.

5.2 Dynamics of the neighbourhood

5.2.1 Dynamics of the floor area

The neighbourhood is characterized by 15 initial individual archetypes, each one represents certain combination of type of building, renovation stage and cohort as described before in table 4.2. In order to differentiate, understand and refer to the archetypes in the report the key in figure 5.2 has been created. Three type of buildings can be distiguished, namely a kindergarden (purple), a school (orange) and SFHs(blue, green and pink). The SFHs can also be differiantiated according to three cohorts, cohort A: 2019 to 2020 (blue) , cohort B: 2021-2025 (green) and cohort C: 2026-2030 (pink). The initial archetype that describes a particular type of building, AK1, AK4, AK7, AK10 and AK13, represents the construction of these building, while the following archetypes under the same type of building represent either the first or the second renovation phase, this are distinguished by a lighter color in figure 5.2.

The initial contruction activity takes place during 11 years, from 2019 until 2030. While the kindergarden and the school are built in 2019, the residential SFHs are built uniformely from 2019 until 2030 divided in 3 cohorts as shown in figure 5.3. In 2019 a

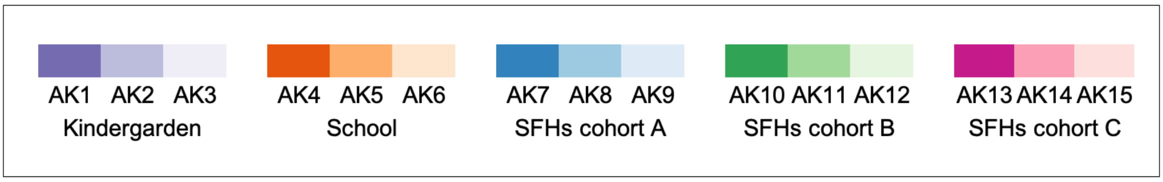


Figure 5.2: Key to understand archetypes

total of 17014 m^2 are built, the following years 8320 m^2 are built each year. The neighbourhood comprises a total built area of 108614 m^2 , of this area 92% correspond to residential SFHs, 6% represent the school and 2% the kindergarden.

Initial constructed buildings go through a first phase renovation (AK2, AK5, AK8, AK11 and AK14) as depicted in figure 5.3. This renovation starts as early as 2035 with few renovation of the SFHs from the first cohort. In 2047 the school is renovated, depicted by the long area in orange in figure 5.3, two years afters the kindergarden is renovated as well. While the renovation of the SFHs vary from year to year, the bulk of the first renovation for the residential buildings happens after 2047. All the SFHs from the first cohort are renovated by 2062, while the SFHs from the second cohort finish their renovation by 2071 and the ones from the third cohort by 2076. All the built area in the neighbourhoood (108614 m^2), goes through a first renovation phase in a period of 41 years.

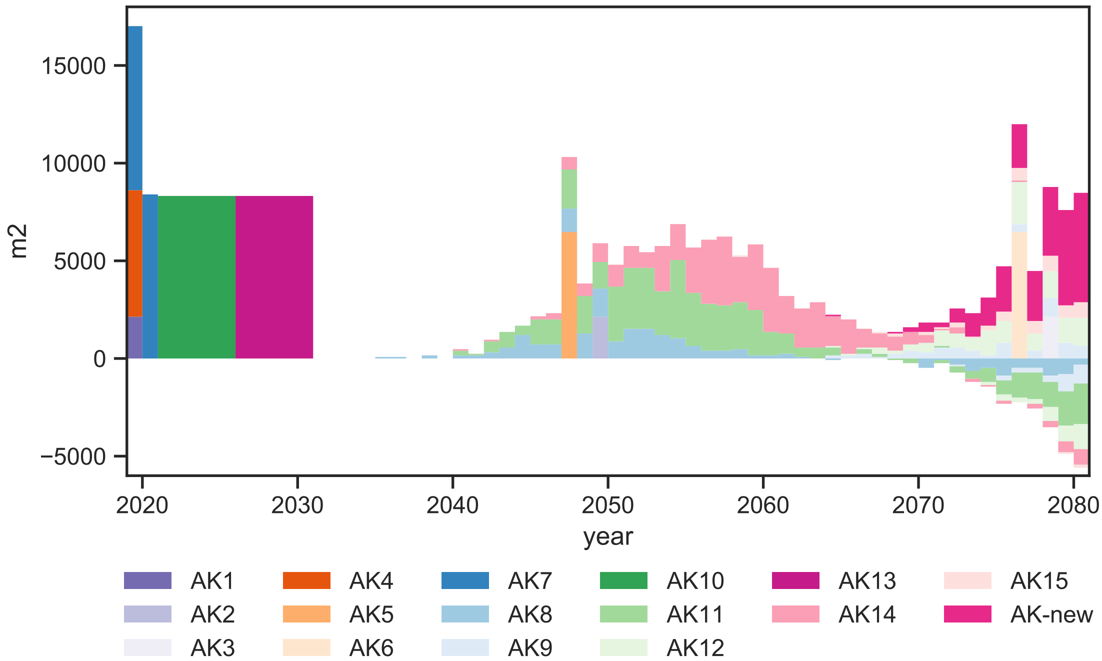


Figure 5.3: Construction, renovation and demolition of floor area in the neighbourhood over the years

Buildings that have been renovated once before can follow a second phase renovation (AK3, AK6, AK9, AK12 and AK15). The school goes through a second renovation in

2076, that is 29 years after the first renovation, this is also the case for the kindergarden that is renovated again in 2078. The SFHs go through a second renovation starting as early as 2058, 43% of the SFHs from the first cohort are renovated by 2080, while 32% and 12% from the second and third cohort, respectively, are renovated by the same year. By 2080, 31% of the neighbourhoods area has gone through a second renovation, including the school and the kindergarden, this is shown in figure 5.3 and accounts for 34214 m^2 .

Residential buildings are assumed to have a technical lifetime of 60 years. Demolition of floor area that has completed its technical lifetime is illustrated in figure 5.3 through the negative floor area. This demolished area comprises 23.6% of the area of the neighbourhood and includes SFHs that have gone through a single or two renovations phases. Due to this demolition a new construction is simulated and depicted by AK-new, it accounts for 25600 m^2 , equivalent to 160 SFHs of 160 m^2 each one. This new construction intends to preserves the demand for living space in the neighbourhood.

5.2.2 Dynamic material flow and embodied emissions

Material flow

The material flow in the ZEN of Ydalir is displayed in the upper part of figure 5.4, the material flow is separated according to the 12 material categories. From this figure, the material flow over time can be distinguished according to three time periods: (i) the initial construction period, from 2019 until 2030, the period where the bulk of the neighbourhood goes through a first renovation, from 2035 until around 2065, and the period where demolition, new construction and second renovation takes places, from around 2067 and on. The negative area shows the material that flows out of the neighbourhood due to renovation and demolition. In total 116 kton of material are needed for the construction and maintenance of the neighbourhood, table 5.1, 14% of this is used in the renovation activity and 16% in the new construction required to keep the same floor area when demolition occurs. In addition, the material outflow due to renovation and demolition equals 34 kton, 16 kton available from the first renovation and the remaining from the third period that includes demolition and second phase renovation.

The flow of material over time clearly shows that the major inflow of material occur in the initial construction phase (70% of the total material) and that the material input in the renovation phase is insignificant in comparison. There is a rapid increase in the material that is accumulated in the neighbourhood in the initial years until 2030, figure 5.5a, after this, the material accumulation remains almost constant over the years until the need for material starts increasing as the technical lifetime of the neighbourhood reaches its limits.

The flow of concrete and wood dominate completely the material flow in the neighbourhood over the years, where 80% of the flow of material is cover by these two categories. Figures 5.5a and 5.4. Concrete is without doubt the dominant flow, with a share of 55% that directly originates from the construction activity; wood, on the other hand, dominates due to its flow in both construction and renovation activities, adding 25% to the material share. The remaining 20% of materials that flow into the neighbourhood are divided in the other 10 categories, gypsum, glass and energy system being the categories that have a slight higher share.

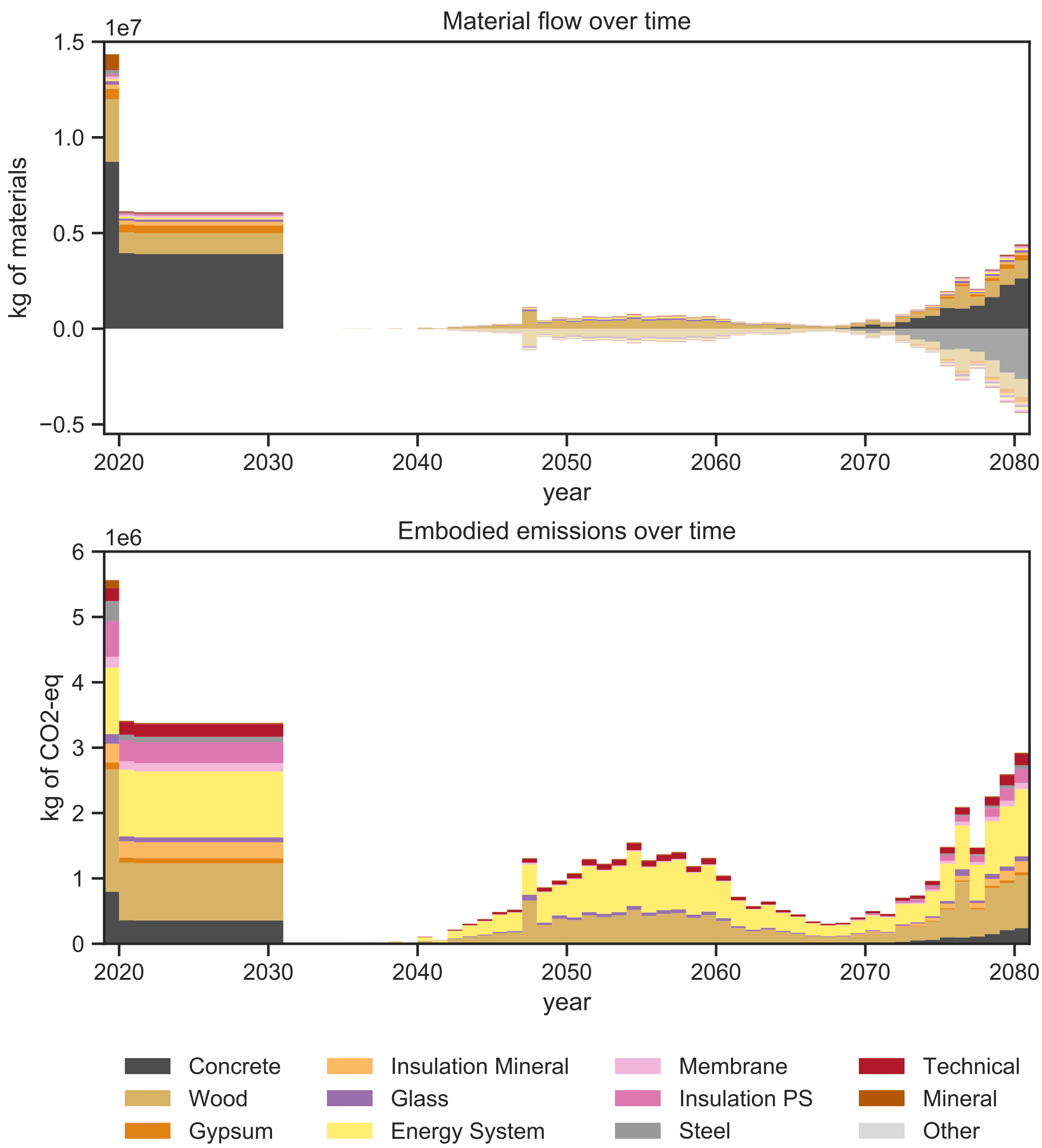


Figure 5.4: Dynamic material flow and embodied emissions by material categories

Embodied emissions

The embodied emissions in Ydalir and the contribution by the 12 material categories are displayed in the lower part of figure 5.4. In total, 82.6 kton of CO_2-eq are generated as embodied emissions, table 5.1. Taking into account the material need of the neighbourhood, Ydalir has an emission intensity of 0.71 kg of CO_2-eqCO per kg for the time period analyzed (2019 to 2080), table 5.2.

Out of the total embodied emissions, 52% are due to the initial construction, 36% due to the renovation activity and the remaining share is due to the required new construction. Possible emission-benefits from the use of the available materials that go out from renovation and demolition activities are not considered part of the boundaries of the system and therefore are not accounted in this analysis.

Table 5.1: Total material input and embodied emissions

Total use of material		Total embodied emissions	
116	kton	82.6	kton CO_2-eq
1.9	kton/year	1.35	kton CO_2-eq/year
1	ton/m^2	761	kg CO_2-eq/m^2
17	kg/m^2 /year	12	kg CO_2-eq/year/m^2

Table 5.2: Emission intensity in terms of material use for Ydalir

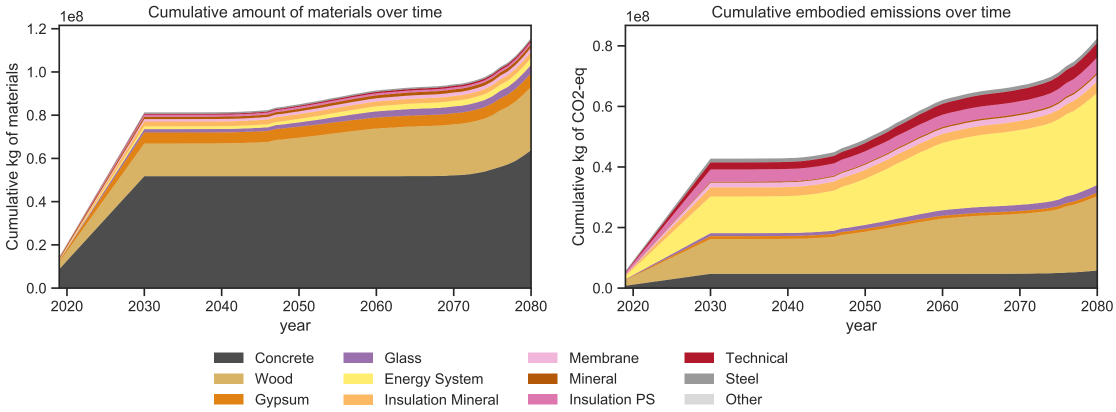
Ydalir's emission intensity
0.71 kg CO_2-eq/kg

Although the majority of embodied emissions are linked to the initial construction process, as the input of material is, the renovation activity has a larger, and not longer insignificant, share in the embodied emissions of the neighbourhood over time. This is clearly seen in 5.4. In fact, almost half of the embodied emissions of the neighbourhood are because of renovation and new construction. However this similarity in emission shares of the initial construction activity and the later activities, one important difference is the time window in which the emissions happen. While 52% of the total embodied emissions are spread in 11 years (2019 to 2030), the remaining 48% occur in a larger timeframe of around 45 years (2035 to 2080).

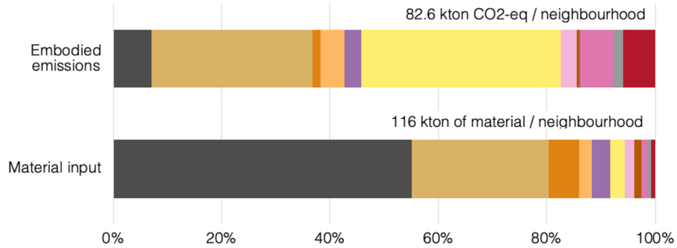
The total embodied emissions are highly dominated by the embodied emissions in the materials of the energy system, particularly the PV panels, and wood materials, with a share of 37% and 30%, respectively. Concrete, insulation-PS, and technical materials are the next material categories that contribute the most, together they complete 20% of the total emissions.

When comparing the material input and the embodied emissions of the neighbourhood for each of the material categories, figure 5.5b, one evident difference is the high contribution of concrete in the material input and its rather insignificant contribution to the overall embodied emissions. Contrary is the case of wood, which has a similar share in material input (25%) and embodied emissions (30%). Other materials such as insulation-PS, mineral insulation, and technical material have also and evident low share in terms of weight and a higher contribution in the embodied emissions.

Figure 5.6 shows the relation between the embodied emissions and the amount of material use in the baseline case of Ydalir, the energy system has the higher relation followed by the technical system and the insulation-PS, a value close to 1 indicate that the embodied emissions from those materials compare to the amount of material used, higher values indicate that the material is more emission intensive in terms of weight and viceversa for the opposite case.



(a) Cumulative input of material and embodied emissions over time



(b) Total input of material and embodied emissions

Figure 5.5: Cumulative material and embodied emissions in Ydalir

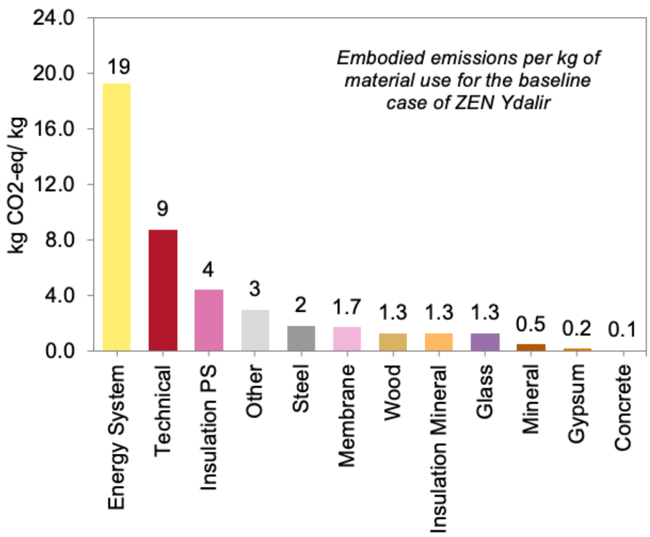


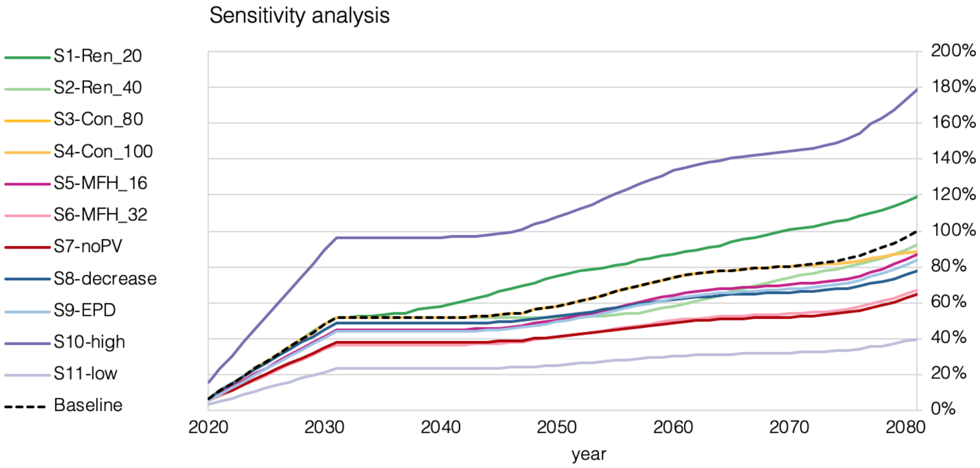
Figure 5.6: Total embodied emissions per total material use by material category in Ydalir for a 60 year timeframe

5.3 Sensitivity analysis

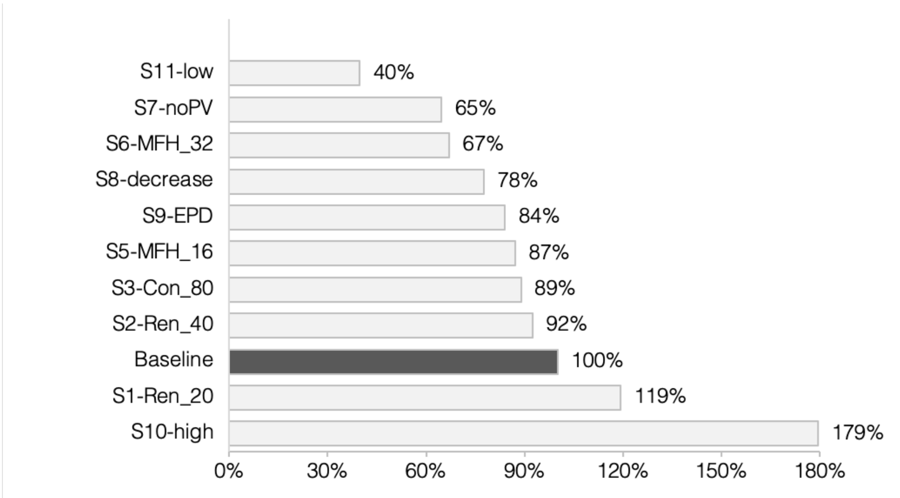
Results from the sensitivity analysis are shown and explained in this section. Initially, results for the 11 sensitivity scenarios are presented, then follows results from the sensitivity analysis of emission intensities for the 12 material categories.

5.3.1 Sensitivity scenarios based on parameters

Figure 5.7 shows how the cumulative emissions over time for the 11 scenarios compare to the baseline scenario.



(a) Cumulative embodied emissions over time for 11 sensitivity analysis scenarios



(b) Percentual change of total embodied emissions relative to the baseline scenario for 11 sensitivity analysis.

Figure 5.7: Total embodied emissions for 11 sensitivity analysis scenarios realtive to the baseline case

The scenarios that explore different renovation rates, *S1-Ren20* and *S2-Ren40*, indicate that renovation rates influence the total embodied emissions of the neighbourhood in the timeframe used. While a renovation rate that makes replacements every 20 years could increase 20% the embodied emissions by 2080, extending the replacement mean from 30 to 40 years would signify 8% less embodied emissions by 2080, delaying the embodied emissions from renovation. This signals that the effect of renovation rates on embodied emissions is greater for higher rates than for lower rates. This, however, does not account for the technical lifetime of the house and the impact that a late renovation would have on the technical lifetime of the building.

In terms of technical lifetime, increasing the mean of the technical lifetime distribution to 80 and 100 years, *S3-Con80* and *S4-Con100*, has the same effect for both cases. This makes sense since the effects of extending the technical lifetime of buildings more than 60 years go beyond the timeframe assessed, indeed a longer lifetime imply a delay in demolition or deep renovation and so the need for more construction or more extensive renovation. The trajectory of these scenarios in figure 5.7 demostrate that the 11% reduction is achieved the last years when there is still no need for more construction.

When it comes to replacing the construction of SFHs by MFHs, scenarios *S5-MFH16* and *S5-MFH32*, show that total embodied emissions are reduced from 13% to even 33% by 2080. The scenario that test MFHs that are built in sets of 32 units have the larger reduction. In addition, the trajectory of the two scenarios show that the reduction manifest itself from the initial construction and until 2080.

The influence of the PV panels is tested by the scenario *S7-noPV*, 35% reduction of total embodied emissions is achieved by excluding PV panels from the material inventory of SFHs. This results corroborates once again that PV-panels have an influential role in the embodied emissions of the neighbourhood. Another interesting finding from this scenario is that a similar reduction with a similar pathway is achieved by the *S5-MFH32* scenario. This is related to the fact that for *S5-MFH32* the available roof area changes and the number of solar panels is halved.

Reducing 40% the emission intensity of materials over time until 2050, scenario *S8-decrease*, result in a 22% decrease in total embodied emissions, while using emission intensities from EPDs in Norway, scenario *S9-EPD*, accomplishes 16% of emission savings. Scenario *S9-EPD* have lower reduction the first 45 years, until around 2055, when scenario *S8-decrease* takes over and achieves and extra 6% emission cutback by 2080. The trajectory of both scenarios suggest that emission intensities for the scenario *S8-decrease* are lower than those from *S9-EPD* by 2050 and forward, thus new consruction is less emission intensive for *S8-decrease*.

Scenarios *S10-high* and *S11-low* show the results from the extreme cases where the effect of using the highest or lowest emission intensity value in the material category, for all categories, is aggregated. For the highest values, total embodied emissions could be augmented as much as 79% more, while using the lowest values could change the embodied emissions result as much as 60% less the emissions from the baseline case.

5.3.2 Sensitivity to emission intensities of materials

Figure 5.8 presents the results from the sensitivity analysis based on the emission intensities variation for the 12 material categories. The graph represents the change in total embodied emissions with respect to the baseline scenario when a material category is subject to the highest, average and lowest emission intensity value of the category in accordance to figure 4.6. Results in this analysis are useful mainly for two things: first, it allows to identify the sensitivity of total emissions to uncertainty in the selection of material specifications and emission intensities, and second, if there is certainty in the material selection, it shows the potential of increasing or reducing the carbon intensity of the material for the sake of the total embodied emission of the neighbourhood.

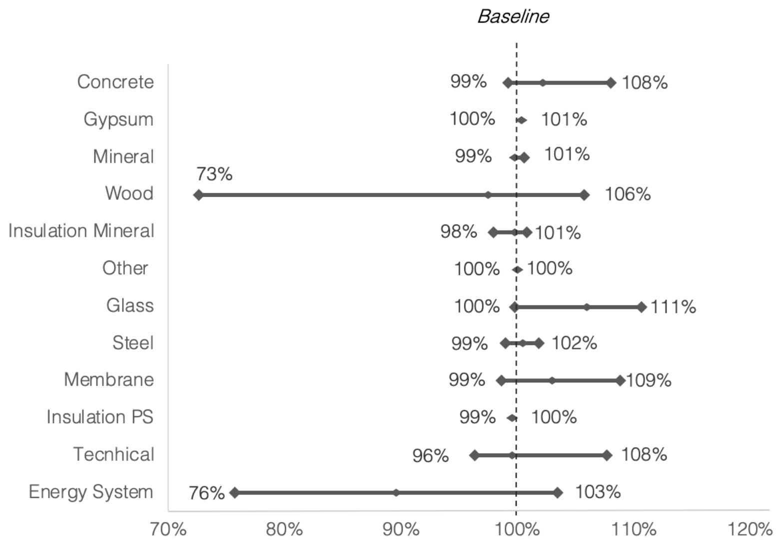


Figure 5.8: Change in total embodied emissions according to change of emission intensity of material categories

The figure hints of where the weighted average of the category lies, in comparison to the average, lowest and highest values of the category. Understanding as weighted average the value that also considers the amount of material used for the different material specifications, represented by the *Baseline* reference. For the material categories concrete, glass, steel and membrane, the weighted average has a lower value than the normal average. This means that for those categories, the material specifications with low emission intensities are more representative in the baseline case. In the case of wood and the energy system the opposite is true, the weighted average is higher than the normal average, which means that higher carbon intensive materials dominate the category when the amount of material used is considered.

In addition, the results suggest that the total embodied emissions are more sensible to the emission intensities used in the material categories of concrete, glass and membrane. Changes in selection of materials could change the result up to 11%, as it is the case for glass.

The same applies for wood materials, where according to the different emission intensities of the category the weight average could be reduce and so the embodied emissions would do. A weigthed average greater than the average could suggest that more high carbon intensive wood is being used.

The technical and energy system material categories, are special because even though the results in figure 5.8 show that this material categories have a large variation according to the emission intensities of the categories, the certainty in the selection of the material specifications is high due to the nature of this category. Thus, results in figure 5.8 for these categories indicate the potential of reducing emission intensities of the technology itself and not the uncertainty of the model.

The results for other materials such as gypsum, mineral, mineral insulation, other, insulation PS and even steel hints that total embodied emissions are less sensible to choices and matches of materials from these categories and the effects of chosing materials with higher or lower emission intensities values, as long as part of the range illustrated in 4.6, will still keep the overall results somehow certain.

Discussion

The dynamic model of the building stock of Ydalir indicates that construction and renovation activities mobilize a total of 116 kton of materials with 82.6 kton CO_2-eq of embodied emissions between 2019 and 2080. This means that the building stock of Ydalir has an embodied emission intensity of 0.71 kg CO_2-eq/kg.

Although the building stock in Ydalir consist of a school, a kindergarden and SFHs, material use and embodied emissions of the neighbourhood are mainly induced by those of the SFHs. This is due to the fact that 92% of the total area built is SFHs. Yet, the construction and maintenance of the school and kindergarden imply peaks in material need and embodied emissions because of their large areas.

Initial construction of buildings is the activity that drives most use of materials and embodied emissions, 70% of materials and 52% of embodied emissions. While the amount of material used in the renovation stages is minuscule when compared to that of the construction activity, the case for embodied emissions is different. More than one third of embodied emissions are attributed to renovation stages, of which more that three-quarters are cause by replacements of PV panels and wood.

The major source of embodied emissions are the PV panels that are part of the energy system in the SFHs. This element is critical for the neighbourhood not only because of its high carbon intensity, 10.55 kg of CO_2-eq/kg, but also because it needs to be replaced every 30 years. The effect of replacing PV-panels is clearly shown in figure 5.6, where the embodied emissions per kg for the energy system become 19 kg of CO_2-eq/kg in the context of Ydalir. The renovation of PV panels alone induce 19% of the total embodied emissions.

The model also shows that wood is the second most used material in the neighbourhood, as well as the second most accountable for the neighbourhood's embodied emissions. While the amount of wood used in the construction process is less than half the amount of concrete, it is the need to replace wood what rises the significancy of the contributions of this material. Even though this category include a diverse range of emission intensities, as seen in figure 4.6, the average emission intensity of this category is not particularly high when compared to other material categories, this hints that what makes relevant this material is the combination of amount of material used and its emission intensity, changes on one or another are relevant for the system.

When it comes to material flow, concrete is without doubt the material that dominates the material requirement of the neighbourhood, where more than half of the material input to the neighbourhood is concrete. In addition, the need for concrete is exclusively linked to the construction activity which is expected to happen in the following 12 years and again after 2070. What strikes the most is that despite concrete being a fundamental material for the construction of buildings, its contribution to the embodied emissions of the neighbourhood is considerably low, with a share of less than 10%.

When the size of the neighbourhood and timeframe is considered, Ydalir has an embodied emission of 12 kg CO_2-eq/m^2 /year. This value is half the estimated embodied emissions of a neighbourhood in Australia found by Stephan et al. (2013), which reported 27 kg CO_2-eq/m^2 /year for embodied emissions, of which 18 kg CO_2-eq/m^2 /year are presumably attributed to the building stock. In addition, the study from Lausselet et al. (2018) reported 4.5 kg CO_2-eq/m^2 /year of embodied emissions from the building stock of a zero emission neighbourhood analysis. Even though the result in the present study and in the one from Stephan et al. (2013) and Lausselet et al. (2018) are subject to uncertainties, that the values are in the same order of magnitude and hold certain proximity indicate that the results from this model are trustworthy.

6.1 Strengths and limitations

The main strength of the model developed is that is dynamic and detailed. By treating each building of the stock as an object and keeping track of its evolution over time, the need to make assumptions about the distribution of the stock or the renovation shares is reduced. In addition, using detailed material inventories closes the uncertainties gaps in material estimations and provide more precise results. The detail of the model make it more transparent and comprehensible and the results easier to understand. In addition, understanding the evolution of embodied emission and material flows of a neighbourhood over time is useful to taylor strategies that can reduce the embodied emissions and reuse materials.

The model is robust because its methodology is thorough, transparent and detailed, yet, certain assumptions and lack of knowledge about the future limits the certainty and exactitude of the results:

When it comes to the construction activity, it was assumed that the construction of the residential area is homogenoeus over the years and until 2030. It is likely that this will not be the case given that there are external factors like demand for living and economic viability that influence the construction process. Even though the effects of distributing construction differently was not tested, it is evident that a later construction will delay the renovation and demolition activities reducing the total embodied emissions by 2080.

On the other hand, it was assumed that all residential buildings that are constructed will be SFHs. In reality, the residential area will be composed of a combination of SFHs and apartment blocks. The extend to which this could change the total embodied emissions of the neighbourhood was tested by assuming MFHs instead of SFHs, reaching a reduction of even 33% for the case where the MFHs included more residential units. The results obtained from these scenarios prove the importance of the type or types of building that are chosen to be constructed. Indeed a SFH is more material intensive than a unit in a MFH or AB, not only SFHs do not share outer walls and roof with other houses but also SFHs tend to be bigger. Yet, the result obtained for the MFHs are limited because their material inventory was based on the material inventory of the SFH, it is plausible that a MFHs will have other material requirements as well, specially if it has multiple stories. In addition, part of the reductions attained in these scenarios emerge from reducing the amount of PV panels used due to roof space.

Another important point regarding the SFHs is that the material inventory used is part of a ZEB concept analysis that is mostly focused on a operation ambition (O) rather than operation and embodied emissions ambition (OM). Using a material inventory of a building that is also design to reduce embodied emissions would definitely have a positive impact on the embodied emissions of the neighbourhood. As an example, already using carbon efficient materials from Norway lowers the emission intensity of the buildings as shown in appendices A.4.

One difficulty when modeling the development of a building stock is to predict renovation rates and its distribution over time. For Ydalir, renovation is modeled using a normal distribution function with a mean of 30 years and it is assumed that all the stock is renovated. In addition, the mean chosen is consistent with the 30 years lifetime of the materials that need to be replaced. In reality, renovation rate is one of the parameters that are more uncertain and difficult to predict and it could be that the renovation happens earlier or later in the lifetime of the building, this is linked with the performance of the material and its need to be replaced but also with the willigness of the owner of the building to renovate. It could also be that the building does not go through renovation at all. Even though the distribution function is meant to contain these uncertainties. The sensitivity analysis shows that total embodied emissions could increase up to 20% if renovation is intensified, and decrease as much as 8% the later it happen.

Along these lines lie also the uncertainty of the materials and quantities that are actually replaced. The material inventories that reflect the renovation activity were developed based on the lifetime of materials reported by (Kristjansdottir et al., 2018) and the lifetimes reported by the EPD specification or the Ecoinvent process, where many times the information of one source was not supported by the other source. Indeed, there is a degree of uncertainty in the predictions made about the specifications that are replaced. This specially applies for the wood category, which includes 19 different specifications making it difficult to predict the specification that needs to be replaced. Selecting the right specification for the wood category is particularly important because of its equally important contribution in material amount and embodied emissions, but also because this category has a diverse range of emission intensities which could easily change the amount of wood replaced for each specification, changing in turn the embodied emissions.

Indeed, selecting the right specification with the right emission intensity in the material inventories is important. This specially applies for concrete, wood, glass and membrane materials which have a major potential of changing the total embodied emissions.

In the case of concrete, the emission intensities for the different concrete specifications that are used in the model are low as depicted in figure 4.6. However, the use of more carbon intensive concrete can result in a significant increase on the overall embodied emissions of the neighbourhood, where the sensitivity analysis shows that an increase of an average intensity of 0.09 kg CO_2-eq/kg to 0.19 kg CO_2-eq/kg already result in a 8% increase in total embodied emissions. Although 0.19 kg CO_2-eq per kg of concrete can be considered a low carbon emission, specially when compared to other material's carbon intensities, the large amount of concrete used in the neighbourhood is the determinant factor in this case.

6.2 Strategies and policy implications

Many of the assumptions made limit the certainty of the results for Ydalir, nevertheless from the findings of this thesis some strategies in relation to embodied emissions and material flow of a neighbourhood's building stock can be already pinpoint:

One of the most straightforward ways of reducing the embodied emissions of the neighbourhood is to delay the construction process. By doing so, not only the embodied emissions from the construction process are delayed, but also the renovation process and associated embodied emissions would be. This strategy, however, is subject to the specific context of the neighbourhood, for example, it may not be possibe to reduce the construction of living space if there is a demand for it. In addition, even though delaying emissions is not the same as reducing emissions, it should be consider and strategy due to the limited carbon budget for the next years.

Considering that the renovation is more unpredictable and difficult to control, predicting the material flows and embodied emissions in the construction activity is valuable, in order to reduce uncertainties. A good way to predict and control the emission embodied in construction is by determining beforehand the split of types of buildings that will be constructed in the neighbourhood. A first step could be to test and find the optimal number and types of buildings that would fulfill the requirement of the neighbourhood.

While it is difficult to predict in advance what will be the design and material need of a building, implementing a requirement that would limit the embodied emission intensity of a buildings, for instance in kg CO_2per kg of material, could be an initial strategy to keep the embodied emissions of the building stock under control and predictable. The architects can focus on keeping their designs under the emission intensity given. The materials chosen, emission intensities and lifetimes would be balanced out to stay under the limit established.

In the same lines, this applies for the neighbourhood, restricting the embodied emission intensity for the building stock could be implemented as a guideline to design the neighbourhood and control the embodied emissions from the building stock. Nevertheless, before implementing a measure of the sort a generic definition of neighbourhood would be needed in which at least the timeframe of analysis, or lifetime of neighbourhood is agreed upon.

In addition, the predictions of material outflow can be used to identify opportunities to reuse or recycle these resources. For instance, in the short term, when renovation occurs, it can be investigated to what extend the same material or part of it could be reused again in the building stock or in other systems within the neighbourhood, for instance the PV panels. In the long term, the anticipated knowledge of how much and what material are flowing out can be used to plan new construction or other activities that will take advantage of those resources.

6.3 Future research

The results indicate that the PV panels represent the main contributors to the embodied emission of the building stock in the neighbourhood. In order to understand the real benefit and use of implementing PV panels, a model that looks at the energy system of the neighbourhood is needed. In addition, estimating the energy demand and energy production of the building stock would give insights on how much of the emissions are balanced by the energy system and if the extra embodied emissions are justified. The model developed by Næss et al. (2018) can be used to accomplish this.

In addition, it would be interesting to integrate the findings of this project with analysis of the mobility, services and infrastructure of Ydalir. Understanding the emission intensities of each part of the neighbourhood over time is necessary to predict emissions and design ZEN.

There is potential to use the materials that flow out of the neighbourhood, The model helps to predict and quantify these materials. This information can be further use to explore the emission benefits of using those materials and encourage a circular economy.

The uncertainty in the embodied emissions calculated for Ydalir could be reduce if the modeling of the neighbourhood resemble the characteristics of the future Ydalir better. To achieve that, parameters such as type of buildings and their construction distribution could be investigate more in detail and model again.

In relation to this, it is also worth analysing what is the level of certainty that is acceptable and desired when the emissions of a neighbourhood and its parts are modeled. Answering this question can point out directions for further research. If more certainty and accuracy is desired models that are more detailed and taylored to the specific cases can keep being seek on. However, if the level of certainty is already acceptable research can be guide in other directions. In order to answer this question, the sensibility of the neighbourhood to uncertainties in its different parts could be investigated, from this, certainty tresholds could be created based on the point where the emissions of a neighbourhood are contained within and acceptable range of uncertainty.

Conclusion

The model developed achieves the goal of estimating the dynamic material flow and associated embodied emissions of a neighbourhood. For the case of Ydalir, the total input ot material is 116 kton which generates 82.6 kton CO_2-eq.

Construction of the building stock is the major driver of materials and emissions, however emissions from renovation activity are also significant. The PV-panels and wood are the materials that contribute the most to the embodied emissions of the neighbourhood. The flow of concrete is important but its emissions are insignificant due to the lower emission intensities used for this material.

The sensitivity analysis suggests that variations in renovation rates, material inventories and emission intensities of materials have an effect in the total embodied emissions, with room to reduce embodied emissions. The sensitivity analysis also shows that the material specifications and emission intensities that are selected in the material categories of concrete, wood, glass and membrane can have a greater impact in the total embodied emissions for the case of Ydalir.

The model is robust because the methodology is thorough an transparent, however, to increase certainty in the case study of Ydalir, some assumptions can be improved, for instance the split of residential buildings, the distribution of their construction over the years and their material inventories.

In order to understand the value of the results obtained in this thesis, it is suggested to include a energy analysis of the model. In addition, it would be interesting to integrate the findings of this project with analysis of the mobility, services and infrastructure of Ydalir. The model can also be used to investigate alternatives to reuse and recycle materiasl that flow out in renovation and demolition processes, where one possibility lies in using the resources within the neighbourhood.

Among the strategies that were identified that could be implemented to reduce embodied emissions of a neighbourhood is to establish limit values for the embodied emission intensities of a building stock. Architects and city planners would balance out material choices and emission intensities to keep their designs within the limits. This could help restrict the embodied emissions of a neighbourhood but also it would be useful to develop models that predict future emissions with more accuracy.

References

Anderson, J. E., Wulfhorst, G., & Lang, W. (2015). Energy analysis of the built environment—a review and outlook. *Renewable and Sustainable Energy Reviews*, *44*, 149 - 158. Retrieved from `http://www.sciencedirect.com/science/article/pii/S136403211401079X` doi: https://doi.org/10.1016/j.rser.2014.12.027

Augiseau, V., & Barles, S. (2017). Studying construction materials flows and stock: A review. *Resources, Conservation and Recycling*, *123*, 153 - 164. Retrieved from `http://www.sciencedirect.com/science/article/pii/S092134491630235X` doi: https://doi.org/10.1016/j.resconrec.2016.09.002

Bremvåg, A., Gustavsen, A., & Hestnes, A. G. (2017). Annual report 2017. In *Research centre on zero emission neighbourhoods in smart cities.* Fagtrykk Trondheim AS.

Bribián, I. Z., Capilla, A. V., & Usón, A. A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment*, *46*(5), 1133 - 1140. Retrieved from `http://www.sciencedirect.com/science/article/pii/S0360132310003549` doi: https://doi.org/10.1016/j.buildenv.2010.12.002

Dokka, T. H., Kristjansdottir, T., Time, B., Mellegård, S., Haase, M., & Tønnesen, J. (2013). A zero emission concept analysis of an office building. *SINTEF Academic Press*.

Dokka, T. H., Wiberg, A. H., Georges, L., Mellegård, S., Time, B., Haase, M., ... Lien, A. G. (2013). A zero emission concept analysis of a single family house. In S. A. Press (Ed.), *Zeb project report 9.* SINTEF Academic Press.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Kadner, S., Minx, J. C., & Brunner, S. (2014). Technical summary. In *Climate change 2014: Mitigation of climate change.* Cambridge University Press, Cam- bridge, United Kingdom and New York, NY, USA.

Fufa, S. M., Schlanbusch, R. D., Sørnes, K., Inman, M., & Andresen, I. (2016). A norwegian zeb definition guideline. In *The research centre on zero emission buildings.* SINTEF Academic Press.

Heeren, N., Mutel, C. L., Steubing, B., Ostermeyer, Y., Wallbaum, H., & Hellweg, S. (2015). Environmental impact of buildings—what matters? *Environmental Science & Technology*, *49*(16), 9832-9841. Retrieved from `https://doi.org/10.1021/acs.est.5b01735` (PMID: 26176213) doi: 10.1021/acs.est.5b01735

Hofmeister, T. B., Kristjansdottir, T., Time, B., Aoife Houlihan Wiberg Tobias Barnes Hofmeister, B. T., Torhildur Kristjansdottir, & Wiberg, A. H. (2015). Life cycle ghg emissions from a wooden load-bearing alternative for a zeb office concept. *SINTEF Academic Press*.

Inman, M. R., & Wiberg, A. H. (2015). Life cycle ghg emissions of material use in the living laboratory. *SINTEF Academic Press*.

Kristjansdottir, T. F., Heeren, N., Andresen, I., & Brattebø, H. (2018). Comparative emission analysis of low-energy and zero-emission buildings. *Building Research & Information*, *46*(4), 367-382. Retrieved from https://doi.org/10.1080/09613218.2017.1305690 doi: 10.1080/09613218.2017.1305690

Kylili, A., & Fokaides, P. A. (2015). European smart cities: The role of zero energy buildings. *Sustainable Cities and Society*, *15*, 86 - 95. Retrieved from http://www.sciencedirect.com/science/article/pii/S2210670714001383 doi: https://doi.org/10.1016/j.scs.2014.12.003

Lausselet, C., Borgnes, V., & Brattebø, H. (2018). Lca modelling for zero emission neighbourhoods in early stage planning. *Building and Environment*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0360132318307777 doi: https://doi.org/10.1016/j.buildenv.2018.12.034

Li, D. H., Yang, L., & Lam, J. C. (2013). Zero energy buildings and sustainable development implications – a review. *Energy*, *54*, 1 - 10. Retrieved from http://www.sciencedirect.com/science/article/pii/S0360544213001035 doi: https://doi.org/10.1016/j.energy.2013.01.070

Lotteau, M., Loubet, P., Pousse, M., Dufrasnes, E., & Sonnemann, G. (2015). Critical review of life cycle assessment (lca) for the built environment at the neighborhood scale. *Building and Environment*, *93*, 165 - 178. Retrieved from http://www.sciencedirect.com/science/article/pii/S0360132315300445 doi: https://doi.org/10.1016/j.buildenv.2015.06.029

Lotteau, M., Yepez-Salmon, G., & Salmon, N. (2015). Environmental assessment of sustainable neighborhood projects through nest, a decision support tool for early stage urban planning. *Procedia Engineering*, *115*, 69 - 76. Retrieved from http://www.sciencedirect.com/science/article/pii/S1877705815016392 (Toward integrated modelling of urban systems) doi: https://doi.org/10.1016/j.proeng.2015.07.356

Lucon, O., Ürge-Vorsatz, D., Ahmed, A. Z., Akbari, H., Bertoldi, P., Cabeza, L. F., ... Vilariño, M. V. (2014). Buildings. In *Climate change 2014: Mitigation of climate change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Marszal, A., Heiselberg, P., Bourrelle, J., Musall, E., Voss, K., Sartori, I., & Napolitano, A. (2011). Zero energy building – a review of definitions and calculation methodologies. *Energy and Buildings*, *43*(4), 971 - 979. Retrieved from http://www.sciencedirect.com/science/article/pii/S0378778810004639 doi: https://doi.org/10.1016/j.enbuild.2010.12.022

Næss, J. S., Sandberg, N. H., Nord, N., Vestrum, M. I., Lausselet, C., Woszczek, A., ... Brattebø, H. (2018). Neighbourhood building stock model for long-term dynamic analyses of energy demand and ghg emissions. In *Zen report no.2 - 2018.* ZEN Research Centre.

Rashid, A. F. A., & Yusoff, S. (2015). A review of life cycle assessment method for building industry. *Renewable and Sustainable Energy Reviews*, *45*, 244 - 248. Retrieved from http://www.sciencedirect.com/science/article/pii/S1364032115000532 doi: https://doi.org/10.1016/j.rser.2015.01.043

Sartori, I., Andresen, I., Wolfgang, O., Sørensen, Å. L., Wiik, M. K., & Fufa, S. M. (2017). Zero emission neighbourhoods in smart cities: Definition, key performance indicators and assessment criteria: Zero emission neighbourhoods in smart cities: Definition, key performance indicators and assessment criteria: Version 1.0. In *Zero* *emission neighbourhoods in smart cities.*

Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*, *39*(3), 249 - 257. Retrieved from `http://www.sciencedirect.com/science/article/pii/S0378778806001873` doi: https://doi.org/10.1016/j.enbuild.2006.07.001

Sharma, A., Saxena, A., Sethi, M., Shree, V., & Varun. (2011). Life cycle assessment of buildings: A review. *Renewable and Sustainable Energy Reviews*, *15*(1), 871 - 875. Retrieved from `http://www.sciencedirect.com/science/article/pii/S1364032110002959` doi: https://doi.org/10.1016/j.rser.2010.09.008

Stephan, A., Crawford, R. H., & de Myttenaere, K. (2013). Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in melbourne, australia. *Building and Environment*, *68*, 35 - 49. Retrieved from `http://www.sciencedirect.com/science/article/pii/S0360132313001819` doi: https://doi.org/10.1016/j.buildenv.2013.06.003

Torcellini, P. A., Pless, S., Deru, M., & Crawley, D. B. (2006, 08/2006). *Zero energy buildings: A critical look at the definition.* Pacific Grove, CA, USA.

Wiik, M. K., Fufa, S. M., Kristjansdottir, T., & Andresen, I. (2018). Lessons learnt from embodied ghg emission calculations in zero emission buildings (zebs) from the norwegian zeb research centre. *Energy and Buildings*, *165*, 25 - 34. Retrieved from `http://www.sciencedirect.com/science/article/pii/S037877881733709X` doi: https://doi.org/10.1016/j.enbuild.2018.01.025

Appendices

Appendices A

A.1 Inputs to the dynamic stock model

The following images show the parameters that were used to calculate the dynamic stock in their respective templates.

Construction activity

NOTE: This sheet is imported to Matlab b

Construction input

Year	New building ID [#]	Building name (if applicable)	Connected to existing building ID in initial stock? {# ID, 0}	Number of identical buildings [#]	Floor area type, dropdown list [string]	Units per building [units/building]	Average heated floor area per unit [m2/unit]
2020	100004	DD2019-20	0	105	Single Family House	1	80.0
2021	100005	DD2021-25	0	104	Single Family House	1	80.0
2022	100006	DD2021-25	0	104	Single Family House	1	80.0
2023	100007	DD2021-25	0	104	Single Family House	1	80.0
2024	100008	DD2021-25	0	104	Single Family House	1	80.0
2025	100009	DD2021-25	0	104	Single Family House	1	80.0
2026	100010	DD2026-30	0	104	Single Family House	1	80.0
2027	100011	DD2026-30	0	104	Single Family House	1	80.0
2028	100012	DD2026-30	0	104	Single Family House	1	80.0
2029	100013	DD2026-30	0	104	Single Family House	1	80.0
2030	100014	DD2026-30	0	104	Single Family House	1	80.0

Figure A.1: Template with paramaters to define construction

Type and cohort definition

Cohorts		
Cohort ID [#]	From Year [year]	To Year [year]
1	2019	2020
2	2021	2025
3	2026	2030
4	2031	2080

Floor area type class				Renovation, distribution parameters Normal	
Class ID [#]	Class name [string]	Number of subvariants given [#]	or service Class? {Residential,	Mu [#]	Sigma [#]
1	Single family house	1	Residential	30	5
2	School	1	Service	30	2
3	Kindergarden	1	Service	30	2

Figure A.2: Template with paramaters that define cohorts, floor area type and renovation function

Initial stock INPUT at start year

NOTE: This sheet is imported to Matlab by importInitialBu

Building data								
Building input ID [#]	Building name (if applicable) [string]	Construction year [year]	Number of identical buildings [#]	Floor area type, dropdown list [string]	Number of units per building [#]	Average heated floor area per unit [m2/unit] [m^2/unit]	Renovation state {1-3}	Previous renovation {Year, 0=unknown}
100000	DD2019-20	2019	105	Single Family House	1	80	1	0
100001	School	2019	1	School	1	6474	1	0
100002	Kindergarden	2019	1	Kindergarden	1	2140	1	0

Figure A.3: Template with paramaters that define initial stock

Demolition input parameters

Distribution		Demolition, distribution parameters Weibull				Normal	
	Chosen demolition distribution {Weibull, Normal}	Average lifetime [year]	Period of years without demolition [year]	Scale parameter a [#]	Shape parameter b [#]	Mu [#]	Sigma [#]
Residential buildings	Normal					60	5
Service buildings	Normal					60	5

Figure A.4: Template with parameters that define demolition function

A.2 Material inventories

This section includes the detailed material inventories for the school, kindergarden and SFH.

Material inventory for the school:

#	Building Part	Material specification	Amount in kg	Lifetime
1	2.1 Groundwork and foundations	Isolasjon, EPS 80 (EPS Gruppen)	113	60
2	2.1 Groundwork and foundations	Isolasjon, EPS 80 (EPS Gruppen)	19062	60
3	2.1 Groundwork and foundations	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	1737096	60
4	2.1 Groundwork and foundations	Stål, armeringsprodukter (betongarmering), 7850kg/m3, scrap metall	25988	60
5	2.1 Groundwork and foundations	Stålfiber til betongarmering, 1250, 1100, 1100 Mpa, L:35, 5	11635	60
6	2.1 Groundwork and foundations	XPS isolasjonsplate 33 mm, 300KPa, 0.033 - 0.039 W/mK,	5416	60
7	2.1 Groundwork and foundations	Radon- og fuktmembran for byggeplass, PP…	4682	60
8	2.2 Superstructure	Limtre, 470 kg/m3, 12% moisture content (Moelven Modus)	32198	60
9	2.2 Superstructure	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	10063	60
10	2.2 Superstructure	Ferdigbetong, ekskludert armeringsstål, C35/45 (B35 M40) (Sa…	1582	60
11	2.2 Superstructure	Stål varmvalset, I, H, U, L, T, og vide flater (EMV Construction)	1758	60
12	2.2 Superstructure	SØYLE, B45 M45 (Spenncon)	82	60
13	2.2 Superstructure	Stål, armeringsprodukter (betongarmering), 7850kg/m3, scrap metall	394	60
14	2.2 Superstructure	Standard limbjelke, 470 kg/m3, Moisr. 12%, 45 mm, Stranda…	6768	60
15	2.3 Outer walls	Bindingsverksystem av tre for yttervegger per kvm (inkl. Luft…	75123	60
16	2.3 Outer walls	Bindingsverksystem av tre for yttervegger per kvm (inkl. Luft…	223173	60
17	2.3 Outer walls	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	761558	60
18	2.3 Outer walls	Gipsplate, 12.5 mm, 9 kg m2, Normal - Standard (Gyproc)	8645	60
19	2.3 Outer walls	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	259144	60
20	2.3 Outer walls	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	762	60
21	2.3 Outer walls	Heltrepanel av bartre til innvendig bruk (Treindustrien)	19845	60
22	2.3 Outer walls	Malm100, 513.32 kg/m3, Malm 100 (Moelven)	46117	30
23	2.3 Outer walls	Utvendig kledning av lauvtre, Foreningen Norske Lauvtrebruk, …	21900	30
24	2.3 Outer walls	Dampsperre i plast, 0.2 mm (Tommen Gram)	337	60
25	2.3 Outer walls	Isolasjon/mineralull, B-plate (Rockwool)	5156	60
26	2.3 Outer walls	Glassull-isolasjon, 42 mm, 0.042 W/mK, 630 g/m2, 15 kg/m3,	210	60
27	2.3 Outer walls	Steel stud per m2 of wall area (air gap included), 42 mm, 40…	57336	60
28	2.3 Outer walls	Standard limbjelke, 470 kg/m3, Moisr. 12%, 45 mm, Stranda…	2891	60
29	2.3 Outer walls	Ferdigbetong, ekskludert armeringsstål, C35/45 (B35 M40) (Sa…	12960	60
30	2.3 Outer walls	Utvendig kledning av lauvtre, Foreningen Norske Lauvtrebruk, …	2052	30
31	2.3 Outer walls	Waterproof membrane from nowoven HDPE for roof and wall und..	11	30
32	2.3 Outer walls	Isolasjon, EPS 80 (EPS Gruppen)	2255	60
33	2.3 Outer walls	Limtre, 470 kg/m3, 12% moisture content (Moelven Modus)	1366	60
34	2.3 Outer walls	Stål, armeringsprodukter (betongarmering), 7850kg/m3, scrap metall	39761	60
35	2.4 Inner walls	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	263727	60
36	2.4 Inner walls	Gipsplate, 12.5 mm, 9 kg m2, Normal - Standard (Gyproc)	58657	60
37	2.4 Inner walls	Stalprofil til innervegg, 0.61 kg/m, 7850 kg/m3 (Norgipd)	10205	60
38	2.4 Inner walls	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	4355	60
39	2.4 Inner walls	Bindingsverksystem av tre for innervegger per kvm (inkl. Luf…	69406	50

40	2.4 Inner walls	Bindingsverksystem av tre for innervegger per kvm (inkl. Luf…	28044	50
41	2.4 Inner walls	Ferdigbetong, normal styrke, generisk, B30, C30/70 (4400/540…	9432	60
42	2.4 Inner walls	XPS isolasjonsplate 33 mm, 300KPa, 0.033 - 0.039 W/mK,	42	60
43	2.4 Inner walls	Gipsplate, 6.5 mm, 5.6 kg/m2, Rehab (Gypsum)	4169	60
44	2.4 Inner walls	Høvellast, bartre (Treindustrien)	580	60
45	2.4 Inner walls	Rubber floor covering, profiled , (3.55 mm); 4.82 kg/m2, 1358…	971	30
46	2.4 Inner walls	Bindingsverksystem av tre for yttervegger per kvm (inkl. Luft…	11366	60
47	2.4 Inner walls	Limtre, 470 kg/m3, 12% moisture content (Moelven Modus)	771	60
48	2.4 Inner walls	Isolasjon/mineralull, B-plate (Rockwool)	102	60
49	2.4 Inner walls	Heltrepanel av lauvtre til innvendig bruk, Foreningen Norske…	242	60
50	2.4 Inner walls	Interior door, 809x2053 mm, 42x92 mm frame, 52 mm door leaf…	24066	30
51	2.5 Floor structure	Linoleum flooring, 2.23 mm, 2.9 kg/m2 (ERFMI)	12819	30
52	2.5 Floor structure	Ferdigbetong, 7540 B45 SV-Standard 22mm, Betong Øst	975408	60
53	2.5 Floor structure	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	74472	60
54	2.5 Floor structure	Isolasjon, EPS 80 (EPS Gruppen)	5764	60
55	2.5 Floor structure	Akustisk sementpanel i treull, grå, 25x600x1200 [mm], 9.7 kg…	78780	50
56	2.5 Floor structure	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	204911	30
57	2.5 Floor structure	HULLDEKKER, 369 kg/m2, T: 265 mm, rebar: 6psc/m2, CEM I, CEM…	127716	60
58	2.5 Floor structure	Ferdigbetong, ekskludert armeringsstål, C35/45 (B35 M40) (Sa…	207816	60
59	2.5 Floor structure	Isolasjon/mineralull, B-plate (Rockwool)	1040	60
60	2.5 Floor structure	Gipsplate, gulvplate, 12.5 mm (Norgips)	24618	60
61	2.5 Floor structure	XPS isolasjonsplate 33 mm, 300KPa, 0.033 - 0.039 W/mK,	736	60
62	2.5 Floor structure	Insulation, acousic glass wool panel, 15 mm, 54 kg/m3, Ecopal	503	50
63	2.5 Floor structure	Bindingsverksystem av tre for innervegger per kvm (inkl. Luf…	2914	50
64	2.5 Floor structure	Massive wooden flooring/parquet, 22-450 x 44-7000 x 8-35mm,…	2500	30
65	2.5 Floor structure	Royalimpregnert trelast, 513 kg/m3, 18% moisture (Moelven W…	1200	60
66	2.5 Floor structure	Isolasjon/mineralull, Drensplate; RockTorv; Støpeplate Pluss…	65	60
67	2.5 Floor structure	Avrettingsmasse, 10-60 mm, 1.7 g/l, C25, Proplan Multi (Hey's)	424924	60
68	2.6 Outer roof	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	298751	30
69	2.6 Outer roof	Stålplater, generisk, 60% recycled content	9051	60
70	2.6 Outer roof	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	1204	60
71	2.6 Outer roof	Aggregat, knust grus, generisk	66000	60
72	2.6 Outer roof	Bindingsverksystem av tre for yttervegger per kvm (inkl. Luft…	19956	60
73	2.6 Outer roof	Bitumenpolymer membrantekking, 1-lags, mekanisk festet (Isol..	25826	30
74	2.6 Outer roof	Utvendig kledning av lauvtre, Foreningen Norske Lauvtrebruk, …	9954	60
75	2.6 Outer roof	Utvendig-X typ EH2 (GU-X), 7.2 kg/m2, 9.5 mm +/- 0.5 mm, Wind…	8890	60
76	2.6 Outer roof	Plywood, srouce, uncoated (Metsä Wood)	3312	60
77	2.6 Outer roof	Asfalt, bærelag, 95% gravel, 5% bitumen bnder, AG 16 (EBA)	7560	60
78	2.7,2.8, 2.9 Other building parts	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	24473	30
79	2.7,2.8, 2.9 Other building parts	Profiled steel sheeting, stainless, 7740 kg/m3 (Outokumpu)	594	60

Material inventory for the kindergarden:

#	Building Parts	Description	Amount in kg	Lifetime
1	2.1 Groundwork and foundations	Isolasjon, EPS 80 (EPS Gruppen)	7164	60
2	2.1 Groundwork and foundations	Ferdigbetong, 7540 B45 SV-Standard 22mm, Betong Øst	195744	60
3	2.1 Groundwork and foundations	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	563616	60
4	2.1 Groundwork and foundations	Stålfiber til betongarmering, 1250, 1100, 1100 Mpa, L:35, 5	3180	60
5	2.1 Groundwork and foundations	Stål, armeringsprodukter (betongarmering), 7850kg/m3, scrap metall	7735	60
6	2.1 Groundwork and foundations	XPS isolasjonsplate 33 mm, 300KPa, 0.033 - 0.039 W/mK,	2167	60
7	2.1 Groundwork and foundations	Radon- og fuktmembran for byggeplass, PP…	1751	60
8	2.2 Superstructure	Standard limbjelke, 470 kg/m3, Moisr. 12%, 45 mm, Stranda…	10965	60
9	2.2 Superstructure	Strukturelle stålprofiler, generisk 60% recyceled content, …	785	60
10	2.3 Outer walls	Høvellast, bartre (Treindustrien)	29566	60
11	2.3 Outer walls	Malm100, 513.32 kg/m3, Malm 100 (Moelven)	12026	30
12	2.3 Outer walls	Bindingsverksystem av tre for yttervegger per kvm (inkl. Luft…	4218	60
13	2.3 Outer walls	Trelast, bartre (Trelastindutrien)	1149	60
14	2.3 Outer walls	Geotextile, generisk, 312 g/m2, Composition: PP net, nonwoov…	18	60
15	2.3 Outer walls	Massivtre Yttervegg, inkl. mineralullisolasjon	8058	60
16	2.3 Outer walls	Heltrepanel av bartre til innvendig bruk (Treindustrien)	2164	60
17	2.3 Outer walls	Fibre cement board, coated, 1550 kg/m3 Construction (Cembrit)	6646	60
18	2.3 Outer walls	Laminert HDPE membran, 0.195 kg/m2, 1.5 m x 50 m, 820 um, Ty…	29	30
19	2.3 Outer walls	Glassull-isolasjon, 42 mm, 0.042 W/mK, 630 g/m2, 15 kg/m3,	4994	60
20	2.3 Outer walls	Dampsperre, 0.2 mm, 185 g/m2, Dampsperre 20 (Baca Plastindustri)	207	60
21	2.3 Outer walls	Kledningsplate, 9.5 mm, 7.2 kg/m2, Bris (Gyproc)	8057	60
22	2.3 Outer walls	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	864	60
24	2.3 Outer walls	Gipsplate, 12.5 mm, 9 kg m2, Normal - Standard (Gyproc)	6759	60
25	2.4 Inner walls	2-veis innadslåsende åpningsvnidu, Frame: 105 mm, 64.4 kg, 1…	1777	30
30	2.4 Inner walls	Limtre, 470 kg/m3, 12% moisture content (Moelven Modus)	1275	60
27	2.4 Inner walls	Gipsplate, 12.5 mm, 9 kg m2, Normal - Standard (Gyproc)	14220	60
28	2.4 Inner walls	Interior door, 809x2053 mm, 42x92 mm frame, 52 mm door leaf…	7415	30
45	2.6 Outer roof	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	105844	30
26	2.4 Inner walls	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	115150	60
31	2.4 Inner walls	Bindingsverksystem av tre for innervegger per kvm (inkl. Luf…	64721	50
32	2.4 Inner walls	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	1645	60
33	2.4 Inner walls	Fastkarm vindu, 0.72 W/m2K, 59.55 kg, 1.23x1.48 m (Norgesvindu)	4187	30

34	2.4 Inner walls	2-veis innadslåsende åpningsvnidu, Frame: 105 mm, 64.4 kg, 1…	4739	30
35	2.4 Inner walls	Climate door, 809xmm, 42x92 mm frame, 52 mm door leaf	2274	30
36	2.5 Floor structure	Ferdigbetong, 7540 B45 SV-Standard 22mm, Betong Øst	152448	60
29	2.4 Inner walls	Solid timber panels (cross laminated timber, CLT) (Stora Ens…	12259	60
38	2.5 Floor structure	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	12220	30
39	2.5 Floor structure	Isolasjon, EPS 80 (EPS Gruppen)	476	60
40	2.5 Floor structure	Isolasjon/mineralull, Flexibatts 35 (Rockwool)	683	60
41	2.5 Floor structure	Akustisk sementpanel i treull, grå, 25x600x1200 [mm], 9.7 kg…	10786	50
42	2.5 Floor structure	Linoleum	1724	30
43	2.5 Floor structure	Avrettingsmasse, 10-60 mm, 1.7 g/l, C25, Proplan Multi (Hey's)	37808	60
44	2.6 Outer roof	Bitumenpolymer membrantekking, 1-lags, mekanisk festet (Isol..	435	30
37	2.5 Floor structure	Heltrepanel av bartre til innvendig bruk (Treindustrien)	4398	30
46	2.6 Outer roof	Isolasjon/mineralull, B-plate (Rockwool)	4028	60
47	2.6 Outer roof	Høvellast, bartre (Treindustrien)	351	60
48	2.6 Outer roof	Kledningsplate, 9.5 mm, 7.2 kg/m2, Bris (Gyproc)	12499	60
49	2.6 Outer roof	Planglass, enkeltglasert, generisk 3-12 mm, 10 kg/m2 (for…	5000	30
50	2.6 Outer roof	Isolasjon, EPS 80 (EPS Gruppen)	8323	60
51	2.6 Outer roof	Bindingsverksystem av tre for innervegger per kvm (inkl. Luf…	105202	50
52	2.6 Outer roof	Flexible bitumen membrane/sheets for roof waterproofing, Eur…	8159	30
53	2.7,2.8, 2.9 Other building parts	Høvellast, bartre (Treindustrien)	630	30
54	2.7,2.8, 2.9 Other building parts	Royalimpregnert trelast, 513 kg/m3, 18% moisture (Moelven W…	8634	30
55	2.7,2.8, 2.9 Other building parts	Stainless stell long products, 7700-8100 kg/m3 (Outokumpu)	3160	60

Material inventory for the SFH:

#	Building Parts	EPD	Amount in kg	Lifetime
1	21 Groundwork and Foundations	Ferdigbetong B25M60	75220	60
2	21 Groundwork and Foundations	Isolasjon, EPS 80 (EPS Gruppen)	758	60
3	21 Groundwork and Foundations	Radon- og fuktmembran for byggeplass, PP…	158	60
4	21 Groundwork and Foundations	Massive wooden flooring/parquet, 22-450 x 44-7000 x 8-35mm,…	1224	30
5	22 Superstructure	Strukturelle stålprofiler, generisk 60% recyceled content, …	800	60
6	23 Outer walls	Konstruksjonsvirke av gran og furu (Treindustrien)	5692	60
7	23 Outer walls	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	2480	60
8	23 Outer walls	Norgips Standard type A (STD)	3524	60
9	23 Outer walls	Waterproof membrane from nowoven HDPE for roof and wall und..	335	60
10	23 Outer walls	Dampsperre, 0.2 mm, 185 g/m2, Dampsperre 20 (Baca Plastindustri)	231	60
11	23 Outer walls	Konstruksjonsvirke av gran og furu (Treindustrien)	244	30
12	23 Outer walls	Konstruksjonsvirke av gran og furu (Treindustrien)	61	30
13	23 Outer walls	Interior door, 809x2053 mm, 42x92 mm frame, 52 mm door leaf…	1523	30
14	23 Outer walls	Fibre cement board, coated, 1550 kg/m3 Construction (Cembrit)	540	30
15	23 Outer walls	Plywood, srouce, uncoated (Metsä Wood)	995	30
16	23 Outer walls	Skurlast av gran eller furu (Treindustrien)	2765	30
17	24 Inner walls	Konstruksjonsvirke av gran og furu (Treindustrien)	147	60
18	24 Inner walls	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	64	60
19	24 Inner walls	Norgips Standard type A (STD)	363	60
20	24 Inner walls	Konstruksjonsvirke av gran og furu (Treindustrien)	578	60
21	24 Inner walls	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	252	60
22	24 Inner walls	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	31	60
23	24 Inner walls	Norgips Standard type A (STD)	2106	60
24	24 Inner walls	Norgips Standard type A (STD)	89	60
25	24 Inner walls	Planglass, enkeltglasert, generisk 3-12 mm, 10 kg/m2 (for…	63	30
26	24 Inner walls	Interior door, 809x2053 mm, 42x92 mm frame, 52 mm door leaf…	490	30
27	24 Inner walls	ceramic tile/ceramic tile production/CH/kg	2318	30
28	25 Floor Structure	Konstruksjonsvirke av gran og furu (Treindustrien)	1398	60
29	25 Floor Structure	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	750	60
30	25 Floor Structure	MDF - Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	1280	30
31	25 Floor Structure	Massive wooden flooring/parquet, 22-450 x 44-7000 x 8-35mm,…	1494	30
32	25 Floor Structure	Dampsperre, 0.2 mm, 185 g/m2, Dampsperre 20 (Baca Plastindustri)	110	60
33	25 Floor Structure	Norgips Standard type A (STD)	873	60
34	25 Floor Structure	Skurlast av gran eller furu (Treindustrien)	119	60

35	26 Outer Roof	Konstruksjonsvirke av gran og furu (Treindustrien)	1666	30
36	26 Outer Roof	Bitumenpolymer membrantekking, 1-lags, mekanisk festet (Isol..	693	30
37	26 Outer Roof	Plywood, srouce, uncoated (Metsä Wood)	1069	60
38	26 Outer Roof	Isolasjon, EPS 80 (EPS Gruppen)	632	60
39	26 Outer Roof	Dampsperre, 0.2 mm, 185 g/m2, Dampsperre 20 (Baca Plastindustri)	159	60
40	26 Outer Roof	Norgips Standard type A (STD)	962	60
41	29 Other	polyethylene, high density, granulate/polyethylene production, high density, granulate/RER/kg - Tech	18	60
42	29 Other	steel, low-alloyed/steel production, converter, low-alloyed/RER/kg	98	60
43	29 Other	hot water tank, 600l/hot water tank production, 600l/CH/unit	260	30
44	29 Other	heat pump, brine-water, 10kW/heat pump production, brine-water, 10kW/CH/unit	131	20
45	31 Ventilation and AC	ventilation duct, steel, 100x50 mm/ventilation duct production, steel, 100x50 mm/RER/m	39	60
46	31 Ventilation and AC	ventilation duct, steel, 100x50 mm/ventilation duct production, steel, 100x50 mm/RER/m	18	60
47	31 Ventilation and AC	ventilation duct, steel, 100x50 mm/ventilation duct production, steel, 100x50 mm/RER/m	28	60
48	31 Ventilation and AC	ventilation duct, steel, 100x50 mm/ventilation duct production, steel, 100x50 mm/RER/m	67	60
49	31 Ventilation and AC	ventilation duct, steel, 100x50 mm/ventilation duct production, steel, 100x50 mm/RER/m	40	60
50	31 Ventilation and AC	ventilation duct, steel, 100x50 mm/ventilation duct production, steel, 100x50 mm/RER/m	4	60
51	49 Other	evacuated tube collector/evacuated tube collector production/GB/m2	246	20
52	49 Other	photovoltaic panel, single-Si wafer/photovoltaic panel production, single-Si wafer/RER/m2	1760	30

A.3 Material categories, specifications and emission intensities

This section includes the material specifications that are part of the 12 material categories. The specifications inlcude the one from EPDs and from Ecoinvent each wih its respective emission intensity.

EPD specifications and Ecoinvent matching process with emission intensity for the 12 material categories

Main material category	Material specification based on EPD	kg CO2-eq/kg (A1-A3)	Material specification based on Ecoinvent	kg CO2-eq/kg (A1-A3)	Region
Concrete	Ferdigbetong, 7540 B45 SV-Standard 22mm, Betong Øst	0.11	concrete, high exacting requirements/concrete production, for building construction, with cement CEM II/A/CH/m3	0.09	CH
	Ferdigbetong, ekskludert armeringsstål, C35/45 (B35 M40) (Sa…	0.15			
	Ferdigbetong, normal styrke, generisk, B30, C30/70 (4400/540…	0.09			
	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	0.08			
	SØYLE, B45 M45 (Spenncon)	0.19			
	Ferdigbetong B25M60	0.08			
	Geotextile, generisk, 312 g/m2, Composition: PP net, nonwoov…	2.81	Geotextile, generisk, 312 g/m2, Composition: PP net, nonwoov…	2.81	-
Energy System	evacuated tube collector/evacuated tube collector production/GB/m2	3.29	evacuated tube collector/evacuated tube collector production/GB/m2	3.29	GB
	photovoltaic panel, single-Si wafer/photovoltaic panel production, single-Si wafer/RER/m2	10.55	photovoltaic panel, single-Si wafer/photovoltaic panel production, single-Si wafer/RER/m2	10.55	RER
Glass	ceramic tile/ceramic tile production/CH/kg	0.60	ceramic tile/ceramic tile production/CH/kg	0.60	CH
	2-veis innadslåsende åpningsvnidu, Frame: 105 mm, 64.4 kg, 1…	2.33	flat glass, coated/flat glass production, coated/RER/kg	1.13	RER
	Fastkarm vindu, 0.72 W/m2K, 59.55 kg, 1.23x1.48 m (Norgesvindu)	2.89			
	Planglass, enkeltglasert, generisk 3-12 mm, 10 kg/m2 (for…	1.70			
Gypsum	Gipsplate, 12.5 mm, 9 kg m2, Normal - Standard (Gyproc)	0.19	gypsum plasterboard/gypsum plasterboard production/CH/kg	0.19	CH
	Gipsplate, 6.5 mm, 5.6 kg/m2, Rehab (Gypsum)	0.29			
	Gipsplate, gulvplate, 12.5 mm (Norgips)	0.22			
	Kledningsplate, 9.5 mm, 7.2 kg/m2, Bris (Gyproc)	0.24			
	Utvendig-X typ EH2 (GU-X), 7.2 kg/m2, 9.5 mm +/- 0.5 mm, Wind…	0.25			
	Norgips Standard type A (STD)	0.23			
Insulation Mineral	Glassull-isolasjon, 42 mm, 0.042 W/mK, 630 g/m2, 15 kg/m3,	1.00	glass wool mat/glass wool mat production/CH/kg	1.32	CH
	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	0.72			
	Insulation, acousic glass wool panel, 15 mm, 54 kg/m3, Ecopal	6.00	Insulation, acousic glass wool panel, 15 mm, 54 kg/m3, Ecopal	6.00	-
	Isolasjon/mineralull, B-plate (Rockwool)	1.07	rock wool, packed/rock wool production, packed/CH/kg	1.42	CH
	Isolasjon/mineralull, Drensplate; RockTorv; Støpeplate Pluss…	1.54			
	Isolasjon/mineralull, Flexibatts 35 (Rockwool)	1.42			
Insulation PS	Isolasjon, EPS 80 (EPS Gruppen)	3.86	polystyrene foam slab/polystyrene foam slab production/RER/kg	4.42	RER

	XPS isolasjonsplate 33 mm, 300KPa, 0.033 - 0.039 W/mK,	3.76	polystyrene, extruded/polystyrene production, extruded, CO2 blown/RER/kg	3.82	RER

Membrane	Bitumenpolymer membrantekking, 1-lags, mekanisk festet (Isol..	0.61	fibre cement roof slate/fibre cement roof slate production/CH/kg	0.63	CH
	Flexible bitumen membrane/sheets for roof waterproofing, Eur…	0.61			
	Laminert HDPE membran, 0.195 kg/m2, 1.5 m x 50 m, 820 um, Ty…	3.87	polyethylene, high density, granulate/polyethylene production, high density, granulate/RER/kg	1.93	RER
	Waterproof membrane from nowoven HDPE for roof and wall und..	4.86			
	Dampsperre i plast, 0.2 mm (Tommen Gram)	2.30	polyethylene, low density, granulate/polyethylene production, low density, granulate/RER/kg	2.10	RER
	Dampsperre, 0.2 mm, 185 g/m2, Dampsperre 20 (Baca Plastindustri)	2.29			
	Radon- og fuktmembran for byggeplass, PP…	2.45			

Mineral	Aggregat, knust grus, generisk	2.E-03	Aggregat, knust grus, generisk	2.E-03	-
	Akustisk sementpanel i treull, grå, 25x600x1200 [mm], 9.7 kg…	0.21	Akustisk sementpanel i treull, grå, 25x600x1200 [mm], 9.7 kg…	0.21	-
	Avrettingsmasse, 10-60 mm, 1.7 g/l, C25, Proplan Multi (Hey's)	0.21	cement cast plaster floor/cement cast plaster floor production/CH/kg	0.16	CH
	Fibre cement board, coated, 1550 kg/m3 Construction (Cembrit)	0.68	fibre cement corrugated slab/fibre cement corrugated slab production/CH/kg	0.58	
	HULLDEKKER, 369 kg/m2, T: 265 mm, rebar: 6psc/m2, CEM I, CEM…	0.16	lean concrete/lean concrete production, with cement CEM II/A/CH/m3	0.06	
	Asfalt, bærelag, 95% gravel, 5% bitumen bnder, AG 16 (EBA)	0.05	mastic asphalt/mastic asphalt production/CH/kg	0.07	

Other	Linoleum	0.90	Linoleum	0.90	-
	Linoleum flooring, 2.23 mm, 2.9 kg/m2 (ERFMI)	0.90	Linoleum flooring, 2.23 mm, 2.9 kg/m2 (ERFMI)	0.90	-
	Rubber floor covering, profiled , (3.55 mm); 4.82 kg/m2, 1358…	2.67	Rubber floor covering, profiled , (3.55 mm); 4.82 kg/m2, 1358…	2.67	-

Steel	Stål, armeringsprodukter (betongarmering), 7850kg/m3, scrap metall	0.36	Stål, armeringsprodukter (betongarmering), 7850kg/m3, scrap metall	0.36	-
	Profiled steel sheeting, stainless, 7740 kg/m3 (Outokumpu)	3.70	steel, low-alloyed, hot rolled/steel production, low-alloyed, hot rolled/RER/kg	2.00	RER
	Stainless stell long products, 7700-8100 kg/m3 (Outokumpu)	2.75			
	Stål varmvalset, I, H, U, L, T, og vide flater (EMV Construction)	1.28			
	Stålfiber til betongarmering, 1250, 1100, 1100 Mpa, L:35, 5	0.77			
	Stålplater, generisk, 60% recycled content	2.28			
	Stalprofil til innervegg, 0.61 kg/m, 7850 kg/m3 (Norgipd)	2.26			
	Steel stud per m2 of wall area (air gap included), 42 mm, 40…	2.57			
	Strukturelle stålprofiler, generisk 60% recyceled content, …	2.56			

Technical	heat pump, brine-water, 10kW/heat pump production, brine-water, 10kW/CH/unit	12.83	heat pump, brine-water, 10kW/heat pump production, brine-water, 10kW/CH/unit	12.83	CH
	hot water tank, 600l/hot water tank production, 600l/CH/unit	2.87	hot water tank, 600l/hot water tank production, 600l/CH/unit	2.87	

	polyethylene, high density, granulate/polyethylene production, high density, granulate/RER/kg - Tech	1.93	polyethylene, high density, granulate/polyethylene production, high density, granulate/RER/kg - Tech	1.93	RER
	steel, low-alloyed/steel production, converter, low-alloyed/RER/kg	2.37	steel, low-alloyed/steel production, converter, low-alloyed/RER/kg	2.37	
	ventilation duct, steel, 100x50 mm/ventilation duct production, steel, 100x50 mm/RER/m	5.40	ventilation duct, steel, 100x50 mm/ventilation duct production, steel, 100x50 mm/RER/m	5.40	

Wood	Climate door, 809xmm, 42x92 mm frame, 52 mm door leaf	2.50	door, outer, wood-aluminium/door production, outer, wood-aluminium/RER/m2	3.35	RER
	Interior door, 809x2053 mm, 42x92 mm frame, 52 mm door leaf…	1.54			
	Heltrepanel av lauvtre til innvendig bruk, Foreningen Norske…	2.18	fibreboard production, hard/RER/m3	1.00	RER
	Massive wooden flooring/parquet, 22-450 x 44-7000 x 8-35mm,…	0.14			
	Massivtre Yttervegg, inkl. mineralullisolasjon	0.78			
	Trelast, bartre (Trelastindutrien)	1.62			
	Limtre, 470 kg/m3, 12% moisture content (Moelven Modus)	0.19	glued laminated timber, for indoor use/glued laminated timber production, for indoor use/RER/m3	0.49	RER
	Standard limbjelke, 470 kg/m3, Moisr. 12%, 45 mm, Stranda…	0.17			
	Konstruksjonsvirke av gran og furu (Treindustrien)	0.13			
	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	0.13	laminated timber element, transversally prestressed, for outdoor use/laminated timber element production, for outdoor use/RER/m3	0.50	RER
	Malm100, 513.32 kg/m3, Malm 100 (Moelven)	0.12			
	Solid timber panels (cross laminated timber, CLT) (Stora Ens…	0.13			
	MDF - Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	0.13	medium density fibreboard/medium density fibre board production, uncoated/RER/m3	0.18	RER
	Plywood, srouce, uncoated (Metsä Wood)	1.86	plywood, for outdoor use/market for plywood, for outdoor use/RER/m3	0.81	RER
	Utvendig kledning av lauvtre, Foreningen Norske Lauvtrebruk, …	2.E-03	sawnwood, hardwood, dried (u=10%), planed/sawnwood production, hardwood, dried (u=10%), planed/RER/m3	0.06	RER
	Bindingsverksystem av tre for innervegger per kvm (inkl. Luf…	0.19	sawnwood, softwood, dried (u=10%), planed/sawnwood production, softwood, dried (u=10%), planed/RER/m3	0.23	RER
	Bindingsverksystem av tre for yttervegger per kvm (inkl. Luft…	0.14			
	Heltrepanel av bartre til innvendig bruk (Treindustrien)	0.12			
	Høvellast, bartre (Treindustrien)	0.12			
	Royalimpregnert trelast, 513 kg/m3, 18% moisture (Moelven W…	0.18	sawnwood, softwood, dried (u=20%), planed/sawnwood production, softwood, dried (u=20%), planed/RER/m3	0.20	RER
	Skurlast av gran eller furu (Treindustrien)	0.10			

A.4 Emission intensity for archetypes using values from EPDs

The figure shows the emission intensities for the 15 archetypes using emission intensities from EPD specifications.

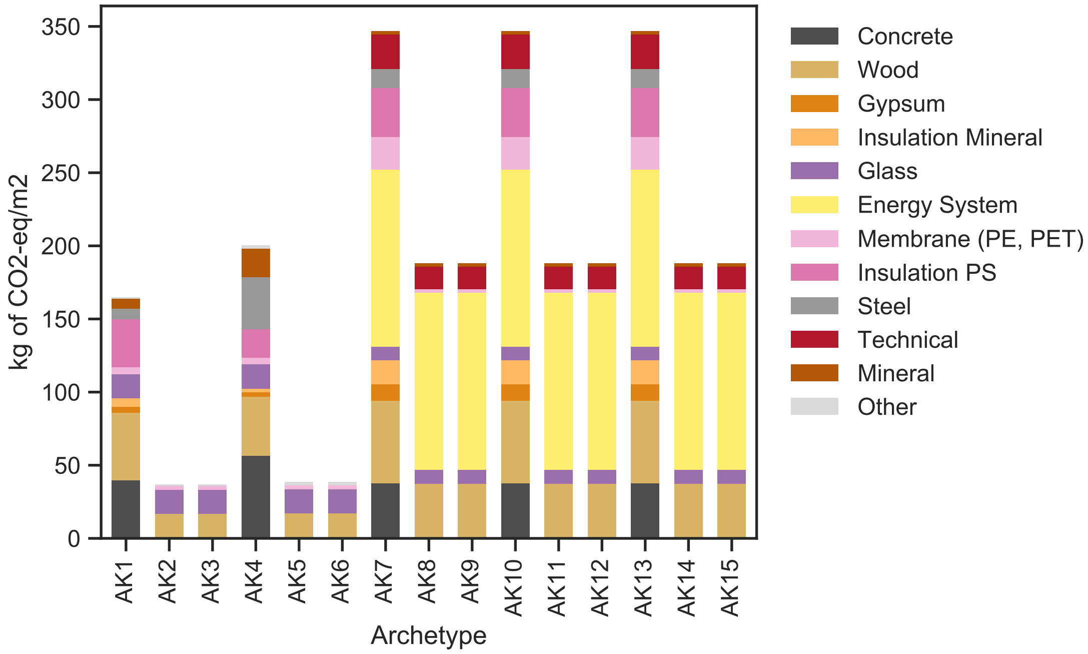


Figure A.5: Emission intensities per m^2 per archetype based on values from EPDs

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