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Scenario Analysis in LCA on the Zero Emission Neighbourhood Ydalir

A Norwegian Case Study

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Energy and Environmental Engineering
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Preface

The objective of this MSc thesis is to use and expand an already existing Life Cycle Analysis (LCA) model for neighbourhoods in an early planning stage. This model was developed by Vilde Sorkmo Borgnes in her MCs in 2017/18 and is based on a modular structure and focuses on the five elements: buildings, mobility, infrastructures, networks and on-site energy, which all contribute to the climate change impacts. The selected Zero Emission Neighbourhood (ZEN) is called Ydalir, located in Elverum, and is in an early building phase. The work is performed in association with IndEcol's participation in the FME ZEN Research Centre and has been carried out during the spring of 2019 at the Norwegian University of Science and Technology.

The thesis consists of two parts; the research article *"Scenario Analysis in LCA on the Zero Emission Neighbourhood Ydalir, a Norwegian Case Study"* and supplement material containing input data and further details for a deeper understanding. The relevant sections in the supplement material are referred to throughout the article.

In addition to the work presented in this thesis, an article was created and accepted to the 1st Nordic Conference on Zero Emission and Plus Energy Buildings. The work will be presented at the conference which is held on the 6th and the 7th of November 2019.

To my supervisor Helge Brattebø and co-supervisor Carine Lausselet, I would like to express my sincere gratitude for providing me with excellent material and follow-up sessions. Further, I would like to thank Anna-Thekla Tonjer from Elverum Vekst, Ola T. Dahl from Eidsiva and Heidi Erikstad from Eleverum Kommune for helping me to collect data from Ydalir.

The picture on the front page is a representation of Ydalir illustrated by Tegn_3.

Abstract

Buildings represent a critical piece of a low-carbon future and their long lifetime necessitates urgent adoption of state-of-the-art performance standards to avoid significant lock-in risk. So far, Life Cycle Analysis (LCA) studies have assessed buildings, mobility and energy systems mainly individually. Zero Emission Neighbourhoods (ZEN) gives a unique chance to combine these elements and thereby contribute to climate change mitigation. In Norway, the Research Centre on ZEN in Smart Cities (https://fmezen.no/) has a goal to enable the transition to a low carbon society by developing sustainable neighbourhoods with zero Greenhouse Gas (GHG) emissions.

In this study, it was applied an LCA model for neighbourhoods based on a modular structure with five physical elements; buildings, mobility, infrastructure, networks and on-site energy infrastructure on Ydalir, a pilot project of the ZEN Centre. The performed LCA revealed that regardless of which scenario considered, the ZEN Ydalir does not manage to achieve their ambitious goal of zero emissions with the present plan. However, the neighbourhood's results represent an important step towards a zero emission society, highlighting several crucial measures for further improvement in the field of ZENs. The results further show that the operation of mobility is the source of a major part of the GHG emissions, accounting for 42-46% of the total. When considering the life cycle stage materials, the buildings and mobility represent 37% and 38% respectively of the GHG emissions from materials in both scenarios. Thus, operation stage of mobility and the material stage of the buildings and mobility have been highlighted as the best options for improvement.

The model and data used in this work is associated with several uncertainty factors. Parameters assumed to have significant uncertainties, or are large contributors to the environmental impact, are included in a sensitivity analysis and have been calculated and discussed. Scenarios based on different measures to achieve zero emissions have also been analysed and discussed.

Sammendrag

Bygg representerer en vesentlig faktor i en framtid med lave utslipp av drivhusgasser. En betydelig konsekvens av deres lange livsløp gjør at det haster å innføre standarder med toppmoderne prestasjoner for å unngå betydelig låsningsrisiko. Hittil har Livssyklusanalysestudier (LCA) betraktet bygg, mobilitet og energisystemer hver for seg. Nullutslippsnabolag (ZEN) gir en unik mulighet til å kombinere disse elementene, og dermed bidra til å begrense klimaendringene. I Norge har forskningssenteret på ZEN i smart byer (https://fmezen.no/) et mål om å tilrettelegge for overgangen til lavkarbonsamfunn ved å utvikle bærekraftige nabolag med null drivhusgassutslipp.

I dette studiet blir det brukt en LCA modell for nabolag som er basert på en modul struktur bestående av fem fysiske elementer; bygg, mobilitet, infrastruktur, nettverk og on-site energiinfrastruktur på Ydalir, et av ZEN senterets pilotprosjekter. Den gjennomførte LCAen viser at uansett hvilket scenario som blir vurdert, klarer ikke ZEN Ydalir innenfor nåværende plan å nå deres ambisiøse mål om null utslipp. Til tross for dette, representerer nabolagets resultater et viktig steg mot et nullutslippssamfunn, og påpeker flere vesentlige tiltak for forbedringer mot målet om nullutslippsnabolag. Resultatene viser at bruksfasen i mobilitet er kilden til en betydelig andel av de totale drivhusgassene fra nabolaget, og representerer 42-46% av de totale utslippene. Når kun livssyklussteget materialer er tatt i betraktning, er bygg og mobilitet kildene til henholdsvis 37% og 38% av drivhusgassene, i begge scenariene. Dette tydeliggjør bruksfasen til mobilitet og materialstegene til bygg og mobilitet som de beste områdene for forbedring.

Modellen og dataen som er benyttet i dette arbeidet har flere usikkerhetsfaktorer. Parametere som er antatt å være knyttet til høy usikkerhet eller som er store bidragsytere til miljøpåvirkningen, er inkludert i en sensitivitetsanalyse og er kalkulert og diskutert. Scenarier basert på tiltak for å oppnå nullutslipp er også analysert og diskutert.

Table of Contents

Article: Scenario Analysis in LCA on the Zero Emission Neighbourhood Ydalir, a Norwegian Case Study

Author: Kristi Marie Lund

Keywords: Life Cycle Assessment (LCA), Zero Emission Neighbourhood (ZEN)

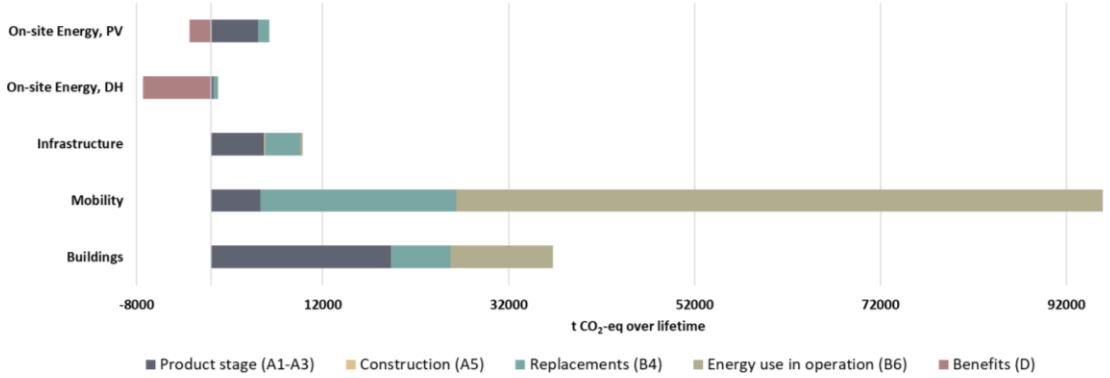
Abstract

Buildings represent a critical piece of a low-carbon future and their long lifetime necessitates urgent adoption of state-of-the-art performance standards. So far, Life Cycle Analysis (LCA) studies have assessed buildings, mobility and energy systems mainly individually. Zero Emission Neighbourhoods (ZEN) give a unique chance to combine these elements. In Norway, the Research Centre on ZEN has a goal of enabling the transition to a low carbon society by developing sustainable ZENs.

In this study, the LCA model is based on a modular structure with five physical elements; buildings, mobility, infrastructure, networks and on-site energy was applied on Ydalir, a pilot project of the ZEN Centre. Revealing that regardless of which scenario considered, the ZEN Ydalir does not achieve their ambitious goal of zero emissions. Further, the results show that the operation of mobility is a major source of the total Greenhouse Gas (GHG) emissions, accounting for 42-46%. Considering only the life cycle stage materials, the buildings and mobility are the largest contributors representing 37% and 38% of all GHG emissions respectively. Thus, these areas are highlighted as the best options for improvement. Parameters related to uncertainties or are large contributors to the environmental impact are included in a sensitivity analysis.

Graphical Abstract

Total emissions by elements and life cycle stages



1. Introduction

In Paris in December 2015, the United Nations Climate Change conference was held. Here the main goal of limiting the global warming to a maximum of 2 degrees compared to pre-industrial time was defined. This has led to a growth of climate awareness and new technology, leading to implementation of climate policies. The building sector is responsible for 40% of the total energy consumption and 30% of all energy-related Greenhouse Gas (GHG) emissions in the European Union (EU) [1]. Thus, reducing the emissions from this sector is critical. To improve the environmental aspect of the building sector, several leading international organizations have taken measures. In Norway, the Research Centre on Zero Emission Buildings (ZEB) had a vision to eliminate the GHG emissions caused by buildings. The main goals were to develop knowledge, competitive products and solutions for both existing and new buildings [2]. The Research Centre on Zero Emission Neighbourhoods (ZEN) was created as a follow-up program to the ZEB Centre and contains today 9 different ZEN projects spread across the country. The ZEN Centre has a goal of reducing the emissions from neighbourhoods to a minimum level through combining local production of local renewable energy, storage and interacting systems. The ZEN program will run over the period from 2017 to 2024 with the vision "*Sustainable neighbourhoods with zero greenhouse emissions*" [3]. By using life cycle analysis (LCA) as a helping tool on ZENs, researchers have consequently had to acknowledge the new challenges that arise regarding functional unit, system boundaries and sensitivity parameters.

1.1 Environmental Assessment of Buildings

To map and assess the source of the emissions from buildings, the well-established methodology LCA is commonly used, as it looks at the entire life span of the building [4]. LCA systematically goes through each life cycle stage from raw materials acquisition, production of energy and materials, usage to end-of-life processing [5]. Anderson *et al.* [6] state in their article that LCA commonly has been used in assessing both individual buildings and neighbourhoods. When performing an LCA of a building, where the building is treated as an independent object, the optimization of both materials and energy has a major effect on the results. However, when expanding the LCAs to an urban scale the focus becomes quite different. Other aspects as to density, transportation, infrastructure and consumption have to be included.

It is argued that a new framework is necessary to be able to assess critical environmental impacts for the LCA methods at neighbourhood scale [6]. However, some important take-away notes from the LCAs on building scale are worth acknowledging. When assessing the buildings individually, the emissions from energy use in operations are historically way higher than the embodied emissions from the materials, accounting for 80-90% of the total emissions [7, 8]. In more recent studies, mainly when low-energy buildings are considered, the embodied emissions from the materials become the major contributors [9-11].

There have also been findings related to user behaviour, construction, energy-positive buildings, alternative and renewable materials from LCA studies on buildings [12-16]. These have been excluded here, despite their potential relevance in complex systems as neighbourhoods.

1.2 From Buildings to Neighbourhoods

When changing the scale from building to neighbourhood level, multiple challenges arise. The complexity of the assessed area increases significantly, and interconnections between units become more important when a cluster of buildings are to be evaluated within the same system boundaries. However, simultaneously more opportunities regarding reduction of emission are created. The relevance of local solutions for energy supply and production increase, in addition to storage and import from/export to the external grid.

The literature on LCAs on neighbourhood level is limited and lack comparability as they are reasoned to be complexity and context dependant. The approaches to these LCA studies are heterogeneous and both Lotteau *et al.* [17] and Mastrucci *et al.* [18] witnessed the studies to have considerable variations.

Defining the system boundaries is crucial for the LCA's results and their reliability. The system boundaries define which life cycle stages and physical elements (i.e. buildings, open spaces and mobility) that are to be included in the analysis. Some LCA studies only assess a cluster of buildings [19], while others also consider the mobility of the inhabitants [6, 20]. The most comprehensive and complex LCA studies are the ones that also include several other elements such as networks and infrastructure in addition to buildings and mobility [14, 21, 22]. There are also variations in what life cycle stages are considered, from studies that only include the usage to the opposite side of the scale where also construction and deconstruction are included [17, 18]. These differences create challenges in comparing results from LCA studies, but some key points are worth noting and include in further development of a standard LCA model.

Studies have shown that transportation of the inhabitants has significant impact on the total emissions. Nichols and Kockelman [14] found that 44-47% of the total emissions from the use stage came from transportation. Similarly, when including materials in the building construction, usage stage and transportation, Bastos *et al.* [20] found that transportation contributed with 51-57% of the total emissions. Studies that also include the manufacture of the transportation modes are lacking, with a few exceptions. Stephan *et al.* [21] found that the indirect emissions (including transportation supporting services such as vehicle manufacturing, building roads and registration) from transportation represent 52% of the emissions from this element. While Anderson *et al.* [6] found the same emission source to represent 22-27% depending on the neighbourhood location. These findings indicate that further research on the field of emissions from mobility connected to the neighbourhoods is necessary. The new Norwegian standard *NS 3720 Method for greenhouse gas calculations for building* [23] approach this by expanding the system boundaries.

The predictions and assumptions of future scenarios are crucial when performing an LCA. The variating service lifetime of each element in a neighbourhood makes the forecasting challenging and a source of uncertainties. Several studies highlight this challenge and emphasize evolving technology, time distribution of environmental impact and emission intensity as key factors [17, 20, 21, 24]. These factors can have great impact on the predictions of future scenarios and long-term decisions, and thus the final results.

The benefits of the LCA tool are properly exploited only when used in the early planning stage of new neighbourhoods. However, up until today most LCAs are done on existing neighbourhood. Yepez-Salmon [25] developed an LCA tool called NEST (Neighbourhood Evaluation for Sustainable Territories) used to assess the environmental impact of urban projects. Lotteau *et al.* [26] further informs that NEST makes it possible to evaluate different solutions for neighbourhood projects by including production, use, maintenance and end-of-life stage for both buildings and open spaces, in addition to the daily mobility of the residents. Another LCA tool called OmrådeLCA, used for early planning stage, use key numbers to calculate the impact of a neighbourhood and compares the results to a reference case [27]. Similar to NEST, OmrådeLCA gives the opportunity of exploring different alternatives for the neighbourhood early in the building project in order to find the optimal solution.

Further research in the field on ZENs is obviously required, on both critical factors for the results and the life cycle stages and physical elements that contribute considerably to the environmental impact categories. This insight should build the foundation in future ZEN projects and a standard should be constructed in order to produce comparable and robust results.

1.3 Problem Statement

The task for this MSc thesis is to use LCA as a helping tool in early planning stages of ZENs, and to decide which factors and parameters have the highest impact on the results. The model used is developed by Vilde Sorkmo Borgnes in her MSc the year 2017/18 and will now be tested at the project Ydalir in Elverum to assess its environmental footprint.

The following research questions have been answered:

- Which life cycle stages are the most significant contributors to the global warming potential when focusing on the elements; buildings, mobility, infrastructures, networks and on-site energy production in the ZEN Ydalir?
- What are the critical factors regarding how the LCA results depend on the system boundary choices?
- To what extent can more ambitious solutions and assumption for mobility reduce the global warming potential at ZEN Ydalir?
- Where must improvements be implemented in order to achieve the “0-ambition”?

2. Method

As a basis for the neighbourhood level LCA in this study, a model with a modular structure developed by Lausselet *et al.* [22] has been used and adapted to this specific case study. The case study is a pilot project of the ZEN Centre located in Elverum, called Ydalir. This project is a ZEN still in the early stages, where the school and kindergarten are planned to be done by autumn 2019, while the residential buildings will be built over the next 15-20 years. The model has some minor modifications to fit the specific case study, Ydalir. However, the methodology and calculation procedures are designed to be applicable to other LCA projects at neighbourhood level.

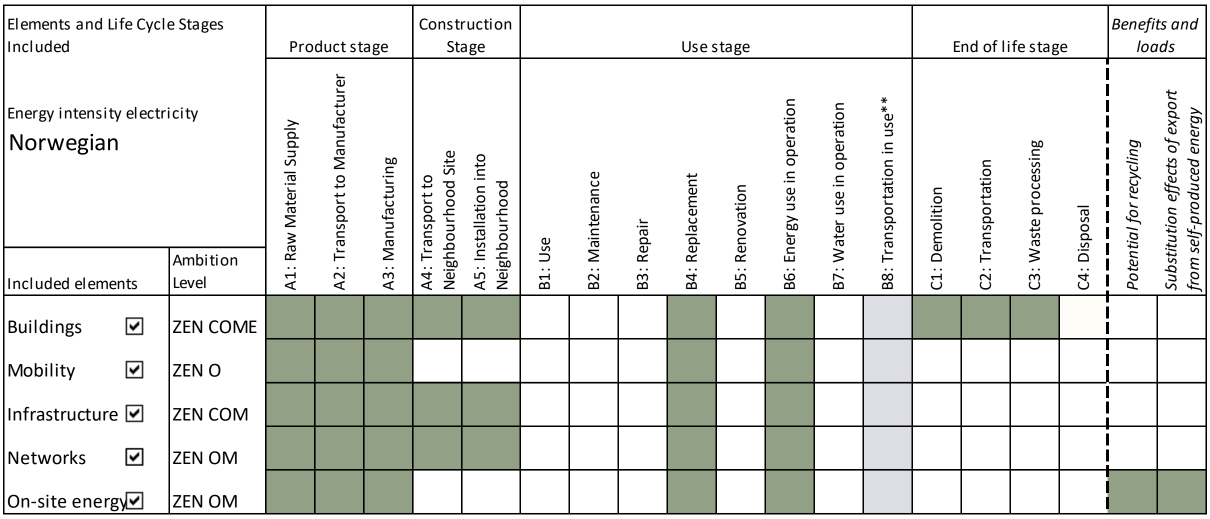
2.1 Model

Figure 2.1 presents the modular structure defined by two dimensions; the physical elements (buildings, mobility, infrastructure, networks and on-site energy) and the included life cycle stages. The latter is based on suggestions made by the NS 3720 standard on different modules (A1-C4) and is further described as ambition levels (see Appendix A.1). As shown in Figure 2.1, B8 is not relevant as mobility is included as a separate element and is therefore marked in grey. Note that gains from outside of the system boundaries (i.e. avoided emissions from exported energy and material recycling) are marked under benefits and loads (D).

The ZEB Centre's approach on ambition levels has been used as a base to describe the included life cycle stages for each physical element. The ZEN ambitions have therefore been developed from the ZEB definition [28, 29] as followed.

- ZEN O: Emissions related to operation "O".
- ZEN OM: Emissions related to operation "O" and embodied emissions from materials "M".
- ZEN COM: The same as OM, as well as emissions related to construction "C".
- ZEN COME: The same as COM, as well as emissions related to the end of life stage "E".

To match the neighbourhood at interest, the elements and ambition levels can be adjusted for each assessment.



Elements and Life Cycle Stages Included Energy intensity electricity Norwegian		Product stage			Construction Stage		Use stage								End of life stage				*Benefits and loads*	
Included elements	Ambition Level	A1: Raw Material Supply	A2: Transport to Manufacturer	A3: Manufacturing	A4: Transport to Neighbourhood Site	A5: Installation into Neighbourhood	B1: Use	B2: Maintenance	B3: Repair	B4: Replacement	B5: Renovation	B6: Energy use in operation	B7: Water use in operation	B8: Transportation in use**	C1: Demolition	C2: Transportation	C3: Waste processing	C4: Disposal	*Potential for recycling*	*Substitution effects of export from self-produced energy*
Buildings ☑	ZEN COME	🟩	🟩	🟩	🟩	🟩				🟩		🟩		▨	🟩	🟩	🟩			
Mobility ☑	ZEN O	🟩	🟩	🟩						🟩		🟩		▨						
Infrastructure ☑	ZEN COM	🟩	🟩	🟩	🟩	🟩				🟩		🟩		▨						
Networks ☑	ZEN OM	🟩	🟩	🟩	🟩	🟩				🟩		🟩		▨						
On-site energy ☑	ZEN OM	🟩	🟩	🟩						🟩		🟩		▨					🟩	🟩

* Not included in present study

** Not relevant (covered by mobility element)

Figure 2.1 The elements and life cycle stages included in the case study (Note that this is only an example, not what is applied in this case study)

At the top left in Figure 2.1, the emission intensity of the analysis is stated. However, the new standard NS 3720 [23] suggests that two different energy intensity scenarios are to be assessed, namely, scenario 1 (NO) and scenario 2 (EU28+NO). These are based on the assumed evolution of the Norwegian and the European electricity mixes respectively. Briefly explained, scenario 1 considers the Norwegian el-mix isolated with no import or export, while scenario 2 considers free flow of electricity between the European countries including Norway. Figure 2.2 illustrates the evolution from 2020 to 2080 for the two scenarios (see Appendix B.1).

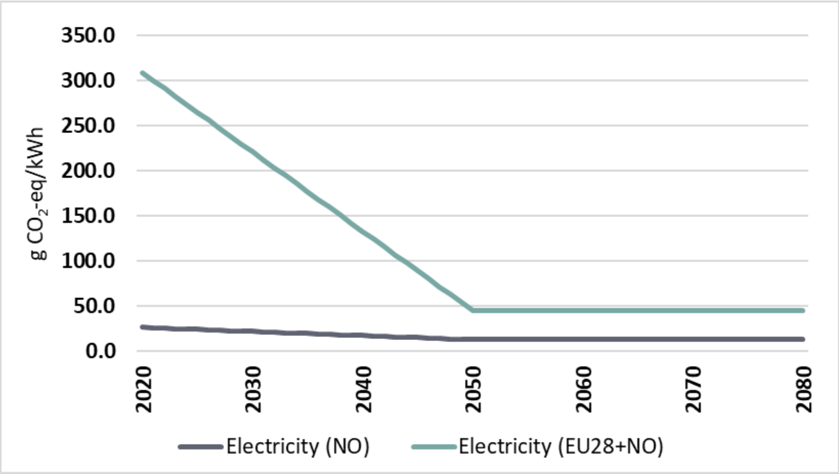


Figure 2.2 Emission intensity evolution for the two scenarios based on the NS 3720

2.1.1 Calculations

The total emissions from the neighbourhood are calculated by Equation 1.

$$E_{tot} = E_{b,mat} + E_{b,oper} + E_{m,mat} + E_{m,oper} + E_{o,mat} + E_{o,oper} \tag{1}$$

Where $E_{b,mat}$, $E_{m,mat}$ and $E_{o,mat}$ are the emissions from the materials from buildings, mobility and infrastructur respectively, and $E_{b,oper}$, $E_{m,oper}$ and $E_{o,oper}$ are the emissions from the energy use in operation respectively from buildings mobility and infrastructure.

Buildings

Equation 2 is used when calculating the emissions from the building materials.

$$E_{b,mat} = \sum_{bt} \left\{ \left[\left(E_{mat,init}\right)_{bt} * A_{bt} \right] + \sum_{i=0}^{60} \left[\left(E_{mat,repl}\right)_{i,bt} * A_{bt} \right] \right\} \tag{2}$$

$E_{mat,init}$ is the embodied emissions from the initial materials in the buildings, while $E_{mat,repl}$ is the embodied emissions from the replacement materials. *A* represents the floor area (m^2), *bt* the building type and *i* is the year.

Equation 3 is used when calculating the emissions from the energy use in operation of the buildings.

$$E_{b,oper} = \sum_{bt} \sum_{et} \sum_{i=0}^{60} \left[(E_{ei})_{i,et} * A_{bt} \right] \tag{3}$$

E_{ei} denotes the emission intensity to each the energy type (*et*), while *bt* represents the building type, *i* the year and *A* the floor area in m^2.

Mobility

Equation 4 is used when calculating the emissions from the mobility materials.

$$E_{m,mat} = \sum_{i=0}^{60} \sum_{tm} \left[(E_{mat})_{tm} * L_{tot,tm,i} \right] \tag{4}$$

E_{mat} represents the emissions from the production of the vehicle types in CO_2-eq/km, while L_{tot} denotes the total annual travel length (km) of the neighbourhood. *tm* represents the travel mode and *i* the year.

The emissions from the energy use in operation of mobility is described by Equation 5.

$$E_{m,oper} = \sum_{i=1}^{60} \sum_{tm} L_{tot,tm} * WtW_{tm,i} \tag{5}$$

L_{tot} is the annual travel length for the neighbourhood, and *tm* and *i* denotes the transportation mode and year respectively. *WtW* represents the emissions per km driven and is calculated by equation 6.

$$WtW_{tm,i} = \left(Energy_{Ttw,i} * I_{TtW}\right) + \left(Energy_{TtW,i} * I_{WtT}\right) \tag{6}$$

$Energy_{TtW,i}$ represents the propulsion energy needed per distance (MJ/vkm). I_{TtW} denotes the direct emission intensity, while I_{WtT} is the emission intensity of the fuel/energy carrier's fuel cycle.

Infrastructure

Equation 7 describes the emission calculations for the infrastructure materials.

$$E_{o,mat} = \sum_{rt} \left\{ \left[\left(E_{mat,init} \right)_{rt} * A_{rt} \right] + \sum_{i=0}^{60} \left[\left(E_{mat,repl} \right)_{i,rt} * A_{rt} \right] \right\} \tag{7}$$

$E_{mat,init}$ is the embodied emissions from the initial materials in the infrastructure, while $E_{mat,repl}$ is the embodied emissions from the replacement materials. *A* represents the road area (in m^2), *rt* the road type and *i* is the year.

The emissions from operation of the public lighting at Ydalir are calculated using Equation 8.

$$E_{o,oper} = \sum_{i=0}^{60} N * P * h * I_{el,i} \tag{8}$$

N denotes the number of lighting units, *P* is the power per unit in kW and *h* is the hours of lighting each year. I_{el} states the emission intensity of the electricity (defined in Appendix B.1) and *i* is the year.

2.2 Ydalir

The LCA model has been applied on the ZEN Ydalir, with the ambition level ZEN-OM, including the elements buildings, mobility, infrastructure, networks and on-site energy. The life cycle stages, production stage (A1-A3), replacements (B4) and energy use in operation (B6) were included for all the elements. For the element infrastructure is construction (A5) also included, while for the element networks is the energy use in operation excluded. For on-site energy the benefits and loads (D) is included. The modular structure for this study case and maps of Ydalir are included in Appendix C and Appendix D respectively. The ZEB Centre defines the service time of a building to be 60 years and has been chosen to be the analysis period [30]. Further, the study focuses on the GHG emissions associated to each of the elements throughout this period. In Ydalir three different sources of energy have been selected; the already existing district heating system, Combined Heat and Power (CHP) machines and Photovoltaic (PV) panels. Both heat energy and electric energy will be exported and considered as negative emissions in the emission accounting (See Appendix B.1 and B.2). As suggested in NS 3720, both scenario 1 (NO) and scenario 2 (EU28+NO) have been applied for both import and export to the external power grid.

2.2.1 Buildings

The building stock at Ydalir consists of 1000 residential buildings and two non-residential buildings, a school and a kindergarten. Resulting in a total building area of 108 614 m^2 [31], as shown in Table 2.1. The residential buildings will be a combination of townhouses and apartments, but have not yet been designed, and the building ZEB 1 from a concept analysis conducted by Kristjansdottir *et al.* [32] has therefore been chosen. It is chosen due to its resemblance with the design of the planned buildings at Ydalir.

Table 2.1 Building stock, area and occupants in Ydalir

Archetype	Area (m2)	Number of dwellings	Number of occupants per dwelling
ZEB 1	100000	1000	2.5
Total residential	**100000**		
Kindergarden	2140		
School	6474		
Total non-residential	**8614**		**Total number of occupants**
Total Ydalir	**108614**		2500

Product and replacement stages

Material lists for all three archetypes are presented in Appendix E.1. The residential buildings are assumed to have the same amount of materials per area as the ZEB 1. The embodied emissions from the non-residential buildings have been collected from EPDs and further calculated with the LCA tool One Click LCA [33].

Energy use in operation

The energy use in operation is based on the passive house standard NS 3700 [34] and NS 3701 [35] for the residential and non-residential buildings respectively. The total thermal load for the buildings in Ydalir is 4.81 GWh/year and the electrical load is 3.93 GWh/year. Figure 2.3 shows the annual load per area for each of the building types. Both the electrical and thermal loads are assumed to remain constant over the service time of the buildings.

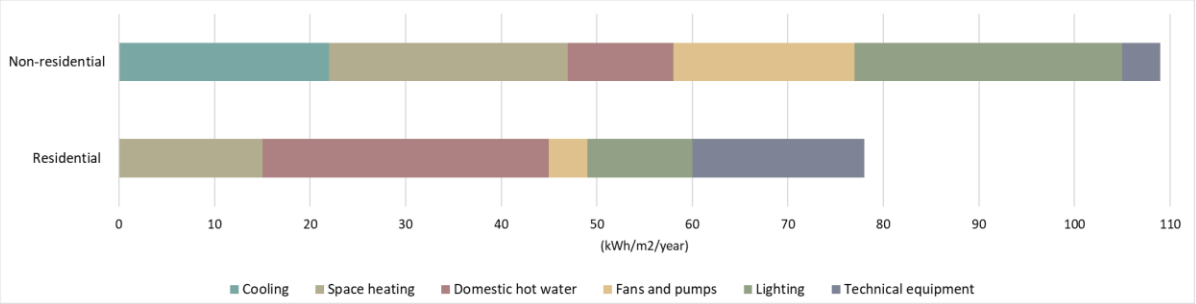


Figure 2.3 Annual load from each building type (kWh/m^2) (see Appendix E.2)

The el-specific energy will be covered by CHP machines and PV panels. The CHP machines use wood chips to produce both heat and electricity. As the heat is the primary product is the electricity seen as a secondary product with no emissions. The CHP machines will produce 1.8 GWh/year electricity. The remaining load will be covered by the PV panels. At Ydalir, there will be 18 m^2 of PV panels per residential building [31], producing 2.34 GWh/year in total.

The heat-specific energy demand for the neighbourhood is going to be covered by district heating. The district heating system will deliver an amount of 5.5 GWh/year to Ydalir, which means that there will be excess heat exported out on the grid.

2.2.2 Mobility

Mobility has proven itself to be the major contributor to the emissions from the neighbourhood and has therefore become the main focus of this study. At Ydalir three means of transportation have been assessed; personal vehicle, bus and light rail. The travel habits of the residents at Ydalir have been based on the National travel survey [36] and further adapted to the specific measures taken at Ydalir (see Appendix F.1). The measures assumed to have an impact are no parking opportunities at school or kindergarten and limited space in the garage which is placed at the periphery of the neighbourhood. To calculate the effects of these measures a report done by the Institute of Transport Economics has been used [37].

Travels related to users of the school and kindergarten that are not residents of Ydalir have also been included and calculated based on two reports prepared by Context [38, 39]. However, the reports state the total emissions associated to the travels related to the school and kindergarten. In order to avoid double counting the emissions, it is assumed that 40% of the emissions comes from the users not living at Ydalir.

NS 3720 [23] suggests including transportation of users, but does not include the methodology on how to calculate the emissions. However, as a source for data regarding the emissions from different means of transportation, it suggests using a project performed by the Norwegian research institute Vestlandsforskning [40]. These numbers are used as initial emissions values for production of the transportation mode and the fuels/energy carriers from well-to-wheel.

Evolution of vehicle stocks

The evolution of the vehicle stocks is adapted to two different scenarios; a trend path and a ultra-low emission path [41]. The trend path defines the base case and is based on the development in earlier years while the ultra-low emission path is an optimistic prediction of the evolution. Both scenarios assess the evolution of the personal vehicle- and bus stock, looking at several fuel/energy carriers. The report only describes the paths from 2010 to 2050 and the development for the last 30 years is therefore assumed to be the same as for the time period 2045-2050 as illustrated in Figure 2.4 and Figure 2.5. Scenarios combining the technology evolution paths and the travel habits of the inhabitants of Ydalir is described in section 2.4.2. Light rail is assumed to be all-electric over the whole analysis period (see Appendix F.2).

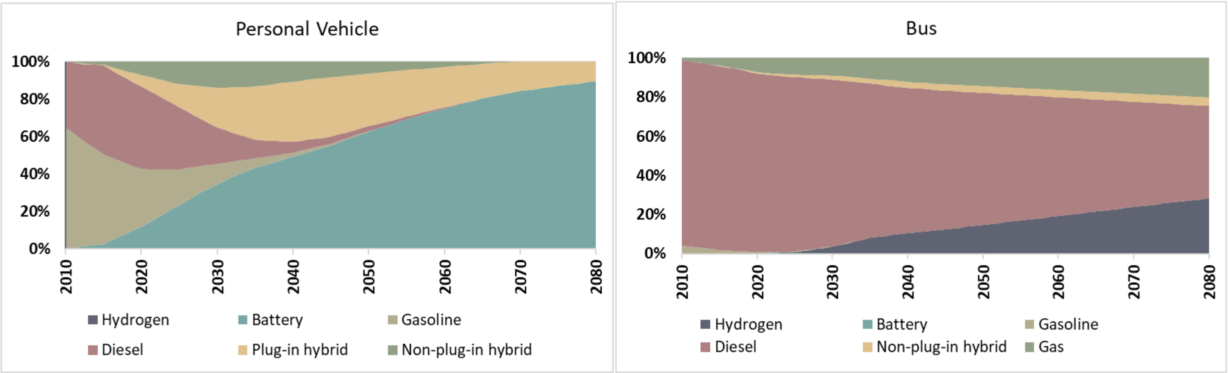


Figure 2.4 Expected evolution of vehicle stock when assuming the trend path for both passenger vehicles and buses divided into energy carriers (see appendix F.2)

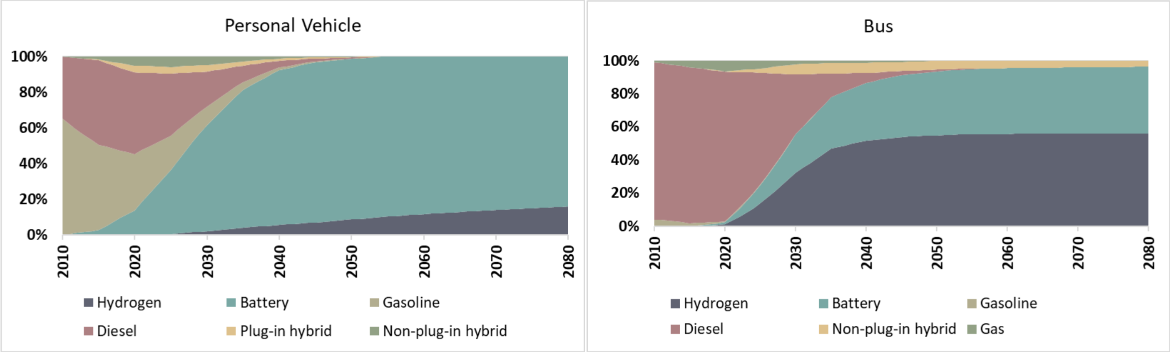


Figure 2.5 Expected evolution of vehicle stock when assuming the ultra-low emission path for both passenger vehicles and buses divided into energy carriers (see appendix F.2)

Production and replacement

The embodied emissions from the transportation modes have been spread over the whole lifetime of the neighbourhood as they are divided per distance driven (see Appendix F.3). However, 20% of the material emissions are assigned as initial material input (A1-A3) and the remaining 80% are assigned as replacements.

The initial emissions are collected from Vestlandsforskning [40] and future evolution of the emission intensities associated production and replacement are collected from the scenario analysis by Lausselet *et al.* [42]. There is only predicted a change over the time period 2030-2050, and after this the emission intensity is assumed.

Energy use in operation

The energy use in operation is connected to the fuel looking at the well-to-wheel emissions. Also here the initial emissions are collected from Vestlandsforskning [40] and further evolution is based on the study performed by Lausselet *et al.* [42] (see Appendix F.4). The scenario analysis predicts a total reduction of the emissions from hydro vehicles to be 50%, battery vehicles on 17%, and a 20% reduction of the remaining powertrain types. The efficiency of the propulsion energy is increased over the years from 2020 to 2050 while the emission per person km is decreased. After 2050 they stay constant. See Figure 2.6.

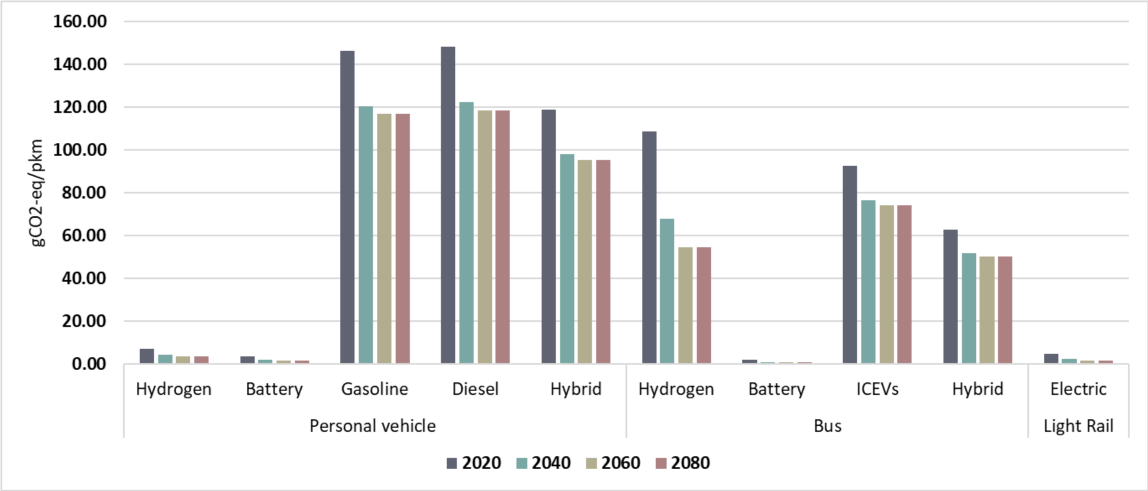


Figure 2.6 Evolution of the emissions related to the propulsion energy for each of the transportation modes

2.2.3 Infrastructure

In the element infrastructure, emissions from roads, sidewalks and lighting have been evaluated. In addition, the diesel consumption used in the preparations of the infrastructure and the associated emissions have been calculated.

Product and replacement

The area of wide roads, narrow roads and sidewalks are defined by the plan description for the residential area B7 (16850 m^2) [43] and then scaled up to match the size of Ydalir (350000 m^2). This gives 20356 m^2 of wide roads, 29911 m^2 of narrow roads and 26588 m^2 of sidewalks. These numbers are associated with high uncertainties, but are included to illustrate a rough estimation of the environmental impact from the infrastructure. Both roads and sidewalks have crushed gravel foundations, but the roads have an asphalt cover and the sidewalks have a concrete cover. The lifetime of gravel and concrete are assumed to be 60 years, while for the asphalt covers it is assumed to be 20 years. Arda was used to collect the emissions (see Appendix G.1).

Energy use in operation

Only the operation of the public lighting has been included in the energy use in operation stage. Other operation activities like snow shovelling, road clearing and other maintenance activities have been neglected from this study. The operation of the public lighting has been calculated from an average of dark hours per day (see Appendix G.2).

Construction

The diesel consumption from constructing the infrastructure has been included. The total diesel consumption is the diesel consumed in the period from September 2016 to October 2018, and has been used for preparing the ground and moving masses on the construction site. Ydalir has assumed an emission intensity for the diesel of 0.376 kg CO_2/l (see Appendix G.3).

2.2.4 On-site Energy Production DH

The district heating system will cover the total heating demand for the buildings at Ydalir. The heat will be produced off-site, and the embodied emissions to the heat production plant are therefore not included.

Production and replacement

The length and size of the pipes are given by Eidsiva Energi and results in 7220 m of pipes. The average diameter of 100 mm and the amount of materials included have been adopted from the study done by Oliver-Solà *et al.* [44] (see Appendix H.1).

Energy use in operation

Some excess heat energy will be exported from the neighbourhood to surrounding area and are seen as negative emissions. The contribution of the exported excess heat is discussed in the report by Wiik *et al.* [45], where the reference emission factor per kWh is calculated by Equation 9.

$$e = \sum s_i * \frac{e_i}{f_i} \tag{9}$$

Where s denote the fuel share, e is the emission intensity and f represents the efficiency factor. The emission intensity factor for the district heat is assumed to stay constant over the whole analysis period and is calculated to be 24.24 g CO_2/kWh (see Appendix B.2).

2.2.5 On-site Energy Production PV

The on-site electricity production at Ydalir consists of both PV panels and CHP machines. The PV panels will be mounted to roofs and facades on the residential buildings and in surrounding area.

Production and replacements

The Masterplan [31] states that there will be 18 m^2 of PV panels per residential building, resulting in 18 000 m^2. The associated emissions are found using Ecoinvent 3.2 (see Appendix I.1). Further, the lifetime of the panels is assumed to be 30 years, resulting in one replacement. As suggested by the ZEB Centre, the emissions from the replacements will have a reduction of 50% from the initial materials, due to technology development and efficiency improvements.

Energy use in operation

The emission intensity associated to the production of electricity is assumed to have a symmetric weighting. Meaning that the electricity produced by the PV panels will replace the electricity from the grid and the emissions are therefore seen as negative contributors in the emission accounting. The electricity is either consumed by the neighbourhood itself or exported to the external grid.

2.3 Sensitivity Analysis

A sensitivity analysis was carried out with the goal of revealing the critical parameters in the LCA model. The factors that were expected to have significant impact on the results or associated with large uncertainties were chosen and increased with 25%. The parameters analysed were mobility energy use in operation, area of PV panels, energy load (thermal and electric), emissions embodied in building materials, emissions associated with vehicle production, travel distance/inhabitant/year, emission intensity district heat and emission intensity electricity. The sensitivity ratio was calculated using Equation 10.

$$SR = \frac{\Delta R/R_0}{\Delta P/P_0} \tag{10}$$

$\Delta R/R_0$ represents the relative change in the results while $\Delta P/P_0$ is the relative change in the input parameters.

2.4 Scenario Analysis

In order to explore the possibility of reaching the zero emissions ambitions, several scenarios were created. As this study goes into the depth of the mobility, several scenarios were created regarding this element. Other scenarios analyse the impact from energy emission intensities, building materials and upscaling the energy production from PV panels.

2.4.1 Energy Emission Intensity

As mentioned in section 2.1 two scenarios regarding the emission intensity have been created, namely scenario 1 (NO) and scenario 2 (EU28+NO). A third scenario explores the effects of asymmetric weighting when looking at scenario 1 (NO). Asymmetrical weighting of the emission intensity assumes different intensities for the imported and exported energy. This way the exported energy counts as negative emissions that match the emission intensity of the European el-mix.

2.4.2 Mobility

Six scenarios regarding the mobility have been created in order to analyse the effects of mobility. Scenario A represents the base case where the travel distance is for Ydalir, and the technology development path for mobility follows the trend path. Scenario B is also for the travel distance Ydalir, but the technology development follows the ultra-low emission path. Scenario C and D illustrate the results for Ydalir including car-sharing for the trend path, and ultra-low emission path respectively. It is assumed that car-sharing will cut the total travel distance in half. Further, a scenario looking at the travel distance in Elverum was created. This scenario analyses the effects of the personal vehicle restriction measures taken at Ydalir. The National travel survey states that 19% of the total travel distance is related to work [36], and the final mobility scenario therefore allocates 19% the travel distance away from Ydalir.

2.4.3 Materials

Studies show that exchanging traditional building materials (such as concrete and steel) to wood will reduce the total emissions from the materials significantly [46-48]. However, as the buildings at Ydalir already are imposed to follow the passive house standard, it is assumed that the impact from using more wood will reduce the emissions from the building materials with only 10%.

2.4.4 Energy Production

The final scenario analyses the impact from upscaling the energy production from PV panels in order to achieve the zero emissions ambition of Ydalir. The area of PV panels needed has been calculated when considering emission intensity scenario 1, mobility scenario D, mobility allocation to workplace, asymmetrical weighting of the energy emission intensity and emission reduction from the building materials. It is noted that increasing the area of PV panels also will increase the emissions from the materials.

3. Results

The results from using the described methodology on the ZEN Ydalir with the emissions associated to the included physical elements (buildings, mobility, infrastructure, networks and on-site energy) and the life cycle stages (A1-3, B4, B6 and D) are described in this section. When assuming the baseline scenario (mobility scenario A and energy emission intensity scenario 1), the total emissions from the neighbourhood over its lifetime of 60 years became 140 ktonne CO_2-eq. Equivalent to 0.9 tonne CO_2-eq/capita/year or 21.5 kg CO_2-eq/m^2/year.

3.1 Overall Results

Figure 3.1 and Figure 3.2 show the results from the two energy emissions intensity scenarios (see Appendix J.1). For both scenarios the energy use in operation of mobility clearly is the highest contributor, representing 42-46% of the total emissions. The second highest contributor for scenario 1 is the replacement of mobility, while for scenario 2 it is the energy use in operation of the buildings. Another important observation is the benefit calculations for each scenario. For scenario 2 the benefits reduce 38% of the total emissions. In scenario 1, however, the benefits only reduce the total emissions with 7%. This is an effect of the low emission intensity of the Norwegian el-mix.

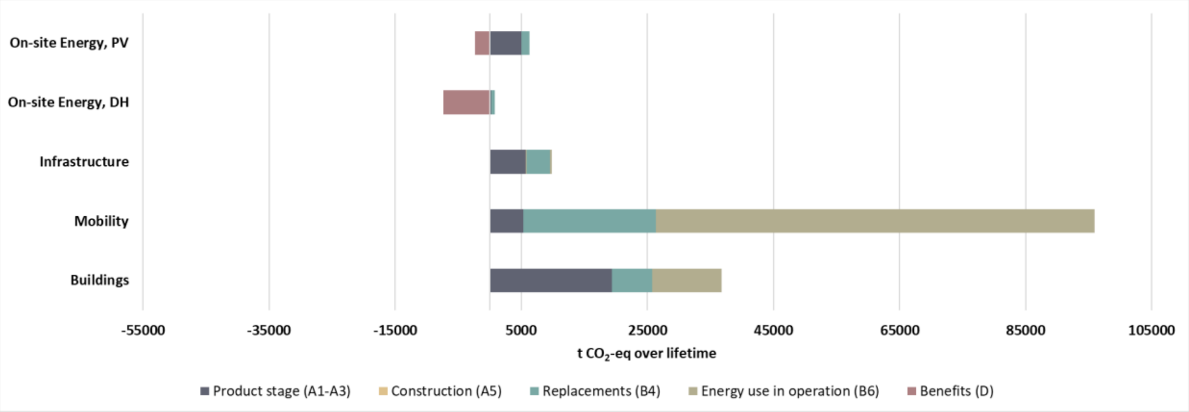


Figure 3.1 Results of total emissions over lifetime for the emission intensity scenario 1 (Note mobility scenario A)

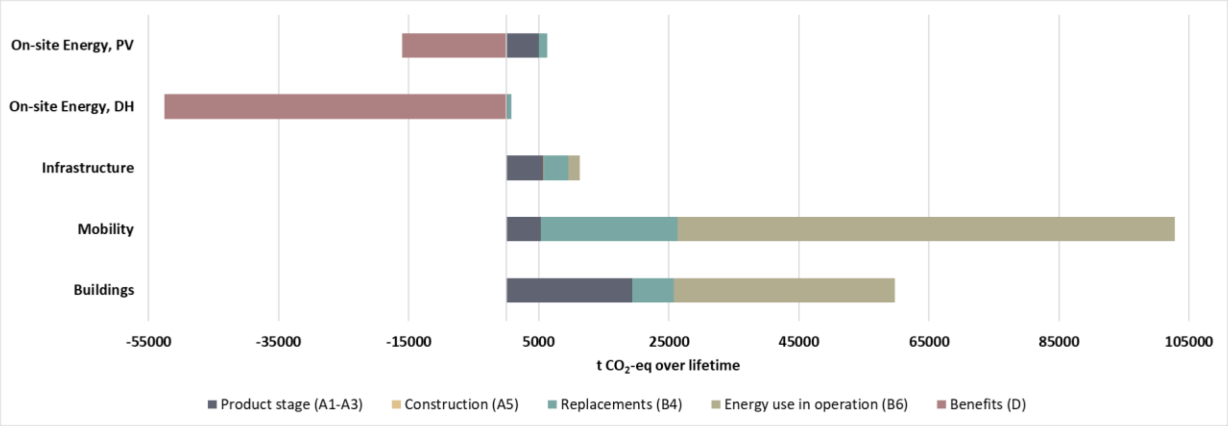


Figure 3.2 Results of total emissions over lifetime for the emission intensity scenario 2 (Note mobility scenario A)

The results further show in Figure 3.3 that the pre-use phase represents a significant part of the total emissions from the neighbourhood. 20% of the total emissions from the neighbourhood are produced before it is even populated. Further, the results show that there are some emission peaks over the lifetime of the neighbourhood, originating from replacements of PV panels and infrastructure.

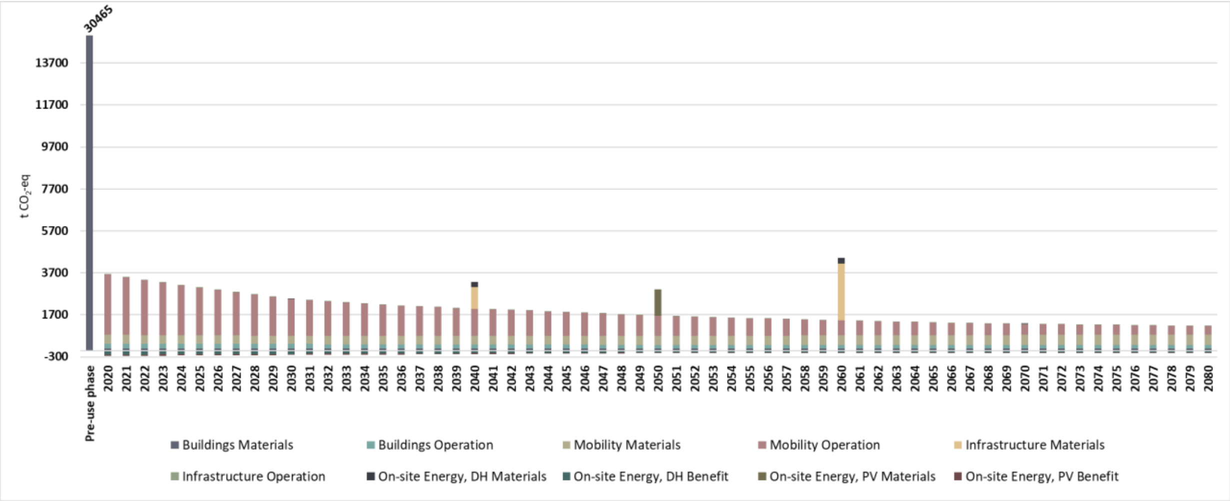


Figure 3.3 Total annual emissions from each year including the pre-use phase (Note mobility scenario A and energy emission intensity scenario 1 (NO))

In Figure 3.4 the use stage is shown excluding the pre-use phase. The emissions from operation of mobility are decreasing over the neighbourhood's lifetime to 14% of the initial emissions. On the other hand, the emissions from the district heating system and mobility materials increase over the years. Further, as a consequence of the decrease of the energy emissions intensity, the negative emissions from the PV panels also decrease over the years for both scenario 1 and 2.

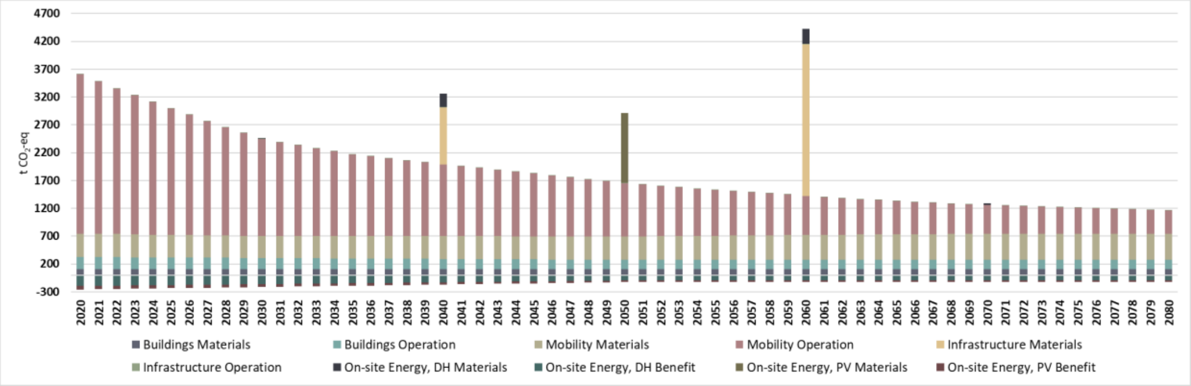


Figure 3.4 Total annual emissions from each year excluding the pre-use phase (Note mobility scenario A and energy emission intensity scenario 1 (NO))

3.2 Mobility Results

As indicated by the results above, the mobility in the neighbourhood represents a considerable share of the total emissions from the neighbourhood, and a deeper analyse of the results was therefore necessary. Figure 3.5 shows the evolution of the emissions from each mode of transportation over the neighbourhood's lifetime. Over the first 20 years there is a significant decrease of the emissions from the powertrains diesel and gasoline for the personal vehicles, and over the next 20 years they fade out totally. However, the emissions from the hybrid personal vehicles expand the first 20 years, before it decreases and become even lower than the initial value. When looking at the buses, the emissions from the hydrogen buses increase over the whole lifetime of the neighbourhood, while the emissions from the hybrid buses decrease.

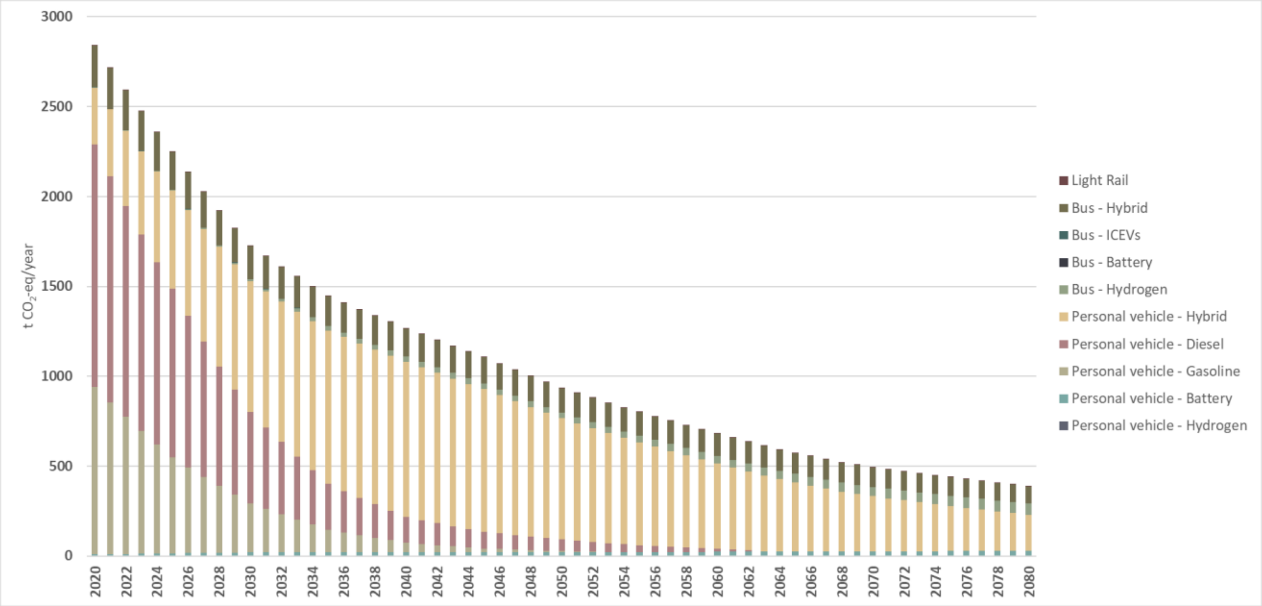


Figure 3.5 Annual emissions from each transportation mode (Note mobility scenario A and energy emission intensity scenario 1 (NO))

3.3 Sensitivity Analysis Results

The sensitivity analysis results are listed in Table 3.1 and reveal the parameters with the largest impact on the total emissions from the neighbourhood. The two parameters with the highest impact are the travel distance/inhabitant/year and the mobility energy use in operation.

Table 3.1 Results from sensitivity analysis, including sensitivity ratio and change in total emissison result relative to the base case

Sensitivity parameters	△P/P0	R	△R/R0	SR	% deviation from basecase
Emission intensity electricity +25%	0.25	138937.5675	-0.007410221	-0.030	-0.7%
Emission intensity district heat +25%	0.25	141752.9444	0.012703233	0.051	1.3%
Travel distance/inhabitant/year +25%	0.25	163601.8536	0.168794954	0.675	16.9%
Emissions associated with vehicle production +25%	0.25	146575.1751	0.047153936	0.189	4.7%
Emissions embodied in building materials +25%	0.25	146415.8245	0.046015513	0.184	4.6%
Energy load (thermal and electric) +25%	0.25	142719.9131	0.019611395	0.078	2.0%
Area of PV panels +25%	0.25	140974.168	0.007139544	0.029	0.7%
Mobility energy use in operation +25%	0.25	157002.4759	0.121648059	0.487	12.2%

Figure 3.6 shows the results from the sensitivity analysis. It is revealed that the two most critical parameters are connected to mobility, namely the mobility energy use in operation and travel distance/habitant/year. It is also worth noticing that the embodied emissions from the building materials have an impact on the resulting emissions of 4.6%.

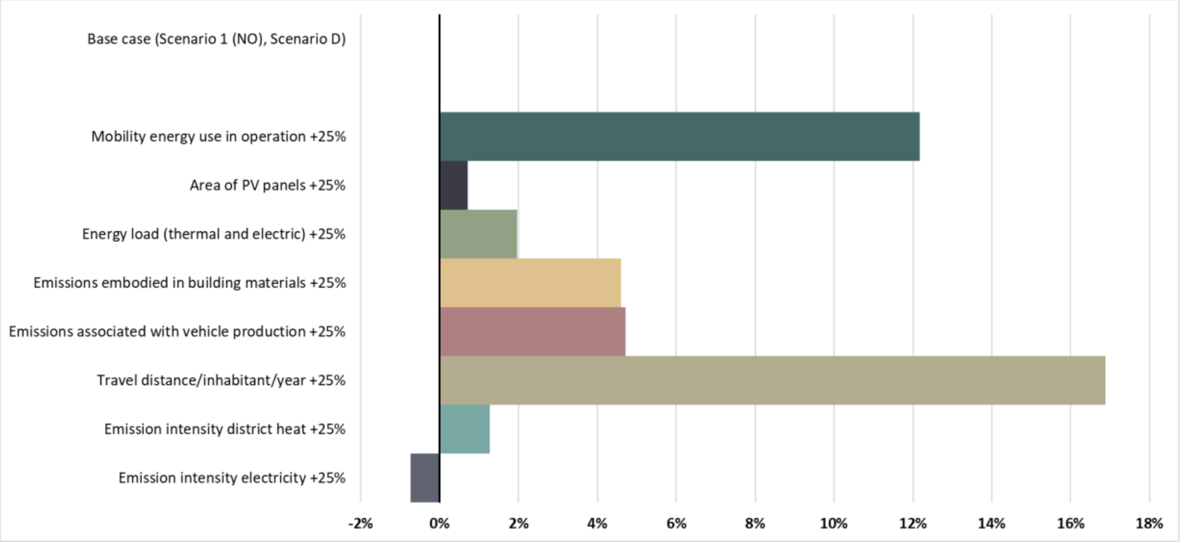


Figure 3.6 Results of sensitivity analysis and critical parameter relative to the base case

3.4 Scenario Analysis Results

The results from the scenario analysis show which measures have the most considerable impact on the results, when assuming the base case (energy emission intensity scenario 1 and mobility scenario A).

3.4.1 General Scenario Results

Figure 3.7 shows the results from the scenario analysis and reveals that the mobility scenarios have the most pronounced impact on the results, as expected. An interesting observation is the consequence of using asymmetrical weighting of the energy emission intensity, which reduces the total emissions with 42.4%. Further, when applying the energy emission intensity scenario 2, the total emissions are reduced with 20%. Note that when doubling the area of PV panels, the total emissions increase with 2.9% when assuming scenario 1. Finally, when applying scenario 1, scenario D and all the measure scenarios, the total emissions from the neighbourhood are reduced by 99.8% making the neighbourhood a ZEN (see Appendix K.1).

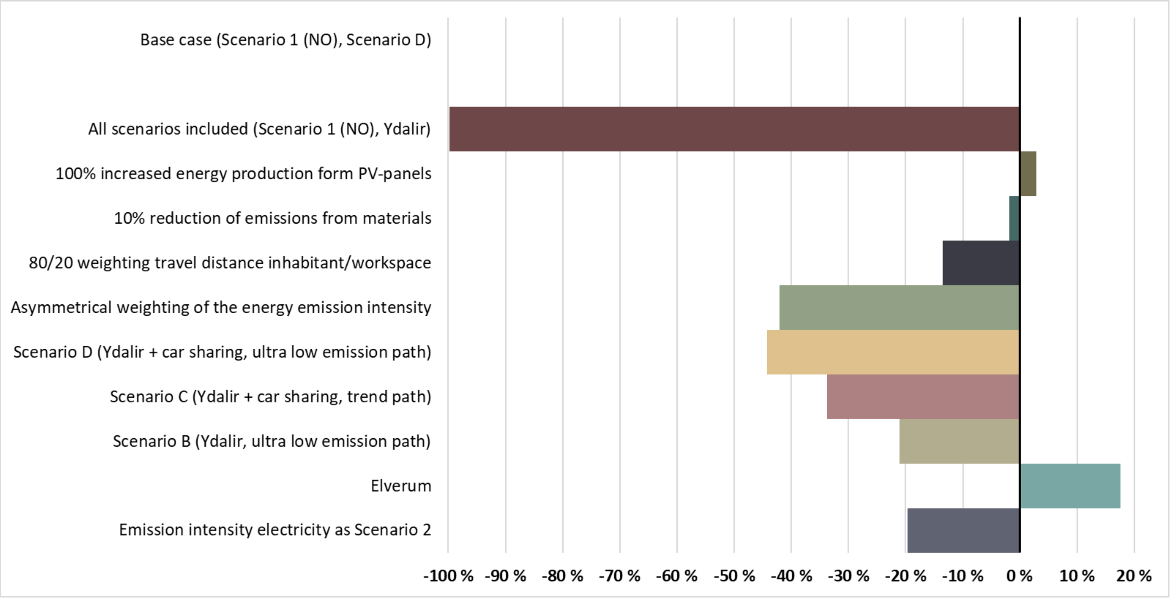


Figure 3.7 Results of scenario analysis relatively to the base case

3.4.2 Mobility Scenario Results

Figure 3.8 shows the results from each mobility scenario. The results for scenario A (base case) have been discussed as scenario 1 in section 3.1. By comparing scenario B and C, it can be concluded that it is the reduction of the daily travels of the residents that have the greatest impact on the total emissions. When looking at scenario D, representing the most optimistic results, the product stage of buildings and energy use in operation of mobility become equal, representing 22% of the total emissions from the neighbourhood each (see Appendix K.2).

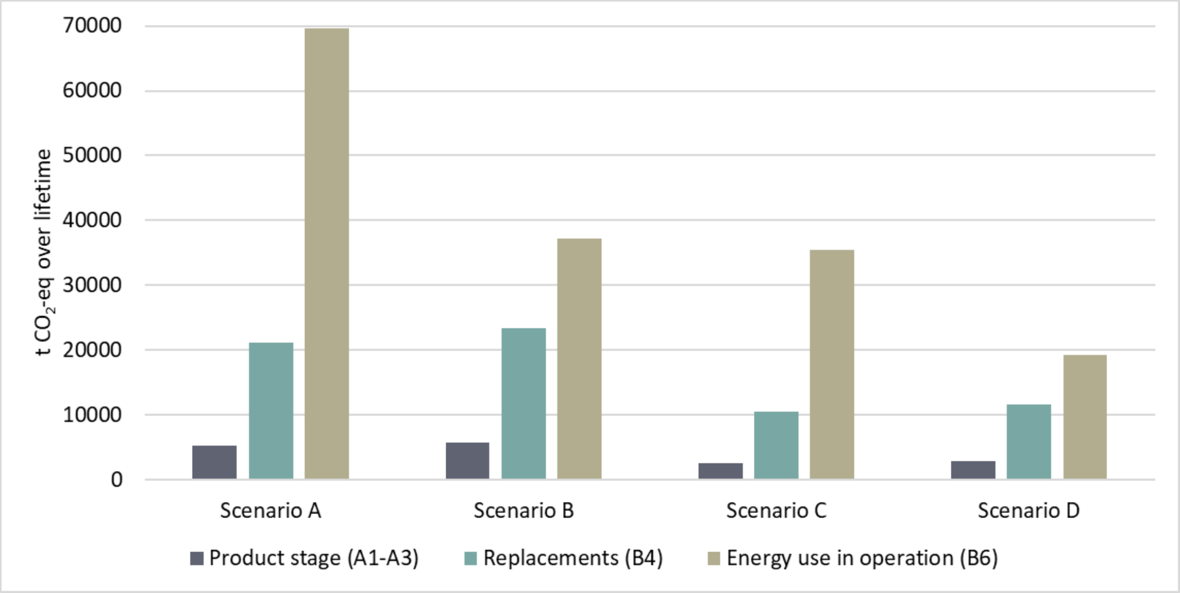


Figure 3.8 Results of total emissions over lifetime. Scenario A: Ydalir & trend path, scenario B: Ydalir & ultra-low emission path, scenario C: Ydalir + car-sharing & trend path and scenario D: Ydalir + car-sharing & ultra-low emission path (Note energy emission intensity scenario 1 (NO))

4. Discussion

This section discusses the modular structure presented in section 2.1 and the model adapted for Ydalir (section 2.2). Further, the results presented in section 3 in regard to the research questions (section 1.3) and uncertainties and limitations are discussed. Finally, further work on the field of LCA modelling for ZENs are suggested.

4.1 Results and Critical Parameters

When expanding the LCA model from individual buildings to complex systems as neighbourhoods, the chosen system boundaries and preconditions made are crucial. The modular approach opens for the opportunity of applying different functional units and mapping the emissions sources both regarding the elements and life cycle stages. The modular structure also makes it easy to adjust the LCA model to different neighbourhood projects while facilitating comparability.

The placement of the system boundaries to decide which life cycle stages and physical elements to include in an LCA, appears to have significant impacts on the results. The results reveal that when all elements are included (energy emissions intensity scenario 1 and mobility scenario A), the buildings account for 25% of the total emissions from the neighbourhood. Of these emissions the materials represent 70% and the energy use in operation represent 30% of the emissions. These results are comparable with Wiik *et al.* [12] that reported the embodied emissions share to be 55-87%. However, Lausselet *et al.* [22] conclude in their article that the buildings represent a majority of the GHG emissions (52%), which is more than twice the emissions found in this study. The low share of emissions from the energy use in operation is caused by the fact that all buildings are passive houses, with low emissions from the district heating based 98% on wood chips.

The model considers two different scenarios regarding the emissions intensity of the energy, as suggested in standard NS 3720 [23]. However, as shown by the sensitivity analysis, the total emissions from the neighbourhood increase with only 0.5% when applying the scenario 2 (EU28+NO) compared to scenario 1 (NO). A surprising result when looking at scenario 1 with the assumption of symmetrical weighting (equal emission intensity for import and export), the gains (negative emissions) from PV panels do not cover the embodied emissions from the PV panels, and the supposedly gains from the district heating do not cover the emissions from producing the heat. However, when applying asymmetrical weighting to scenario 1 (emission intensity for export equals the European emission intensity) the total emissions are reduced by 42%. As local energy production releases the Norwegian el-mix for export, using asymmetrical weighting becomes more realistic. In addition, it is a political decision that the use of fossil fuels shall be reduced, and the use of asymmetrical weighting can thereby be defended [42]. The choice of emission intensity for both electricity and several other elements, such as the emission intensity of district heat, are debated in LCA studies [9, 49, 50].

When all elements considered, the model reveals that the operation of mobility contributes with 42-46% of the total emissions depending on the scenario and its preconditions. This is comparable to the results of Nichols and Kockelman [14] and Bastos *et al.* [20] that found mobility to represent 44-47% and 51-57% respectively. The variations result from optimistic or conservative assumptions of the future evolutions of mobility. Looking at scenario A when considering only the element mobility, 28% of the emissions origin from the embodied emissions of the materials. For scenario D, on the other hand, the materials constitute 43% of the emissions. This is a consequence of the significantly improvement in the fuel/energy carrier technology and a shift in the share of the powertrains used. An important notion to the assumptions made for the mobility is that the impacts of the measures done in the base case scenario (scenario A) are offensive and the results are conservative. However, when considering the most optimistic scenario (scenario D), the results still show mobility to be the largest contributor to the total emissions from the neighbourhood. The travel habits of the inhabitants are based on national numbers and is a source of uncertainties as there are expected lower values for the inhabitants at Ydalir. Further studies on the travel habits of the inhabitants of neighbourhoods are recommended in order to conduct a deeper analysis of the element mobility.

The infrastructure element includes roads, sidewalks, public lighting and construction of the infrastructure, in addition to the network element including pipes for the district heating system. This element constitutes 7-11% of the total neighbourhood emissions, depending on the scenarios. The embodied emissions from the materials have been highly simplified and higher emissions from this element is therefore expected. When looking at the operation of the infrastructure, only public lighting has been considered, while other operational elements as road maintenance and snow clearance have been excluded.

The results in this study derive from detailed input data, and it is therefore limited how early in the planning stage of a neighbourhood this model can be used. In comparison, the two early planning stage LCA models NEST [26] and OmrådeLCA [27], use key numbers in their calculations and can therefore be used to decide whether or not to build the neighbourhood. However, all three models acknowledge the huge effects preconditions and design choices have on the environmental impacts. When performing LCA at an early planning stage, the goal is to identify the best combination of solutions that give the lowest emissions.

4.2 Limitations and Further Work

There are several advantages with the model. It maps dominant drivers related to both physical elements and life cycle stages, and facilitates comparability between different projects. However, the model has some weakening limitations and parameters that need further attention.

The neighbourhood will be built over a period of 15-20 years and production development, improvement in technology and changes in the Norwegian building regulations (TEK) over both the construction period and the neighbourhood's lifetime are expected. However, this study assumes no improvement in these areas for neither the initial construction or the replacement of materials in both buildings and infrastructure. Other temporal aspects such as technology development and increased energy efficiency of both materials and fuels/energy carriers in mobility, and the behaviour of the inhabitants are related to high uncertainties. These temporal aspects are all objects for further work.

An LCA often includes several impact categories to show a comprehensive picture of the product or process at hand. In this model only GHG emissions have been analysed and discussed, and in order to avoid problem shifting phenomena more impact categories should be included. An example here is a reduction of GHG emissions, but an increase of other impact categories as land use change, acidification and human toxicity. The LCA model should therefore be expanded to include more impact categories.

A discussion regarding whether the inhabitants of the neighbourhood or the workplace is responsible for the emissions related to work travels, has also been approached. The results state that it is the daily travel distance of the inhabitants that is the main challenge, and an allocation of the work travels to the workplace will decrease the total travel distance of the neighbourhood's inhabitants and thereby the total emissions from the neighbourhood.

The data for energy consumption and production in the model are based on yearly averages rather than hourly data. Basically, assuming the external grid to be an infinite battery, not considering whether the electricity is consumed locally or exported. This is justified by the symmetric weighting used, stating that the emissions intensity stays constant over the year. Another interesting factor that should be added to future studies is the economical perspective. The relation between imported and exported energy is commonly asymmetrical, where the price for the exported energy usually is lower than for the imported. Implementing other factors such as energy storage and vehicle-to-grid concepts then also become relevant.

In order to achieve the 0-ambition goal, what to include in the definition of 0-ambition must be determined. In this study, ZEN OM has been applied on the elements; buildings, mobility, infrastructure, networks and on-site energy production. In the scenario analysis several measures were taken; downscaling of the mobility, upscaling of PV panel energy production, asymmetric calculations of the energy emission intensity and reducing the embodied emissions in the buildings. When assuming these scenarios in addition to scenario D on mobility and the energy emission intensity scenario 1, the total emissions were reduced by 99.8% relative to the base case. This states that action to reduce the total emissions from neighbourhoods must be done, but the 0-ambition is possible in the future.

Regardless of the choice of emission intensity scenario the results show that Ydalir does not achieve their goal of zero emissions. Nevertheless, this study highlights the neighbourhood's areas of improvement. The mobility represents the highest share of emissions, and in order for this to reduce, more restrictions regarding the use of personal vehicles are needed. Further, the emissions from the element buildings can also be reduced by increasing the use of wood, and design them to become even better than the passive house standard. Finally, upscaling of the energy production from PV panels is needed to be able to export more energy and thereby reduce emissions from fossil fuels used in mobility, embodied emissions in the materials and other emission sources in the neighbourhood. Other measures such as carbon capture systems, zero emission construction site and including the end-of-life stage will also reduce the emissions from the neighbourhood, but these have not been approached in this study.

5. Conclusion

In order to highlight the dominant emission sources from the ZEN Ydalir at an early planning stage, a model based on a modular structure was chosen. The model was adjusted to fit the specifics of Ydalir, located in Elverum, Norway, with the goal of mapping the main drivers regarding physical elements and life cycle stages.

The results show that Ydalir does not achieve its goal of zero emissions regardless of the scenario, when considering the elements; buildings, mobility, infrastructure, networks and on-site energy generation, in addition to the life cycle stages; production, replacement and energy use in operation. When looking at the Norwegian el-mix the mobility (64%) represents the majority of the GHG emissions, while buildings represents 25%. Regarding the life cycle stages, the energy use in operation represents 54% of the total emissions from the neighbourhood, followed by the production and replacement (46%). The dominant source of emissions is the energy use in operation of mobility (46%), mainly caused by the use of personal vehicles. This study has considered the restriction of available parking spaces at Ydalir. However, the results are offensive and may in reality have a greater impact on the mobility at Ydalir. These results show emission intensity, daily travel distance of the inhabitants and the mobility element to be critical parameters when reaching for the ZEN goal.

The model is weakened by simplifications and assumptions related to technology development and evolution over the neighbourhood's lifetime which are associated to uncertainties. Further work on forecast of energy emission intensity, mobility technology and materials, habits of the inhabitants, and asymmetric weighting is therefore required. The model has a potential to contribute in decision making in early stage planning of ZENs, providing the dominant drivers both related to physical elements and life cycle stages. The modular structure of the model makes it easy to adapt to different neighbourhood projects and produce comparable results. By exploring the possibilities of the scenario analysis, it becomes obvious that the 0-ambition in ZENs is within reach.

Acknowledgements

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The work is performed in association with NTNU's and Sintef's participation in the FME-ZEN Research Centre and has been carried out during the Spring of 2019 at the Norwegian University of Science and Technology.

Supplement Material

The supplementary material is a document consisting of appendices referred to throughout the article. They provide detailed information about the model and the results.

Supplement Material

This document contains the supplementary materials for the article *“Scenario Analysis in LCA on the Zero Emission Neighbourhood Ydalir, a Norwegian Case Study”*. It describes further details around the inventory lists and assumptions made throughout the study case and provides a deeper understanding of the model.

A. Life Cycle Stages

A.1 The Life Cycle Stages of Buildings Defined by NS 3720

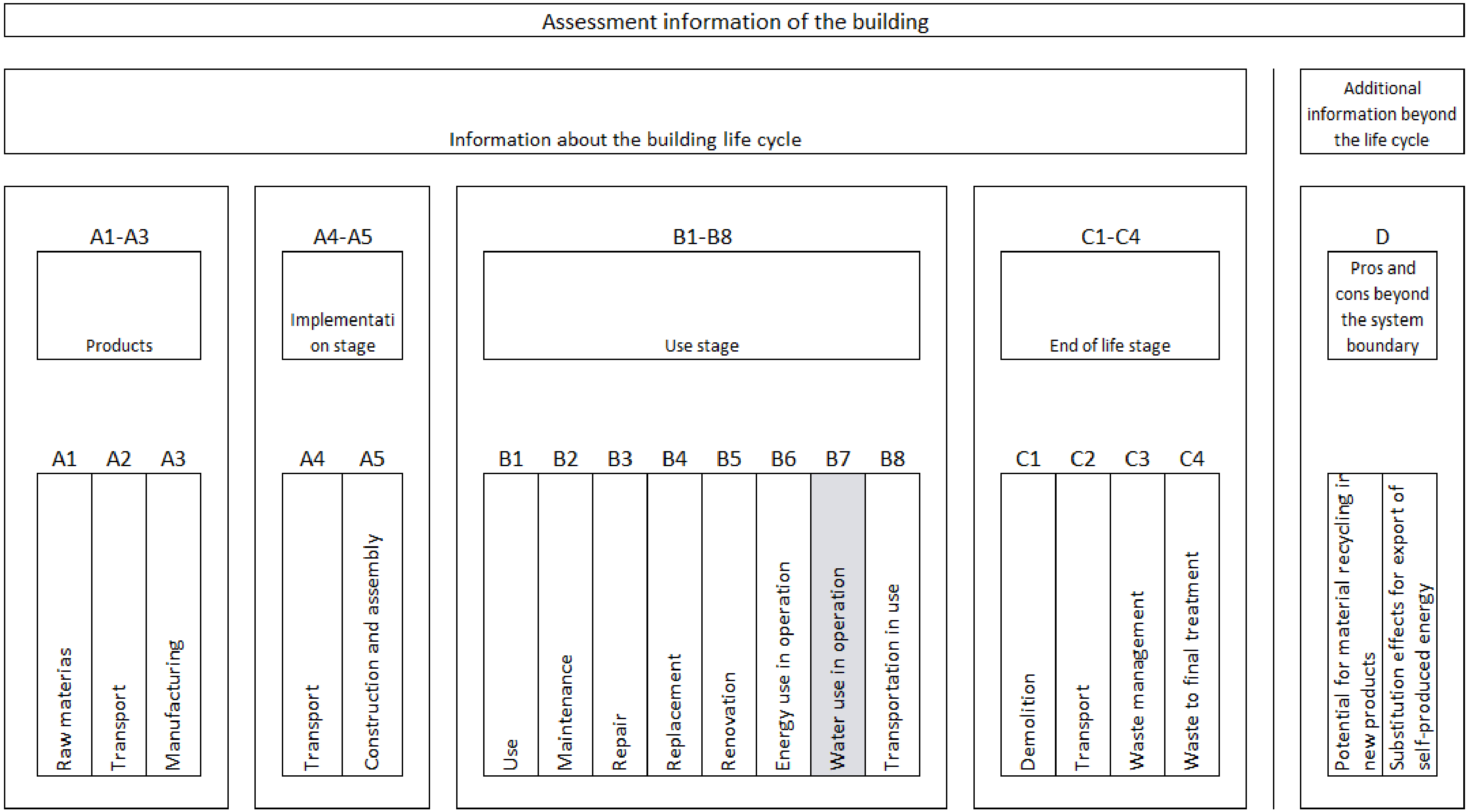


Figure A.1 Building's life cycle, adapted from NS 3720

B. Emission Intensities

B.1 Electricity

The Norwegian standard NS 3720 suggests two scenarios for electricity's emissions intensity, namely scenario 1 the NO and scenario 2 the EU28+NO. For both the production mixes the starting point is defined by todays production mix. Over the next 30 years is the factor calculated by assuming a linear function until the expected production mix in 2050. This study then holds the factor constant until the end of the analysis period. Table B.1 shows the production technologies the standard provides as a basis for calculation of the emission intensities for year 2015 and 2050.

Table B.1 Calculated production mix in 2015 and expected production mix in 2050, Eurostat, EEA, SSB, EUs Roadmap 2050. The table defines a baseline for the scenario 1 and scenario 2

Production technology	CO2-factors (gCO2/kWh)	2015 Norway	2015 EU28+NO	2050 Norway	2050 EU28+NO
Hydro	11	95.0 %	18.0 %	85.0 %	8.0 %
Wind	22	1.0 %	8.0 %	15.0 %	33.0 %
Thermal Norway	450	4.0 %			
Thermal Europe	800		43.0 %		
PV	100		3.0 %		10.0 %
Geo/biothermal	59		0.4 %		10.0 %
Nuclear	6		28.0 %		19.0 %
Thermal with CCS	100				20.0 %

B.2 District Heat

The district heating system in Elverum is run and owned by Eidsiva Fjernvarme, and the emission intensity of the fuel mix is calculated for this specific study case. Table B.2 shows the annual energy production and the associated emissions by source. The energy demand for the neighbourhood is calculated from the Masterplan [31] and the guidelines for energy consumption for passive houses [31]. The energy delivered is given from the supplier Eidsiva Fjernvarme while the shares of input fuel (Table B.3) is collected from Norsk Fjernvarme [51].

Table B.2 Energy and emission source for district heat Elverum each year

	Energy demand (GWh)	Energy delivered (GWh)	Emission intensity (g CO_2-eq/kWh)	CO2-emissions (ton CO_2-eq)
Fossil oil (light oil)	0.096	0.11	289.00	31.79
Wood chips (heat)	4.714	5.39	14.00	75.46
SUM	4.810	5.50		107.25

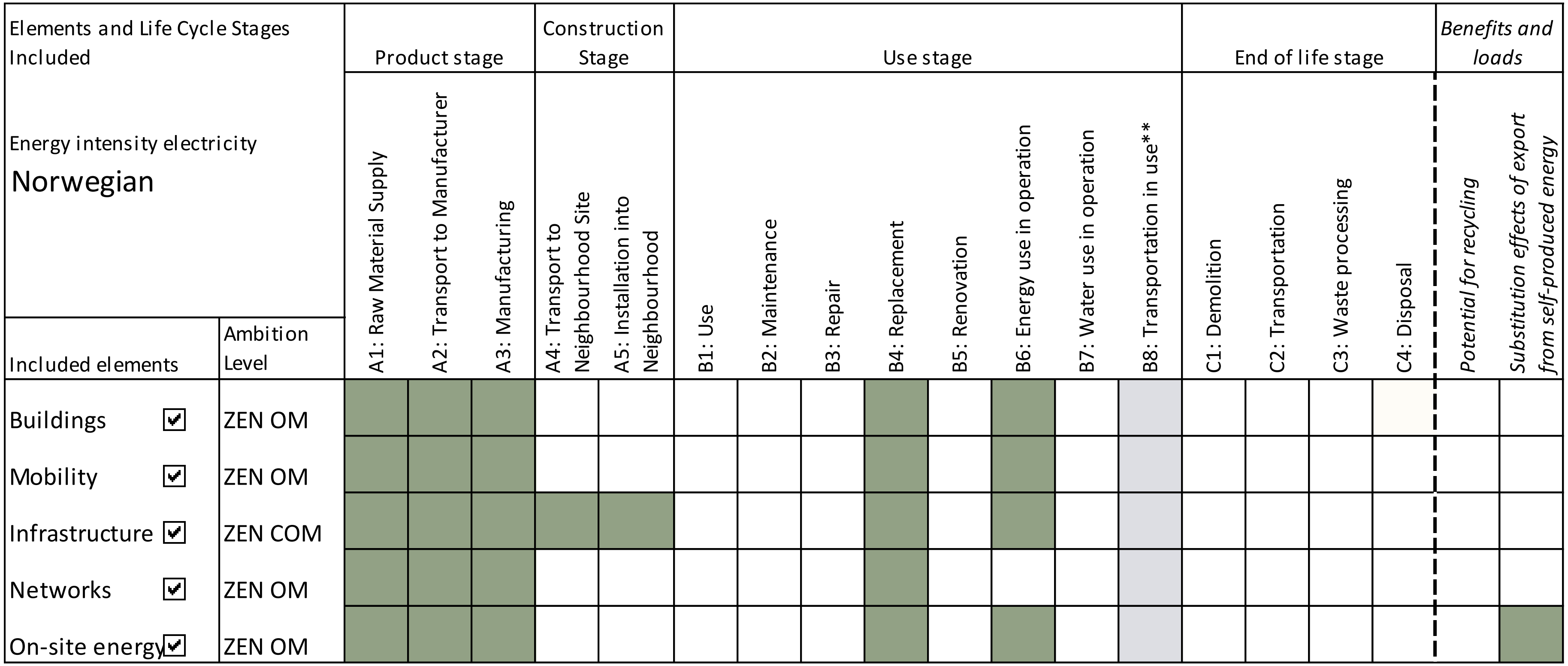
Table B.3 Shares of input fuel to the district heating

CHP input fuel	%
Light oil	0.02
Wood chips	0.98

The Norwegian district heating organization informs that the fuel mix in Elverum is 98% wood chips and 2% light oil [51]. Further, the emission intensity is defined to be 14 g CO_2-eq/kWh for the wood chips with an efficiency of 0.77. While for the light oil, the emission intensity is 289 g CO_2-eq/kWh with an efficiency of 0.9 [52]. Thus, the reference emission factor per kWh for the excess heat energy calculated is:

$$e = 0.98 * \frac{14\frac{g\,CO_2}{kWh}}{0.77} + 0.02 * \frac{289\frac{(gCO_2)}{kWh}}{0.9} = 24.24\,\frac{gCO_2}{kWh} \tag{B.1}$$

C. Modular Structure Ydalir



Elements and Life Cycle Stages Included Energy intensity electricity Norwegian		Product stage			Construction Stage		Use stage								End of life stage				*Benefits and loads*	
Included elements	Ambition Level	A1: Raw Material Supply	A2: Transport to Manufacturer	A3: Manufacturing	A4: Transport to Neighbourhood Site	A5: Installation into Neighbourhood	B1: Use	B2: Maintenance	B3: Repair	B4: Replacement	B5: Renovation	B6: Energy use in operation	B7: Water use in operation	B8: Transportation in use**	C1: Demolition	C2: Transportation	C3: Waste processing	C4: Disposal	*Potential for recycling*	*Substitution effects of export from self-produced energy*
Buildings ☑	ZEN OM	🟩	🟩	🟩						🟩		🟩		▨						
Mobility ☑	ZEN OM	🟩	🟩	🟩						🟩		🟩		▨						
Infrastructure ☑	ZEN COM	🟩	🟩	🟩	🟩	🟩				🟩		🟩		▨						
Networks ☑	ZEN OM	🟩	🟩	🟩						🟩				▨						
On-site energy ☑	ZEN OM	🟩	🟩	🟩						🟩		🟩		▨						🟩

* Not included in present study

** Not relevant (covered by mobility element)

Figure C.1 Modular structure for Ydalir

D. Map of Ydalir

Figure D.1 Map over Ydalir. Credits to Tegn_3

Figure D.2 Map over Ydalir. Credits to Asplan Viak and Elverum vekst

E. Buildings

E. 1 Materials in Buildings

The material list for the residential buildings are equal to the ZEB 1 buildings used in the article by Kristjansdottir *et al.* [32].

Table E.1 Materials kindergarten

Building Parts	Material	Amount	Unit	GWP ton CO2-eq	Type of reference	Specification	Estimated service life
2 Building							
2.1 Groundwork and foundations	Insulation	1592	m2	29	EPD	Isolasjon, EPS 80 (EPS Gruppen)	60
	Concrete	81.56	m3	25	EPD	Ferdigbetong, 7540 B45 SV-Standard 22mm, Betong Øst	60
	Concrete	234.84	m3	53.9	EPD	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	60
	Steel	3180	kg	2.6	EPD	Stålfiber til betongarmering, 1250, 1100, 1100 Mpa, L:35, 5	60
	Steel	7735	kg	2.7	EPD	Stål, armeringsprodukter (betongarmering), 7850kg/m3, scrap metall	60
	Insulation	72.6	m3	8.5	EPD	XPS isolasjonsplate 33 mm, 300KPa, 0.033 - 0.039 W/mK,	60
	Radon membrane	1592	m2	4.8	EPD	Radon- og fuktmembran for byggeplass, PP…	60
2.2 Superstructure	Timber	23.33	m3	4.68	EPD	Standard limbjelke, 470 kg/m3, Moisr. 12%, 45 mm, Stranda…	60
	Steel	0.1	m3	2.1	EPD	Strukturelle stålprofiler, generisk 60% recyceled content, …	60
2.3 Outer walls	Timber	259.71	m3	4.89	EPD	Høvellast, bartre (Treindustrien)	60
	Timber	1233	m2	3.42	EPD	Malm100, 513.32 kg/m3, Malm 100 (Moelven)	60
	Timber	218	m2	0.06	EPD	Bindingsverksystem av tre for yttervegger per kvm (inkl. Luft…	60
	Timber	57	m2	0.16	EPD	Trelast, bartre (Trelastindutrien)	60
	Concrete	57	m2	0.05	EPD	Geotextile, generisk, 312 g/m2, Composition: PP net, nonwoov…	60
	Massive wood	161	m2	11.5	EPD	Massivtre Yttervegg, inkl. mineralullisolasjon	60
	Timber	368	m2	0.66	EPD	Heltrepanel av bartre til innvendig bruk (Treindustrien)	40
	Cement	134	m2	4.9	EPD	Fibre cement board, coated, 1550 kg/m3 Construction (Cembrit)	60
	Membrane	150	m2	0.39	EPD	Laminert HDPE membran, 0.195 kg/m2, 1.5 m x 50 m, 820 um, Ty…	60
	Insulation	332.9	m3	5.5	EPD	Glassull-isolasjon, 42 mm, 0.042 W/mK, 630 g/m2, 15 kg/m3,	60
	Membrane	1119	m2	1.2	EPD	Dampsperre, 0.2 mm, 185 g/m2, Dampsperre 20 (Baca Plastindustri)	60
	Gypsum	751	m2	1.5	EPD	Kledningsplate, 9.5 mm, 7.2 kg/m2, Bris (Gyproc)	60
	Insulation	338	m2	0.38	EPD	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	60
	Gypsum	368	m2	0.75	EPD	Kledningsplate, 9.5 mm, 7.2 kg/m2, Bris (Gyproc)	60
	Gypsum	751	m2	1.6	EPD	Gipsplate, 12.5 mm, 9 kg m2, Normal - Standard (Gyproc)	60
2.4 Inner walls	Window	48	m2	4.6	EPD	2-veis innadslåsende åpningsvnidu, Frame: 105 mm, 64.4 kg, 1…	40
	Timber	245	m3	18.1	EPD	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	50
	Gypsum	1580	m2	3.32	EPD	Gipsplate, 12.5 mm, 9 kg m2, Normal - Standard (Gyproc)	60
	Door	204	m2	7.8	EPD	Interior door, 809x2053 mm, 42x92 mm frame, 52 mm door leaf…	60
	Timber	1197	m2	5.36	EPD	Solid timber panels (cross laminated timber, CLT) (Stora Ens…	60
	Timber	3	m3	0.18	EPD	Limtre, 470 kg/m3, 12% moisture content (Moelven Modus)	60
	Timber	1068	m2	0.18	EPD	Bindingsverksystem av tre for innervegger per kvm (inkl. Luf…	60
	Insulation	940	m2	2.23	EPD	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	60
	Window	128	m2	13	EPD	Fastkarm vindu, 0.72 W/m2K, 59.55 kg, 1.23x1.48 m (Norgesvindu)	40
	Window	128	m2	12	EPD	2-veis innadslåsende åpningsvnidu, Frame: 105 mm, 64.4 kg, 1…	40
	Door	59	m2	3.7	EPD	Climate door, 809xmm, 42x92 mm frame, 52 mm door leaf	60
2.5 Floor structure	Concrete	1588	m2	19	EPD	Ferdigbetong, 7540 B45 SV-Standard 22mm, Betong Øst	60
	Timber	476	m2	0.75	EPD	Heltrepanel av bartre til innvendig bruk (Treindustrien)	40
	Timber	26	m3	2	EPD	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	50
	Insulation	1588	m2	2	EPD	Isolasjon, EPS 80 (EPS Gruppen)	60
	Insulation	785	m2	1.1	EPD	Isolasjon/mineralull, Flexibatts 35 (Rockwool)	60
	Cement	1112	m2	2.68	EPD	Akustisk sementpanel i treull, grå, 25x600x1200 [mm], 9.7 kg…	60
	Linoleum	556	m2	3.6	EPD	Linoleum	30
	Cement	37808	kg	7.1	EPD	Avrettingsmasse, 10-60 mm, 1.7 g/l, C25, Proplan Multi (Hey's)	60
2.6 Outer roof	Membrane	82	m2	0.62	EPD	Bitumenpolymer membrantekking, 1-lags, mekanisk festet (Isol..	30
	Timber	225.2	m3	17	EPD	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	50
	Insulation	347.2	m2	5	EPD	Isolajson/mineralull, B-plate (Rockwool)	60
	Timber	82	m2	0.16	EPD	Høvellast, bartre (Treindustrien)	20
	Gypsum	1736	m2	3.5	EPD	Kledningsplate, 9.5 mm, 7.2 kg/m2, Bris (Gyproc)	60
	Glas	3	m3	9.6	EPD	Planglass, enkeltglasert, generisk 3-12 mm, 10 kg/m2 (for…	60
	Insulation	1387.2	m2	33	EPD	Isolasjon, EPS 80 (EPS Gruppen)	60
	Timber	1736	m2	0.3	EPD	Bindingsverksystem av tre for innervegger per kvm (inkl. Luf…	60
	Membrane	1736	m2	0.3	EPD	Flexible bitumen membrane/sheets for roof waterproofing, Eur…	30
2.7 Inventory, 2.8 Stairs and balconies, 2.9 Other building parts	Timber	1.5	m3	0.1	EPD	Høvellast, bartre (Treindustrien)	20
	Timber	374	m2	3.5	EPD	Royalimpregnert trelast, 513 kg/m3, 18% moisture (Moelven W…	60
	Steel	0.4	m3	11	EPD	Stainless stell long products, 7700-8100 kg/m3 (Outokumpu)	60

Table E.2 Materials school

Building Parts	Material	Amount	Unit	GWP ton CO2-eq	Type of reference	Specification	Estimated service life
2 Building							
2.1 Groundwork and foundations	Insulation	7.51	m3	0.46	EPD	Isolasjon, EPS 80 (EPS Gruppen)	60
	Insulation	1270.77	m3	77	EPD	Isolasjon, EPS 80 (EPS Gruppen)	60
	Concrete	723.79	m3	115.8	EPD	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	60
	Steel	25988	kg	8.8	EPD	Stål, armeringsprodukter (betongarmering), 7850kg/m3, scrap metall	60
	Steel	11634.69	kg	9.9	EPD	Stålfiber til betongarmering, 1250, 1100, 1100 Mpa, L:35, 5	60
	Insulation	181.45	m3	20.5	EPD	XPS isolasjonsplate 33 mm, 300KPa, 0.033 - 0.039 W/mK,	60
	Membrane	4256	m2	12	EPD	Radon- og fuktmembran for byggeplass, PP…	60
2.2 Superstructure	Timber	75.76	m3	4.26	EPD	Limtre, 470 kg/m3, 12% moisture content (Moelven Modus)	60
	Concrete	4.193	m3	0.88	EPD	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	60
	Concrete	0.659	m3	0.11	EPD	Ferdigbetong, ekskludert armeringsstål, C35/45 (B35 M40) (Sa…	60
	Steel	3.584	m3	38.35	EPD	Stål varmvalset, I, H, U, L, T, og vide flater (EMV Construction)	60
	Concrete	0.034	m3	0.02	EPD	SØYLE, B45 M45 (Spenncon)	60
	Steel	393.8	kg	0.14	EPD	Stål, armeringsprodukter (betongarmering), 7850kg/m3, scrap metall	60
	Timber	91.87	m2	15.67	EPD	Standard limbjelke, 470 kg/m3, Moisr. 12%, 45 mm, Stranda…	60
2.3 Outer walls	Timber	4401.357	m2	2.73	EPD	Bindingsverksystem av tre for yttervegger per kvm (inkl. Luft…	60
	Concrete	371.016	m3	65.92	EPD	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	60
	Gypsum	568.957	m3	2.01	EPD	Gipsplate, 12.5 mm, 9 kg m2, Normal - Standard (Gyproc)	60
	Timber	2385.44	m3	32.7	EPD	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	50
	Insulation	1281.26	m2	7.5	EPD	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	60
	Timber	47.25	m3	0.14	EPD	Heltrepanel av bartre til innvendig bruk (Treindustrien)	40
	Timber	3379	m2	13.2	EPD	Malm100, 513.32 kg/m3, Malm 100 (Moelven)	60
	Timber	36.5	m3m	15	EPD	Utvendig kledning av lauvtre, Foreningen Norske Lauvtrebruk, …	60
	Membrane	1846.12	m3	52.87	EPD	Dampsperre i plast, 0.2 mm (Tommen Gram)	60
	Insulation	286.9	m3	6.37	EPD	Isolasjon/mineralull, B-plate (Rockwool)	60
	Insulation	13.99	m3	0.23	EPD	Glassull-isolasjon, 42 mm, 0.042 W/mK, 630 g/m2, 15 kg/m3,	60
	Steel	7.304	m3	0.18	EPD	Steel stud per m2 of wall area (air gap included), 42 mm, 40…	60
	Timber	6.15	m3	1.2	EPD	Standard limbjelke, 470 kg/m3, Moisr. 12%, 45 mm, Stranda…	60
	Concrete	54	m2	1	EPD	Ferdigbetong, ekskludert armeringsstål, C35/45 (B35 M40) (Sa…	60
	Timber	3.42	m3	0	EPD	Utvendig kledning av lauvtre, Foreningen Norske Lauvtrebruk, …	60
	Membrane	166.5	m2	0.18	EPD	Waterproof membrane from nowoven HDPE for roof and wall und..	60
	Insulation	150.36	m3	9.2	EPD	Isolasjon, EPS 80 (EPS Gruppen)	60
	Timber	220.5	m2	0.18	EPD	Limtre, 470 kg/m3, 12% moisture content (Moelven Modus)	60
	Steel	39760.86	kg	12.8	EPD	Stål, armeringsprodukter (betongarmering), 7850kg/m3, scrap metall	60
2.4 Inner walls	Timber	311.87	m3	41.68	EPD	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	50
	Gypsum	218.75	m3	12.98	EPD	Gipsplate, 12.5 mm, 9 kg m2, Normal - Standard (Gyproc)	60
	Steel	1.3	m3	26	EPD	Stalprofil til innervegg, 0.61 kg/m, 7850 kg/m3 (Norgipd)	60
	Insulation	698.24	m3	5.81	EPD	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	60
	Timber	600.217	m3	0.41	EPD	Bindingsverksystem av tre for innervegger per kvm (inkl. Luf…	60
	Concrete	3.93	m3	1.2	EPD	Ferdigbetong, normal styrke, generisk, B30, C30/70 (4400/540…	60
	Insulation	42.44	m2	0.16	EPD	XPS isolasjonsplate 33 mm, 300KPa, 0.033 - 0.039 W/mK,	60
	Gypsum	744.41	m2	1.43	EPD	Gipsplate, 6.5 mm, 5.6 kg/m2, Rehab (Gypsum)	60
	Timber	1.38	m3	0.09	EPD	Høvellast, bartre (Treindustrien)	20
	Rubber	0.715	m3	5.8	EPD	Rubber floor covering, profiled , (3.55 mm); 4.82 kg/m2, 1358…	60
	Timber	587.37	m2	0.18	EPD	Bindingsverksystem av tre for yttervegger per kvm (inkl. Luft…	60
	Timber	80.63	m2	0.1	EPD	Limtre, 470 kg/m3, 12% moisture content (Moelven Modus)	60
	Insulation	87.89	m2	0.13	EPD	Isolasjon/mineralull, B-plate (Rockwool)	60
	Timber	8.96	m2	0.13	EPD	Heltrepanel av lauvtre til innvendig bruk, Foreningen Norske…	40
	Door	662.09	m2	25	EPD	Interior door, 809x2053 mm, 42x92 mm frame, 52 mm door leaf…	60
2.5 Floor structure	Linoleum	14.6	m3	35	EPD	Linoleum flooring, 2.23 mm, 2.9 kg/m2 (ERFMI)	30
	Concrete	406.42	m3	120.3	EPD	Ferdigbetong, 7540 B45 SV-Standard 22mm, Betong Øst	60
	Concrete	31.03	m3	6.6	EPD	Lavkarbon ferdigbetong, Lavkarbonklasse A - B30 M60 (Skedsmo betong)	60
	Insulation	108.85	m3	29.77	EPD	Isolasjon, EPS 80 (EPS Gruppen)	60
	Cement	203.04	m3	18.87	EPD	Akustisk sementpanel i treull, grå, 25x600x1200 [mm], 9.7 kg…	60
	Timber	435.98	m3	32.22	EPD	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	50
	Cement	91.72	m3	20	EPD	HULLDEKKER, 369 kg/m2, T: 265 mm, rebar: 6psc/m2, CEM I, CEM…	60
	Concrete	86.59	m3	16	EPD	Ferdigbetong, ekskludert armeringsstål, C35/45 (B35 M40) (Sa…	60
	Insulation	35.86	m3	1.3	EPD	Isolasjon/mineralull, B-plate (Rockwool)	60
	Gypsum	21.98	m3	6.3	EPD	Gipsplate, gulvplate, 12.5 mm (Norgips)	60
	Insulation	19.72	m3	2.3	EPD	XPS isolasjonsplate 33 mm, 300KPa, 0.033 - 0.039 W/mK,	60
	Insulation	4.94	m3	0.58	EPD	XPS isolasjonsplate 33 mm, 300KPa, 0.033 - 0.039 W/mK,	60
	Insulation	9.31	m3	2.33	EPD	Insulation, acousic glass wool panel, 15 mm, 54 kg/m3, Ecopal	60
	Timber	5.77	m3	0.01	EPD	Bindingsverksystem av tre for innervegger per kvm (inkl. Luf…	60
	Massive wood	4.27	m3	3.3	EPD	Massive wooden flooring/parquet, 22-450 x 44-7000 x 8-35mm,…	60
	Timber	2.34	m3	0.49	EPD	Royalimpregnert trelast, 513 kg/m3, 18% moisture (Moelven W…	60
	Insulation	2.24	m3	0.31	EPD	Isolasjon/mineralull, Drensplate; RockTorv; Støpeplate Pluss…	60
	Cement	424924	kg	78	EPD	Avrettingsmasse, 10-60 mm, 1.7 g/l, C25, Proplan Multi (Hey's)	60
2.6 Outer roof	Timber	635.54	m3	46.8	EPD	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	60
	Steel	1153	m2	25	EPD	Stålplater, generisk, 60% recycled content	60
	Insulation	68.82	m3	1.6	EPD	Isolasjon, glassull/mineralull,, 17 kg/m3 (Glava)	60
	Gravel	44	m3	3.2	EPD	Aggregat, knust grus, generisk	60
	Timber	46.41	m3	0.15	EPD	Bindingsverksystem av tre for yttervegger per kvm (inkl. Luft…	60
	Membrane	21.43	m3	36	EPD	Bitumenpolymer membrantekking, 1-lags, mekanisk festet (Isol..	30
	Timber	16.59	m3	7	EPD	Utvendig kledning av lauvtre, Foreningen Norske Lauvtrebruk, …	60
	Timber	11.73	m3	2.6	EPD	Utvendig-X typ EH2 (GU-X), 7.2 kg/m2, 9.5 mm +/- 0.5 mm, Wind…	60
	Timber	7.2	m3	1.1	EPD	Plywood, srouce, uncoated (Metsä Wood)	60
	Asphalt	3.6	m3	1	EPD	Asfalt, bærelag, 95% gravel, 5% bitumen bnder, AG 16 (EBA)	60
2.7 Inventory, 2.8 Stairs and balconies, 2.9 Other building parts	Timber	52.071	m3	3.41	EPD	Cross laminated timber (CLT) pine or sprouce, C24, 470 kg/m3…	50
	Steel	594	kg	2.2	EPD	Profiled steel sheeting, stainless, 7740 kg/m3 (Outokumpu)	60

E. 2 Energy Use in Operation

The annual energy consumption for all the three archetypes are represented in Table E.3.

Table E.3 Electric and thermal energy loads divided on archetypes

	Thermal load (kWh/y)	Electric load (kWh/y)
ZEB 1	4500000	3300000
Total residential	**4500000**	**3300000**
Total non-residential	310104	628822
Total Ydalir	**4810104**	**3928822**

F. Mobility

F. 1 Travel Habits at Ydalir

The mode of transportation distribution is based on the Norwegian National Travel Survey 2013/14 [36]. Assuming that the travel habits of the category “Mindre byer” (towns) is the average travel habits of the inhabitants of Elverum, two scenarios for the travel habits of Ydalir’s residents have been created. The first scenario is Ydalir, where the measures taken regarding reduction of mobility have been accounted for. The second scenario have the same travel habits as Ydalir, in addition to car sharing. This is considered by shorting down the daily travel distance by 50%, from 36.7km to 18.35km. Further, it has been calculated from the Masterplan [31] that 8% of the public transportation is done by light rail.

Table F.1 Travel habits scenario Elverum

Daily travels by purpose	**Total**		**By foot**		**Bike**		**Personal vehicle**		**Public transportation**	
	Percent	km	Percent	km	Percent	km	Percent	km	Percent	km
Work	19%	6.97	11%	0.77	7%	0.49	65%	4.53	17%	1.19
School	4%	1.47	29%	0.43	12%	0.18	33%	0.48	26%	0.38
Care	11%	4.04	7%	0.28	1%	0.04	89%	3.59	3%	0.12
Shopping	30%	11.01	19%	2.09	4%	0.44	74%	8.15	3%	0.33
Leisure and visiting services	31%	11.38	32%	3.64	5%	0.57	58%	6.60	5%	0.57
Other	5%	1.84	19%	0.35	4%	0.07	74%	1.36	3%	0.06
Sum	100%	36.70	20.59%	7.56	4.87%	1.79	67.34%	24.71	7.20%	2.64

Table F.2 Travel habits scenario Ydalir

Daily travels by purpose	**Total**		**By foot**		**Bike**		**Personal vehicle**		**Public transportation**	
	Percent	km	Percent	km	Percent	km	Percent	km	Percent	km
Sum	100%	36.70	31.77%	11.66	5.58%	2.05	49.52%	18.17	13.13%	4.82

Table F.3 Travel habits scenario Ydalir + car-sharing

Daily travels by purpose	**Total**		**By foot**		**Bike**		**Personal vehicle**		**Public transportation**	
	Percent	km	Percent	km	Percent	km	Percent	km	Percent	km
Sum	100%	18.35	31.77%	5.83	5.58%	1.02	49.52%	9.09	13.13%	2.41

F. 2 Evolution of Vehicle Stocks

Table F.4 Evolution of the trend path

	Personal Vehicle						Bus					
Year	Hydrogen	Battery	Gasoline	Diesel	Plug-in hybrid	Non-plug-in hybrid	Hydrogen	Battery	Gasoline	Diesel	Non-plug-in hybrid	Gas
2010	0%	0%	65%	35%	0%	0%	0%	0%	4%	95%	0%	1%
2011	0%	1%	61%	38%	0%	0%	0%	0%	4%	95%	0%	2%
2012	0%	1%	58%	40%	0%	1%	0%	0%	3%	95%	0%	2%
2013	0%	2%	54%	43%	0%	1%	0%	0%	3%	94%	0%	3%
2014	0%	2%	51%	45%	0%	1%	0%	0%	2%	94%	0%	3%
2015	0%	3%	48%	47%	0%	2%	0%	0%	2%	94%	0%	4%
2016	0%	5%	44%	47%	2%	3%	0%	0%	2%	94%	0%	4%
2017	0%	6%	41%	46%	3%	4%	0%	0%	1%	93%	0%	5%
2018	0%	8%	38%	45%	4%	5%	0%	0%	1%	92%	0%	6%
2019	0%	10%	34%	45%	5%	6%	0%	0%	1%	92%	1%	7%
2020	0%	12%	31%	44%	6%	7%	0%	0%	1%	91%	1%	7%
2021	0%	14%	29%	42%	7%	8%	0%	0%	1%	91%	1%	8%
2022	0%	17%	26%	40%	9%	9%	0%	0%	0%	90%	1%	8%
2023	0%	19%	24%	37%	10%	10%	0%	0%	0%	90%	1%	8%
2024	0%	21%	21%	35%	11%	11%	1%	0%	0%	90%	1%	8%
2025	0%	23%	19%	33%	12%	12%	1%	0%	0%	89%	1%	8%
2026	0%	26%	17%	30%	14%	12%	1%	0%	0%	88%	1%	9%
2027	0%	28%	16%	28%	16%	13%	2%	0%	0%	88%	2%	9%
2028	0%	30%	14%	25%	18%	13%	2%	0%	0%	87%	2%	9%
2029	0%	33%	12%	22%	19%	14%	3%	0%	0%	86%	2%	9%
2030	0%	35%	11%	20%	21%	14%	4%	0%	0%	85%	2%	9%
2031	0%	37%	10%	18%	23%	14%	4%	0%	0%	84%	2%	9%
2032	0%	38%	8%	16%	24%	14%	5%	0%	0%	83%	2%	10%
2033	0%	40%	7%	14%	26%	13%	6%	0%	0%	81%	2%	10%
2034	0%	42%	6%	12%	27%	13%	7%	0%	0%	80%	2%	10%
2035	0%	43%	5%	10%	29%	13%	8%	0%	0%	79%	3%	10%
2036	0%	45%	4%	9%	29%	13%	9%	0%	0%	78%	3%	11%
2037	0%	46%	4%	8%	30%	12%	9%	0%	0%	77%	3%	11%
2038	0%	47%	3%	7%	31%	12%	10%	0%	0%	76%	3%	11%
2039	0%	48%	3%	7%	32%	11%	10%	0%	0%	75%	3%	12%
2040	0%	49%	2%	6%	32%	11%	11%	0%	0%	74%	3%	12%
2041	0%	51%	2%	5%	32%	10%	11%	0%	0%	74%	3%	12%
2042	0%	52%	2%	5%	32%	10%	11%	0%	0%	73%	3%	13%
2043	0%	53%	1%	4%	32%	9%	12%	0%	0%	72%	3%	13%
2044	0%	54%	1%	4%	32%	9%	12%	0%	0%	72%	3%	13%
2045	0%	55%	1%	4%	32%	8%	12%	0%	0%	71%	3%	13%
2046	0%	57%	1%	3%	31%	8%	13%	0%	0%	70%	3%	14%
2047	0%	58%	1%	3%	30%	7%	13%	0%	0%	69%	3%	14%
2048	0%	60%	1%	3%	30%	7%	14%	0%	0%	69%	3%	14%
2049	0%	61%	0%	3%	29%	7%	14%	0%	0%	68%	3%	14%
2050	0%	63%	0%	3%	28%	6%	15%	0%	0%	67%	3%	14%
2051	0%	64%	0%	2%	27%	6%	15%	0%	0%	67%	3%	15%
2052	0%	65%	0%	2%	27%	5%	16%	0%	0%	66%	3%	15%
2053	0%	67%	0%	2%	26%	5%	16%	0%	0%	65%	3%	15%
2054	0%	68%	0%	2%	25%	5%	17%	0%	0%	65%	4%	15%
2055	0%	69%	0%	2%	25%	4%	17%	0%	0%	64%	4%	15%
2056	0%	70%	0%	1%	24%	4%	18%	0%	0%	63%	4%	16%
2057	0%	72%	0%	1%	24%	4%	18%	0%	0%	63%	4%	16%
2058	0%	73%	0%	1%	23%	3%	18%	0%	0%	62%	4%	16%
2059	0%	74%	0%	1%	22%	3%	19%	0%	0%	61%	4%	16%
2060	0%	75%	0%	1%	22%	3%	19%	0%	0%	61%	4%	16%
2061	0%	76%	0%	0%	21%	2%	20%	0%	0%	60%	4%	16%
2062	0%	77%	0%	0%	20%	2%	20%	0%	0%	59%	4%	17%
2063	0%	78%	0%	0%	20%	2%	21%	0%	0%	59%	4%	17%
2064	0%	79%	0%	0%	19%	1%	21%	0%	0%	58%	4%	17%
2065	0%	80%	0%	0%	19%	1%	22%	0%	0%	57%	4%	17%
2066	0%	81%	0%	0%	18%	1%	22%	0%	0%	57%	4%	17%
2067	0%	82%	0%	0%	17%	0%	23%	0%	0%	56%	4%	18%
2068	0%	83%	0%	0%	17%	0%	23%	0%	0%	55%	4%	18%
2069	0%	84%	0%	0%	16%	0%	23%	0%	0%	55%	4%	18%
2070	0%	84%	0%	0%	16%	0%	24%	0%	0%	54%	4%	18%
2071	0%	85%	0%	0%	15%	0%	24%	0%	0%	53%	4%	18%
2072	0%	86%	0%	0%	14%	0%	25%	0%	0%	52%	4%	19%
2073	0%	86%	0%	0%	14%	0%	25%	0%	0%	52%	4%	19%
2074	0%	87%	0%	0%	13%	0%	26%	0%	0%	51%	4%	19%
2075	0%	87%	0%	0%	13%	0%	26%	0%	0%	50%	4%	19%
2076	0%	88%	0%	0%	12%	0%	27%	0%	0%	50%	4%	19%
2077	0%	88%	0%	0%	12%	0%	27%	0%	0%	49%	4%	20%
2078	0%	89%	0%	0%	11%	0%	28%	0%	0%	48%	4%	20%
2079	0%	89%	0%	0%	11%	0%	28%	0%	0%	48%	4%	20%
2080	0%	90%	0%	0%	10%	0%	28%	0%	0%	47%	4%	20%

Table F.5 Evolution of the ultra-low emission path

	Personal Vehicle						Bus					
Year	Hydrogen	Battery	Gasoline	Diesel	Plug-in hybrid	Non-plug-in hybrid	Hydrogen	Battery	Gasoline	Diesel	Non-plug-in hybrid	Gas
2010	0%	0%	65%	35%	0%	0%	0%	0%	4%	95%	0%	1%
2011	0%	1%	61%	38%	0%	0%	0%	0%	4%	95%	0%	2%
2012	0%	1%	58%	40%	0%	1%	0%	0%	3%	95%	0%	2%
2013	0%	2%	54%	43%	0%	1%	0%	0%	3%	94%	0%	3%
2014	0%	2%	51%	45%	0%	1%	0%	0%	2%	94%	0%	3%
2015	0%	3%	48%	47%	0%	2%	0%	0%	2%	94%	0%	4%
2016	0%	5%	45%	47%	1%	2%	0%	0%	2%	93%	0%	4%
2017	0%	7%	41%	47%	2%	3%	0%	0%	1%	93%	0%	5%
2018	0%	9%	38%	46%	3%	4%	1%	1%	1%	92%	0%	5%
2019	0%	12%	35%	46%	3%	4%	1%	1%	1%	91%	0%	6%
2020	0%	14%	32%	46%	4%	5%	1%	1%	1%	90%	0%	6%
2021	0%	18%	29%	43%	4%	5%	3%	3%	1%	86%	1%	6%
2022	0%	23%	27%	41%	4%	5%	6%	5%	1%	82%	1%	6%
2023	0%	27%	24%	39%	4%	5%	8%	7%	0%	78%	2%	5%
2024	0%	32%	22%	37%	4%	6%	11%	9%	0%	73%	2%	5%
2025	1%	36%	19%	35%	4%	6%	14%	11%	0%	68%	3%	5%
2026	1%	41%	17%	31%	4%	5%	17%	13%	0%	62%	3%	4%
2027	1%	46%	16%	28%	4%	5%	21%	16%	0%	56%	4%	4%
2028	2%	51%	14%	25%	4%	5%	24%	18%	0%	49%	5%	3%
2029	2%	55%	12%	22%	4%	5%	28%	21%	0%	43%	5%	3%
2030	2%	60%	10%	20%	4%	5%	32%	23%	0%	36%	6%	2%
2031	3%	63%	9%	17%	3%	4%	35%	25%	0%	32%	6%	2%
2032	3%	67%	8%	15%	3%	4%	38%	26%	0%	27%	6%	2%
2033	3%	70%	7%	13%	3%	3%	41%	28%	0%	23%	6%	2%
2034	4%	74%	6%	11%	3%	3%	44%	29%	0%	19%	6%	1%
2035	4%	77%	4%	9%	2%	3%	47%	31%	0%	14%	6%	1%
2036	4%	79%	4%	8%	2%	2%	48%	32%	0%	13%	6%	1%
2037	5%	81%	3%	7%	2%	2%	49%	33%	0%	11%	6%	1%
2038	5%	83%	3%	6%	2%	2%	50%	33%	0%	9%	6%	1%
2039	5%	85%	2%	5%	1%	1%	51%	34%	0%	8%	6%	1%
2040	6%	87%	2%	4%	1%	1%	52%	35%	0%	6%	6%	1%
2041	6%	87%	1%	3%	1%	1%	52%	36%	0%	5%	6%	1%
2042	6%	88%	1%	3%	1%	1%	53%	36%	0%	4%	6%	1%
2043	6%	89%	1%	2%	1%	1%	53%	37%	0%	4%	6%	1%
2044	7%	89%	1%	2%	1%	0%	53%	37%	0%	3%	6%	1%
2045	7%	90%	1%	2%	1%	0%	54%	38%	0%	2%	6%	1%
2046	7%	90%	0%	1%	1%	0%	54%	38%	0%	2%	5%	1%
2047	8%	90%	0%	1%	1%	0%	54%	38%	0%	2%	5%	1%
2048	8%	90%	0%	1%	1%	0%	54%	38%	0%	2%	5%	0%
2049	8%	90%	0%	1%	0%	0%	55%	38%	0%	1%	5%	0%
2050	9%	90%	0%	1%	0%	0%	55%	39%	0%	1%	5%	0%
2051	9%	90%	0%	0%	0%	0%	55%	39%	0%	1%	5%	0%
2052	9%	90%	0%	0%	0%	0%	55%	39%	0%	1%	5%	0%
2053	10%	90%	0%	0%	0%	0%	55%	39%	0%	1%	5%	0%
2054	10%	90%	0%	0%	0%	0%	55%	39%	0%	0%	5%	0%
2055	10%	90%	0%	0%	0%	0%	56%	39%	0%	0%	5%	0%
2056	11%	89%	0%	0%	0%	0%	56%	39%	0%	0%	5%	0%
2057	11%	89%	0%	0%	0%	0%	56%	39%	0%	0%	5%	0%
2058	11%	89%	0%	0%	0%	0%	56%	40%	0%	0%	5%	0%
2059	11%	89%	0%	0%	0%	0%	56%	40%	0%	0%	5%	0%
2060	12%	88%	0%	0%	0%	0%	56%	40%	0%	0%	5%	0%
2061	12%	88%	0%	0%	0%	0%	56%	40%	0%	0%	5%	0%
2062	12%	88%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2063	12%	88%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2064	13%	87%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2065	13%	87%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2066	13%	87%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2067	13%	87%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2068	14%	86%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2069	14%	86%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2070	14%	86%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2071	14%	86%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2072	14%	86%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2073	15%	85%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2074	15%	85%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2075	15%	85%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2076	15%	85%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2077	15%	85%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2078	16%	84%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2079	16%	84%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%
2080	16%	84%	0%	0%	0%	0%	56%	40%	0%	0%	4%	0%

F. 3 Embodied Emissions

Table F.6 Embodied emissions in mobility (g CO_2-eq/vkm)

	Personal vehicles					Bus				Light Rail
Year	Hydrogen	Battery	Gasoline	Diesel	Hybrid	Hydrogen	Battery	ICEVs	Hybrid	Electric
2020	34.30	49.50	30.50	30.50	31.60	30.00	48.10	30.00	30.00	306.80
2021	34.04	48.55	30.26	30.26	31.35	29.44	47.18	29.76	29.76	300.89
2022	33.77	47.60	30.01	30.01	31.09	28.86	46.25	29.52	29.52	294.99
2023	33.49	46.65	29.77	29.77	30.84	28.28	45.33	29.28	29.28	289.10
2024	33.22	45.70	29.53	29.53	30.59	27.71	44.40	29.04	29.04	283.20
2025	32.94	44.74	29.28	29.28	30.34	27.13	43.48	28.80	28.80	277.31
2026	32.67	43.79	29.04	29.04	30.09	26.55	42.55	28.56	28.56	271.41
2027	32.40	42.84	28.80	28.80	29.83	25.98	41.63	28.33	28.33	265.52
2028	32.12	41.89	28.55	28.55	29.58	25.40	40.71	28.09	28.09	259.63
2029	31.85	40.94	28.31	28.31	29.33	24.82	39.78	27.85	27.85	253.73
2030	31.58	39.99	28.07	28.07	29.08	24.25	38.86	27.61	27.61	247.84
2031	31.47	39.80	27.97	27.97	28.98	24.13	38.67	27.51	27.51	246.65
2032	31.36	39.61	27.87	27.87	28.88	24.02	38.49	27.42	27.42	245.46
2033	31.25	39.41	27.78	27.78	28.78	23.90	38.30	27.32	27.32	244.28
2034	31.14	39.22	27.68	27.68	28.67	23.78	38.11	27.22	27.22	243.09
2035	31.03	39.03	27.58	27.58	28.57	23.67	37.93	27.13	27.13	241.90
2036	30.92	38.84	27.48	27.48	28.47	23.55	37.74	27.03	27.03	240.72
2037	30.81	38.65	27.39	27.39	28.37	23.43	37.56	26.94	26.94	239.53
2038	30.70	38.46	27.29	27.29	28.27	23.32	37.37	26.84	26.84	238.34
2039	30.59	38.27	27.19	27.19	28.17	23.20	37.18	26.75	26.75	237.16
2040	30.48	38.07	27.09	27.09	28.07	23.09	37.00	26.65	26.65	235.97
2041	30.37	37.88	27.00	27.00	27.97	22.97	36.81	26.55	26.55	234.78
2042	30.26	37.69	26.90	26.90	27.87	22.85	36.63	26.46	26.46	233.60
2043	30.15	37.50	26.80	26.80	27.77	22.74	36.44	26.36	26.36	232.41
2044	30.04	37.31	26.71	26.71	27.67	22.62	36.25	26.27	26.27	231.22
2045	29.93	37.12	26.61	26.61	27.57	22.51	36.07	26.17	26.17	230.04
2046	29.82	36.93	26.51	26.51	27.46	22.39	35.88	26.08	26.08	228.85
2047	29.71	36.73	26.41	26.41	27.36	22.27	35.70	25.98	25.98	227.66
2048	29.61	36.54	26.32	26.32	27.26	22.16	35.51	25.88	25.88	226.48
2049	29.50	36.35	26.22	26.22	27.16	22.04	35.32	25.79	25.79	225.29
2050	29.39	36.16	26.12	26.12	27.06	21.93	35.14	25.69	25.69	224.10
2051	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2052	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2053	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2054	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2055	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2056	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2057	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2058	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2059	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2060	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2061	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2062	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2063	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2064	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2065	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2066	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2067	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2068	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2069	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2070	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2071	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2072	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2073	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2074	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2075	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2076	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2077	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2078	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2079	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92
2080	29.28	35.97	26.02	26.02	26.96	21.81	34.95	25.60	25.60	222.92

F. 4 Energy Use in Operation (Evolution)

When retrieving the initial values from the database, the well-to-wheel emissions had to be calculated by adding the well-to-tank and tank-to-well values together. Table F.7 and Table F.8 show the resulting emission per vehicle kilometre for each mode of transportation and powertrain.

Table F.7 Emissions from energy use in operation of personal vehicles

	Energy TtW kWh/vkm	Well-to-Wheel (g CO2-eq/vkm)				
year	Electric	Hydrogen	Battery	Gasoline	Diesel	Hybrid
2020	0.17	8.60	4.44	181.32	183.79	147.65
2021	0.17	8.39	4.36	178.60	181.03	145.44
2022	0.17	8.17	4.25	175.88	178.28	143.22
2023	0.16	7.96	4.14	173.16	175.52	141.01
2024	0.16	7.74	4.03	170.44	172.76	138.79
2025	0.16	7.53	3.92	167.72	170.01	136.58
2026	0.16	7.31	3.81	165.00	167.25	134.36
2027	0.16	7.10	3.70	162.28	164.49	132.15
2028	0.16	6.88	3.60	159.56	161.74	129.93
2029	0.16	6.67	3.49	156.84	158.98	127.72
2030	0.15	6.45	3.39	154.12	156.22	125.50
2031	0.15	6.34	3.33	153.67	155.76	125.13
2032	0.15	6.24	3.25	153.22	155.30	124.76
2033	0.15	6.13	3.17	152.76	154.84	124.40
2034	0.15	6.02	3.09	152.31	154.38	124.03
2035	0.15	5.91	3.01	151.86	153.92	123.66
2036	0.15	5.81	2.93	151.40	153.46	123.29
2037	0.15	5.70	2.85	150.95	153.01	122.92
2038	0.15	5.59	2.77	150.50	152.55	122.55
2039	0.15	5.48	2.69	150.04	152.09	122.18
2040	0.15	5.38	2.61	149.59	151.63	121.81
2041	0.15	5.27	2.53	149.14	151.17	121.44
2042	0.15	5.16	2.46	148.68	150.71	121.07
2043	0.15	5.05	2.38	148.23	150.25	120.70
2044	0.15	4.95	2.30	147.78	149.79	120.33
2045	0.15	4.84	2.23	147.32	149.33	119.97
2046	0.15	4.73	2.15	146.87	148.87	119.60
2047	0.14	4.62	2.08	146.42	148.41	119.23
2048	0.14	4.52	2.00	145.96	147.95	118.86
2049	0.14	4.41	1.93	145.51	147.49	118.49
2050	0.14	4.30	1.86	145.06	147.03	118.12
2051	0.14	4.30	1.86	145.06	147.03	118.12
2052	0.14	4.30	1.86	145.06	147.03	118.12
2053	0.14	4.30	1.86	145.06	147.03	118.12
2054	0.14	4.30	1.86	145.06	147.03	118.12
2055	0.14	4.30	1.86	145.06	147.03	118.12
2056	0.14	4.30	1.86	145.06	147.03	118.12
2057	0.14	4.30	1.86	145.06	147.03	118.12
2058	0.14	4.30	1.86	145.06	147.03	118.12
2059	0.14	4.30	1.86	145.06	147.03	118.12
2060	0.14	4.30	1.86	145.06	147.03	118.12
2061	0.14	4.30	1.86	145.06	147.03	118.12
2062	0.14	4.30	1.86	145.06	147.03	118.12
2063	0.14	4.30	1.86	145.06	147.03	118.12
2064	0.14	4.30	1.86	145.06	147.03	118.12
2065	0.14	4.30	1.86	145.06	147.03	118.12
2066	0.14	4.30	1.86	145.06	147.03	118.12
2067	0.14	4.30	1.86	145.06	147.03	118.12
2068	0.14	4.30	1.86	145.06	147.03	118.12
2069	0.14	4.30	1.86	145.06	147.03	118.12
2070	0.14	4.30	1.86	145.06	147.03	118.12
2071	0.14	4.30	1.86	145.06	147.03	118.12
2072	0.14	4.30	1.86	145.06	147.03	118.12
2073	0.14	4.30	1.86	145.06	147.03	118.12
2074	0.14	4.30	1.86	145.06	147.03	118.12
2075	0.14	4.30	1.86	145.06	147.03	118.12
2076	0.14	4.30	1.86	145.06	147.03	118.12
2077	0.14	4.30	1.86	145.06	147.03	118.12
2078	0.14	4.30	1.86	145.06	147.03	118.12
2079	0.14	4.30	1.86	145.06	147.03	118.12
2080	0.14	4.30	1.86	145.06	147.03	118.12

Table F.8 Emissions from energy use in operation of buses and light rail

	Bus					Light Rail	
	Energy TtW MJ/vkm	Well-to-Wheel (g CO2-eq/vkm)				Energy TtW MJ/vkm	Well-to-Wheel (g CO2-eq/vkm)
Year	Electric	Hydrogen	Battery	ICEVs	Hybrid		
2020	3.95	1522.70	28.95	1298.50	878.60	21.32	156.24
2021	3.85	1484.63	27.44	1279.02	865.42	21.00	149.66
2022	3.75	1446.57	26.27	1259.55	852.24	20.69	144.76
2023	3.66	1408.50	25.14	1240.07	839.06	20.37	139.98
2024	3.57	1370.43	24.05	1220.59	825.88	20.07	135.30
2025	3.48	1332.36	23.00	1201.11	812.71	19.77	130.74
2026	3.39	1294.30	21.99	1181.64	799.53	19.47	126.28
2027	3.31	1256.23	21.01	1162.16	786.35	19.18	121.92
2028	3.23	1218.16	20.07	1142.68	773.17	18.89	117.67
2029	3.15	1180.09	19.16	1123.20	759.99	18.61	113.51
2030	3.07	1142.03	18.28	1103.73	746.81	18.33	109.45
2031	2.99	1122.99	17.63	1100.48	744.61	18.05	106.51
2032	2.92	1103.96	16.81	1097.23	742.42	17.78	102.64
2033	2.84	1084.92	16.03	1093.99	740.22	17.52	98.87
2034	2.77	1065.89	15.27	1090.74	738.02	17.25	95.18
2035	2.70	1046.86	14.55	1087.49	735.83	17.00	91.59
2036	2.63	1027.82	13.84	1084.25	733.63	16.74	88.08
2037	2.57	1008.79	13.17	1081.00	731.43	16.49	84.65
2038	2.50	989.75	12.52	1077.76	729.24	16.24	81.31
2039	2.44	970.72	11.89	1074.51	727.04	16.00	78.04
2040	2.38	951.69	11.29	1071.26	724.85	15.76	74.86
2041	2.38	932.65	10.99	1068.02	722.65	15.52	71.76
2042	2.38	913.62	10.69	1064.77	720.45	15.29	68.73
2043	2.38	894.59	10.38	1061.52	718.26	15.06	65.78
2044	2.38	875.55	10.08	1058.28	716.06	14.83	62.89
2045	2.38	856.52	9.78	1055.03	713.86	14.61	60.08
2046	2.38	837.48	9.47	1051.79	711.67	14.39	57.35
2047	2.38	818.45	9.17	1048.54	709.47	14.18	54.67
2048	2.38	799.42	8.87	1045.29	707.27	13.96	52.07
2049	2.38	780.38	8.57	1042.05	705.08	13.75	49.53
2050	2.38	761.35	8.26	1038.80	702.88	13.55	47.06
2051	2.38	761.35	8.26	1038.80	702.88	13.34	47.06
2052	2.38	761.35	8.26	1038.80	702.88	13.14	47.06
2053	2.38	761.35	8.26	1038.80	702.88	12.95	47.06
2054	2.38	761.35	8.26	1038.80	702.88	12.75	47.06
2055	2.38	761.35	8.26	1038.80	702.88	12.56	47.06
2056	2.38	761.35	8.26	1038.80	702.88	12.37	47.06
2057	2.38	761.35	8.26	1038.80	702.88	12.19	47.06
2058	2.38	761.35	8.26	1038.80	702.88	12.01	47.06
2059	2.38	761.35	8.26	1038.80	702.88	11.82	47.06
2060	2.38	761.35	8.26	1038.80	702.88	11.65	47.06
2061	2.38	761.35	8.26	1038.80	702.88	11.47	47.06
2062	2.38	761.35	8.26	1038.80	702.88	11.30	47.06
2063	2.38	761.35	8.26	1038.80	702.88	11.13	47.06
2064	2.38	761.35	8.26	1038.80	702.88	10.96	47.06
2065	2.38	761.35	8.26	1038.80	702.88	10.80	47.06
2066	2.38	761.35	8.26	1038.80	702.88	10.64	47.06
2067	2.38	761.35	8.26	1038.80	702.88	10.48	47.06
2068	2.38	761.35	8.26	1038.80	702.88	10.32	47.06
2069	2.38	761.35	8.26	1038.80	702.88	10.17	47.06
2070	2.38	761.35	8.26	1038.80	702.88	10.01	47.06
2071	2.38	761.35	8.26	1038.80	702.88	9.86	47.06
2072	2.38	761.35	8.26	1038.80	702.88	9.72	47.06
2073	2.38	761.35	8.26	1038.80	702.88	9.57	47.06
2074	2.38	761.35	8.26	1038.80	702.88	9.43	47.06
2075	2.38	761.35	8.26	1038.80	702.88	9.28	47.06
2076	2.38	761.35	8.26	1038.80	702.88	9.15	47.06
2077	2.38	761.35	8.26	1038.80	702.88	9.01	47.06
2078	2.38	761.35	8.26	1038.80	702.88	8.87	47.06
2079	2.38	761.35	8.26	1038.80	702.88	8.74	47.06
2080	2.38	761.35	8.26	1038.80	702.88	8.61	47.06

G. Infrastructure

G. 1 Materials in Infrastructure

Dimensions and materials used for the roads and sidewalks are according to the manuals N100 *Veg- og gateutforming* [53] and N200 *Vegbygging* [54] given by the Norwegian Public Roads Administration.

Table G.1 Materials included in the infrastructure

Open Space category	Open Space Component	Material	Amount/m	Unit	kgCO2-eq/unit	GWP/unit	Type of reference	Specification	Estimated service life
1. Road (wide)					/m				
1.1 Lane	Surface course	Asphalt gravel concrete	0.32	ton	16.11	51.15 kgCO2-eq/ton	EPD	Agb 11. Asfalt (slitelag), 2,5t/m3	20
	Base course	Asphalt gravel	1.05	ton	51.20	48.76 kgCO2-eq/ton	EPD	Ag 16. Asfalt (bærelag)	40
	Granular base	Crushed stone construction aggregate products	2.38	ton	4.95	2.08 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	3.63	ton	6.31	1.74 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
1.2 Reserve	Granular base	Crushed stone construction aggregate products	1.02	ton	2.12	2.08 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	2.55	ton	4.44	1.74 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
1.3 Bicycle lane	Surface course	Asphalt gravel concrete	0.09	ton	4.60	51.15 kgCO2-eq/ton	EPD	Agb 11. Asfalt (slitelag), 2,5t/m3	20
	Base course	Asphalt gravel	0.36	ton	17.55	48.76 kgCO2-eq/ton	EPD	Ag 16. Asfalt (bærelag)	40
	Granular base	Crushed stone construction aggregate products	0.77	ton	1.59	2.08 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	2.02	ton	3.51	1.74 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
1.4 Shoulder	Granular subbase	Crushed stone construction aggregate products	4.12	ton	7.16	1.74 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
2. Road (narrow)					/m				
2.1 Lane	Surface course	Asphalt gravel concrete	0.32	ton	16.11	51.15 kgCO2-eq/ton	EPD	Agb 11. Asfalt (slitelag), 2,5t/m3	20
	Base course	Asphalt gravel	1.05	ton	51.20	48.76 kgCO2-eq/ton	EPD	Ag 16. Asfalt (bærelag)	40
	Granular base	Crushed stone construction aggregate products	2.38	ton	4.95	2.08 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	3.63	ton	6.31	1.74 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
2.4 Shoulder	Granular subbase	Crushed stone construction aggregate products	4.12	ton	7.16	1.74 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
3. Sidewalk					/m				
3.1 Lane	Surface course	Asphalt gravel concrete	0.09	ton	4.60	51.15 kgCO2-eq/ton	EPD	Agb 11. Asfalt (slitelag), 2,5t/m3	20
	Base course	Asphalt gravel	0.36	ton	17.55	48.76 kgCO2-eq/ton	EPD	Ag 16. Asfalt (bærelag)	40
	Granular base	Crushed stone construction aggregate products	0.77	ton	1.59	2.08 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	2.02	ton	3.51	1.74 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
4. Parking (outside)			Amount/m2		/m2				
4.1 Parking surface	Surface course	Asphalt gravel concrete		ton	0.00	51.15 kgCO2-eq/ton	EPD	Agb 11. Asfalt (slitelag), 2,5t/m3	20
	Base course	Asphalt gravel		ton	0.00	48.76 kgCO2-eq/ton	EPD	Ag 16. Asfalt (bærelag)	40
	Granular base	Crushed stone construction aggregate products		ton	0.00	2.08 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products		ton	0.00	1.74 kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60

G. 2 Energy Use in Operation (Public Lighting)

The number of operation hours for the public lighting has been based on an average and calculated in Table G.2.

Table G.2 Average number of hours with darkness

Date	Number of hours with darkness
21st of December	17.58
21st of June	4.98
Average	11.3

Table G.3 states the variables that have been used at Ydalir when calculating the annual power consumption from the public lighting.

Table G.3 Annual energy consumption by public lighting

Number of lighting units	Power/unit (W/unit)	Tot power (W)	Number of hours dark, average	Tot power/y (kWh)
346	180.00	62273.11	11.30	256845.44

G. 3 Diesel Consumption in Construction

It is assumed that there will be some diesel consumption in the future, but it has been neglected as it is assumed to have minimal impact on the results.

Table G.4 Diesel consumption for constructing the infrastructure

Month	Litre	kg CO2-eq
Sep-16	6.70E+03	2.52E+03
Oct-16	2.56E+04	9.62E+03
Nov-16	2.14E+04	8.05E+03
Dec-16	1.92E+04	7.21E+03
Jan-17	1.06E+04	4.00E+03
Feb-17	1.19E+04	4.47E+03
Mar-17	2.00E+04	7.52E+03
Apr-17	6.19E+03	2.33E+03
May-17	5.18E+03	1.95E+03
Jun-17	1.99E+04	7.50E+03
Jul-17	7.71E+03	2.90E+03
Aug-17	9.77E+03	3.67E+03
Sep-17	4.80E+03	1.81E+03
Oct-17	1.23E+04	4.61E+03
Nov-17	5.00E+03	1.88E+03
Dec-17	7.83E+03	2.94E+03
Jan-18	7.33E+03	2.76E+03
Feb-18	1.19E+04	4.47E+03
Mar-18	4.94E+03	1.86E+03
Apr-18	6.24E+03	2.35E+03
May-18	1.61E+03	6.06E+02
Jun-18	8.31E+03	3.12E+03
Jul-18	8.93E+03	3.36E+03
Aug-18	1.39E+04	5.23E+03
Sep-18	1.09E+04	4.11E+03
Oct-18	1.42E+04	5.35E+03
Total	2.82E+05	1.06E+05

H. On-site Energy, District Heating

H. 1 Materials in District Heating

The emissions listed in Table H.1 are collected from both EPDs and the database Ecoinvent 3.2. However, version 1.2 was used in the study done by Oliver-Solà *et al.* [44], and Table H.2 shows the equivalent processes/products from version 3.2. ReCiPe Midpoint method was used in order to find the intensities.

Table H.1 Embodied emissions from the district heating materials

Network part	Network component	Material	Amount	Unit	GWP kg CO2-eq	GWP/unit		Type of reference	Specification	Estimated service life
Main grid	District heating pi	Steel	84474	kg	144712.41	1.71	kgCO2-eq/kg	Ecoinvent	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	20
		Foamed polyurethane	14873.2	kg	64253.71	4.32	kgCO2-eq/kg	Ecoinvent	polyurethane, rigid foam/polyurethane production, rigid foam/RE	20
		HDPE	16967	kg	32729.34	1.93	kgCO2-eq/kg	Ecoinvent	polyethylene, high density, granulate/polyethylene production, hi	20
the main grid	Surface box	Water	0	kg	0	0.00036433	kgCO2-eq/kg	Ecoinvent	tap water/market for tap water/Europe without Switzerland/kg	15
		Sand	0	kg	0	0.00313	kgCO2-eq/kg	EPD	Franzefoss, Crushed stone construction aggregate products, Oslo a	15
		Limestone	0	kg	0	0.1737	kgCO2-eq/kg	Ecoinvent	gypsum plasterboard/gypsum plasterboard production/CH/kg	15
		Cement	0	kg	0	0.5377	kgCO2-eq/kg	EPD	Cemex, Miljøsement, Cem II/B-S 52,5 N	15
		Cast iron	0	kg	0	1.6362	kgCO2-eq/kg	Ecoinvent	cast iron/cast iron production/RER/kg	15
		Ceramic brick	0	kg	0	0.24295	kgCO2-eq/kg	Ecoinvent	clay brick/clay brick production/RER/kg	15
		Electricity	0	kWh	0	26.3814286	kgCO2-eq/kWh	Standard	Scenario 1 (NO)	15
	Tap	Bronze	0	kg	0	5.0532	kgCO2-eq/kWh	Ecoinvent	bronze/bronze production/CH/kg	10
		Synthetic rubber	0	kg	0	4.991	kgCO2-eq/kWh	Ecoinvent	silicon, metallurgical grade/silicon production, metallurgical grad	10
	Pump	Stainless steel	15.1	kg	75.38	4.99	kgCO2-eq/kWh		steel, chromium steel 18/8, hot rolled/steel production, chromium	10
		Cast iron	136	kg	222.52	1.64	kgCO2-eq/kg	Ecoinvent	cast iron/cast iron production/RER/kg	10

Table H.2 Conversion from Ecoinvent 1.2 to Ecoinvent 3.2

Ecoinvent 1.2	Ecoinvent 3.2
RER: steel, low-alloyed, at plant	steel, low-alloyed/market for steel, low-alloyed/GLO/kg
RER: polyurethane, rigid foam, at plant	polyurethane, rigid foam/polyurethane production, rigid foam/RER/kg
RER: polyethylene, HDPE, granulate, at plant	polyethylene, high density, granulate/polyethylene production, high density, granulate/RER/kg
RER: cast iron, at plant	cast iron/cast iron production/RER/kg
DE: stainless steel sheet PE	steel, chromium steel 18/8, hot rolled/steel production, chromium steel 18/8, hot rolled/RER/kg

I. On-site Energy, Photovoltaic

I. 1 Materials in Photovoltaic Panels

Table I.1 Embodied emissions from the PV panels materials

Building Parts	Building component	Material	Amount	Unit	GWP kg CO2-eq	GWP/unit		Type of reference	Specification	Estimated service life
On-site energy	PV-panels	photovoltaic panel	18000	m2	5040900	280.05	kgCO2-eq/m2	Ecoinvent	photovoltaic	30

J. General Results

J. 1 Results Energy Emission Intensity

Element	Product stage (A1-A3)	Construction (A5)	Replacements (B4)	Energy use in operation (B6)	Benefits (D)	Total
Buildings	19353.1		6411.0	10980.4		36744.5
Mobility	5279.5		21118.0	69539.2		95936.7
Infrastructure	5722.5	106.19	3750.8	252.9		9832.4
On-site Energy, DH	242.0		544.5		-7322.7	-6536.2
On-site Energy, PV	5040.9		1260.2		-2303.7	3997.4
Total	35638.0	106.2	33084.6	80772.5	-9626.4	139974.8

Figure J.1 Results energy emission intensity scenario 1, mobility scenario A (t CO_2-eq over lifetime)

Element	Product stage (A1-A3)	Construction (A5)	Replacements (B4)	Energy use in operation (B6)	Benefits (D)	Total
Buildings	19353.1		6411.0	33989.7		59753.7
Mobility	5279.5		21118.0	76451.6		102849.1
Infrastructure	5722.5	106.19	3750.8	1757.1		11336.6
On-site Energy, DH	242.0		544.5		-52548.6	-51762.0
On-site Energy, PV	5040.9		1260.2		-16008.0	-9706.9
Total	35638.0	106.2	33084.6	112198.3	-68556.6	112470.5

Figure J.2 Results energy emission intensity scenario 2, mobility scenario A (t CO_2-eq over lifetime)

K. Scenario Analysis Results

K. 1 Scenario Analysis Results

Table K.1 Results of scenario analysis relatively to the base case (Note base case includes scenario 1 and scenario A)

Scenario analysis		% deviation from basecase
Emission intensity electricity as Scenario 2	112470.51	-19.6%
Elverum	164642.30	17.6%
Scenario B (Ydalir, ultra low emission path)	110470.60	-21.1%
Scenario C (Ydalir + car sharing, trend path)	92720.73	-33.8%
Scenario D (Ydalir + car sharing, ultra low emission path)	77968.62	-44.3%
Asymmetrical weighting of the energy emission intensity	81044.64	-42.1%
80/20 weighting travel distance inhabitant/workspace	121073.18	-13.5%
10% reduction of emissions from materials	137398.41	-1.8%
100% increased energy production form PV-panels	143972.24	2.9%
All scenarios included (Scenario 1 (NO), Ydalir)	254.79	-99.8%
Base case (Scenario 1 (NO), Scenario D)	139974.81	0.0%

K. 2 Mobility Scenario Analysis Results

Table K.2 Results from mobility scenarios analysis (Note energy emission intensity scenario 1)

	Product stage (A1-A3)	Replacements (B4)	Energy use in operation (B6)	Total
Scenario A	5279.50	21118.01	69539.18	95936.69
Scenario B	5834.69	23338.77	37259.02	66432.48
Scenario C	2639.75	10559.00	35483.86	48682.61
Scenario D	2917.35	11669.38	19343.78	33930.50

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