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LCA Modelling for Zero Emission Neighbourhoods in Early Stage Planning

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Master of Energy and Environmental Engineering
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MASTER THESIS

for

Student Vilde Borgnes

Spring 2018

Scenario assessment in LCA for Zero Emission Neighbourhoods

Scenariovurdering i LCA for nullutslippsområder

Background and objective

Future climate change mitigation targets will require large energy savings and greenhouse gas emission reductions in building stocks. One of the strategies as a response to these policies is the development of zero emission neighborhood (ZEN) concepts; for instance by urban development where the interplay of activities and subsystems at the neighborhood level give close to zero emissions. This MSc thesis work is on the development of life cycle assessment (LCA) models to support the evaluation of ZEN concepts with respect to greenhouse gas emissions and environmental impacts. Previous studies have mainly investigated the LCA characteristics and impacts of individual buildings. In parallel, much research has been done on energy-efficiency solutions for individual buildings. The Zero Emission Neighbourhood ini Smart Cities Research Centre (FME-ZEN) studies the energy and emission performance on a neighbourhood scale and investigates the combination of building-specific measures and local solutions on the neighbourhood scale. This thesis is related to the ongoing work at the ZEN Research Centre.

The overall objective of this thesis is to contribute to consistent use of LCA methods for ZEN concepts, with an appropriate structure of inventory datasets and a modelling framework for the evaluation of selected zero emission concepts with measures at different levels (temporal, spatial, organizational) in ZEN systems, with interacting subsystems such as building stock demand, inhabitants mobility needs, onsite energy generation, local energy storage and heat distribution, and import/export to external electricity or heat grids.

Previous research indicate that the following parameters may play an important role in such assessment: system boundaries, functional unit (absolute, spatial, per capita or multiple), inhabitants mobility, carbon intensity of the energy mix and building materials. The particular objective of this thesis is to examine how these different parameters influence LCA results (in particular climate change impacts) by developing scenarios, when modelling a ZEN system on a modular basis in a long-term perspective.

The work is linked to IndEcol's participation in the FME-ZEN research center and PhD-student Carine Lausselet's research work, hence she will act as co-supervisor.

The following tasks are to be considered:

1. Carry out a literature study relevant to the work of the project.
2. Develop a modular structure of a generic ZEN system, including buildings, mobility, infrastructure and energy supply and storage components, as a basis for an LCA inventory of the ZEN system. Then, use the modular structure to represent and specify more in detail a given case that may serve as an example of a ZEN project, such as Zero Village Bergen.
3. Develop an LCA model in Arda of the generic ZEN concept, or the specified case ZEN project. Collect data and information needed to populate the model with inputs to be run.
4. Develop scenarios based on development paths of chosen important factors/variables towards 2080.
5. Implement these scenarios in your LCA model and present results in order to document the case system performance under different scenarios. Discuss how the different core factors/variables influence the environmental performance of your system, with particular attention to the influence of system boundaries, on-site energy generation and storage, and the dynamics of emission intensity of electricity towards 2080.
6. Discuss strengths and weaknesses of your work, and suggestions for follow-up research.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student’s name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 15. January 2018

H. Brattebø
Helge Brattebø
Academic Supervisor

Co-supervisor: PhD student Carine Lausselet, IndEcol

Preface

The objective of this MSc thesis is to contribute to expedient use of life cycle assessment (LCA) of neighborhoods in an early planning stage, by focusing on contributors to environmental impacts and critical factors. The work is linked to IndEcol's participation in the FME-ZEN Research Centre and was carried out during the spring of 2018 at the Norwegian University of Science and Technology.

The scope and content are decided in consultation with the supervisor of the thesis and are to some extent deviating from the assignment text. This includes change of the title because of omission of development of scenarios (task 4 and 5). Instead, the model is based on a specified project (Zero Village Bergen) and in addition to a base case, a sensitivity assessment is performed to find critical parameters. Also, the model is not developed in Arda, but as a clean excel model (see task 3).

The thesis consists of (1) a research article with the title *"Scenario assessment in LCA for Zero Emission Neighborhoods",* and (2) a supplement material describing the LCA model in detail to provide a broader understanding. The relevant parts of the supplement material are referred to in the article.

Thanks to my supervisor Helge Brattebø and co-supervisor Carine Lausselet for valuable help during the work.

The picture on the front page is illustrated by Snøhetta [1].

Abstract

The building sector is a major driver of climate change and recent years it has been a growing focus on limiting greenhouse gas (GHG) emissions associated with the built environment. In Norway, the Research Centre on Zero Emissions Neighborhoods (ZEN Centre) has a goal of developing future buildings and neighborhoods with no GHG emissions. To estimate the total emissions caused by buildings throughout the entire life cycle, life cycle assessment (LCA) is a commonly used and well-established tool. When studying more complex systems as neighborhoods however, the existing research is scarce.

The objective of the work in hand is to contribute to expedient use of LCA of neighborhoods at an early planning stage, by focusing on contributors to environmental impacts and critical factors. An LCA model for ZENs based on a modular structure was developed with five included elements; buildings, mobility, open spaces, networks and on-site energy infrastructure. The model was tested on Zero Village Bergen, a pilot project for the ZEN Centre. The results give a total of 117 kg tonne CO_2-eq over 60 years. The buildings constitute the largest share of emissions among the elements with 52%, and the emissions embodied in the materials account for 56% when all elements are included. Critical parameters are emission intensities for electricity and heat production by waste incineration, as well as the daily distance travelled by the inhabitants.

The model has clear potential to facilitate decision making in early stage planning of ZENs, as it provides information on dominant elements and life cycle stages, and its modular structure ensures comparability and adaptability. On the other hand, the LCA model, and consequently also the results, suffer from uncertainties and simplifications, particularly on how technology and behavior may change in a long-term perspective. Further work is therefore suggested.

Sammendrag

Bygningssektoren er en betydelig bidragsyter til klimaendringene og de siste årene har det vært et stadig økende fokus på å begrense utslipp av drivhusgasser fra denne sektoren. I Norge har forskningssenteret for nullutslippsområder i smarte byer (FME ZEN) et mål om å utvikle fremtidens bygninger og nabolag uten klimagassutslipp. For å beregne utslippene fra bygninger gjennom hele livsløpet er LCA et anerkjent og godt etablert verktøy. Dersom vi utvider systemgrensene og ser på mer komplekse systemer som nabolag, er den tidligere forskningen noe mangelfull.

Målet med dette arbeidet er å bidra til hensiktsmessig bruk av LCA på nabolagnivå i tidligfase planlegging, gjennom å fokusere på bidragsytere til miljøpåvirkning og kritiske faktorer. Det er utviklet en LCA modell for nullutslippsområder basert på en modulær struktur bestående av fem elementer; bygninger, mobilitet, åpne plasser, nettverk og energiinfrastruktur. Modellen er brukt på Zero Village Bergen, som er et av pilotprosjektene i FME ZEN med alle de fem elementene inkludert. Både produksjonsfasen, utskiftninger av materialer og energibruk i drift inngår i analysen. Resultatene viser et utslipp av totalt 117 kg tonn CO2-eq over analyseperioden på 60 år. Blant elementene er det bygningene som står for den største delen av utslippene, med 52%. Når man ser på fasene i livsløpet til nabolaget, er det utslipp innbundet i materialer (produktfasen og utskiftninger) som utgjør hoveddelen av utslippene, med 56%. Kritiske parametere er utslippsintensiteter for elektrisitet og avfallsforbrenning i tillegg til den daglige reiseavstanden til innbyggerne.

Den utviklede modellen har et klart potensiale for å legge til rette for tidligfase planlegging for nullutslippsområder, og den gir verdifull informasjon om betydelige bidragsytere og livssyklusfaser. I den modulære strukturen er det mulig å justere systemgrenser og funksjonell enhet for å muliggjøre sammenligning av ulike prosjekter. På den annen side er modellen, og dermed også resultatene, preget av usikkerhetsmomenter og forenklinger, spesielt når det kommer til hvordan teknologi og brukeratferd vil endre seg i et langtidsperspektiv. Videre arbeider er derfor foreslått.

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Author: Vilde Borgnes

Keywords: Life Cycle Assessment (LCA), Zero Emission Neighbourhoods, Early stage planning

Abstract

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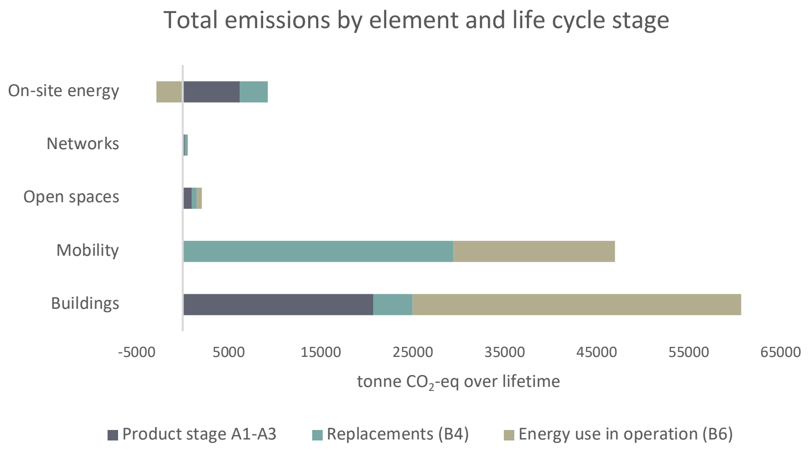
Graphical Abstract



1. Introduction

The 2015 Paris agreement of an average global temperature rise of maximum 2 degrees compared with pre-industrial times [2] has led to a growing focus on climate change. The building sector is a major driver, accounting for about one third of both energy consumption and greenhouse gas (GHG) emissions globally (2010) [3]. With the aim of reducing the energy use in buildings through country-level regulation, the EU has established two legislative directives; the Energy Performance of Buildings Directive (EPBD) [4] and the Energy Efficiency Directive [5]. This has motivated research, creation of building codes and development of concepts, which add guidance for energy efficiency in buildings. In Norway, the Norwegian Research Centre on Zero Emission Buildings (ZEB Centre) was a research project running from 2009 to 2017, with a vision to eliminate the GHG emissions caused by buildings. Its main objective was to develop competitive products and solutions for existing and new buildings leading to market penetration of buildings that have zero emission of GHGs related to their production, operation and demolition [6]. A Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Centre) is recently started as a follow-up of the ZEB Centre, with a goal to develop solutions for future buildings and neighbourhoods with no GHG emissions and thereby contribute to a low carbon society [7]. With this expansion in scope, the ZEN Centre researchers already acknowledge that many additional questions and challenges arise, and it is less obvious what good choices are and how to use LCA for decision support, e.g. regarding functional unit(s), system boundaries and assumed input values for critical variables and parameters.

1.1. Environmental Assessment of Buildings

To implement efficient reductions of environmental impacts from buildings, knowledge on the impacts over the entire life span of the building is essential. For this purpose, life cycle assessment (LCA) is a common and well-established tool [8-10]. LCA systematically addresses the environmental impacts of a system through the life cycle stages, from raw material acquisition, through energy and material production, to use and end-of-life treatment [11]. LCA studies at building level have led to valuable results that are used to pave the way for emission reductions in the building sector [12, 13].

One important finding is how the relative importance of the emissions from the operation of the individual building (heating, cooling, lighting, ventilation and appliances) compared to the emissions embodied in the materials used in the building have changed over time as a consequence of improved technology and building codes. Historically, the results have shown that the use stage is dominating, accounting for 80-90% of the total emissions [13-15]. More recent studies however, concluded that especially when low-energy buildings are evaluated, the share of the emissions from the materials are considerable [16-20]. Wiik et al. [19] found that the embodied emissions (including the production stage of materials and replacements during the life cycle of the building) accounted for as much as 55-87% of the total GHG emissions for Norwegian ZEB case studies examined by the ZEB Centre.

When focusing on the other stages of the life cycle, previous research indicates that 2-15% of the emissions are driven by the construction stage [19, 21, 22]. Yang et al. [21] however, found that among all the life cycle stages, the construction and the demolition stages together represented less than 1% of the total carbon emissions for a residential building in China.

Other lessons-learnt from LCA on buildings are related to e.g. alternative and renewable materials, architectural design (as shape, envelope and passive heating and cooling systems), user behaviour, and energy-positive buildings and the associating consequences of a greater exchange of self-produced energy to external grids [23-27]. Findings here may be just as relevant when focusing on more complex systems as neighbourhoods, it is nevertheless chosen not to go into detail about these topics here.

1.2. From Buildings to Neighbourhoods

In recent years it has been a focus shift when performing environmental assessments – from concentrating on individual buildings, treated as objects independent of the surrounding environment, to consider stocks of buildings and larger systems, as cities or neighbourhoods [28-30].

Still, the LCA literature on neighbourhood level is scarce and highly reasoned by the complexity and context dependency of the systems studied, the LCAs are characterized by heterogeneous approaches [20, 29].

The choice of system boundaries is a factor that excels from previous research, and the boundaries are shown to have considerable impacts on the results. The boundaries define what to include in the analysis, both regarding life cycle stages and physical elements such as buildings, mobility, open spaces and infrastructure. Some research is concentrated on clusters of buildings [31, 32], other take into consideration also the users´ mobility [30, 33-35]. The most complex LCA studies include both buildings, mobility and other elements as open spaces and networks [24, 36, 37]. The life cycle stages considered also vary, from only looking at the use stage, to consider also the construction and deconstruction stages [20, 29]. The different choices of system boundaries lead to difficulties when it comes to comparing results from LCA studies. Nevertheless, some important take-away messages are worth noting.

When focusing on the physical elements, the daily mobility of inhabitants seems to have a considerable impact on total emissions. Bastos et al. [35] found that user transportation contributed to 51-57% of the total GHG emissions when materials included in construction of the buildings, the use stage, and transportation were included in the analysis. Also Nichols and Kockelman [24] found that transportation constituted a considerable share of the impacts, with 44-47% of the total use stage emissions. There is a lack of studies including also the manufacturing of the modes of transport, but there are exceptions; Stephan et al. [36] found that indirect emissions, (including among other things vehicle manufacturing and building roads) constituted 52% of the total emissions from transportation. Anderson et al. [30] found the same number to be 22-27%, depending on the location of the neighbourhood (city centre, periphery or district). The large contributions and difference in results from these studies indicate that much more research is required on the field of indirect impacts from mobility related to zero emission neighbourhoods. Fortunately, these issues are already on their way into standards, such as the proposed new Norwegian standard *prNS 3720 Method for greenhouse gas calculations for buildings* [38], which expands the system boundaries compared to the European standard *EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method* [39], by including transport in the use stage as a new module in calculations of GHG emissions from buildings, see S1 in supplement material.

Temporal aspects and assumptions about the future are crucial when performing LCA, and the long lifespan of elements in neighbourhoods makes the forecasting of emissions difficult and a subject to uncertainty. This is highlighted in several studies, and especially the emission intensity of electricity (g CO_2-eq/kWh), evolving technology and time distribution of environmental impacts are considered key factors [29, 30, 35, 36, 40]. These factors may have considerable impact on long-term decisions and prediction of future emissions and should therefore be investigated further.

Furthermore, a common feature for the existing research is that the studies are usually conducted on existing neighbourhoods, cities or districts. However, the power of LCA is only fully utilized when it is also used as a tool in early stage planning of new neighbourhood projects. Lotteau et al. [41] describe a tool called NEST (Neighbourhood Evaluation for Sustainable Territories), an LCA tool for assessment of environmental impact of urban projects, developed by Yepez-Salmon [42]. By including the production stage, maintenance, use and end-of-life for both buildings and open spaces, as well as the daily mobility of the inhabitants, the tool makes it possible to look at different solutions for neighbourhood projects. The tool has been used in urban planning projects in France, and a holistic approach like this should be explored also in neighbourhood projects elsewhere.

More research is obviously required in the field of LCA on Zero Emissions Neighbourhoods. This regard both what life cycle stages and physical elements in the neighbourhood that contribute significantly to different categories of environmental impact, and wider knowledge of critical factors that affect the results under varying context situations. Such knowledge is fundamental and should serve as a foundation for the development of ZEN concepts.

1.3. Problem Statement

The objective of the work in hand is to contribute to expedient use of LCA of neighbourhoods at an early planning stage, by focusing on contributors to environmental impacts and critical factors. Through development of a model tested for a ZEN project in the early planning stage located in Bergen, Norway, the following research questions are answered:

- What are the dominant physical elements and life cycle stages contributing to the total environmental impact on a neighbourhood scale?
- What are the critical factors that affect these contributions and what are their sensitivity?
- What are the strength and weaknesses of the model that is developed? Can it provide useful inputs to the early stage planning process of a Zero Emission Neighbourhood?

2. Material and Methods

The work in hand consists of a suggestion of an expedient modular structure that works as a basis for LCA on neighbourhood level as well as the development of an LCA model for a specific neighbourhood using this structure. The specific case study is based on a pilot project for the ZEN Centre, called Zero Village Bergen (ZVB), located in Norway. The project is in the planning stage with presumed commencement in some years, and it is going to be Norway's biggest zero emission project for buildings [1]. Although the model is adapted to the specific case, the methodology and calculation procedures are intended to also be applicable to other LCA projects at neighbourhood level.

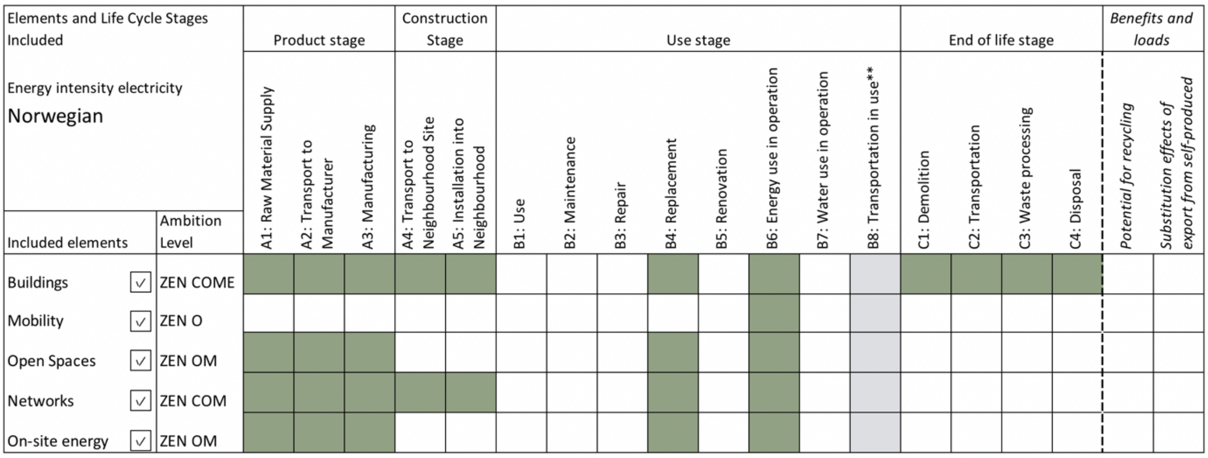
2.1. Modular Structure

The modular structure suggested is presented in Figure 1 and consists of two dimensions to cover both the physical elements (buildings, mobility, open spaces, networks and on-site energy infrastructure), and the life cycle stage modules included in the LCA. The latter is described by ambition levels, and the different modules (A1-C4) are based on the suggestions in prNS 3720 [38]. Because mobility is included as a separate element, the transportation in use (B8) is considered irrelevant (marked with grey in the figure).

The ambition levels are based on the approach used by the ZEB Centre and describe the life cycle stages included for each of the physical elements. The following description of these is adapted from the ZEB definition [43].

- ZEN O: Emissions related to all operational energy "O".
- ZEN OM: Emissions related to all operational energy "O" plus embodied emissions from materials "M.".
- ZEN COM: The same as OM, but also considers emissions relating to the construction "C" stage.
- ZEN COME: The same as ZEB-COM, but also considers emissions relating to the end of life "E" stage.

The elements and ambition levels (and associated life cycle stages) can be adjusted to match the neighbourhood of interest for each assessment.



Elements and Life Cycle Stages Included			Product stage			Construction Stage		Use stage								End of life stage				*Benefits and loads*	
Energy intensity electricity Norwegian			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*
Included elements		Ambition Level																			
Buildings	☑	ZEN COME	🟩	🟩	🟩	🟩	🟩				🟩		🟩		▨	🟩	🟩	🟩	🟩		
Mobility	☑	ZEN O											🟩		▨						
Open Spaces	☑	ZEN OM	🟩	🟩	🟩						🟩		🟩		▨						
Networks	☑	ZEN COM	🟩	🟩	🟩	🟩	🟩				🟩		🟩		▨						
On-site energy	☑	ZEN OM	🟩	🟩	🟩						🟩		🟩		▨						

Figure 1 Modular structure used as basis for LCA at neighbourhood level. Note: the elements and ambition levels are randomly selected and serve as an example of the use of the structure.

At the top left side of the structure, the emission intensity for electricity is stated (here it is chosen to be "Norwegian"). In Norway, the coming standard on method for greenhouse gas calculations in buildings [38] suggests to look at two different scenarios for the emission intensity of electricity, scenario 1 (NO) and scenario 2 (EU28+NO) based on the Norwegian and the European production mix, respectively. In practice, scenario 1 considers Norway as an isolated electricity system without import/export of electricity, and scenario 2 assumes that electricity is flowing freely between European countries, including Norway. Details on the emission intensities are given in S2.1 and Figure 2 represents the two scenarios with evolution from 2015 to 2080.

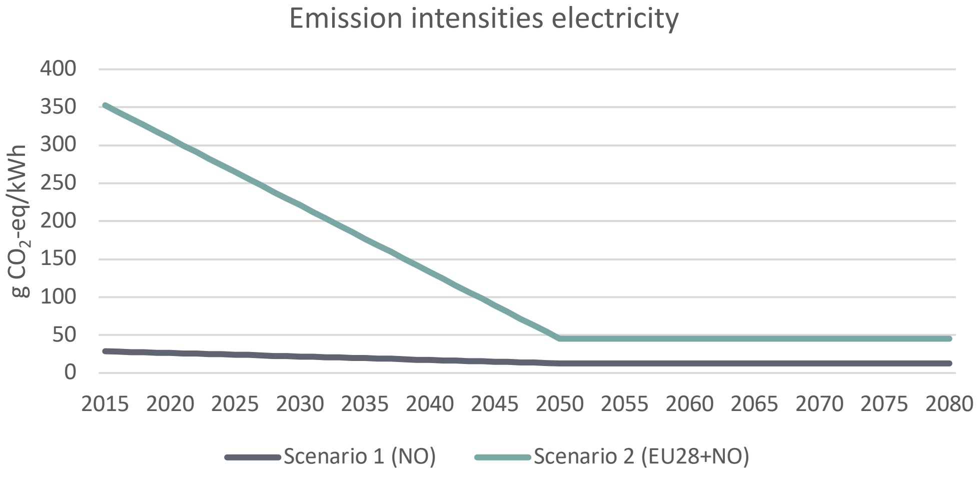


Figure 2 Evolution of emission intensities for electricity (g CO_2-eq/kWh) 2015-2080 based on scenarios suggested in prNS 3720 [38].

2.2. LCA Model for Zero Village Bergen

An LCA model was developed for Zero Village Bergen (ZVB) using the modular structure presented in Section 2.1. For all the elements (buildings, mobility, open spaces, networks and on-site energy infrastructure) ambition level “ZEN-OM” was applied, including the production stage (A1-A3), as well as replacements (B4) and energy use in operation (B6). An exception is for the networks, where the energy use in operation is excluded due to an assumed low impact. The modular structure adapted to the present study, as well as a map of the neighbourhood is presented in S3 and S4 respectively. The analysis period, equivalent with the assumed lifetime of buildings and infrastructure, is 60 years and it is focused on GHG emissions associated with each of the elements throughout this period. At the planning stage in the project, different energy system alternatives are under consideration, including joining the district heating system already present in Bergen, a local CHP plant or ground source heat pumps [44]. In the present study it is assumed that the heat demand is covered by connecting to the district heating system in Bergen, and that the electricity demand is supplied from the external power grid and with local production of electricity by photovoltaic panels. Regarding the emission intensity, scenario 1 (NO) is chosen for both import and export of electricity between the neighbourhood and the external power grid.

2.2.1. Buildings

The building stock in ZVB consists of residential buildings and non-residential buildings, with a total area of 91 891 m^2 [45], see Table 1. The total number of dwellings is 695 and based on statistics these are home to 1 340 inhabitants, see S5.1. The underground parking garages are not included in the total floor area of ZVB, but the embodied emissions in their materials are included in the product stage and replacements. The area of parking is estimated based on information of number of parking spots [45], see S5.2.

Table 1 Building stock and areas in ZVB [45].

Building type	**Floor area (m^2)**
Terraced house	62 136
Apartment block	23 028
Total residential	85 164
Kindergarten	1 061
Office	2 833
Shop	2 833
Underground parking	*21 657*
Total non-residential (excl. parking)	6 727
Total ZVB (excl. parking)	**91 891**

Production and replacement stages

The emissions embodied in building materials, $E_{b,mat}$, come from the initial materials contained in the buildings, as well as replacements of materials each year throughout the 60 years period, see Equation 1.

Equation 1 Emission from building materials (products stage and replacements)

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

$E_{mat,init}$ represents the emissions embodied in the materials initially contained in the buildings (CO_2-eq/m^2*)*, $E_{mat,repl}$ denotes the emissions embodied in the materials used in replacements (CO_2-eq/m^2), *bt* is the building type, *A* the area (m^2 floor area) and *i* is the year.

Material lists are presented in S5.3. Because of a limited access to detailed data, and uncertainties in design choices at the early stage planning, all the residential buildings (both apartment blocks and terraced houses) were assumed consisting of the same amount of materials per area. The same goes for the non-residential buildings (all the non-residential buildings considered are equal in materials as the office building). For residential buildings and parking garages the material lists were provided by SINTEF (operator of the ZEN Centre), and for non-residential buildings the material list was based on the materials included in a pilot project for an office building performed by the ZEB Centre [46]. For both building types, the emission of GHGs per amount of material was based on either EPDs or the Ecoinvent database. The replacements are based on estimated service life of each material, and the emissions embodied in the replacement materials (B4) are assumed equal to the ones in the initial product stage (A1-A3).

Energy use in operation

The energy use in the buildings is based on work performed by the ZEB Centre [45] where the buildings in ZVB were simulated, giving a total thermal load of 3 283 MWh and a total electric load of 3 257 MWh per year, see S5.4. Figure 3 shows the yearly load in kWh/m^2 for the different building types.

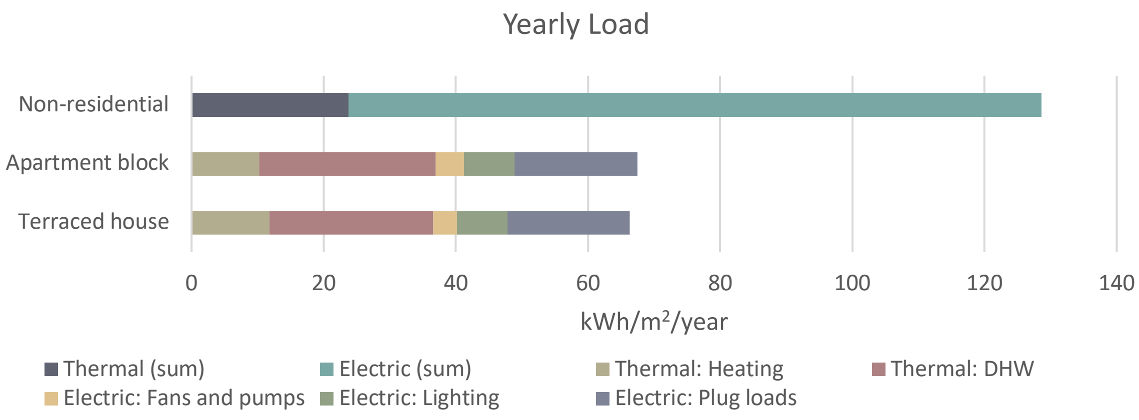


Figure 3 Yearly load (in kWh/m²) (adopted from [45])

It is assumed that the loads are constant for all the years in the analysis period. While the electric load is covered by electricity, the thermal demand (for space heating and domestic hot water) is covered by connecting to the district heating network in Bergen. The intensity of the district heat is calculated based on the emission intensities for the specific sources of energy. In Bergen, 87% of the energy comes from waste incineration and the emission intensity of the district heat is assumed to be 163.2 g CO_2-eq/kWh in 2020 when emissions from waste incineration are allocated to the district heating production, see S2.2.

2.2.2. Mobility

Three means of transport are considered for the mobility in ZVB; personal vehicle, bus and light rail. Due to the extensive planning for public transport and cycling facilities [1], the distance travelled with each type is based on statistics on travel habits for people with very good access to public transport, see S6.1.

Although the new Norwegian standard prNS 3720 suggests including transportation of users, it does not include a methodology for calculating the emissions for different means of transport. Nevertheless, it is suggested to use a project performed by the Norwegian research institute Vestlandsforskning, completed in 2011, as a source for indicative emission factors for todays´ situation [38]. The documentation behind the results reveals large heterogeneity when it comes to data on energy use and emissions from different means of transport from previous research [47], but concludes with providing chosen estimates for several transportation modes intended for Norwegian conditions.

Future evolution of the fuel types/energy carriers, together with technical improvements for vehicles and fuel chains make the forecast of emissions from transport a complex task. In prNS 3720, it is emphasized that development and technical improvements influenced by regulation and tax systems will lead to reduced emissions per distance driven during the buildings´ life cycle, and that this should be taken into account through scenario assessment [38]. In the work in hand, numbers from Vestlandsforskning is used as a basis for 2010, and several studies from the literature are used to predict the evolution in time (for both fuel types and technological improvements) up to 2080.

Evolution of vehicle stocks

The evolution of vehicle stocks is based on a "ultra-low emission policy scenario" developed by Fridstrøm and Østli [48]. The scenario is based on targets compiled by the transportation agencies, and the evolution of passenger cars and buses distributed between fuel types/energy carriers is forecasted from 2010 to 2050. In the present study, the situation is simplified to only consider four types of fuel/energy carriers; battery, hydrogen, diesel and gasoline, and the trend is assumed to continue up to 2080 (see Figure 4). It is assumed that the light rail is all-electric throughout the entire period.

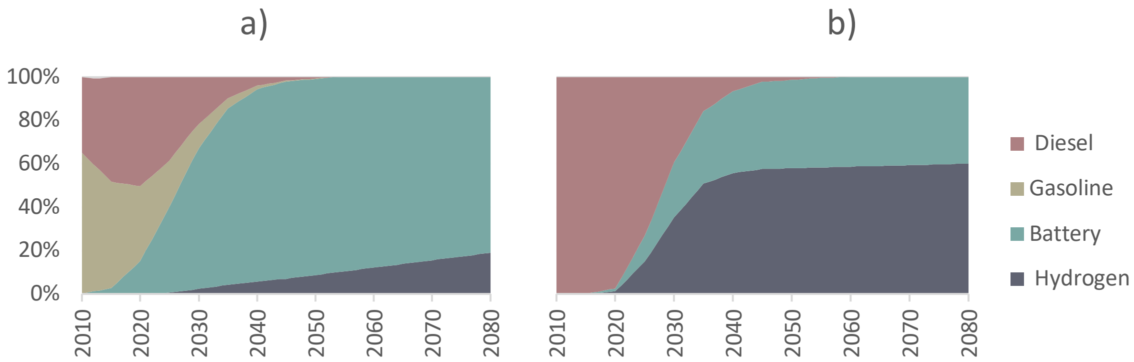


Figure 4 Evolution of vehicle stock for a) passenger cars and b) buses by fuel type/energy carrier used in present study (See data in S6.2)

Product and replacement stages

The emissions embodied in the materials for the mobility, $E_{m,mat}$, were calculated using Equation 2.

Equation 2 Emission from materials in mobility (products stage and replacements)

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

E_{mat} denotes the emissions from the production of different vehicle types (CO_2-eq/km) and L_{tot} describes the total neighbourhood yearly travel length (km). *Tm* is the transport mode (e.g. personal vehicle diesel), and *i* is the year.

The emissions from the product and replacement stages of the transportation are based on the project performed by Simonsen [47]. Because of the continuous replacements of vehicles, the emissions are considered per distance driven (see S6.3), and it is not distinguished between the initial material inputs (A1 – A3) and replacements (B4).

The emissions embodied in the vehicles per distance are assumed constant throughout the 60 years period, but the total emissions from production of vehicles change due to the evolution of fuel/energy carrier types as described in Figure 4.

Energy use in operation
When it comes to the operation of the mobility it is distinguished between the vehicle cycle and the fuel cycle. *Tank-to-wheel* is used to describe the energy the vehicle uses for the actual propulsion (used regardless of the fact that the vehicle has actual wheels). *Well-to-tank* is used to describe the energy that is required to transform the energy source to a useful energy carrier as well as transport of the energy carrier to the user. Finally, *well-to-wheel* describes the summation of the two.

The total emissions from the operation of mobility, $E_{m,oper}$, is calculated using Equation 3.

Equation 3 Total neighbourhood emissions from mobility operation

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

Here, $L_{tot,tm}$ is again the total neighbourhood yearly travel length (km/y), *tm* stands for transport mode and *i* is the year. $WtW_{tm,i}$ therefore denotes the emissions per km driven by transport mode *tm* in year *i* (kg CO_2-eq/km).

The results from the project performed by Simonsen [47] were used as a starting point in 2010, see S6.4. Improvements in the fuel intensities were based on a study performed by Ajanovic [49], where scenarios for fuel intensities of new passenger cars were forecasted up to 2050, see S6.5. The formula used to calculate the *WtW* emissions from each of the transport modes, *tm*, a given year, *i*, is represented in Equation 4.

Equation 4 Well-to-wheel (WtW) emissions

$$WtW_{tm,i} = (Energy_{TtW,i} * I_{TtW}) + (Energy_{TtW,i} * I_{WtT})$$

In the equation, $Energy_{TtW}$ denotes the propulsion energy needed (MJ/vkm), I_{TtW} is the direct emission intensity (g CO_2-eq/MJ) and I_{WtT} is the emission intensity for the fuel cycle of the fuel/energy carrier (g CO_2-eq/MJ). The latter are emissions associated with producing and transporting the fuel needed for the given energy in the propulsion of the vehicle.

As Equation 4 indicates, the intensities (both tank-to-wheel and well-to-tank) are held constant, while the propulsion energy is assumed to change during the years. Figure 5 shows the evolution in the WtW emissions in g CO_2-eq/passenger-km for the relevant modes of transport in snapshots for 2020, 2040, 2060 and 2080.

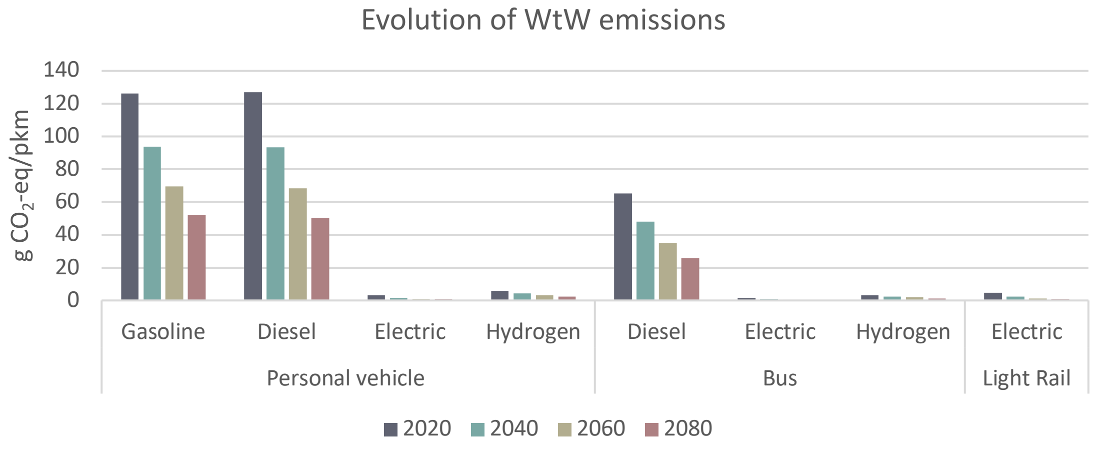


Figure 5 Evolution of WtW emissions from different modes of transport (see Table 15 in S6.5)

2.2.3. Open Spaces

Included in the open spaces element are emissions embodied in roads (included bicycle lanes), sidewalks and outside parking, as well as emissions from the operation of public lighting.

Product and replacement stage

It is assumed that the road network in ZVB consists of two types of road; (1) wide road with two lanes and bicycle lanes at each side and (2) narrow road without bicycle lanes. The road structure (material and dimension) is adopted from the work performed by Birgisdóttir et al. [50], see S7.1. The area of each of the sub-elements are roughly estimated based on the map of ZVB (S4), see Table 2.

Table 2 Open spaces ZVB

Open spaces element	**Length (m)**	**Area (m^2)**
Road type 1	3 700	63 640
Road type 2	4 400	49 280
Sidewalk	3 700	11 100
Parking	-	2 900

The emissions from the materials in the open spaces elements are based on data from EPDs. It is assumed lifetimes of 20 and 40 years for the surface asphalt and base asphalt courses respectively and 60 years for the aggregates. S7.2 shows the materials included in the open spaces elements.

Energy use in operation

The emissions from the public lighting in ZVB, $E_{o,oper}$, are calculated using Equation 5.

Equation 5 Total neighbourhood emissions from operation of open spaces (public lighting)

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

N is the number of lighting units, *P* is the power per unit (kW) and *h* denotes hours with lighting per year. The number of hours the units are turned on is calculated using specific data for Bergen, see S7.3. I_{el} is the emission intensity for electricity and *i* represents the year.

2.2.4. Networks

For all the alternative energy system solutions in ZVB (district heat, local CHP or ground source heat pump), a local thermal network will connect the buildings with the energy central [44]. In the present study, this is the district heating network that connects ZVB to the already existing network in Bergen, see S8.1. The emissions embodied in the materials included in the part of this network geographically located inside the neighbourhood is therefore considered, with components at the neighbourhood system level (not on building or dwelling level). The energy use in operation of the network is not included.

Production and replacement stages

The length of pipes and number of units of the components are roughly estimated based on the design of ZVB, resulting in 5 000 m of new pipes (including both flow and return pipes) and one new pump. The amount of materials included is adopted from the study by Oliver-Solà et al. [51], where LCA was performed on a 100 m district heating system delivering energy to 240 dwellings by both including the neighbourhood-, building- and dwelling systems. The average diameter of the pipelines (100 mm) is from the study. The resulting material list and estimated service life for the pipes and the pump are presented in S8.2.

2.2.5. On-site Energy

The on-site energy in ZVB consists of photovoltaic panels placed on the building roofs. The dimensions and the generation of electricity used in the calculations are according to the report by Sartori et al. [45].

Production and replacements

The panels are placed on available roof area at the buildings, and the total PV area is 22 045 m^2 [45]. Emissions associated with the production of the panels are found using Ecoinvent, see S9.1. The lifetime of the photovoltaic panels is assumed to be 30 years [52], and based on a suggestion from the ZEB Centre, a reduction of 50% of environmental impacts compared to the initial production due to technology development and efficiency improvements is applied in the replacement [43].

Energy use in operation
Based on available roof area, meteorological data, system efficiency and losses, and generation profiles, the yearly PV generation is estimated to 2 941 MWh [45]. Emissions associated with this generation are calculated using the emissions intensity for electricity (scenario 1), and these emissions are seen as negative contributions to (i.e. avoided) emission because the electricity production from the PVs is a contribution to the electricity demand. It is either self-consumed in the neighbourhood or exported to the external electricity network.

2.3. Sensitivity Analysis

With the goal of investigating the critical parameters in the LCA model, a sensitivity analysis was performed on selected factors that were expected to have considerable impacts on the results and/or were associated with large uncertainties. All of the selected factors were increased with 25%, and the sensitivity ratio (*SR*) was measured using Equation 6.

Equation 6 Sensitivity ratio method

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

ΔP/P0 represents the relative change in the input parameter and *ΔR/R0* denotes the relative change in results.

In addition to this, two different assumptions expected to have a great impact on the results were examined, namely the emission intensity for electricity and the allocation of emissions associated with waste incineration at the district heating energy central. For the latter, the emission intensity for district heat was estimated to 16.1 g CO_2-eq/kWh assuming significantly less emissions from the heat generated by waste incineration (compared to 163.2 g CO_2-eq/kWh used in base case), see S2.2.

3. Results

3.1. *General Results*

With the methodology described, the total emissions associated with the physical elements (buildings, mobility, open spaces, networks and on-site energy) and the life cycle stages (A1-A3, B4 and B6) were calculated, resulting in a total of approximately 117 kg tonne CO_2-eq over the lifetime of 60 years. This equals 1.5 tonne CO_2-eq/capita/year and 21.2 kg CO_2-eq/m^2/year (heated building area). The emissions are distributed between the elements and life cycle stages as shown in Figure 6. As indicated in the figure, the building element stands for the majority of the emissions, accounting for about 52% of the total emissions over the lifetime. The mobility is the second most contributing element, responsible for 40% of the total emissions. The emissions from the networks and open spaces constitute only 2.3% together. Further, it is worth noticing the relatively small negative emissions from the on-site energy which, with the assumptions made, are actually less than the emissions associated with the production of the photovoltaic panels.

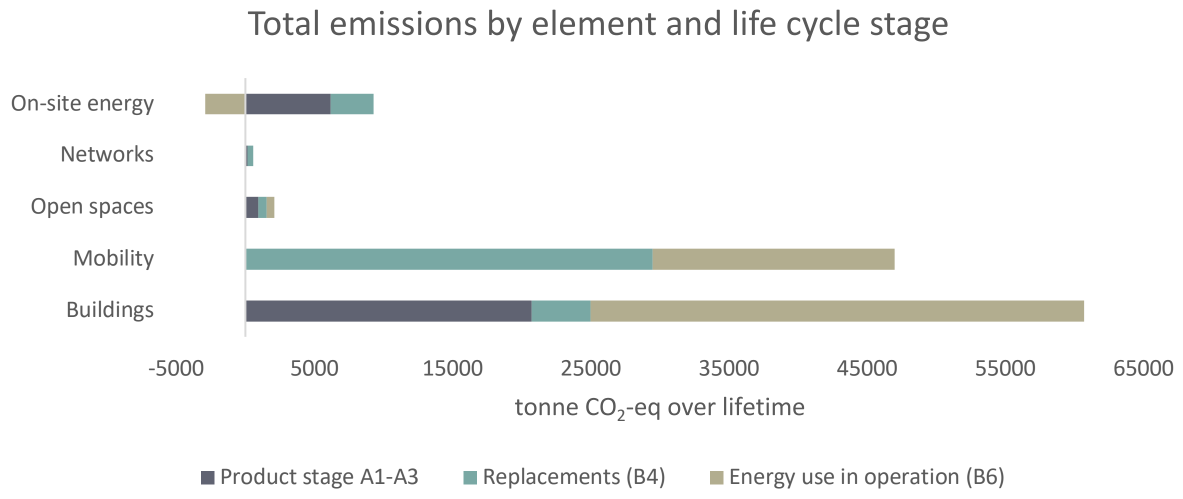


Figure 6 Total emissions for ZVB distributed between elements and life cycle stages (see S10.1 for data)

The results show that the emissions from the product stage (pre-use, A1-A3) represent a significant share (24%) of the total emissions when all elements are considered. This is without the production stage of vehicles in the mobility element (recall that this is merged with the replacement stage due to the shorter service life of vehicles). If we disregard these emissions and focus on the emissions occurring in the use stage, the emissions are distributed over the years as presented in Figure 7. Emissions embodied in materials used in replacements for buildings, open spaces, networks and on-site energy (PV panels) are represented with emission peaks at certain points in time, while the emissions associated with the replacements of vehicles in the mobility element are distributed over the years (light green bars). These emissions are slowly increasing due to the shift from fossil fuel vehicles to battery electrical and hydrogen electrical vehicles.

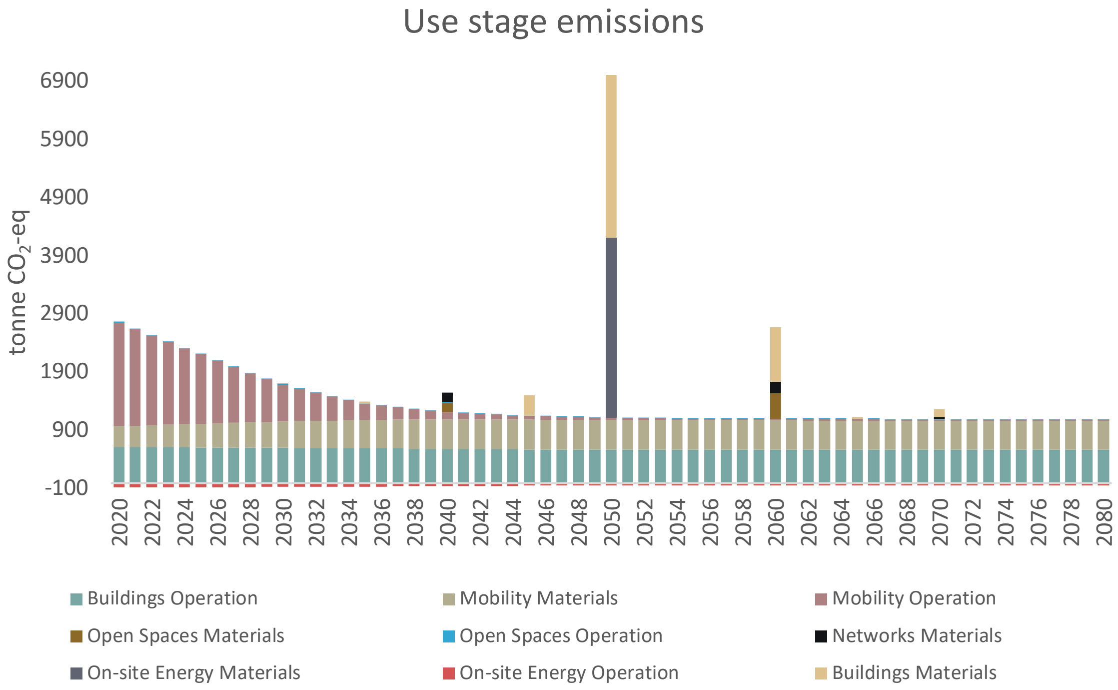


Figure 7 Total use stage emissions by year distributed by element and life cycle stage

To take a closer look at the parameters leading to the overall emissions, the two elements that stand for the major part of the emissions, buildings and mobility, are reported in detail. For the mobility element, replacement of vehicles is the major emission source and production of personal vehicles stand for as much as 96% of these emissions, see S10.1 and S10.2. While these emissions increase over the lifetime due to the increased share of battery electric vehicles, the emissions associated with the operation of the mobility decrease drastically for the same reason. When the total period of 60 years is considered, the internal combustion engine vehicles (both personal vehicles and buses) are dominating with 89% of the emissions, this despite the fact that these vehicles are assumed being completely phased out by 2060, see S10.3.

When focusing on the buildings, it is revealed that energy use in operation accounts for the majority of the emissions with 59%. Out of this, 91% is from district heat for space heating and domestic hot water. Regarding the materials, residential buildings obviously account for most of the emissions (the neighbourhood consists of 93% residential buildings), but this is amplified by the fact that also when looking at emissions per area, the residential buildings stand for relatively more emissions, see S10.4.

3.2. Results Sensitivity Analysis

The results of the sensitivity analysis are represented in Table 3, and reveal that the two parameters with the largest sensitivity ratio, and therefore the largest influence on change in total emissions results, are the travel distance per inhabitant and the buildings' energy loads.

Table 3 Results sensitivity analysis selected parameters

Sensitivity parameter	Sensitivity ratio	Change in total emissions result from base case
Emission intensity electricity +25%	0.021	0.5%
Emission intensity district heat +25%	0.279	7.0%
Travel distance/inhabitant/year +25%	0.403	10.1%
Emissions associated with vehicle production +25%	0.252	6.3%
Emissions embodied in building materials +25%	0.165	4.1%
Energy load (thermal and electric) +25%	0.306	7.7%
Area of PV panels +25%	0.055	1.4%
Energy public lightng +25%	0.005	0.1%

Figure 8 shows the change relatively to the base case for each of the parameters and also for two fundamental assumptions that are shown to have a considerable impact on the results, namely the emission intensity for the electricity and the assumption of allocating the emissions associated with the waste incineration to the waste management system rather than to the district heating production. If scenario 2 (see section 2.1) is used, the total emissions over the 60 years analysis period of the neighborhood will increase with 12.5%. This is despite that also the negative emissions from the on-site electricity production will be larger. If the emissions from waste incineration is not allocated to the district heating production, the total emissions are decreased with 25.3%.

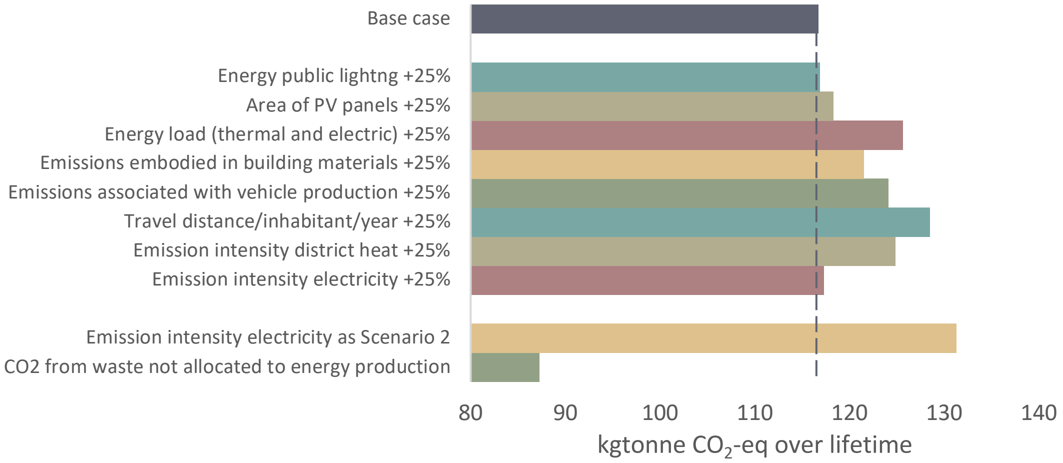


Figure 8 Results sensitivity analysis relatively to the base case. Notice that the axis does not start at zero.

4. Discussion

In this section the modular structure presented in section 2.1 and the model developed for Zero Village Bergen described in section 2.2 are discussed. The results obtained from the model (section 3) are discussed in the context of the research questions presented in section 1.3, and critical factors and uncertainties are deliberated. Finally, usefulness and limitations are discussed, and further work required on the field of LCA modelling for Zero Emission Neighbourhoods is suggested.

4.1. LCA Modelling on Neighbourhood Scale – Results and Critical Parameters

When moving from individual buildings to complex systems as neighbourhoods in LCA modelling, it is crucial to clearly understand the effect of preconditions made, and elements and life cycle stages included. With the modular approach, it is possible to look at the effect of changing the system boundaries, both regarding elements and life cycle stages included, and also to present the results with several functional units. The modules make it possible to easily adjust the LCA to fit different neighbourhood projects (with different preconditions) and to compare different projects with different premises.

The model developed for Zero Village Bergen based on the modular structure led to results that provide useful insight in the dominant physical elements and lifecycle stages contributing to environmental impact. It revealed that buildings account for as much as 52% of the total emissions (with a ZEN OM ambition level for all elements). When looking at the buildings alone, the emissions embodied in the materials stand for 41% of the total emissions (for the three stages considered). This is comparable to, but not quite as much as reported by Wiik et al. [19], who stated that the share was between 55% and 87%. It should be noted that the emissions embodied in materials in the present study may be underestimated because of uncompleted material lists for the residential buildings. Another important aspect is the fact that out of the remaining 59% of the emissions caused by energy use, as much as 91% is associated with heat supply for space heating and domestic hot water. This again, is mainly because of one single assumption; the allocation of the emissions associated with waste incineration to the district heating production. In the present LCA, an emission intensity for heat production for waste incineration of 161.5 g CO_2/kWh based on criteria from the ZEB Centre [53] was used. Figure 8 shows that if the emissions from waste incineration are not allocated to the heat production, the total emissions would decrease with as much as 25.2%. Hence, a change in this parameter will make considerable impact on the total results. Whether or not the assumption used here is right is debatable. On one hand it can be argued that heat is a by-product from the waste incineration process, and therefore should be allocated to the waste management system. This is currently the allocation principle that is suggested in the proposed new Norwegian standard prNS 3720. On the other side, as pointed out by M. Lien [54]: *"waste is today an internationally tradable commodity that should be utilized where it gives maximum energy per unit greenhouse gas emitted".* In such a view, emissions from waste incineration should clearly be allocated to the heat production in a district heating system.

Something that may be surprising is that when the Norwegian emission intensity is used and with the assumption of symmetric weighting (the same emission intensity for import and export), the negative emissions “gained” from on-site production does not even cover the emissions embodied in the PV panels (see Figure 6). Here, and also for several of the other elements, the choice of emission intensity for electricity becomes relevant. Similar to the intensity for district heat, also this is a debated subject in LCA studies [55-57]. First of all, the future electricity mix is hard to predict. Further, the electricity network is a complex system with varying exchange of energy between countries and continents, depending on season, accessibility and propagation of transfer possibilities. The sensitivity ratio for the intensity indicates that a change in this parameter does not drastically affect the total result, see Table 3. This however, is when all the emissions are included, also the negative emissions associated with the on-site production of electricity from the PV panels. Because symmetric weighting is assumed, both the positive and negative emissions increase when changing the emission intensity. If the negative emissions are disregarded, the total emissions from the neighbourhood (including all elements) would increase with 30% when changing from scenario 1 (NO) to scenario 2 (EU28+NO). This clearly shows how critical this parameter is for the results. Because of the high sensitivity of the emission intensity of electricity, it is important to adopt a value (and evolution) that is as realistic as possible to facilitate decision making and choices of energy system in early stage planning.

The emissions from mobility constitute 40% of the total neighbourhood emissions and out of this 37% come from the operation of the transportation modes. If the system boundaries are adjusted to match the ones examined by Bastos et al. [35], large differences in the results are revealed. While Bastos et al. found that transportation contributed with 51-57% of the emission when buildings (materials and operation) and transportation of the users were included, the comparable percentage was only 22% in the present study. This is probably partly because of inclusion of (an optimistic?) future evolution of the personal vehicle stock regarding the share of electric vehicles, in combination with the low emission intensity for electricity. The remaining 63% of the emissions from mobility come from the production of vehicles. If adopting the system boundaries used by Anderson et al. [30] including buildings and mobility, the product stage for vehicles constitutes 27%, which is exactly the same as reported by Anderson et al. Their study however, concludes that emissions from the operation stage constitute a larger share than the vehicle production, something that may indicate that the agreeing percentages are a coincidence.

The open spaces element consisting of roads, sidewalks, outside parking, and public lighting together with the network element including the district heating pipes only constitute a total of 2.3% of the total neighbourhood emissions over the lifetime. It is expected that this number will be higher “as-built” due to possible underestimated amounts of materials included in the model, as well as lack of detailed data for the modules. The low share still indicates a relatively small contribution when comparing to the building and mobility elements.

Performing an LCA in early stage planning of projects is useful to gain knowledge that serves as basis for decision making. Some choices that are done in early stage are crucial for the design of the project and will affect the environmental impacts in the entire lifetime. Examples here are structural building materials, spatial planning and choice of energy system. Some choices are more difficult to control, e.g. the evolution of the energy mix in electricity and district heat and the evolution of vehicle stocks. However, it is possible to address these uncertainties by choosing a flexible energy system, such as waterborne heat systems in the buildings and by dimensioning the electricity network to be able to meet a growing electrical vehicle stock. In practice, when performing LCA at an early stage, the main focus should be on the decisions that facilitate as low as possible emissions in the future.

4.2. Limitations and Further Work

Although the model has several advantages in highlighting the dominant drivers both related to physical elements and life cycle stages and facilitating for comparability between design choices and between projects, there are still limitations that weaken the model.

First of all, the model does not account for long term changes in technology development and improvements in production processes for the replacement materials. The only exception is for the PV panels, where the emissions are assumed to decrease with 50% in the replacement. This affects especially mobility emissions due to the frequent replacements of vehicles. With the current rapid technology improvement in the transportation sector, especially for electric vehicles, there will be less emissions from production processes, both for the vehicle itself and for their fuel cycles. Further research is required to make realistic and quantitative scenarios on production of vehicles in the future. Emissions per distance for 2010 as reported by Simonsen [47], and recommendations as in the proposed new standard prNS 3720 [38], are not sufficient to do robust calculations on neighbourhoods with an analysis period of 60 years.

Together with emissions associated with replacements of materials (and vehicles), there are also large uncertainties when it comes to the evolution of parameters as emission intensities, the behaviour of inhabitants (travel habits, energy use etc.) and the distribution between vehicle types. In order to make the model more complete and realistic, more research is required on the likely future evolution.

When performing LCA, it is often considered several impact categories to show a holistic picture of the product or process. Here however, only climate change measured in greenhouse gas equivalent emissions is reported. A broader analysis is needed to avoid problem shifting phenomena, e.g. reduced GHG emissions but increased environmental impacts in other impact categories such as acidification, land use change and photochemical smog. Therefore, the LCA model should be extended to also consider other relevant impact categories.

At last, the model is based on yearly values rather than hourly data for consumption and production of energy. In practice this means that the external electricity network is considered an infinite capacity battery and that it does not make any difference if the self-produced electricity is consumed locally in the neighbourhood or exported to the grid. This assumption can be justified by the fact that a symmetric weighting factor for electricity is used and that the intensity is constant over the year. This is a simplification and may not reflect reality. Also, if the economic perspective is added, the prices of imported vs. exported energy is commonly asymmetric, which favours a high self-consumption, because the price of exported energy is usually less than the price for import. Here, also other factors as energy storage and vehicle-to-grid concepts become relevant, however, they are outside the scope of this study.

5. Conclusion

In order to contribute to expedient use of LCA of neighbourhoods, it was proposed a modular structure that works as a basis for assessments of Zero Emissions Neighbourhood (ZEN) projects at an early planning stage. Based on this structure, an LCA model specific for a ZEN project in Bergen, Norway was developed. The goal was to find the dominant physical elements and life cycle stages contributing to the total environmental impact of this project.

The results show that when considering the elements buildings, mobility, open spaces, networks and on-site energy generation, as well as the three life cycle stages product stage, replacement stage and energy use in operation, buildings represent the majority (52%) of greenhouse gas emissions, closely followed by mobility (40%). Among the life cycle stages, the total emissions are dominated by those embodied in materials from the production stage and replacements (56%) and with the remaining coming from energy use in operation (44%). For all the elements except for buildings, embodied emissions dominate over the emissions from energy use. This is not the case for the buildings, mainly because of the emission intensity for district heat, where the emissions associated with incineration of waste is allocated to the heat production. This assumption is therefore a critical parameter, together with the emission intensity for electricity, the daily travel distance per day for the inhabitants and the emissions associated with vehicle production.

The model has clear potential to facilitate decision making in early stage planning of ZENs, as it can provide information on dominant elements and life cycle stages, and its modular structure ensures comparability and adaptability. On the other hand, the LCA model, and consequently also the results, suffer from uncertainties and simplifications, particularly on how technology and behaviour may change in a long-term perspective. Further work is therefore required when it comes to e.g. forecast of emissions intensities, emissions associated with production of materials and vehicles in the future and the consequence of assuming symmetric weighting for emission intensities.

Acknowledgements

This work was conducted as a part of a MSc. thesis at the Norwegian University of Science and Technology. I would like to thank my supervisor Helge Brattebø, as well as my co-supervisor PhD student Carine Lausselet, for valuable follow-up and discussions during the work.

Supplement Material

As a supplement to the paper, a document consisting of appendices are provided in order to serve detailed information related to the model. The supplement material is referred to throughout the text.

Supplement Material

This document is meant as a supplement to the paper *LCA modelling for zero emission neighbourhoods in early stage planning.* It describes the LCA model in detail to provide a broader understanding. It also goes deeper into assumptions made, and calculation procedures used.

S1. The Life Cycle Stages of The Building (From prNS 3720)

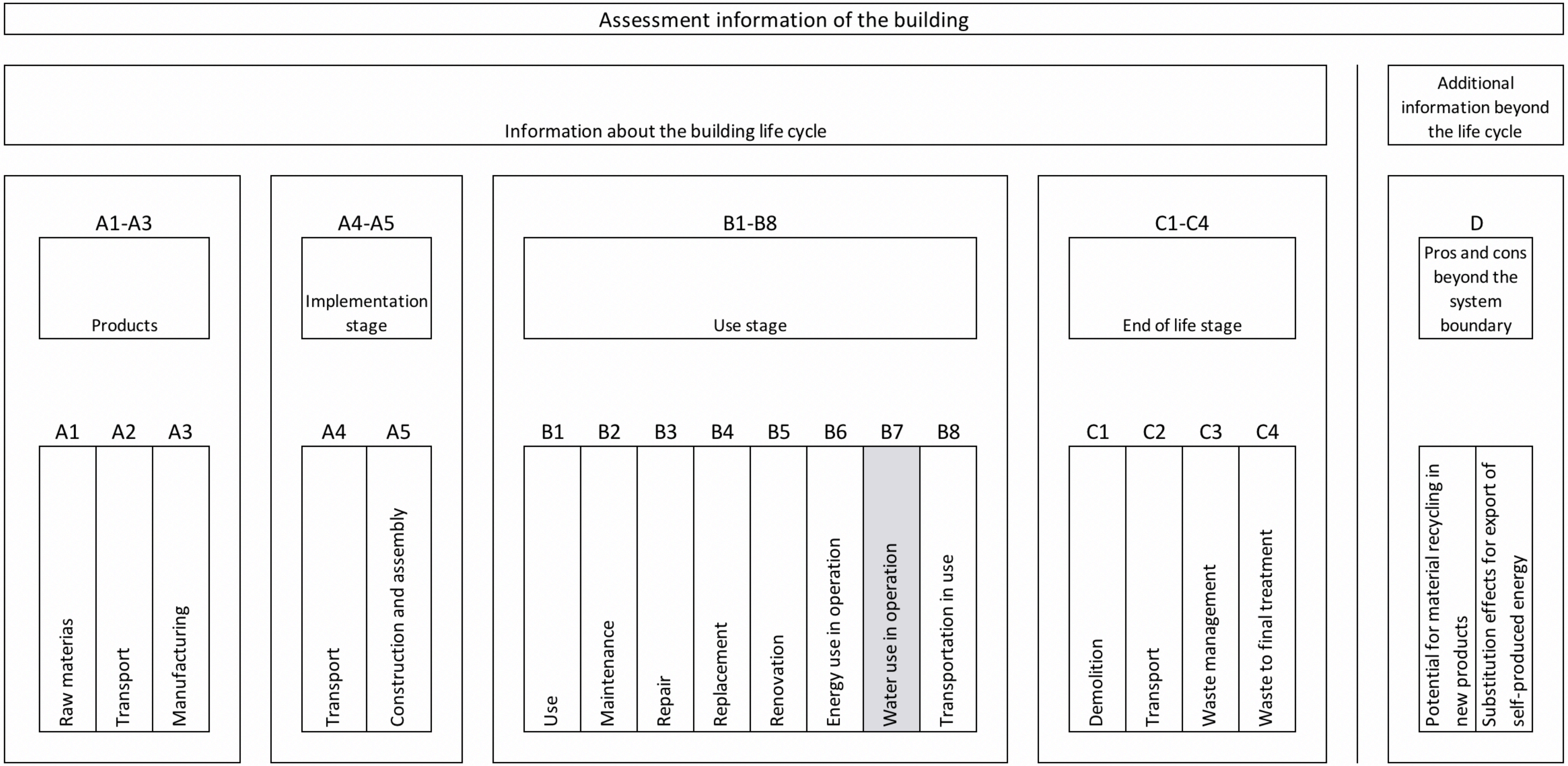


Figure 9 Information about the building life cycle, translated from prNS 3720 [38]

S2. Emission Intensities

S2.1 Electricity

The coming standard on method for greenhouse gas calculations in buildings (prNS 3720) suggests to look at two different scenarios for the emission intensity for electricity [38]. Scenario 1 is based on Norwegian production mix and scenario 2 is based on European (EU28+NO) mix. Both scenarios use the todays´ production mix as a reference and assume that the intensity follows a linear function to expected production mix in 2050. In the following years (30 years in the present study), the factor is held constant at this level until the end of the period of analysis. The standard provides assumed production mix in 2015 and 2050 for both scenarios and CO_2 factors for several production technologies that can be used as a basis for calculating the intensities, see Table 4.

Table 4 CO2-factors for different production technologies and production mix 2015 and 2050 for Norway and Europe (EU28+NO). Adopted from Standards Norway [38].

Production technology	**CO_2-factor (g/kWh)**	**2015**		**2020**	
		Norway	Europe28+NO	Norway	Europe28+NO
Hydro power	11 (2-20)	95%	18%	85%	8%
Wind power	22 (3-41)	1%	8%	15%	33%
Thermal power Norway	450	4%			
Thermal power EU	800		43%		
PV	100 (13-190)		3%		10%
Geo/biothermal	59 (8.5-130)		0.4%		10%
Nuclear	566 (380-1000)		28%		19%
Thermal power CCS	~100				20%

S2.2 District Heat

When it comes to district heating; the ZEB Centre suggests basing the calculations on specific emission intensities depending on the sources used to produce the energy. Therefore, this section is considering the district heat in Bergen specifically.

Table 5 shows the energy produced distributed by source, as well as associated emission intensities (as used in the ZEB Centre) and resulting total emissions for 2017, as stated in the product declaration that addresses the district heat system in Bergen [58]. The numbers in parenthesis is the number used if the emissions from the waste incineration is not allocated to the district heat production [59]. According to BKK (Norwegian power company located in Bergen), the district heat in Bergen is going to be fossil free by 2020, and that this in practice is going to be achieved by replacing the peak load sources with bio oil [60]. Based on this, the mix, and associated emissions in 2020 is assumed to be as described in Table 6. It should be noted that the emission intensity for electricity is as stated in S2.1. Further, the emissions from the district heating is estimated assuming a constant production and share of the sources, and with an evolution in the emission intensity for electricity as described in S2.1. Figure 10 shows the intensity for the district heat from 2020 to 2080 with and without the emissions from the waste incineration allocated.

Table 5 Energy and emissions district heat Bergen 2017 [58]

	Energy produced (GWh)	**Energy delivered (GWh)**	**Emission intensity (g CO_2/kWh)**	**CO_2 emission (g CO_2)**
Waste incineration	243.3	216.5	161.5 (11.1)	39293.0
Fossil oil	1.1	1.0	285.0	313.5
Fossil gas	13.2	11.7	210.0	2772.0
Electricity	21.8	19.4	130.0	2834.0
SUM	**279.3**	**248.6**		**45212.5**
SUM (g CO_2/kWh)$_{delivered}$			**181.8 (34.7)**	

Table 6 Energy and associated emissions Bergen assumed in 2020

	Energy produced (GWh)	**Energy delivered (GWh)**	**Emission intensity (gCO_2/kWh)***	**CO_2 emission (gCO_2)**
Waste incineration	243.3	216.5	161.5 (11.1)	39293.0
Bio	14.3	12.7	50.0	200.2
Electricity	21.8	19.4	26.4	575.5
SUM	**279.4**	**248.6**		**40068.7**
SUM (g CO_2/kWh)$_{delivered}$			**163.2 (16.1)**	

*From ZEB Centre [43] except for electricity which follows the evolution as described in S2.1.

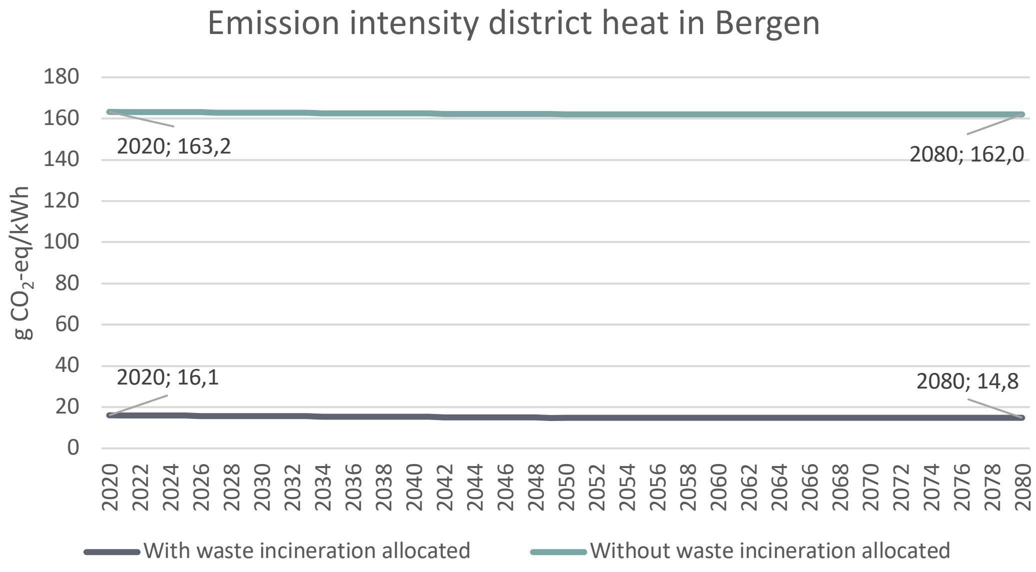


Figure 10 Emission intensity district heat Bergen with and without the emissions from waste incineration allocated to heat production

S3. Modular Structure Zero Village Bergen

Table 7 Modular structure ZVB

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									🟩		🟩		▨						
Open Spaces ☑	ZEN OM	🟩	🟩	🟩						🟩		🟩		▨						
Networks ☑	ZEN OM	🟩	🟩	🟩						🟩		🟩		▨						
On-site energy ☑	ZEN OM	🟩	🟩	🟩						🟩		🟩		▨						

* Not included in present study

** Not relevant (covered by mobility element)

S4. Map

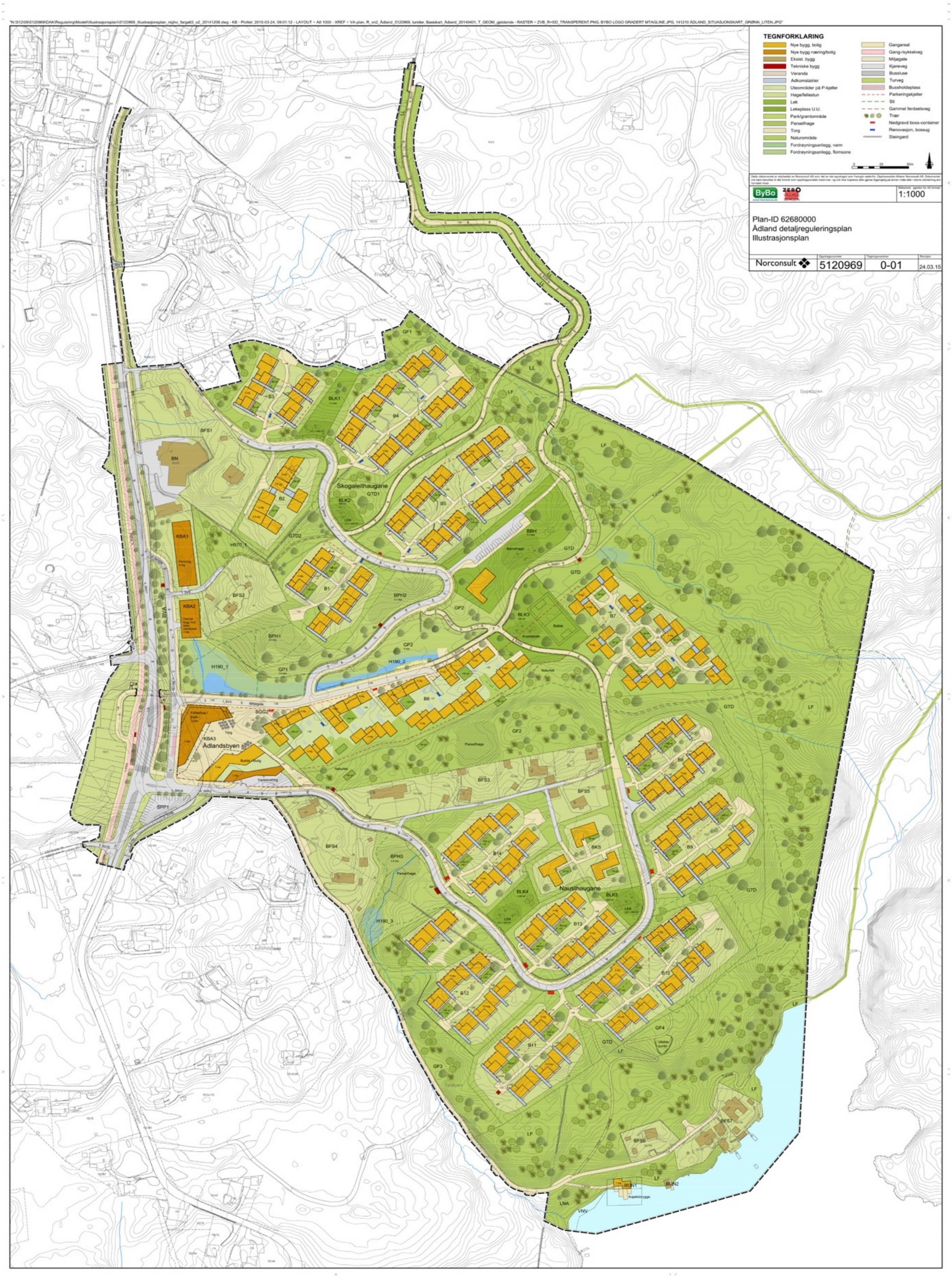


Figure 11 Map over ZVB, scale: 1:1000 (for A0 format), equivalent to 841x1189m in real size

S5. Buildings

S5.1 Number of Inhabitants

The number of occupants per dwelling (Table 8) is based on data from Statistics Norway [61], and works as basis for the total number of occupants living in ZVB. The apartment buildings are considered equivalent with multi-dwelling building, and terraced house as row house in the statistics. This leads to a total of 1 340 inhabitants.

Table 8 Average number of occupants per dwelling for relevant building types

Type of building	Occupants per dwelling	Number of dwellings (ZVB)	Total number of occupants
Row house, linked house and house with 3 dwellings or more	2.1	455	956
Multi-dwelling building	1.6	240	384
Total		**695**	**1 340**

S5.2 Area Inside Parking

The floor area of the inside parking is estimated based on information given in the report by Sartori et al. [45] and recommendations for parking garages [62]. With 1 165 parking spots and an estimated area of 17 m^2 per spot, the area of inside parking is 19 689 m^2. It is added additionally 10% due to turning areas and exits/entries, leading to a total of 21 657 m^2 of parking garage area.

S5.3 Materials Buildings

The material lists used as a basis for the embodied emissions for residential buildings, non-residential buildings and parking garages are represented in Table, 9, 10 and 11 respectively.

Table 9 Materials residential buildings /m²

Building Parts	Building component	Material	Amount/ m²				Type of reference	Specification	ESL
2 Building									
2.1 Groundwork and foundations	215 Piled foundations	Concrete	0,21	m3	270,00	kg CO2-eq/m3	EPD	*Norbetong EPD*	60
		Steel	12,38	kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
2.2 Superstructure	222 Columns	Concrete		m3	248,00	kg CO2-eq/m3	EPD	B35 M45 Unicon	60
		Reinforcing steel		kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
		Columns Bubbledeck		m2	2,00	kg CO2-eq/m2 BRA	Master thesis	B35 Columns supporting Bubbledeck - 10 m grid span	60
2.3 Outer walls	231 Loadbearing outer walls	Concrete	0,27	m3	270,00	kg CO2-eq/m3	EPD	Norbetong EPD	60
		Reinforcing steel	6,72	kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
		Insulation		kg	11,11	kg CO2-eq/kg	Ecoinvent	Polystyrene, extruded (XPS), at plant/RER U	60
		Timber	26,03	kg	0,04	kg CO2-eq/kg	EPD	Tømmer produksjon, MIKADO, med interntransport	60
	232 Non load bearing outer walls	Insulation	1,34	m2	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	60
		Weather barrier	1,35	m2	2,64	kg CO2-eq/m2	EPD	Glasroc storm EPD	60
		Vapour barrier	1,36	m2	0,11	kg CO2-eq/1m2*15mm	Ecoinvent	Vapour barrier	30
		Inner plates	1,32	m2	2,39	kg CO2-eq/m2	EPD	12,5 plasterboard gyproc	30
		Facade material	1,35	m2	2,12	kg CO2-eq/m2	EPD	EPD-Norwegian timber cladding painted	30
	234 Windows, doors, portals	Nordan	0,30	m2	70,31	kg CO2-eq/m2	EPD	Nordan EPD - 3 layer window	40
	235 Wall to staricase	Timber	41,97	m3	0,04	kg CO2-eq/kg	EPD	Tømmer produksjon, MIKADO, med interntransport	30
2.4 Inner walls	241 Load bearing inner walls	Concrete	0,02	m3	270,00	kg CO2-eq/m3	EPD	Norbetong EPD	30
		Reinforcing steel	1,17	kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	30
	242 Non-load bearing wall/EI60 (separation stair/tech) wood studs	Insulation		m2	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	30
		Wood studs		kg	0,04	kg CO2-eq/kg	EPD	Treindustrien, EPD: Planed Timber, Cradle-to-gate	30
		Plaster board	1,71	m2	2,39	kg CO2-eq/m2	EPD	12,5 plasterboard gyproc	60
		Wind barrier	0,10	m2	1,83	kg CO2-eq/m2	EPD	Hunton, EPD: Asphalt wind barrier	60

	242 Non-load bearing wall/Gypsum wall (shaft/wc)	Steel stud	0,51	kg	1,45	kg CO2-eq/kg	Ecoinvent	Steel, low-alloyed, at plant/RER U	30
		Insulation		kg	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	30
		Wood studs		kg	0,04	kg CO2-eq/kg	EPD	Treindustrien, EPD: Planed Timber, Cradle-to-gate	30
		Plaster board		m2	3,13	kg CO2-eq/m2	EPD	12,5 mm Robust GR13 Gyproc	30
		Ceramic tiles		kg	0,78	kg CO2-eq/kg	Ecoinvent	Ceramic tiles, at regional storage/CH U	30
	242 Non-bearing inner wall/Standard office partition wall	Insulation		m2	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	30
		Wood studs		kg	0,04	kg CO2-eq/kg	EPD	Treindustrien, EPD: Planed Timber, Cradle-to-gate	30
		Plywood		m3	225,86	kg CO2-eq/m3	Ecoinvent	Plywood, indoor use, at plant/RER U (of project KlimaTre - yttervegg)	30
	243 System wall/Office front -50% glass/wood finish	Wood frame		m2	245,00	kg CO2-eq/m2	Ecoinvent	Window frame, wood-metal, U=1.6 W/m2K, at plant/RER U	30
		Glass		kg	0,98	kg CO2-eq/kg	Ecoinvent	Flat glass, uncoated, at plant/RER U (of project KlimaTre - yttervegg)	30
		Wood door		m2	36,69	kg CO2-eq/m2	Ecoinvent	Door, inner, wood, at plant/RER U (of project Ecoinvent unit processes)	30
		Insulation (glava)		m2	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	30
		Wood studs		kg	3,10	kg CO2-eq/kg	Ecoinvent	Aluminium, production mix, cast alloy, at plant/RER U	30
		Plywood		m3	225,86	kg CO2-eq/m3	Ecoinvent	Plywood, indoor use, at plant/RER U (of project KlimaTre - yttervegg)	30
	243 System wall/100% glass	Wood frame		kg	0,04	kg CO2-eq/kg	EPD	Treindustrien, EPD: Planed Timber, Cradle-to-gate	30
		Glass		kg	0,98	kg CO2-eq/kg	Ecoinvent	Flat glass, uncoated, at plant/RER U (of project KlimaTre - yttervegg)	30
2.5 Floor structure	251 Load bearing deck	Timber	125,04	kg	0,04	kg CO2-eq/kg	EPD	Tømmer produksjon, MIKADO, med interntransport	60
	252 Slab on ground	Concrete		m3	248,00	kg CO2-eq/m3	EPD	B35 M40 Unicon	60
		Reinforcing steel		kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
		Insulation		kg	11,11	kg CO2-eq/kg	Ecoinvent	Polystyrene, extruded (XPS), at plant/RER U	60
	254 Floor system	Particleboard	0,02	m3	185,00	kg CO2-eq/m3	Calculation	Fibreboard - Forrestia 2011-Analysis Kari Sørnes	25
	255 Floor surfaces	Lamell parquett	1,00	m2	3,05	kg CO2-eq/m2	EPD	Laminate flooring EGGER Flooring EPD 2011	30
				m3	82,17	kg CO2-eq/m3	Ecoinvent	Sawn timber, hardwood, planed, air / kiln dried, u=10%, at plant/RER U NORDEL el	30
				kg	0,29	kg CO2-eq/kg	Ecoinvent	Polyethylene, LDPE, granulate, at plant/RER U	30
	257 Suspended ceiling	Plaster	1,00	m2	2,39	kg CO2-eq/m2	EPD	12,5 plasterboard gyproc	30
		Timber	1,00	kg	0,04	kg CO2-eq/kg	EPD	Tømmer produksjon, MIKADO, med interntransport	60

2.6 Outer roof	261 Primary construction	Timber	38,54	kg	0,04	kg CO2-eq/kg	EPD	Tømmer produksjon, MIKADO, med interntransport	60
	262 Roof covering	Insulation	0,26	m3	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	30
		Membrane	0,51	m2	0,11	kg CO2-eq/1m2*15mm	Ecoinvent	Vapour barrier	30
		Gypsum	0,51	m2	2,39	kg CO2-eq/m2	EPD	12,5 plasterboard gyproc	30
2.8 Stairs and balconies	281 Internal stairs	Steel	19,15	kg	0,11	kg CO2-eq/kg	ZEB	Reinforcing steel, at plant/RER U ZEB	60
		Cement	72,24	kg	0,82	kg CO2-eq/kg		Portland cement, strength class Z 42.5, at plant/NORDEL el	60
		Gravel	52,72	kg	0,00	kg CO2-eq/kg	Ecoinvent	Gravel, crushed, at mine/CH U	60
3 Heating, Ventilation and Air conditioning									
3.6 Ventilation and air conditioning	362 Duct system for air conditioning	Ventilation ducts		m	6,34	kg CO2-eq/m	Ecoinvent	Ventilation duct, steel, 100x50 mm, at plant/RER U	60
		Elbow 90 deg		m	1,20	kg CO2-eq/m	Ecoinvent	Elbow 90°, steel, 100x50 mm, at plant/RER U	60
		Insulation spiral-seam		m	17,99	kg CO2-eq/m	Ecoinvent	Insulation spiral-seam duct, rockwool, DN 400, 30 mm, at plant/RER U	60
	364 Equipment for ar distribution	Fittings, vents etc.		kg	8,55	kg CO2-eq/kg	Ecoinvent	Aluminium, production mix, at plant/RER U	60
		Fittings, vents etc.		kg	1,45	kg CO2-eq/kg	Ecoinvent	Steel, low-alloyed, at plant/RER U	60
	365 Equipment for air treatment	AHU		p	3792,52	kg CO2-eq/p		AHU - Olav Rådstuga	60
4. Electric power supply									
4.3 Low-voltage supply	431 Power outlet system	Cable bridges	0,14	m	5,85	kg CO2-eq/m			60
	432 Main distribution systems	Cable	1,93	m	2,45	kg CO2-eq/m	Ecoinvent	Cable, three-conductor cable, at plant/GLO U	60
		Cable	1,93	m	0,35	kg CO2-eq/m	Ecoinvent	Cable, connector for computer, without plugs, at plant/GLO U	60
		Cable	1,93	m	0,17	kg CO2-eq/m	Ecoinvent	Cable, data cable in infrastructure, at plant/GLO U	60
6. Other Installations									
6.2 Passenger and goods transport	621 Lifts/elevator	Elevator		p	5610,00	kg CO2-eq/p		Elevator from KONE EPD information - raw materials	60

Table 10 Material list non-residential buildings per m2

Building Parts	Building component	Material	Amount/ m2	Unit	GWP/ unit		Type of reference	Specification	ESL
2 Building									
2.1 Groundwork and foundations	214 Support structures	Reinforcement steel	10,22	kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
	216 Direct foundation	Reinforcement steel	3,94	kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
		Concrete	0,05	m3	270,00	kg CO2-eq/m3	EPD	*Norbetong EPD*	60
2.2 Superstructure	222 Columns	Reinforcement steel	5,11	kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
		Concrete	0,00	m3	270,00	kg CO2-eq/m3	EPD	*Norbetong EPD*	60
	223 Beams	Reinforcement steel	11,38	kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
2.3 Outer walls	231 Loadbearing outer walls	Timber	7,92	kg	0,04	kg CO2-eq/kg	EPD	Tømmer produksjon, MIKADO, med interntransport	60
		Concrete	0,06	m3	270,00	kg CO2-eq/m3	EPD	*Norbetong EPD*	60
		Reinforcement steel	4,13	kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
	232 Non-loadbearing outer walls	Gypsum plates outer	0,35	m2	2,39	kg CO2-eq/m2	EPD	12,5 plasterboard gyproc	60
		Insulation	4,32	m2	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	60
		Vapour barrier	0,06	kg	0,29	kg CO2-eq/kg	Ecoinvent	Polyethylene, LDPE, granulate, at plant/RER U	60
	234 Windows, doors, portals	Windows (glazing + frame)	0,21	m2	70,31	kg CO2-eq/m2	EPD	Nordan EPD - 3 layer window	40
		Outer doors	0,01	m2	89,51	kg CO2/m2	Ecoinvent	Door, outer, wood-glass, at plant/RER U	30
	235 Facade material	Cembrit fiber cement	6,10	kg	0,07	kg CO2-eq/kg	EPD	Cembrit True Etna- Fiber cement facade element EPD	30
	236 Inner surface	Gypsum plates inner	0,35	kg	2,39	kg CO2-eq/m2	EPD	12,5 plasterboard gyproc	30
2.4 Inner walls	237 Sun screening	Aluminium	1,40	kg	8,55	kg CO2-eq/kg	Ecoinvent	Aluminium, production mix, at plant/RER U	30
	241 Bearing inner walls	Concrete	0,07	m3	270,00	kg CO2-eq/m3	EPD	*Norbetong EPD*	60
		Reinforcement steel	4,17	kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
	242 Non-bearing inner walls	Insulation	1,57	m2	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	30
		Gypsum plates	2,33	m2	2,39	kg CO2-eq/m2	EPD	12,5 plasterboard gyproc	30
		Steel studs	0,51	kg	1,45	kg CO2-eq/kg	Ecoinvent	Steel, low-alloyed, at plant/RER U	30
		Zink coating	0,02	m2					30
		Aluminium - rist	4,76	kg	8,55	kg CO2-eq/kg	Ecoinvent	Aluminium, production mix, at plant/RER U	60
		Wood veneers	0,00	m3	0,04	kg CO2-eq/kg	EPD	Treindustrien, EPD: Planed Timber, Cradle-to-gate	60
	243 System walls/glass walls	Timber - office front	0,00	m3	225,86	kg CO2-eq/m3	Ecoinvent	Plywood, indoor use, at plant/RER U (of project KlimaTre - yttervegg)	30
		Glass	1,60	kg	0,98	kg CO2-eq/kg	Ecoinvent	Flat glass, uncoated, at plant/RER U (of project KlimaTre - yttervegg)	30
	244 Windows and doors	Steel	6,50	kg	1,45	kg CO2-eq/kg	Ecoinvent	Steel, low-alloyed, at plant/RER U	30

		Timber doors	0,05	m2	36,62	kg CO2-eq/m2	Ecoinvent	Door, inner, wood, at plant/RER U	30
2.5 Floor structure	251 Load bearing deck	Concrete	0,24	m3	270,00	kg CO2-eq/m3	EPD	*Norbetong EPD*	60
		Reinforcement steel	7,08	kg	0,39	kg CO2-eq/kg	EPD	Celca Steel Service OY, EPD: Reinforcement	60
	252 Slab on ground	Membrane	0,04	kg	0,29	kg CO2-eq/kg	Ecoinvent	Polyethylene, LDPE, granulate, at plant/RER U	60
		Insulation	2,39	m2	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	60
	253 Concrete for equalization	Concrete	0,03	m3	248,00	kg CO2-eq/m3	EPD	B35 M40 Unicon	60
	254 Floor systems	Vinyl	0,09	kg	8,74	kg CO2-eq/m2	EPD	Homogenouse Vinyl http://www.erfmi.com Manufacturing	15
		Linoleum	0,50	kg	2,23	kg CO2-eq/m2	EPD	Linoleum http://www.erfmi.com EPD database	15
		Laminate	0,14	m2	3,05	kg CO2-eq/m2	EPD	Laminate flooring EGGER Flooring EPD 2011	15
		Carpet	0,21	kg	9,64	kg CO2-eq/m2	EPD	Carpet- EPD-BauUmwelt Desso - 100 % PA6 fra nov. 2011	15
	257 Ceiling system	Insulation	2,78	m2	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	60
		Gypsum	1,30	m2	2,39	kg CO2-eq/m2	EPD	12,5 plasterboard gyproc	60
		Steel studs	1,13	kg	1,45	kg CO2-eq/kg	Ecoinvent	Steel, low-alloyed, at plant/RER U	60
		Zink coating	0,09	m2					60
2.6 Outer roof	261 Primary construction	Insulation	3,07	m2	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	60
		Membrane	1,26	kg	0,49	kg CO2-eq/kg		Bitumen, at refinery/RER U (of project KlimaTre - yttervegg)	30
2.8 Stairs and balconies	281 Inner stairs	Steel	1,49	kg	0,11	kg CO2-eq/kg	ZEB	Reinforcing steel, at plant/RER U ZEB	60
		Cement	5,65	kg	0,82	kg CO2-eq/kg		Portland cement, strength class Z 42.5, at plant/NORDEL el	60
		Gravel	4,16	kg	0,00	kg CO2-eq/kg	Ecoinvent	Gravel, crushed, at mine/CH U	60
	282 Outer stairs	Steel	0,25	kg	1,45	kg CO2-eq/kg	Ecoinvent	Steel, low-alloyed, at plant/RER U	60
3 Heating, Ventilation and Air conditioning									
3.6 Ventilation and air conditioning	36 Ventilation air estimate	Mixed input	1,00	p				Steel, alu, copper, plastics	60
4. Electric power supply									
4.3 Low-voltage supply	431 Power outlet system	Cable bridge	0,42	kg	1,45	kg CO2-eq/kg	Ecoinvent	Steel, low-alloyed, at plant/RER U	60
		Zink coating	0,02	m2					60
	432 Main distribution systems	Cables	1,52	m	2,45	kg CO2-eq/m	Ecoinvent	Cable, three-conductor cable, at plant/GLO U	30

Table 11 Material list parking garage per m^2

Building Parts	Building component	Material	Amount/m^2	Unit	GWP/ unit		Type of reference	Specification	ESL
2 Building									
2.4 Inner walls	242 Non-bearing inner walls	Plastic	1,00	m2	2,64	kgCO2-eq/m2	EPD	Glasroc storm EPD, 9,5mm	60
		Vapour Barrier	1,00	m2	0,11	kgCO2-eq/m2	Ecoinvent		30
		Gypsum	1,00	m2	2,39	kgCO2-eq/m2	EPD	12,5 plasterboard gyproc	60
		XPS	1,53	kg	11,11	kgCO2-eq/kg	Ecoinvent	Polystyrene, extruded (XPS), at plant/RER U	60
		Timber	1,80	kg	0,04	kgCO2-eq/kg	EPD	Treindustrien, EPD: Planed Timber, Cradle-to-gate	60
		Insulation	1,00	m2	0,57	kg CO2-eq/m2*37mm	EPD	Glava, EPDnr 221: Glass wool, Cradle-to-gate	60
		Timber	1,00	m2	2,12	kgCO2-eq/m2	EPD	EPD-Norwegian timber cladding painted	30
		Timber	1,30	kg	0,04	kgCO2-eq/kg	EPD	Treindustrien, EPD: Planed Timber, Cradle-to-gate	30
2.5 Floor structure	252 Slab on ground	Concrete	0,10	m3	188,23	kg CO2-eq/m3	EPD	*Norbetong EPD*	60
		Steel	7,50	kg	0,11	kg CO2-eq/kg	ZEB	Reinforcing steel, at plant/RER U ZEB	60
		EPS	0,25	m3	59,00	kg CO2-eq/m3	EPD	EPS-Hartschaum (Styropor ®) B/P-035	60
2.6 Outer roof	261 Primary construction	Massivtre	1,00	m3	0,04	kg CO2-eq/m3	EPD	Tømmer produksjon, MIKADO, med interntransport	60
		Limtre	0,07	m3	79,00	kg CO2-eq/m3	EPD	Moelven Limtre	60

S5.4 Energy Use in Operation of Buildings

Table 12 shows summery information about energy loads in the buildings in ZVB provided in the ZEB project report *"Zero Village Bergen - Aggregated loads and PV generation profiles"* [45].

Table 12 Electric and thermal loads ZVB divided between building types

	Electric load		**Thermal load (kWh/y)**	
	MWh/y	kWh/m^2/y	MWh/y	kWh/m^2/y
Terraced houses	1849	29.8	2272	36.3
Apartment blocks	704	30.6	852	37.0
Total residential	***2553***		***3124***	
Non-residential (sum)	705	104.8	160	23.8
Total ZVB	***3257***		***3283***	

S6. Mobility

S6.1 Travel Distances by Transport Mode

The distance travelled per person by different transport modes is based on the report *2013/14 National travel survey* for Norway [63]. Here, the average number of travels per day for people with very good access to public transport is 3.34 travels per day. Table 13 gives information on the travel habits resulting from the survey.

Table 13 Average travel length/person per day by different types of transportation

Transport mode	Fraction of the travels	Average travel length/travel	Average travel length per person/day
By foot	0.29	2.2	2.1
Bicycle	0.06	5.1	1.0
Car (driver)	0.40	15.8	21.1
Car (passenger)	0.07	21.7	5.1
Public transport	0.17	35.6	20.2
MC/other	0.01	11.2	0.4

For the public transport, it is assumed that 60% of the travels are by bus, and 40% are by light rail. This assumption is due to the fact that the light rail station is planned further away from the neighbourhood than the bus station.

Although the travel habits have been evolving over time, the numbers are assumed to stay constant from 2020 to 2080 in this assessment. Based on this, and with 1 340 inhabitants, the resulting yearly travel length per transport mode is as reported in Figure 12.

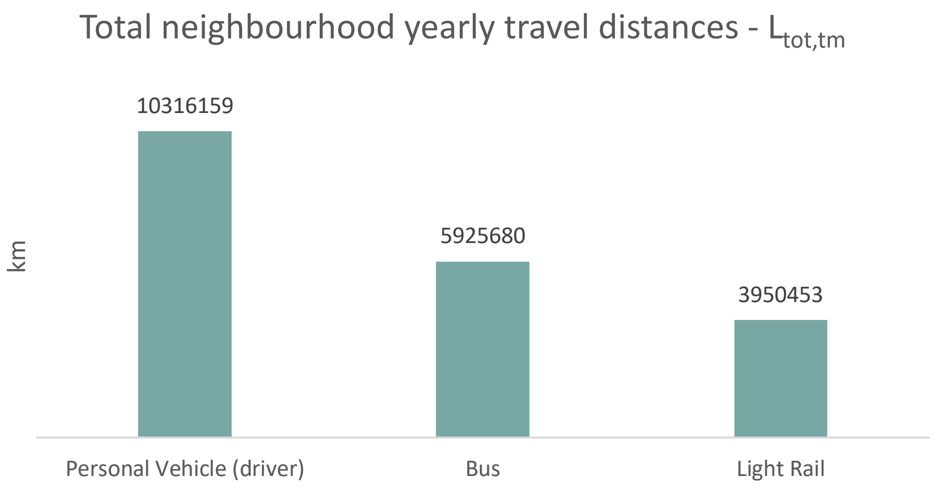


Figure 12 Total neighbourhood yearly travel distances (km/y) by transportation mode – $L_{tot,tm}$

S6.2 Evolution of Vehicle Stocks

Table 14 Evolution of personal vehicle (left) and bus (right) stock ZVB

Year	Hydrogen	Battery	Gasoline	Diesel	Hydrogen	Battery	Gasoline	Diesel
2010	0 %	0 %	65 %	35 %	0 %	0 %	0 %	100 %
2011	0 %	1 %	62 %	37 %	0 %	0 %	0 %	100 %
2012	0 %	1 %	59 %	40 %	0 %	0 %	0 %	100 %
2013	0 %	2 %	55 %	42 %	0 %	0 %	0 %	100 %
2014	0 %	2 %	52 %	45 %	0 %	0 %	0 %	100 %
2015	0 %	3 %	49 %	48 %	0 %	0 %	0 %	100 %
2016	0 %	5 %	46 %	49 %	0 %	0 %	0 %	99 %
2017	0 %	8 %	43 %	49 %	1 %	1 %	0 %	99 %
2018	0 %	10 %	40 %	49 %	1 %	1 %	0 %	98 %
2020	0 %	15 %	35 %	50 %	1 %	1 %	0 %	97 %
2021	0 %	20 %	32 %	48 %	4 %	3 %	0 %	93 %
2022	0 %	25 %	29 %	45 %	7 %	6 %	0 %	88 %
2023	0 %	30 %	27 %	43 %	9 %	8 %	0 %	83 %
2024	1 %	35 %	24 %	41 %	12 %	10 %	0 %	78 %
2025	1 %	40 %	21 %	38 %	15 %	12 %	0 %	73 %
2026	1 %	45 %	19 %	35 %	19 %	15 %	0 %	66 %
2027	1 %	50 %	17 %	32 %	23 %	17 %	0 %	60 %
2028	2 %	55 %	15 %	28 %	27 %	20 %	0 %	53 %
2029	2 %	60 %	13 %	25 %	31 %	23 %	0 %	46 %
2030	2 %	65 %	11 %	21 %	35 %	25 %	0 %	39 %
2031	3 %	68 %	10 %	19 %	38 %	27 %	0 %	35 %
2032	3 %	72 %	9 %	17 %	42 %	29 %	0 %	30 %
2033	3 %	75 %	7 %	14 %	45 %	30 %	0 %	25 %
2034	4 %	78 %	6 %	12 %	48 %	32 %	0 %	20 %
2035	4 %	81 %	5 %	10 %	51 %	33 %	0 %	16 %
2036	5 %	83 %	4 %	9 %	52 %	34 %	0 %	14 %
2037	5 %	84 %	3 %	7 %	53 %	35 %	0 %	12 %
2038	5 %	86 %	3 %	6 %	54 %	36 %	0 %	10 %
2040	6 %	89 %	2 %	4 %	56 %	38 %	0 %	6 %
2041	6 %	89 %	1 %	3 %	56 %	38 %	0 %	6 %
2042	6 %	90 %	1 %	3 %	57 %	39 %	0 %	5 %
2043	7 %	90 %	1 %	3 %	57 %	39 %	0 %	4 %
2044	7 %	90 %	1 %	2 %	57 %	40 %	0 %	3 %
2045	7 %	91 %	1 %	2 %	58 %	40 %	0 %	2 %
2046	7 %	91 %	0 %	1 %	58 %	40 %	0 %	2 %
2047	8 %	91 %	0 %	1 %	58 %	40 %	0 %	2 %
2048	8 %	91 %	0 %	1 %	58 %	41 %	0 %	2 %
2049	8 %	91 %	0 %	1 %	58 %	41 %	0 %	1 %
2050	9 %	90 %	0 %	1 %	58 %	41 %	0 %	1 %
2051	9 %	90 %	0 %	0 %	58 %	41 %	0 %	1 %
2052	9 %	90 %	0 %	0 %	58 %	41 %	0 %	1 %
2053	10 %	90 %	0 %	0 %	58 %	41 %	0 %	1 %
2054	10 %	90 %	0 %	0 %	58 %	41 %	0 %	0 %
2055	10 %	90 %	0 %	0 %	58 %	41 %	0 %	0 %
2056	11 %	89 %	0 %	0 %	58 %	41 %	0 %	0 %
2057	11 %	89 %	0 %	0 %	58 %	41 %	0 %	0 %
2058	11 %	89 %	0 %	0 %	59 %	41 %	0 %	0 %
2060	12 %	88 %	0 %	0 %	59 %	41 %	0 %	0 %
2061	12 %	88 %	0 %	0 %	59 %	41 %	0 %	0 %
2062	13 %	87 %	0 %	0 %	59 %	41 %	0 %	0 %
2063	13 %	87 %	0 %	0 %	59 %	41 %	0 %	0 %
2064	14 %	86 %	0 %	0 %	59 %	41 %	0 %	0 %
2065	14 %	86 %	0 %	0 %	59 %	41 %	0 %	0 %
2066	14 %	86 %	0 %	0 %	59 %	41 %	0 %	0 %
2067	15 %	85 %	0 %	0 %	59 %	41 %	0 %	0 %
2068	15 %	85 %	0 %	0 %	59 %	41 %	0 %	0 %
2069	15 %	85 %	0 %	0 %	59 %	41 %	0 %	0 %
2070	16 %	84 %	0 %	0 %	59 %	41 %	0 %	0 %
2071	16 %	84 %	0 %	0 %	59 %	41 %	0 %	0 %
2072	16 %	84 %	0 %	0 %	60 %	40 %	0 %	0 %
2073	17 %	83 %	0 %	0 %	60 %	40 %	0 %	0 %
2074	17 %	83 %	0 %	0 %	60 %	40 %	0 %	0 %
2075	17 %	83 %	0 %	0 %	60 %	40 %	0 %	0 %
2076	18 %	82 %	0 %	0 %	60 %	40 %	0 %	0 %
2077	18 %	82 %	0 %	0 %	60 %	40 %	0 %	0 %
2078	18 %	82 %	0 %	0 %	60 %	40 %	0 %	0 %
2080	19 %	81 %	0 %	0 %	60 %	40 %	0 %	0 %

S6.3 Embodied Emissions Mobility

Table 15 shows the emissions per vehicle-km and passenger-km for the different transport modes. For the passenger vehicles, it is assumed that there are 1.2 passengers per vehicle based on Table 13 in S6.1. For buses and the light rail, the numbers of passengers are 17 and 34 respectively [47]. The emission from the electric and hydrogen buses is assumed based on a constant relative ratio compared to the ICVs for the personal vehicles.

Table 15 Emissions per distance travelled for each transport mode

	Personal vehicles			Bus			Light Rail
Passengers/vehicle	1.2			17			34
	ICEVs	BEVs	FCEVs	ICEVs	BEVs	FCEVs	Electric
gCO_2/vkm	30.5	48.9	34.3	30.0	48.1	33.7	39.7
gCO_2/pkm	25.0	40.1	28.1	1.8	2.8	2.0	1.2

S6.4 Energy Use and Emissions in Operation (B6) (2010 values)

The parameters used in Equation 4 are from the project performed by Simonsen [47], see Table 16 (2010 values). Exceptions are the data for electric and hydrogen fuel cell buses, where the energy consumption was calculated assuming the same relative ratio to diesel as for personal vehicles. This assumption seems to align with numbers found in literature (1.1-1.6 kWh/km for electric buses [64-66] and 1.8-2.0 kWh/km for hydrogen buses [67, 68]). The WtT fuel cycle emission intensities for buses were assumed being equal to the ones for personal vehicles. Simonsen [69] considers three different sources to direct hydrogen; central reforming of natural gas with or without carbon capture and storage and wind power plus central electrolysis of water. For all the options it is considered pipeline transportation. In the present study, the data that are given for direct hydrogen with wind power and central electrolysis is used. For vehicles with electricity as energy carrier, the emission intensity is taken from scenario 1 (see S2.1).

The numbers are valid for Norwegian passenger cars in 2010, and the data was corrected in 2017 after the “diesel gate scandal”, where it was found large differences in measured and real emissions. The new factors constituted an increase of tank-to-wheel CO_2 equivalent emissions of 25% and 14% for diesel and gasoline vehicles respectively [70].

Table 16 Data used to calculate WtW emissions (in 2010) from different means of transport

Transport mode	TtW Energy (MJ/vkm) 2010	TtW Direct emission intensity (g CO_2-eq/MJ)	WtT Fuel cycle emission intensity (g CO_2-eq/MJ)	WtW Emission (g CO_2-eq/km)
Personal vehicle – Gasoline	2.14	73.75	10.98	181.3
Personal vehicle – Diesel	2.07	74.36	14.33	183.6
Personal Vehicle – Electric	0.61	0	8.66***	6.4
Personal vehicle – hydrogen	0.94	0	9.10	8.6
Bus – diesel	15.7	71.08	11.62	1298.4
Bus – electric	4.6*	0	8.66***	48.1
Bus – hydrogen	7.1*	0	9.10	64.6
Light rail – electric **	24.8	0	8.66***	259.4

* Assumed by using the same relative ratio to diesel as for personal vehicles

** Based on numbers for the tram in Oslo

*** Based on emission intensity for electricity, changing over time

S6.5 Future Emissions from Operation

Improvements in the fuel intensities were based on a study performed by Ajanovic et al. [71], where scenarios for fuel intensities of new passenger cars were forecasted up to 2050. Resulting yearly decrease in fuel intensity (MJ/vkm) assumed in the present study was 1.47% and 1.53% for gasoline and diesel vehicles respectively, and 1.50% for electricity and hydrogen vehicles, see Figure 13. The numbers are assumed to be transferable also to the buses and the light rail, and the trend was assumed to be continuing up to 2080.

These improvements will affect the emissions from the fuel cycle (less produced fuel), but for both the ICEVs and the hydrogen vehicles, the emissions intensity for the fuel cycle was considered constant. For the hydrogen vehicles this assumption can be justified by that the hydrogen already is assumed being produced using renewable energy. For the electric vehicles however, the emission intensity for the electricity is assumed to follow the scenario 1 (NO) evolution described in S2.1.

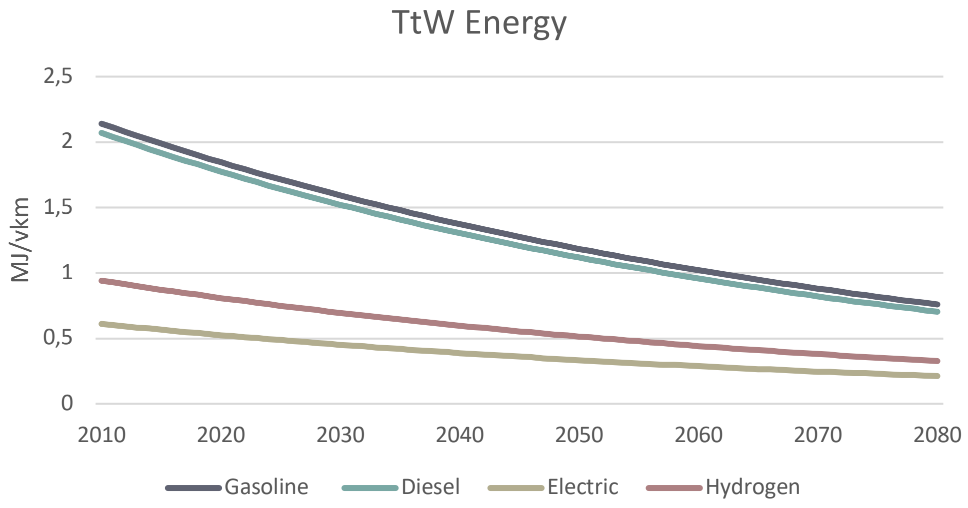


Figure 13 Improvements in TtW energy 2010 to 2080

Table 15 shows the WtW emissions per passenger-km for the different means of transport in snapshots for 2020, 2040, 2060 and 2080.

Table 17 WtW emissions snapshots (g CO2-eq/pkm)

	Personal vehicle				Bus			Light Rail
year	Gasoline	Diesel	Electric	Hydrogen	Diesel	Electric	Hydrogen	Electric
2020	126,10	127,04	3,10	5,93	65,46	1,70	3,27	4,57
2040	93,77	93,33	1,50	4,38	48,09	0,82	2,42	2,20
2060	69,74	68,57	0,81	3,24	35,33	0,45	1,79	1,20
2080	51,86	50,37	0,60	2,39	25,96	0,33	1,32	0,88

S7. Open Spaces

S7.1 Dimensions of the Road

Figure 14 is from a study performed by Birgisdóttir et al. [50] and describes the dimensions of the road used to estimate the amounts of each of the materials included in the open spaces sub-elements. The wide road (1) is assumed to be equal to the one in the figure, while the narrow road (2) is assumed to be have the same dimensions, but without the shoulders and the bicycle lanes. The sidewalks and the parking lots are identical to the bicycle lanes in dimensions.

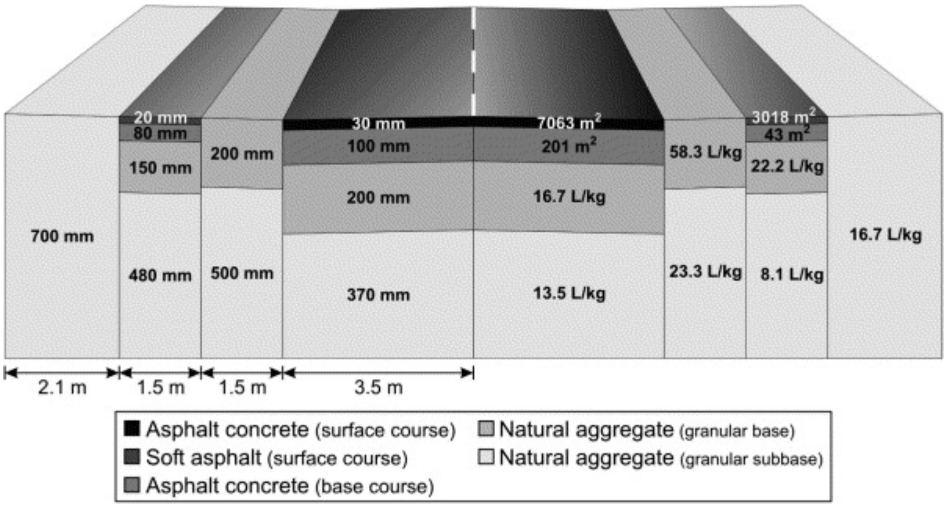


Figure 14 Dimensions and materials included in the roads (from Birgisdóttir et al. [50])

S7.2 Materials included in the Open Spaces

Table 18 Material open spaces (initial, pre-use stage)

Open Space category	Open Space Component	Material	Amount/m	Unit	GWP /unit		Type of reference	Specification	ESL
1. Road (wide)									
1.1 Lane	Surface course	Asphalt gravel concrete	0,32	ton	51,15	kgCO2-eq/ton	EPD	Agb 11. Asfalt (slitelag), 2,5t/m3	20
	Base course	Asphalt gravel	1,05	ton	48,76	kgCO2-eq/ton	EPD	Ag 16. Asfalt (bærelag)	40
	Granular base	Crushed stone construction aggregate products	2,38	ton	2,08	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	3,63	ton	1,74	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
1.2 Reserve	Granular base	Crushed stone construction aggregate products	1,02	ton	2,08	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	2,55	ton	1,74	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
1.3 Bicycle lane	Surface course	Asphalt gravel concrete	0,09	ton	51,15	kgCO2-eq/ton	EPD	Agb 11. Asfalt (slitelag), 2,5t/m3	20
	Base course	Asphalt gravel	0,36	ton	48,76	kgCO2-eq/ton	EPD	Ag 16. Asfalt (bærelag)	40
	Granular base	Crushed stone construction aggregate products	0,77	ton	2,08	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	2,02	ton	1,74	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
1.4 Shoulder	Granular subbase	Crushed stone construction aggregate products	4,12	ton	1,74	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
2. Road (narrow)									
2.1 Lane	Surface course	Asphalt gravel concrete	0,32	ton	51,15	kgCO2-eq/ton	EPD	Agb 11. Asfalt (slitelag), 2,5t/m3	20
	Base course	Asphalt gravel	1,05	ton	48,76	kgCO2-eq/ton	EPD	Ag 16. Asfalt (bærelag)	40
	Granular base	Crushed stone construction aggregate products	2,38	ton	2,08	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	3,63	ton	1,74	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
2.4 Shoulder	Granular subbase	Crushed stone construction aggregate products	4,12	ton	1,74	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
3. Sidewalk									
3.1 Lane	Surface course	Asphalt gravel concrete	0,09	ton	51,15	kgCO2-eq/ton	EPD	Agb 11. Asfalt (slitelag), 2,5t/m3	20
	Base course	Asphalt gravel	0,36	ton	48,76	kgCO2-eq/ton	EPD	Ag 16. Asfalt (bærelag)	40
	Granular base	Crushed stone construction aggregate products	0,77	ton	2,08	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	2,02	ton	1,74	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60
4. Parking									
4.1 Parking surface	Surface course	Asphalt gravel concrete	0,05	ton	51,15	kgCO2-eq/ton	EPD	Agb 11. Asfalt (slitelag), 2,5t/m3	20
	Base course	Asphalt gravel	0,15	ton	48,76	kgCO2-eq/ton	EPD	Ag 16. Asfalt (bærelag)	40
	Granular base	Crushed stone construction aggregate products	0,34	ton	2,08	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 1	60
	Granular subbase	Crushed stone construction aggregate products	0,52	ton	1,74	kgCO2-eq/ton	EPD	Franzefoss, Crushing state 0	60

S7.3 Number of Hours with Need for Public Lighting ZVB

The number of hours the public lighting units are turned on during a year is found based on data from Bergen [72], see Table 19.

Table 19 Number of hours with darkness (included twilight) in December and June

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

S8. Networks

S8.1 District Heating Network in Bergen

The concession area of the district heating system in Bergen is represented in Figure 15. The red dot marks the location of Ådland, where Zero Village Bergen is situated.

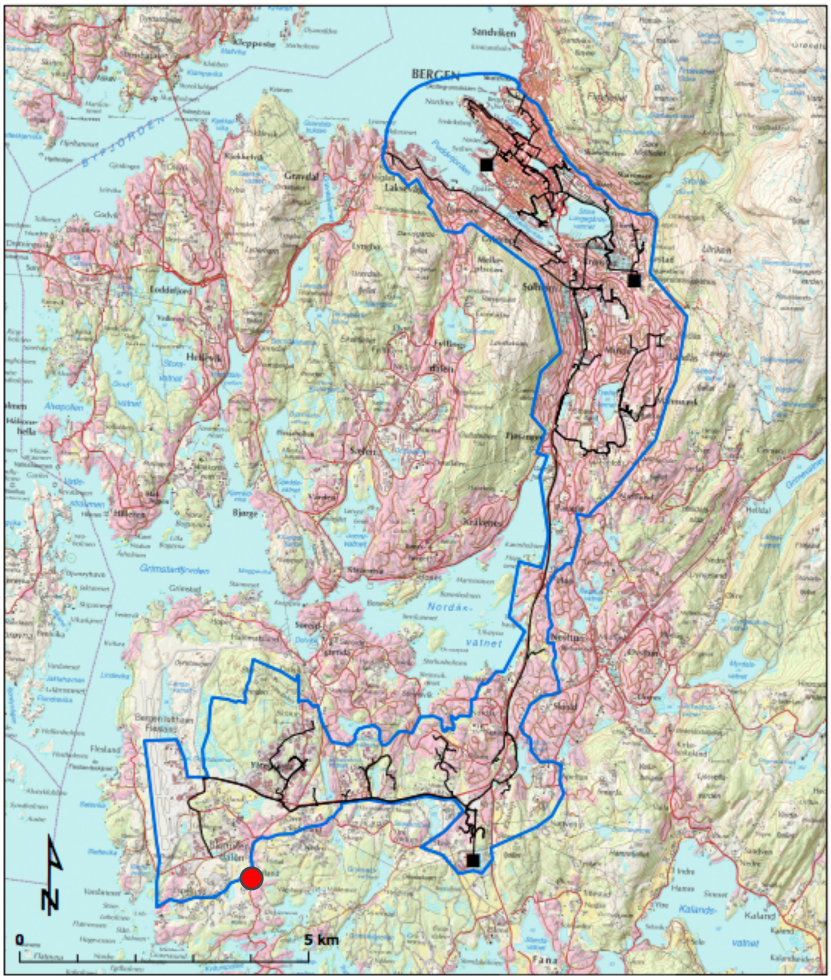


Figure 15 District heating system in Bergen [73]

S8.2 Materials included in the District Heating Network

Table 20 Materials included in the networks element

Network part	Network component	Material	Amount		GWP		Type of reference	Specification	ESL
Main grid	District heating pipes	Steel	58500	kg	1,71	kgCO2-eq/kg	Ecoinvent	steel, low-alloyed/market for steel, low-alloyed/GLO/kg	20
		Foamed polyurethane	10300	kg	4,32	kgCO2-eq/kg	Ecoinvent	polyurethane, rigid foam/polyurethane production, rigid foam/RER/kg	20
		HDPE	11750	kg	1,93	kgCO2-eq/kg	Ecoinvent	polyethylene, high density, granulate/polyethylene production, high density, granulate/RER/kg	20
	Pump	Stainless steel	15,1	kg	4,99	kgCO2-eq/kWh	Ecoinvent	steel, chromium steel 18/8, hot rolled/steel production, chromium steel 18/8, hot rolled/RER/kg	10
		Cast iron	136	kg	1,64	kgCO2-eq/kg	Ecoinvent	cast iron/cast iron production/RER/kg	10

In order to find the intensities per material represented Table 20, Ecoinvent database 3.2 was used. In the study by Oliver-Solà et al. [51] however, version 1.2 was used. Table 21 shows the assumed equivalent processes/products in version 3.2. To find the intensities (kg CO2-eq/fu) the ReCiPe Midpoint (H) method was used.

Table 21 The materials used for the district heat network in [51] and in the present study

Used in [51] (Ecoinvent 1.2)	Used in the present study (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

S9. On-site Energy

S9.1 Emissions embodied in PV

Table 22 Materials included in on-site energy

Material	Amount	Unit	GWP/unit		Type of reference	Specification	ESL
PV panel	22045	m2	280,05	kgCO2-eq/m2	Ecoinvent	photovoltaic panel, single-Si wafer/photovoltaic panel production, single-Si wafer/RER/m2	30

S10. Results

S10.1 Total Emissions by Element and Life Cycle Stage

Table 23 Results, total emissions over lifetime by element and life cycle stage (tonne CO_2-eq)

Element	Product stage A1-A3	Replacements (B4)	Energy use in operation (B6)	Total
Buildings	20709,8	4272,7	35729,7	60712,3
Mobility		29462,0	17522,7	46984,7
Open spaces	952,9	601,5	544,3	2098,7
Networks	167,7	395,9		563,6
On-site energy	6173,7	3086,9	-2895,8	6364,8
Total	28004,1	37819,0	50900,9	116724,0

Table 24 Results, total emissions over lifetime by element and life cycle stage. Percentage.

Element	Product stage A1-A3	Replacements (B4)	Energy use in operation (B6)	Total
Buildings	18 %	4 %	31 %	52 %
Mobility	0 %	25 %	15 %	40 %
Open spaces	1 %	1 %	0 %	2 %
Networks	0 %	0 %	0 %	0 %
On-site energy	5 %	3 %	-2 %	5 %
Total	24 %	32 %	44 %	100 %

S10.2 Mobility – Emissions associated with Replacements

Table 25 Emissions associated with replacement of vehicles by sub-element and year (kg CO2-eq)

	Personal vehicles			**Buses**			**Light rail**	
Year	ICEVs	BEVs	FCEVs	ICEVs	BEVs	FCEVs	Electric	Total
2020	267283	75856	53	10190	226	142	4583	358332
2021	251395	100717	482	9684	579	463	4583	367902
2022	235506	125578	912	9179	931	784	4583	377473
2023	219617	150439	1342	8673	1283	1105	4583	387043
2024	203729	175300	1772	8168	1635	1426	4583	396613
2025	187840	200161	2202	7663	1987	1747	4583	406183
2026	170842	225697	3407	6952	2439	2228	4583	416148
2027	153843	251233	4611	6242	2891	2709	4583	426113
2028	136844	276768	5816	5531	3343	3191	4583	436078
2029	119846	302304	7021	4821	3795	3672	4583	446043
2030	102847	327840	8226	4111	4248	4153	4583	456008
2031	91319	344403	9573	3616	4520	4517	4583	462532
2032	79790	360967	10919	3122	4793	4881	4583	469056
2033	68262	377531	12265	2628	5066	5245	4583	475581
2034	56733	394095	13612	2134	5338	5609	4583	482105
2035	45205	410659	14958	1640	5611	5973	4583	488630
2036	39621	418027	16070	1447	5755	6089	4583	491592
2037	34036	425395	17182	1254	5899	6205	4583	494555
2038	28452	432763	18293	1061	6043	6321	4583	497517
2039	22868	440132	19405	868	6188	6437	4583	500480
2040	17284	447500	20517	675	6332	6553	4583	503442
2041	15137	449747	21355	585	6413	6597	4583	504416
2042	12989	451994	22194	496	6493	6640	4583	505390
2043	10842	454241	23032	407	6574	6684	4583	506363
2044	8695	456488	23871	317	6655	6728	4583	507337
2045	6548	458735	24709	228	6736	6772	4583	508311
2046	5733	458267	25955	208	6756	6780	4583	508281
2047	4917	457799	27200	188	6776	6788	4583	508251
2048	4102	457331	28445	168	6796	6797	4583	508222
2049	3287	456863	29690	148	6816	6805	4583	508192
2050	2471	456395	30935	128	6836	6813	4583	508162
2051	1656	455983	32141	108	6857	6821	4583	508149
2052	841	455571	33347	88	6877	6830	4583	508136
2053	97	455045	34553	68	6897	6838	4583	508081
2054	0	453481	35759	48	6917	6846	4583	507634
2055	0	451762	36964	28	6937	6855	4583	507129
2056	0	450041	38171	23	6934	6863	4583	506616
2057	0	448321	39378	17	6932	6871	4583	506102
2058	0	446601	40584	11	6929	6879	4583	505588
2059	0	444881	41791	6	6926	6888	4583	505074
2060	0	443161	42997	0	6924	6896	4583	504561
2061	0	441441	44204	0	6912	6904	4583	504044
2062	0	439721	45410	0	6900	6913	4583	503526
2063	0	438000	46617	0	6888	6921	4583	503009
2064	0	436280	47824	0	6876	6929	4583	502492
2065	0	434560	49030	0	6864	6937	4583	501975
2066	0	432840	50237	0	6853	6946	4583	501458
2067	0	431120	51443	0	6841	6954	4583	500941
2068	0	429400	52650	0	6829	6962	4583	500424
2069	0	427679	53856	0	6817	6971	4583	499907
2070	0	425959	55063	0	6805	6979	4583	499389
2071	0	424239	56270	0	6793	6987	4583	498872
2072	0	422519	57476	0	6782	6995	4583	498355
2073	0	420799	58683	0	6770	7004	4583	497838
2074	0	419079	59889	0	6758	7012	4583	497321
2075	0	417359	61096	0	6746	7020	4583	496804
2076	0	415638	62302	0	6734	7029	4583	496287
2077	0	413918	63509	0	6722	7037	4583	495770
2078	0	412198	64716	0	6711	7045	4583	495252
2079	0	410478	65922	0	6699	7053	4583	494735
2080	0	408758	67129	0	6687	7062	4583	494218
	2610477	23828056	1935034	102930	350870	355102	279568	29462037

S10.3 Mobility – Operation

Table 26 Emissions associated with operation of mobility by sub-element and year (kg CO_2-eq)

year	Personal Vehicle - Gasoline	Personal Vehicle - Diesel	Personal Vehicle - Battery	Personal Vehcle - Hydrogen	Bus - Diesel	Bus - Battery	Bus - Hydrogen	Light Rail	Total
2020	559,4	816,9	6,0	0,0	378,0	0,1	0,2	18,2	1778,8
2021	509,1	766,0	7,7	0,1	353,7	0,3	0,8	17,6	1655,3
2022	460,0	716,5	9,2	0,2	330,2	0,5	1,3	17,0	1535,0
2023	412,4	668,4	10,7	0,3	307,2	0,7	1,7	16,4	1417,8
2024	366,0	621,5	12,1	0,4	284,9	0,9	2,2	15,9	1303,8
2025	320,9	575,9	13,3	0,4	263,2	1,0	2,7	15,4	1192,8
2026	286,1	517,2	14,5	0,7	235,1	1,2	3,4	14,9	1073,0
2027	252,3	460,2	15,6	0,9	207,9	1,4	4,0	14,3	956,6
2028	219,5	404,7	16,6	1,1	181,4	1,5	4,7	13,9	843,4
2029	187,5	350,9	17,5	1,3	155,7	1,7	5,3	13,4	733,3
2030	156,5	298,6	18,3	1,5	130,7	1,8	5,9	12,9	626,2
2031	136,0	262,0	18,5	1,7	113,2	1,9	6,3	12,4	552,1
2032	116,1	226,4	18,7	2,0	96,3	1,9	6,7	12,0	480,1
2033	96,8	191,8	18,9	2,2	79,8	1,9	7,1	11,6	410,0
2034	78,0	158,2	19,0	2,4	63,8	2,0	7,5	11,1	341,9
2035	59,7	125,7	19,0	2,6	48,3	2,0	7,8	10,7	275,8
2036	51,0	109,0	18,6	2,7	41,9	2,0	7,9	10,3	243,4
2037	42,5	92,8	18,2	2,8	35,8	1,9	7,9	9,9	212,0
2038	34,3	77,1	17,8	3,0	29,8	1,9	7,9	9,5	181,4
2039	26,3	61,9	17,4	3,1	24,0	1,9	8,0	9,1	151,7
2040	18,6	47,1	17,0	3,3	18,4	1,8	8,0	8,8	122,9
2041	15,9	40,8	16,4	3,3	15,7	1,8	7,9	8,4	110,1
2042	13,3	34,6	15,8	3,4	13,1	1,7	7,8	8,0	97,8
2043	10,7	28,6	15,2	3,5	10,6	1,7	7,8	7,7	85,7
2044	8,3	22,8	14,6	3,6	8,1	1,6	7,7	7,4	74,1
2045	5,8	17,2	14,0	3,6	5,8	1,6	7,6	7,0	62,7
2046	5,0	14,9	13,3	3,8	5,2	1,5	7,5	6,7	57,9
2047	4,2	12,6	12,7	3,9	4,6	1,4	7,4	6,4	53,3
2048	3,4	10,4	12,1	4,0	4,0	1,4	7,3	6,1	48,8
2049	2,6	8,2	11,5	4,1	3,5	1,3	7,2	5,8	44,4
2050	1,9	6,2	10,9	4,2	3,0	1,3	7,1	5,5	40,1
2051	1,2	4,2	10,8	4,3	2,5	1,2	7,0	5,4	36,6
2052	0,5	2,2	10,6	4,4	2,0	1,2	6,9	5,4	33,2
2053	0,0	0,3	10,4	4,5	1,5	1,2	6,8	5,3	30,1
2054	0,0	0,0	10,2	4,6	1,1	1,2	6,8	5,2	29,0
2055	0,0	0,0	10,0	4,7	0,6	1,2	6,7	5,1	28,3
2056	0,0	0,0	9,8	4,7	0,5	1,2	6,6	5,1	27,9
2057	0,0	0,0	9,7	4,8	0,4	1,1	6,5	5,0	27,4
2058	0,0	0,0	9,5	4,9	0,2	1,1	6,4	4,9	27,0
2059	0,0	0,0	9,3	5,0	0,1	1,1	6,3	4,8	26,6
2060	0,0	0,0	9,1	5,0	0,0	1,1	6,2	4,8	26,2
2061	0,0	0,0	9,0	5,1	0,0	1,1	6,1	4,7	25,9
2062	0,0	0,0	8,8	5,2	0,0	1,1	6,0	4,6	25,7
2063	0,0	0,0	8,6	5,2	0,0	1,0	6,0	4,5	25,4
2064	0,0	0,0	8,5	5,3	0,0	1,0	5,9	4,5	25,1
2065	0,0	0,0	8,3	5,3	0,0	1,0	5,8	4,4	24,8
2066	0,0	0,0	8,1	5,4	0,0	1,0	5,7	4,3	24,6
2067	0,0	0,0	8,0	5,4	0,0	1,0	5,6	4,3	24,3
2068	0,0	0,0	7,8	5,5	0,0	1,0	5,6	4,2	24,0
2069	0,0	0,0	7,7	5,5	0,0	0,9	5,5	4,2	23,8
2070	0,0	0,0	7,5	5,5	0,0	0,9	5,4	4,1	23,5
2071	0,0	0,0	7,4	5,6	0,0	0,9	5,3	4,0	23,2
2072	0,0	0,0	7,3	5,6	0,0	0,9	5,3	4,0	23,0
2073	0,0	0,0	7,1	5,6	0,0	0,9	5,2	3,9	22,7
2074	0,0	0,0	7,0	5,7	0,0	0,9	5,1	3,8	22,5
2075	0,0	0,0	6,8	5,7	0,0	0,8	5,0	3,8	22,2
2076	0,0	0,0	6,7	5,7	0,0	0,8	5,0	3,7	22,0
2077	0,0	0,0	6,6	5,8	0,0	0,8	4,9	3,7	21,7
2078	0,0	0,0	6,5	5,8	0,0	0,8	4,8	3,6	21,5
2079	0,0	0,0	6,3	5,8	0,0	0,8	4,8	3,6	21,3
2080	0,0	0,0	6,2	5,8	0,0	0,8	4,7	3,5	21,0
	4461,8	7751,9	710,8	227,4	3461,6	75,8	356,6	476,8	17522,7

S10.4 Result Details Buildings

Table 27 Total emissions from buildings operation by type of energy use (tonne CO_2-eq)

	Thermal	**El**	**Total**
total over lifetime	32 522	3 207	35 730
	91%	9%	100%

Table 28 Emissions associated with product stage (A1-A3) by type of building (kg CO_2-eq/m^2/y)

	Emissions per area (kg CO_2-eq/m^2/year)
Residential buildings	3.77
Non-residential buildings	3.57
Parking garage	1.08

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