Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

LIFE-CYCLE ASSESSMENT METHODOLOGY TO ASSESS ZERO EMISSION NEIGHBOURHOOD CONCEPT

A NOVEL MODEL

ZEN REPORT No. 12 – 2019

C Lausselet, V Borgnes, L Ager-Wick Ellingsen, A Hammer Strømman and H Brattebø | NTNU

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Life-cycle assessment methodology to assess Zero Emission Neighbourhood concept

A novel model

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Preface

Acknowledgements

This report has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The authors gratefully acknowledge the support from the Research Council of Norway, the Norwegian University of Science and Technology (NTNU), SINTEF, the municipalities of Oslo, Bergen, Trondheim, Bodø, Bærum, Elverum and Steinkjer, Trøndelag county, Norwegian Directorate for Public Construction and Property Management, Norwegian Water Resources and Energy Directorate, Norwegian Building Authority, ByBo, Elverum Tomteselskap, TOBB, Snøhetta, Tegn_3 , Asplan Viak, Multiconsult, Sweco, Civitas, FutureBuilt, Hunton, Moelven, Norcem, Skanska, GK, Caverion, Nord-Trøndelag Elektrisitetsverk (NTE), Smart Grid Services Cluster, Statkraft Varme, Energy Norway and Norsk Fjernvarme.

The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities

The ZEN Research Centre develops solutions for future buildings and neighbourhoods with no greenhouse gas emissions and thereby contributes to a low carbon society.

Researchers, municipalities, industry and governmental organizations work together in the ZEN Research Centre in order to plan, develop and run neighbourhoods with zero greenhouse gas emissions. The ZEN Centre has nine pilot projects spread over all of Norway that encompass an area of more than 1 million m^2 and more than 30 000 inhabitants in total.

In order to achieve its high ambitions, the Centre will, together with its partners:

- Develop neighbourhood design and planning instruments while integrating science-based knowledge on greenhouse gas emissions;
- Create new business models, roles, and services that address the lack of flexibility towards markets and catalyze the development of innovations for a broader public use; This includes studies of political instruments and market design;
- Create cost effective and resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies;
- Develop technologies and solutions for the design and operation of energy flexible neighbourhoods;
- Develop a decision-support tool for optimizing local energy systems and their interaction with the larger system;
- Create and manage a series of neighbourhood-scale living labs, which will act as innovation hubs and a testing ground for the solutions developed in the ZEN Research Centre. The pilot projects are Furuset in Oslo, Fornebu in Bærum, Sluppen and Campus NTNU in Trondheim, an NRK-site in Steinkjer, Ydalir in Elverum, Campus Evenstad, NyBy Bodø, and Zero Village Bergen.

The ZEN Research Centre will last eight years (2017-2024), and the budget is approximately NOK 380 million, funded by the Research Council of Norway, the research partners NTNU and SINTEF, and the user partners from the private and public sector. The Norwegian University of Science and Technology (NTNU) is the host and leads the Centre together with SINTEF.

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Abstract

Buildings represent a critical piece of a low-carbon future and their long lifetime necessitates urgent adoption of state-of-the-art performance standards to avoid significant lock-in risk. So far, life-cycle assessment (LCA) studies have assessed buildings (conventional and Zero Emission Building (ZEB)), mobility and energy systems mainly individually. Yet, these elements are closely linked, and to assess the nexus of housing, mobility, and energy associated with human settlements by aiming for Zero Emission Neighborhoods (ZENs) gives a unique chance to contribute to climate change mitigation. ZEBs and ZENs are likely to be critical components in a future climate change mitigation policy.

This study addresses the challenge of how to use LCA when implementing such a policy, in line also with the introduction of the more stringent Energy Performance of Buildings Directive in 2010 that requires new buildings to be built with nearly ZEB standards by the end of 2020. The specific aims of this report are fourfold. First, to develop and apply an LCA model to support the evaluation of ZEN design concepts with respect to greenhouse gas (GHG) emissions and other potential environmental impacts. Second, to clarify important contributing factors as well as revealing criticalities and sensitivities for GHG emission reductions and environmental performance of such ZEN design concepts. Third, to establish a model basis for other LCA studies on a neighbourhood scale, in terms of a high-quality modelling approach regarding consistency, transparency, and flexibility. Fourth, to apply our model on two cases; a hypothetical case of a neighbourhood consisting of single family house of passive house standard and on Zero Emission Village Bergen (ZVB).

For the first case, the neighbourhood consists of single-family houses built according to the Norwegian passive house standard. We designed four scenarios where we tested the impact of the house sizes, household size, energy used and produced in the buildings, and mobility patterns. Also, we ran our scenarios with different levels of decarbonization of the electricity mix over a time period of 60 years.

Our results show the importance of the operational phases of both building and mobility at year 1, and its decline over time induced by the decarbonization of the electricity mix. In year 60, embodied emissions are then responsible for the majority of the emissions when the electricity mix is decarbonized. The most important contributing factors have been identified as the operational phases of the Building and Mobility subsystems when the carbon intensity of the electricity mix is high, and as the embodied emissions in materials when the carbon intensity of the electricity mix becomes low. A reduction of the following factors has been identified as beneficial for the overall GHG emissions of a ZEN: (1) building floor area by house either/or by inhabitants, (2) passenger cars travel distances by household, which can be achieved by several means; e.g. commuting with public transport and/or by carpooling initiatives, (3) energy use in the buildings, which is reduced by the use of the passive house standard, and (4) carbon intensity of the electricity mix.

The second case – ZVB - consists of residential and non-residential buildings, with a total area of 91 891 m^2; 695 dwellings and 1 340 inhabitants. 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) resulted in a total of 117 kton CO_2-eq over the lifetime. This equals 1.5 ton CO_2-eq/capita/year and 21.2 kg CO_2-eq/m^2/year, referring to heated building floor area and as yearly average emissions over the 60 year analysis period. The emissions are distributed between the elements and life cycle stages. Buildings stand for the majority of the total 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. A sensitivity analysis showed the emission intensity for electricity and the assumption of allocating

emissions from waste incineration to the waste management system rather than to district heat to have a considerable impact on the results. If an EU28+NO electricity production mix is used instead of the Norwegian electricity production mix, total emissions over the 60 years analysis period will increase with 12.5%. This is despite the fact that also negative emissions from the on-site electricity production will be larger, due to the significant increase in emissions from electricity consumed in mobility. If the emissions from waste incineration is not allocated to the district heating production, the total emissions are decreased with 25.3%. Hence, this is a most critical assumption in the LCA model.

The most important contributing factors have been identified as the operational phases of the Building and Mobility subsystems when the carbon intensity of the electricity mix is high, and as the embodied emissions in materials when the carbon intensity of the electricity mix becomes low. A reduction of the following factors have been identified as beneficial for the overall GHG emissions of a ZEN: (1) building floor area by house or by inhabitants, (2) passenger cars travel distances by household, which can be achieved by several means; e.g. commuting with public transport and/or by carpooling initiatives, (3) energy use in the buildings, which is reduced by the use of the passive house standard, and (4) carbon intensity of the electricity mix.

Introducing passive house standards on buildings has the potential to drastically decrease the overall CO_2-eq emissions of a ZEB, but also of a ZEN; up to by 191% when assuming an average European electricity mix. Yet, by using a highly decarbonized electricity mix, such as is the case in Norway, the decrease is much lower, around 12%.

Also, we found the choice of the functional unit to be decisive for the conclusion of the study. When conducting LCAs on a neighbourhood scale, we thus argue for the use of a primary functional unit “per neighbourhood”, and a second “per person”. The use of a “per m^2 floor area” unit is misleading as it does not give credits for reducing the total built floor area.

All these findings demonstrate that the model is capable of long-term analyses of both homogenous and complex neighbourhoods, and provides a detailed understanding of possible future development of the different elements of the neighbourhood and their GHG emissions.

This report is a part of FME ZEN Work Package 1 Analytic framework for design and planning of zero emission neighbourhoods (ZEN). The goal for WP 1 is to develop definitions, targets and benchmarking for ZEN, based on customized indicators and quantitative and qualitative data. Additionally, an LCA methodology for energy and emissions at neighbourhood scale is developed, as well as a citizen-centred architectural and urban toolbox for design and planning of ZEN.

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1 Introduction

A reduction in global greenhouse gas (GHG) emissions can slow down the global warming rate, but a stabilization of the temperature can only occur if GHG emissions approach zero (Myhre, Shindell et al. 2013). Globally, buildings account for 32% of total final energy use, 19% of energy-related GHG emissions, and approximately one third of black carbon emissions. Transport is responsible for 14% of the energy-related GHG emissions, with road transport as the main contributor (Victor, Zhou et al. 2014). The nexus of housing, mobility, and energy associated with human settlements is assessed by widening the system boundary from a building to a neighbourhood scale, and aiming for Zero Emission Neighborhoods (ZENs) gives a unique chance to contribute to climate change mitigation.

Buildings represent a critical piece of a low-carbon future, and their long lifetime necessitates urgent adoption of state-of-the-art performance standards to avoid significant lock-in risk, both for new and renovated buildings (Lucon, Ürge-Vorsatz et al. 2014, Sandberg, Sartori et al. 2016). The European Parliament has addressed this urgency by the introduction of the Energy Performance of Buildings Directive (EPBD); all new buildings within the European Union shall be nearly Zero Energy Buildings (nZEB) by the end of 2020 (European Commission 2010). In Norway, the new standard NS 3720:2018 "Method for greenhouse gas calculations for buildings" addresses the nexus and includes transport in the use stage as one module in calculations of GHG emissions from buildings.

Life-cycle assessment (LCA) is a standardized method frequently used to give an overview of how various types of environmental impacts accumulate over the different life-cycle phases and elements of a system. It provides a basis for identifying environmental bottlenecks of specific technologies and for comparing a set of alternative scenarios with respect to environmental impacts (Finnveden, Hauschild et al. 2009, Hellweg and Canals 2014). Within the last decade, LCA has been used extensively to evaluate the environmental performance of buildings, energy systems, and mobility, and the life-cycle perspective should be well-integrated into decision-making processes (Lucon, Ürge-Vorsatz et al. 2014). However, this is yet hardly the case in practical planning of neighbourhoods today, and few LCA studies are published on the neighbourhood scale, despite the growing interest for such in modern urban planning.

1.1 LCA on buildings

Buildings are complex systems; they incorporate multiple construction materials and processes that can come from different industries and producers. LCA is a useful tool to address the tradeoffs between different building life-cycle phases and building components and to help identifying the most effective opportunities for reducing impacts (Soares, Bastos et al. 2017). LCA has been applied widely to buildings the last past 15 years with the following trends. The life-cycle GHG emissions of conventional buildings are dominated by high energy consumption in the use phase with a share of about 80% of life-cycle GHG emissions (Sartori and Hestnes 2007, Blengini and Di Carlo 2010). Embodied GHG emissions are somewhat higher for low-energy buildings and passive house designs, mainly due to the higher use of insulation materials and the drastically reduced energy demand (Houlihan Wiberg, Georges et al. 2014); they can account from 50% (Dahlstrøm, Sørnes et al. 2012) to 70% (Kristjansdottir, Heeren et al. 2017, Wiik, Fufa et al. 2018) of the total emissions in such building designs. Overall, the magnitude of total emissions is driven by the embodied emissions in construction materials on one hand and by the carbon intensity of the consumed energy carriers on the other (Dahlstrøm, Sørnes et al. 2012, Heeren, Mutel et al. 2015). In a country like Norway, electricity is the main energy carrier to serve energy demand in buildings, and the national power grid is highly dominated by hydropower with relatively small shares of import and export. Hence, the electricity mix has a very low carbon intensity (18 g CO_2 eq./kWh), and the construction phase will play a greater relative role. In this situation, the passive house design can appear less favorable than buildings designed according to the current building codes, while it would be more favorable in situations where the carbon intensity of energy carriers in the supply system increases and the use-phase more clearly dominates the life-cycle. This would be the case also in Norway, when assuming marginal technologies in the supply system, and a Nordic average electricity mix (190 g CO_2 eq./kWh) or an European average electricity mix.

A study by Moschetti, Mazzarella et al. (2015) assessed the definition of reference values for building sustainable parameters by assessing several impact categories. For all building types (single-family house, terraced house, multi-family building and apartment block), they found the use phase to constitute the clear majority of the life-cycle impacts. Yet, the construction phase dominates the global cost and the impact categories ozone depletion and marine eutrophication. Kristjansdottir, Heeren et al. (2017) compared GHG emissions of different low-energy and zero-emission designs of Norwegian single-family houses and found embodied emissions to represent 60– 75% of the life-cycle climate change impacts, confirming the importance of materials in strategies for zero emission buildings (ZEBs) in Norway. Houlihan Wiberg, Georges et al. (2014) aimed at investigating the possibility to achieve a net ZEB (nZEB) by balancing emissions from the energy used for operation and embodied emissions from materials with those from on-site renewable electricity generation in Norway. Their study confirmed the dominating role of embodied emission in a total life-cycle perspective, and that emission gains from surplus on-site PV electricity production exported to the grid will not be sufficient to compensate for the embodied emissions. Heeren, Mutel et al. (2015) conducted a study to identify drivers of the environmental impact of wood and massive wood residential and office buildings in a central European climate. The parameters ranking highest in influencing climate change were found to be the electricity mix, the ventilation rate, the heating system and the construction materials. As ZEBs will represent a major part of the life cycle inventory in a ZEN concept, it is obvious that LCA literature on the ZEB level should strongly inform LCA modelling on the ZEN level.

1.2 LCA on urban scale

Robust and accurate methods have been developed to quantify the built environment at both individual and urban scales (Anderson, Wulfhorst et al. 2015). Despite the clear overlap of the developed methods, case studies largely remain confined in their scale, the main difference between the two scales being the analysis boundary. By confining the analysis to an individual building level, the building is isolated from its context, and treated as a stand-alone object. Typically, the environmental performance of a building located in a dense urban center may differ from a building located in an automobile-dependent suburb. Mobility needs and the corresponding environmental impacts are closely related to building location (Bastos, Batterman et al. 2016, Stephan and Stephan 2016) and the individual buildings must be set in a holistic impact analysis to capture these effects. Saner, Heeren et al. (2013) assessed the housing and mobility demands of individual households for a small village in Switzerland and found a mean value per year of 4.30 ton CO_2 eq./pers. Harter, Weiler et al. (2017) developed a roadmap for the modernization of a block of buildings in a city and found refurbishment of the block to be more favorable than demolition and reconstruction for primary energy demand and GHG emissions, as long as the structural condition of the building allows it. Stephan, Crawford et al. (2013) conducted a multi-scale life-cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia, and found shares in the range of 15-39% for embodied emissions in buildings and infrastructure, 29-52% for operation of buildings and 24-46% for transport, in accordance with Stephan, Crawford et al. (2012).

Lotteau, Loubet et al. (2015) conducted a review on the built environment at the neighbourhood scale based on four aspects: (1) buildings, (2) open space (roads, green spaces) (3) networks (water, telecommunication, sewage, heating and electricity distribution) and (4) mobility. They reported the following main findings: (1) the type of assessed neighbourhoods was mainly residential, (2) the numbers of inhabitants per neighbourhood ranged from 650 to almost 152,000, (3) the functional units were multiple - per inhabitant, per km^2 neighbourhood, per m^2 of living space/pers., per m^2 energy reference area, per m^2 floor area or per neighbourhood, (4) the residential density ranged from 370 pers./km^2 to 27,000 pers./km^2, (5) transports requirement for daily mobility was based on local or regional average empirical data or statistical models, (6) the overall emission results varied from 0.4 - 5.4 to kton CO_2 eq./neighbourhood/year, 0.6-8.6 ton CO_2 eq./pers./year, 3.6-7.8 ton CO_2 eq./m^2 neighbourhood/year and 10.8-123.8 kg CO2 eq./ m^2 floor area/year.

Mastrucci, Marvuglia et al. (2017) reported another review article on selected bottom-up LCA studies from urban to transnational scale. They highlighted that the potential for improvements in the aggregated building stock can be found in the refinement of the archetypes and building-by-building techniques, and in the integration of Geographical Information System and stock dynamic models. Their review showed buildings to rank highest with respect to emission contributions, closely followed by mobility, depending on the neighbourhood. The operational phase was in general predominant, but in the case of a low-energy neighbourhood, the share of emission contributions from the construction phase and the operational phase became similar in the overall picture.

1.3 Aim and scope

The objective of this work is to contribute to expedient use of LCA of neighbourhoods at an early planning stage, by focusing on important contributors and critical factors to environmental impacts. Through development of a model tested on two cases; a hypothetical case of a neighbourhood consisting of single family house of the passive house standard and on Zero Emission Village Bergen (ZVB). The following research questions are to be answered:

– What are the dominant physical elements and life cycle stages contributing to the total GHG emissions on a neighbourhood scale?
– What are the critical factors that affect these contributions and what are their sensitivity?
– What are the strengths and weaknesses of the model that is developed? Can it provide useful inputs to the early stage planning process of a ZEN project?

2 Methodology

2.1 From Zero Emission Buildings to Zero Emission Neighbourhoods

A method based on different ZEB ambition levels has been developed in the context of the Norwegian ZEB Centre (Mamo Fufa, Dahl Schlanbusch et al. 2016). The focus was on nZEBs, which are buildings where the required low amount of delivered energy to a significant extent is covered by energy generation from on-site or local renewable sources, including electricity and heat produced inside or nearby the neighbourhood boundary such as by heat pumps, biomass co-heat and power (CHP) or photovoltaic (PV) technologies. Higher ambition levels would include more life cycle modules from the production, operation and end-of-life phases of the building, according to the standard NS 3720:2018 (Standard Norge 2018). The goal is to compensate for the total life-cycle GHG emission measured in CO_2 eq. by producing more on-site energy than needed for self-consumption. The energy locally produced is based on renewable sources, and the emission credits gained by feeding the grid with this extra produced energy lead to emission credits by using a marginal approach.

As a follow-up of the ZEB Centre, the ZEN research defines a neighbourhood as a group of interconnected buildings with associated infrastructure, located within a confined geographical area. A ZEN aims to reduce its direct and indirect GHG emissions towards zero over the analysis period, in line with a chosen ambition level with respect to which life cycle modules, buildings and infrastructure elements to include (Wiik, Mamo Fufa et al. 2018).

2.2 LCA for Zero Emission Neighbourhood

The proposed LCA model uses a modular approach based on the following subsystems; 1) buildings, 2) mobility and 3) energy systems. The life-cycle phases of the different subsystems are based on the ZEB definition, and the ambition level undertaken in this study is "ZEB-OM", where O refers to all operational energy, equipment and appliances (B6 in figure S1 in the supplementary material), and M to the embodied emissions from the materials production (A1-A3 in figure S1) and replacement (B1-B5 in figure S1). Hence, this ambition level means that the neighbourhood aims to be zero emission when including all life cycle modules A1-A3 from production of materials and B1-B8 from operation from all subsystems, as shown in figure S1 in the supplementary materials. We have thus emission contributions from Building O, Building M, Mobility O, Mobility M and energy systems for on-site energy production (photovoltaic panels (PV)), as shown in figure 1. Material efficiency improvement over time is included and further described in the sections below.

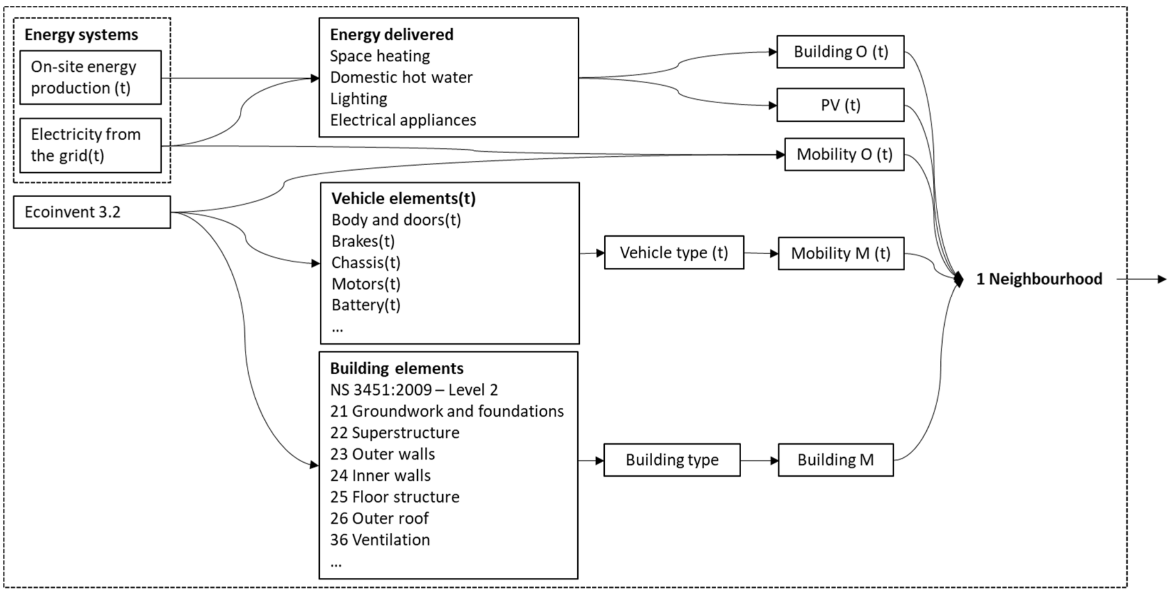

Figure 1: Subsystem approach to assess Zero Emission Neighbourhoods (ZENs)

Ecoinvent v3.2 (Ecoinvent Centre 2015) is used for background data. ReciPe v1.12 (with a hierarchist perspective) is chosen for the midpoint category global warming potential (GWP100) (Goedkoop, Heijungs et al. 2009). Other impacts categories are not included in the present article, as the focus in the

ZEN Centre is GHG emissions. Arda, a Matlab routine based program developed at NTNU (Majeau-Bettez and Strømman 2016) is used for the LCA calculations.

The total life-cycle GHG emissions of the neighbourhood is the sum of the total GHG emissions, Building M, Building O, Mobility O, Mobility M and energy systems for on-site energy production (photovoltaic panels (PV)) as shown in equation (1) and further described in Appendix A.

$$GHG_{neighbourhood} = B_M + B_O + PV + M_M + M_O \quad (1)$$

2.3 Case study I – Hypothetical case

2.3.1 Scenarios development

The neighbourhood consists of 20 single-family houses with the passive house standard, and the functional unit is "to build and refurbish 20 single family houses with the passive house standard over a 60 years period, deliver energy for heating and electric appliances, and provide mobility by passenger cars for all the inhabitants."

The functional unit can be fulfilled by different means; (1) the house can have different sizes, (2) the size of the household can vary, (3) heating requirements can vary between households based on individual comfort standards or individual commitments, (4) the mobility habits depend on the inhabitants' preferences and access to other transport modes, which will also change over time, and (5) the rate of electric car penetration will vary over time.

We developed four scenarios to explore the different and likely development of the neighbourhood over a service lifetime of 60 years. The scenarios are developed using the subsystem approach presented above, and key parameters are presented in table 1.

Scenario 1 (S1) is the baseline, based on average values and statistics. Scenario 2 (S2) is the higher range where both the energy delivered and the driving distances are increased. Scenario 3 (S3) includes technological improvements in both the buildings and the vehicle fleet by faster penetration of electric vehicles. Scenario 4 (S4) includes technological improvements as well as positive inhabitant behavior, such as smaller living space per inhabitant and shorter driving distances.
All scenarios are assumed to include 20 houses, but the total heated floor area and the number of inhabitants per house vary. The total heated floor area is 3200 m^2 for S1 and S2 and 2400 m^2 for S3 and S4. The number of inhabitants is 80 for S1, S2 and S3 and 100 for S4.

Table 1: Key parameters in the scenarios

		Scenarios			
		S1	**S2**	**S3**	**S4**
	Units	**Baseline**	**Higher range**	**Techno**	**S3 + behavior**
Buildings					
Heated floor area	m^2	160	160	120	120
# houses	house	20	20	20	20
Inhabitants	pers./house	4	4	4	5
Energy					
Heat supply		Heat pump + Solar collector			
Electricity supply		Solar PV panels - "all electric"			
Energy delivered[a]					
Space heating	kWh/m^2	31	49	19	19
Domestic hot water	kWh/m^2	4	4	4	3
Fans and pumps	kWh/m^2	3	3	3	3
Lighting	kWh/m^2	8	10	8	6
Electrical appliances	kWh/m^2	15	17	15	13
Total	kWh/m^2	**61**	**83**	**49**	**44**
PV electricity bonus	kWh/m^2	53	53	104	104
Net energy demand	**kWh/m^2**	**8**	**30**	**-55**	**-60**
Mobility					
# Cars	car/house	1,2	2	1,2	0,6
El car scenarios [b]		Baseline	Baseline	Ultra low scenario	Ultra low scenario
Driving distance	km/car.year	12480[c]	13728	12480[c]	8736

[a] based on Kristjansdottir, Houlihan-Wiberg et al. (2018), [b] from Fridstrøm and Østli (2016), [c] from Statistics Norway (2017)

2.3.2 Sensitivity analysis

The neighbourhood includes buildings of the passive energy standards, and a sensitivity analysis is conducted to test the scenarios against a national average energy use of 180 kWh/m^2.

The future carbon intensity of the grid electricity mix is expected to decrease, but future levels are uncertain. To cope with this uncertainty, we have run our scenarios with three different decarbonization scenarios; the 2°C, 4°C and 6°C degree Energy Technology Perspectives scenarios from IEA (2015) for the European Union (EU). In addition, we use a typical Norwegian electricity production mix of 18 g CO2 eq./kWh as specified in NS3720 (Standard Norge 2018).

2.4 Case study II – Zero Emission Village Bergen

The building stock in ZVB consists of residential and non-residential buildings, with a total area of 91 891 m^2 (Sartori, Merlet et al. 2016), see Table 1. There will be 695 dwellings and 1 340 inhabitants. The area for parking is estimated based on information about the number of parking spots.

Table 2: Building stock and areas in ZVB (Sartori et al. 2016).

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

2.4.1 Energy use in operation

The energy use in the buildings is based on work performed by the ZEB Centre (Sartori, Merlet et al. 2016) where the buildings planned in the ZVB project were already estimated by IDA-ICI simulations. This gave a total thermal load of 3 283 MWh and a total electric load of 3 257 MWh per year. Figure 3 shows the yearly load in kWh/m^2 for the different residential building types.

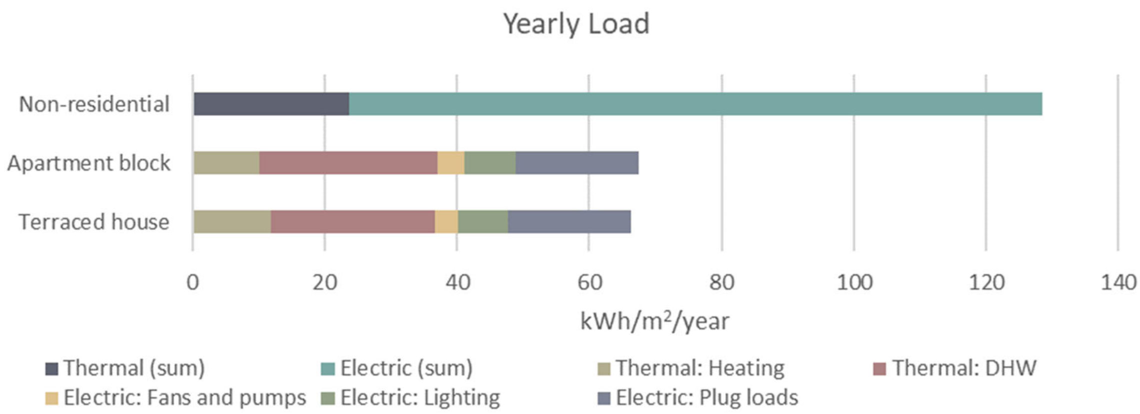

Figure 2: Yearly energy load of residential buildings in ZVB (in kWh/m^2) (adopted from Sartori et al. 2016)

It is assumed that the loads are constant for all future 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 emission intensity of the district heat is calculated based on the emission factors 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.

2.4.2 Mobility

Three means of transport are considered for the mobility in ZVB; personal vehicle, bus and light rail. Due to the planning for extensive public transport and cycling facilities (Massarutto 2015), the distance travelled with each type is based on statistics on travel habits for people with very good access to public transport.

2.4.3 On-site Energy

The on-site energy in ZVB consists of photovoltaic (PV) panels placed on the building roofs with a total PV area of 22 045 m^2. Emissions associated with the production of PV panels are found using Ecoinvent

3.2. The yearly PV generation is estimated to be 2 941 MWh (Sartori, Merlet et al. 2016). The negative emissions associated with this generation are calculated using the emissions intensity for electricity (scenario 1).

2.4.4 Sensitivity Analysis

All input parameters selected for sensitivity analysis were given a relative change in input value of +25%, and the sensitivity ratio (*SR*) was measured using Equation 6.

$$SR = \frac{\Delta R/R_0}{\Delta P/P_0} \tag{2}$$

$\Delta P/P_0$ represents the relative change in the input parameter, and $\Delta R/R_0$ denotes the relative change in results. Hence, parameters with a high *SR* value have a high influence on 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 alternative emission intensity for district heat was estimated to be 16.1 g CO_2-eq/kWh, assuming significantly less emissions from the district heat compared to 163.2 g CO_2-eq/kWh as used in base case.

3 Results

3.1 Case study I – Hypothetical case

3.1.1 Yearly results

The results are presented for the four scenarios and for the four different energy mixes used by time steps of one year in figures 3-6. The legends in the figures means the following: 'Mobility O' gives emissions from fuel and electricity from vehicles used for mobility, i.e. well-to-wheel emissions from fuel consumption in combustion engine vehicles and upstream emissions from consumption of electricity in ELVs. These emissions decrease rapidly during the first 10-30 years due to the fact that ELVs replace combustion engine vehicles. 'Mobility M' gives emissions embodied in materials in vehicles used for mobility. 'PV' gives emissions from the use of photovoltaic technologies. 'Building O' gives emissions from operation of buildings, and 'Building M' gives emissions embodied in materials consumed in buildings.

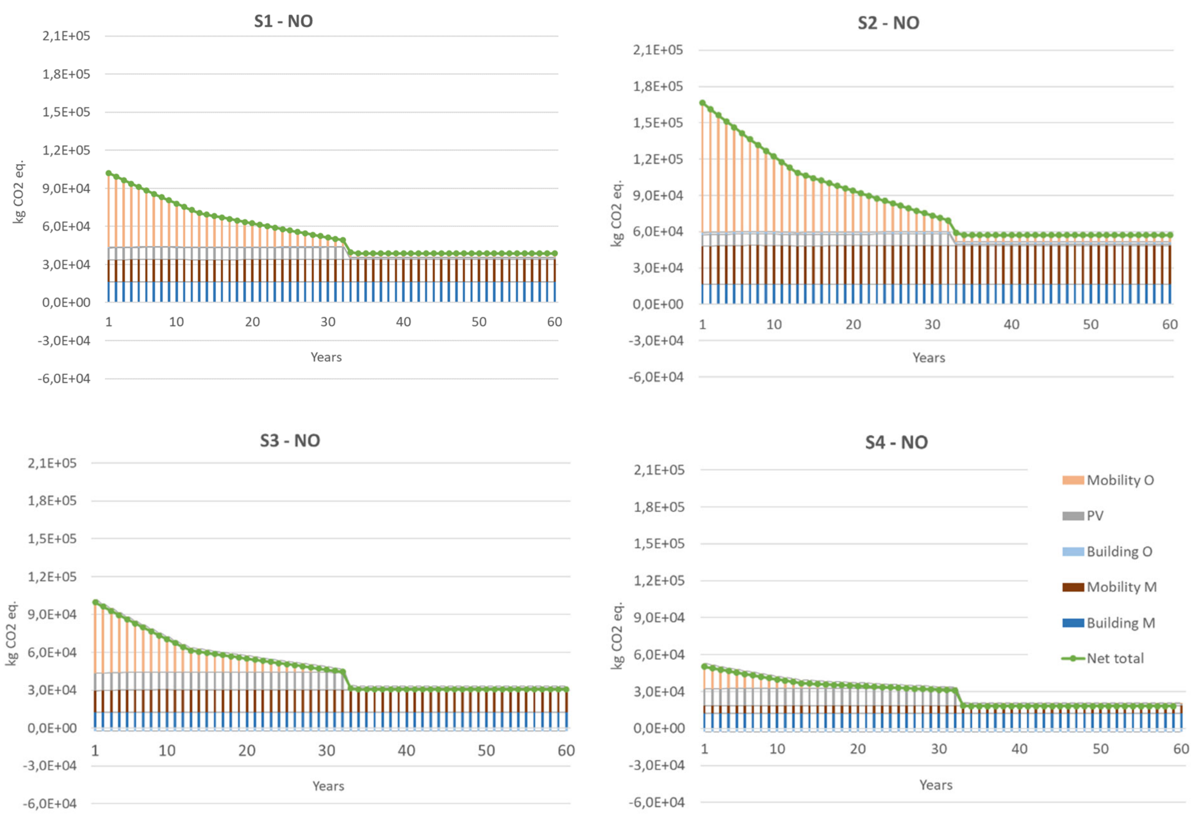

Figure 3: Absolute GHG emissions for the whole neighbourhood and for each scenario, by time steps of one year for the Norwegian electricity scenario

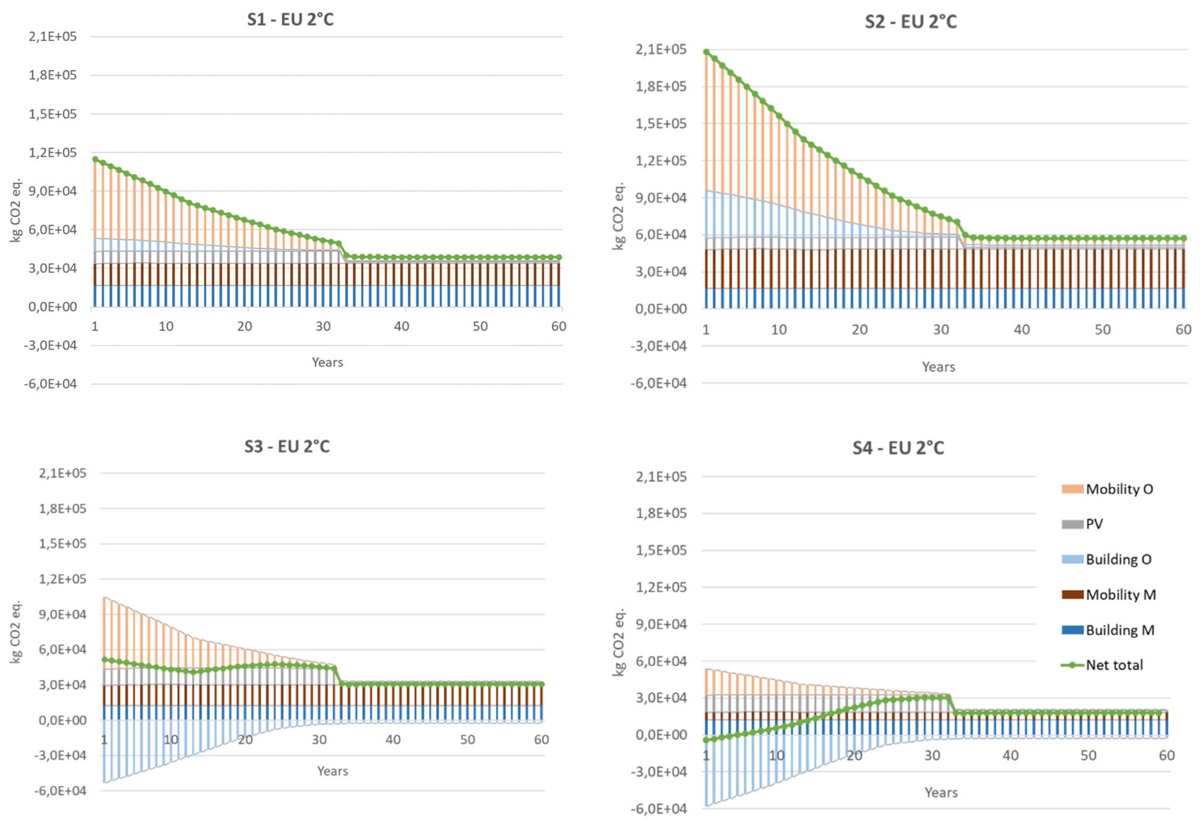

Figure 4: Absolute GHG emissions for the whole neighbourhood and for each scenario, by time steps of one year for the 2°C decarbonization scenario

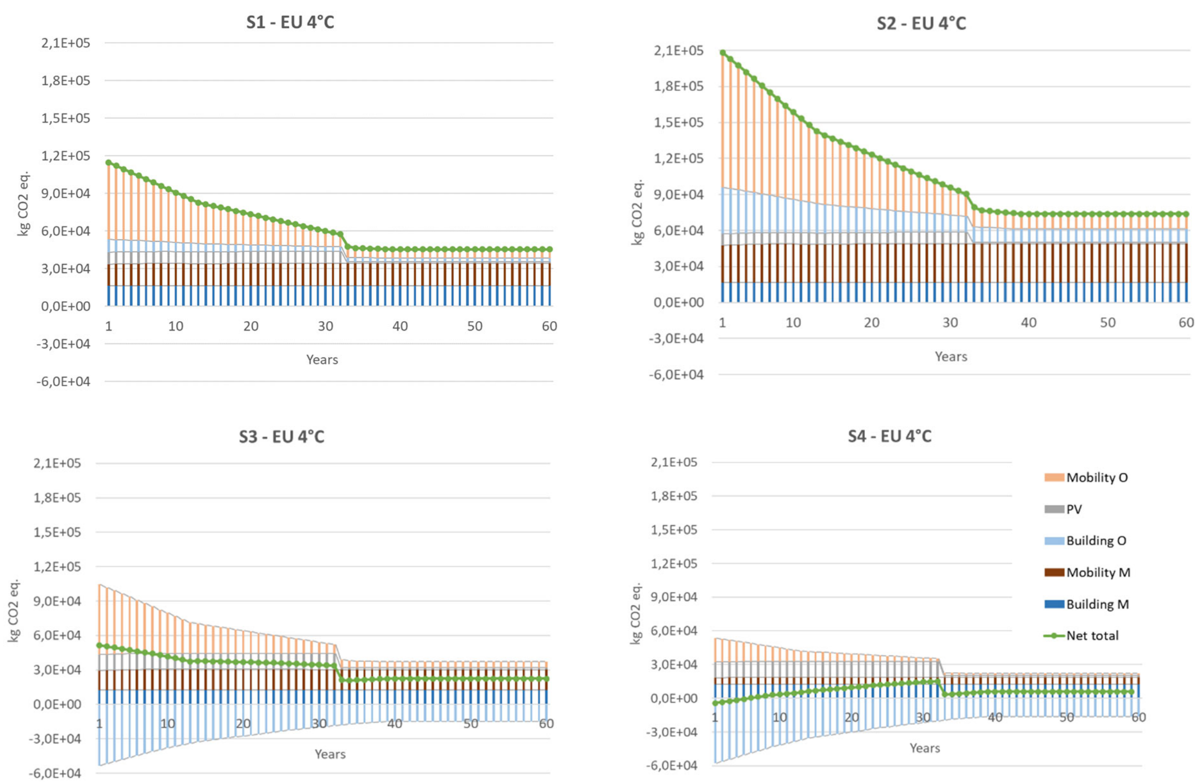

Figure 5: Absolute GHG emissions for the whole neighbourhood and for each scenario, by time steps of one year for the 4°C decarbonization scenario

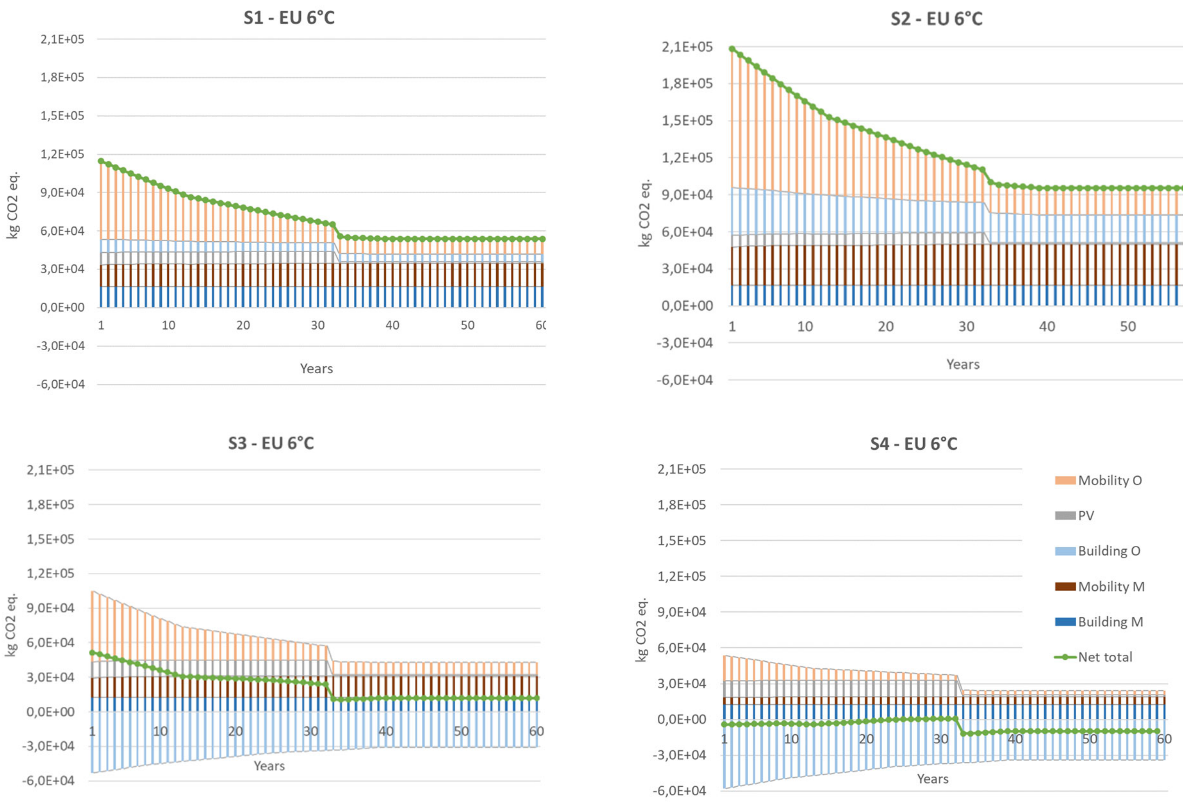

Figure 6: Absolute GHG emissions for the whole neighbourhood and for each scenario, by time steps of one year for the 6°C decarbonization scenario

The yearly results per neighbourhood vary inside one order of magnitude; with results in the range of 20.7 - 208 ton CO_2 eq./year. The lowest range is found for S4-NO from year 2051(34) to 2077(60) while the highest range is found for S2- EU 2°C, S2- EU 4°C and S2- EU 6°C in year 2018 (1). Looking at the net total, the lowest value is a decrease by 60%.

In year 1, GHG emissions are dominated by the operational phases (i.e. Building O, Mobility O and PV) for all the scenarios. In year 60, the opposite is the case when the electricity mix is decarbonized (NO, 2°C scenario, 4°C scenario) and not the case when the carbon intensity of the el-mix is still high, as is the case when using the 6°C scenario.

Emissions embodied in building materials (i.e. Building M) are constant over time as the peak emissions of construction in year 1 and replacements of some building parts at the respective years are distributed over the neighbourhood lifetime.

Emissions embodied in mobility materials (Mobility M) increase slightly over time for all the scenarios; by 5% for S1 and S2 and by 6% for S3 and S4. The increase is marginally higher for S3 and S4 due to the faster penetration of electric vehicles in the future vehicle fleet. The technology assets in the vehicles and battery production improve over time and compensate for a larger increase of Mobility M driven by an increased share of BEV over time.

The emissions related to photovoltaic panels (PV) are divided in two periods, according to the lifetime of PV technologies. Because the same PV technology is used for all scenarios in a given year, the decrease is the same; i.e. -88% from year 1 to year 31. Yet, the magnitude of PV emissions varies across the scenarios depending on the installed area, which is largest for S3 and S4.

The impact of the operational phase of the buildings Building O is negative for S3 and S4, where the on-site production exceeds the building energy needs, and positive for S1 and S2, where the electricity is imported from the grid. The magnitude of Building O depends on the two following factors: the net energy demand of the buildings and the carbon intensity of the grid electricity mix. When using the Norwegian electricity mix, the impact of Building O is marginal on a yearly basis for all the scenarios. When using an electricity mix with a higher carbon intensity, as is the case in year 1 for all the other electricity mix used, Building O becomes more visible when either the energy delivered is in the higher range (S2), or when the electricity sent to the grid is significant (S3 and S4). The magnitude of Building O over time depends of the decarbonization rate over time; Building O becomes marginal for the 2°C scenario, moderate for the 4°C scenario and significant for the 6°C scenario.

Because the share of BEVs increases in the vehicle fleet over time, the pattern of impacts from Mobility O follows the pattern of Building O, and its intensity depends on the level of decarbonization of the electricity mix, with a difference in trends for S3 and S4.

When following the ZEB Centre GHG emission compensation procedure, only some yearly emissions of scenario 4 are compensated by the operational phase of the buildings (i.e. Building O). This is the case when both the carbon intensity of the electricity mix is high and the energy use is low, as it is the case in years 2018(1)-2022(5) for S4-EU 2°C and S4-EU 4°C and all the years for S4-EU 6°C.

3.1.2 Results over the lifetime

The results from figures 2-5 are now aggregated over the whole lifetime and presented in figure 7 for the whole neighbourhood, per m^2 heated floor area and per inhabitant.

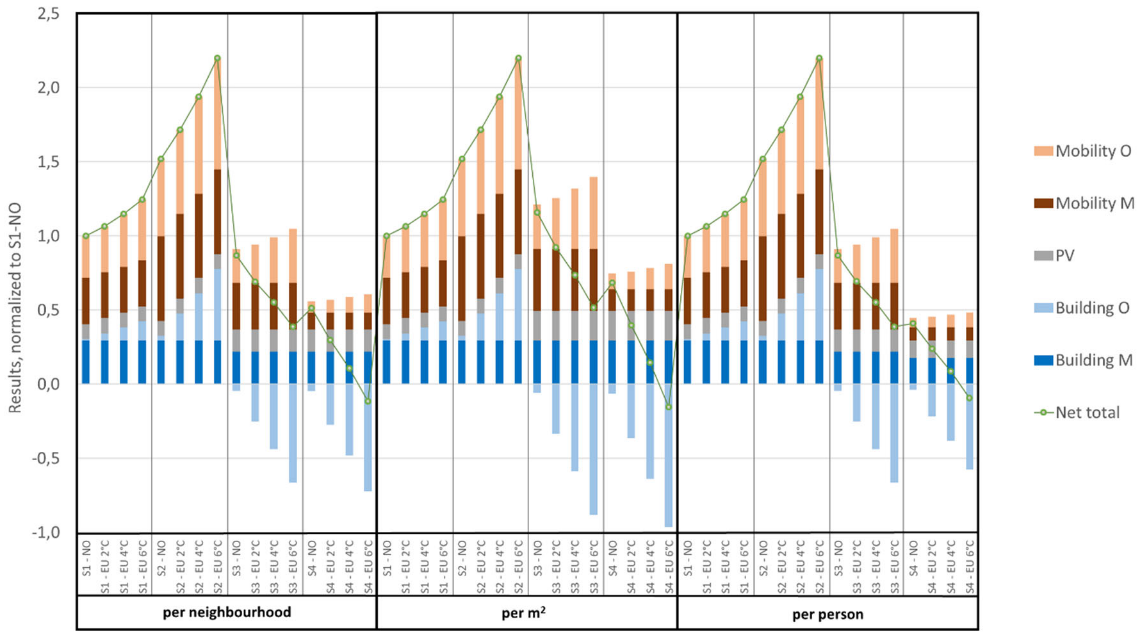

Figure 7: CO_2 eq. emissions, per neighbourhood, m^2 heated floor area and inhabitant, normalized to S1

Without considering the emission credits from Building O, the contributions from Building O to the total vary from 1% to 22%, from Building M 13% to 40%, from PV 5% to 27%, from Mobility O 14% to 35%, and from Mobility M 18% to 38%.

For all scenarios (S1-S4) we see that the contribution to the total of Building M and Mobility M decreases with an increase in carbon intensity of the electricity mix. For instance, from S1 - NO to S1 - EU 6°C, the share of Building M decreases from 30% to 25% and Mobility M decreases from 31% to 25%. The opposite is true for the operational phases, where the contribution of Building O increases from 1% to 10% while the Mobility O increases from 28% to 33%.

Comparing scenarios using the same functional unit leads to a different conclusion. While comparing S1 to S2 leads to the same conclusion, comparing S1 to S3 leads to a different conclusion. With the functional units of "per neighbourhood" and "per person", passing from S1 to S3 leads to decreases of -9% to -20%, while it leads to an increase of 15% to 21% for a "per m^2" functional unit. The conclusion is the same when comparing S1 to S4, but the magnitude is different; from -44% to -64% per neighbourhood, from -25% to -44% per m^2, and from -55% to 68% per person. Comparing S1 to S4 leads to the same conclusion across the functional units, but the effect of reducing living space is better captured with a per person functional unit.

When considering the Net totals and taking into account the benefits gained from Building O over the lifetime, the totals are either constant when Building O is positive (S1-S2) or decreased when the excess on-site produced is sent to the grid (S3-S4). The emissions credits lead to a decrease in the total ranging from -4% to -96%.

3.1.3 Sensitivity analysis

All the scenarios are run once again with a final average national delivered energy use of 180 kWh/m^2 and presented in figure 7. The total emission results from figure 6 are increased by 5% (S4-NO) up to 191% (S1 - EU 6°C).

The on-site energy production, which was calculated to meet ZEB or nZEB energy standards, is now all used internally, and Building O becomes positive across all the scenarios. The share of impacts from Building O increases and passes from 1% to 22% in figure 3 to 6% to 65% (S1 - EU 6°C) in figure 7.

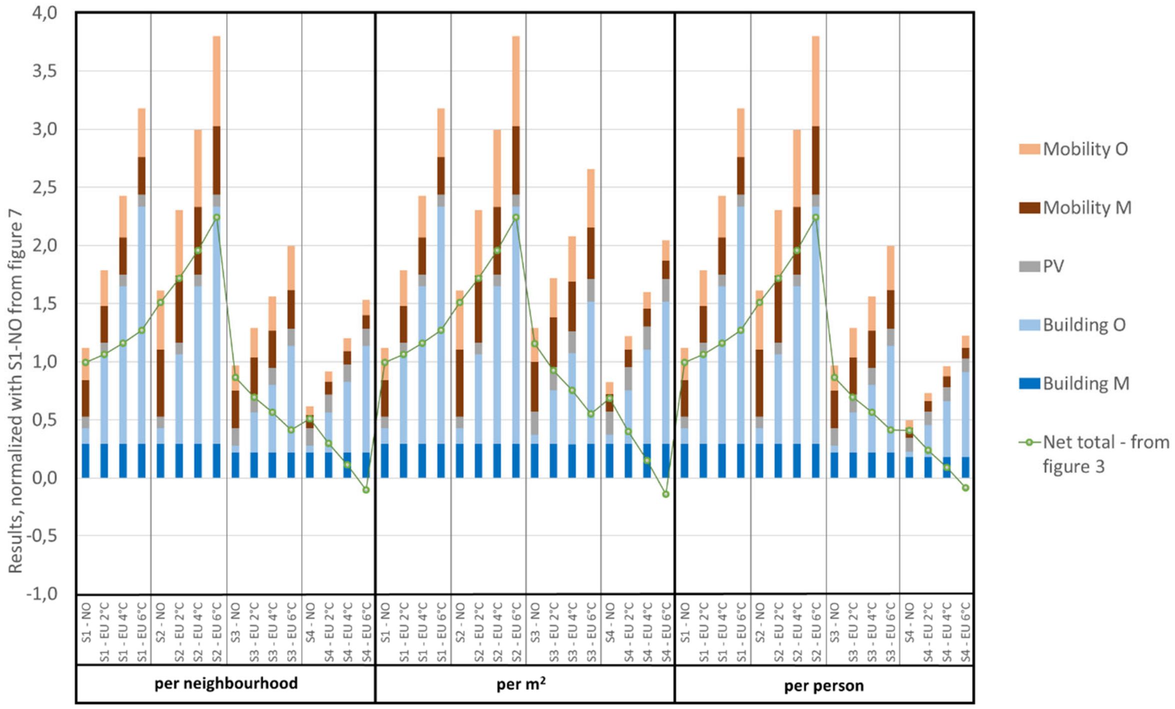

Figure 8: Total GHG emission results from sensitivity analysis, normalized to S1-NO from figure 7

3.2 Case study II – Zero Emission Village Bergen

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) resulted in a total of 117 kton CO_2-eq over the lifetime. This equals 1.5 ton CO_2-eq/capita/year and 21.2 kg CO_2-eq/m^2/year, referring to the heated building floor area and as yearly average emissions over the 60 year analysis period. The emissions are distributed between the elements and life cycle stages as shown in figure 8. The Building element accounts for the majority of the emissions, amounting to approximately 52% of the total lifetime emissions. Mobility is the second greatest contributing element, responsible for 40% of the total emissions. The emissions from the Networks and Open spaces together constitute only 2.3%. Furthermore, it is worth noting the relatively low level of negative emissions from On-site energy production that, using our assumptions, are actually less than the emissions associated with producing the PV panels.

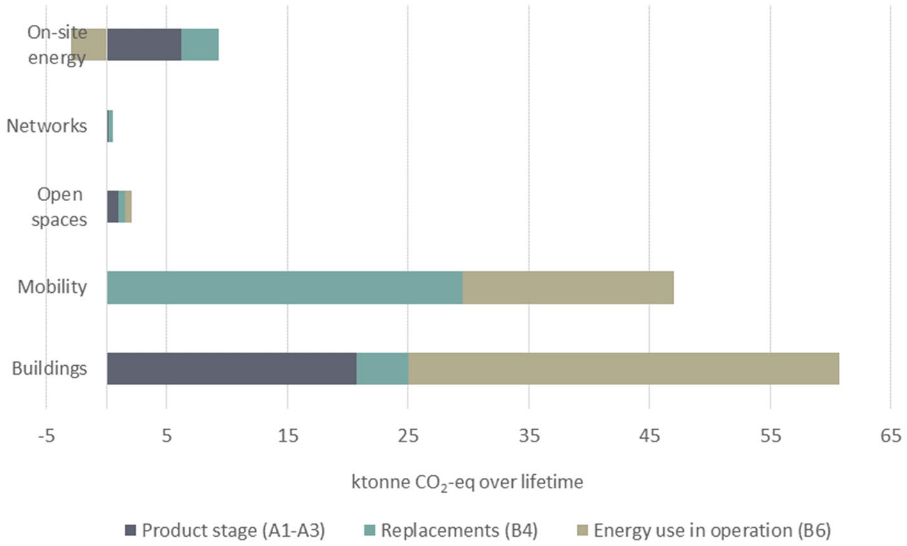

Figure 9: Total emissions for ZVB, distributed between elements and life cycle stages

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 does not include the product stage of vehicles in the mobility element; recall that this is merged with the replacement stage of vehicles, due to the shorter service life of vehicles.

The operational emissions are distributed over the years as presented in figure 10. Emissions embodied in materials that are used for 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 replacement 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 - and hydrogen based - electrical vehicles. 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.

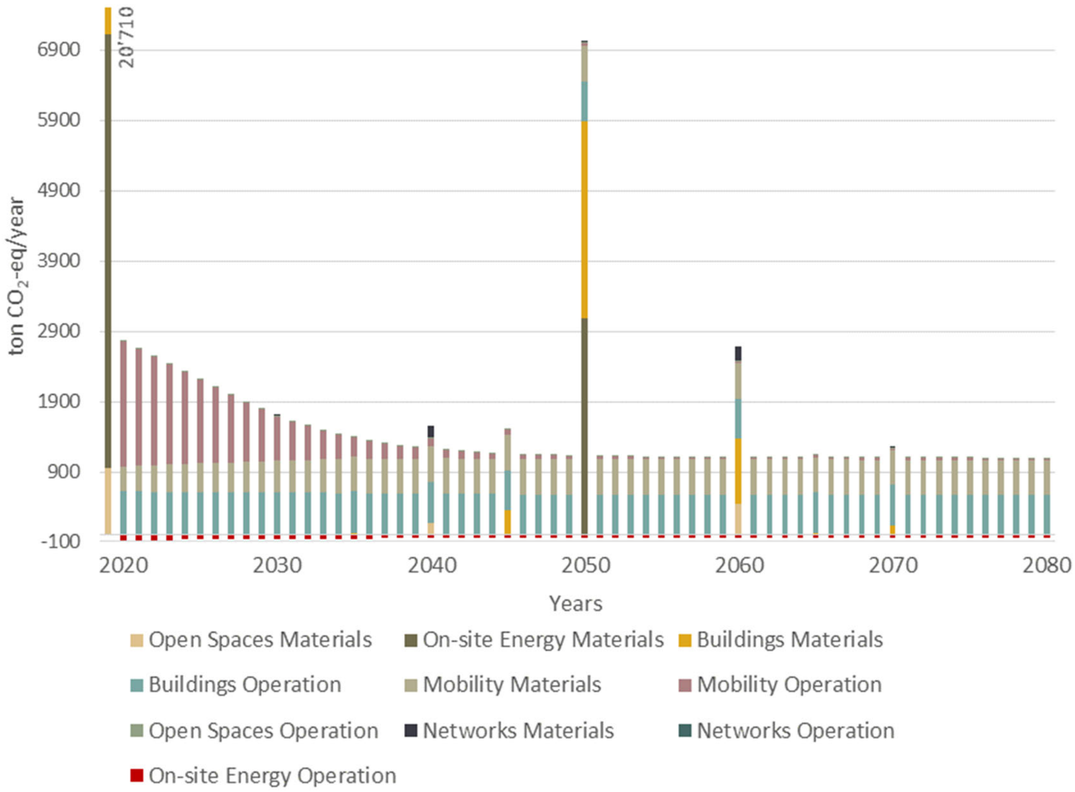

Figure 10: Total use stage emissions by year, distributed by element and life cycle stage

For buildings, 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.

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 load.

Table 3 Results of sensitivity analyses for 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 10 shows the change relative to the base case for each of the parameters and also for the two fundamental assumptions that are shown to have a considerable impact on the results, namely the emission intensity for electricity and the assumption of allocating emissions from waste incineration to the waste management system rather than to district heat production. If scenario 2 (see section 2.1) is used, referring to the EU28+NO electricity production mix instead of the Norwegian electricity production mix, total emissions over the 60 years analysis period increases with 12.5%. This is despite the fact that negative emissions from the on-site electricity production will also be greater, due to the significant increase in emissions from electricity consumed in mobility. If the emissions from waste incineration are not allocated to the district heating production, total emissions decrease by 25.3%. Hence, this is a most critical assumption in the LCA model.

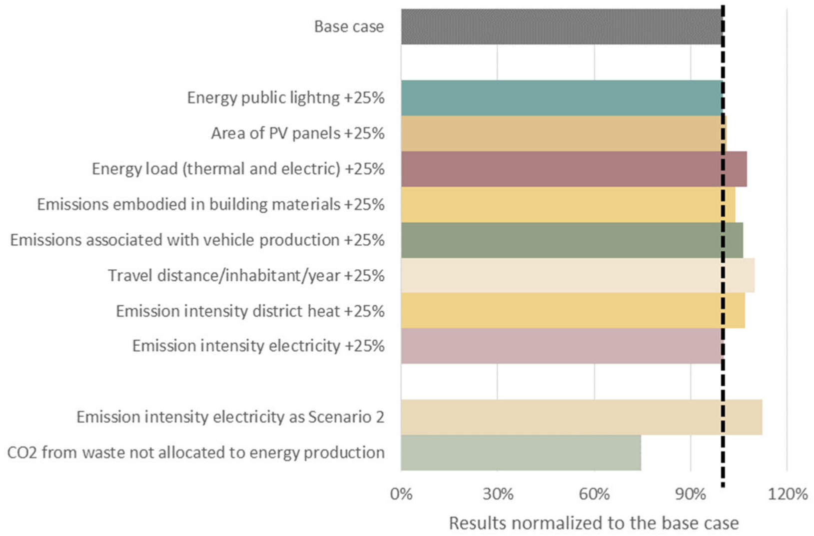

Figure 11: Results of sensitivity analyses relative to the base case

4 Discussion

Our LCA model yields results similar to those reported in the literature. Yet, our study has the particularity to assess houses with a ZEB or nZEB standard, where the energy consumed in the operational phase of the house is drastically reduced. Bastos, Batterman et al. (2016) found user transportation to account for the largest share of emissions, with 51-57%, which is in accordance with our results. On the other hand, Stephan, Crawford et al. (2013) found the shares of the GHG emissions related to the production and replacement of building materials and infrastructures to constitute 16-22% of the total, shares related to operational emissions to 42-43% of the total, and shares related to transport requirements to 36-41% of the total. The higher share of the building operational emissions is due to the lower energy standard of the houses. Yet, by assuming higher energy standards, as is the case in our study, the share of operational emissions decrease, and the share of mobility and embodied emissions in buildings increase in the overall picture.

4.1 Choice of functional unit

The combination of different types of functional units (absolute, spatial and per person) has been recommended in several studies (Bastos, Batterman, & Freire, 2014; Lotteau, Loubert, Pousse, Dufrasnes, & Sonnemann, 2015; Stephan et al., 2013a). In our opinion, the use of a "per neighbourhood" functional unit gives a good overview and allows to depict the main bottlenecks of the actual neighbourhood project under study, allowing to draw local strategies to reduce the environmental footprint of the given neighbourhood. Subsequently, the use of a "per m^2 building floor area" functional unit depicts the impact intensity of resource use emissions of an urban project. The further normalization with respect to number of inhabitants allows to capture social differences and life styles, or deliberate choices such as the house size, and allows for the assessment of the efficiency of use of resources and emissions of the population (Lotteau, Loubet et al. 2015).

In our opinion, the use of a fourth functional unit, that would normalize the emission results per km^2 of neighbourhood would not depict, or give credits to, technical improvements in the different modules of the neighbourhood, or to positive inhabitant behavior. Rather, it would mainly give credits to neighbourhoods with large green areas that in some instances could compensate for suboptimal material choices or user behavior when it comes to heating habits or mobility use. Also, the use of "per km^2 of neighbourhood" functional unit would enhance the rural contra urban paradigm, and could most probably disfavor urban neighbourhoods due to higher density.

In some specific cases, the use of "per m^2" or "per person" functional units leads to different conclusions. Norman, MacLean et al. (2006) found that a low-density neighborhood used around 2 to 2.5 times more energy than a high-density neighborhood on a per capita basis, but only 1 to 1.5 as much energy on a per "unit of living space" (area of building floor area) basis. Stephan, Crawford et al. (2013) found an increase of impact per km^2 when benchmarking a baseline scenario of single-family houses with a four-story apartment building, but a decrease when assessing the same scenarios per person. This was also the case when we benchmarked our scenarios S1 to S3 and found a reduction of net total over the lifetime by 24% "per neighbourhood" and "per person", but an increase by 2% when considering the results "per m^2 heated floor area".

Given these results and considerations, we argue for the use of a primary functional unit "per neighbourhood" and a secondary functional unit "per person" when conducting LCA on a neighbourhood scales. To optimize sub-systems of the neighbourhood, sub-units have to be used, such as "per km" for the different vehicle fleets, "per m^2 floor area" for the buildings, and "per specific unit" for the infrastructure elements in the neighbourhood.

4.2 Inertia in materials used in buildings versus the volatility of the energy mix

Assessing the nexus of housing, mobility, and the connected energy system in a given time frame is about combining different subsystems that evolve at very different paces of change. The pace of change of buildings is slow. Once built, the dynamic or internal pace can be assumed to be constant until the next renovation or refurbishment event takes place. Car lifetimes are much shorter than building lifetimes. While a lifetime of 50 to 100 years is often assumed in LCA of buildings, the lifetime of a car is often considered to be around 150'000 km (Ellingsen, Singh et al. 2016, Cox, Mutel et al. 2018). The development of on-site renewable energy production and demand management at a building and/or neighbourhood scale calls for a deeper understanding of the interaction between building operation and the electricity grid. We suggest that the further development of our operational modules Building O and Mobility O should go in the direction taken by Roux, Schalbart et al. (2016); i.e. hourly impacts from grid electricity should be used to account for the temporal variation in consumption, production, storage and import/export of electricity. This would offer better understanding of the temporal mismatch between demand and supply, as well as temporal emission dynamics in the electricity grid and capacity peak shaving opportunities by energy storage technologies, such as batteries or underground thermal storage at the neighbourhood scale.

4.3 Dynamic MFA to assess ZEN

Long lifetimes of building and infrastructure stocks cause path dependencies and lock-in of materials and installed energy technologies (Pauliuk and Müller 2014). On the other hand, both short lifetimes and the construction of new capacity for renewable energy technologies lead to increased material inputs (Wiebe, Bjelle et al. 2018). Also, a reduction of materials in the existing stock would most easily be achieved by the prolongation of its lifetimes as an effect of adequate maintenance (Wiedenhofer, Steinberger et al. 2015). The LCA methodology for neighbourhoods used so far only assesses new built infrastructure and buildings. The model will need further development to understand how previously built and ageing buildings in a neighbourhood are likely to change over a 60 year future period, and the implications of future renovation and demolition measures with respect to material consumption, energy use, and related emissions. Typically, dynamic segmented building stock models have proven to be powerful tools in that context. These type of models can be used for both historical analysis (Sandberg, Sartori et al. 2016) and forecasting scenarios (Sandberg, Sartori et al. 2017, Sandstad, Sandberg et al. 2018),where energy efficiency improvements of the stock through renovation rates are captured. Dynamic stock driven models can also be used to assess the introduction of nZEB policy and the renovation rate to test policy goals for emission reduction (Vásquez, Løvik et al. 2016). These models can also be combined with LCA to extend the system boundary beyond direct emissions and include embodied emissions from construction materials, construction energy and end-of-life stages (Pauliuk, Sjöstrand et al. 2013). Most importantly, such models can pinpoint the urgency of acting now (Sandberg, Sartori et al. 2017). In fact, 50% of the Norwegian dwelling stock existing in 2020 will not need a "natural" renovation before 2050, while the other 50% holds significant potentials for energy efficiency improvements due to their expected renovation cycle. Thus, renovation of old inefficient buildings, in addition to new construction with passive house standards, will be key factors to further improve the overall energy efficiency of the building stock.

4.4 Other climate forcers

Climate change is affected by a variety of forcing agents. In addition to the conventional well-mixed GHGs (or WMGHGs, such as CO_2, CH_4, N_20), human activities disturb the climate system through emissions of pollutants such as NO_x, CO, volatile organic compounds (VOCs), black carbon (BC), organic carbon (OC), and sulphur oxides (SO_x). The net climate impacts of the latter pollutants, also called near-term climate forcers, are the result of many complex opposing effects with different temporal evolutions at play. NO_x, CO, VOCs are tropospheric ozone formation precursors. BC and OC are primary aerosols, while NO_x, SO_x, NH_3 are precursors to secondary aerosols. Quantifying them is subject to uncertainties that are larger than for WMGHGs (Cherubini, Fuglestvedt et al. 2016).

BC, largely emitted through the use of fuelwood in wood stoves (Aasestad 2013) is an extremely potent climate forcing agent, with a characterization factor for global warming potential with time horizon 100 years (GWP100) reported as high as 846 (Myhre, Shindell et al. 2013). Near-term climate forcers, in addition to conventional GHGs, should thus be considered when assessing ZENs. In addition, the temporality included in this study, and thus development of GHG factors over time for the different modules, have to be further examined.

4.5 Uncertainties and limitations

Manufacturing, transport, and construction are often not fully assessed in LCA. LCAs of renewable power production, in particular, need to have wide enough system boundaries to appropriately capture these effects. The sometime low present and future GHG emission results reported in some energy studies can be the results of system boundaries that are too narrow, and these results should be handled with care (Hertwich, Gibon et al. 2015).

Decarbonizing the power sector has direct implications for other sectors (Wiebe 2018). In addition to energy efficiency improvements along the production chains, the retrofit of the power sector over time in the production chains have to be taken into account when assessing prospective scenarios. Here, we included some rough improvements in these demand-side technologies in our scenario analyses, but a more systematic analysis of potential and expected improvements in material production, manufacturing, and transport is needed. In fact, neglecting such improvements could result in an underestimation of the environmental benefit of climate mitigation policies (Hertwich, Gibon et al. 2015).

Conducting LCA on buildings requires a lot of specific data, and the use of site-specific materials such as reported in environmental products declarations (EPD) can lead to a reduction of embodied emissions in the order of magnitude of 20% (Wiik, Fufa et al. 2018).

So far, this study assumed the use of passenger cars for mobility only. Norwegians mainly use cars for private travels today, as the yearly mileage of buses represents only 2% of the yearly mileage of the private car fleet (Statistics Norway 2017). In the future, an increased use of public transport is expected, and this is relevant to potentially serve large shares of the mobility needs of a ZEN project. Hence, public transport modes have to be integrated in the mobility subsystem of the LCA model.
The user behavior was addressed by introducing factors increasing (S2) or decreasing (S4) some key variables in our scenarios. One should expect high uncertainties in how user behavior in the future will influence such variables, and more appropriate measures, such as surveys, would be beneficial to increase the accuracy and representativeness of this aspect.

5 Conclusion and outlook

We assessed the nexus of housing, mobility, and energy needs associated with human settlements by developing an LCA model to support the evaluation of ZEN design concepts with respect to GHG emissions.

The most important contributing factors have been identified as the operational phases of the Building and Mobility subsystems when the carbon intensity of the electricity mix is high, and as the embodied emissions in materials when the carbon intensity of the electricity mix becomes low. A reduction of the following factors has been identified as beneficial for the overall GHG emissions of a ZEN: (1) building floor area by house or by inhabitants, (2) passenger car travel distances by household, which can be achieved by several means; e.g. commuting with public transport and/or by carpooling, (3) energy use in the buildings, which is reduced by use of the passive house standard, and (4) carbon intensity of the electricity mix.

Introducing the passive house standard for buildings has the potential to decrease the overall impact of a ZEB but also of a ZEN drastically; up to by 191% when assuming an average European electricity mix. Yet, by using a highly decarbonized energy mix such as is the case in Norway, the decrease is much lower, around 12%.

The choice of the functional unit is crucial for the results and can lead to different conclusion when comparing scenarios. When presenting the results, we argue for the use of per neighbourhood as a primary functional unit and per person as a secondary one when conducting LCA on a neighbourhood scale. We find the use of m^2 of building floor area to be misleading as it does not give credits to reduced or optimized use of floor area. Yet, the use of emissions per m^2 is well-suited to assess the subsystem Building M of the ZEN, and so is the use of per km unit to assess Mobility M and O.

Future work building on this work should including energy storage, for example by feeding the excess produced electricity for the electric vehicles. Also, infrastructure elements should be included.

6 Reference list

Aasestad, K. 2013. Emissions of Black carbon and Organic carbon in Norway 1990-2011. Statistics Norway.

Ajanovic, A. 2015. The future of electric vehicles: Prospects and impediments. Wiley Interdisciplinary Reviews: Energy and Environment **4**:521-536.

Anderson, J. E., G. Wulfhorst, and W. Lang. 2015. Energy analysis of the built environment - A review and outlook. Renewable and Sustainable Energy Reviews **44**:149-158.

Bastos, J., S. A. Batterman, and F. Freire. 2016. Significance of mobility in the life-cycle assessment of buildings. Building Research and Information **44**:376-393.

Blengini, G. A., and T. Di Carlo. 2010. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy and Buildings **42**:869-880.

Cherubini, F., J. Fuglestvedt, T. Gasser, A. Reisinger, O. Cavalett, M. A. J. Huijbregts, D. J. A. Johansson, S. V. Jørgensen, M. Raugei, G. Schivley, A. H. Strømman, K. Tanaka, and A. Levasseur. 2016. Bridging the gap between impact assessment methods and climate science. Environmental Science and Policy **64**:129-140.

Cox, B., C. L. Mutel, C. Bauer, A. Mendoza Beltran, and D. P. Van Vuuren. 2018. Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles. Environmental Science and Technology **52**:4989-4995.

Dahlstrøm, O., K. Sørnes, S. T. Eriksen, and E. G. Hertwich. 2012. Life cycle assessment of a single-family residence built to either conventional- or passive house standard. Energy and Buildings **54**:470-479.

Ecoinvent Centre. 2015. Ecoinvent 3.2. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Ellingsen, L. A. W., G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen, and A. H. Strømman. 2014. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. Journal of Industrial Ecology **18**:113-124.

Ellingsen, L. A. W., B. Singh, and A. H. Strømman. 2016. The size and range effect: Lifecycle greenhouse gas emissions of electric vehicles. Environmental Research Letters **11**.

ESU, and IFEU. 2008. New Energy Externalities Developments for Sustainability (NEEDS) - LCA of background processes.*in* U. ESU Services, CH, editor.

European Commission. 2010. Energy Performance of Buildings Directive, Directive 2010/31/EU.

Finnveden, G., M. Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, and S. Suh. 2009. Recent developments in Life Cycle Assessment. Journal of Environmental Management **91**:1-21.

Fridstrøm, L., and V. Østli. 2016. Vehicle fleet forecasts based on stock-flow modeling (in Norwegian). Institute of Transport Economics.

Gibon, T., A. Arvesen, and E. G. Hertwich. 2017. Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. Renewable and Sustainable Energy Reviews **76**:1283-1290.

Goedkoop, M., R. Heijungs, M. A. J. Huijbregts, A. D. Schryver, J. Struijs, and R. V. Zelm. 2009. ReCiPe 2008. Dutch Ministery of the Environment, The Hague, Netherlands.

Harter, H., V. Weiler, and U. Eicker. 2017. Developing a roadmap for the modernisation of city quarters – Comparing the primary energy demand and greenhouse gas emissions. Building and Environment **112**:166-176.

Hawkins, T. R., B. Singh, G. Majeau-Bettez, and A. H. Strømman. 2013. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Journal of Industrial Ecology **17**:53-64.

Heeren, N., C. L. Mutel, B. Steubing, Y. Ostermeyer, H. Wallbaum, and S. Hellweg. 2015. Environmental Impact of Buildings - What Matters? Environmental Science and Technology **49**:9832-9841.

Hellweg, S., and L. M. I. Canals. 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science **344**:1109-1113.

Hertwich, E. G., T. Gibon, E. A. Bouman, A. Arvesen, S. Suh, G. A. Heath, J. D. Bergesen, A. Ramirez, M. I. Vega, and L. Shi. 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proceedings of the National Academy of Sciences of the United States of America **112**:6277-6282.

Houlihan Wiberg, A., L. Georges, T. H. Dokka, M. Haase, B. Time, A. G. Lien, S. Mellegård, and M. Maltha. 2014. A net zero emission concept analysis of a single-family house. Energy and Buildings **74**:101-110.

IEA. 2015a. Energy Technology Perspectives 2015 - Mobilising Innovation to Accelerate Climate Action. International Energy Agency (IEA), Paris, France.

IEA. 2015b. World Energy Outlook.

Kristjansdottir, T. F., N. Heeren, I. Andresen, and H. Brattebø. 2017. Comparative emission analysis of low-energy and zero-emission buildings. Building Research and Information:1-16.

Kristjansdottir, T. F., A. Houlihan-Wiberg, I. Andresen, L. Georges, N. Heeren, C. S. Good, and H. Brattebø. 2018. Is a net life cycle balance for energy and materials achievable for a zero emission single-family building in Norway? Energy and Buildings **168**:457-469.

Lotteau, M., P. Loubet, M. Pousse, E. Dufrasnes, and G. Sonnemann. 2015. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Building and Environment **93**:165-178.

Lucon, O., D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L. F. Cabeza, N. Eyre, A. Gadgil, L. D. D. Harvey, Y. Jiang, E. Liphoto, S. Mirasgedis, S. Murakami, J. Parikh, C. Pyke, and M. V. Vilariño. 2014a. Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel

on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S.

Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)].

Lucon, O., D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L. F. Cabeza, N. Eyre, A. Gadgil, L. D. D. Harvey, Y. Jiang, E. Liphoto, S. Mirasgedis, S. Murakami, J. Parikh, C. Pyke, and M. V. Vilariño. 2014b. Buildings. In: Climate Change 2014: Mitigation

of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel

on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S.

Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. .

Majeau-Bettez, G., and A. H. Strømman. 2016. Documentation for Arda Calculator, version 1.8.3. 2016.

Mamo Fufa, S., R. Dahl Schlanbusch, K. Sørnes, M. Inman, and I. Andresen. 2016. A Norwegian ZEB Definition Guideline. Sintef, NTNU.

Massarutto, A. 2015. Economic aspects of thermal treatment of solid waste in a sustainable WM system. Waste Management **37**:45-57.

Mastrucci, A., A. Marvuglia, U. Leopold, and E. Benetto. 2017. Life Cycle Assessment of building stocks from urban to transnational scales: A review. Renewable and Sustainable Energy Reviews **74**:316-332.

Moschetti, R., L. Mazzarella, and N. Nord. 2015. An overall methodology to define reference values for building sustainability parameters. Energy and Buildings **88**:413-427.

Myhre, G., D., F.-M. Shindell, W. Bréon, J. Collins, J. Fuglestvedt, D. Huang, J.-F. Koch, D. Lamarque, B. Lee, T. Mendoza, A. Nakajima, G. Robock, T. Stephens, Takemura, and Zhang. 2013a. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge, United.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang. 2013b. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge, United Kingdom and New York, NY, USA.

Norman, J., H. L. MacLean, and C. A. Kennedy. 2006. Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions. Journal of Urban Planning and Development **132**:10-21.

Pauliuk, S., and D. B. Müller. 2014. The role of in-use stocks in the social metabolism and in climate change mitigation. Global Environmental Change **24**:132-142.

Pauliuk, S., K. Sjöstrand, and D. B. Müller. 2013. Transforming the Norwegian dwelling stock to reach the 2 degrees celsius climate target: Combining material flow analysis and life cycle assessment techniques. Journal of Industrial Ecology **17**:542-554.

Roux, C., P. Schalbart, and B. Peuportier. 2016. Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house. Journal of Cleaner Production **113**:532-540.

Sandberg, N. H., I. Sartori, O. Heidrich, R. Dawson, E. Dascalaki, S. Dimitriou, T. Vimm-r, F. Filippidou, G. Stegnar, M. Šijanec Zavrl, and H. Brattebø. 2016a. Dynamic building stock modelling:

Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. Energy and Buildings **132**:26-38.

Sandberg, N. H., I. Sartori, M. I. Vestrum, and H. Brattebø. 2016b. Explaining the historical energy use in dwelling stocks with a segmented dynamic model: Case study of Norway 1960–2015. Energy and Buildings **132**:141-153.

Sandberg, N. H., I. Sartori, M. I. Vestrum, and H. Brattebø. 2017a. Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016-2050. accepted for publication in Energy and Buildings.

Sandberg, N. H., I. Sartori, M. I. Vestrum, and H. Brattebø. 2017b. Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016–2050. Energy and Buildings **146**:220-232.

Sandstad, J. N., N. H. Sandberg, N. Nord, M. I. Vestrum, C. Lausselet, A. Woszczek, Ø. Rønneseth, and H. Brattebø. 2018. Neighbourhood Building Stock Model for Long-Term Dynamic Analyses of Energy Demand and GHG Emissions - General model description and case studies. NTNU/Sintef.

Saner, D., N. Heeren, B. Jäggi, R. A. Waraich, and S. Hellweg. 2013. Housing and mobility demands of individual households and their life cycle assessment. Environmental Science and Technology **47**:5988-5997.

Sartori, I., and A. G. Hestnes. 2007. Energy use in the life cycle of conventional and low-energy buildings: A review article. Energy and Buildings **39**:249-257.

Sartori, I., S. Merlet, B. Thorud, T. Haug, and I. Andresen. 2016. Zero Village Bergen - Aggregated loads and PV generation profiles.

Soares, N., J. Bastos, L. D. Pereira, A. Soares, A. R. Amaral, E. Asadi, E. Rodrigues, F. B. Lamas, H. Monteiro, M. A. R. Lopes, and A. R. Gaspar. 2017. A review on current advances in the energy and environmental performance of buildings towards a more sustainable built environment. Renewable and Sustainable Energy Reviews **77**:845-860.

Standard Norge. 2009. NS 3451:2009 Table of building elements (in Norwegian).

Standard Norge. 2018. NS 3720:2018 - Methods for greenhouse gas calculations for buildings (in Norwegian).

Statistics Norway. 2017. Road traffic volumes, by type of vehicle.

Stephan, A., R. H. Crawford, and K. De Myttenaere. 2012. Towards a comprehensive life cycle energy analysis framework for residential buildings. Energy and Buildings **55**:592-600.

Stephan, A., R. H. Crawford, and K. de Myttenaere. 2013. Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia. Building and Environment **68**:35-49.

Stephan, A., and L. Stephan. 2016. Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. Applied Energy **161**:445-464.

Thomas, M., L. A. W. Ellingsen, and C. R. Hung. 2018. Battery-powered electric vehicles: market development and lifecycle emissions. European Parliament.

Vásquez, F., A. N. Løvik, N. H. Sandberg, and D. B. Müller. 2016. Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock. Energy and Buildings **111**:37-55.

Victor, D. G., D. Zhou, E. H. M. Ahmed, P. K. Dadhich, J. G. J. Olivier, H.-H. Rogner, K. Sheikho, and M. Yamaguchi. 2014. Introductory Chapter. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. .

Wiebe, K. S. 2018. Identifying emission hotspots for low carbon technology transfers. Journal of Cleaner Production **194**:243-252.

Wiebe, K. S., E. L. Bjelle, J. Többen, and R. Wood. 2018. Implementing exogenous scenarios in a global MRIO model for the estimation of future environmental footprints. Journal of Economic Structures **7**.

Wiedenhofer, D., J. K. Steinberger, N. Eisenmenger, and W. Haas. 2015. Maintenance and Expansion: Modeling Material Stocks and Flows for Residential Buildings and Transportation Networks in the EU25. Journal of Industrial Ecology **19**:538-551.

Wiik, M. K., S. M. Fufa, T. Kristjansdottir, and I. Andresen. 2018a. Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB research centre. Energy and Buildings **165**:25-34.

Wiik, M. K., S. Mamo Fufa, J. Krogstie, D. Ahlers, A. Wyckmans, P. Driscoll, and A. Gustavsen. 2018b. Zero Emission Neighbourhoods in Smart Cities: Definition, Key Performance Indicators and Assessment Criteria: Version 1.0.

Appendix A: mathematical framework

A.1. Emissions from Building Materials

The assessed neighbourhood consists of one state-of-the-art single-family house type with high-energy performance standard. The classification of the building parts is done according to the Norwegian table of building elements NS 3451:2009 (Standard Norge 2009), and the material inventory of the house is from Houlihan Wiberg, Georges et al. (2014). The house is designed according to the Norwegian passive-house standard, has two floors, and a total heated floor area of 160 m^2. Material replacement according to their respective lifetime is included.

The total GHG emissions embodied in building materials B_M is calculated according to equation (2). $GHG_{mat,init}$ (CO_2 eq./m^2) represents the emissions embodied in the materials initially contained in the buildings, $GHG_{mat,repl}$ (CO_2 eq./m^2) the emissions embodied in the materials used in replacements, bt the building type, A (m^2) the heated floor area and i is the year.

$$B_M = \sum_{bt} A_{bt} \cdot \left(GHG_{mat,init_{bt}} + \sum_{i=1}^{60} GHG_{mat,repl_{i,bt}} \right) \tag{1}$$

A.2. Emissions from Building Operation

The heating system is "all-electric", with heating pumps, solar collectors and PV panels on the roof. The electricity produced from the PVs is either used entirely on-site, or sent to the grid if in excess. Following the ZEB guidelines, a marginal approach is used to give credits for the excess on-site produced electricity sent to the grid (module D in figure S1). The total GHG emissions resulting from the operational phase of the buildings B_O is calculated according to equation (3), where $el_{delivered}$[1] (kWh/m^2) is the electricity delivered on a yearly basis, el_{onsite} (kWh/m^2) the yearly on-site electricity produced and GHG_{el} (CO_2 eq./kWh) the grid electricity GHG intensity. GHG_{el} follows the Energy Technology Perspectives (ETP) scenarios from the International Energy Agency (IEA 2015) and is given in S2. If $(el_{delivered} - el_{onsite}) < 0$, $B_O < 0$ and B_O is credited negative emissions.

$$B_O = \sum_{bt} \sum_{i=1}^{60} A_{bt} \cdot (el_{delivered_{bt}} - el_{onsite_{bt}}) \cdot GHG_{el_i} \tag{2}$$

A.3. Emissions from PV systems

The GHG emissions embodied in the PVs is calculated with equation (4) with GHG_{PV} (CO_2 eq./kWh) the PV material GHG intensity, r the numbers of replacements over the lifetime (30 years) and C_{PV} (kWh/m^2) the installed capacity according to the building type bt. GHG_{PV} is of 56 g CO_2/kWh in year 2018 (i=1) and of 7 g CO_2/kWh in year 2038 (i=31), according to Gibon, Arvesen et al. (2017).

$$PV = \sum_{bt} \sum_{i=1}^{60} A_{bt} \cdot C_{PV_{bt}} \cdot (GHG_{PV,i})(1 + r_i) \tag{3}$$

A.4. Emissions from Mobility Materials

The composition of the car stock is predicted to change drastically during the next years, with a rapid penetration of electric vehicles (Thomas, Ellingsen et al. 2018). We based our estimates on the baseline

[1] The energy delivered is defined as in Sandberg, N. H., I. Sartori, M. I. Vestrum and H. Brattebø (2016). "Explaining the historical energy use in dwelling stocks with a segmented dynamic model: Case study of Norway 1960–2015." Energy and Buildings **132**: 141-153.; the amount of energy supplied to a dwelling in order to provide the energy need. The conversion from energy need to delivered energy depends on 1) the share of the energy need that is covered by local energy (heat pump) 2) the shares covered by various energy sources and 3) the system efficiencies of the heating systems.

and ultralow-emission policy scenario performed by the Institute of Transport Economics (Fridstrøm and Østli 2016), as presented in figure S3. For both scenarios, the ICEVs are phased out by around 2050.

Private passengers cars only are considered, with three different vehicle types; BEV, ICEV powered by gasoline, and ICEV powered by diesel. The vehicle material inventories are based on Hawkins, Singh et al. (2013), Ellingsen, Majeau-Bettez et al. (2014), and Ellingsen, Singh et al. (2016), and are updated to Ecoinvent 3.2. Also, material efficiency improvement over time is included based on material efficiency rates as described in ESU and IFEU (2008) and used in Hertwich, Gibon et al. (2015), and presented in figure S4. We assumed the lifetime of the batteries of the BEVs used in our scenarios to be equal the car lifetime, and to be produced in Korea in 2018, half in Korea and half in Europe in 2030 and in Europe only in 2050 with improvement in the production chain, as shown in figure S4. The total GHG emissions embodied in mobility M_M are calculated according to equation (5). α_{vt} stands for the share of the different vehicle type *vt* of time *i*, GHG_{mat} (CO_2 eq./km) for the emissions from the production of the different vehicle types v*t* and L_{tot} (km/year) the total neighbourhood yearly travel length.

$$M_m = \sum_{vt}\sum_{i=0}^{60} \alpha_{vt,i} \cdot V_{tot_i} \cdot GHG_{mat_{vt}} \cdot L_{tot,i} \tag{4}$$

A.5. Emissions from Mobility Operation

The total GHG emissions from Mobility O M_O are calculated according to equation (6) with α_{vt} as the share of the different vehicle type *vt* at time *i*, GHG_{Op} (CO_2 eq./km) the emissions per km driven by vehicle type v*t* at year *i* and $L_{tot,i}$ (km/y) the total neighbourhood yearly travel length.

$$M_O = \sum_{vt}\sum_{i=0}^{60} \alpha_{vt,i} \cdot GHG_{op_{vt}} \cdot L_{tot,i} \tag{5}$$

Vehicle operational energy for both gasoline and diesel fueled ICEVs are taken from Ecoinvent 3.2, and are assumed to decrease with 15% by 2030 and 20% by 2050 based on values from Ajanovic (2015) and Cox, Mutel et al. (2018), as shown in figure S5. The electricity consumption of the BEV is assumed to decrease over time; from 15 kWh/100 km in 2018 (assuming the efficiency of the battery to be at 95 %, the electric motor at 95 % and the inverter at 97 %), 13.5 kWh/100 km in 2030 to 12.5 kWh/100 km in 2050 as shown in figure S5.

Appendix B – LCA Modelling for Zero Emission Neighbourhoods in Early Stage Planning

LCA Modelling for Zero Emission Neighbourhoods in Early Stage Planning

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Abstract

The building sector is a major driver of climate change, and the increased focus on significantly reducing greenhouse gas (GHG) emissions in recent years calls for major initiatives in the way we plan, build and operate buildings and neighbourhoods. Life-cycle assessment (LCA) is a commonly used and well-established tool to estimate the total emissions caused by buildings throughout their entire life cycle. Yet, LCAs of more complex systems such as neighbourhoods are scarce.

We have developed an LCA model for neighbourhoods with a focus on GHG emissions based on a modular structure with five physical elements: buildings, mobility, open spaces, networks and on-site energy infrastructure. We applied it on the Zero Village Bergen pilot project in Norway.

The results give total GHG emissions of 117 ktonnes CO_2-eq over 60 years, equivalent to 1.5 tonnes CO_2-eq/capita/year or 21.2 kg CO_2-eq/m^2/year on average over the period. The buildings constitute the largest share of emissions among the elements with 52%, then mobility with 40%, and only 2.3% from networks and open spaces. Emissions embodied in the materials consumed in all the elements of the neighbourhood account for as much as 56% of total emissions, with a large share coming from materials consumed in mobility vehicles. Critical parameters are emission intensities for electricity and heat production by waste incineration, as well as the daily distance travelled by the inhabitants.

1. Introduction

The 2015 Paris agreement of an average global temperature rise of maximum 2 degrees compared with pre-industrial times has led to a growing focus on climate change. The building sector is a major source, accounting for about one third of both energy consumption and greenhouse gas (GHG) emissions globally (Lucon, Ürge-Vorsatz et al. 2014). With the aim of reducing energy use in buildings through country-level regulation, the EU has established two legislative directives: the Energy Performance of Buildings Directive (EPBD) (European Commission 2010) and the Energy Efficiency Directive (European Commission 2012) (European Parliament and the Council 2012). This has motivated research, new building codes and the development of concepts that provide guidance for high energy efficiency in buildings. In Norway, the Research Centre on Zero Emission Buildings (ZEB Centre) was named a research centre of excellence 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 a market penetration of buildings that have zero emission of GHGs related to their production, operation and demolition (The Research Centre on Zero Emission Buildings (ZEB)). In 2018, the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Centre) was started as a follow-up to the ZEB Centre, envisioning 'Sustainable neighbourhoods with zero GHG emissions' and with a goal to develop solutions for future buildings and neighbourhoods with no GHG emissions, thereby contributing to a low carbon society (ZEN 2018). With this expansion in scope, the ZEN Centre researchers already acknowledge that many additional questions and challenges have arisen. However, it is less obvious what the good choices are and how to use LCA for decision-making support at the neighbourhood level, e.g. regarding functional unit(s), system boundaries and assumed input values for critical variables and parameters. In particular, this will have to be much better understood in the early stage planning process of ZEN projects, where LCA should play a role in the decision-making. Unfortunately, the research literature is scarce in this area at present.

1.1 Environmental Assessment of Buildings

Knowing what factors drive emissions and impacts over the entire life span of a building is essential to achieve significant environmental improvements in the building stock. For this purpose, life cycle assessment (LCA) is a common and well-established tool (Rossi, Marique et al. 2012, Rossi, Marique et al. 2012, Hellweg and Canals 2014). LCA systematically addresses the environmental impacts of a system through its life cycle stages, from raw material acquisition, through energy and material production, to use and end-of-life treatment (ISO 2006). LCA studies at the building level have led to valuable insights that can now pave the way for emission reductions in the building sector (Khasreen, Banfill et al. 2009, Cabeza, Rincón et al. 2014).

One important finding is how the relative importance of emissions from the operation of the individual building (heating, cooling, lighting, ventilation and appliances) compared to the emissions embodied in materials used in the building have changed over time, as a consequence of improved technology and new building codes. Historically, results have shown the dominating role of the use stage, which traditionally accounts for some 80-90% of total emissions (Ramesh, Prakash et al. 2010, Sharma, Saxena et al. 2011, Cabeza, Rincón et al. 2014). However, more recent studies have concluded that especially when buildings with low energy consumption are evaluated, such as in low-energy or passive-house designs, the share of embodied emissions from materials is considerable (Brown, Olsson et al. 2014, Chastas, Theodosiou et al. 2016, Kristjansdottir, Heeren et al. 2017, Mastrucci, Marvuglia et al. 2017, Wiik, Fufa et al. 2017). Wiik, Fufa et al. (2017) found that the embodied emissions over 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 (Junnila, Horvath et al. 2006, Wiik, Fufa et al. 2017, Yang, Hu et al. 2018). Yang, Hu et al. (2018) however, found that among all the life cycle stages, the construction and 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 the use of alternative and renewable materials, different architectural design options (such as shape, envelope and passive heating and cooling systems), user behaviour, the potential of energy-positive buildings and the associated consequences of a greater exchange of self-produced energy to external grids (Kuzman, Grošelj et al. 2013, Bayoumi and Fink 2014, Nichols and Kockelman 2014, Salom, Marszal et al. 2014, Anderson, Wulfhorst et al. 2015).

1.2 From Buildings to Neighbourhoods

In recent years, the focus has shifted from studying individual buildings treated as objects independent of the surrounding environment, to considering stocks of buildings and larger systems such as cities or neighbourhoods (Oliver-Solà, Josa et al. 2011, Anderson, Wulfhorst et al. 2015, Lotteau, Loubet et al. 2015). Still, the LCA literature at the neighbourhood level is scarce and highly influenced by the complexity and context dependency of the systems studied, which leads to heterogeneous approaches in how LCA modelling is done (Lotteau, Loubet et al. 2015, Mastrucci, Marvuglia et al. 2017).

The choice of system boundaries is a factor that stands out from previous research, and is shown to have considerable impact on the results. The boundaries define what to include in the analysis, both regarding different life cycle stages and various physical elements in a neighbourhood, such as buildings, mobility, open spaces and infrastructure. Some research concentrates on clusters of buildings (Cherqui 2005, Davila and Reinhart 2013), while others also consider the users´ mobility (Li and Wang 2009, Riera Pérez and Rey 2013, Anderson, Wulfhorst et al. 2015, Bastos, Batterman et al. 2016). The most complex LCA studies include both buildings, mobility and other elements like open spaces and networks (Norman, Maclean et al. 2006, Stephan, Crawford et al. 2013, Nichols and Kockelman 2014). The life cycle stages considered also vary, from only looking at the use stage, to also considering the production and end-of-life stages (Lotteau, Loubet et al. 2015, Mastrucci, Marvuglia et al. 2017). Such different choices of system boundaries clearly lead to difficulties in 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, Batterman et al. (2016) found that user transportation contributed to 51-57% of the total GHG emissions, when including the materials consumed in constructing the buildings, in replacements in the use stage, and transportation in the analysis. Nichols and Kockelman (2014) found that transportation constituted a considerable share of the impacts, with 44-47% of the total use stage emissions. Studies that also include the manufacturing of the modes of transport are lacking, with a few exceptions: Stephan, Crawford et al. (2013) found that indirect emissions (including, among other things, vehicle manufacturing and building roads) constituted 52% of the total emissions from transportation. Anderson, Wulfhorst et al. (2015) found the same share 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 indirect impacts from mobility related to ZENs. Fortunately, these issues are already making their way into standards, such as the new Norwegian standard NS 3720 Method for GHG calculations

for buildings (Standard Norge 2018), which expands the system boundaries compared to the standard EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method (Standard Norge 2012), by including transport in the use stage as a new module (B8) in calculations of GHG emissions from buildings; see S1 in the supplementary material.
Temporal aspects and assumptions about the future are often crucial when conducting an LCA, and in particular, the long lifespan of the physical elements of a neighbourhood makes forecasting emissions difficult and subject to high uncertainty. This is highlighted in several studies, and key factors that drive this uncertainty are the future emission intensity of electricity (g CO_2-eq/kWh), future technologies in buildings, infrastructure and mobility, and the temporal distribution of environmental impacts (Stephan, Crawford et al. 2013, Anderson, Wulfhorst et al. 2015, Lotteau, Loubet et al. 2015, Bastos, Batterman et al. 2016, Roux, Schalbart et al. 2016). Also, the forecasted climate change is expected to decrease heating energy use while at the same time increasing cooling energy use, leading to a net increase of energy use in the building sector (Roux, Schalbart et al. 2016, Cellura, Guarino et al. 2018).

Furthermore, existing 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 the early stage planning of new neighbourhood projects. Lotteau, Yepez-Salmon et al. (2015) describe a tool called NEST (Neighbourhood Evaluation for Sustainable Territories), an LCA tool for assessing the environmental impact of urban projects, developed by Yepez-Salmon (2011). By including the production, maintenance, use and end-of-life stages 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 this holistic approach should be explored in neighbourhood projects elsewhere. It has also been an inspiration in this study.
More research is obviously required in the field of LCA at the neighbourhood level, and in particular for ZEN projects that are motivated by transitions to a low-carbon future. Such research is needed both on what life cycle stages and physical elements in the neighbourhood contribute significantly to different categories of environmental impact, and on the need for a broader knowledge of the critical factors that influence emissions and impact results in varying contexts. 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 the expedient use of LCA of neighbourhoods at an early planning stage, by focusing on important contributors to and critical factors for climate change impacts. Through the 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 GHG emissions at neighbourhood scale?
- What are the critical factors that affect these contributions and what are their sensitivities?
- What are the strengths and weaknesses of the model that has been developed? Can it provide useful inputs to the early stage planning process of a ZEN project?

2. Material and Methods

In this work, we developed a modular structure that serves as a basis for LCA with a focus on climate change at the neighbourhood level. Then, we applied it in a case study; called Zero Village Bergen (ZVB) located outside the city of Bergen in Norway, which is a ZEN pilot project for the ZEN Centre. The project is in the early planning stages with a presumed launch in 3-4 years. According to the present plans, it will be Norway's biggest zero emission project for buildings (Massarutto 2015). Although the model is adapted to the specific case, the methodology and calculation procedures are intended to be applicable to any other LCA study at neighbourhood level.

2.1 Modular Structure

The modular structure of the LCA model is presented in Figure 1 and consists of two dimensions to cover both the physical elements in the neighbourhood (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 new national standard NS 3720 (Standards Norway 2017). Since mobility is defined as a separate element in the model, the transportation in use (B8, marked with grey in the figure) is excluded in the analysis of emissions from the 'buildings' element.

The zero emission ambition levels are based on a previous approach recommended by the ZEB Centre, called the 'ZEB Definition' (Fufa, Schlanbusch et al. 2016). It refers to the fact that a different number of life cycle modules from A1 to C4 – a few or many, depending on the ambition level determined by a given project owner – can be included in the zero emission ambition for each of the physical elements. The following description of these ambition levels is adapted from the ZEB definition.

- ZEN O: Emissions related to all operational energy "O", i.e. module B6 in Figure 1.
- ZEN OM: Emissions related to all operational energy "O" plus all embodied emissions from materials "M.", i.e. modules A1-A3 and B4.
- ZEN COM: The same as OM, but also including emissions relating to the construction "C" stage, i.e. modules A4-A5.
- ZEN COME: The same as ZEN-COM, but also including emissions relating to the end of life "E" stage, i.e. modules C1-C4.

For any given ZEN project, the elements and life cycle stages to include in the LCA analysis can be adjusted to match the policy choices of the project, or questions of interest for each LCA study. Hence, the modular structure of the model offers flexibility regarding varying scopes and objectives of a given study.

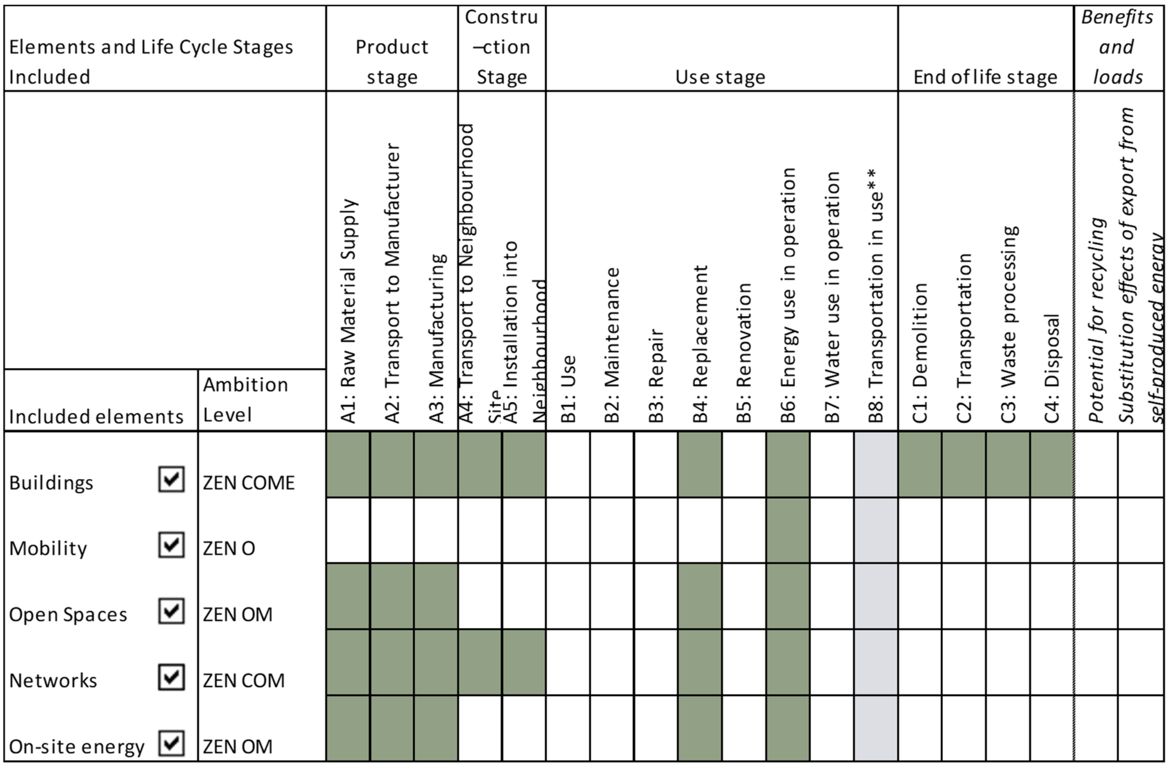

Figure 1: Modular structure used as basis for LCA at neighbourhood level. Note: the elements and ambition levels marked in this figure are here randomly selected and serve only as an example of the use of the structure

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 new standard NS 3720 on GHG calculations in buildings (Standards Norway 2017) recommends looking at two different scenarios for the future 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. These two scenarios must be regarded as extreme variants of the nationally consumed electricity mix, since each year includes both the import and export of electricity. Details on the emission intensities are given in S2.1, and Figure 2 represents the two scenarios as they evolve from 2015 to 2080.

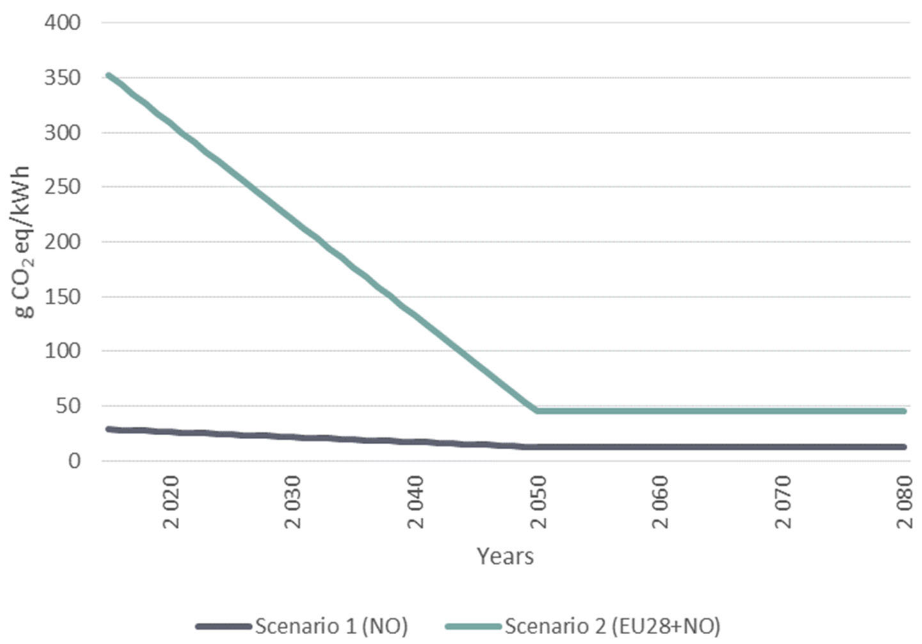

Figure 2: Evolution of emission intensities for electricity (g CO2-eq/kWh) 2015-2080 based on scenarios recommended in NS 3720 (Standards Norway 2018)

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), the “ZEN-OM” ambition level was applied in this study, 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 assumed very low emissions compared to the other elements. 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 is 60 years, equivalent with the assumed lifetime of buildings and infrastructure, and the focus in this study is on GHG emissions associated with each of the elements throughout this period. At the current planning stage of the project, different energy system alternatives are under consideration, including joining the presently existing district heating system in Bergen, the use of a new local CHP plant, or the use of new ground source heat pumps (Sartori, Skeie et al. 2018). We assumed that the heat demand is covered by connecting to the district heating system, 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) was chosen for both import and export of electricity between the neighbourhood and the external power grid.

Aiming for the “ZEN-OM” ambition level implies setting the waste system outside the system boundary. In the case of a neighbourhood covering its thermal load by district heating, fed partly by heat resulting from waste incineration as is the case in Bergen, the GHG emissions from waste incineration will be assigned to the energy use in the operation (B6) module. Also, because of the ongoing debate in Norway asto whether the emissions from waste incineration should be assigned to the waste producer (an inhabitant) or to the end-user of the waste (the district heating company), we consider both allocations method in a sensitivity analysis.

2.2.1 Buildings

The building stock in ZVB consists of residential and non-residential buildings, with a total area of 91 891 m^2 (Sartori, Merlet et al. 2016), see
Table 1. There will be 695 dwellings and 1 340 inhabitants, see S5.1. The estimated area for parking is based on information on the number of parking spots, see S5.2.

Table 1: Building stock and areas in Zero Emission Village Bergen (ZVB) (Sartori, Merlet et al. 2016).

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 the replacement of materials throughout the 60 years period, see Equation 1.

$$E_{b,mat} = \sum_{bt} \left\{ \left[\left(E_{mat,init} \right)_{bt} \cdot A_{bt} \right] + \sum_{i=0}^{60} \left[\left(E_{mat,repl} \right)_{i,bt} \cdot A_{bt} \right] \right\} \tag{1}$$

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

Material lists are presented in S5.3. Because of limited access to detailed data and uncertainties in design choices in the early planning stages, all residential buildings were assumed to consiste of the same amount of materials per unit of floor area. The same goes for the non-residential buildings (all the non-residential buildings considered are equal in materials to an office building). For residential buildings and parking garages the material lists were provided by SINTEF (research partner with the ZEN Centre), and for non-residential buildings, the materials list was based on the materials included in a pilot project for a ZEB office building performed by the ZEB Centre (Dokka, Kristjansdottir et al. 2013). For both building types, the GHG emissions per amount of material were based on either relevant national EPDs or the Ecoinvent database. The replacements are based on the estimated service life of each material, and the emissions embodied in 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 (Sartori, Merlet et al. 2016) where the buildings planned for the ZVB project were already estimated by IDA-ICI simulations. This gave 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 residential building types.

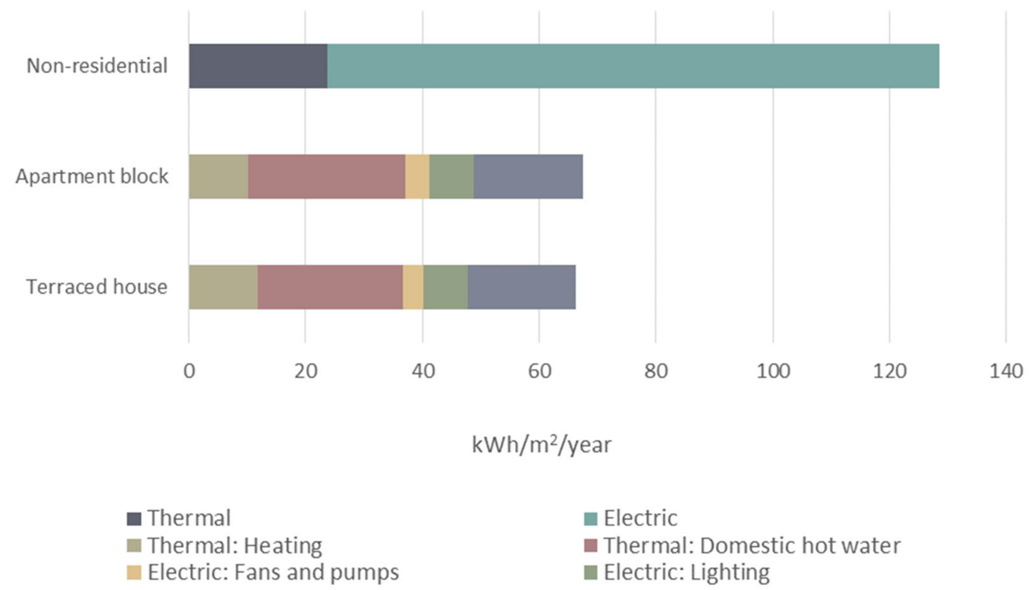

Figure 3: Yearly energy load of residential buildings in ZVB (kWh/m2(year) (adopted from Sartori et al. 2016)

It is assumed that the loads are constant for all future 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 emission intensity of the district heat is calculated based on the emission factors 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 vehicles, buses and light rail. Due to the extensive planning for public transport and cycling facilities (Massarutto 2015), the distance travelled with each mobility 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 NS 3720 suggests including transportation of users, it does not specify a methodology for calculating the emissions for different means of transport. Nevertheless, the standard suggests using a project conducted by the Norwegian research institute Vestlandsforskning, completed in 2011, as a source for indicative emission factors for the current situation (Standards Norway 2017). The documentation behind the results reveals large heterogeneity on data on energy use and emissions from different means of transport from previous research (Simonsen 2010), but concludes with providing chosen estimates for several transportation modes intended for Norwegian conditions.

The future evolution of fuel types/energy carriers, together with technical improvements for vehicles and fuel chains, makes the forecast of emissions from transport a complex task. The NS 3720 standard emphasizes that development and technical improvements influenced by regulation and tax systems will lead to reduced emissions per distance driven during a buildings´ service life, and that this should be taken into account through scenario assessment (Standards Norway 2017).

Evolution of vehicle stocks

The evolution of vehicle stocks is based on an "ultra-low emission policy scenario" developed by Fridstrøm and Østli (2016). The scenario is based on targets compiled by the Norwegian transportation agencies, and the evolution of passenger cars and buses distributed among 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 towards 2080 (see Figure 4). It is assumed that the use of light rail is all-electric throughout the entire period.

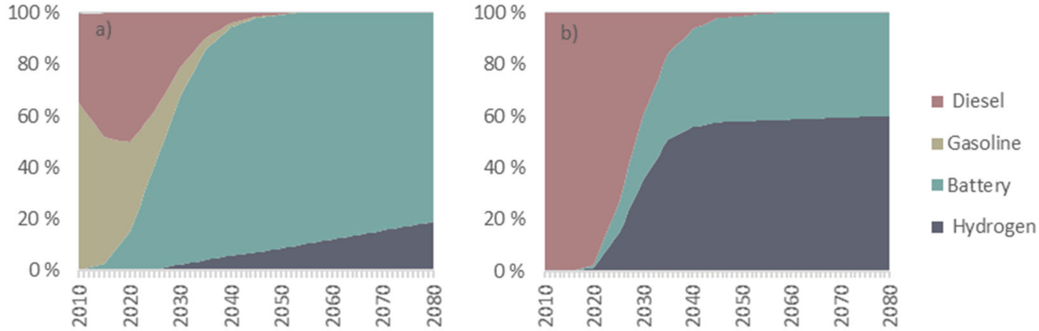

Figure 4: Evolution of vehicle stock for a) passenger cars and b) buses by fuel type/energy carrier used in present study (See data in S6.2)

Product and replacement stages

The emissions embodied in the materials for mobility, $E_{m,mat}$, were calculated using Equation 2**Error! Reference source not found.**.

$$E_{m,mat} = \sum_{i=0}^{60} \sum_{tm} \left[(E_{mat})_{tm} \cdot L_{tot,tm,i} \right] \tag{2}$$

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

The emissions from the product and replacement stages of the transportation are based on a study by Simonsen (2010). Due to the continuous replacements of vehicles, the emissions are considered per distance driven (see S6.3) and do not distinguish between the initial material inputs (A1 – A3) and replacements (B4).

Emissions embodied in vehicles per unit of distance are assumed constant throughout the 60-year period, but the total emissions of the vehicle stock change with time due to the evolution of fuel/energy carrier types as described in Figure 4.

Energy use in operation

Total emissions from the operation of mobility, $E_{m,oper}$, are calculated using Equation 3.

$$E_{m,oper} = \sum_{i=1}^{60} \sum_{tm} L_{tot,tm} \cdot WtW_{tm,i} \tag{3}$$

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

The results from the study by Simonsen (2010) were used as a starting point in 2010, see S6.4. Improvements in the fuel intensities were based on a study performed by Ajanovic (2015), where scenarios for fuel intensities of new passenger cars were forecasted up to 2050, see S6.5. The well-to-wheel GHG emissions $WtW_{tm,i}$ from each of the transport modes *tm* at a given year *i* are calculated using Equation 4.

$$WtW_{tm,i} = Energy_{TtW,i} \cdot (I_{TtW} + I_{WtT}) \tag{4}$$

$Energy_{TtW}$ denotes the propulsion energy needed (MJ/vkm), I_{TtW} the tank-to-wheel or direct emission intensity (kg CO_2-eq/MJ) and I_{WtT} the well-to-tank emission intensity of the fuel cycle of the fuel/energy carrier (kg 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. I_{WtT} and I_{TtW} are held constant, while the propulsion energy is assumed to change over 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.

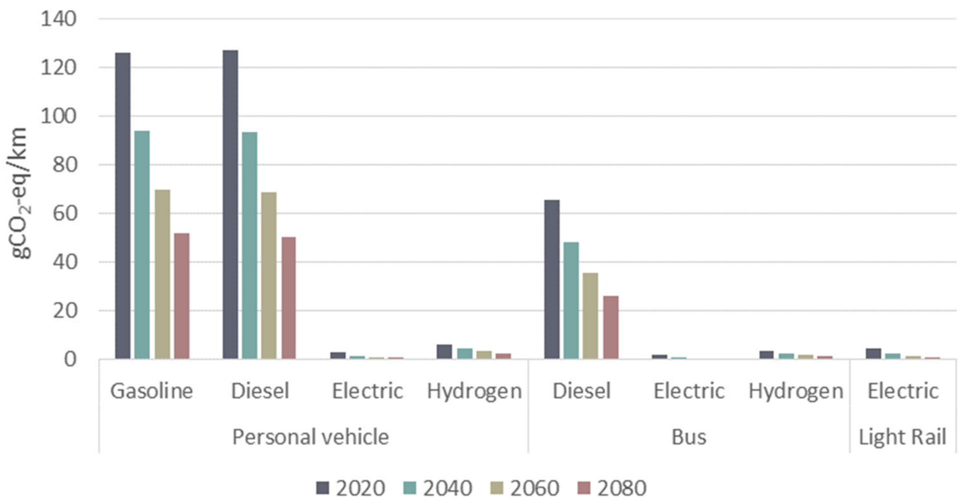

Figure 5: Evolution of Well-to-Wheel (WtW) emissions from different modes of transport (see Table 15 in S6.5)

2.2.3 Open Spaces

Included in the open spaces element are emissions embodied in roads (including 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 roads; (1) wide roads with two lanes and bicycle lanes on each side and (2) narrow roads without bicycle lanes. The road structure (materials and dimensions) is adopted from the work performed by Birgisdóttir, Pihl et al. (2006), see S7.1. The area of each of the sub-elements is roughly estimated based on the map of ZVB (S4), see Table 2.
The emissions from the materials in the open spaces elements are based on data from EPDs. Lifetimes of 20 and 40 years are assumed 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.

Table 2: Open spaces in Zero Emission Village Bergen (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

Energy use in operation

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

$$E_{o,oper} = \sum_{i=0}^{60} N \cdot P \cdot h \cdot I_{el,i} \qquad (5)$$

N is the number of lighting units, P the power per unit (kW), h the hours with lighting per year and I_{el} the emission intensity for electricity (kg CO_2-eq/kWh) at year i. The number of hours the units are turned on is calculated using specific data for Bergen, see S7.3.

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 central energy network (Sartori, Skeie et al. 2018). 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 that is geographically located inside the neighbourhood have therefore been incorporated, with components at the neighbourhood system level (but not at the building or dwelling level). The energy used to operate the network is not included.

Production and replacement stages

The length of pipes and the number of components units are a rough estimate 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, Gabarrell et al. (2009), where an LCA was carried out on a 100 m district heating system delivering energy to 240 dwellings by including the neighbourhood-, building- and dwelling pipeline systems. We assumed the average diameter of the pipelines to be 100 mm. The resulting material list and estimated service life for the pipes and the pump are presented in S8.2.

2.2.4 On-site Energy

The on-site energy in ZVB consists of photovoltaic (PV) panels placed on the building roofs. The dimensions of the PV panels area and the generation of electricity are according to Sartori, Merlet et al. (2016).

Production and replacements

The panels are placed on the available roof area of the buildings, with a total PV area of 22045 m^2 (Sartori, Merlet et al. 2016). Emissions associated with the production of PV panels are found using Ecoinvent, see S9.1. The lifetime of the panels is assumed to be 30 years (Granata, Pagnanelli et al. 2014), 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 to the replacement (Fufa, Schlanbusch et al. 2016).

Energy use in operation

Based on available roof area, meteorological data, system efficiency and losses, and generation profiles, the yearly PV generation is estimated at 2 941 MWh (Sartori, Merlet et al. 2016). This local generation of electricity is assumed to generate so-called negative (i.e. avoided) emissions, since the PV panels cover some of the electricity demand of the buildings and are thereby assumed to reduce electricity use from the external power grid. The negative emissions associated with this generation are calculated using the emissions intensity for electricity (Scenario 1). The PV-generated electricity is either use within the neighbourhood or exported to the external electricity network.

2.2.5 Sensitivity Analysis

To adress the goal of investigating critical parameters in the LCA model, a sensitivity analysis was performed on selected factors that were expected to have considerable impact on the results and/or are associated with large uncertainties. All input parameters selected for sensitivity analysis were given a relative change in input value of +25%, and the sensitivity ratio (*SR*) was measured using Equation 6.

$$SR = \frac{\Delta R / R_0}{\Delta P / P_0} \tag{6}$$

$\Delta P/P_0$ represents the relative change in the input parameter and $\Delta R/R_0$ denotes the relative change in results. Hence, parameters with a high *SR* value have a high influence on 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 central energy plant. For the latter, the alternative emission intensity for district heat was estimated at 16.1 g CO_2-eq/kWh, assuming significantly fewer emissions from the district heat compared to 163.2 g CO_2-eq/kWh as 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) resulted in a total of 117 ktonnes CO_2-eq over their lifetime. This equals 1.5 tonnes CO_2-eq/capita/year and 21.2 kg CO_2-eq/m^2/year, referring to the heated building floor area and as yearly average emissions over the 60-year analysis period. The emissions are distributed between the elements and life cycle stages as shown in Figure 6. As indicated in the figure, the building element accounts for the majority of the emissions, amounting to approximately 52% of the total lifetime emissions. Mobility is the second greatest contributing element, responsible for 40% of the total emissions. The emissions from the networks and open spaces together constitute only 2.3%. Furthermore, it is worth noting the relatively low level of negative emissions from the on-site energy production that, using our assumptions, are actually less than the emissions associated with producting the photovoltaic panels.

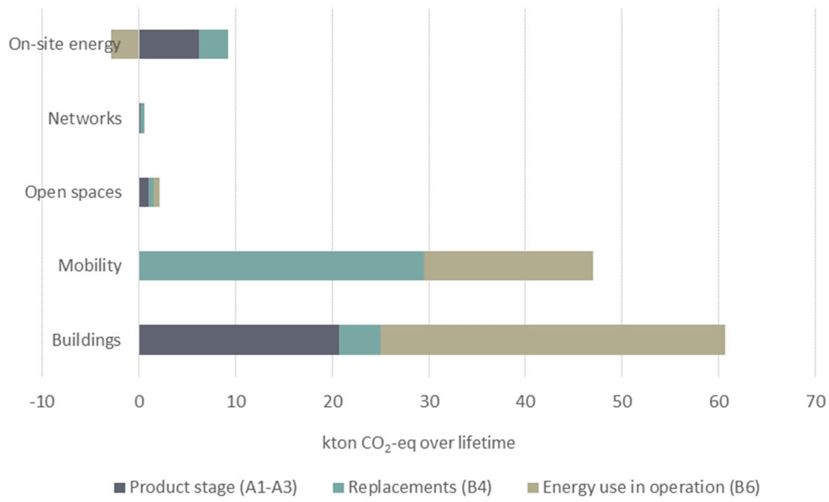

Figure 6: Total emissions for Zero Emission Village Bergen (ZVB) distributed between elements and life cycle stages (see S10.1 for data)

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 does not include the product stage of vehicles in the mobility element; recall that this is merged with the replacement stage of vehicles due to the shorter service life of vehicles.

The total emissions are distributed over the years as presented in Figure 7. Emissions embodied in materials that are used for 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 slowly increase due to the shift from fossil fuel vehicles to battery– and hydrogen-based electrical vehicles.

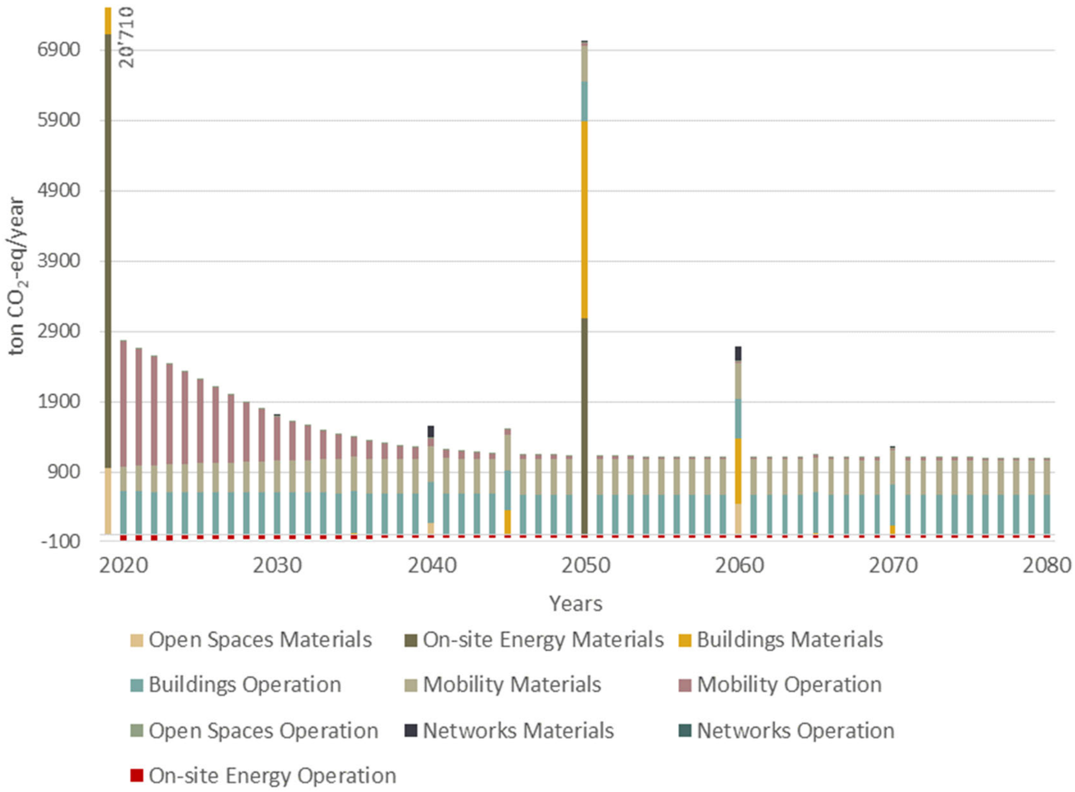

Figure 7: Total emissions by year distributed by element and life cycle stage

When taking a closer look at the parameters leading to overall emissions, the two elements that account 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 account for as much as 96% of these emissions, see S10.1 and S10.2. While these emissions increase over the vehicles' lifetime due to the increased share of battery-based electric vehicles, the emissions associated with mobility operation decrease drastically for the same reason. In considering the total period of 60 years, the use of internal combustion engine vehicles (both personal vehicles and buses) dominates with 89% of the emissions, despite the assumption that these vehicles will be completely phased out by 2060, see S10.3.

When focusing on the buildings, the results reveal that energy use in operation accounts for the majority of the emissions at 59%. Of this amount, 91% is sourced from district heat for space heating and domestic hot water. Regarding materials, residential buildings obviously account for most of the emissions, given that 93% of the floor area in the neighbourhood is in residential buildings. This is amplified by the fact that residential buildings account for relatively more emissions when looking at emissions per floor area, 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 with the largest influence on change in total emissions results, are the travel distance per inhabitant and the buildings' energy load.

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 lightning +25%	0.005	0.1%

Figure 8 shows the change relative to the base case for each of the parameters and also for the two fundamental assumptions that are shown to have a considerable impact on the results, namely the emission intensity for electricity and the assumption of allocating emissions from waste incineration to the waste management system rather than to district heat production. If Scenario 2 (see Section 2.1) is used, referring to the EU28+NO electricity production mix instead of the Norwegian electricity production mix, total emissions over the 60-year analysis period increases by 12.5%. This is despite the fact that negative emissions from the on-site electricity production will also be greater, due to the significant increase in emissions from electricity consumed in mobility. If the emissions from waste incineration are not allocated to the district heating production, total emissions decreased by 25.3%. Hence, this is one of the most critical assumption in the LCA model.

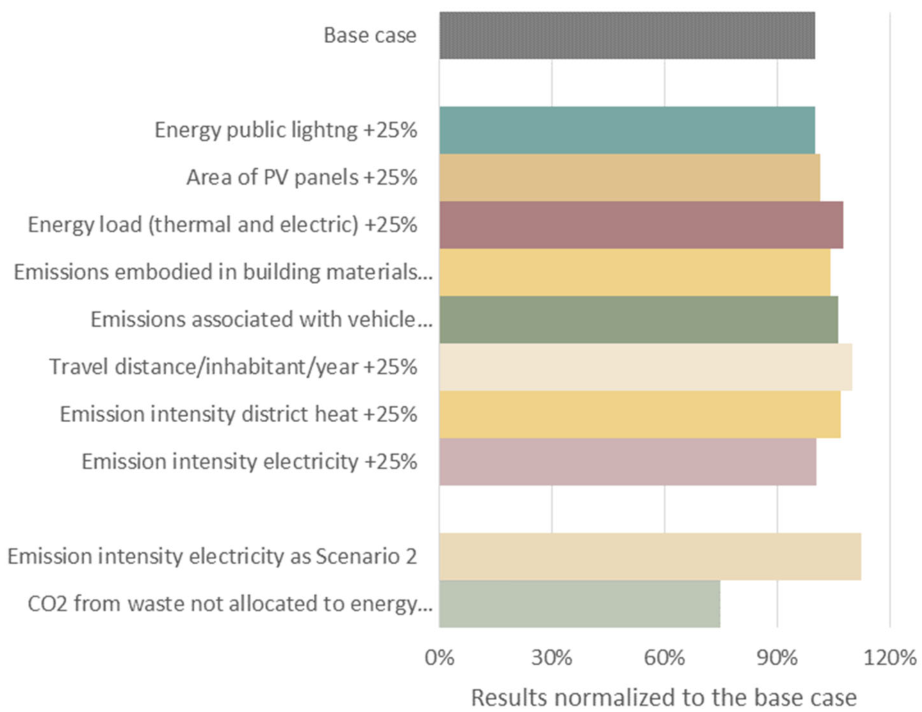

Figure 8: Sensitivity analysis results relatively to the base case. Notice that the axis does not start at zero.

4. Discussion

This section discusses the modular structure presented in Section 2.1 and the model developed for ZVB described in Section 2.2. The results obtained from the model are discussed in the context of the research questions presented in Section 1.3, and critical factors and uncertainties are deliberated. Finally, the usefulness and limitations of the analysis are discussed, and further work required on the field of LCA modelling for ZENs is suggested.

4.1 LCA Modelling on Neighbourhood Scale – Results and Critical Parameters

When moving from individual buildings to the more complex system of a neighbourhood in LCA modelling, it is crucial to clearly understand the effect of the assumed preconditions, and of which physical elements and life cycle stages are included. The modular approach used in this study enables us to examine the effect of changing system boundaries, both as regards the included elements and life cycle stages and in presenting the results with several functional units. The modules make it possible to easily adjust the LCA to fit different ZEN projects, with different preconditions, and to compare different projects with different premises.

The model developed for ZVB, as a case study based on the given modular structure, yielded results that offer useful insights. It revealed that buildings account for as much as 52% of the total emissions, given a ZEN OM ambition level for all physical elements in the neighbourhood. When looking at buildings alone, the emissions embodied in materials account for 41% of the total emissions, for the life cycle modules considered in the ZEN OM ambition level. This is comparable to, but not quite as much as, what was reported by Wiik, Fufa et al. (2017), who stated that the share of embodied emissions was between 55% and 87%. It should be noted that the emissions embodied in materials in the present study might be underestimates because of incomplete material lists for the residential buildings.

Another important finding is that of the remaining 59% of buildings emissions due to energy use, as much as 91% is associated with heat supply for space heating and domestic hot water. This again is mainly due to the single assumption that allocates the emissions associated with waste incineration to district heat production. In the present LCA, an emission intensity for heat production of 161.5 g CO_2/kWh based on criteria from the ZEB Centre (Multiconsult 2017) was used. Figure 8 shows that if the emissions from waste incineration were not allocated to heat production, the total emissions would decrease by as much as 25.2%. Hence, a change in this parameter makes considerable impact on the total results. Whether or not the assumption used here is the correct one is debatable. On the one hand, it can be argued that heat is a by-product of waste incineration technology, the main purpose of which is thermal destruction of waste, and therefore emissions from the incineration process should be allocated to the waste management system. This is currently the allocation principle that is suggested in the new Norwegian standard NS 3720. On the other hand, as pointed out by M. Lien (2013), *'waste is today an internationally tradable commodity that should be utilized where it gives maximum energy per unit greenhouse gas emitted'.* According to this view*,* emissions from waste incineration should clearly be allocated to heat production in a district heating system.

Something that may be surprising is that when Norwegian emission intensity is used, and assuming of symmetric weighting (i.e. using the same emission intensity for both directions of electricity exchanges between the power grid and the neighbourhood), 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, this is also a much debated subject in LCA studies (Dahlstrøm, Sørnes et al. 2012, Heeren, Mutel et al. 2015, Kristjansdottir, Heeren et al. 2018). First of all, the future electricity mix is hard to predict. Further, the electricity network is a complex system with varying exchanges of energy between countries and continents that depend on the season, accessibility and propagation of transfer possibilities. The sensitivity ratio for the emission intensity of electricity indicates that a change in this parameter does not drastically affect the total result, see Table 3. This is the case when all emissions are accounted for, including negative emissions associated with the on-site production of electricity from PV panels. Because symmetric weighting is assumed, both the positive and negative emissions increase when changing the emission intensity. If negative emissions are disregarded, the total emissions from the neighbourhood, including all elements, would increase by 30% when changing from Scenario 1 (NO) to Scenario 2 (EU28+NO). This clearly shows how critical this parameter is for the results. Due to the high sensitivity of the emission intensity of electricity, it is important to agree upon an emission intensity evolution over time, or an average value over the analysis period, that is as realistic as possible to facilitate decision making and choices of energy solutions for a ZEN project in the early planning stages.

The emissions from mobility in ZVB constitute 40% of the total neighbourhood emissions, and 37% of this comes from the operation of the transportation modes, i.e. the fuel/energy consumed in mobility. If the system boundaries are adjusted to match the ones examined by Bastos, Batterman et al. (2016), the results reveal large differences. While Bastos et al. found that transportation contributed 51-57% of the emissions 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 this study includes an optimistic future evolution in the share of electric personal vehicle stock combined with the low emission intensity for electricity. The remaining 63% of emissions from mobility come from the production of vehicles. If one adopts the system boundaries used by Anderson, Wulfhorst et al. (2015) that include 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 vehicle production does, which may indicate that the percentages is a coincidence.

The open spaces element consisting of roads, sidewalks, outside parking, and public lighting, plus the network element including the district heating pipes, only constitute 2.3% of the total lifetime neighbourhood emissions. This number is expected to be higher for an as-built project, due to the possibility of underestimating amounts of materials included in the model, and a lack of detailed data. The low share still indicates a relatively small contribution compared to the building and mobility elements, which also indicates that open spaces elements may not have to be accounted for in the early stages of planning of a ZEN project.

Conducting an LCA in the early stages of planning a project is useful to gain knowledge that serves as basis for decision making. Some choices made in the early planning stages are crucial for the design of the project and will affect its environmental performance over the project's entire lifetime. Examples in this study include the choice of structural building materials, spatial planning designs and technologies in the energy system. Some choices are more difficult to control, such as the future evolution of the energy mix in the electricity and district heat supply system, and the evolution of technologies in the vehicle stock. 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 with local storage capacity to be able to meet a rapidly growing share of electrical vehicles. In practice, when conducting an LCA at an early stage of planning, the main focus should be on the decisions that can facilitate as the lowest possible emissions in the future. This study points to the importance of such possibilities that can reduce yearly emissions particularly during the next few decades.

4.2 Limitations and Further Work

Although the LCA model in this study offers several advantages in highlighting the dominant drivers related both to the physical elements and life cycle stages and facilitating for comparability between design choices and between projects, certain limitations do still weaken the model.

First of all, the model does not yet 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 by 50% in the replacement. This limitation especially affects the accuracy of future mobility emissions, due to the frequent replacements of vehicles. With the current rapid technology improvement in the transportation sector, especially for electric vehicles, emissions from production processes will decrease, both for the vehicles themselves and for their fuel cycles. Further research is required to predict more accurate scenarios on future vehicle production. Emissions per distance driven for 2010 as reported by Simonsen (2010) and recommendations such as in the new NS 3720 standard (Standards Norway 2017) are not sufficient to make robust calculations on ZEN or other neighbourhood projects with an analysis period of 60 years. Also, the model does not consider the potential effect of climate changes on local climate. In Norway, the number of "warm days" (< 20°C) is expected to triple by 2010, and the heating season is predicted to become shorter (Hanssen-Bauer, Førland et al. 2017).

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

When conducting an LCA, several environmental impact categories are commonly used to show a more holistic environmental performance profile of a product or process. However, this study only reports climate change measured in GHG equivalent emissions. A broader analysis is needed to avoid problem-shifting phenomena. For example, a set of technology choices in a given ZEN project yields reduced GHG emissions but increased environmental impacts in other impact categories such as acidification, land use change and photochemical smog. Therefore, the LCA model need to be extended to also consider other relevant impact categories, despite the fact that the present political focus is on energy use and GHG emissions.

Finally, the model is based on yearly values rather than hourly data for the consumption and production of energy. In practice, this means that the external electricital 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, or at what times during the year. This assumption can be justified by the fact that a symmetric weighting factor for electricity is used and that the emission intensity of electricity in Norway is fairly constant over the whole year. This is a simplification and may not reflect reality. Also, if the economic perspective is added, the price of imported vs. exported energy is commonly asymmetric. This perspective favours high self-consumption, because the price of exported energy is usually less than the price for import. Other factors such as energy storage and vehicle-to-grid concepts also become relevant here; however, they are outside the scope of this study.

5. Conclusion

In order to contribute to expedient use of LCA at the level of neighbourhood projects, and particularly in the context of several emerging ZEN projects, a modular structure that works as a basis for assessing ZEN projects at an early planning stage was proposed. An LCA model based on this structure was developed specifically for a ZEN project in Bergen, Norway. The goal was to determine the most important physical elements and life cycle stages contributing to the total GHG emissions of this project.

The results show that when considering the building, mobility, open spaces, network and on-site energy generation elements, as well as the three life cycle stages of the product stage, replacement stage and energy use in operation, buildings represent the majority (52%) of total GHG emissions, closely followed by mobility (40%). Among the life cycle stages, the total emissions are dominated by the emissions embodied in materials from the product stage and replacements (56%), with the remaining emissions resulting from energy use in operation (44%). For all the elements except for buildings, embodied emissions exceed 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 are allocated to heat production. This assumption is therefore a critical factor, along with the value of the emission intensity for electricity, the daily travel distance per day for the inhabitants, and the emissions associated with vehicle production.

The LCA model has clear potential to facilitate decision making in early stages planning ZEN projects. It can provide information on dominant elements and life cycle stages, and its modular structure ensures comparability, transparency and adaptability. On the other hand, the LCA model, and consequently also its results, suffers from uncertainties and simplifications, particularly on how technologies, user behaviour and climate may change in a long-term perspective. Further work is therefore required when it comes to forecasting emission intensities, emissions associated with the production of materials and vehicles in the future, and the consequences of assuming symmetric weighting for emissions related to both directions of electricity exchanges between the power grid and the neighbourhood.

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References

Ajanovic, A. 2015. The future of electric vehicles: prospects and impediments. Wiley Interdisciplinary Reviews: Energy and Environment **4**:521-536.

Anderson, J. E., G. Wulfhorst, and W. Lang. 2015a. Energy analysis of the built environment—A review and outlook. Renewable and Sustainable Energy Reviews **44**:149-158.

Anderson, J. E., G. Wulfhorst, and W. Lang. 2015b. Expanding the use of life-cycle assessment to capture induced impacts in the built environment. Building and Environment **94**:403-416.

Bastos, J., S. A. Batterman, and F. Freire. 2016. Significance of mobility in the life-cycle assessment of buildings. Building Research and Information **44**:376-393.

Bayoumi, M., and D. Fink. 2014. Maximizing the performance of an energy generating façade in terms of energy saving strategies. Renewable Energy **64**:294-305.

Birgisdóttir, H., K. A. Pihl, G. Bhander, M. Z. Hauschild, and T. H. Christensen. 2006. Environmental assessment of roads constructed with and without bottom ash from municipal solid waste incineration. Transportation Research Part D: Transport and Environment **11**:358-368.

Brown, N. W. O., S. Olsson, and T. Malmqvist. 2014. Embodied greenhouse gas emissions from refurbishment of residential building stock to achieve a 50% operational energy reduction. Building and Environment **79**:46-56.

Cabeza, L. F., L. Rincón, V. Vilariño, G. Pérez, and A. Castell. 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews **29**:394-416.

Cellura, M., F. Guarino, S. Longo, and G. Tumminia. 2018. Climate change and the building sector: Modelling and energy implications to an office building in southern Europe. Energy for Sustainable Development **45**:46-65.

Chastas, P., T. Theodosiou, and D. Bikas. 2016. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Building and Environment **105**:267-282.

Cherqui, F. 2005. Methodology for assessing sustainable urban district project - ADEQUA method. Université de La Rochelle.

Dahlstrøm, O., K. Sørnes, S. T. Eriksen, and E. G. Hertwich. 2012. Life cycle assessment of a single-family residence built to either conventional- or passive house standard. Energy and Buildings **54**:470-479.

Davila, C. C., and C. Reinhart. 2013. Urban energy lifecycle: An analytical framework to evaluate the embodied energy use of urban developments.

Dokka, T. H., T. F. Kristjansdottir, B. Time, S. Mellegård, M. Haase, and J. Tønnesen. 2013. A zero emission concept analysis of an office building.

European Commission. 2010. Energy Performance of Buildings Directive, Directive 2010/31/EU.

European Commission. 2012. Energy Efficiency Directive.

European Parliament and the Council. 2012. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. http://data.europa.eu/eli/dir/2012/27/oj.

Fridstrøm, L., and V. Østli. 2016. Vehicle fleet forecasts based on stock-flow modeling.

Fufa, S. M., R. D. Schlanbusch, K. Sørnes, M. Inman, and I. Andresen. 2016. A Norwegian ZEB Definition Guideline.

Granata, G., F. Pagnanelli, E. Moscardini, T. Havlik, and L. Toro. 2014. Recycling of photovoltaic panels by physical operations. Solar Energy Materials and Solar Cells **123**:239-248.

Hanssen-Bauer, I., E. J. Førland, I. Haddeland, H. Hisdal, S. Mayer, A. Nesje, J. E. Ø. Nilsen, S. Sandven, A. B. Sandø, A. Sorteberg, and B. Ådlandsvik. 2017. Climate in Norway 2100– a knowledge base for climate adaptation.

Heeren, N., C. L. Mutel, B. Steubing, Y. Ostermeyer, H. Wallbaum, and S. Hellweg. 2015. Environmental Impact of Buildings—What Matters? Environmental Science & Technology **49**:9832-9841.

Hellweg, S., and L. M. I. Canals. 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science **344**:1109-1113.

ISO. 2006. ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework.

Junnila, S., A. Horvath, and A. Guggemos. 2006. Life-Cycle Assessment of Office Buildings in Europe and the United States.

Khasreen, M., P. F. Banfill, and G. Menzies. 2009. Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. Sustainability **1**:674.

Kristjansdottir, T. F., N. Heeren, I. Andresen, and H. Brattebø. 2017. Comparative emission analysis of low-energy and zero-emission buildings. Building Research and Information:1-16.

Kristjansdottir, T. F., N. Heeren, I. Andresen, and H. Brattebø. 2018. Comparative emission analysis of low-energy and zero-emission buildings. Building Research & Information **46**:367-382.

Kuzman, M. K., P. Grošelj, N. Ayrilmis, and M. Zbašnik-Senegačnik. 2013. Comparison of passive house construction types using analytic hierarchy process. Energy and Buildings **64**:258-263.

Li, D., and R. Wang. 2009. Hybrid Emergy-LCA (HEML) based metabolic evaluation of urban residential areas: The case of Beijing, China. Ecological Complexity **6**:484-493.

Lotteau, M., P. Loubet, M. Pousse, E. Dufrasnes, and G. Sonnemann. 2015a. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Building and Environment **93**:165-178.

Lotteau, M., G. Yepez-Salmon, and N. Salmon. 2015b. Environmental Assessment of Sustainable Neighborhood Projects through NEST, a Decision Support Tool for Early Stage Urban Planning. Procedia Engineering **115**:69-76.

Lucon, O., D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L. F. Cabeza, N. Eyre, A. Gadgil, L. D. D. Harvey, Y. Jiang, E. Liphoto, S. Mirasgedis, S. Murakami, J. Parikh, C. Pyke, and M. V. Vilariño. 2014. Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel

on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S.

Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)].

M. Lien, K. 2013. CO2 emissions from Biofuels and District Heating in Zero Emission Buildings (ZEB). The Research Centre on Zero Emissions Buildings.

Massarutto, A. 2015. Economic aspects of thermal treatment of solid waste in a sustainable WM system. Waste Management **37**:45-57.

Mastrucci, A., A. Marvuglia, U. Leopold, and E. Benetto. 2017. Life Cycle Assessment of building stocks from urban to transnational scales: A review.

Multiconsult. 2017. Varedeklarasjon fjernvarme BKK - BREEAM-NOR 2016.

Nichols, B. G., and K. M. Kockelman. 2014. Life-cycle energy implications of different residential settings: Recognizing buildings, travel, and public infrastructure. Energy Policy **68**:232-242.

Norman, J., H. Maclean, M. Asce, and C. A Kennedy. 2006. Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions.

Oliver-Solà, J., X. Gabarrell, and J. Rieradevall. 2009. Environmental impacts of the infrastructure for district heating in urban neighbourhoods. Energy Policy **37**:4711-4719.

Oliver-Solà, J., A. Josa, A. P. Arena, X. Gabarrell, and J. Rieradevall. 2011. The GWP-Chart: An environmental tool for guiding urban planning processes. Application to concrete sidewalks. Cities **28**:245-250.

Ramesh, T., R. Prakash, and K. K. Shukla. 2010. Life cycle energy analysis of buildings: An overview. Energy and Buildings **42**:1592-1600.

Riera Pérez, M. G., and E. Rey. 2013. A multi-criteria approach to compare urban renewal scenarios for an existing neighborhood. Case study in Lausanne (Switzerland). Building and Environment **65**:58-70.

Rossi, B., A.-F. Marique, M. Glaumann, and S. Reiter. 2012a. Life-cycle assessment of residential buildings in three different European locations, basic tool. Building and Environment **51**:395-401.

Rossi, B., A.-F. Marique, M. Glaumann, and S. Reiter. 2012b. Life-cycle assessment of residential buildings in three different European locations, basic tool.

Roux, C., P. Schalbart, E. Assoumou, and B. Peuportier. 2016. Integrating climate change and energy mix scenarios in LCA of buildings and districts. Applied Energy **184**:619-629.

Salom, J., A. J. Marszal, J. Widén, J. Candanedo, and K. B. Lindberg. 2014. Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data. Applied Energy **136**:119-131.

Sartori, I., S. Merlet, B. Thorud, T. Haug, and I. Andresen. 2016. Zero Village Bergen - Aggregated loads and PV generation profiles.

Sartori, I., K. S. Skeie, K. Sørnes, and I. Andresen. 2018. Zero Village Bergen - Energy system analysis.

Sharma, A., A. Saxena, M. Sethi, V. Shree, and Varun. 2011. Life cycle assessment of buildings: A review. Renewable and Sustainable Energy Reviews **15**:871-875.

Simonsen, M. 2010. Transport, energi og miljø.

Standard Norge. 2012. NS-EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method (in Norwegian).
Standard Norge. 2018. NS 3720:2018 - Methods for greenhouse gas calculations for buildings (in Norwegian).
Standards Norway. 2017. prNS 3720 Method for greenhouse gas calculations for buildings.
Stephan, A., R. H. Crawford, and K. de Myttenaere. 2013. Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia. Building and Environment **68**:35-49.
The Research Centre on Zero Emission Buildings (ZEB). The Research Centre on Zero Emission Buildings (ZEB).
Wiik, M. K., S. M. Fufa, T. Kristjansdottir, and I. Andresen. 2017. Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB researh centre.
Yang, X., M. Hu, J. Wu, and B. Zhao. 2018. Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China. Journal of Cleaner Production **183**:729-743.
Yepez-Salmon, G. 2011. Construction d'un outil d'évaluation environnementale des écoquartiers : vers une méthode systémique de mise en œuvre de la ville durable. Université Bordeaux.
ZEN, F. 2018. ZEN Research Centre.

B.2 Supplementary 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)

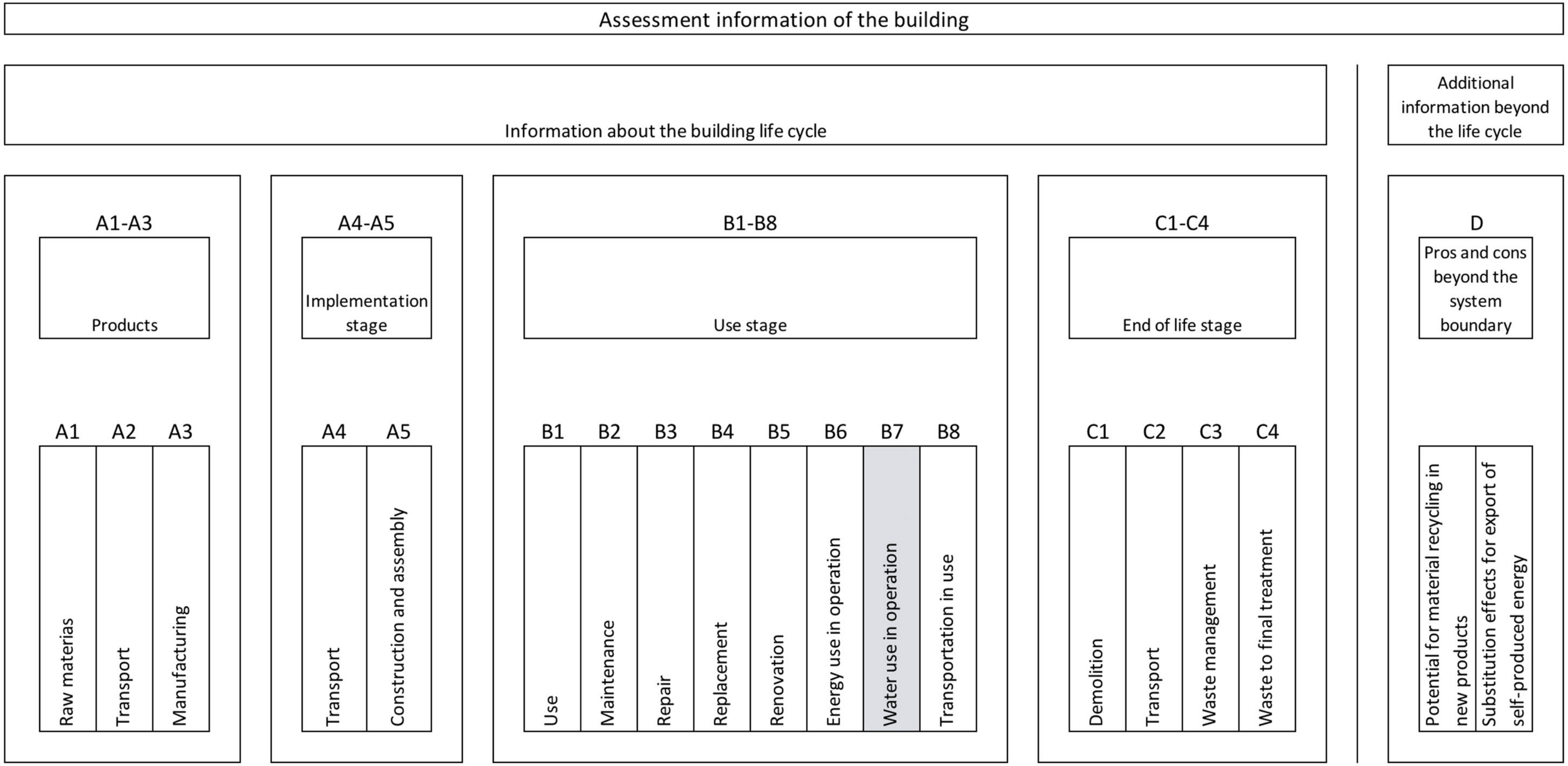

Figure 1 Information about the building life cycle, translated from prNS 3720 (Standards Norway 2017)

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 (Standards Norway 2017). 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 1.

Table 1 CO2-factors for different production technologies and production mix 2015 and 2050 for Norway and Europe (EU28+NO). Adopted from Standards Norway (2017).

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

For 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 considers the district heat in Bergen specifically.

Table 2 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 (AS 2017). The numbers in parenthesis is the number used if the emissions from the waste incineration is not allocated to the district heat production, but to the waste management system (Løseth 2011). According to BKK (Norwegian power company located in Bergen), the district heat in Bergen is going to be fossil free by 2020. In practice, it will be achieved by replacing the peak load sources with bio oil (Horne 2018). Based on this, the mix, and associated emissions in 2020 is assumed to be as described in Table 3. It should be noted that the emission intensity for electricity is as stated in S2.1. Further, the emissions from the district heating are 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 2 shows the intensity for the district heat from 2020 to 2080 with and without the emissions from the waste incineration allocated.

Table 2 Energy and emissions district heat Bergen 2017 (AS 2017)

	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 3 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 (Fufa et al. 2016) except for electricity which follows the evolution as described in S2.1.

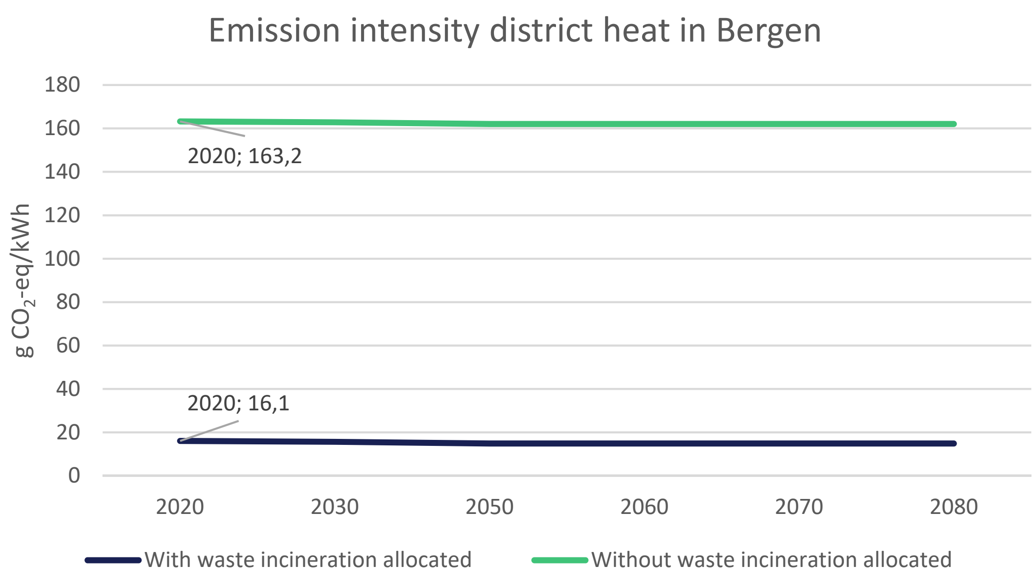

Figure 2 Emission intensity district heat Bergen with and without the emissions from waste incineration allocated to heat production

S3. Modular Structure Zero Village Bergen

Table 4 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

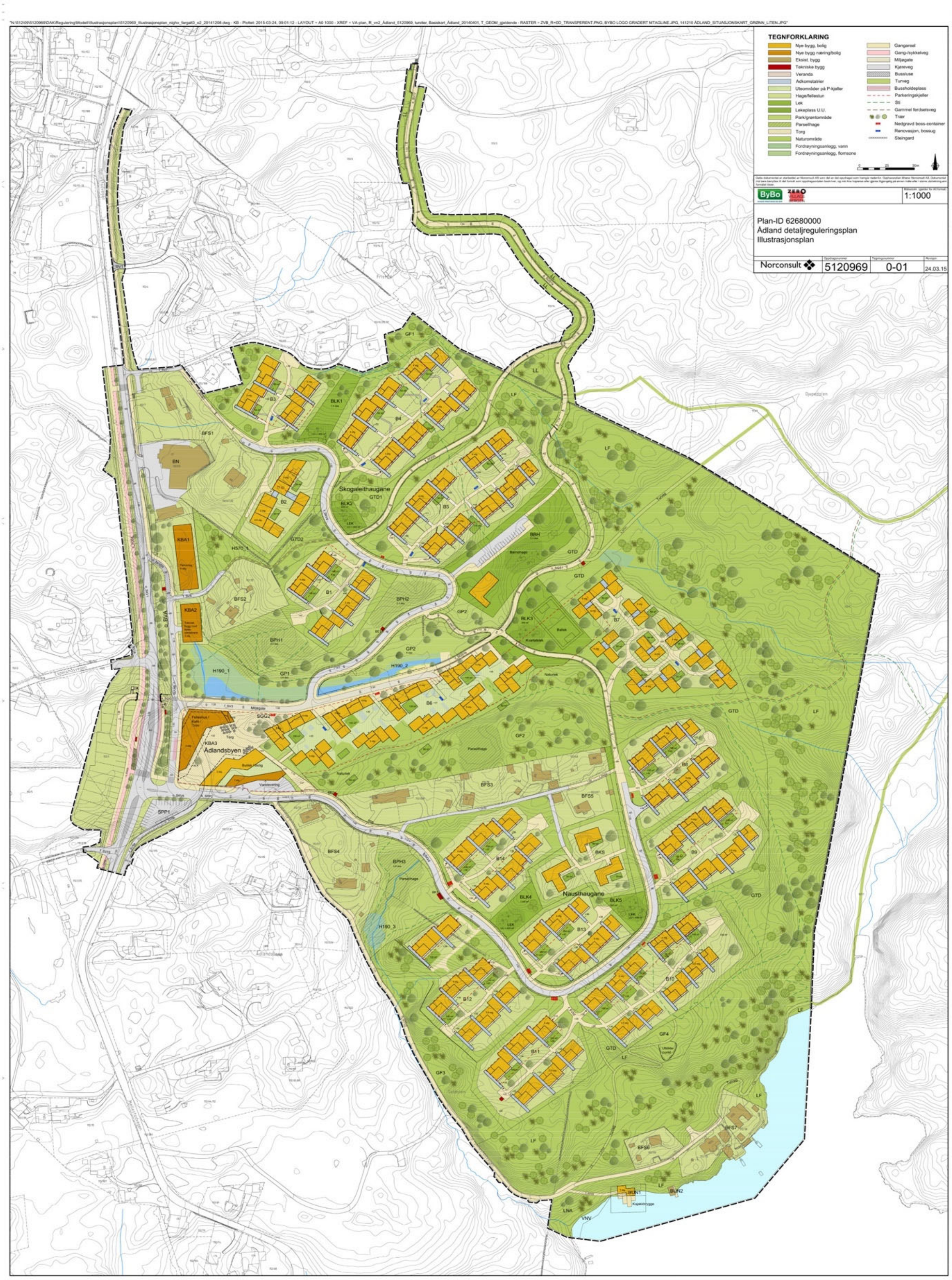

Figure 3 Map over ZVB, scale: 1:1000 (for A0 format), equivalent to 841x1189m in real size

S5. Buildings

S5.1 Number of Inhabitants

The number of occupants per dwelling (Table 5) is based on data from Statistics Norway (Norway 2013), 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 5 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. (2016) and recommendations for parking garages (Kirkhus 2015). 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 Tables 6, 7 and 8 respectively.

Table 6 Materials residential buildings /m^2

Building Parts	Building component	Material	Amount/m^2				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*37 mm	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/El60 (separation stair/tech) wood studs	Insulation		m2	0,57	kg CO2-eq/m2*37 mm	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
		Steel stud	0,51	kg	1,45	kg CO2-eq/kg	Ecoinvent	Steel, low-alloyed, at plant/RER U	30
	242 Non-load bearing wall/Gypsum wall (shaft/wc)	Insulation		kg	0,57	kg CO2-eq/m2*37 mm	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*37 mm	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*37 mm	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*37 mm	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 7 Material list non-residential buildings per m^2

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 8 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 9 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"* (Sartori et al. 2016).

Table 9 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 (Hjorthol et al. 2014). Here, the average number of travels per day for people with very good access to public transport is 3.34 travels per day. Table 10 gives information on the travel habits resulting from the survey.

Table 40 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 4.

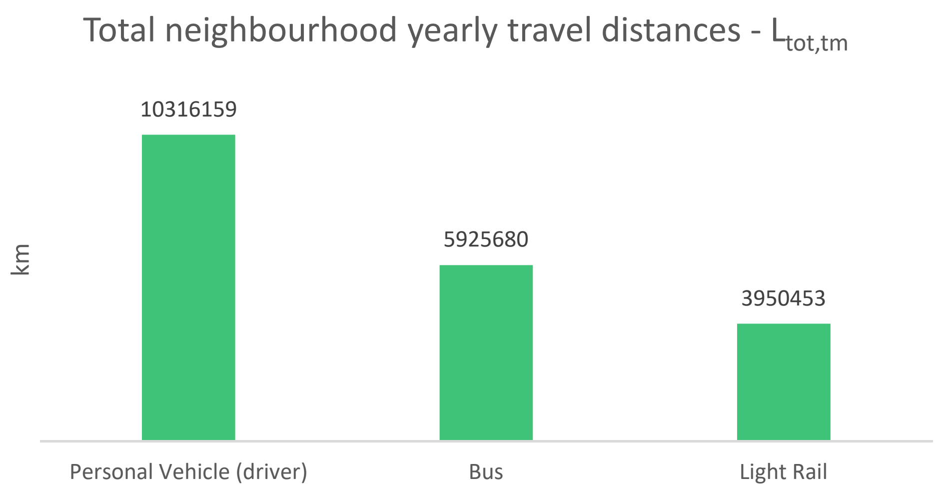

Figure 4 Total neighbourhood yearly travel distances (km/y) by transportation mode – $L_{tot,tm}$

S6.2 Evolution of Vehicle Stocks

Table 11 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 12 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 10 in S6.1. For buses and the light rail, the numbers of passengers are 17 and 34 respectively (Simonsen 2010b). 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 12 Emissions per distance travelled for each transport mode

Passengers/vehicle	Personal vehicles 1.2			Bus 17			Light Rail 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 (2010b), see Table 13 (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 aligns with numbers found in literature (1.1-1.6 kWh/km for electric buses (Grütter 2014, Varga and Iclodean 2015, Jungmeier 2017) and 1.8-2.0 kWh/km for hydrogen buses (Jenné 2015, Starikovs 2017)). The WtT fuel cycle emission intensities for buses were assumed being equal to the ones for personal vehicles. Simonsen (2010a) 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 is 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 (Andersen 2017).

Table 13 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. (2013), 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 5. 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.

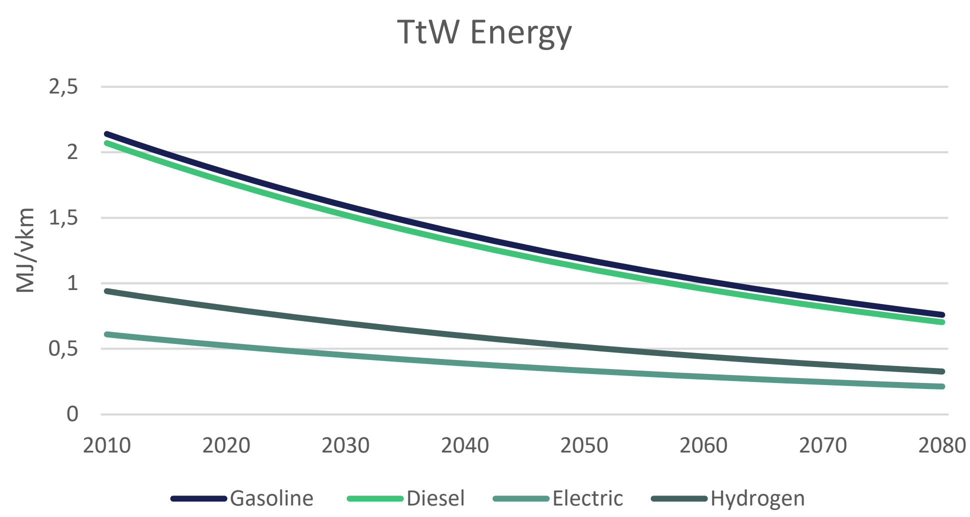

Figure 5 Improvements in TtW energy 2010 to 2080

Table 14 shows the WtW emissions per passenger-km for the different means of transport in snapshots for 2020, 2040, 2060 and 2080.

Table 14 WtW emissions snapshots (g CO_2-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 6 is from a study performed by Birgisdóttir et al. (2006) 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, 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.

S7.2 Materials included in the Open Spaces

Table 15 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 (Mills et al. 2014), see Table 16.

Table 16 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 6. The red dot marks the location of Ådland, where Zero Village Bergen is situated.

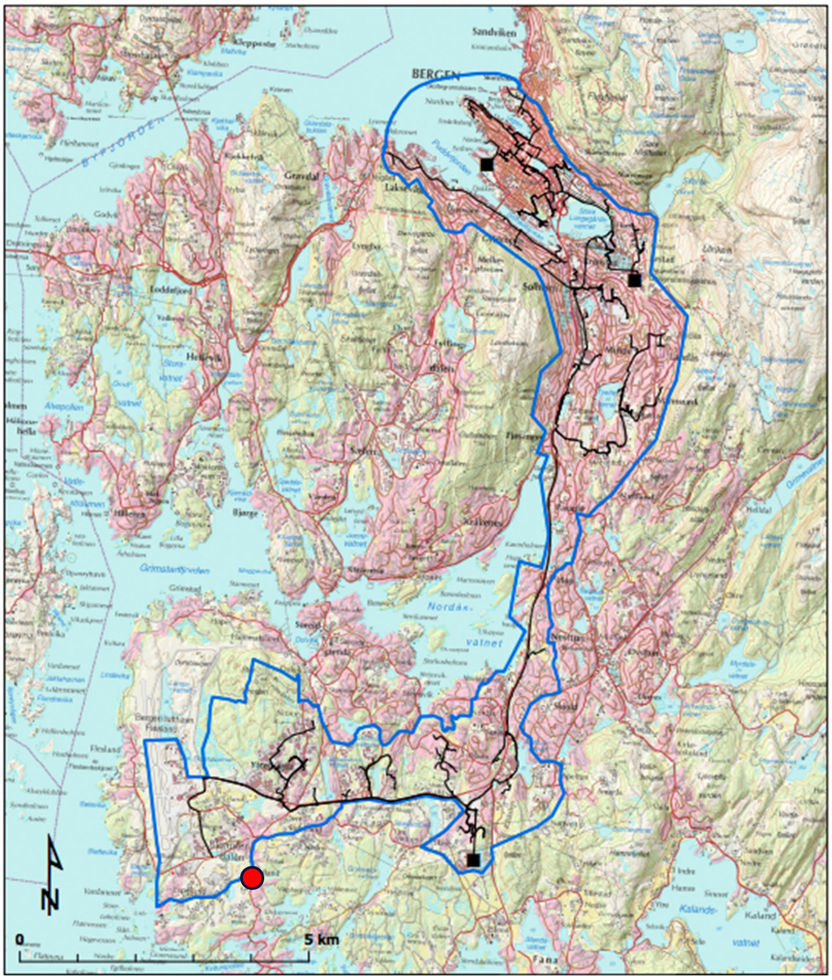

Figure 6 District heating system in Bergen (BKK 2012)

S8.2 Materials included in the District Heating Network

Table 17 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 in Table 17, Ecoinvent database 3.2 was used. In the study by Oliver-Solà et al. (2009) however, version 1.2 was used. Table 18 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 18 The materials used for the district heat network in (Oliver-Solà et al. 2009) and in the present study

Used in (Oliver-Solà et al. 2009) (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 19 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 20 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 21 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 22 Emissions associated with replacement of vehicles by sub-element and year (kg CO_2-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 23 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 24 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 25 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

References

Ajanovic, A., G. Jungmeier, M. Beermann, and R. Haas. 2013. Driving on Renewables—On the Prospects of Alternative Fuels up to 2050 From an Energetic Point-of-View in European Union Countries.

Andersen, O. 2017. Effekter av Dieselgate-skandalen på energiforbruk og CO2-utslipp. Vestlandsforskning.

AS, M. N. 2017. Varedeklarasjon fjernvarme BKK.

Birgisdóttir, H., K. A. Pihl, G. Bhander, M. Z. Hauschild, and T. H. Christensen. 2006. Environmental assessment of roads constructed with and without bottom ash from municipal solid waste incineration. Transportation Research Part D: Transport and Environment **11**:358-368.

BKK. 2012. Her er det fjernvarme. BKK.

Fufa, S. M., R. D. Schlanbusch, K. Sørnes, M. Inman, and I. Andresen. 2016. A Norwegian ZEB Definition Guideline.

Grütter, J. M. 2014. Real World Performance of Hybrid and Electric Buses.

Hjorthol, R., Ø. Engebretsten, and T. P. Uteng. 2014. 2013/14 National travel survey - key results.

Horne, M. 2018. Utvikling av utslippsintensitet fjernvarme Bergen.*in* V. Borgnes, editor.

Jenné, P. 2015. Fuel Cell Electric Bus Projects – Status and Outlook from an Industry Perspective. Lyon.

Jungmeier, G. 2017. IEA HEV Task 33 "Battery Electric Busses". International Conference on Electric Mobility and Public Transport Santiago, Chile.

Kirkhus, A. 2015. Planleggng av parkeringsplasser og garasjeanlegg. Sintef Byggforsk.

Løseth, M. 2011. Klimaregnskap for fjernvarme - Felles utslippsfaktorer for den norske fjernvarmebransjen. Norsk Energi.

Mills, N., P. Pearce, J. Farrow, R. B. Thorpe, and N. F. Kirkby. 2014. Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. Waste Management **34**:185-195.

Norway, S. 2013. Population and housing census, dwellings, 19 November 2011. ssb.no.

Oliver-Solà, J., X. Gabarrell, and J. Rieradevall. 2009. Environmental impacts of the infrastructure for district heating in urban neighbourhoods. Energy Policy **37**:4711-4719.

Sartori, I., S. Merlet, B. Thorud, T. Haug, and I. Andresen. 2016. Zero Village Bergen - Aggregated loads and PV generation profiles.

Simonsen, M. 2010a. Energibruk og utslipp fra persontransport med personbil. En livsløpsanalyse. . Vestlandsforskning.

Simonsen, M. 2010b. Transport, energi og miljø.

Standards Norway. 2017. prNS 3720 Method for greenhouse gas calculations for buildings.

Starikovs, A. 2017. Fuel cell electric buses across North-East Europe. BSR Hydrogen Network Conference, Riga.

Varga, B. O., and C. Iclodean. 2015. Electric Buses for Urban Transportation: Assessment on cost, Infrastructure and Exploitation.

Appendix C – A novel LCA model for the zero emission neighbourhood concept

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Abstract

Buildings represent a critical piece of a low-carbon future and their long lifetime necessitates urgent adoption of state-of-the-art performance standards to avoid significant lock-in risk. So far, LCA studies have assessed buildings, mobility and energy systems mainly individually. Yet, these elements are closely linked together, and to assess the nexus of housing, mobility, and energy associated with human settlements by aiming for Zero Emission Neighborhoods (ZENs) gives a unique chance to contribute to climate change mitigation.

We conducted an LCA of a neighbourhood of single-family houses built according to Norwegian passive house standard. We designed four scenarios where we tested the impact of the house sizes, household size, energy used and produced in the buildings, and mobility patterns. Also, we ran our scenarios with different levels of decarbonization of the electricity mix over a time period of 60 years.

Our results show the importance of the operational phases of both building and mobility at year 1, and its decline over time induced by the decarbonization of the electricity mix. In year 60, embodied emissions are then responsible for the majority of the emissions when the electricity mix is decarbonized. The choice of functional unit is decisive for the conclusion of the study. When conducting LCAs on a neighbourhood scale, we thus argue for the use of a primary functional unit "per neighbourhood", and a second "per person". The use of a "per m^2" is misleading as does not give credits to precautionary use of floor area.

1. Introduction

A reduction in global greenhouse gas (GHG) emissions can slow down the global warming rate, but a stabilization of the temperature can only occur if GHG emissions approach zero (Myhre, Shindell et al. 2013). Globally, buildings account for 32% of total final energy use, 19% of energy-related GHG emissions, and approximately one third of black carbon emissions. Transport is responsible for 14% of the energy-related GHG emissions, with road transport as the main contributor (Victor, Zhou et al. 2014). The nexus of housing, mobility, and energy associated with human settlements is assessed by widening the system boundary from a building to a neighbourhood scale, and aiming for Zero Emission Neighborhoods (ZENs) gives a unique chance to contribute to climate change mitigation.

Buildings represent a critical piece of a low-carbon future and their long lifetime necessitates urgent adoption of state-of-the-art performance standards to avoid significant lock-in risk, both for new and renovated buildings (Lucon, Ürge-Vorsatz et al. 2014, Sandberg, Sartori et al. 2016). The European Parliament has addressed this urgency by the introduction of the Energy Performance of Buildings Directive (EPBD); all new buildings within the European Union shall be nearly Zero Energy Buildings (nZEB) by the end of 2020 (European Commission 2010). In Norway, the new standard NS 3720:2018 "Method for greenhouse gas calculations for buildings" addresses the nexus and includes transport in the use stage as one module in calculations of GHG emissions from buildings.

Life-cycle assessment (LCA) is a standardized method frequently used to give an overview of how various types of environmental impacts accumulate over the different life-cycle phases and elements of a system. It provides a basis for identifying environmental bottlenecks of specific technologies and for comparing a set of alternative scenarios with respect to environmental impacts (Finnveden, Hauschild et al. 2009, Hellweg and Canals 2014). Within the last decade, LCA has been used extensively to evaluate the environmental performance of buildings, energy systems, and mobility, and the life-cycle perspective should be well-integrated into decision-making processes (Lucon, Ürge-Vorsatz et al. 2014). However, this is yet hardly the case in practical planning of neighbourhoods today, and few LCA studies are published on the neighbourhood scale, despite the growing interest for such in modern urban planning.

1.1 LCA of buildings

The life-cycle GHG emissions of conventional buildings are dominated by high energy consumption in the use phase with a share of about 80% of life-cycle GHG emissions (Sartori and Hestnes 2007, Blengini and Di Carlo 2010). Embodied GHG emissions are somewhat higher for low-energy buildings and passive house designs mainly due to the higher use of insulation materials and the drastically reduced energy demand (Houlihan Wiberg, Georges et al. 2014); they can account from 50% (Dahlstrøm, Sørnes et al. 2012) to 70% (Kristjansdottir, Heeren et al. 2017, Wiik, Fufa et al. 2018) of the total emissions in such building designs. The magnitude of the contribution of the use phase is driven by the embodied emissions in construction materials, and by the carbon intensity of the consumed energy carriers (Dahlstrøm, Sørnes et al. 2012, Heeren, Mutel et al. 2015). Electricity is the main energy carrier to serve energy demand in buildings in Norway, and the national power grid is highly dominated by hydropower and with relatively small shares of import and export. Hence, the electricity mix has a very low carbon intensity (18 g CO_2 eq./kWh), and the construction phase play a greater relative role.

For all building types (single-family house, terraced house, multi-family building and apartment block), Moschetti, Mazzarella et al. (2015) found the use phase to constitute the clear majority of the life-cycle impacts. Yet, the construction phase dominates the global cost and the impact categories ozone depletion and marine eutrophication. Kristjansdottir, Heeren et al. (2017) compared GHG emissions of different low-energy and zero-emission designs of Norwegian single-family houses, and found embodied emissions to represent 60– 75% of the life-cycle climate change impacts, confirming the importance of materials in strategies for zero emission buildings (ZEBs) in Norway. Houlihan Wiberg, Georges et al. (2014) aimed at investigating the possibility to achieve a net ZEB (nZEB) by balancing emissions from the energy used for operation and embodied emissions from materials with those from on-site renewable electricity generation in Norway. Their study confirmed the dominating role of embodied emission in a total life-cycle perspective, the emission gains from surplus on-site PV electricity production exported to the grid not to be sufficient to compensate for the embodied emissions. Heeren, Mutel et al. (2015) conducted a study to identify drivers of the environmental impact of wooden and massive residential and office buildings in a central European climate. The parameters ranking highest in influencing climate change were found to be the electricity mix, the ventilation rate, the heating system and the construction materials.

As ZEBs will represent a major part of the life cycle inventory in a ZEN concept, it is obvious that LCA literature on the ZEB level should strongly inform LCA modelling on the ZEN level.

1.2 LCA of passenger cars

Road transport accounts for 16% of the national GHG emissions, and passenger cars for 54% of the road transport GHG emissions (Statistics Norway 2018), and is a sector with high priority in climate actions. The overall performance of the private vehicle fleet is mainly determined by the car size and the number of km driven (Pauliuk, Dhaniati et al. 2012). In opposition to internal combustion engine vehicles (ICEVs), fully battery electric vehicles (BEVs) have no tailpipe emission. Yet, indirect emissions associated with electricity production and materials can be significant, and a life-cycle approach is required to assess trade-offs along the whole value chain. LCA studies on BEVs showed the life-cycle performance to be driven by the carbon intensity of the electricity sources used in the battery production and to charge the BEV (Hawkins, Singh et al. 2013, Ellingsen, Majeau-Bettez et al. 2014, Ellingsen, Singh et al. 2016, Cox, Mutel et al. 2018). Typically, the overall life-cycle GHG emissions of BEVs compared to ICEVs are reduced moderately for a BEV powered by the average European electricity, increased for a BEV powered by coal-based electricity, and can be more than halved for a BEV powered by renewable electricity sources (Ellingsen, Singh et al. 2016).

Few studies combine prospective LCA of buildings and transport to serve the users' housing and mobility needs at neighbourhood scale, and the relative importance of the two must be understood much better under different context situations in order to inform urban development and neighbourhood design policies.

1.3 LCA on urban scale

Robust and accurate methods have been developed to quantify the built environment at both individual and urban scales (Anderson, Wulfhorst et al. 2015). Despite the clear overlap of the developed methods, case studies largely remain confined in their scale. By confining the analysis on an individual building level, the building is isolated from its context, and treated as a stand-alone object. Mobility needs and the corresponding environmental impacts are closely related to building location (Bastos, Batterman et al. 2016, Stephan and Stephan 2016) and the individual buildings must be set in a holistic impact analysis to capture these effects. Saner, Heeren et al. (2013) assessed the housing and mobility demands of individual households for a small village in Switzerland, and found a mean value per year of 4.30 ton CO_2 eq./pers. Stephan, Crawford et al. (2013) conducted a multi-scale life-cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia, and found shares in the range of 15-39% for embodied emissions in buildings and infrastructure, 29-52% for operation of buildings and 24-46% for transport, in accordance with Stephan, Crawford et al. (2012). Harter, Weiler et al. (2017) developed a roadmap for the modernization of a city quarter, and found refurbishment of the city quarter to be more favorable than demolition and reconstruction for primary energy demand and GHG emissions, as long as the structural condition of the building allows it.

Lotteau, Loubet et al. (2015) conducted a review on the built environment at the neighbourhood scale, and reported the following main findings: (1) the type of assessed neighbourhoods was mainly residential, (2) the numbers of inhabitants per neighbourhood ranged from 650 to almost 152,000, (3) the functional units were multiple - per inhabitant, per km^2 neighbourhood, per m^2 of living space/pers., per m^2 energy reference area, per m^2 floor area or per neighbourhood, (4) the residential density ranged from 370 pers./km^2 to 27,000 pers./km^2, (5) transports requirement for daily mobility was based on local or regional average empirical data or statistical models, (6) the overall emission results varied from 0.4

- 5.4 to kton CO_2 eq./neighbourhood/year, 0.6-8.6 ton CO_2 eq./pers./year, 3.6-7.8 ton CO_2 eq./m^2 neighbourhood/year and 10.8-123.8 kg CO2 eq./ m^2 floor area/year.

In another review, Mastrucci, Marvuglia et al. (2017) highlighted the potential for improvements in the aggregated building stock can be found in the refinement of the archetypes and building-by-building techniques, and in the integration of Geographical Information System and stock dynamic models. Their review showed buildings to rank highest with respect to emission contributions, closely followed by mobility, depending on the neighbourhood. The operational phase was in general predominant, but in the case of a low-energy neighbourhood, the share of emission contributions from the construction phase and the operational phase became similar in the overall picture.

1.4 Future energy systems

Energy industries have contributed to approximately 32% of global GHG emissions over the last 20 years (Janssens-Maenhout, Dentener et al. 2012). The deployment of power generation technologies harnessing wind and solar resources will reduce the carbon intensity of the power grid (Barnhart, Dale et al. 2013, Berrill, Arvesen et al. 2016, Gibon, Arvesen et al. 2017). So far, photovoltaic solar energy systems have been the most common energy source installed in ZEB or ZEN projects. (Seljom, Lindberg et al. 2017). But, other technologies such as micro scale (<0.1 MW) combined heat and power plants (CHPs) are typically installations for single family houses (Voss, Musall et al. 2011) whereas small scale (<2MW) CHPs can play a part in local thermal grids on a neighbourhood scale (Sartori, Skeie et al. 2018). CHP installations offer a good complement to PV in terms of equalizing the energy exchange between a neighbourhood and the grid. Many renewable energy and waste heat sources have a mismatch between production capacity and heat demand from buildings. This makes solutions for short-term and longer-term energy storage attractive. Example are the use of batteries for electricity storage and 'peak load shaving' in the supply system (Barnhart, Dale et al. 2013), or seasonal thermal energy storage (STES) of high temperature energy, such as underground storage of surplus district heat during summer to be used in high demand periods during winter. Yet, STES is a complex and high cost solution which will induce additional energy losses (Taxt and Fredriksen 2018). Renewable energies such as solar and wind leads to new energetic implications such as the effect of the curtailment or the storage of excess production (Barnhart, Dale et al. 2013). Finding the right trade-off between the benefit of flexibility and storage losses will be an important optimization problem in the design of ZENs.

1.5 Aim and scope

ZEBs and ZENs are likely to be critical components in a future climate change mitigation policy. This study addresses the challenge of how to use LCA when implementing such a policy, in line also with the introduction of the more stringent EPBD in 2010 that requires new buildings to be built with nZEB standards by the end of 2020 in the EU.

The specific aims of this study are threefold: First, to develop and apply an LCA model to support the evaluation of ZEN design concepts with respect to GHG emissions and other potential environmental impacts. Second, to clarify important contributing factors as well as revealing criticalities and sensitivities for GHG emission reductions and environmental performance of such ZEN design concepts. Third, to establish a model basis for other LCA studies on neighbourhood scale, in terms of a high-quality modelling approach regarding consistency, transparency, and flexibility.

2. Methodology

The proposed LCA model uses a modular approach based on the following subsystems; 1) buildings, 2) mobility and 3) energy systems. The ambition level undertaken in this study is "ZEB-OM" (Mamo Fufa, Dahl Schlanbusch et al. 2016, Standard Norge 2018), where O refers to all operational energy, equipment and appliances (B6 in figure S1 in the supplementary material), and M to the embodied emissions from the materials production (A1-A3 in figure S1) and replacement (B1-B5 in figure S1). Hence, this ambition level means that the neighbourhood aims to be zero emission when including all life cycle modules A1-A3 from production of materials and B1-B8 from operation from all subsystems, as shown in figure S1 in the supplementary materials. We have thus emission contributions from Building O, Building M, Mobility O, Mobility M and energy systems for on-site energy production (photovoltaic panels (PV)), as shown in figure 1.

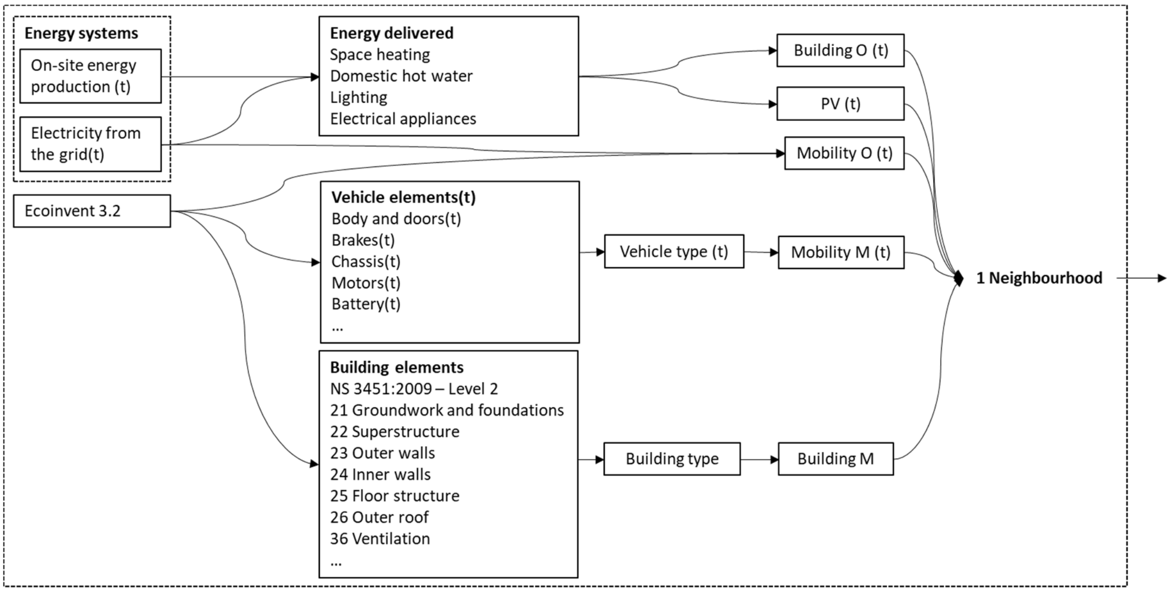

Figure 1: Absolute GHG emissions for the whole neighbourhood and for each scenario, by time step of one year, Norwegian electricity scenario

Ecoinvent v3.2 (Ecoinvent Centre 2015) is used for background data. ReciPe v1.12 (with a hierarchist perspective) is chosen for the midpoint category global warming potential (GWP100) (Goedkoop, Heijungs et al. 2009). Other impacts categories are not included in the present article, as the focus in the ZEN Centre is GHG emissions. Arda, a Matlab routine based program developed at NTNU (Majeau-Bettez and Strømman 2016) is used for the LCA calculations.

The total life-cycle GHG emissions of the neighbourhood is the sum of the total GHG emissions Building M, Building O, Mobility O, Mobility M and energy systems for on-site energy production (photovoltaic panels (PV)) as shown in equation (1) and described in the following sections.

$$GHG_{neighbourhood} = B_M + B_O + PV + M_M + M_O \quad (1)$$

Emissions from Building Materials

The assessed neighbourhood consists of one state-of-the-art single-family house type designed according to the Norwegian passive-house standard. The classification of the building parts is done according to the Norwegian table of building elements NS 3451:2009 (Standard Norge 2009), and the material inventory of the house is from Houlihan Wiberg, Georges et al. (2014). The house has two floors and a total heated floor area of 160 m^2.

The total GHG emissions embodied in building materials B_M is calculated according to equation (2). $GHG_{mat,init}$ (CO_2 eq./m^2) represents the emissions embodied in the materials initially contained in the buildings, $GHG_{mat,repl}$ (CO_2 eq./m^2) the emissions embodied in the materials used in replacements, bt the building type, A (m^2) the heated floor area and i is the year.

$$B_M = \sum_{bt} A_{bt} \cdot \left(GHG_{mat,init_{bt}} + \sum_{i=1}^{60} GHG_{mat,repl_{i,bt}} \right) \tag{2}$$

2.1 Emissions from Building Operation

The heating system is "all-electric", with heating pumps, solar collectors and PV panels on the roof. The electricity produced from the PVs is either used entirely on-site, or sent to the grid if in excess. Following the ZEB guidelines, a marginal approach is used to give credits for the excess on-site produced electricity sent to the grid (module D in figure S1). The total GHG emissions resulting from the operational phase of the buildings B_O is calculated according to equation (3), where $el_{delivered}$[2] (kWh/m^2) is the electricity delivered on a yearly basis, el_{onsite} (kWh/m^2) the yearly on-site electricity produced and GHG_{el} (g CO_2 eq./kWh) the grid electricity GHG intensity. GHG_{el} follows the Energy Technology Perspectives (ETP) scenarios from the International Energy Agency (IEA 2015) and is given in S2, in addition to a Norwegian electricity mix of 18 g CO_2 eq./kWh (Standard Norge 2018). If $(el_{delivered} - el_{onsite}) < 0$, $B_O < 0$ and B_O is credited negative emissions.

$$B_O = \sum_{bt} \sum_{i=1}^{60} A_{bt} \cdot (el_{delivered_{bt}} - el_{onsite_{bt}}) \cdot GHG_{el_i} \tag{3}$$

2.2 Emissions from PV systems

The GHG emissions embodied in the PVs is calculated with equation (4) with GHG_{PV} (CO_2 eq./kWh) the PV material GHG intensity, r the numbers of replacements over the lifetime (30 years) and C_{PV} (kWh/m^2) the installed capacity according to the building type bt. GHG_{PV} is of 56 g CO_2/kWh in year 2018 (i=1) and of 7 g CO_2/kWh in year 2038 (i=31), according to Gibon, Arvesen et al. (2017).

$$PV = \sum_{bt} \sum_{i=1}^{60} A_{bt} \cdot C_{PV_{bt}} \cdot \left(GHG_{PV,i}\right)(1 + r_i) \tag{4}$$

2.3 Emissions from Mobility Materials

The composition of the car stock is predicted to change drastically during the next years, with a rapid penetration of electric vehicles (Thomas, Ellingsen et al. 2018). We based our estimates on the baseline and ultralow-emission policy scenario performed by the Institute of Transport Economics (Fridstrøm and Østli 2016), as presented in figure S3. For both scenarios, the ICEVs are phased out by around 2050.

The three different passenger car vehicle types considered are BEV, ICEV powered by gasoline, and diesel. The vehicle material inventories are based on Hawkins, Singh et al. (2013), Ellingsen, Majeau-Bettez et al. (2014), and Ellingsen, Singh et al. (2016), and are updated to Ecoinvent 3.2. Also, material

[2] The energy delivered is defined as in ibid.; the amount of energy supplied to a dwelling in order to provide the energy need. The conversion from energy need to delivered energy depends on 1) the share of the energy need that is covered by local energy (heat pump) 2) the shares covered by various energy sources and 3) the system efficiencies of the heating systems.

efficiency improvement over time is included based on material efficiency rates as described in ESU and IFEU (2008) and used in Hertwich, Gibon et al. (2015), and presented in figure S4. We assumed the lifetime of the batteries of the BEVs used in our scenarios to be equal the car lifetime, and to be produced in Korea in 2018, half in Korea and half in Europe in 2030 and in Europe only in 2050 with improvement in the production chain, as shown in figure S4. The total GHG emissions embodied in mobility M_M are calculated according to equation (5). α_{vt} stands for the share of the different vehicle type vt of time i, GHG_{mat} (CO_2 eq./km) for the emissions from the production of the different vehicle types vt and L_{tot} (km/year) the total neighbourhood yearly travel length.

$$M_m = \sum_{vt} \sum_{i=0}^{60} \alpha_{vt,i} \cdot V_{tot_i} \cdot GHG_{mat_{vt}} \cdot L_{tot,i} \tag{5}$$

2.4 Emissions from Mobility Operation

The total GHG emissions from Mobility O M_O are calculated according to equation (6) with α_{vt} as the share of the different vehicle type vt at time i, GHG_{Op} (CO_2 eq./km) the emissions per km driven by vehicle type vt at year i and $L_{tot,i}$ (km/y) the total neighbourhood yearly travel length.

$$M_O = \sum_{vt} \sum_{i=0}^{60} \alpha_{vt,i} \cdot GHG_{op_{vt}} \cdot L_{tot,i} \tag{5}$$

Vehicle operational energy for both gasoline and diesel fueled ICEVs are taken from Ecoinvent 3.2, and are assumed to decrease with 15% by 2030 and 20% by 2050 based on values from Ajanovic (2015) and Cox, Mutel et al. (2018), as shown in figure S5. The electricity consumption of the BEV is assumed to decrease over time; from 15 kWh/100 km in 2018 (assuming the efficiency of the battery to be at 95 %, the electric motor at 95 % and the inverter at 97 %), 13.5 kWh/100 km in 2030 to 12.5 kWh/100 km in 2050 as shown in figure S5.

2.5 Scenarios development

The neighbourhood consists of 20 single-family houses of passive house standards, and the functional unit is “to build and refurbish 20 single family houses of passive house standards over a 60 years period, deliver energy for heating and electric appliances, and provide mobility by passenger cars for all the inhabitants.”

The functional unit can be fulfilled by different means; (1) the house can have different sizes, (2) the size of the household can vary, (3) heating requirements can vary between households based on individual comfort standards or individual commitments, (4) the mobility habits depend on the inhabitants’ preferences and access to other transport modes, which will also change over time, and (5) the rate of electric car penetration will vary over time.

We developed four scenarios to explore the different and likely development of the neighbourhood over a service lifetime of 60 years. The scenarios are developed on the subsystem approach presented above, and key parameters are presented in table 1.

Scenario 1 (S1) is the baseline, based on average value and statistics. Scenario 2 (S2) is the higher range where both the energy delivered and the driving distance are increased. Scenario 3 (S3) includes technological improvements in both the buildings and the vehicle fleet by faster penetration of electric vehicles. Scenario 4 (S4) includes technological improvements as well as positive inhabitants behaviors such as lower living space per inhabitant and driving distances.

Table 1: Scenario's key parameters

		Scenarios			
		S1	**S2**	**S3**	**S4**
	Units	**Baseline**	**Higher range**	**Techno**	**S3 + behavior**
Buildings					
Heated floor area	m^2/house	160	160	120	120
# houses	house	20	20	20	20
Inhabitants	pers./house	4	4	4	5
Energy					
Heat supply		Heat pump + Solar collector			
Electricity supply		Solar PV panels - "all electric"			
Energy delivered[a]					
Space heating	kWh/m^2/year	31	49	19	19
Domestic hot water	kWh/m^2/year	4	4	4	3
Fans and pumps	kWh/m^2/year	3	3	3	3
Lighting	kWh/m^2/year	8	10	8	6
Electrical appliances	kWh/m^2/year	15	17	15	13
Total	kWh/m^2/year	**61**	**83**	**49**	**44**
PV electricity bonus	kWh/m^2/year	53	53	104	104
Net energy demand	**kWh/m^2/year**	**8**	**30**	**-55**	**-60**
Mobility					
# Cars	car/house	1,2	2	1,2	0,6
El car scenarios [b]		Baseline	Baseline	Ultra low scenario	Ultra low scenario
Driving distance	km/car/year	12480[c]	13728	12480[c]	8736

2.6 Sensitivity analysis

A sensitivity analysis is conducted to test the scenarios against a national average energy use of 180 kWh/m^2/year.

3. Results

The results are first presented for the whole neighbourhood by time steps of one year in figures 2-5, and then for the whole lifetime for the different functional units in figure 6. The results of the sensitivity analysis are shown in figure 7.

3.1 Yearly results

The results are presented for the four scenarios and for the four different energy mixes used by time step of one year in figures 2-5. The yearly absolute numbers are given in table S1-S6.

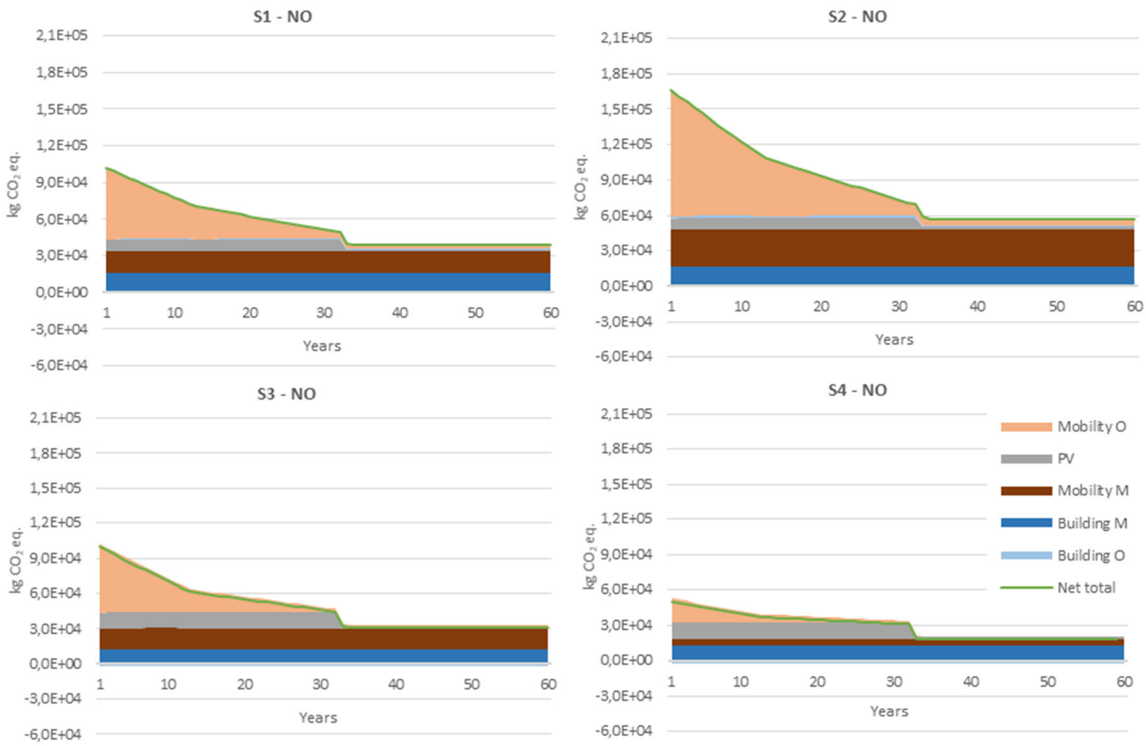

Figure 2: Absolute GHG emissions for the whole neighbourhood and for each scenario, by time step of one year, Norwegian electricity scenario

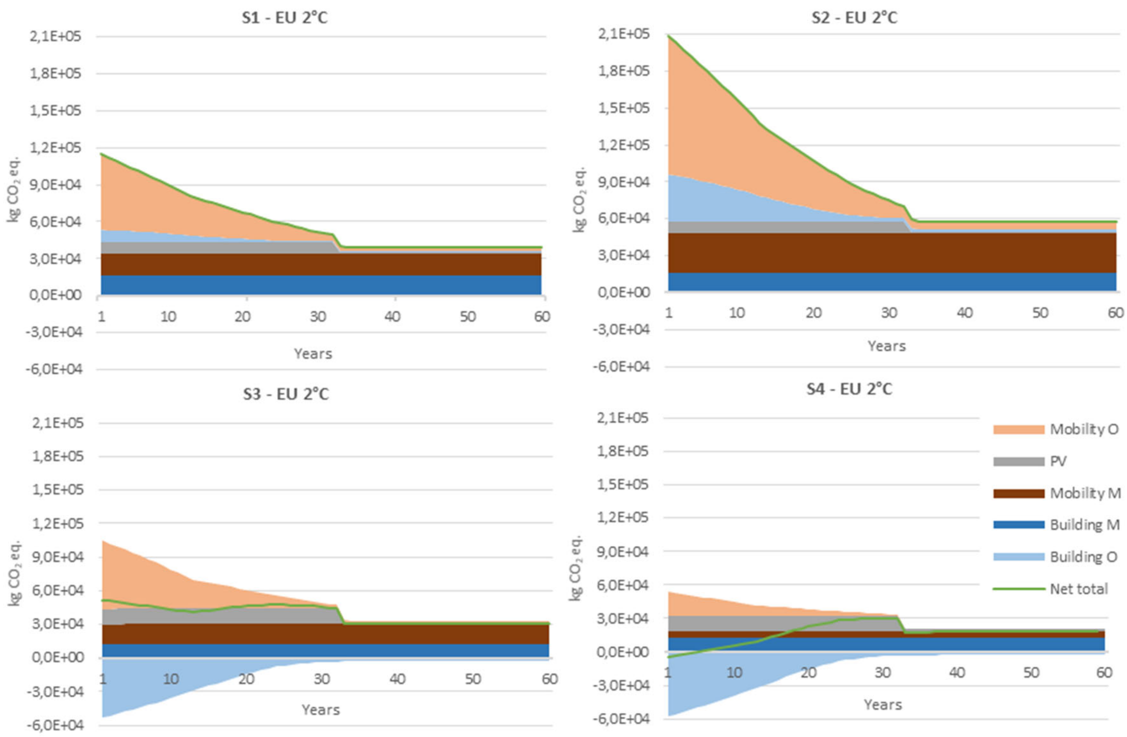

Figure 3: Absolute GHG emissions for the whole neighbourhood and for each scenario, by time step of one year, 2°C electricity scenario

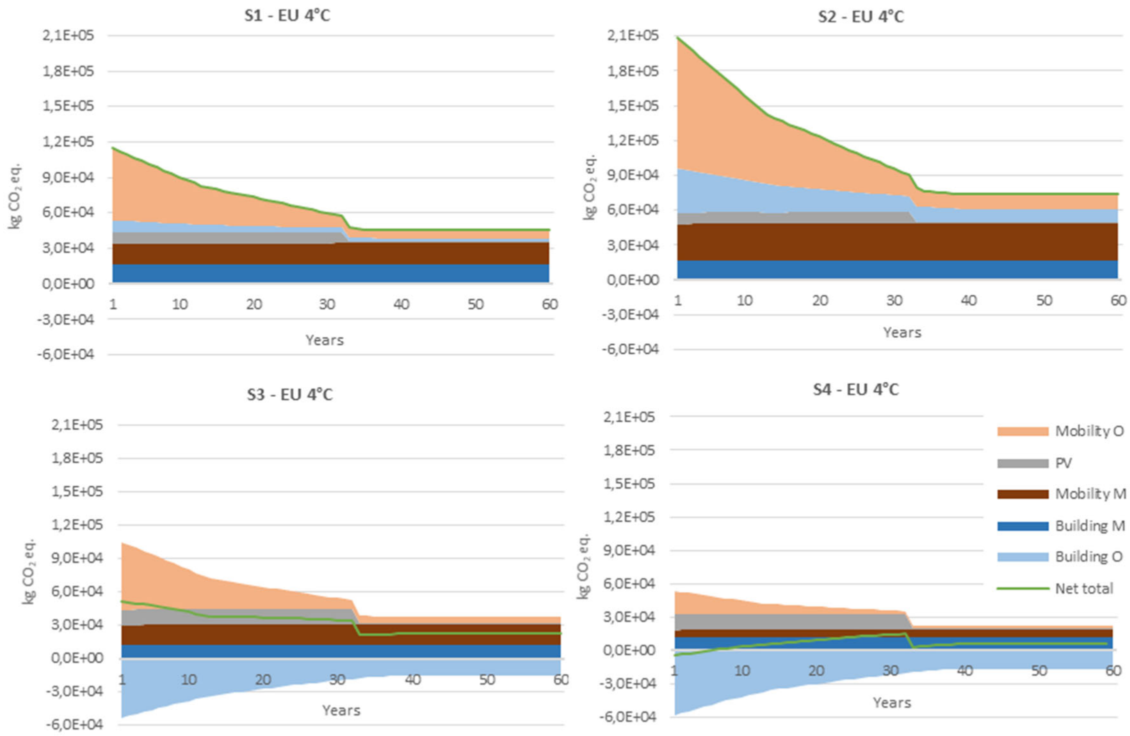

Figure 4: Absolute GHG emissions for the whole neighbourhood and for each scenario, by time step of one year, 4°C electricity scenario

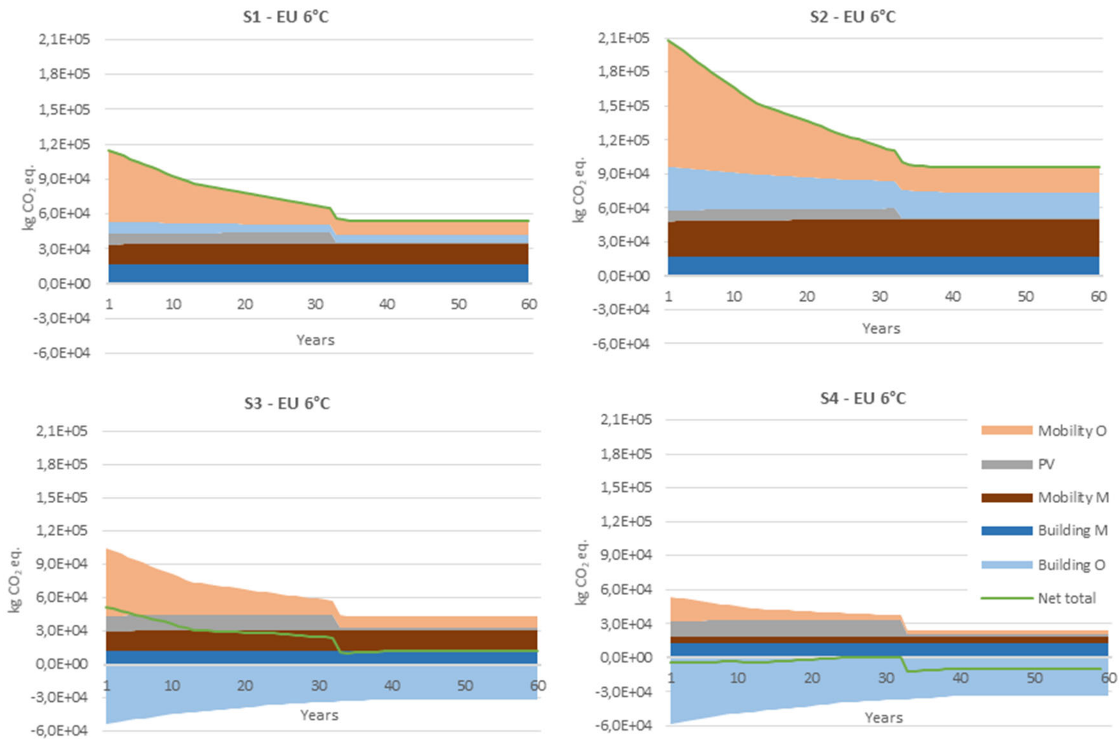

Figure 5: Absolute GHG emissions for the whole neighbourhood and for each scenario, by time step of one year, 6°C electricity scenario

The yearly results per neighbourhood vary inside one order of magnitude; from results in the range of 20.7 - 208 ton CO_2 eq./year. The lowest range is found for S4-NO from year 2051(34) to 2077(60) while the highest range is found for S2- EU 2°C, S2- EU 4°C and S2- EU 6°C in year 2018 (1). Looking at the net total, the lowest range is decrease by 60%.

Normalizing with the total m^2 number of heated floor area within each scenario, the results are in the range of 8.6 – 65.1 kg CO_2 eq./m^2/year. Normalizing with the total number of inhabitants for each scenario, the results are in the range of 0.21 - 2.6 ton CO_2 eq./pers./year. Both the lowest ranges are found for S4-NO in the years 2051(34) to 2077(60) while both the highest ranges are for the year 2018(1) of scenarios S2-EU 2°C, S2-EU 4°C and S2-EU 6°C.

In year 1, GHG emissions are dominated by the operational phases (i.e. Building O, Mobility O and PV) for all the scenarios. In year 60, the opposite is the case when the electricity mix is decarbonized (NO, 2°C scenario, 4°C scenario) and not the case when the carbon intensity of the el-mix is still high, as it is the case when using the 6°C scenario.

Impacts embodied in building materials (i.e. Building M) are constant over time as the peak impacts of construction in year 1 and replacements of some building parts at the respective years are distributed over the neighbourhood lifetime.

Impacts embodied in mobility materials (Mobility M) increase slightly over time for all the scenarios; by 5% for S1 and S2 and by 6% for S3 and S4. The increase is marginally higher for S3 and S4 due to the faster penetration of electric vehicles in the future vehicle fleet. The technology assets in the vehicles and battery production improve over time, and compensate for a larger increase of Mobility M driven by an increase share of BEV over time.

PV is divided in two periods, according to its lifetime. Because the same PV technology is used along the scenarios in a given year, the decrease is the same; -88% from year 1 to year 31. Yet, the magnitude of PV varies along the scenarios depends of the installed area, which is largest for S3 and S4.

The impact of the operational phase of the buildings Building O is negative for S3 and S4 where the on-site production excess the building energy needs and positive for S1 and S2 where the electricity is imported from the grid. The magnitude of Building O depends on the two following factors: the net energy demand of the buildings and the carbon intensity of the grid electricity mix. When using the Norwegian electricity mix, the impact of Building O is marginal on a yearly basis for all the scenarios. When using an electricity mix with a higher carbon intensity, as it is the case in year 1 for all the other el-mix used, Building O becomes more visible when either the energy delivered is in the higher range (S2), or when the electricity send to the grid is significant (S3 and S4). The magnitude of Building O over time depends of the decarbonization rate over time; Building O becomes marginal for the 2°C scenario, moderate for the 4°C scenario and significant for the 6°C scenario.

Because the share of BEVs increase in the vehicle fleet over time, the pattern of impacts from Mobility O follows the pattern of Building O, and its intensity depends on the level of decarbonization of the el-mix, with a difference in trends for S3 and S4.

When following the ZEB Centre GHG emission compensation procedure, only some yearly emissions of scenario 4 are compensated by the operational phase of the buildings (i.e. Building O). This is the case when both the carbon intensity of the electricity mix is high and the energy use is low, as it is the case in years 2018(1)-2022(5) of S4-EU 2°C and S4-EU 4°C and all the years of S4-EU 6°C.

3.3 Results over the lifetime

The results from figures 2-5 are now aggregated over the whole lifetime and presented in figure 6 for the whole neighbourhood, per m^2 heated floor area, and per inhabitant. The absolute results over the lifetime are given in tables S7-S9.

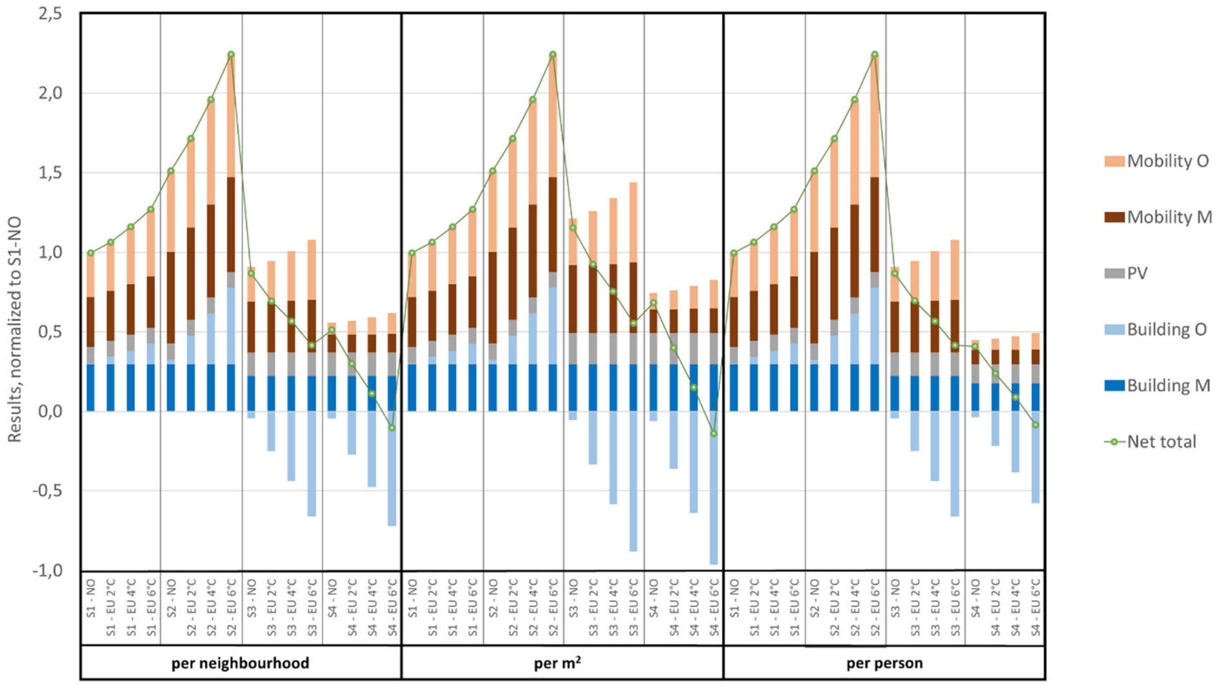

Figure 6: Results over the lifetime normalized to S1-NO, per neighbourhood, m^2 heated floor area and inhabitant

Compared to the total impact (without considering the emissions credits from Building O), the contribution of Building O varies from 1% to 22%, Building M from 13% to 40%, PV from 5% to 27%, Mobility O from 14% to 35%, and Mobility M from 18% to 38%.

For each scenario (S1-S4), we see the contribution to the total of Building M and Mobility M decreases with an increase in carbon intensity of the electricity mix. For instance, from S1 - NO to S1 - EU 6°C, the share of Building M decreases from 30% to 25% Mobility M decreases from 31% to 25%. The opposite is true for the operational phases and the contribution of Building O increases from 1% to 10% while the Mobility O increases from 28% to 33%.

Comparing scenarios amongst the same functional unit leads to different conclusion. While comparing S1 to S2 leads to the same conclusion, comparing S1 to S3 lead to different conclusion. With functional units of “per neighbourhood” and “per person”, passing from S1 to S3 leads to decreases of -9% to -20% while it lead to increase of 15% to 21% for a “per m^2“ functional unit. The conclusion are the same when comparing S1 to S4, but the magnitude is different; from -44% to -64% per neighbourhood, from -25% to -44% per m^2 and from -55% to 68% per person. Comparing S1 to S4 lead to the same conclusion across the functional units, but the effect of positive choice of reducing living space is better captured with a per person functional unit.

When considering the Net totals and taking into account the benefits gained from Building O over the lifetime, the totals are either constant when Building O is positive (S1-S2) or decreased when the excess on-site produced is sent to the grid (S3-S4). The emissions credits lead to a decrease of the total ranging from -4% to -96%.

3.4 Results from the sensitivity analysis

The total emission results from figure 6 are increased by 5% (S4-NO) up to 191% (S1 - EU 6°C). The on-site energy production, which was calculated to meet ZEB or nZEB energy standards is now all used internally, and Building O becomes positive across all the scenarios. The share of impacts from Building O increases, and passes from 1% to 22% in figure 3 to 6% to 65% (S1 - EU 6°C) in figure 4.

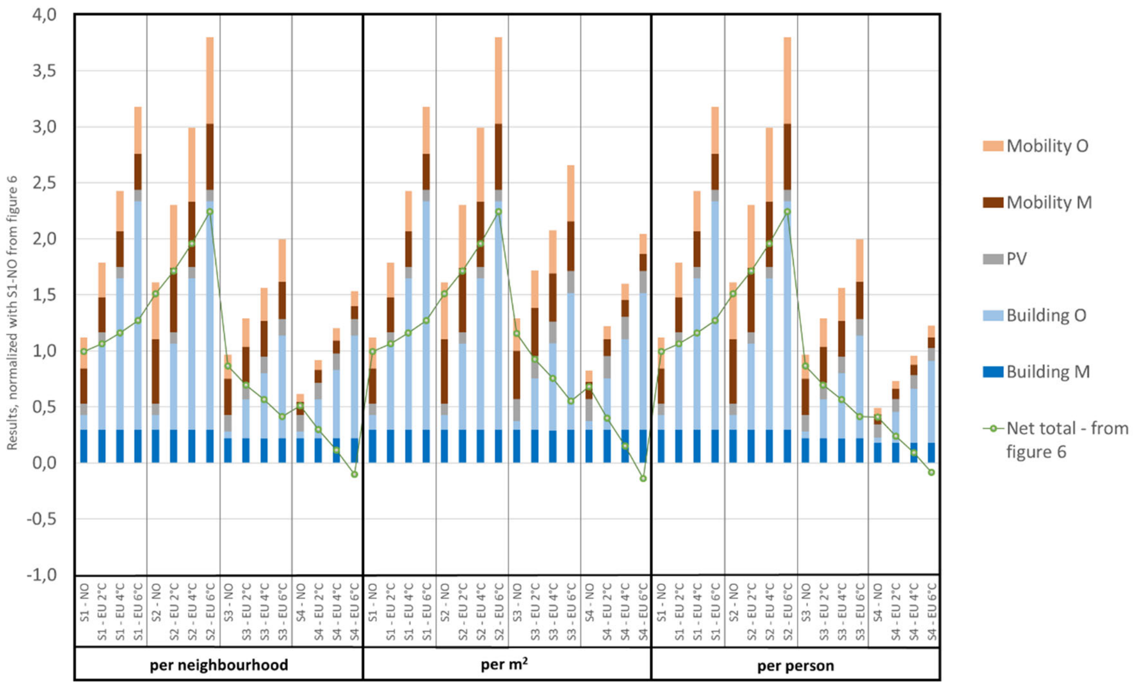

Figure 7: Results from the sensitivity analysis, normalized to S1-NO from figure 6

4. Discussion

Our LCA model yields similar results compared to those reported in the literature. Yet, our study has the particularity to assess houses with a ZEB or nZEB standard, where the energy consumed in the operational phase of the house is drastically reduced. Bastos, Batterman et al. (2016) found user transportation to account for the largest share of emissions with 51-57%, which is in accordance with our results. On the other hand, Stephan, Crawford et al. (2013) found the shares of the GHG emissions related to the production and replacement of building materials and infrastructures to constitute 16-22% of the total, shares related to operational emissions to 42-43% of the total, and shares related to transport requirements to 36-41% of the total. The higher share of the building operational emissions is due to the lower energy standard of the houses. Yet, by assuming higher energy standards, as it the case in our study, the share of operational emissions decrease, and the share of mobility and embodied emissions in buildings increase in the overall picture.

On an absolute scale, our results are in line with the results found in the literature as presented in the review by Lotteau, Loubet et al. (2015). On a per m^2 building heated floor area basis, our results range from -5.20 to 103 kg CO_2 eq./m^2/year while their results range from 10.8 to 123.8 kg CO_2 eq./m^2 heated floor area/year. Finally, on a per person basis our results range from -0.002 to 4.15 ton CO_2 eq./pers./year, and lie in the lower range of their results of 0.6-8.6 ton CO_2 eq./pers./year.

4.1 Choice of functional unit

The combination of different types of functional units (absolute, spatial and per person) has been recommended in several studies (Bastos, Batterman, & Freire, 2014; Lotteau, Loubert, Pousse, Dufrasnes, & Sonnemann, 2015; Stephan et al., 2013a). In our opinion, the use of a "per neighbourhood" functional unit gives a good overview and allows to depict the main bottlenecks of the actual neighbourhood project under study, allowing to draw local strategies to reduce the environmental footprint of the given neighbourhood. Subsequently, the use of a "per m^2 building floor area" functional unit depicts the impact intensity of resource use emissions of an urban project. The further normalization with respect to number of inhabitants allows to capture social differences and life styles, or deliberate choices such as the house size, and allows for the assessment of the efficiency of use of resources and emissions of the population (Lotteau, Loubet et al. 2015).

In some specific cases, the use of "per m^2" or "per person" functional units leads to different conclusions. Norman, MacLean et al. (2006) found that a low-density neighborhood used around 2 to 2.5 times more energy than a high-density neighborhood on a per capita basis, but only 1 to 1.5 as much energy on a per "unit of living space" (area of building floor area) basis. Stephan, Crawford et al. (2013) found an increase of impact per km^2 when benchmarking a baseline scenario of single-family houses with a four-storey apartment buildings, but a decrease when assessing the same scenarios per person. This was also the case when we benchmarked our scenarios S1 to S3, and found a reduction of net total over the lifetime by 24% "per neighbourhood" and "per person", but an increase by 2% when considering the results "per m^2 heated floor area".

We argue for the use of a primary functional unit "per neighbourhood" and a secondary functional unit "per person" when conducting LCA on a neighbourhood scales. To optimize sub-systems of the neighbourhood, sub-units have to be used, such as "per km" for the different vehicle fleets, "per m^2 floor area" for the buildings, and "per specific unit" for the infrastructure elements in the neighbourhood.

4.2 Inertia in material used in buildings versus volatility of the energy mix

Assessing the nexus of housing, mobility, and the connected energy system in a given time frame is about combining different subsystems that evolve at very different paces. The pace of buildings is by definition slow. Once built, the dynamic or internal pace can be assumed constant until the next renovation or refurbishment event takes place. Car lifetimes are much shorter than building lifetimes. While a lifetime of 50 to 100 years is often assumed in LCA of buildings, the lifetime of a car is often considered to be around 150'000 km (Ellingsen, Singh et al. 2016, Cox, Mutel et al. 2018). The development of on-site renewable energy production and demand management at a building and/or neighbourhood scale calls for a deeper understanding of the interaction between building operation and the electricity grid. We suggest that the further development of our operational modules Building O and Mobility O should go in the direction taken by Roux, Schalbart et al. (2016); i.e. hourly impacts from grid electricity should be used to account for the temporal variation in consumption, production, storage and import/export of electricity. This would offer better understanding of the temporal mismatch between demand and supply, as well as temporal emission dynamics in the electricity grid and capacity peak shaving opportunities by energy storage technologies, such as batteries or underground thermal storage at neighbourhood scale.

4.3 Dynamic MFA to assess ZEN

Long lifetimes of in-use building and infrastructure stocks cause path dependencies and lock-in of materials and installed energy technologies (Pauliuk and Müller 2014). On the other hand, both short lifetimes and the construction of new capacity for renewable energy technologies lead to increased material inputs (Wiebe, Bjelle et al. 2018). Also, a reduction of materials in the in-use stock would most easily be achieved by the prolongation of its lifetimes as an effect of adequate maintenance (Wiedenhofer, Steinberger et al. 2015). The LCA methodology for neighbourhoods used so far only assesses new built infrastructure and buildings. The model will need further development to understand how previously built and ageing buildings in a neighbourhood are likely to change over a 60 year future period, and the implications of future renovation and demolition measures with respect to material consumption, energy use, and related emissions. Typically, dynamic segmented building stock models have proven to be powerful tools in that context. These type of models can be used for both historical analysis (Sandberg, Sartori et al. 2016) and forecasting scenarios (Sandberg, Sartori et al. 2017, Sandstad, Sandberg et al. 2018),where energy efficiency improvements of the stock through renovation rates are captured. Dynamic stock driven models can also be used to assess the introduction of nZEB policy and the renovation rate to test policy goal for emission reduction (Vásquez, Løvik et al. 2016). These models can also be combined with LCA to extend the system boundary beyond direct emissions and include embodied emissions from construction material, construction energy and end-of-life stages (Pauliuk, Sjöstrand et al. 2013). Most importantly, such models can pinpoint the urgency of acting now (Sandberg, Sartori et al. 2017). In fact, 50% of the Norwegian standing dwelling stock in 2020 will not need a “natural” renovation towards 2050, while the other 50% holds significant potentials for energy efficiency improvements due to their expected renovation cycle. Thus, renovation of old inefficient buildings in addition to new construction with passive-house standards will be key factors to further improve the overall energy efficiency of the building stock.

4.4 Uncertainties and limitations

Decarbonizing the power sector has direct implications for other sectors (Wiebe 2018). In addition to energy efficiency improvements along the production chains, the retrofit of the power sector over time in the production chains have to be taken into account when assessing prospective scenarios. Here, we included some rough improvements in these demand-side technologies in our scenario analysis, but a more systematic analysis of potential and expected improvements in material production, manufacturing, and transport is needed. In fact, neglecting such improvements could result in an underestimation of the environmental benefit of climate mitigation policies (Hertwich, Gibon et al. 2015).

Conducting LCA on buildings requires a lot of specific data, and the use of site-specific materials such as reported in environmental products declarations (EPD) can lead to a reduction of embodied emissions in the order of magnitude of 20% (Wiik, Fufa et al. 2018).

So far, this study assumed the use of passenger cars for mobility only. Norwegians use mainly car for private travels today, as the yearly mileage of buses represents only 2% of the yearly mileage of the private car fleet (Statistics Norway 2017). In the future, an increased use of public transport is expected, and this is relevant to potentially serve large shares of the mobility needs of a ZEN project. Hence, public transport modes has to be integrated in the mobility subsystem of the LCA model.

The user behavior was addressed by introducing factors increasing (S2) or decreasing (S4) some key variables in our scenarios. One should expect high uncertainties in how user behavior in future will influence such variables, and more appropriate measures such as surveys would be beneficial to increase the accuracy and representativeness of this aspect.

5. Conclusion and outlook

We assessed the nexus of housing, mobility, and energy needs associated with human settlements by developing an LCA model to support the evaluation of ZEN design concepts with respect to GHG emissions.

The most important contributing factors have been identified as the operational phases of the Building and Mobility subsystems when the carbon intensity of the electricity mix is high, and as the embodied emissions in materials when the carbon intensity of the electricity mix becomes low. A reduction of the following factors have been identified as beneficial for the overall GHG emissions of a ZEN: (1) building floor area by house either/or by inhabitants, (2) passenger cars travel distances by household, which can be achieved by several means; e.g. commuting with public transport and/or by carpooling initiatives, (3) energy use in the buildings, which is reduced by the use of passive house standard, and (4) carbon intensity of the electricity mix.

Introducing passive house standards on buildings have the potential to decrease the overall impacts of a ZEB but also of a ZEN drastically; up to by 191% for an average European mix. Yet, by using a high decarbonized energy mix like it is the case in Norway, the decrease is much lower, around 12%.
The choice of the functional unit is crucial for the results, and can lead to different conclusion when comparing scenarios. When presenting the results, we argue for the use of a primary functional unit per neighbourhood, and a secondary per person when conducting LCA on a neighbourhood scale. We find the use of m^2 of building floor area to be misleading as it does not give credits to precautionary use of floor area. Yet, the use of impacts per m^2 is well-suited to assess the subsystem Building M of the ZEN, and so is the use of per km unit to assess Mobility M and O.
Future work building on this work should including energy storage, for example by feeding the excess produced electricity to feed in the electric vehicles. Also, infrastructure elements should be included.

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Reference list

Aasestad, K. (2013). Emissions of Black carbon and Organic carbon in Norway 1990-2011, Statistics Norway.

Ajanovic, A. (2015). "The future of electric vehicles: prospects and impediments." Wiley Interdisciplinary Reviews: Energy and Environment 4(6): 521-536.

Anderson, J. E., G. Wulfhorst and W. Lang (2015). "Energy analysis of the built environment—A review and outlook." Renewable and Sustainable Energy Reviews 44: 149-158.

Anderson, J. E., G. Wulfhorst and W. Lang (2015). "Energy analysis of the built environment - A review and outlook." Renewable and Sustainable Energy Reviews 44: 149-158.

Anderson, J. E., G. Wulfhorst and W. Lang (2015). "Expanding the use of life-cycle assessment to capture induced impacts in the built environment." Building and Environment 94: 403-416.

Barnhart, C. J., M. Dale, A. R. Brandt and S. M. Benson (2013). "The energetic implications of curtailing versus storing solar- and wind-generated electricity." Energy and Environmental Science 6(10): 2804-2810.

Bastos, J., S. A. Batterman and F. Freire (2016). "Significance of mobility in the life-cycle assessment of buildings." Building Research and Information 44(4): 376-393.

Bayoumi, M. and D. Fink (2014). "Maximizing the performance of an energy generating façade in terms of energy saving strategies." Renewable Energy 64: 294-305.

Berrill, P., A. Arvesen, Y. Scholz, H. C. Gils and E. G. Hertwich (2016). "Environmental impacts of high penetration renewable energy scenarios for Europe." Environmental Research Letters 11(1).

Birgisdóttir, H., K. A. Pihl, G. Bhander, M. Z. Hauschild and T. H. Christensen (2006). "Environmental assessment of roads constructed with and without bottom ash from municipal solid waste incineration." Transportation Research Part D: Transport and Environment 11(5): 358-368.

Blengini, G. A. and T. Di Carlo (2010). "The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings." Energy and Buildings 42(6): 869-880.

Brown, N. W. O., S. Olsson and T. Malmqvist (2014). "Embodied greenhouse gas emissions from refurbishment of residential building stock to achieve a 50% operational energy reduction." Building and Environment 79: 46-56.

Cabeza, L. F., L. Rincón, V. Vilariño, G. Pérez and A. Castell (2014). "Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review." Renewable and Sustainable Energy Reviews 29: 394-416.

Cellura, M., F. Guarino, S. Longo and G. Tumminia (2018). "Climate change and the building sector: Modelling and energy implications to an office building in southern Europe." Energy for Sustainable Development 45: 46-65.

Chastas, P., T. Theodosiou and D. Bikas (2016). "Embodied energy in residential buildings-towards the nearly zero energy building: A literature review." Building and Environment 105: 267-282.

Cherqui, F. (2005). Methodology for assessing sustainable urban district project - ADEQUA method, Université de La Rochelle.

Cherubini, F., J. Fuglestvedt, T. Gasser, A. Reisinger, O. Cavalett, M. A. J. Huijbregts, D. J. A. Johansson, S. V. Jørgensen, M. Raugei, G. Schivley, A. H. Strømman, K. Tanaka and A. Levasseur (2016). "Bridging the gap between impact assessment methods and climate science." Environmental Science and Policy 64: 129-140.

Cox, B., C. L. Mutel, C. Bauer, A. Mendoza Beltran and D. P. Van Vuuren (2018). "Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles." Environmental Science and Technology 52(8): 4989-4995.

Dahlstrøm, O., K. Sørnes, S. T. Eriksen and E. G. Hertwich (2012). "Life cycle assessment of a single-family residence built to either conventional- or passive house standard." Energy and Buildings 54: 470-479.

Davila, C. C. and C. Reinhart (2013). Urban energy lifecycle: An analytical framework to evaluate the embodied energy use of urban developments.

Dokka, T. H., T. F. Kristjansdottir, B. Time, S. Mellegård, M. Haase and J. Tønnesen (2013). A zero emission concept analysis of an office building. ZEB Project report no 8.
Ecoinvent Centre. (2015). "Ecoinvent 3.2." Retrieved 24.08, 2016, from http://www.ecoinvent.org/support/documents-and-files/information-on-ecoinvent-3/information-on-ecoinvent-3.html.
Ellingsen, L. A. W., G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen and A. H. Strømman (2014). "Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack." Journal of Industrial Ecology 18(1): 113-124.
Ellingsen, L. A. W., B. Singh and A. H. Strømman (2016). "The size and range effect: Lifecycle greenhouse gas emissions of electric vehicles." Environmental Research Letters 11(5).
ESU and IFEU (2008). New Energy Externalities Developments for Sustainability (NEEDS) - LCA of background processes. U. ESU Services, CH.
European Commission (2010). Energy Performance of Buildings Directive, Directive 2010/31/EU.
European Commission (2012). Energy Efficiency Directive.
European Parliament and the Council (2012). Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. http://data.europa.eu/eli/dir/2012/27/oj.
Finnveden, G., M. Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington and S. Suh (2009). "Recent developments in Life Cycle Assessment." Journal of Environmental Management 91(1): 1-21.
Fridstrøm, L. and V. Østli (2016). Vehicle fleet forecasts based on stock-flow modeling.
Fridstrøm, L. and V. Østli (2016). Vehicle fleet forecasts based on stock-flow modeling (in Norwegian), Institute of Transport Economics.
Fufa, S. M., R. D. Schlanbusch, K. Sørnes, M. Inman and I. Andresen (2016). "A Norwegian ZEB Definition Guideline."
Gibon, T., A. Arvesen and E. G. Hertwich (2017). "Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options." Renewable and Sustainable Energy Reviews 76: 1283-1290.
Goedkoop, M., R. Heijungs, M. A. J. Huijbregts, A. D. Schryver, J. Struijs and R. V. Zelm (2009). ReCiPe 2008. The Hague, Netherlands, Dutch Ministery of the Environment.
Granata, G., F. Pagnanelli, E. Moscardini, T. Havlik and L. Toro (2014). "Recycling of photovoltaic panels by physical operations." Solar Energy Materials and Solar Cells 123: 239-248.
Hanssen-Bauer, I., E. J. Førland, I. Haddeland, H. Hisdal, S. Mayer, A. Nesje, J. E. Ø. Nilsen, S. Sandven, A. B. Sandø, A. Sorteberg and B. Ådlandsvik (2017). Climate in Norway 2100– a knowledge base for climate adaptation. NCCS report no. 1/2017

Harter, H., V. Weiler and U. Eicker (2017). "Developing a roadmap for the modernisation of city quarters – Comparing the primary energy demand and greenhouse gas emissions." Building and Environment 112: 166-176.
Hawkins, T. R., B. Singh, G. Majeau-Bettez and A. H. Strømman (2013). "Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles." Journal of Industrial Ecology 17(1): 53-64.
Heeren, N., C. L. Mutel, B. Steubing, Y. Ostermeyer, H. Wallbaum and S. Hellweg (2015). "Environmental Impact of Buildings—What Matters?" Environmental Science & Technology 49(16): 9832-9841.
Heeren, N., C. L. Mutel, B. Steubing, Y. Ostermeyer, H. Wallbaum and S. Hellweg (2015). "Environmental Impact of Buildings - What Matters?" Environmental Science and Technology 49(16): 9832-9841.
Hellweg, S. and L. M. I. Canals (2014). "Emerging approaches, challenges and opportunities in life cycle assessment." Science 344(6188): 1109-1113.
Hertwich, E. G., T. Gibon, E. A. Bouman, A. Arvesen, S. Suh, G. A. Heath, J. D. Bergesen, A. Ramirez, M. I. Vega and L. Shi (2015). "Integrated life-cycle assessment of electricity-supply scenarios

confirms global environmental benefit of low-carbon technologies." Proceedings of the National Academy of Sciences of the United States of America 112(20): 6277-6282.

Houlihan Wiberg, A., L. Georges, T. H. Dokka, M. Haase, B. Time, A. G. Lien, S. Mellegård and M. Maltha (2014). "A net zero emission concept analysis of a single-family house." Energy and Buildings 74(Supplement C): 101-110.

IEA (2015). Energy Technology Perspectives 2015 - Mobilising Innovation to Accelerate Climate Action. Paris, France, International Energy Agency (IEA).

IEA (2015). "World Energy Outlook."

ISO (2006). ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework.

Janssens-Maenhout, G., F. Dentener, J. Van Aardenne, S. Monni, V. Pagliari, L. Orlandini, Z. Klimont, J. Kurokawa, H. Akimoto, T. Ohara, R. Wankmueller, B. Battye, D. Grano, A. Zuber and T. Keating (2012). EDGAR-HTAP: a harmonized gridded air pollution emission dataset based on national inventories, European Commissio- Joint Resarch Center (JRC). EUR 25 299 - 2012.

Junnila, S., A. Horvath and A. Guggemos (2006). Life-Cycle Assessment of Office Buildings in Europe and the United States.

Khasreen, M., P. F. Banfill and G. Menzies (2009). "Life-Cycle Assessment and the Environmental Impact of Buildings: A Review." Sustainability 1(3): 674.

Kristjansdottir, T. F., N. Heeren, I. Andresen and H. Brattebø (2017). "Comparative emission analysis of low-energy and zero-emission buildings." Building Research and Information: 1-16.

Kristjansdottir, T. F., N. Heeren, I. Andresen and H. Brattebø (2018). "Comparative emission analysis of low-energy and zero-emission buildings." Building Research & Information 46(4): 367-382.

Kristjansdottir, T. F., A. Houlihan-Wiberg, I. Andresen, L. Georges, N. Heeren, C. S. Good and H. Brattebø (2018). "Is a net life cycle balance for energy and materials achievable for a zero emission single-family building in Norway?" Energy and Buildings 168: 457-469.

Kuzman, M. K., P. Grošelj, N. Ayrilmis and M. Zbašnik-Senegačnik (2013). "Comparison of passive house construction types using analytic hierarchy process." Energy and Buildings 64: 258-263.

Li, D. and R. Wang (2009). "Hybrid Emergy-LCA (HEML) based metabolic evaluation of urban residential areas: The case of Beijing, China." Ecological Complexity 6(4): 484-493.

Lotteau, M., P. Loubet, M. Pousse, E. Dufrasnes and G. Sonnemann (2015). "Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale." Building and Environment 93(P2): 165-178.

Lotteau, M., G. Yepez-Salmon and N. Salmon (2015). "Environmental Assessment of Sustainable Neighborhood Projects through NEST, a Decision Support Tool for Early Stage Urban Planning." Procedia Engineering 115: 69-76.

Lucon, O., D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L. F. Cabeza, N. Eyre, A. Gadgil, L. D. D. Harvey, Y. Jiang, E. Liphoto, S. Mirasgedis, S. Murakami, J. Parikh, C. Pyke and M. V. Vilariño (2014). Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel

on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S.

Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)].

Lucon, O., D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L. F. Cabeza, N. Eyre, A. Gadgil, L. D. D. Harvey, Y. Jiang, E. Liphoto, S. Mirasgedis, S. Murakami, J. Parikh, C. Pyke and M. V. Vilariño (2014). Buildings. In: Climate Change 2014: Mitigation

of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel

on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S.

Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. . C. Cambridge University Press, United Kingdom and New York, NY, USA.

M. Lien, K. (2013). CO2 emissions from Biofuels and District Heating in Zero Emission Buildings (ZEB). ZEB Project Report, The Research Centre on Zero Emissions Buildings.

Majeau-Bettez, G. and A. H. Strømman (2016). Documentation for Arda Calculator, version 1.8.3. 2016.

Mamo Fufa, S., R. Dahl Schlanbusch, K. Sørnes, M. Inman and I. Andresen (2016). A Norwegian ZEB Definition Guideline, Sintef, NTNU.

Massarutto, A. (2015). "Economic aspects of thermal treatment of solid waste in a sustainable WM system." Waste Management 37: 45-57.

Mastrucci, A., A. Marvuglia, U. Leopold and E. Benetto (2017). "Life Cycle Assessment of building stocks from urban to transnational scales: A review." Renewable and Sustainable Energy Reviews 74: 316-332.

Mastrucci, A., A. Marvuglia, U. Leopold and E. Benetto (2017). Life Cycle Assessment of building stocks from urban to transnational scales: A review.

Moschetti, R., L. Mazzarella and N. Nord (2015). "An overall methodology to define reference values for building sustainability parameters." Energy and Buildings 88: 413-427.

Multiconsult (2017). Varedeklarasjon fjernvarme BKK - BREEAM-NOR 2016.

Myhre, G., D. , F.-M. Shindell, W. Bréon, J. Collins, J. Fuglestvedt, D. Huang, J.-F. Koch, D. Lamarque, B. Lee, T. Mendoza, A. Nakajima, G. Robock, T. Stephens, Takemura and Zhang (2013). Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge, United.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang (2013). Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. C. U. Press. Cambridge, United Kingdom and New York, NY, USA.

Nichols, B. G. and K. M. Kockelman (2014). "Life-cycle energy implications of different residential settings: Recognizing buildings, travel, and public infrastructure." Energy Policy 68: 232-242.

Norman, J., H. Maclean, M. Asce and C. A Kennedy (2006). Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions.

Norman, J., H. L. MacLean and C. A. Kennedy (2006). "Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions." Journal of Urban Planning and Development 132(1): 10-21.

Oliver-Solà, J., X. Gabarrell and J. Rieradevall (2009). "Environmental impacts of the infrastructure for district heating in urban neighbourhoods." Energy Policy 37(11): 4711-4719.

Oliver-Solà, J., A. Josa, A. P. Arena, X. Gabarrell and J. Rieradevall (2011). "The GWP-Chart: An environmental tool for guiding urban planning processes. Application to concrete sidewalks." Cities 28(3): 245-250.

Pauliuk, S., N. M. A. Dhaniati and D. B. Müller (2012). "Reconciling sectoral abatement strategies with global climate targets: The case of the chinese passenger vehicle fleet." Environmental Science and Technology 46(1): 140-147.

Pauliuk, S. and D. B. Müller (2014). "The role of in-use stocks in the social metabolism and in climate change mitigation." Global Environmental Change 24(1): 132-142.

Pauliuk, S., K. Sjöstrand and D. B. Müller (2013). "Transforming the Norwegian dwelling stock to reach the 2 degrees celsius climate target: Combining material flow analysis and life cycle assessment techniques." Journal of Industrial Ecology 17(4): 542-554.

Ramesh, T., R. Prakash and K. K. Shukla (2010). "Life cycle energy analysis of buildings: An overview." Energy and Buildings 42(10): 1592-1600.

Riera Pérez, M. G. and E. Rey (2013). "A multi-criteria approach to compare urban renewal scenarios for an existing neighborhood. Case study in Lausanne (Switzerland)." Building and Environment 65: 58-70.

Rossi, B., A.-F. Marique, M. Glaumann and S. Reiter (2012). Life-cycle assessment of residential buildings in three different European locations, basic tool.

Rossi, B., A.-F. Marique, M. Glaumann and S. Reiter (2012). "Life-cycle assessment of residential buildings in three different European locations, basic tool." Building and Environment 51: 395-401.

Roux, C., P. Schalbart, E. Assoumou and B. Peuportier (2016). "Integrating climate change and energy mix scenarios in LCA of buildings and districts." Applied Energy 184: 619-629.

Roux, C., P. Schalbart and B. Peuportier (2016). "Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house." Journal of Cleaner Production 113: 532-540.

Salom, J., A. J. Marszal, J. Widén, J. Candanedo and K. B. Lindberg (2014). "Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data." Applied Energy 136: 119-131.

Sandberg, N. H., I. Sartori, O. Heidrich, R. Dawson, E. Dascalaki, S. Dimitriou, T. Vimm-r, F. Filippidou, G. Stegnar, M. Šijanec Zavrl and H. Brattebø (2016). "Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU." Energy and Buildings 132: 26-38.

Sandberg, N. H., I. Sartori, M. I. Vestrum and H. Brattebø (2016). "Explaining the historical energy use in dwelling stocks with a segmented dynamic model: Case study of Norway 1960–2015." Energy and Buildings 132: 141-153.

Sandberg, N. H., I. Sartori, M. I. Vestrum and H. Brattebø (2017). "Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016-2050." accepted for publication in Energy and Buildings.

Sandberg, N. H., I. Sartori, M. I. Vestrum and H. Brattebø (2017). "Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016–2050." Energy and Buildings 146: 220-232.

Sandstad, J. N., N. H. Sandberg, N. Nord, M. I. Vestrum, C. Lausselet, A. Woszczek, Ø. Rønneseth and H. Brattebø (2018). Neighbourhood Building Stock Model for Long-Term Dynamic Analyses of Energy Demand and GHG Emissions - General model description and case studies. Z. R. N. 2018, NTNU/Sintef.

Saner, D., N. Heeren, B. Jäggi, R. A. Waraich and S. Hellweg (2013). "Housing and mobility demands of individual households and their life cycle assessment." Environmental Science and Technology 47(11): 5988-5997.

Sartori, I. and A. G. Hestnes (2007). "Energy use in the life cycle of conventional and low-energy buildings: A review article." Energy and Buildings 39(3): 249-257.

Sartori, I., S. Merlet, B. Thorud, T. Haug and I. Andresen (2016). Zero Village Bergen - Aggregated loads and PV generation profiles. ZEB Project Reports.

Sartori, I., K. S. Skeie, K. Sørnes and I. Andresen (2018). Zero Village Bergen - Energy system analysis. ZEB Project report no 40.

Sartori, I., R. B. Skeie, K. Sørnes and I. Andresen (2018). Zero Village Bergen - Energy system analysis. ZEB Project report 40. S. A. Press.

Seljom, P., K. B. Lindberg, A. Tomasgard, G. Doorman and I. Sartori (2017). "The impact of Zero Energy Buildings on the Scandinavian energy system." Energy 118: 284-296.

Sharma, A., A. Saxena, M. Sethi, V. Shree and Varun (2011). "Life cycle assessment of buildings: A review." Renewable and Sustainable Energy Reviews 15(1): 871-875.

Simonsen, M. (2010). Transport, energi og miljø.

Soares, N., J. Bastos, L. D. Pereira, A. Soares, A. R. Amaral, E. Asadi, E. Rodrigues, F. B. Lamas, H. Monteiro, M. A. R. Lopes and A. R. Gaspar (2017). "A review on current advances in the energy and environmental performance of buildings towards a more sustainable built environment." Renewable and Sustainable Energy Reviews 77: 845-860.

Standard Norge (2009). NS 3451:2009 Table of building elements (in Norwegian).

Standard Norge (2012). NS-EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method (in Norwegian).

Standard Norge (2018). NS 3720:2018 - Methods for greenhouse gas calculations for buildings (in Norwegian).

Standards Norway (2017). prNS 3720 Method for greenhouse gas calculations for buildings.

Statistics Norway. (2017). "Road traffic volumes, by type of vehicle." Retrieved 13.06.2018, from https://www.ssb.no/en/transport-og-reiseliv/statistikker/klreg.

Statistics Norway. (2018). "Emission of greenhouse gases." Retrieved August, 2018, from https://www.ssb.no/en/natur-og-miljo/statistikker/klimagassn.

Stephan, A., R. H. Crawford and K. De Myttenaere (2012). "Towards a comprehensive life cycle energy analysis framework for residential buildings." Energy and Buildings 55: 592-600.

Stephan, A., R. H. Crawford and K. de Myttenaere (2013). "Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia." Building and Environment 68: 35-49.

Stephan, A. and L. Stephan (2016). "Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings." Applied Energy 161: 445-464.

Taxt, H. W. and E. Fredriksen (2018). Thermal Energy Systems in ZEN - Review of technologies relevant for ZEN pilots. Z. R. N. 3.

The Research Centre on Zero Emission Buildings (ZEB). "The Research Centre on Zero Emission Buildings (ZEB)." Retrieved 01.12, 2017, from http://zeb.no.

Thomas, M., L. A. W. Ellingsen and C. R. Hung (2018). Battery-powered electric vehicles: market development and lifecycle emissions, European Parliament.

Vásquez, F., A. N. Løvik, N. H. Sandberg and D. B. Müller (2016). "Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock." Energy and Buildings 111: 37-55.

Victor, D. G., D. Zhou, E. H. M. Ahmed, P. K. Dadhich, J. G. J. Olivier, H.-H. Rogner, K. Sheikho and M. Yamaguchi (2014). Introductory Chapter. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. . C. Cambridge University Press, United Kingdom and New York, NY, USA.

Voss, K., E. Musall and M. Lichtmeß (2011). "From low-energy to net zero-energy buildings: Status and perspectives." Journal of Green Building 6(1): 46-57.

Wiebe, K. S. (2018). "Identifying emission hotspots for low carbon technology transfers." Journal of Cleaner Production 194: 243-252.

Wiebe, K. S., E. L. Bjelle, J. Többen and R. Wood (2018). "Implementing exogenous scenarios in a global MRIO model for the estimation of future environmental footprints." Journal of Economic Structures 7(1).

Wiedenhofer, D., J. K. Steinberger, N. Eisenmenger and W. Haas (2015). "Maintenance and Expansion: Modeling Material Stocks and Flows for Residential Buildings and Transportation Networks in the EU25." Journal of Industrial Ecology 19(4): 538-551.

Wiik, M. K., S. M. Fufa, T. Kristjansdottir and I. Andresen (2017). Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB researh centre.

Wiik, M. K., S. M. Fufa, T. Kristjansdottir and I. Andresen (2018). "Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB research centre." Energy and Buildings 165: 25-34.

Wiik, M. K., S. Mamo Fufa, J. Krogstie, D. Ahlers, A. Wyckmans, P. Driscoll and A. Gustavsen (2018). Zero Emission Neighbourhoods in Smart Cities: Definition, Key Performance Indicators and Assessment Criteria: Version 1.0. Z. Centre.

Yang, X., M. Hu, J. Wu and B. Zhao (2018). "Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China." Journal of Cleaner Production 183: 729-743.

Yepez-Salmon, G. (2011). Construction d'un outil d'évaluation environnementale des écoquartiers : vers une méthode systémique de mise en œuvre de la ville durable, Université Bordeaux.
ZEN, F. (2018). "ZEN Research Centre." Retrieved 13th of Mars, 2018, from http://fmezen.no/about-us/.

C.2 Supplementary material

Methodology

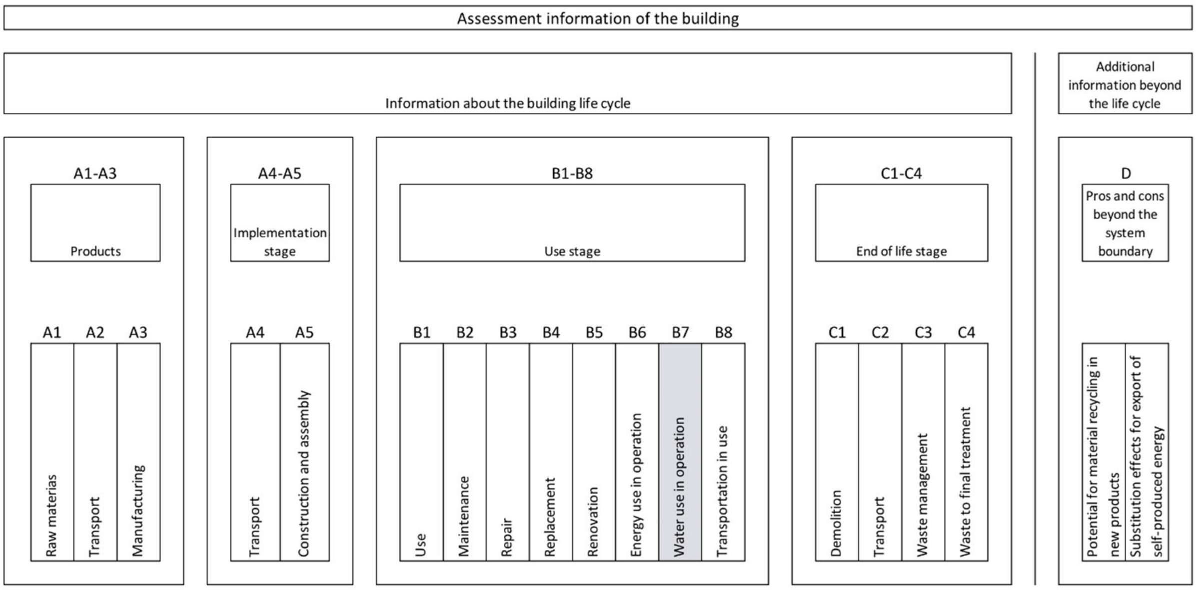

Figure S4: : Building life-cycle phases, divided by modules (A1-C4), translated and adapted from Standard Norge (2018)

Carbon intensities of the grid electricity over time- GHG_{el}

The carbon intensities of the grid electricity GHG_{el} used in equations (2) and (6) are taken from the Energy Technology Perspectives (EPT)scenarios from the International Energy Agency (IEA 2015).

ETP 2015 presents scenarios and strategies to 2050, with the aim of guiding decision makers on energy trends and what needs to be done to build a clean, secure and competitive energy future. Based on the ETP modelling framework, the scenarios are constructed using a combination of forecasting to reflect known trends in the near term and back-casting to develop plausible pathways for a desired long-term outcome. The ETP scenarios should not be considered as predictions of what is going to happen, rather, they explore the impacts and trade-offs of different technology and policy choices, thereby providing a quantitative approach to support decision making in the energy sector. While different, the ETP scenarios are complementary to those explored in the IEA World Energy Outlook (WEO).

The 6°C Scenario (6DS) is largely an extension of current trends. By 2050, primary energy use grows by almost two-thirds (compared with 2012) and total GHG emissions rise even more. In the absence of efforts to stabilise atmospheric concentration of GHGs, average global temperature rise above pre-industrial levels is projected to reach almost 5.5°C in the long term (i.e. after 2100) and almost 4°C by the end of this century. Already, a 4°C increase within this century is likely to stimulate severe impacts, such as sea level rise, reduced crop yields, stressed water resources or disease outbreaks in new areas.

The 4°C Scenario (4DS) takes into account recent pledges made by countries to limit emissions and step up efforts to improve energy efficiency, which helps limit long-term temperature rise to 4°C. In many respects, it is already an ambitious scenario that requires significant changes in policy and technologies compared with the 6°C Scenario. This long-term target also requires significant additional cuts in emissions in the period after 2050, yet with average temperature likely to rise by almost 3°C by 2100, it still carries the significant hazard of bringing forth drastic climate impacts.

The 2°C Scenario (2DS) lays out the pathway to deploy an energy system and emissions trajectory consistent with what recent climate science research indicates would give at least a 50% chance of limiting average global temperature increase to 2°C. The 2DS sets the target of cutting energy- and process-related CO_2 emissions by almost 60% by 2050 (compared with 2012) and ensuring they continue to decline thereafter. It identifies changes that help ensure a secure and affordable energy system in the long run, while also emphasising that transforming the energy sector is vital but not solely capable of meeting the ultimate goal. Substantial effort must also be made to reduce CO_2 and GHG emissions in non-energy sectors.

We used the 6°C-, 4°C – and 2°C EPT scenarios for the European Union, as shown in figure S5. The lifetime of our study is 60 years, and the study does thus end in 2080. For the period 2050-2080, we assume the same value as in 2050 for each scenario.

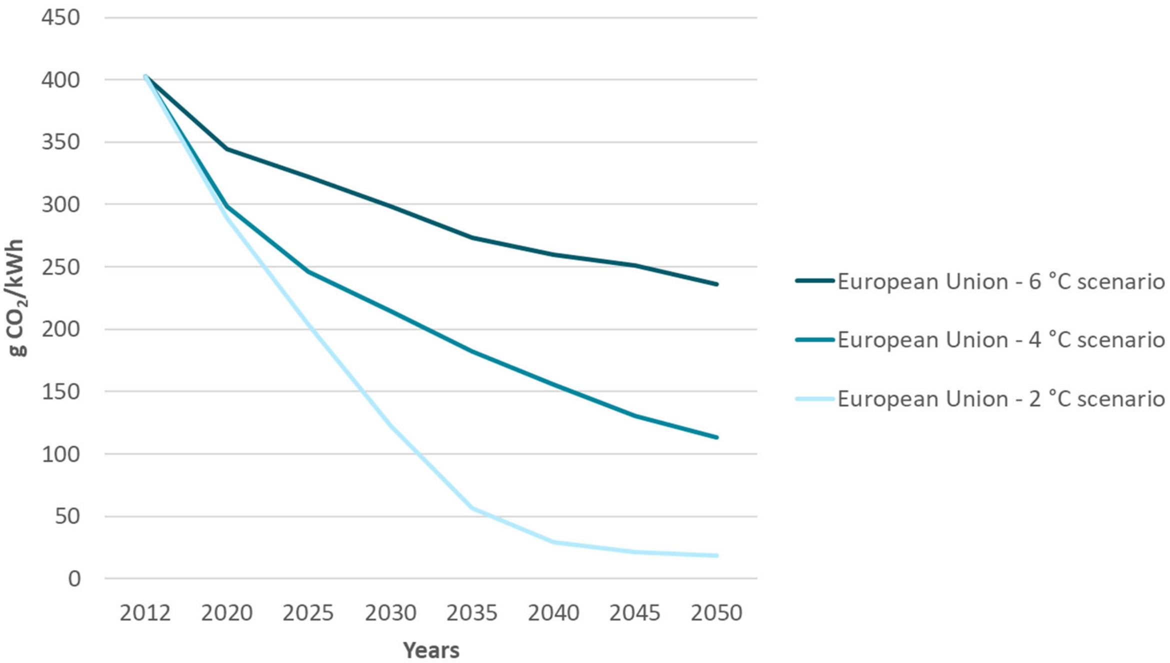

Figure S5: Energy Technology Perspectives (EPT)scenarios (IEA 2015)

Mobility Material

The number of cars in Norway has increased by 70% since 1990, and the national average is today 0.52 car per inhabitant or 1.2 car per household. Private cars consist of 50% of the national vehicle fleet with 48% diesel driven cars, 42% gasoline driven cars, 5% electric cars and 5% hybrid cars. Despite the 5% share of electric cars in the private cars vehicle fleet and small population size, the Norwegian electric car stock accounts to as much as 6% of the global electric cars stock (Thomas et al. 2018), and is rapidly growing.

The composition of the car stock is predicted to change drastically during the next years, with a rapid penetration of electric vehicles. We based our estimates on the baseline and ultralow-emission policy scenario performed by the Institute of Transport Economics (Fridstrøm and Østli 2016), as presented in figure S3. For both scenarios, the ICEVs are phased out by around 2050.

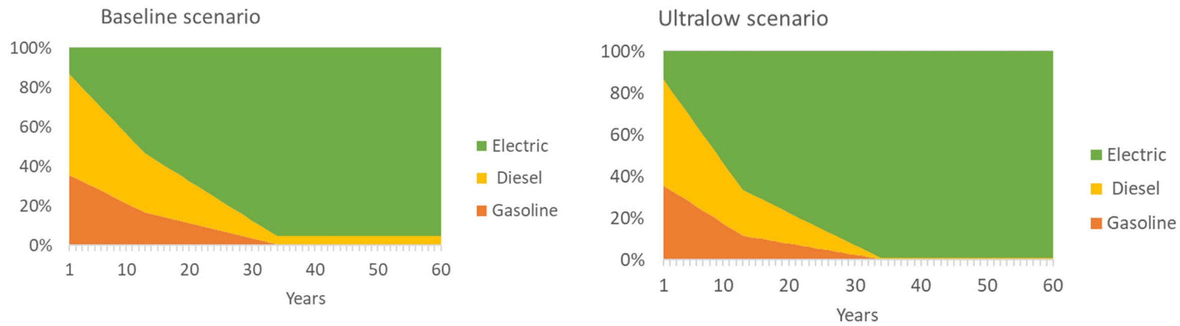

Figure S6: Evolution of the Norwegian passenger car stock composition over time

Both the battery and the material for the vehicle are assumed to be more efficient over time. The performance improvements of key material production technologies were based on the realistic-optimistic assessment developed by ESU and IFEU (2008) and used in Hertwich et al. (2015).

In 2018, the battery production uses 586 MJ/kWh battery cell and occurs in South Korea with an elecattricity GHG intensity of 639 g $C0_2$/kWh from Ecoinvent 3.2.

In 2030, the battery production is assumed to use 293 MJ/kWh per battery cell; 50 % more energy efficient than in 2018 and to occur half in South Korea and half in Europe. The EPT scenario (IEA 2015) are followed again, and this time the trajectory of China is followed to determine the carbon intensity of the Korean electricity mix over time. Based on these numbers, we assume a GHG intensity of the Korean electricity mix in 2030 and 2050 of respectively 599 and 561 g $C0_2$/kWh for the 6°C Scenario, 531 and 357 g $C0_2$/kWh for the 4°C Scenario and 415 and 46 g $C0_2$/kWh for the 2°C Scenario.

In 2050, the battery production is assumed to use 234 MJ/kWh per battery cell; 60 % more energy efficient than in 2018 and to occur in Europe only (for the battery that we use in our Norwegian scenarios).

The GHG emissions of the production of the BEV, ICEV and the battery are presented in figure S4 for all the energy scenarios. The GHG emissions of the battery production decrease over time with 32-38% in 2030 and 41-49% in 2050 compared with 2018's levels. The GHGs emissions of the BEV and ICEV vehicles production are decreasing over time with 10% in 2030 and 17% in 2050 compared with 2018's levels. The overall GHG emissions are thus decreasing with 20-23% by 2030 and 28-32% by 2050 for the BVE car and with 10% by 2030 and 17% by 2050 for the ICE car.

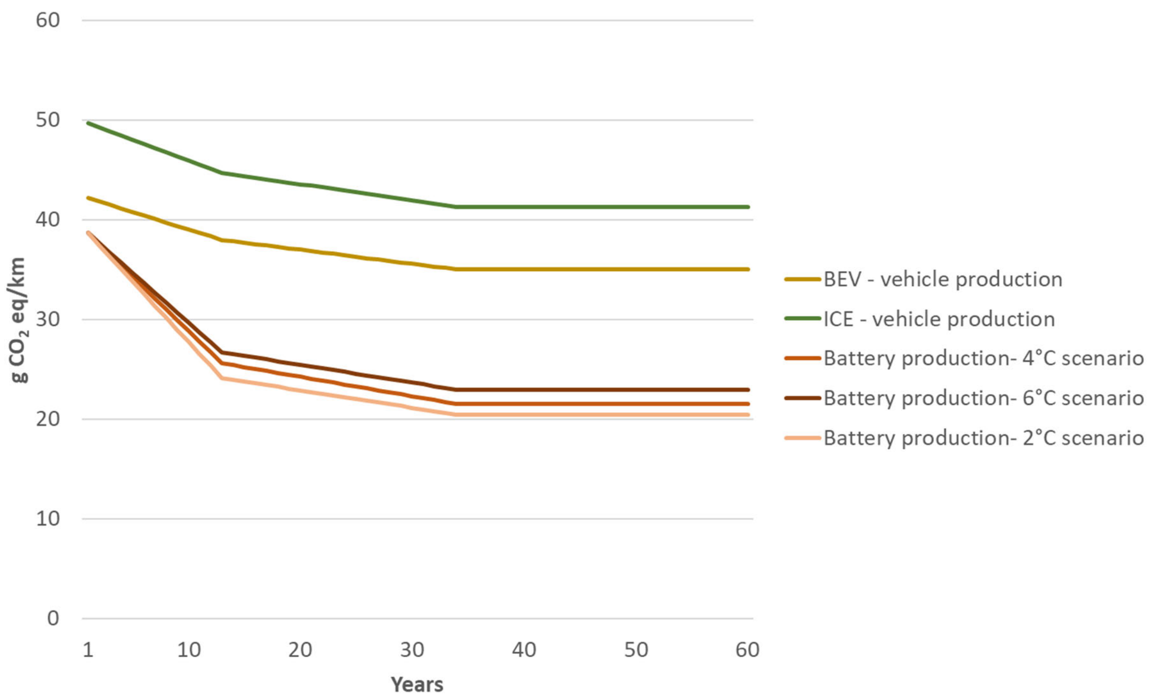

Figure S7: Evolution of the embodied emissions in passenger cars over time

Mobility Operation

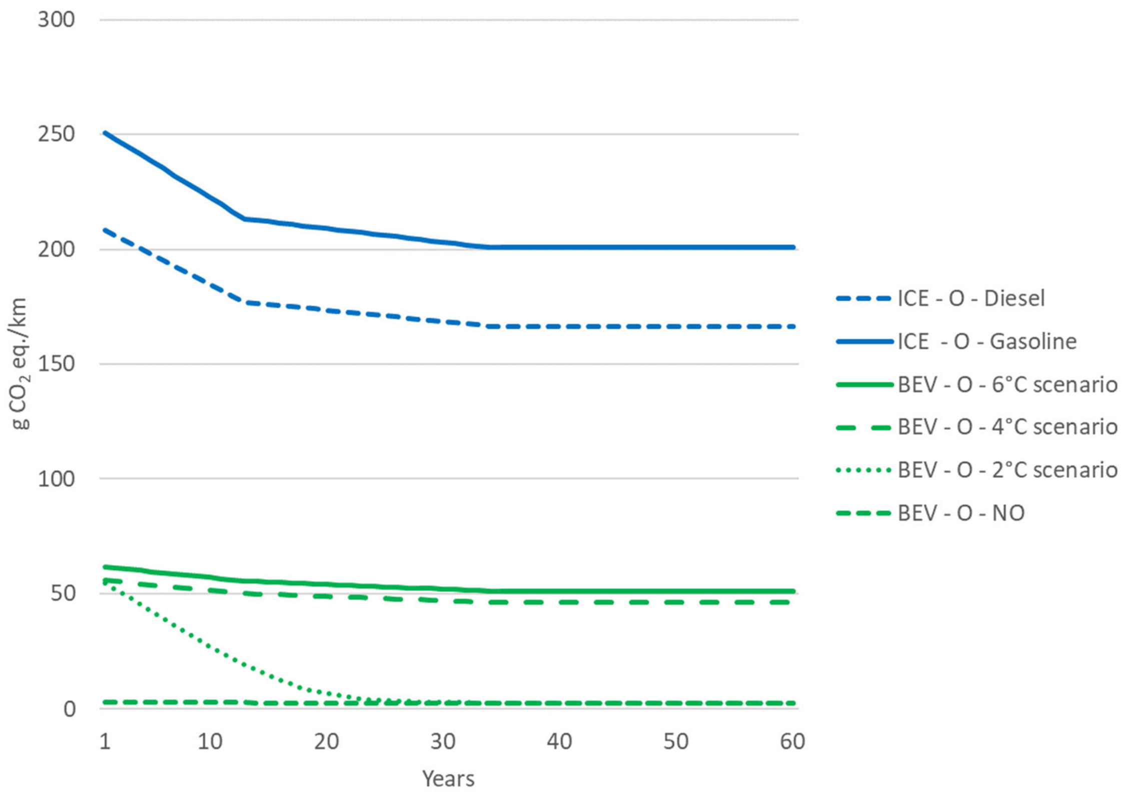

Figure S8: Evolution of the operational emissions of the different passenger cars over time

Results

Yearly results - per neighbourhood

Table S5: Yearly absolute results, per neighbourhood

		S1-NO ton CO2 eq.	S1-EU 2°C ton CO2 eq.	S1-EU 4°C ton CO2 eq.	S1-EU 6°C ton CO2 eq.	S2-NO ton CO2 eq.	S2-EU 2°C ton CO2 eq.	S2-EU 4°C ton CO2 eq.	S2-EU 6°C ton CO2 eq.	S3-NO ton CO2 eq.	S3-EU 2°C ton CO2 eq.	S3-EU 4°C ton CO2 eq.	S3-EU 6°C ton CO2 eq.	S4-NO ton CO2 eq.	S4-EU 2°C ton CO2 eq.	S4-EU 4°C ton CO2 eq.	S4-EU 6°C ton CO2 eq.
1	2018	102	115	115	115	166	208	208	208	102	105	105	105	53	54	54	54
2	2019	99,3	112,0	112,0	112,2	161,3	202,7	202,9	203,5	98,6	102,0	102,0	102,1	51,6	52,8	52,8	52,8
3	2020	96,5	109,3	109,4	109,8	156,2	197,1	197,4	198,7	95,2	99,2	99,3	99,4	50,4	51,8	51,8	51,9
4	2021	93,8	106,6	106,7	107,4	151,2	191,4	191,9	194,0	91,9	96,4	96,5	96,8	49,3	50,9	50,9	51,0
5	2022	91,1	103,8	104,0	105,0	146,2	185,7	186,4	189,2	88,6	93,6	93,8	94,2	48,1	49,9	49,9	50,1
6	2023	88,4	101,0	101,4	102,6	141,3	179,9	180,8	184,4	85,3	90,8	91,0	91,5	47,0	48,9	48,9	49,1
7	2024	85,7	98,3	98,7	100,2	136,4	174,1	175,2	179,7	82,1	87,9	88,2	88,9	45,8	47,9	48,0	48,2
8	2025	83,1	95,5	95,9	97,8	131,6	168,3	169,6	174,9	78,9	85,1	85,4	86,3	44,7	46,9	47,0	47,3
9	2026	80,5	92,7	93,2	95,4	126,9	162,4	164,0	170,2	75,8	82,2	82,5	83,7	43,6	45,9	46,0	46,4
10	2027	78,0	89,7	90,6	93,1	122,2	156,2	158,7	165,8	72,7	79,2	79,7	81,2	42,6	44,8	45,0	45,5
11	2028	75,4	86,7	88,0	90,9	117,6	149,9	153,3	161,5	69,7	76,1	77,0	78,7	41,5	43,7	44,0	44,6
12	2029	73,0	83,7	85,4	88,7	113,0	143,6	148,0	157,2	66,7	73,1	74,2	76,2	40,4	42,7	43,1	43,8
13	2030	70,5	80,7	82,8	86,4	108,5	137,2	142,7	152,9	63,8	70,0	71,4	73,8	39,4	41,6	42,1	42,9
14	2031	69,3	78,9	81,2	85,3	106,4	133,0	139,4	150,6	62,8	68,7	70,3	72,9	39,1	41,1	41,7	42,6
15	2032	68,2	77,0	80,0	84,2	104,3	128,8	136,7	148,3	61,9	67,3	69,3	72,0	38,8	40,7	41,4	42,3
16	2033	67,0	75,1	78,7	83,0	102,2	124,5	134,1	146,0	61,0	66,0	68,3	71,2	38,5	40,2	41,0	42,0
17	2034	65,9	73,2	77,4	81,9	100,0	120,3	131,4	143,6	60,1	64,7	67,3	70,3	38,1	39,7	40,7	41,7
18	2035	64,7	71,3	76,0	80,7	97,9	116,0	128,6	141,3	59,2	63,3	66,4	69,4	37,8	39,3	40,3	41,4
19	2036	63,6	69,4	74,7	79,6	95,8	111,6	125,9	139,0	58,3	61,9	65,4	68,5	37,5	38,8	40,0	41,1
20	2037	62,4	67,6	73,4	78,4	93,8	107,7	123,1	136,6	57,4	60,6	64,4	67,6	37,2	38,3	39,6	40,8
21	2038	61,3	65,8	72,0	77,2	91,7	103,7	120,3	134,1	56,5	59,3	63,3	66,7	36,9	37,9	39,3	40,4
22	2039	60,2	63,9	70,7	76,0	89,6	99,7	117,5	131,7	55,6	58,0	62,3	65,8	36,6	37,4	38,9	40,1
23	2040	59,1	62,1	69,3	74,8	87,5	95,7	114,7	129,3	54,7	56,6	61,3	64,9	36,3	36,9	38,5	39,8
24	2041	57,9	60,2	67,9	73,6	85,5	91,6	111,8	126,8	53,9	55,3	60,2	64,0	35,9	36,5	38,2	39,5
25	2042	56,8	58,8	66,6	72,5	83,4	88,7	109,1	124,7	53,0	54,2	59,3	63,1	35,6	36,1	37,8	39,2
26	2043	55,7	57,4	65,3	71,5	81,4	85,8	106,5	122,6	52,1	53,2	58,3	62,3	35,3	35,7	37,5	38,9
27	2044	54,6	56,0	64,0	70,4	79,4	82,9	103,8	120,5	51,2	52,1	57,3	61,5	35,0	35,3	37,1	38,6
28	2045	53,5	54,5	62,6	69,3	77,3	80,0	101,1	118,3	50,4	51,0	56,3	60,6	34,7	35,0	36,8	38,3
29	2046	52,4	53,1	61,3	68,2	75,3	77,1	98,4	116,2	49,5	49,9	55,3	59,8	34,4	34,6	36,4	38,0
30	2047	51,3	51,9	60,0	67,2	73,3	74,9	95,7	114,3	48,6	49,0	54,3	59,0	34,1	34,3	36,1	37,7
31	2048	50,2	50,7	58,7	66,2	71,3	72,6	93,1	112,3	47,8	48,1	53,3	58,2	33,8	33,9	35,7	37,5
32	2049	49,1	49,5	57,3	65,2	69,3	70,4	90,4	110,3	46,9	47,2	52,3	57,4	33,5	33,6	35,4	37,2
33	2050	39,7	40,0	47,7	55,8	59,0	59,8	79,4	100,1	33,8	34,0	39,0	44,4	21,0	21,1	22,8	24,7
34	2051	38,7	38,9	46,4	54,8	57,1	57,6	76,7	98,1	33,0	33,1	38,0	43,6	20,7	20,7	22,5	24,4
35	2052	38,7	38,8	46,2	54,6	57,1	57,5	76,2	97,6	33,0	33,1	37,9	43,4	20,7	20,7	22,4	24,4
36	2053	38,7	38,8	45,9	54,4	57,1	57,4	75,6	97,1	33,0	33,1	37,7	43,3	20,7	20,7	22,4	24,3
37	2054	38,7	38,8	45,7	54,2	57,1	57,4	75,0	96,6	33,0	33,1	37,6	43,2	20,7	20,7	22,3	24,3
38	2055	38,7	38,7	45,5	54,0	57,1	57,3	74,4	96,1	33,0	33,0	37,5	43,1	20,7	20,7	22,3	24,2
39	2056	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
40	2057	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
41	2058	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
42	2059	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
43	2060	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
44	2061	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
45	2062	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
46	2063	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
47	2064	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
48	2065	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
49	2066	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
50	2067	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
51	2068	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
52	2069	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
53	2070	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
54	2071	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
55	2072	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
56	2073	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
57	2074	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
58	2075	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
59	2076	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
60	2077	38,7	38,7	45,3	53,8	57,1	57,2	73,8	95,6	33,0	33,0	37,3	42,9	20,7	20,7	22,2	24,2
Total kton CO_2 eq.		**3,32**	**3,56**	**3,87**	**4,24**	**5,04**	**5,73**	**6,54**	**7,49**	**3,04**	**3,15**	**3,36**	**3,60**	**1,87**	**1,91**	**1,98**	**2,06**

Table S6: Yearly net absolute results, per neighbourhood

		S3-NO	S3-EU 2°C	S3-EU 4°C	S3-EU 6°C	S4-NO	S4-EU 2°C	S4-EU 4°C	S4-EU 6°C
		ton CO2 eq.	ton CO2 eq.	ton CO2 eq.	ton CO2 eq.	ton CO2 eq.	ton CO2 eq.	ton CO2 eq.	ton CO2 eq.
1	2018	99,7	51,5	51,5	51,5	50,2	-4,3	-4,3	-4,3
2	2019	96,2	50,7	50,5	49,8	49,0	-3,2	-3,4	-4,2
3	2020	92,8	49,8	49,5	48,1	47,8	-2,1	-2,4	-4,0
4	2021	89,5	48,9	48,5	46,5	46,7	-1,0	-1,5	-3,9
5	2022	86,2	48,0	47,4	44,8	45,5	0,1	-0,6	-3,8
6	2023	82,9	47,0	46,4	43,1	44,4	1,1	0,3	-3,7
7	2024	79,7	46,0	45,3	41,5	43,2	2,2	1,2	-3,5
8	2025	76,6	45,0	44,2	39,8	42,1	3,2	2,0	-3,4
9	2026	73,4	44,0	43,1	38,2	41,0	4,2	2,9	-3,3
10	2027	70,4	43,2	41,7	36,3	40,0	5,6	3,5	-3,5
11	2028	67,3	42,5	40,3	34,4	38,9	7,0	4,0	-3,7
12	2029	64,3	41,7	38,9	32,5	37,9	8,4	4,6	-3,9
13	2030	61,4	40,8	37,5	30,6	36,8	9,8	5,1	-4,1
14	2031	60,5	41,7	37,8	30,4	36,5	11,8	6,3	-3,8
15	2032	59,5	42,6	37,7	30,1	36,2	13,6	6,8	-3,4
16	2033	58,6	43,4	37,5	29,9	35,9	15,5	7,4	-3,0
17	2034	57,7	44,1	37,3	29,6	35,5	17,4	7,9	-2,7
18	2035	56,8	44,9	37,2	29,3	35,2	19,2	8,5	-2,3
19	2036	55,9	45,7	37,0	29,0	34,9	21,1	9,0	-2,0
20	2037	55,0	46,1	36,8	28,8	34,6	22,5	9,6	-1,6
21	2038	54,1	46,5	36,7	28,6	34,3	23,9	10,2	-1,2
22	2039	53,2	47,0	36,5	28,3	34,0	25,4	10,8	-0,8
23	2040	52,4	47,4	36,4	28,1	33,7	26,8	11,4	-0,4
24	2041	51,5	47,8	36,2	27,8	33,4	28,2	12,0	0,0
25	2042	50,6	47,4	35,9	27,3	33,0	28,7	12,4	0,1
26	2043	49,7	47,1	35,7	26,9	32,7	29,1	12,8	0,3
27	2044	48,8	46,8	35,4	26,4	32,4	29,5	13,3	0,4
28	2045	48,0	46,4	35,1	25,9	32,1	30,0	13,7	0,5
29	2046	47,1	46,1	34,8	25,5	31,8	30,4	14,1	0,6
30	2047	46,2	45,4	34,5	24,9	31,5	30,3	14,5	0,6
31	2048	45,4	44,7	34,1	24,3	31,2	30,2	14,9	0,5
32	2049	44,5	44,0	33,8	23,8	30,9	30,1	15,2	0,5
33	2050	31,5	31,0	21,2	11,0	18,4	17,8	3,4	-11,7
34	2051	30,6	30,3	20,9	10,4	18,1	17,7	3,7	-11,7
35	2052	30,6	30,4	21,2	10,7	18,1	17,8	4,2	-11,4
36	2053	30,6	30,4	21,5	11,0	18,1	17,8	4,6	-11,0
37	2054	30,6	30,4	21,8	11,2	18,1	17,9	5,1	-10,6
38	2055	30,6	30,5	22,1	11,5	18,1	17,9	5,5	-10,2
39	2056	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
40	2057	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
41	2058	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
42	2059	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
43	2060	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
44	2061	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
45	2062	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
46	2063	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
47	2064	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
48	2065	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
49	2066	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
50	2067	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
51	2068	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
52	2069	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
53	2070	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
54	2071	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
55	2072	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
56	2073	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
57	2074	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
58	2075	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
59	2076	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8
60	2077	30,6	30,5	22,4	11,8	18,1	18,0	5,9	-9,8

Net total kton CO_2 eq.	**2,89**	**2,32**	**1,89**	**1,39**	**1,71**	**1,00**	**0,38**	**-0,35**
Decrease - from Total to Net total	**-5 %**	**-26 %**	**-44 %**	**-61 %**	**-8 %**	**-48 %**	**-81 %**	**-117 %**

Yearly results - per floor area

Table S7: Yearly absolute results, per m^2 floor area

		S1-NO	S1-EU 2°C	S1-EU 4°C	S1-EU 6°C	S2-NO	S2-EU 2°C	S2-EU 4°C	S2-EU 6°C	S3-NO	S3-EU 2°C	S3-EU 4°C	S3-EU 6°C	S4-NO	S4-EU 2°C	S4-EU 4°C	S4-EU 6°C
		kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2	kg CO_2 eq./m^2
1	2018	32	36	36	36	52	65	65	65	43	44	44	44	22	22	22	22
2	2019	31,0	35,0	35,0	35,1	50,4	63,4	63,4	63,6	41,1	42,5	42,5	42,5	21,5	22,0	22,0	22,0
3	2020	30,2	34,1	34,2	34,3	48,8	61,6	61,7	62,1	39,7	41,3	41,4	41,4	21,0	21,6	21,6	21,6
4	2021	29,3	33,3	33,3	33,6	47,2	59,8	60,0	60,6	38,3	40,2	40,2	40,3	20,5	21,2	21,2	21,2
5	2022	28,5	32,4	32,5	32,8	45,7	58,0	58,2	59,1	36,9	39,0	39,1	39,2	20,0	20,8	20,8	20,9
6	2023	27,6	31,6	31,7	32,1	44,1	56,2	56,5	57,6	35,5	37,8	37,9	38,1	19,6	20,4	20,4	20,5
7	2024	26,8	30,7	30,8	31,3	42,6	54,4	54,8	56,1	34,2	36,6	36,7	37,0	19,1	20,0	20,0	20,1
8	2025	26,0	29,8	30,0	30,6	41,1	52,6	53,0	54,7	32,9	35,4	35,6	36,0	18,6	19,5	19,6	19,7
9	2026	25,2	29,0	29,1	29,8	39,6	50,8	51,2	53,2	31,6	34,2	34,4	34,9	18,2	19,1	19,2	19,3
10	2027	24,4	28,0	28,3	29,1	38,2	48,8	49,6	51,8	30,3	33,0	33,2	33,8	17,7	18,7	18,8	19,0
11	2028	23,6	27,1	27,5	28,4	36,7	46,8	47,9	50,5	29,0	31,7	32,1	32,8	17,3	18,2	18,3	18,6
12	2029	22,8	26,2	26,7	27,7	35,3	44,9	46,3	49,1	27,8	30,4	30,9	31,8	16,9	17,8	17,9	18,2
13	2030	22,0	25,2	25,9	27,0	33,9	42,9	44,6	47,8	26,6	29,2	29,7	30,7	16,4	17,3	17,5	17,9
14	2031	21,7	24,6	25,4	26,7	33,3	41,6	43,6	47,1	26,2	28,6	29,3	30,4	16,3	17,1	17,4	17,8
15	2032	21,3	24,1	25,0	26,3	32,6	40,2	42,7	46,3	25,8	28,1	28,9	30,0	16,2	16,9	17,2	17,6
16	2033	20,9	23,5	24,6	26,0	31,9	38,9	41,9	45,6	25,4	27,5	28,5	29,6	16,0	16,8	17,1	17,5
17	2034	20,6	22,9	24,2	25,6	31,3	37,6	41,0	44,9	25,0	26,9	28,1	29,3	15,9	16,6	16,9	17,4
18	2035	20,2	22,3	23,8	25,2	30,6	36,2	40,2	44,2	24,7	26,4	27,6	28,9	15,8	16,4	16,8	17,2
19	2036	19,9	21,7	23,4	24,9	29,9	34,9	39,4	43,4	24,3	25,8	27,2	28,5	15,6	16,2	16,7	17,1
20	2037	19,5	21,1	22,9	24,5	29,3	33,6	38,5	42,7	23,9	25,3	26,8	28,2	15,5	16,0	16,5	17,0
21	2038	19,2	20,6	22,5	24,1	28,6	32,4	37,6	41,9	23,5	24,7	26,4	27,8	15,4	15,8	16,4	16,9
22	2039	18,8	20,0	22,1	23,8	28,0	31,2	36,7	41,2	23,2	24,2	26,0	27,4	15,2	15,6	16,2	16,7
23	2040	18,5	19,4	21,7	23,4	27,4	29,9	35,8	40,4	22,8	23,6	25,5	27,0	15,1	15,4	16,1	16,6
24	2041	18,1	18,8	21,2	23,0	26,7	28,6	34,9	39,6	22,4	23,0	25,1	26,7	15,0	15,2	15,9	16,5
25	2042	17,8	18,4	20,8	22,7	26,1	27,7	34,1	39,0	22,1	22,6	24,7	26,3	14,9	15,0	15,8	16,3
26	2043	17,4	17,9	20,4	22,3	25,4	26,8	33,3	38,3	21,7	22,1	24,3	26,0	14,7	14,9	15,6	16,2
27	2044	17,1	17,5	20,0	22,0	24,8	25,9	32,4	37,6	21,3	21,7	23,9	25,6	14,6	14,7	15,5	16,1
28	2045	16,7	17,0	19,6	21,7	24,2	25,0	31,6	37,0	21,0	21,3	23,4	25,3	14,5	14,6	15,3	16,0
29	2046	16,4	16,6	19,2	21,3	23,5	24,1	30,7	36,3	20,6	20,8	23,0	24,9	14,3	14,4	15,2	15,8
30	2047	16,0	16,2	18,7	21,0	22,9	23,4	29,9	35,7	20,3	20,4	22,6	24,6	14,2	14,3	15,0	15,7
31	2048	15,7	15,8	18,3	20,7	22,3	22,7	29,1	35,1	19,9	20,0	22,2	24,2	14,1	14,1	14,9	15,6
32	2049	15,4	15,5	17,9	20,4	21,7	22,0	28,2	34,5	19,5	19,7	21,8	23,9	14,0	14,0	14,7	15,5
33	2050	12,4	12,5	14,9	17,4	18,4	18,7	24,8	31,3	14,1	14,2	16,3	18,5	8,7	8,8	9,5	10,3
34	2051	12,1	12,1	14,5	17,1	17,8	18,0	24,0	30,7	13,7	13,8	15,8	18,2	8,6	8,6	9,4	10,2
35	2052	12,1	12,1	14,4	17,1	17,8	18,0	23,8	30,5	13,7	13,8	15,8	18,1	8,6	8,6	9,3	10,1
36	2053	12,1	12,1	14,4	17,0	17,8	17,9	23,6	30,3	13,7	13,8	15,7	18,0	8,6	8,6	9,3	10,1
37	2054	12,1	12,1	14,3	16,9	17,8	17,9	23,4	30,2	13,7	13,8	15,7	18,0	8,6	8,6	9,3	10,1
38	2055	12,1	12,1	14,2	16,9	17,8	17,9	23,3	30,0	13,7	13,8	15,6	17,9	8,6	8,6	9,3	10,1
39	2056	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
40	2057	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
41	2058	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
42	2059	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
43	2060	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
44	2061	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
45	2062	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
46	2063	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
47	2064	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
48	2065	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
49	2066	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
50	2067	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
51	2068	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
52	2069	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
53	2070	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
54	2071	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
55	2072	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
56	2073	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
57	2074	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
58	2075	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
59	2076	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
60	2077	12,1	12,1	14,1	16,8	17,8	17,9	23,1	29,9	13,7	13,8	15,5	17,9	8,6	8,6	9,3	10,1
Total kg CO2 eq./m^2		**1039**	**1112**	**1210**	**1325**	**1576**	**1790**	**2044**	**2342**	**1265**	**1314**	**1400**	**1499**	**778**	**795**	**825**	**859**

Table S8: Yearly absolute net results, per m^2 floor area

		S3-NO kg CO_2 eq./m^2	S3-EU 2°C kg CO_2 eq./m^2	S3-EU 4°C kg CO_2 eq./m^2	S3-EU 6°C kg CO_2 eq./m^2	S4-NO kg CO_2 eq./m^2	S4-EU 2°C kg CO_2 eq./m^2	S4-EU 4°C kg CO_2 eq./m^2	S4-EU 6°C kg CO_2 eq./m^2
1	2018	41,5	21,5	21,5	21,5	20,9	-1,79	-1,79	-1,79
2	2019	40,1	21,1	21,0	20,8	20,4	-1,33	-1,40	-1,74
3	2020	38,7	20,7	20,6	20,1	19,9	-0,87	-1,02	-1,69
4	2021	37,3	20,4	20,2	19,4	19,4	-0,42	-0,64	-1,64
5	2022	35,9	20,0	19,8	18,7	19,0	0,02	-0,26	-1,58
6	2023	34,6	19,6	19,3	18,0	18,5	0,46	0,11	-1,53
7	2024	33,2	19,2	18,9	17,3	18,0	0,90	0,48	-1,48
8	2025	31,9	18,8	18,4	16,6	17,6	1,33	0,85	-1,42
9	2026	30,6	18,3	17,9	15,9	17,1	1,77	1,22	-1,37
10	2027	29,3	18,0	17,4	15,1	16,7	2,35	1,45	-1,46
11	2028	28,0	17,7	16,8	14,3	16,2	2,93	1,68	-1,55
12	2029	26,8	17,4	16,2	13,5	15,8	3,50	1,91	-1,63
13	2030	25,6	17,0	15,6	12,8	15,3	4,07	2,14	-1,71
14	2031	25,2	17,4	15,8	12,7	15,2	4,90	2,62	-1,56
15	2032	24,8	17,7	15,7	12,6	15,1	5,68	2,85	-1,42
16	2033	24,4	18,1	15,6	12,4	14,9	6,46	3,07	-1,27
17	2034	24,1	18,4	15,6	12,3	14,8	7,23	3,30	-1,12
18	2035	23,7	18,7	15,5	12,2	14,7	8,00	3,53	-0,97
19	2036	23,3	19,0	15,4	12,1	14,5	8,77	3,76	-0,82
20	2037	22,9	19,2	15,4	12,0	14,4	9,38	4,01	-0,65
21	2038	22,6	19,4	15,3	11,9	14,3	10,0	4,25	-0,49
22	2039	22,2	19,6	15,2	11,8	14,2	10,6	4,50	-0,32
23	2040	21,8	19,7	15,2	11,7	14,0	11,2	4,75	-0,15
24	2041	21,4	19,9	15,1	11,6	13,9	11,8	4,99	0,01
25	2042	21,1	19,8	15,0	11,4	13,8	11,9	5,17	0,06
26	2043	20,7	19,6	14,9	11,2	13,6	12,1	5,35	0,11
27	2044	20,4	19,5	14,7	11,0	13,5	12,3	5,53	0,15
28	2045	20,0	19,3	14,6	10,8	13,4	12,5	5,71	0,20
29	2046	19,6	19,2	14,5	10,61	13,3	12,7	5,88	0,24
30	2047	19,3	18,9	14,4	10,38	13,1	12,6	6,04	0,24
31	2048	18,9	18,6	14,2	10,14	13,0	12,6	6,19	0,23
32	2049	18,6	18,3	14,1	9,91	12,9	12,6	6,35	0,22
33	2050	13,1	12,9	8,84	4,58	7,67	7,42	1,41	-4,89
34	2051	12,8	12,6	8,70	4,35	7,54	7,38	1,56	-4,89
35	2052	12,8	12,7	8,82	4,46	7,54	7,40	1,74	-4,73
36	2053	12,8	12,7	8,95	4,57	7,54	7,42	1,93	-4,57
37	2054	12,8	12,7	9,08	4,68	7,54	7,45	2,11	-4,41
38	2055	12,8	12,7	9,20	4,79	7,54	7,47	2,29	-4,25
39	2056	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
40	2057	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
41	2058	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
42	2059	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
43	2060	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
44	2061	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
45	2062	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
46	2063	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
47	2064	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
48	2065	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
49	2066	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
50	2067	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
51	2068	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
52	2069	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
53	2070	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
54	2071	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
55	2072	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
56	2073	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
57	2074	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
58	2075	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
59	2076	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
60	2077	12,8	12,7	9,33	4,91	7,54	7,49	2,47	-4,09
Total kg CO2 eq./m^2		**1206**	**966**	**789**	**578**	**713**	**415**	**158**	**-146**

Yearly results - per person

Table S9: Yearly absolute results, per person

		S1-NO ton CO2eq./pers.	S1-EU 2°C ton CO2eq./pers.	S1-EU 4°C ton CO2eq./pers.	S1-EU 6°C ton CO2eq./pers.	S2-NO ton CO2eq./pers.	S2-EU 2°C ton CO2eq./pers.	S2-EU 4°C ton CO2eq./pers.	S2-EU 6°C ton CO2eq./pers.	S3-NO ton CO2eq./pers.	S3-EU 2°C ton CO2eq./pers.	S3-EU 4°C ton CO2eq./pers.	S3-EU 6°C ton CO2eq./pers.	S4-NO ton CO2eq./pers.	S4-EU 2°C ton CO2eq./pers.	S4-EU 4°C ton CO2eq./pers.	S4-EU 6°C ton CO2eq./pers.
1	**2018**	1,3	1,4	1,4	1,4	2,1	2,6	2,6	2,6	1,3	1,3	1,3	1,3	0,53	0,54	0,54	0,54
2	**2019**	1,2	1,4	1,4	1,4	2,0	2,5	2,5	2,5	1,2	1,3	1,3	1,3	0,52	0,53	0,53	0,53
3	**2020**	1,2	1,4	1,4	1,4	2,0	2,5	2,5	2,5	1,2	1,2	1,2	1,2	0,50	0,52	0,52	0,52
4	**2021**	1,2	1,3	1,3	1,3	1,9	2,4	2,4	2,4	1,1	1,2	1,2	1,2	0,49	0,51	0,51	0,51
5	**2022**	1,1	1,3	1,3	1,3	1,8	2,3	2,3	2,4	1,1	1,2	1,2	1,2	0,48	0,50	0,50	0,50
6	**2023**	1,1	1,3	1,3	1,3	1,8	2,2	2,3	2,3	1,1	1,1	1,1	1,1	0,47	0,49	0,49	0,49
7	**2024**	1,1	1,2	1,2	1,3	1,7	2,2	2,2	2,2	1,0	1,1	1,1	1,1	0,46	0,48	0,48	0,48
8	**2025**	1,0	1,2	1,2	1,2	1,6	2,1	2,1	2,2	1,0	1,1	1,1	1,1	0,45	0,47	0,47	0,47
9	**2026**	1,0	1,2	1,2	1,2	1,6	2,0	2,0	2,1	0,9	1,0	1,0	1,0	0,44	0,46	0,46	0,46
10	**2027**	1,0	1,1	1,1	1,2	1,5	2,0	2,0	2,1	0,91	1,0	1,0	1,0	0,43	0,45	0,45	0,46
11	**2028**	0,9	1,1	1,1	1,1	1,5	1,9	1,9	2,0	0,87	0,95	1,0	1,0	0,41	0,44	0,44	0,45
12	**2029**	0,91	1,0	1,1	1,1	1,4	1,8	1,9	2,0	0,83	0,91	0,93	0,95	0,40	0,43	0,43	0,44
13	**2030**	0,88	1,0	1,0	1,1	1,4	1,7	1,8	1,9	0,80	0,87	0,89	0,92	0,39	0,42	0,42	0,43
14	**2031**	0,87	1,0	1,0	1,1	1,3	1,7	1,7	1,9	0,79	0,86	0,88	0,91	0,39	0,41	0,42	0,43
15	**2032**	0,85	1,0	1,0	1,1	1,3	1,6	1,7	1,9	0,77	0,84	0,87	0,90	0,39	0,41	0,41	0,42
16	**2033**	0,84	0,94	1,0	1,0	1,3	1,6	1,7	1,8	0,76	0,83	0,85	0,89	0,38	0,40	0,41	0,42
17	**2034**	0,82	0,92	1,0	1,0	1,3	1,5	1,6	1,8	0,75	0,81	0,84	0,88	0,38	0,40	0,41	0,42
18	**2035**	0,81	0,89	0,95	1,0	1,2	1,4	1,6	1,8	0,74	0,79	0,83	0,87	0,38	0,39	0,40	0,41
19	**2036**	0,79	0,87	0,93	1,0	1,2	1,4	1,6	1,7	0,73	0,77	0,82	0,86	0,38	0,39	0,40	0,41
20	**2037**	0,78	0,84	0,92	1,0	1,2	1,3	1,5	1,7	0,72	0,76	0,80	0,85	0,37	0,38	0,40	0,41
21	**2038**	0,77	0,82	0,90	1,0	1,1	1,3	1,5	1,7	0,71	0,74	0,79	0,83	0,37	0,38	0,39	0,40
22	**2039**	0,75	0,80	0,88	0,95	1,1	1,2	1,5	1,6	0,70	0,72	0,78	0,82	0,37	0,37	0,39	0,40
23	**2040**	0,74	0,78	0,87	0,94	1,1	1,2	1,4	1,6	0,68	0,71	0,77	0,81	0,36	0,37	0,39	0,40
24	**2041**	0,72	0,75	0,85	0,92	1,1	1,1	1,4	1,6	0,67	0,69	0,75	0,80	0,36	0,36	0,38	0,39
25	**2042**	0,71	0,74	0,83	0,91	1,0	1,1	1,4	1,6	0,66	0,68	0,74	0,79	0,36	0,36	0,38	0,39
26	**2043**	0,70	0,72	0,82	0,89	1,0	1,1	1,3	1,5	0,65	0,66	0,73	0,78	0,35	0,36	0,37	0,39
27	**2044**	0,68	0,70	0,80	0,88	1,0	1,0	1,3	1,5	0,64	0,65	0,72	0,77	0,35	0,35	0,37	0,39
28	**2045**	0,67	0,68	0,78	0,87	1,0	1,0	1,3	1,5	0,63	0,64	0,70	0,76	0,35	0,35	0,37	0,38
29	**2046**	0,65	0,66	0,77	0,85	0,94	1,0	1,2	1,5	0,62	0,62	0,69	0,75	0,34	0,35	0,36	0,38
30	**2047**	0,64	0,65	0,75	0,84	0,92	0,94	1,2	1,4	0,61	0,61	0,68	0,74	0,34	0,34	0,36	0,38
31	**2048**	0,63	0,63	0,73	0,83	0,89	0,91	1,2	1,4	0,60	0,60	0,67	0,73	0,34	0,34	0,36	0,37
32	**2049**	0,61	0,62	0,72	0,81	0,87	0,88	1,1	1,4	0,59	0,59	0,65	0,72	0,34	0,34	0,35	0,37
33	**2050**	0,50	0,50	0,60	0,70	0,74	0,75	1,0	1,3	0,42	0,43	0,49	0,55	0,21	0,21	0,23	0,25
34	**2051**	0,48	0,49	0,58	0,69	0,71	0,72	0,96	1,2	0,41	0,41	0,48	0,54	0,21	0,21	0,22	0,24
35	**2052**	0,48	0,49	0,58	0,68	0,71	0,72	0,95	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
36	**2053**	0,48	0,49	0,57	0,68	0,71	0,72	0,94	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
37	**2054**	0,48	0,48	0,57	0,68	0,71	0,72	0,94	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
38	**2055**	0,48	0,48	0,57	0,68	0,71	0,72	0,93	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
39	**2056**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
40	**2057**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
41	**2058**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
42	**2059**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
43	**2060**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
44	**2061**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
45	**2062**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
46	**2063**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
47	**2064**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
48	**2065**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
49	**2066**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
50	**2067**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
51	**2068**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
52	**2069**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
53	**2070**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
54	**2071**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
55	**2072**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
56	**2073**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
57	**2074**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
58	**2075**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
59	**2076**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
60	**2077**	0,48	0,48	0,57	0,67	0,71	0,72	0,92	1,2	0,41	0,41	0,47	0,54	0,21	0,21	0,22	0,24
Total, ton CO_2 eq./pers.		**41,6**	**44,5**	**48,4**	**53,0**	**63,1**	**71,60**	**81,78**	**93,68**	**38,0**	**39,4**	**42,0**	**45,0**	**18,7**	**19,1**	**19,8**	**20,6**

Table S10: Yearly absolute net results, per person

		S3-NO ton CO2eq./pers.	S3-EU 2°C ton CO2eq./pers.	S3-EU 4°C ton CO2eq./pers.	S3-EU 6°C ton CO2eq./pers.	S4-NO ton CO2eq./pers.	S4-EU 2°C ton CO2eq./pers.	S4-EU 4°C ton CO2eq./pers.	S4-EU 6°C ton CO2eq./pers.
1	2018	1,2	0,64	0,64	0,64	0,50	-0,04	-0,04	-0,04
2	2019	1,2	0,63	0,63	0,62	0,49	-0,03	-0,03	-0,04
3	2020	1,2	0,62	0,62	0,60	0,48	-0,02	-0,02	-0,04
4	2021	1,1	0,61	0,61	0,58	0,47	-0,01	-0,02	-0,04
5	2022	1,1	0,60	0,59	0,56	0,46	0,00	-0,01	-0,04
6	2023	1,0	0,59	0,58	0,54	0,44	0,01	0,00	-0,04
7	2024	1,0	0,58	0,57	0,52	0,43	0,02	0,01	-0,04
8	2025	1,0	0,56	0,55	0,50	0,42	0,03	0,02	-0,03
9	2026	0,92	0,55	0,54	0,48	0,41	0,04	0,03	-0,03
10	2027	0,88	0,54	0,52	0,45	0,40	0,06	0,03	-0,03
11	2028	0,84	0,53	0,50	0,43	0,39	0,07	0,04	-0,04
12	2029	0,80	0,52	0,49	0,41	0,38	0,08	0,05	-0,04
13	2030	0,77	0,51	0,47	0,38	0,37	0,10	0,05	-0,04
14	2031	0,76	0,52	0,47	0,38	0,37	0,12	0,06	-0,04
15	2032	0,74	0,53	0,47	0,38	0,36	0,14	0,07	-0,03
16	2033	0,73	0,54	0,47	0,37	0,36	0,15	0,07	-0,03
17	2034	0,72	0,55	0,47	0,37	0,36	0,17	0,08	-0,03
18	2035	0,71	0,56	0,46	0,37	0,35	0,19	0,08	-0,02
19	2036	0,70	0,57	0,46	0,36	0,35	0,21	0,09	-0,02
20	2037	0,69	0,58	0,46	0,36	0,35	0,23	0,10	-0,02
21	2038	0,68	0,58	0,46	0,36	0,34	0,24	0,10	-0,01
22	2039	0,67	0,59	0,46	0,35	0,34	0,25	0,11	-0,01
23	2040	0,65	0,59	0,45	0,35	0,34	0,27	0,11	0,00
24	2041	0,64	0,60	0,45	0,35	0,33	0,28	0,12	0,00
25	2042	0,63	0,59	0,45	0,34	0,33	0,29	0,12	0,001
26	2043	0,62	0,59	0,45	0,34	0,33	0,29	0,13	0,003
27	2044	0,61	0,58	0,44	0,33	0,32	0,30	0,13	0,004
28	2045	0,60	0,58	0,44	0,32	0,32	0,30	0,14	0,005
29	2046	0,59	0,58	0,43	0,32	0,32	0,30	0,14	0,006
30	2047	0,58	0,57	0,43	0,31	0,32	0,30	0,14	0,006
31	2048	0,57	0,56	0,43	0,30	0,31	0,30	0,15	0,005
32	2049	0,56	0,55	0,42	0,30	0,31	0,30	0,15	0,005
33	2050	0,39	0,39	0,27	0,14	0,18	0,18	0,03	-0,12
34	2051	0,38	0,38	0,26	0,13	0,18	0,18	0,04	-0,12
35	2052	0,38	0,38	0,26	0,13	0,18	0,18	0,04	-0,11
36	2053	0,38	0,38	0,27	0,14	0,18	0,18	0,05	-0,11
37	2054	0,38	0,38	0,27	0,14	0,18	0,18	0,05	-0,11
38	2055	0,38	0,38	0,28	0,14	0,18	0,18	0,05	-0,10
39	2056	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
40	2057	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
41	2058	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
42	2059	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
43	2060	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
44	2061	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
45	2062	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
46	2063	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
47	2064	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
48	2065	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
49	2066	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
50	2067	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
51	2068	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
52	2069	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
53	2070	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
54	2071	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
55	2072	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
56	2073	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
57	2074	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
58	2075	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
59	2076	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
60	2077	0,38	0,38	0,28	0,15	0,18	0,18	0,06	-0,10
Net total ton CO_2 eq./pers		**36,2**	**29,0**	**23,7**	**17,3**	**17,1**	**9,97**	**3,79**	**-3,49**

Results over the lifetime

Table S11: Absolute results over the lifetime, per neighbourhood

per neighbourhood					
Total	Units	Scenarios	Net total	Units	Scenarios
7,49	kton CO2 eq	S2-EU 6°C	7,49	kton CO2 eq	S2-EU 6°C
6,54	kton CO2 eq	S2-EU 4°C	6,54	kton CO2 eq	S2-EU 4°C
5,73	kton CO2 eq	S2-EU 2°C	5,73	kton CO2 eq	S2-EU 2°C
5,04	kton CO2 eq	S2-NO	5,04	kton CO2 eq	S2-NO
4,24	kton CO2 eq	S1-EU 6°C	4,24	kton CO2 eq	S1-EU 6°C
3,87	kton CO2 eq	S1-EU 4°C	3,87	kton CO2 eq	S1-EU 4°C
3,60	kton CO2 eq	S3-EU 6°C	3,56	kton CO2 eq	S1-EU 2°C
3,56	kton CO2 eq	S1-EU 2°C	3,32	kton CO2 eq	S1-NO
3,36	kton CO2 eq	S3-EU 4°C	2,89	kton CO2 eq	S3-NO
3,32	kton CO2 eq	S1-NO	2,32	kton CO2 eq	S3-EU 2°C
3,15	kton CO2 eq	S3-EU 2°C	1,89	kton CO2 eq	S3-EU 4°C
3,04	kton CO2 eq	S3-NO	1,71	kton CO2 eq	S4-NO
2,06	kton CO2 eq	S4-EU 6°C	1,39	kton CO2 eq	S3-EU 6°C
1,98	kton CO2 eq	S4-EU 4°C	1,00	kton CO2 eq	S4-EU 2°C
1,91	kton CO2 eq	S4-EU 2°C	0,38	kton CO2 eq	S4-EU 4°C
1,87	kton CO2 eq	S4-NO	-0,35	kton CO2 eq	S4-EU 6°C

Table S12: Absolute results over the lifetime, per m^2

per m2					
Total	Units	Scenarios	Net total	Units	Scenarios
2342	kg CO2 eq./m2	S2-EU 6°C	2342	kg CO2 eq./m2	S2-EU 6°C
2044	kg CO2 eq./m2	S2-EU 4°C	2044	kg CO2 eq./m2	S2-EU 4°C
1790	kg CO2 eq./m2	S2-EU 2°C	1790	kg CO2 eq./m2	S2-EU 2°C
1576	kg CO2 eq./m2	S2-NO	1576	kg CO2 eq./m2	S2-NO
1499	kg CO2 eq./m2	S3-EU 6°C	1325	kg CO2 eq./m2	S1-EU 6°C
1400	kg CO2 eq./m2	S3-EU 4°C	1210	kg CO2 eq./m2	S1-EU 4°C
1325	kg CO2 eq./m2	S1-EU 6°C	1206	kg CO2 eq./m2	S3-NO
1314	kg CO2 eq./m2	S3-EU 2°C	1112	kg CO2 eq./m2	S1-EU 2°C
1265	kg CO2 eq./m2	S3-NO	1039	kg CO2 eq./m2	S1-NO
1210	kg CO2 eq./m2	S1-EU 4°C	966	kg CO2 eq./m2	S3-EU 2°C
1112	kg CO2 eq./m2	S1-EU 2°C	789	kg CO2 eq./m2	S3-EU 4°C
1039	kg CO2 eq./m2	S1-NO	713	kg CO2 eq./m2	S4-NO
859	kg CO2 eq./m2	S4-EU 6°C	578	kg CO2 eq./m2	S3-EU 6°C
825	kg CO2 eq./m2	S4-EU 4°C	415	kg CO2 eq./m2	S4-EU 2°C
795	kg CO2 eq./m2	S4-EU 2°C	158	kg CO2 eq./m2	S4-EU 4°C
778	kg CO2 eq./m2	S4-NO	-146	kg CO2 eq./m2	S4-EU 6°C

Table S13: Absolute results over the lifetime, per person

per pers.					
Total	Units	Scenarios	Net total	Units	Scenarios
93,7	ton CO2eq./pers.	S2-EU 6°C	93,7	ton CO2eq./pers.	S2-EU 6°C
81,8	ton CO2eq./pers.	S2-EU 4°C	81,8	ton CO2eq./pers.	S2-EU 4°C
71,6	ton CO2eq./pers.	S2-EU 2°C	71,6	ton CO2eq./pers.	S2-EU 2°C
63,1	ton CO2eq./pers.	S2-NO	63,1	ton CO2eq./pers.	S2-NO
53,0	ton CO2eq./pers.	S1-EU 6°C	53,0	ton CO2eq./pers.	S1-EU 6°C
48,4	ton CO2eq./pers.	S1-EU 4°C	48,4	ton CO2eq./pers.	S1-EU 4°C
45,0	ton CO2eq./pers.	S3-EU 6°C	44,5	ton CO2eq./pers.	S1-EU 2°C
44,5	ton CO2eq./pers.	S1-EU 2°C	41,6	ton CO2eq./pers.	S1-NO
42,0	ton CO2eq./pers.	S3-EU 4°C	36,2	ton CO2eq./pers.	S3-NO
41,6	ton CO2eq./pers.	S1-NO	29,0	ton CO2eq./pers.	S3-EU 2°C
39,4	ton CO2eq./pers.	S3-EU 2°C	23,7	ton CO2eq./pers.	S3-EU 4°C
38,0	ton CO2eq./pers.	S3-NO	17,3	ton CO2eq./pers.	S3-EU 6°C
20,6	ton CO2eq./pers.	S4-EU 6°C	17,1	ton CO2eq./pers.	S4-NO
19,8	ton CO2eq./pers.	S4-EU 4°C	10,0	ton CO2eq./pers.	S4-EU 2°C
19,1	ton CO2eq./pers.	S4-EU 2°C	3,8	ton CO2eq./pers.	S4-EU 4°C
18,7	ton CO2eq./pers.	S4-NO	-3,5	ton CO2eq./pers.	S4-EU 6°C

References

ESU, and IFEU. 2008. New Energy Externalities Developments for Sustainability (NEEDS) - LCA of background processes.*in* U. ESU Services, CH, editor.

Fridstrøm, L., and V. Østli. 2016. Vehicle fleet forecasts based on stock-flow modeling (in Norwegian). Institute of Transport Economics.

Hertwich, E. G., T. Gibon, E. A. Bouman, A. Arvesen, S. Suh, G. A. Heath, J. D. Bergesen, A. Ramirez, M. I. Vega, and L. Shi. 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proceedings of the National Academy of Sciences of the United States of America **112**:6277-6282.

IEA. 2015. Energy Technology Perspectives 2015 - Mobilising Innovation to Accelerate Climate Action. International Energy Agency (IEA), Paris, France.

Standard Norge. 2018. NS 3720:2018 - Methods for greenhouse gas calculations for buildings (in Norwegian).

Thomas, M., L. A. W. Ellingsen, and C. R. Hung. 2018. Battery-powered electric vehicles: market development and lifecycle emissions. European Parliament.

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