ISBN 978-82-326-6233-3 (printed ver.)
ISBN 978-82-326-5755-1 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (electronic ver.)

Doctoral thesis

Carine Lausselet

Doctoral theses at NTNU, 2021:364

NTNU
Norwegian University of
Science and Technology
Thesis for the degree of
Philosophiae Doctor
Faculty of Engineering
Department of Energy and Process Engineering

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Doctoral theses at NTNU, 2021:364

PRINTED IN NORWAY
NO - 1598

NORDIC SWAN ECOLABEL
Printed matter
2041 0731

Printed by Skipnes Kommunikasjon AS

Preface

This thesis has been submitted to the Faculty of Engineering Science of the Norwegian University of Science and Technology (NTNU) for the partial fulfilment of the requirements for the degree of Philosophiae Doctor. This work was carried out at the Industrial Ecology Programme Department of Energy and Process Engineering, in the period from March 2017 to April 2021, under the supervision of Professor Helge Brattebø and co-supervision of Professor Anders Strømman. Robert Crawford, Associate Professor in the Faculty of Architecture, Building and Planning of the University of Melbourne, acted as guest-supervisor in the period from January to June 2020. The research presented is funded by the Research Council of Norway through the Research Centre on Zero Emission Neighbourhood in Smart Cities (FME ZEN) through contracts 257660.

Carine Lausselet

Trondheim, October 2021

Abstract

In this thesis, the nexus of buildings, mobility, and energy systems is assessed by aiming for net-zero emission neighbourhoods (nZENs). The concept of nZENs relies upon the concept of net-zero-emission buildings (nZEBs), which involves the use of passive-house technologies in combination with the choice of low-carbon materials and local renewable-energy production to meet the internal energy demand in addition to the export of surplus energy to the external power grid, in order to offset emissions from use of high-carbon energy elsewhere. The nZEN concept extends this principle to include emissions from all buildings in a neighbourhood, as well as the emissions from infrastructure and mobility of the users in the neighbourhood.

Low-energy building standards shift the focus from the operational to the material phases, making material efficiency strategies important for climate mitigation. Demand-side material-efficiency strategies are complementary to those obtained through the decarbonisation of our energy system and may offer substantial climate-mitigation potentials. To assess their combination, life-cycle assessment (LCA) is used to assess the environmental potential co-benefits and trade-offs of nZENs, with a focus on decision support to nZEN projects in the early planning stages. Climate-mitigation strategies (CMSs) are developed to provide recommendations. By including a temporal dimension, the aspiration is to identify strategic choices needed at different points in time, to make the necessary provisions allowing for nZENs to deploy their full potential.

The following elements of a neighbourhood system are considered: buildings, mobility, infrastructure, and on-site energy generation. The model developed to analyse the emission profiles of such elements and the neighbourhood in total is adjusted to fit the specificities of several nZEN projects in the early planning stages.

LCA modelling is based on a bottom-up approach that is well suited to capture the potential life-cycle environmental impacts and bottlenecks of a product or system. The further combination of LCA with Input-Output methods, as applied in hybrid LCA, allows us to account for a more comprehensive system boundary, beyond the process-LCA approach, and can therefore include emissions from background system activities that are typically not captured by a conventional LCA. Moreover, the combination of LCA with dynamic material-flow analysis allows to capture the environmental impacts and material and energy flows at different points in time, for instance in relation to future construction, renovation, and demolition activities in the neighbourhood.

The critical factors for the LCA performance of nZEN projects over a 60 year time horizon are found to be, fairly much in decreasing order of importance: the dwelling size in floor area per capita, the daily distance travelled by the inhabitants, the product lifetime, the decarbonisation rate of the material-production chains, the buildings' energy load, the emission intensity of the electricity, the emissions associated with vehicle production, the emission intensities for electricity and heat production by waste incineration and the time horizon of the climate metrics and the choice of the functional unit in the LCA model.

The use of several climate metrics has shed light on the use of fossil fuels in the material-production value chains to provide the mobility and shelter services to the inhabitants of nZENs and highlights the importance of short-lived greenhouse gas such as methane.

Environmental co-benefits of 5–20% for individual CMSs and of 22–54% for combined CMSs are shown across the impact categories. The highest environmental co-benefits are of 42% and are found for Metal Depletion, shedding light on the close interlink between climate-change mitigation and reduced pressure on resource use.

To best mitigate climate change, CMSs should be implemented at different points in time. In the early planning stages, incentive that will favour the dwelling size–measured per habitants–should be in place. Also, materials with low environmental intensity should be preferred, and the building should be designed in a way that allows for reuse of elements. A good maintenance of the buildings will postpone renovation needs and extend the buildings' lifetime and thus reduce the need for new construction. A culture of not only car- but also ride-sharing will be of great help in the climate-mitigation challenge. Car-sharing will reduce the pressure on the use of resources by diminishing the in-use stock of metals. In addition to those environmental advantages, ride-sharing will have climate and environmental co-benefits in several other aspects such as improved air quality and reduced traffic noise and congestion. When deploying strategies to renovate national building stocks, the opportunity to reshape dwellings into dwellings of smaller sizes should be assessed in favour of a sole focus on nZEB standards.

Other elements that constitute the footprint of the Norwegian citizens should be incorporated to assess the overall climate-mitigation potential of the nZEN inhabitants. Also, a better understanding of the user behaviour will help in the understanding of a potential rebound effect induced by the budget left-overs of the households thanks to material-efficiency measures that will reduce their monthly bills related to shelter, heating, and mobility needs and open for other spending.

The main contribution of this thesis is the combined analysis of several sub-systems at the neighbourhood level, which evolve at very different paces over a long time horizon of 60 years, in order to reveal critical system variables across sub-systems and time, with the aim to offer practical recommendations for decision makers in the early-stage planning process.

Sammendrag

I denne avhandlingen vurderes sammenhengen mellom bygninger, mobilitet og energisystemer ved å sikte mot netto-nullutslippsområder (nZEN). Konseptet med nZENs bygger videre på konseptet med netto-nullutslippsbygninger (nZEB), som innebærer bruk av passivhusteknologier i kombinasjon med valg av lav-karbon materialer og lokal produksjon av fornybar energi for å møte det interne energibehovet i tillegg til eksport av overskuddsenergi til det eksterne kraftnettet, for å kompensere for utslipp fra bruk av høy-karbon energi andre steder. Konseptet nZEN utvider dette prinsippet til å omfatte utslipp fra alle bygninger i et nabolag, samt utslipp fra infrastruktur og mobilitet til brukerne i nabolaget.

Lavenergi byggstandard skifter fokus fra driftsfasen til materialfasen, noe som gjør materialeffektivitetsstrategier viktige for klimavern. Materialeffektivitetsstrategier på etterspørselssiden er komplementære til de som oppnås ved avkarbonisering av energisystemet, og kan gi betydelig klimagevinst. Her brukes livssyklsusanalyse (LCA) til å vurdere de miljømessige potensielle fordelene og avveiningene av nZEN, med fokus på beslutningsstøtte til nZEN-prosjekter i de tidlige planleggingsstadiene. Klimavennlige strategier (CMS) er utviklet for å gi anbefalinger. Ved å inkludere en tidsmessig dimensjon, er ambisjonen å identifisere strategiske valg som trengs på forskjellige tidspunkter, for å gjennomføre de nødvendige tiltakene som gjør det mulig for nZEN å utnytte sitt fulle potensiale.

Følgende elementer vurderes i et nabolagssystem: bygninger, mobilitet, infrastruktur og lokal energiproduksjon. Modellen er utviklet for å analysere utslippsprofilene til disse elementene og nabolaget totalt. Modellen er justert for å passe spesifisitetene til flere nZEN-prosjekter i de tidlige planleggingsstadiene.

LCA-modellering er basert på en «bottom-up» tilnærming som er godt egnet til å fange opp potensielle livssykluseffekter og flaskehalser på et produkt eller system. Den videre kombinasjonen av LCA med kryssløpsanalyser, som anvendt i hybrid LCA, lar oss redegjøre for en mer omfattende systemgrense utover prosess-LCA tilnærmingen. Dette gjør det mulig å inkludere utslipp fra bakgrunnssystemaktiviteter som vanligvis ikke fanges opp av en konvensjonell LCA. Videre tillater kombinasjonen av LCA og dynamisk materialflytanalyse å fange opp miljøpåvirkninger, og material- og energistrømmer på forskjellige tidspunkt. For eksempel relatert til fremtidig bygging, rehabilitering og riving i nabolaget.

De kritiske faktorene for bruk av LCA i nZEN prosjekter over en 60-års tidshorisont er funnet å være (i avtagende rekkefølge): boligstørrelsen i gulvareal per innbygger, den daglige avstanden reist av innbyggerne, produktets levetid, boligstørrelsen i gulvareal per innbygger, dekarboniseringsgraden for materialproduksjonskjedene, bygningens energilast, utslippsintensiteten til elektrisiteten, utslippene knyttet til kjøretøyproduksjon, utslippsintensiteten for elektrisitet og varmeproduksjon ved avfallsforbrenning , bygningers energilast, produktlevetid, tidshorisont for klimamålingene og valget av funksjonell enhet i LCA modellen.

Bruken av flere klimaberegningsmetoder har belyst bruken av fossile brensler i materialkjedene for å gi mobilitet og bolig til innbyggerne i nZEN og fremhever viktigheten av kortvarige klimagasser som metan.

Miljøfordeler på 5–20% for individuelle CMS og 22–54% for kombinerte CMS er vist på tvers av påvirkningskategoriene. De største bi-miljøfordelene på 42% er funnet for «Metal Depletion», og belyser den nære sammenhengen mellom reduksjon av klimaendringer og redusert press på ressursbruk.

For å best mulig redusere klimaendringene, bør CMS implementeres på forskjellige tidspunkter. I de tidlige planleggingsstadiene bør insentiv som vil favorisere boligstørrelsen - målt per innbygger - være på plass. Også materialer med lav miljøintensitet bør foretrekkes, og bygningen skal utformes på en måte som muliggjør gjenbruk av elementer. Godt vedlikehold av bygningene vil utsette rehabiliteringsbehovet, forlenge bygningens levetid og dermed også redusere behovet for nybygg. En kultur med ikke bare bildeling, men også kjøreturdeling vil gi stor klimagevinst. Bildeling vil redusere presset på ressursbruken ved å redusere bruken av metaller. I tillegg vil deling av kjøreturen gi andre miljøfordeler, som forbedret luftkvalitet, redusert trafikkstøy og redusert kødannelse. Ved implementering av strategier for rehabilitering av nasjonale bygningsmasser bør muligheten til å redusere boligstørrelsen i eksisterende bygg vurderes til fordel for et eneste fokus på nZEB-standarder.

Andre elementer som utgjør de norske statsborgernes karbonfotavtrykk bør inkluderes for å vurdere nZEN-innbyggernes samlede potensial for klimagevinster. Materialeffektivitetstiltak kan føre til at husholdninger får et lavere kostnadsnivå relatert til bolig, oppvarming og mobilitet. Dette kan åpne for at andre utgiftsposter øker. Mer kunnskap om brukeratferd er nødvendig for å forstå hvordan en potensiell tilbakeslagseffekt (rebound-effekt) forårsaket av budsjettrester og endrede forbruksmønstre vil kunne påvirke klimabudsjettet.

Hovedbidraget til denne oppgaven er den kombinerte analysen av flere delsystemer på nabolagsnivå, som utvikler seg i svært forskjellige trinn over en lang tidshorisont på 60 år, for å avsløre kritiske systemvariabler på tvers av delsystemer og tid, med mål om å tilby praktiske anbefalinger til beslutningstakere på et tidlig stadium i planleggingsprosesser.

Acknowledgements

First and foremost, I would like to thank my main supervisor Helge Brattebø for having given me the chance to undertake this incredible PhD adventure. Your careful and sincere supervision has been priceless to me and gave me the opportunity to grow as a researcher and as a person.

I would like to thank Anders Hammer Strømman for having acted as second supervisor and being a strong supporter along the way. My sincere gratitude to Robert Crawford for having acted as guest supervisor while I was visiting at the University of Melbourne and to Andre Stephan for helping me pave the way there. I would like to thank Francesca Verones for her friendship and very useful advice and guidance at several critical turning points in my career and Francesco Cherubini for his active role in the early stages of my academical career for contributing to me being the academician I am today. Daniel Müller, I appreciated our informal talks. Edgar Hertwich, thank you for giving me the chance to continue in academia. I look forward to the next journey. I thank Anne Devismes for her careful proofreading and encouragements. Arild Gustavsen, thank you for making it financially possible to go on research stay with my husband and our three kids. Terese Løvås and Tove Rødder, your support has given us the courage to come back from Australia in the middle of the Corona pandemic. I would also like to thank the administrative staff at EPT for their help and smooth collaboration.

To all my co-authors, it was a great pleasure to share research ideas with you, and I am blessed you agreed to contribute in your own ways. To all the anonymous reviewers who read my manuscripts carefully and came back with comments and suggestions, thank you so much for having helped me improve their quality and relevance.

To all my colleagues and friends at IndEcol, at NTNU and other places, it was a great pleasure to share this PhD journey with you all. Each of you contributed in one way or another to render my PhD time much smoother and joyful. In particular, I would like to thank you for the chats in the corridors, the great time at the IndEcol retreats, the cabin trips, the wine evenings, sharing an apartment in Chicago at the ISIE conference, the useful advice on teaching duties, the bottle of champagne opened when I got the PhD position, the coffee breaks, the lunch in the sun on the tables in front of the previous IndEcol head-quarters, the careful listening of my concerns and frustrations here and there, the sharing of office(s), the women-in-science lunches and discussions, the smiles in the corridor in the middle of a busy day, the questions and discussions that highlighted different perspectives on the same research object and the trip by land to conferences on the continent.

Thanks to my father, mother, Janek, my brothers, and all the members of the enlarged families who have contributed to help me being the person I am today and who have encouraged but also offered useful advices whenever I asked for them.

Yago, Stian, and Noémie, thank you for being the persons you are, each of you in your own way.

Vincent, from a skiing trip in the Alps to a sailing trip after a hard day of study back in the days, our paths have crossed and joined to write this incredible adventure we are sharing together. I could never have gone through all the joyful, and less joyful, life events that life has presented to me without your continuous love and support. I look forward to the next pages!

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List of scientific publications and other research outputs

The scientific publications and other research outputs during my time as PhD candidate are listed here. The primary publications refer to the peer-reviewed journal articles that I consider as the core of my work and that are presented in this thesis. The secondary publications refer to peer-reviewed journal articles, conference articles and reports that I have work on as part of my PhD project, but that I do not consider as core of my PhD. Other research outputs include blogs, a video and contributions to a module of an exhibition.

Primary publications

In all the primary publication, I was the **main responsible** for the research co-design, method and tool development, data collection, data analysis, and writing:

I. Lausselet, Carine; Borgnes, Vilde Sorkmo; Brattebø, Helge. (2019) LCA modelling for Zero Emission Neighbourhoods in early stage planning. *Building and Environment.* vol. 149: 379-389.

II. Lausselet, Carine; Ellingsen, Linda Ager-Wick; Strømman, Anders Hammer; Brattebø, Helge. (2020) A life-cycle assessment model for zero emission neighbourhoods. *Journal of Industrial Ecology.* vol. 24: 500-516

III. Lausselet, Carine; Urrego, Johana Paola Forero; Resch, Eirik; Brattebø, Helge. (2020) Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighbourhood building stock. *Journal of Industrial Ecology.* vol. 25: 419-434.

IV. Lausselet, Carine; Lund, Kristi Marie; Brattebø, Helge. (2021) LCA and scenario analysis of a Norwegian net-zero GHG emission neighbourhood: The importance of mobility and surplus energy from PV technologies. *Building and Environment.* vol. 189: 107528.

V. Lausselet, Carine; Brattebø, Helge. Environmental co-benefits and trade-offs of climate mitigation strategies applied to net-zero emissions neighbourhoods. (2021) *International Journal of Life-cycle assessment.* Published online 23 September 2021

VI. Lausselet, Carine; Crawford, Robert; Brattebø, Helge. Hybrid life-cycle assessment of net-zero emission neighbourhood in Norway. *In a review process in the Journal of Cleaner Engineering and Technology.*

Secondary publications

For all the secondary publications, I contributed with (1) giving feedback on the method and thus helping shape the results and the interpretation of the results, the discussion, and conclusions, (2) part of the writing, and (3) giving detailed feedbacks on the manuscript.

Peer-reviewed journal articles

i. Resch, Eirik; Lausselet, Carine; Brattebø, Helge; Andresen, Inger. (2020) An analytical method for evaluating and visualizing embodied carbon emissions of buildings. Building and Environment. vol. 168.

Peer-reviewed conference articles

ii. Wiik, Marianne Rose Kjendseth; Selvig, Eivind; Fuglseth, Mie Sparby; Lausselet, Carine; Resch, Eirik; Andresen, Inger; Brattebø, Helge; Hahn, Ulla. (2020) GHG emission requirements and benchmark values in Norwegian building codes. IOP Conference Series: Earth and Environmental Science (EES). vol. 588.

Reports

iii. Wiik, Marianne Rose Kjendseth; Selvig, Eivind; Fuglseth, Mie Sparby; Resch, Eirik; Lausselet, Carine; Andresen, Inger; Brattebø, Helge; Hahn, Ulla. (2020) KLIMAGASSKRAV TIL MATERIALBRUK I BYGNINGER. Utvikling av grunnlag for å sette absolutte krav til klimagassutslipp fra materialbruk i norske bygninger. SINTEF akademisk forlag. 2020. ISBN 978-82-536-1664-3. ZEN Report (24).

iv. Skaar, Christofer; Bergsdal, Håvard; Lausselet, Carine; Resch, Eirik; Brattebø, Helge. (2019) *User-oriented LCA database for inventory of ZEN projects.* SINTEF akademisk forlag. 2019. ZEN Memo (17).

v. Næss, Jan Sandstad; Sandberg, Nina Holck; Nord, Natasa; Vestrum, Magnus Inderberg; Lausselet, Carine; Woszczek, Aleksandra; Rønneseth, Øystein; Brattebø, Helge. (2018) Neighbourhood building stock model for long-term dynamic analyses of energy demand and GHG emissions. SINTEF akademisk forlag. 2018. ISBN 978-82-536-1569-1. ZEN Report (2).

vi. Backe, Stian; Sørensen, Åse Lekang; Pinel, Dimitri; Clauß, John; Lausselet, Carine; Woods, Ruth. (2019) Consequences of Local Energy Supply in Norway: A case study on the ZEN pilot project Campus Evenstad. SINTEF akademisk forlag. 2019. ISBN 978-82-536-1630-8. ZEN Report (17).

Other research outputs

I designed and wrote the two blogs (a. and b.). I created the script of the video (c.) together with Miguel Lars Heras Hernandez. I participated in “The city of the future” module of the exhibition (d.) and contributed in the design, content and presence at the event.

Blogs

a. Lausselet, Carine. (2020) PhD life abroad in the time of Corona. https://www.ntnu.no/blogger/teknat/en/tag/abroad-en/

b. Lausselet, Carine. (2019) All you need to know about buildings to plan sustainable, green neighbourhoods. https://www.ntnutechzone.no/en/2019/05/all-you-need-to-know-about-buildings-to-plan-sustainable-green-neighbourhoods/

Video

c. Lausselet, Carine; Las Heras Hernandez, Miguel. (2021) Temporal analysis of the material flows and embodied greenhouse gas emission of gas emission of a (net) zero emission neighbourhood https://www.youtube.com/watch?v=-VGc29pFZPk&feature=emb_logo

Exhibition

d. FUTURUM (2019) was a “forward-looking exhibition focusing 'the green shift’ and how we can approach the low-emission society towards 2050. Research groups at NTNU with some of their external partners presented examples from their own work related to climate change and transitions towards a more sustainable future. The exhibition was interactive and made use of new dissemination methods and knowledge with the aim to help visitors experience and reflect upon some of the most pressing challenges we face as society.” I participated in “The city of the future» module. https://www.ntnu.edu/museum/futurum

1. Introduction

1.1. Climate urgency

Global warming induced by human activities is increasing at an unprecedented rate. To limit global warming at a safe level of 1.5°C, deep emission reductions in all sectors combined with rapid, far-reaching, and unprecedented changes in all aspects of society are required (IPCC 2018). Holistic multi-layers climate-mitigation strategies (CMSs) based on better material efficiency will be most effective.

In 2019, the total global final energy use of the building sector remained at the same level compared to previous years. However, CO_2 emissions stemming from the operational phase of the buildings were at the *highest level ever recorded*, with a share of 28% of the total global energy-related CO_2 emissions. The continued use of coal, oil and natural gas for heating and cooking in combination with high-activity levels in regions with carbon-intensive electricity were responsible for the increase. In addition, 10% of the total global energy-related CO_2 emissions can be reallocated from the overall industry sector to the industries devoted to manufacturing construction materials such as steel, cement, and glass (IEA 2020). For the building sector, the energy demand should be reduced. At the same time, this sector should be decarbonised and strategies that reduce life-cycle material CO_2 emissions should be implemented (UNEP 2020).

A better material efficiency can help reduce the life-cycle material greenhouse gas (GHG) emissions and will result in the same material services provided but with less material production and processing (Allwood, Ashby et al. 2011). Material efficiency can be measured by quantifying material use by the total weight of materials or in service units to provide for human needs such as housing or recreation (Zhang, Chen et al. 2018). According to Hertwich, Ali et al. (2019), material efficiency strategies such as (1) more intensive use, (2) lifetime extension, (3) light-weighting, (4) reuse of components, (5) recycling, upcycling, and cascading, and (6) improving the yield in production, fabrication and waste processing, will help to provide shelter and automotive transport with a lower material consumption and lower overall GHG emissions. Demand-side material efficiency strategies are complementary to those obtained through the decarbonisation of our energy system and may offer substantial GHG-mitigation potentials (UNEP 2019). But the importance of material use and related embodied emissions is still overshadowed by policies focusing mainly on energy efficiency and the deployment of low-carbon energy supply. Climate-change mitigation policies would benefit from a greater integration of material efficiency strategies that could significantly increase the emission coverage of existing product policies (Scott, Roelich et al. 2018).

The ongoing climate urgency has led to CO_2 and other GHG emissions being the most often inventoried lifecycle indicators. But, in order **to draw holistic comprehensive CMSs, adverse potential environmental side-effects and trade-offs should be assessed as well**. A holistic approach will (1) give an overview of how various types of environmental impacts accumulate over the different life-cycle phases and elements of a project system over time, (2) allow for comparison of a set of alternative scenarios with respect to environmental impacts, and (3) help to identify strategic choices needed at different points in time to make the necessary provisions to counteract the climate urgency and potential environmental side effects. Industrial Ecology as a scientific area of study and its analytical methods are based on such a holistic approach, and Industrial Ecology is thus a potent approach to tackle climate change.

1.2. Industrial Ecology approaches to holistically address the climate urgency

Jelinski, Graedel et al. (1992) introduced the concept of Industrial Ecology to the industrial design of products and processes to aim for sustainable manufacturing strategies. Industrial systems are not isolated anymore but are set in a **holistic perspective**, and the overall **material cycle** from virgin material, to component, product, waste product, and ultimate disposal is optimised. In their view, material and energy flows are promoted or constrained by human institutions. Cyclic behaviour can thus be promoted by engineering excellence, which can design processes to promote material reuse. The wish to avoid toxic waste can be the driver to reduce the quantity of waste or to replace the components of the value chain that leads to toxic waste. Cyclisation may be impeded as well by taxation, that may promote flows or import-export flows that are contrary to cyclisation.

The term **metabolism** is commonly used in the Industrial Ecology area to refer to the flows and conversion processes of materials and energy in modern industrial society, entailing the whole value chain from extraction, production, and consumption to disposal (Fischer-Kowalski 1998).

The **analogy between the industrial and ecological ecosystems** has also been drawn by Frosch and Gallopoulos (1989) who underline that an ideal industrial ecosystem may never be reached in practice but that opportunities are there to optimise the energy and material consumption, reduce the waste generation, and better integrate the outputs of some processes as inputs to other processes. For instance, the effluents from some processes such as spent catalysts from petroleum refining, fly and bottom ash from electric-power generation, or discarded plastic containers from consumer products have potentials to be reused as inputs to other processes. In an industrial ecosystem, materials are not depleted anymore but simply transformed from one form to another. Those transformation procedures still require the expenditure of energy and the unavoidable generation of waste and harmful by-product, but at a much lower level than in a linear economy.

The ***IPAT* equation** (Chertow 2000) is a commonly used equation in Industrial Ecology to calculate the total environmental impact of a given system that has a certain population, welfare level, and technological development. I stands for the total environmental impact, P stands for the population, A stands for the affluence level, and T stands for the technology characteristics. The following sub-chapters describe the elements P and T of the IPAT equation.

1.2.1. Population, carrying capacity and limits to biological resources

The extent of whether the planet's carrying capacity and limits to biological resources are at stress is closely linked to how population is a metabolic driver, that is, its present size and future prediction on its growth or decline (Ehrlich and Holdren 1971). Frosch and Gallopoulos (1989) predicted the population not only to likely increase to 10 billion people by 2030 but also to ideally enjoy standards of living equivalent to those of industrial democracies such as the U.S. or Japan. According to their predictions, such an equilibrium would last a decade or less before critical natural resources such as copper, cobalt, molybdenum, nickel and petroleum would be overconsumed.

In an attempt to combine the concept of **human carrying capacity and natural capital**, Rees (1992) shed light on the appropriation by the wealthy nations of more than a fair share of the planet's carrying capacity. He set the dichotomy between the concept of carrying capacity defined by ecologists and human beings. For ecologists, the carrying capacity refers to "the population of a given species that can be supported indefinitely in a given habitat without permanently damaging the ecosystem upon which it depends". For human beings, this same concept is interpreted as "the maximum rate effect of resource consumption and waste discharge that can be sustained indefinitely in a given region without progressively impairing the functional integrity and productivity of relevant ecosystems". The inverse of the carrying capacity can thus be used as a first estimate on how much natural capital can be produced by area of productive landscape. The focus is thus turned from whether a population is sustainable to how much land (in various categories) is required to support the material standard requirements of a population.

Not only the size of the population but also the **standard of living** of the population are the drivers of the total environmental pressure. The standard of living of consumers may encourage long product use but can also promote early product disposal (Jelinski, Graedel et al. 1992).

One potential side effect of the population increasing its affluence is the risk of **rebound effects**–or changes in behaviour that may offset part of the environmental gain and lead to problem shifting. In energy economics, the rebound effect encompasses both the behavioural and systems responses to cost reductions of energy services as a result of energy-efficiency measures. But this definition of the rebound-effect concept in not sufficient for use in Industrial Ecology research. In Industrial Ecology, we are concerned about more than just energy use, and we ambition to capture the different secondary (system-wide) effects that a change in technology may induce. Also, we often observe that a given technology strategy or intervention measure gives changes in the various environmental impact indicators that are not necessarily pointing in the same direction (Hertwich 2005), and hence, there is a need for trade-off assessment in the decision-making process.

1.2.2. System effects of new technologies

New technologies and industries are created to **meet human needs more effectively and at a lower cost** (Frosch and Gallopoulos 1989). Yet, innovators' incomplete knowledge can lead to undesirable side effects. In historical times, Icarus plummeted from the sky after the sun heat melted the wax from his wings. After globalisation, such inadvertent effects could then have global impacts. For instance, in 1930, chlorinated fluorocarbons (CFCs) have been developed to prevent the use of ammonia or sulfur dioxide in refrigerators, which are both toxic. The introduction of CFCs led to a positive local effect; it saved lives and prevented people from eating untainted food. Only some decades later have the climate scientists discovered that the use and further release of CFCs in the atmosphere led to undesirable effect; CFCs have the potential to destroy the ozone layer.

The application of further technologies can help bring under control many of the adverse effects first brought by a new technology. Waste incineration is a typical example of the application of further technologies to prevent the environmental burden of a new technology by setting emission limits. The implementation of new flue-gas cleaning technology made it possible to lower the concentration of dioxins, particulate matters, heavy metals, and other toxic components released in the environment and to legislate accordingly to promote the dispersion of these new gas cleaning technologies (Damgaard, Riber et al. 2010). According to Frosch and Gallopoulos (1989), government regulation on emissions at the local, national, and international levels will continue to play a strong role in the transition from traditional methods of manufacturing to an industrial-ecosystem approach. **For regulation to be as effective as possible, it has to be based on sound technology and to let room for technological innovations**. In practice, it is not always clear whether a stricter legislation leads to the invention of new technology or whether the new technologies already are out, waiting for a new market to be implemented. I believe it is a mix of the two.

Successful **new materials** have shown improved properties per ton of materials, thus leading to a lower intensity of use for a given task. The ratio of weight to power in industrial boilers which decreased in size by almost 100 times over time is a good example. Yet, the use of new materials in order to lower the weight of the products can potentially lead to more complex materials, which are later on more complex to sort out in the end-of-life stage (Gordon, Bertram et al. 2006, Graedel 2011).

Energy-efficiency improvements are often achieved by the deployment of new energy-efficient infrastructure, equipment, or technology (Suh, Hertwich et al. 2016). The deployment of such measures has in turn implications for net life-cycle environmental and natural-resource impacts. When considering impact categories other than climate change (i.e. global-warming potential), the time needed to overcome the impact of the pulse emission which happened when manufacturing the product can play an important role. This is the case for light-emitting diodes (LED) that increase metal-resource consumption in the midterm, which is subsequently offset by material efficiency improvements in the long term. For industrial technologies, the potential for further environmental improvements in the future is closely linked to changes in the electricity mix.

This brief discussion on system effects of new technologies points to the high importance of evaluating new strategies, concepts, and solutions by holistic and systems-wide approaches, and this is precisely where Industrial Ecology comes to mind. Industrial Ecology makes it possible to examine the material and energy metabolism of a given system, such as a nZEN project, as a consequence of technology and design choices, and to estimate the life-cycle environmental impact profile of the project over its service life. The nature and context of a given nZEN project may be unique to the project at hand; however, Industrial Ecology offers a set of scientific analytical methods, or tools, that can be used to examine more in-depth how such a project can be designed in order to meet environmental targets.

1.2.3. Industrial Ecology methods

Common methods used in Industrial Ecology are typically environmental extended input-output (EEIO), multi-regional EEIO (MRIO), life-cycle assessment (LCA), or material flow analysis (MFA). From my observation, at the Industrial Ecology Programme (IndEcol) at NTNU but also from what I have seen internationally, one may get the impression that **Industrial Ecology researchers get specialised in their field of expertise, with focus mainly on one of these methods, and neither use nor combine the others too much**. I also believe that this might have to do with a question of definition. For instance, when do we start calling an LCA a 'hybrid LCA-MFA' when we first assess individual technology portfolios and then scale them up?

Pauliuk, Sjöstrand et al. (2013) have succeeded in combining MFA and LCA to assess the Norwegian dwelling stock and the potentials to reach the 2°C target. Vásquez, Løvik et al. (2016) have used dynamic MFA to assess energy-reduction strategies in the building stock in three different countries. To assess technology changes, Gibon, Wood et al. (2015) successfully combined the top-down perspective embedded in the input-output (IO) methodology with the bottom-up approach used in LCA.

Industrial Ecology methods allow for a more precise and detailed description of a situation at different points in time. In an attempt to model the future, Sandberg, Sartori et al. (2016) and Gibon, Wood et al. (2015) used two different approaches. Sandberg, Sartori et al. (2016) used a probabilistic approach and applied a Weibull distribution function on a segment of the total Norwegian dwelling stock which is likely to be renovated during the next 40 years. Gibon, Wood et al. (2015) used a linear approach to go from one set of technology description to the next set of technology description. But, when applying LCA and MRIO for prospective technology assessment and scenario analysis, most of the research fails to account for future changes in energy supply and other industries (Pauliuk, Arvesen et al. 2017).

Industrial Ecology models can help improve other types of models such as integrated assessment models (IAMs) (Pauliuk, Arvesen et al. 2017). IAMs ignore material cycles and recycling, incoherently describe the life-cycle impacts of technology, and miss linkages regarding buildings and infrastructure. Including the Industrial Ecology perspective to IAMs will add new constraints and allow for the study of new mitigation options, both of which may lead to more robust and policy-relevant mitigation scenarios.

1.3. Net-zero-emissions neighbourhoods (nZENs)

Neighbourhoods are at the nexus of human needs because they provide shelter, are closely connected to mobility services and induce the energy supply required to satisfy basic need such as heating, hot water, and cooking. Neighbourhoods represent a critical piece of a low-carbon future, but the long lifetime of their buildings necessitates urgent adoption of state-of-the-art performance standards to avoid significant lock-in risk regarding the choice of long-lasting technology solutions. Neighbourhoods thus typically represent an arena where the holistic view and quantitative methods available in Industrial Ecology are required to address their environmental sustainability.

Energy losses can be minimised both by renovating the existing building stock and by constructing new buildings according to low-energy-use standards such as what is found today for passive houses and nearly zero-energy buildings. According to the Energy Performance of Building Directive (European Commission 2010), a nearly zero-energy building is a "building that has very high energy performance and where the nearly zero- or very low-energy need is covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby."

In Norway, the nearly zero-energy building concept is extended in GHG-emission terms and thereby becomes a net-zero-emission building (nZEB) balance (Fufa, Dahl Schlanbusch et al. 2016). By undertaking a consequential approach, the GHG emissions occurring during the different life-cycle stages of an nZEB are compensated by sending the surplus renewable energy produced locally to the grid. Several nZEBs may constitute a nZEN (Wiik, Mamo Fufa et al. 2018). **By using the surplus energy locally produced in a nZEN to substitute power generated from fossil fuels, or to replace fossil fuels used in mobility, nZEN projects will contribute to a low-carbon society**.

In the following sub-sections, the different main sub-systems (buildings, mobility, and energy systems) of an nZEN project as well as their upscaling to an urban scale are addressed.

1.3.1. Building scale research relevant to nZENs

Internationally, the potential of the building sector stands out compared to other sectors, where climate-change mitigation strategies are more difficult to achieve (Edenhofer, Pichs-Madruga et al. 2014). Material efficiency strategies such as reusing steel, reviewing the amount of materials used in buildings and the frequency of replacement, reducing the use of cement, reusing concrete in constructions, and extending the lifespan of buildings and infrastructure offer tremendous climate-mitigation potentials for the built environment (Fischedick, Roy et al. 2014, Malmqvist, Nehasilova et al. 2018, Wiik, Fufa et al. 2018, Eberhardt, Birgisdottir et al. 2019). Planning authorities, major clients, developers, and individual designers are important to encourage innovative approaches to further reduce the embodied GHG emissions (EGHGEs) (Moncaster, Rasmussen et al. 2019).

Previous LCAs on residential **buildings with conventional energy standards showed that the total lifetime GHG emissions are dominated by the use phase, with 80–90% of the total** (Sharma, Saxena et al. 2011, Abd Rashid and Yusoff 2015, Heeren, Mutel et al. 2015, Moschetti, Mazzarella et al. 2015). The magnitude of the different life-cycle phases is driven by the building's energy use, the emission intensity of the energy carriers, and the EGHGEs of construction materials (Dahlstrøm, Sørnes et al. 2012). In most cases, buildings with low-energy-use standards, such as passive-house concepts, zero-energy buildings, and zero-emission buildings (ZEBs), have lower GHG emissions from the operational phase but higher EGHGEs from building materials than conventional buildings. **For ZEBs, the share of GEEs from materials is found to range from 55 to 87% of the total lifetime GHG emissions** (Kristjansdottir, Houlihan-Wiberg et al. 2018, Wiik, Fufa et al. 2018).

Houlihan Wiberg, Georges et al. (2014) aimed at investigating the possibility of achieving a 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 **dominant role of embodied emissions in a total life-cycle perspective** and that the emission gains from surplus on-site electricity production from solar photovoltaic (PV) panels exported to the grid were not 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. Because low operational energy demand is already a regulatory priority in most countries, a stronger focus must be set on embodied emission from materials (Moschetti, Brattebø et al. 2019).

Although considerable efforts have been focused on understanding the energy dimension of buildings, efforts to **reduce the embodied EGHGE from the production of materials** and from the construction, maintenance, and end-of-life stages of buildings require more attention (Lotteau, Loubet et al. 2015). Also, whereas the literature regarding building-material stock and flow dynamics is rich (Lanau, Liu et al. 2019), **the role of material efficiency strategies and building-specific decisions**, such as per-capita apartment size or material choices, **is less understood** (Heeren and Hellweg 2018). More accurate estimates of material intensities and lifetimes can be achieved by local case studies, and cross-cutting modeling frameworks such as combining MFA and LCA can help capture the environmental impact of materials use (Augiseau and Barles 2017). Hence, these are also promising modeling approaches to explore the temporal EGHGE power of material efficiency strategies.

1.3.2. Mobility related research relevant to nZENs

Road transport accounts for 16% of Norwegian GHG emissions and passenger cars account for 54% of the road-transport GHG emissions (Statistics Norway 2018). It 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 kilometers driven (Pauliuk, Dhaniati et al. 2012). In contrast to internal-combustion-engine vehicles (ICEVs), pure 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 BEVs during use throughout their service life (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 average European electricity, they are increased for a BEV powered by coal-based electricity, and they can be more than halved for a BEV powered by renewable electricity sources (Ellingsen, Singh et al. 2016). **The electrification of the vehicle park leads to positive effects in countries or regions where the electricity mix is not carbon-intensive**, and vehicle electrification does, in some cases but not in all, result in GHG emissions reduction (Suh, Hertwich et al. 2016).

For passenger vehicles, material efficiency measures such as more intensive use by means of increased vehicle occupancy and vehicle downsizing by switching to a smaller vehicle will allow for quick emission reductions (Wolfram, Tu et al. 2020).

1.3.3. Energy-system-related research relevant to nZENs

To achieve high shares of renewable energy in the energy-generation mix, a combination of **large-scale and centralised facilities for energy generation and storage needs to be supplemented by small-scale and distributed resources**, typically at a neighbourhood scale (FME ZEN 2018). So far, PV solar-energy systems have been the most common energy source installed in ZEB or nZEN projects (Seljom, Lindberg et al. 2017). But other technologies such as micro-scale (<0.1 MW) combined-heat-and-power (CHP) plants are typically installations for single-family houses (Voss, Musall et al. 2011), whereas small-scale (<2MW) CHP plants can play a part in local thermal grids at a neighbourhood scale (Stene, Justo Alonso et al. 2018). CHP installations offer a good complement to PV installations in terms of equalising the energy exchange between a neighbourhood and the grid. Many renewable energy and waste heat sources have a mismatch between the timing of production capacity and heat demand from buildings. This mismatch makes solutions for short-term and longer-term energy storage attractive. Examples of electricity storage and peak-load-shaving in the supply system are the use of batteries or vehicle-to-grid solutions. For thermal energy storage, borehole thermal energy storage (seasonal storage in bedrock), accumulator tanks with water, or using the thermal mass of building materials are potential storage technologies (Stene, Justo Alonso et al. 2018). Renewable energies such as solar and wind lead 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 benefits of local energy generation, energy efficiency and energy flexibility** will be an important optimisation problem in the design of nZENs. In an European context, nZENs have a potentially important role to play in decarbonising the European electricity and heat systems by either feeding them with local electricity produced from solar and biomass sources or by using their locally produced electricity and thus freeing Norwegian hydropower to be used for other purposes (FME ZEN 2018). A recent report from Backe, Pinel et al. (2021) showed that surplus renewable power produced by European nZENs will most probably replace electricity produced by other low carbon sources elsewhere in the European power system, and heat from fossil sources. This because the European electricity mix is expected to decarbonise rapidly in the coming decade. However, the upscaling of European nZENs is likely to result in the emission allowance prices and total system costs to decrease. Thus, European nZENs will play a role in reducing the cost of reaching the GHG emission targets. If this is a robust and true conclusion, it challenges the way we think of avoided emissions in LCA for nZEN projects. Models such as the ones used in the study of this report, however, can be seen as what is needed in a consequential-LCA approach, where you want to understand how the background economic system, including power generation technologies, change as a consequence of policy changes or new concepts being introduced to the market.

1.3.4. Urban-scale research relevant to nZENs

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 to 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 the building or neighbourhood 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 tonnes 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. The authors found absolute numbers ranging from 5.12 to 6.22 tonnes CO_2 eq./pers./year with 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 modernisation of a city quarter, and found refurbishment of the city quarter to be more favourable than demolition and reconstruction for primary energy demand and GHG emissions, as long as the structural condition of the building allowed it.

Lotteau, Loubet et al. (2015) conducted a review on the built environment at a 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 to 27,000 pers./km^2, (5) transport requirements for daily mobility were based on local or regional average empirical data or statistical models, (6) the overall emission results varied from 0.4 to 5.4 to ktonnes CO_2 eq./neighbourhood/year, from 0.6 to 8.6 tonnes CO_2 eq./pers./year, from 3.6 to 7.8 tonnes CO_2 eq./m^2 neighbourhood/year and from 10.8 to 123.8 kg CO2 eq./ m^2 floor area/year.

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

Those studies all show (1) the shared environmental impact of the built environment and the mobility vehicle fleet and (2) the importance of the embodied emissions in materials, especially when high energy-performance standards are in place.

Buildings should not be analysed as individual elements but should be contextualised to fully capture the broader impacts linked to their inhabitants' choices and their location such as the mobility patterns.

1.4. Motivation, research objectives and research questions

1.4.1. Motivation for my research

LCAs have been increasingly used to evaluate the environmental performance of buildings (Zhao, Zuo et al. 2019), energy systems (Suh, Hertwich et al. 2016) and mobility (Hawkins, Singh et al. 2013, Cox, Mutel et al. 2018). **A life-cycle perspective should be well integrated into decision-making processes** (Lucon, Ürge-Vorsatz et al. 2014). However, this is still rarely the case in the practical planning of neighbourhoods today, and few LCA studies have been published at the neighbourhood scale (Stephan, Crawford et al. 2013, Lotteau, Loubet et al. 2015, Stephan and Crawford 2016), despite their growing relevance and interest in modern urban planning. This is in contrast to the growing interest in nZEBs and nZENs concepts, which are very likely to be critical components in a future climate-change mitigation policy.

Further LCA research in the field on nZENs is required to better understand what are the robust design principles, the favourable solutions and technologies, and the critical factors, sources of uncertainties, sensitivities, and critical assumptions for a successful mitigation of GHG emissions and other environmental impacts over time. In particular, due to their likely high importance, the effect of the following parameters should be better investigated: (1) the functional unit choice, (2) different decarbonisation rates of the electricity mix, (3) better efficiency in the material production value chains, (4) dwelling size, and (5) inhabitants' behaviour.

Whereas the literature on building-material stock and flow dynamics is rich (Lanau, Liu et al. 2019), more accurate estimates of material intensities and in-use lifetimes can be achieved by local case studies. **Cross-cutting modeling frameworks** such as combining LCA and MFA or IO can help capture the environmental impacts stemming from the material use for the construction, renovation, and demolition activities of a neighbourhood (Augiseau and Barles 2017), in order to capture the main gaps or products and processes that are typically not captured by conventional LCA. Hence, these are also promising modeling approaches to explore the temporal environmental impacts of CMSs.

In addition to building-related factors, the influence of mobility- and energy-related factors should be better understood. This includes factors such as (1) mobility patterns in terms of distances driven, choice of transport modes, and penetration rate of new technologies (e.g., electric vehicles), (2) local electricity production from PV technology, and (3) GHG emission benefits gained by sending the surplus electricity production to the grid in reaching a net-zero-GHG-emission target.

By including a time dimension in the nZEN system modelling, the aspiration is to identify the effects of strategic choices that can be taken at different points in time to make the necessary provisions allowing for nZENs to deploy their full potential.

The ongoing climate urgency has led to CO_2 and other GHG emissions to be the most often inventoried life-cycle indicators. But, to draw comprehensive CMSs, other **adverse potential environmental side effects and trade-offs should be assessed as well**.

This PhD research contributes to increase the number of studies at neighbourhood scale and thus will provide a better understanding of the nexus of buildings, mobility, and energy systems. It also challenges LCA methodology, which has so far mainly been used on building, mobility, and energy systems separately and has seldom been combined with other methods such as MFA/DMFA and IO at a neighbourhood scale.

1.4.2. Research objectives

The main research question of the ZEN Centre is formulated as follows:

"How should the sustainable neighbourhoods of the future be designed, built, transformed, and managed to reduce their GHG emissions toward zero".

The specific objectives of this ZEN sub-project and PhD research are to:

1. contribute on how LCA as a method can be applied for nZEN projects in the planning and design, and clarify how LCA results and findings may give directions for such projects in practice
2. reveal critical factors and contributing elements for overall GHG emissions in nZEN projects
3. assess uncertainties and sensitivities for GHG emission reductions and environmental performance of a few promising nZEN projects, including data quality and availability.

In this PhD project, the methodological development of the LCA model is limited to the development of an LCA methodology to assess ZEN pilot projects on a conceptual base. With conceptual base I mean that we will not go into details in specific technical solutions for nZEN projects but keep a holistic and more overarching view of what the most important aspects of the nZEN concept are when applied to a Norwegian context. This means that I also do not aim to go into technical details such as examining alternative ventilation options, integrated shading devices, or visual thermal comfort.

1.4.3. Research questions

1. How can LCA be applied to examine net-zero-emission opportunities in projects at the neighbourhood scale and what are the limitations and applicability of LCA methods?
2. What are the critical factors, system elements, variables, assumptions, and sensitivities for LCA performance of nZEN projects over a 60 year analysis horizon?
3. What kind of individual measure or group of measures have the largest potential for emission reduction in nZEN projects?
4. What would be an appropriate structure and format of inventory datasets in LCA modeling framework for neighbourhoods?

1.5. Structure of the thesis

In this thesis, the context, a literature review as well as the motivation and research questions are given in the Section 1. Then, the methods used throughout the primary publications are explained in Section 2. A useful and explanatory recapitulating table of the methods used in the six primary publications is given at the end of Section 2. In Section 3, the results of each of the six primary publications are given, preceded by their rationale and a brief explanation of the methods. In Section 4, the main findings of each primary publication are given in relation to the four research questions followed by the policy implications, the scientific contribution of this thesis, and an outlook in terms of future work and policy recommendations. Finally, a conclusion is drawn in Section 5.

2. Methods

2.1. Life-cycle assessment

LCA is a standardised method (ISO 14040 2006, ISO 14044 2006). According to the standards, LCA is the "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle".

In other words, LCA aims to track environmental impacts emerging from the production, use, and disposal of goods and processes. By embracing a **systemic perspective and modelling the cause-effect relationship in the environment,** LCA results give an overview of how various types of environmental impacts accumulate over the different life-cycle phases, providing a basis for identifying environmental bottlenecks of specific systems and for comparing a set of alternative scenarios with respect to environmental impacts. As such, LCA results can support environmentally informed decisions in policy-making, product development and procurement, and consumer choices (Finnveden, Hauschild et al. 2009, Hellweg and Milà i Canals 2014).

LCA consists of four steps: (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment and (4) Interpretation. The four steps are described in the following sub-sections, according to (ISO 14040 2006).

2.1.1. Goal and scope definition

In the first phase, the goal and scope, the functional unit, the system boundary and the allocation procedures are defined. The level of detail is study-dependent and can vary according to the goal of a particular LCA. But the scope should be "sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal." The functional unit should reflect and quantify the function of the assessed system. Including time and location helps to reduce the uncertainty when comparing results from other studies. The system boundary is set to define the elements and sub-elements of the product or system assessed that will be included or excluded. Cut-off criteria can be used as selection criteria to exclude certain elementary flows in the second LCA phase. A high degree of transparency in the choices and assumptions made in this first phase is crucial and will increase the reliance on the results by a wide audience.

2.1.2. Inventory analysis

In the second phase, also called the life-cycle inventory (LCI) phase, the elementary flows (i.e., materials, energy, or space that are taken directly from the environment or released directly back into the environment) are collected on the basis of a physical inventory that represents the technical elements included in the system boundary. The completeness of the data collection mirrors the goal and scope of the study defined previously.

Two main LCI modeling approaches can be differentiated: attributional and consequential (UNEP and SETAC 2011). The attributional approach—also referred to as an accounting or descriptive approach—attempts "to provide information on what portion of global burdens can be associated with a product".

On the other hand, the consequential approach—also called change-oriented approach—attempts to "provide information on the environmental burdens that occur as a consequence of a decision".

2.1.3. Impact assessment

The third phase, also called the life-cycle impact assessment (LCIA) phase, aims at evaluating the potential environmental impacts of the elementary flows compiled in the LCI. The elementary flows are thus multiplied with their respective characterisation factors (units of environmental impact per unit of elementary flow) for a chosen set of impact categories. This multiplication step requires that the characterisation factors from the chosen LCIA method(s) match the elementary flows of the LCI. This step is critical and can induce discrepancy in the LCIA results when several LCA databases are used because of the varying number of elementary flows included. Edelen, Ingwersen et al. (2018) recorded a number of elementary flows included in the LCI to differ among LCA databases varying from 10s to 10,000s.

The characterisation factors are modelled and given by the LCIA methods. Although an international consensus has been reached on both the data and the modeling principles used for some impact categories (e.g., human and eco toxicity (Rosenbaum, Bachmann et al. 2008)), diverse methods exist for some other impact categories such as impact on land and water use, acidification, and eutrophication (Hellweg and Milà i Canals 2014). To cope with this lack of consensus and provide global guidance for LCIA indicators, the United Nations Environment Programme (UNEP)/Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative has been launched (UNEP SETAC Life Cycle Initiative 2017).

According to Steinmann, Schipper et al. (2016) the use of four to six impact categories should cover most of the variance (84–92%) in product rankings.

Further optional steps can be included: Grouping, Normalisation and Weighting. The mid-point results are grouped together to end-point results in the Grouping. The emissions are normalised by, for example, capita emissions in the normalisation steps. The normalisation step is required to prepare for weighting across impact categories, if this is to be done, setting the significance of a damage into perspective and finding errors in the study. The impact categories can then be aggregated into one single score in the weighting step based on value choices.

2.1.4. Interpretation

In the fourth phase, the results of the LCA are delivered and interpreted along with their limitations and recommendations.

2.2. Hybrid life-cycle assessment

Process-based pLCA is a preferred method for quantifying direct and embodied building-related GHG emissions (Zhao, Zuo et al. 2019). pLCA provides a very detailed inventory and information on various types of environmental effects (Finnveden, Hauschild et al. 2009, Hellweg and Milà i Canals 2014). However, it is not well suited to understanding wider environmental effects of products and services across international supply chains. MRIO models are well suited for this task because they provide a set of multi-regional LCIs of supply chains up to the point of sale to the final consumer (Wiedmann, Wilting et al. 2011).

However, whereas pLCA suffers from truncation errors because of its incomplete system boundary, MRIO models are embedded with aggregation errors (Majeau-Bettez, Strømman et al. 2011). The truncation errors may have a very broad range, between 3 and 89% (Treloar 1997, Lenzen 2000, Crawford 2008, Yu, Robati et al. 2020). A high truncation error occurs when the pLCA results are not suited for capturing the complete product inputs along the value chain. To achieve a better system-boundary completeness, the combination of top-down (IO or MRIO) and bottom-up (pLCA) approaches to form a hybrid LCA (hLCA) is widely recognised as a more comprehensive approach (Treloar 1997, Gibon and Schaubroeck 2017, Crawford, Bontinck et al. 2018, Agez, Wood et al. 2020).

Several hLCA techniques (tiered, path exchange (PXC), matrix augmentation, and integrated) have been identified in a review by Crawford, Bontinck et al. (2018). All the hLCA techniques are complex and can be time-consuming. As a result, hLCA techniques are seldom applied outside of a dedicated group of experts (Bontinck, Crawford et al. 2017). The recent efforts by Stephan, Crawford et al. (2019) and Agez, Wood et al. (2020) to streamline the computation of hLCA by automating various components should help in their uptake by a wider community.

2.3. Combined life-cycle assessment and dynamic material flow analysis

When widening the scope from a building to the scale of a neighbourhood, city, country, or region, MFA is a well-suited method to determine the material flows and stock of the built environment. Likewise, dynamic MFA (DMFA) can describe the temporal aspects of the historical (Sandberg, Sartori et al. 2016, Athanassiadis, Bouillard et al. 2017) or future (Sandberg, Sartori et al. 2017) evolution of a building stock, the effect of energy-reduction strategies (Pauliuk, Sjöstrand et al. 2013, Sandberg, Sartori et al. 2016, Vásquez, Løvik et al. 2016, Ostermeyer, Nägeli et al. 2018), future material inflow and outflow, as well as the related environmental impacts (Brattebø, Bergsdal et al. 2009, Müller, Liu et al. 2013, Pauliuk, Sjöstrand et al. 2013, Heeren and Hellweg 2018).

By combining LCA with DMFA, the environmental influence of the timing of the construction, renovation, and demolition activities happening during the neighbourhood's lifetime can be more accurately predicted.

The combined DMFA-LCA model consists of three parts: (1) simulating the long-term building stock of the neighbourhood by determining the amount of annual construction, renovation, and demolition activities, (2) setting up the material inventories that characterise each archetype of the building stock and determining the annual GEE intensities for each material, and (3) combining (1) and (2) to calculate the material flows and GEEs over the 60 year time horizon.

The long-term dynamic building-stock modeling is based on the principles of MFA (Brunner and Rechberger 2004). The building stock at a given year is equal to the stock of the previous year plus the change in building stock that year. The building stock is categorised by archetypes defined by a building type, cohort, and renovation state, such as single-family houses (SFHs) from the 1970s after standard renovation. A material inventory that contains the amount and lifetime of each material is set up for each archetype. By assigning an emission intensity to each material, the yearly material and emission flows are obtained.

2.4. The nZEN definition and case studies examined in this thesis

In this sub-section, the definition of a nZEN is given first, followed by the description of the hypothetical case and the two case studies that both refer to pilot nZEN projects in the ZEN Research Centre.

2.4.1. Net-zero-emission neighbourhood definition

According to the ZEN research Centre (Wiik, Fufa et al. 2021), a nZEN is defined as

"*a group of interconnected buildings with associated infrastructure*[1] *located within a confined geographical area*[2]*. **A zero-emission neighbourhood** aims to reduce its direct and indirect **GHG emissions** towards zero over the analysis period*[3]*, in line with a **chosen ambition level** with respect to which life cycle modules and building and infrastructure elements to include*[4]*. The neighbourhood should focus the following, where the first four points have direct consequences for energy and emissions:*

*a. Plan, design and operate buildings and associated infrastructure components towards zero life cycle **GHG emissions.***

*b. Become highly **energy efficient** and powered by a high share of new **renewable energy** in the neighbourhood energy supply system.*

*c. Manage energy flows (within and between buildings) and exchanges with the surrounding energy system in a smart and **flexible** way*[5]*.*

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[1] *Buildings can be of different types, e.g. new, existing, retrofitted or a combination. Infrastructure includes grids and technologies for exchange, generation and storage of electricity and heat. Infrastructure may also include grids and technologies for water, sewage, waste, mobility and ICT.*

[2] *The area has a defined physical boundary to external grids (electricity and heat, and if included, water, sewage, waste, mobility and ICT). However, the system boundary for analysis of energy facilities serving the neighbourhood is not necessarily the same as the geographical area.*

[3] *The analysis period is normally 60 years into the future, assuming 60 years service life of buildings and 100 years service life of infrastructure, and relevant service life for components that will be replaced.*

[4] *The standard NS-EN 15978 "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method" and the proposed new standard NS 3720 "Methods for greenhouse gas calculations for buildings", defines a set of life cycle modules; material production (A1-A3), construction (A4-A5), operation (B1-B7 in NS-EN 15978 and B1-B8 in NS 3720), end-of-life (C1-C4), and benefits and loads beyond the system boundary (D). NS 3451 "Table of building elements" provides a structured nomenclature checklist of building elements which can be used to define the physical system boundary. A given zero emission neighbourhood should have a defined ambition level with respect to which of these life cycle modules to include, and which building and infrastructure elements to include. It is up to the owner of a ZEN project to decide such an ambition level, but this should be unambiguously defined according to the modulus principle of NS-EN 15978 and NS 3720. In the FME-ZEN Centre, further work is carried out to clarify what should be the recommended minimum ambition level for ZEN pilot projects. Further work is done to clarify how to calculate CO2 emission gains from local renewable energy production, and the FME-ZEN does not currently bind to the method of emission calculations in NS-EN 15978 and NS 3720.*

[5] *Flexibility should facilitate the transition to a decarbonized energy system and reduction of power and heat capacity requirements.*

d. Promote sustainable transport patterns and smart mobility systems.

e. Plan, design and operate with respect to **economic sustainability**, by minimizing total life cycle costs.

f. Plan and locate amenities in the neighbourhood to provide good **spatial qualities** and stimulate **sustainable behaviour**.

g. Development of the area is characterized by innovative processes based on new forms of cooperation between the involved partners leading to innovative solutions.“

2.4.2. Hypothetical case study

The hypothetical case study consists of a nZEN of 20 single-family houses of passive house standards. The houses are “all electric” and thus fed by electricity only. The energy use is based on standards and varies throughout the scenarios. Passenger cars only are considered for the mobility sub-systems. Travelled distances are from national statistics.

This hypothetical case study is created in order to test for (1) the functional unit choice, (2) different decarbonisation rates of the electricity mix, (3) better efficiency in the material production chains, (4) dwelling size, and (5) inhabitants’ behaviour; second, to clarify important contributing factors as well as to reveal criticalities and sensitivities for GHG-emission reductions and the environmental performance of such nZEN design projects; and third, to establish a model basis for other LCA studies at a neighbourhood scale, in terms of a high-quality modelling approach regarding consistency, transparency, and flexibility.

2.4.3. The Zero Village Bergen (ZVB) pilot project

The building stock in ZVB consists of residential and non-residential buildings, with a total area of 91,891 m^2, 695 dwellings, and 1,340 inhabitants.

At the current planning stage of the project, different energy-system alternatives are under consideration, including connecting to 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). The heat demand is assumed to be covered by connecting to the district heating system, and the electricity demand is assumed to be supplied by the external power grid and with local production of electricity by PV panels.

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 an important allocation decision emerges, because a waste incineration facility is a multifunctional process. According to the recent Norwegian standard on the methods for GHG emissions calculations for buildings (Standard Norge 2018) that bases its decision on the Product category rules (The International EPD system 2015) for electricity, steam and hot/cold water generation and distribution, the emissions stemming from the waste incineration with subsequent energy recovery shall be allocated to the waste emitter, based on the polluter-paid principle. Three means of transport are considered: personal vehicles, buses, and light rail.

2.4.4. The Ydalir pilot project

Ydalir is a nZEN project in the early planning stages located in Elverum, Norway. Ydalir consists of one school (6,474 m^2), one kindergarten (2,140 m^2), and 1,000 residential buildings (of ca 100 m^2 each) for an expected population of 2,500 inhabitants. The school and the kindergarten were taken into use in autumn 2019, and the residential buildings will be built over the next 15–20 years.

Ydalir has high climate-change-mitigation ambitions clearly stated in its master plan (Ydalir 2017). Ydalir will "produce its energy locally through renewable sources, have passive-house standards or higher for all its buildings, choose wood or other materials with low GHG intensity as main building materials, and reduce the mobility of its inhabitants and find climate-friendly solutions."

The on-site electricity production at Ydalir consists of a district heating plant, PV panels, and 9 CHP machines fuelled by wood chips with an electric power of 40 kW each, a heating power of 100 kW, and assumed 7,000 annual operating hours. In addition, Ydalir has signed an agreement with the local district company.

2.5. The LCA model developed and used in this thesis

The modular-type LCA model developed in this thesis includes five physical elements: buildings, mobility, infrastructure, networks, and on-site energy. The model is applied on several nZENs in the early planning phases in Norway.

Ecoinvent (version 3.2 , allocation cut-off, Wernet, Bauer et al. (2016)) and Environmental Product Declarations are used for background data. When Ecoinvent is used, ReciPe v1.12 (with a hierarchist perspective) is chosen for the impact method (Goedkoop, Heijungs et al. 2013). Arda, a Matlab routine-based program developed at NTNU (Majeau-Bettez and Strømman 2016) is used for the LCA calculations and further structural path analyses to analyse the results. Matlab and Python are also used when LCA is combined with DMFA and MRIO. Excel spreadsheets are used for structuring the inventory data.

For each impact category i, the total environmental impacts of the neighbourhood $EI_{tot,i}$ over the period of assessment is described in Equation (1).

$$EI_{tot,i} = EI_{B(Mc),i} + EI_{B(Mr),i} + EI_{Mob(Mc),i} + EI_{Mob(O),i} + EI_{Inf-Mob(Mc),i} + EI_{Inf,nZEN(Mc+Mr),i} + EI_{En(Mc+Mr,O),i} - EI_{El(surplus),i} \quad (1)$$

$EI_{tot,i}$ is equal to the sum of the environmental impacts caused by the construction of the buildings $EI_{B(Mc),i}$, the replacement of building materials $EI_{B(Mr),i}$, the production of the transportation modes $EI_{Mob(Mc),i}$ used to fulfil the mobility needs of the inhabitants, the operational phase of those transportation modes $EI_{Mob(O),i}$, the related mobility infrastructure $EI_{Inf-Mob(Mc),i}$, the construction and replacement of the infrastructure in the neighbourhood $EI_{Inf-nZEN(Mc+Mr),i}$, as well as the production and operation of the on-site energy $EI_{En(Mc+Mr,O)i}$. Subtracted from this sum is the environmental benefits or credits $EI_{El(surplus),i}$ gained by sending the surplus electricity produced locally to the grid that can substitute an equal amount of electricity that is produced elsewhere, assuming for instance an average European electricity mix including fossil fuels.

When referring to the European Committee for Standardization (2012) *Mc* refers to the "Product stage" or embodied emissions stemming from material production (modules A1–A3), *Mr* refers to the material replacement (B4) in the "Use stage", and "O" refers to the operational energy use in buildings (B6) and in mobility in the use phase of buildings (B8), according to the new Norwegian standard NS 3720 "Method for greenhouse-gas calculations for building" (NS 2018) that accounts for transportation in a separate module.

Throughout the papers, three sets of datapoints have been used, for 2021, 2030, and 2050, to dynamically develop certain model input parameters over time. The input parameters are developed linearly from 2021–2030 and 2030–2050 and kept constant from 2050 to the end of the 60 year long period of analysis.

Each element of Equation (1) is further explained and developed in the journal articles. The number of elements of Equation (1) included varies along the journal articles, according to the purpose, scope, and method of each article.

2.6. Scenario design

Scenarios are useful to examine future possible development paths. In this thesis, scenarios are created to explore alternative mobility patterns and the effects of an upscaling of on-site electricity production and to test which material efficiency strategies are promising. To provide shelter and automotive transport with less materials and lower overall GHG, typical material efficiency strategies are (1) more intensive use, (2) lifetime extension, (3) light-weighting, (4) reuse of components, (5) recycling, upcycling, and cascading, and (6) improving yield in production, fabrication, and waste processing (Hertwich, Ali et al. 2019).

2.7. Sensitivity analysis

A sensitivity analysis is carried out to reveal critical parameters in the LCA model. The factors having a significant impact on the results or associated with large uncertainties were chosen and increased by 25%. The sensitivity ratio is calculated by dividing the relative change in the results by the relative change in the input parameters.

2.8. Summary of the methods used in each paper

The summary of the methods, system boundary, case study, functional unit, impact category, scenario development, and databases used in each primary publication is given in Table 1.

Table 1: Summary of the methods used in each paper

			Methods			System boundary						Case study				Impact category									Databases		
			Process-based LCA	Hybrid LCA	LCA + dynamic MFA	Buildings	Mobility	Infrastructure, on-site	Infrastructure, mobility	On-site energy	Emissions gains	Bergen	Hypothetical	Ydalir	Functional unit	CCIP(GWP20)	CCIP(GWP100)	CCIP(GWP500)	FEP	HTTP	MDP	TAP	Material efficiency	Sensitivity analysis	Ecoinvent 3.2	EPD	Exiobase 3
Peer-reviewed journal papers	I	LCA modelling for Zero Emission Neighbourhoods in early stage planning	+			+	+	+		+	+	+			To fulfill the residential and non-residential housing (91 891 m^2 and 695 dwellings)and mobility demands of the 1 340 inhabitants of the Zero Village Bergen for a timeframe of 60 years starting in 2019.		+							+	+	+	
	II	A life-cycle assessment model for zero emission neighborhoods	+			+	+			+	+		+		To build and refurbish 20 single-family houses of passive house standards over a 60 year period, deliver energy for heating and electric appliances, and provide mobility by passenger cars for all the inhabitants.		+						+	+	+		
	III	Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock			+	+								+	To fulfill the housing demand in terms of residential buildings for the 2,500 inhabitants of Ydalir, including a school and a kindergarten, for a timeframe of 60 years starting in 2019.		+						+		+	+	
	IV	LCA and scenario analysis of a Norwegian net-zero GHG emission neighbourhood: The importance of mobility and surplus energy from PV technologies	+			+	+	+		+	+			+	To fulfil the housing, school, kindergarten, and mobility needs of the 2 500 inhabitants of Ydalir over a 60 year time period.		+						+	+	+	+	
	V	Environmental co-benefits and trade-offs of climate mitigation strategies applied to net-zero emissions neighbourhoods	+			+	+	+	+	+	+			+	To fulfil the housing, school, kindergarten, and mobility needs of the 2 500 inhabitants of Ydalir over a 60-year time period.	+	+	+	+	+	+	+	+		+		
	VI	Hybrid life-cycle assessment to inform neighborhoods in the early planning stages		+		+								+	To fulfil the housing, school, kindergarten of the 2500 inhabitants of Ydalir over a 60 years time period.		+								+		+

3. Results

The results of the six primary publications are presented in the six following sub-sections. Each paper is presented in terms of its rationale, methods used, and main results.

3.1. Paper I

"LCA modelling for Zero Emission Neighbourhoods in early stage planning"

Lausselet, C., V. Borgnes and H. Brattebø (2019). *Building and Environment* 149: 379-389.

Rationale The building sector is a major driver of climate change, and the increased focus on significantly reducing GHG emissions in recent years calls for major initiatives in the way we plan, build, and operate buildings and neighbourhoods. 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.

In Norway, the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Centre) was started in 2018 envisioning 'Sustainable neighbourhoods with net-zero GHG emissions' and with a goal to develop solutions for future buildings and neighbourhoods with close-to-net-zero GHG emissions, thereby contributing to a low carbon society (Wiik, Mamo Fufa et al. 2018). The same year, the new Norwegian standard NS 3720:2018 "Methods for greenhouse gas calculations for buildings" (in Norwegian) (Standard Norge 2018) was published. This standard has the novelty to also include emissions from use-phase mobility activities when assessing GHG emissions of buildings. This increases the complexity of analysing how to meet climate-change policy targets when planning building projects, and it also helps set up the stage from scaling up LCAs from a building to a neighbourhood scale. Moreover, the inclusion of emissions from mobility means that the challenge of reaching net-zero-overall-emission targets for a neighbourhood becomes indeed more comprehensive and difficult to realise in practice.

Unfortunately, the research literature is scarce in this area at present, in particular in the early stage planning process of nZEN projects, where LCA should play a role in the decision making.

Methods We developed a modular structure that serves as a basis for LCA with a focus on climate change at the neighbourhood level, and we first applied it to a case study called Zero Village Bergen (ZVB). ZVB is located in the outskirts of the city of Bergen in Norway and is one of the nZEN pilot projects for the ZEN Centre. The project is in the early planning stages with a presumed launch in 2022–2023 years. Although the LCA model is initially adapted to the specific case, the methodology and calculation procedures are intended to be applicable to any other LCA study at neighbourhood level.

The modular structure of the LCA model is presented in Figure 1 and consists of two dimensions to cover both the main physical elements in the neighbourhood (buildings, mobility, open spaces, networks, and on-site energy infrastructure) and the selected life-cycle stage modules included in the LCA. Such a modular structure can be directly used for the choice of different net-zero-emission ambition levels, depending on how many life-cycle modules (A1–C4) are included when aiming at net-zero emissions, and the ambition can also be flexible with respect to how many physical elements to include.

To address 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.

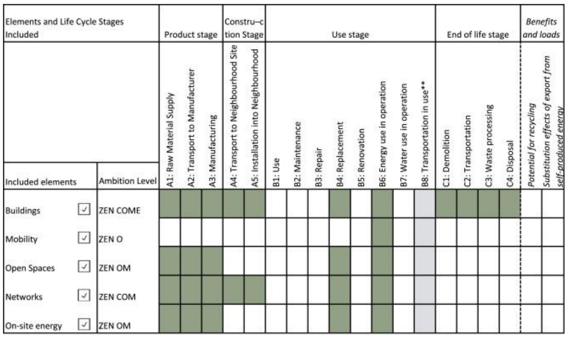

Figure 1: *Modular structure used as basis for LCA at neighbourhood level. Note: the elements and ambition levels marked in this figure are randomly selected and serve only as an example of the use of the structure.*

Results 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 (A1–A3), replacement stage (B4) and energy use in operation (B6 and B8), buildings represent the majority (52%) of total GHG emissions, closely followed by mobility (40%), as shown in Figure 6 of Paper I. The emissions from the on-site energy generation constitute 5% and networks and open spaces together represent only 2%.

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%), as shown in Figure 6 of Paper I. For all the physical 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.

Furthermore, it is worth noting the relatively low level of negative emissions from the on-site energy production that, when using our assumptions, are actually less than the emissions associated with producing the PV panels.

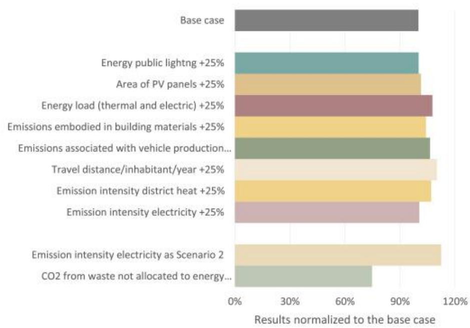

Figure 2: *Sensitivity- analysis results relatively to the base case.*

The results of the sensitivity analysis presented in Figure 2 reveal the travel distance per inhabitant, the buildings' energy load, the allocation of emissions of waste combustion to the heat production or waste generation, the emission intensity for electricity, and the daily travel distance for the inhabitants, to have the largest influence on the total-emission results.

3.2. Paper II

A life-cycle assessment model for zero emission neighbourhoods

Lausselet, C., L. A. W. Ellingsen, A. H. Strømman and H. Brattebø (2020). *Journal of Industrial Ecology* 24: 500-516.

Rationale 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 risks regarding long-lasting technology solution choices. Buildings, mobility, and energy systems are closely linked, and assessing their nexus by aiming for nZEN provides a unique chance to contribute to climate change mitigation. However, few LCA studies have been published at the neighbourhood scale (Stephan, Crawford et al. 2013, Lotteau, Loubet et al. 2015, Stephan and Crawford 2016), despite their growing importance in modern urban planning.

The specific aims of this study are threefold: first, to further develop the model developed in Paper I in order to investigate more closely the effects of (1) the functional unit choice, (2) different decarbonisation rates of the electricity mix, (3) better efficiency in the material production chains, (4) dwelling size, and (5) inhabitants' behaviour; second, to clarify important contributing factors as well as to reveal criticalities and sensitivities for GHG-emission reductions and the environmental performance of such nZEN design projects; and third, to establish a model basis for other LCA studies at a neighbourhood scale, in terms of a high-quality modelling approach regarding consistency, transparency, and flexibility.

Methods We propose a modular LCA model based on the use of the following subsystems: (1) buildings, (2) mobility, and (3) energy systems, as shown in Figure 3 below.

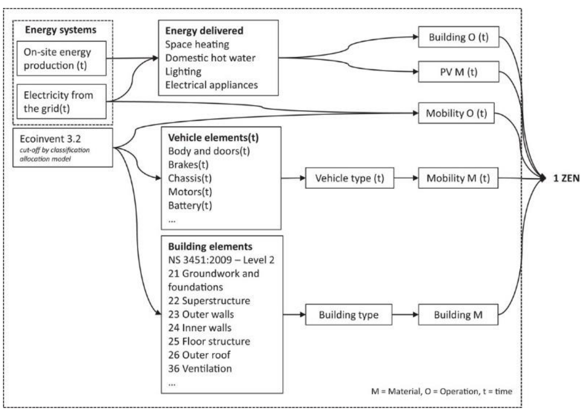

Figure 3: Subsystem approach to assess net-Zero-Emission Neighbourhoods (nZENs).

By assuming an open European market, nZENs will play a potential role in decarbonising the electricity grid because they will supply a surplus of electricity produced from local renewable energy sources. By undertaking a marginal approach, nZENs benefit from GHG-emission credits for the surplus energy sent to the grid that replaces electricity produced from fossil fuels. In this case, local electricity is produced from PV.

The hypothetical nZEN 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 period of 60 years, deliver energy for heating and electric appliances, and provide mobility by passenger cars for all the inhabitants".

Ecoinvent (version 3.2, allocation cut-off) is used for background data. ReciPe v1.12 (with a hierarchist perspective) is chosen for the midpoint-category global-warming potential (GWP100). Other impact categories are not included in the present study, because the focus in the ZEN Centre is GHG emissions. Arda (Majeau-Bettez and Strømman 2016), a Matlab routine-based program developed at NTNU, is used for the LCA calculations.

We designed four scenarios to test the influence of the house size, household size, and energy used and produced in the buildings as well as mobility patterns. We ran our scenarios with different levels of decarbonisation of the electricity mix over a period of 60 years.

Results Our yearly results show the importance of the operational phases of both the buildings and mobility at the beginning of the period of analysis, and its decline over time induced by the decarbonisation of the electricity mix. At the neighbourhood end-of-life, embodied emissions then become responsible for the majority of the emissions when the electricity mix is decarbonised. The emission compensations decrease the results by 4–7% for an electricity mix that is already decarbonised (NO), by 24–40% when a highly decarbonised path is followed (EU 2°C), by 40–69% for a middle decarbonised path (EU 4°C) and by 56–100% for a little decarbonised path (EU 6°C).

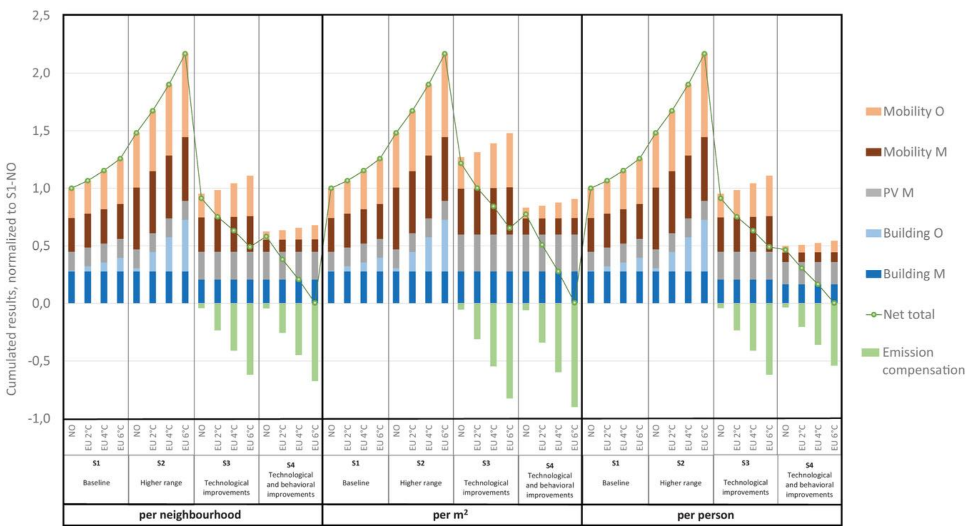

Figure 4: Results over the lifetime normalised to S1-NO, per neighbourhood, m² heated floor area, and inhabitant.

The choice of the functional unit turns out to be decisive, and 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" functional unit is misleading because it does not give credits to the precautionary use of floor area, and it is also not well-linked to the mobility activity of a neighbourhood. To best mitigate climate change, climate-positive behaviours should be combined with energy efficiency standards that incorporate embodied energy, and absolute threshold levels on energy and emission intensity (such as kWh/m^2, $kgCO_2e/m^2$,kWh/pers. and $kgCO_2e$/pers.) for specific services could be combined with behavioural changes.

3.3. Paper III

"Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighbourhood building stock."

Lausselet, C., J. P. F. Urrego, E. Resch and H. Brattebø (2020). *Journal of Industrial Ecology* 25: 419-434.

Rationale Low-energy building standards shift environmental impacts from the operational to the embodied emissions, making material efficiency measures important for climate mitigation. Material efficiency means providing material services with less material production and processing (Allwood, Ashby et al. 2011). However, the importance of material use in buildings is today still overshadowed by policies focusing on energy efficiency and low GHG emissions in the energy supply (Scott, Roelich et al. 2018).

Demand-side material efficiency strategies are complementary to those obtained through the decarbonisation of our energy system and may offer substantial GHG-mitigation potentials (UNEP 2019). A pluralistic material efficiency-oriented approach that englobes stronger policy drivers for the use of low-GHG-emission materials and increased material reuse is key for a quicker transition to low-GHG-emission built environment (Pomponi and Moncaster 2016).

Methods To better understand the effects of decisions taken in the early planning phase of a neighbourhood, we developed a combined DMFA-LCA model that estimates the GHG emissions from construction, renovation, and demolition activities of a neighbourhood over a 60 year time horizon. The model was applied to the Norwegian nZEN project Ydalir. The combined DMFA-LCA model consists of three parts, as shown in Figure 5: (1) simulating the long-term building stock of the neighbourhood by determining the amount of annual construction, renovation, and demolition activities, measured in number of m^2 of floor area, (2) setting up the material inventories that characterize each archetype of the building stock, measured in kg of material per m^2 of floor area and determining the annual GHG intensities for each material, measured in $kgCO_2$-eq per kg of each material, and (3) combining (1) and (2) to calculate the material flows and GHG over the 60 year time horizon, measured in kg per year and $kgCO_2$-eq per year, or kg and $kgCO_2$-eq for the whole period, respectively. The combination of the cohort, building type, and renovation state results in 16 archetypes: 6 construction archetypes and 10 renovation archetypes.

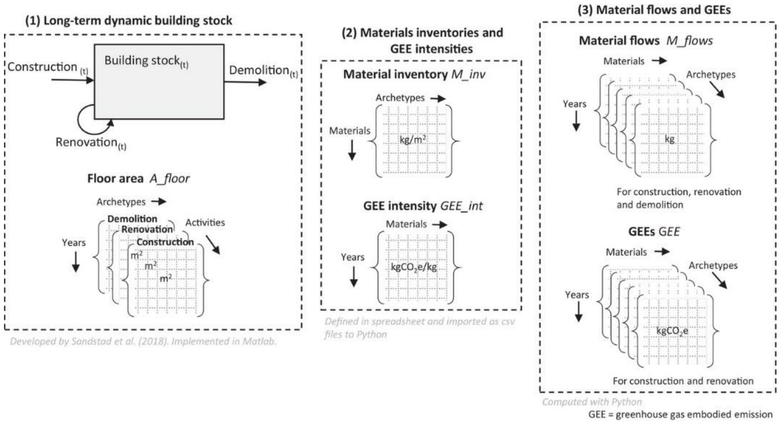

Figure 5: Model description.

We developed 8 material efficiency scenarios to test for (1) a more intensive use, (2) lifetime extension (building and material), (3) an improved yield in production, and (4) a combination of material efficiency strategies.

Results The yearly and cumulative material and EGHGE flows are shown in Figure 6 by material categories. A total of 114 kton material is needed: 71% for the construction, 13% for the renovation, and 16% for the new construction required to maintain the building stock floor area constant over time, equivalent to an average material use of 1,049 kg/m^2, in-use stock of 43 tons/cap. Rapid material stock accumulation occurs in the first 11 years because of construction activity. After 2030, the material stock accumulation remains almost constant until around 2045, when the first wave of renovation activities start. The flow of concrete and wood dominates the material flows over the years, with 55% and 25% of the total material flows, respectively.

A total of 82 kton CO2e is emitted, equivalent to 294 kgCO2e/m2. 52% of the total GEEs are due to the initial construction activities, 36% are due to the renovation activities, and the remaining 12% are due to the new constructions at the end of the analysis period. The most dominant sources of GEEs are the PV panels, followed by wood and concrete.

Although the GGEs from initial construction activities are fairly similar to those from the later renovation and new construction activities, the time window in which they occur is different. Whereas 52% of the total GEEs are spread over the first 11 years (2019 to 2030), the remaining 48% occur in a distant timeframe of 45 years (2035 to 2080). Hence, a significant share of the total emissions is delayed a lot and thereby also subject to potential technology improvements with decreasing emission intensities.

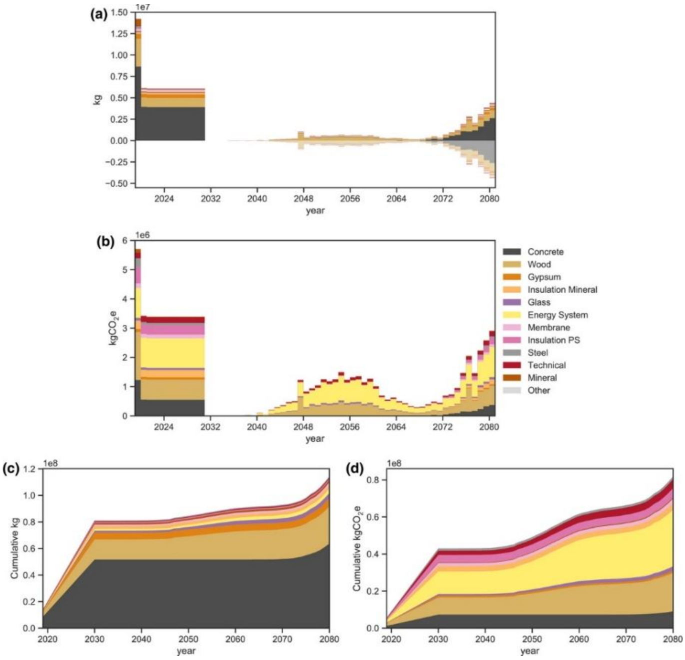

Figure 6: (a) Yearly material; (b) greenhouse gas embodied emissions (GEEs); (c) cumulative material flows by material categories; (d) GEEs flows by material categories.

The results of the material efficiency scenarios show EGHGE mitigation potentials ranging from 7 to 44%. The combination of different material efficiency strategies shows the highest mitigation potential of the cumulative EGHGEs. Combining a more intensive use of buildings with a longer material lifetime has a cumulative mitigation potential of 29%, whereas a further combination of the former scenario with an improved yield in material production leads to a further mitigation of 15% for a total of 44%.

3.4. Paper IV

"LCA and scenario analysis of a Norwegian net-zero GHG emission neighbourhood: The importance of mobility and surplus energy from PV technologies."

Lausselet, C., K. M. Lund, and H. Brattebø. 2021. *Building and Environment*. vol. 189: 107528

Rationale Buildings are commonly treated as independent objects when performing LCAs and separate from emissions from infrastructure and mobility. However, when conducting LCAs at a neighbourhood scale, aspects such as density, transportation, and infrastructure should be considered because some of these sources of emissions might have a great influence on the overall performance of the neighbourhood.

Previous studies have shown that the mobility needed to fulfil the transportation needs of the inhabitants and users has a significant impact on the total GHG emissions of urban areas (Stephan, Crawford et al. 2013, Nichols and Kockelman 2014, Bastos, Batterman et al. 2016).

In Norway, the new standard NS 3720 "Method for greenhouse-gas calculations for building" (Standard Norge 2018) is a tool to synchronise LCA studies on building at a neighbourhood scale. Transportation is here accounted for by introduction of a new and separate life-cycle module (B8) in the use stage of a building.

In this paper, we aim to better understand the influence of mobility and on-site PV electricity production, examining factors such as the (1) mobility patterns in terms of distances driven, choice of transport modes, and penetration rate of new technologies (e.g., electric vehicle), (2) local electricity production from PV technology, and (3) GHG-emission benefits gained by sending the surplus electricity production to the grid in reaching a net-zero-GHG-emission target.

Methods The model developed in Papers I and II is adjusted to fit the specifics of the nZEN Ydalir, located in Elverum, Norway. The following elements are considered: buildings, mobility, infrastructure, networks, and on-site energy generation.

Ydalir has high climate-change-mitigation ambitions clearly stated in its master plan (Ydalir 2017). The master plan states that Ydalir will produce its energy locally through renewable sources, have passive-house standards or higher for all its buildings, choose wood or other materials with low GHG intensity as main building materials, and reduce the mobility of its inhabitants and find climate-friendly solutions.

The functional unit of the LCA model is "to fulfil the housing, school, kindergarten, and mobility needs of the 2 500 inhabitants of Ydalir over a 60 year time period."

Three means of transportation are assessed: personal vehicles, bus and light rail, and walking and cycling. The on-site electricity production in Ydalir consists of a district heating plant, PV panels, and 9 CHP machines fuelled by wood chips.

Seven scenarios were created to explore different mobility patterns, and other scenarios analyse the impact from energy-emission intensities, building materials, and upscaling the energy production from PV panels.

A sensitivity analysis was carried out to reveal critical parameters in the LCA model, with focus on the sensitivity of mobility energy use in operation, area of PV panels, emissions embodied in building materials, emissions associated with vehicle production, travel distance per inhabitant and per year, and emission intensity of electricity in the power grid.

Results The most critical parameters for reaching the nZEN goal are the daily travel distance of the inhabitants followed by the emission intensity of the energy mix when surplus electricity from local PV production substitutes more carbon-rich power or fuels generated elsewhere.

Figure 7 shows the results from the scenario analysis and reveals that the mobility scenarios have the most pronounced impact on the overall results, as expected when considering the results from the sensitivity analysis. The results show that Ydalir can at the most cut its total emission by 54%, which is a lot but still far from the net-zero-emission ambition. The dominant source of emissions is mobility with 38–62%, mainly caused by the use of personal vehicles.

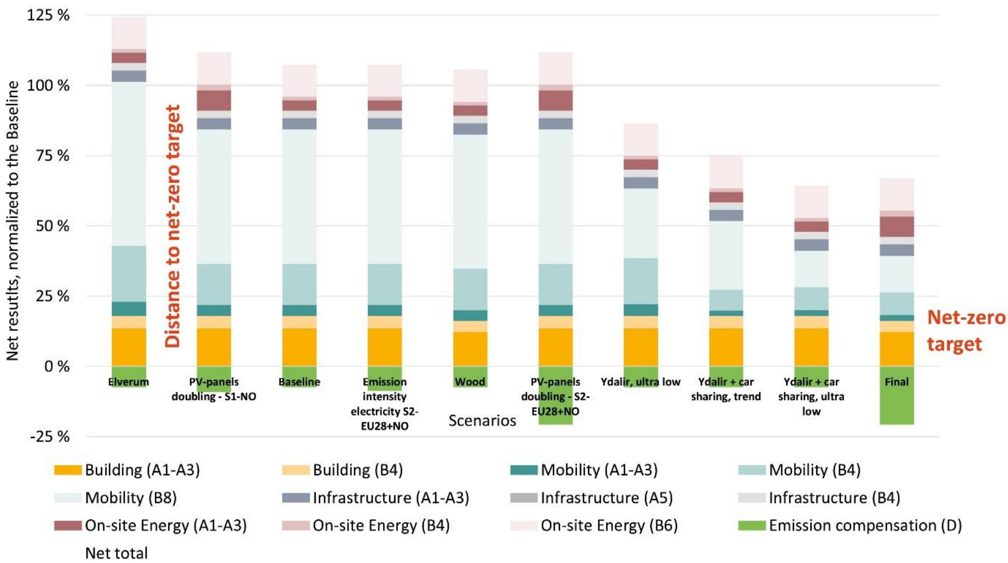

Figure 7: Total GHG-emission results of scenario analysis relatively to the Baseline scenario.

In fact, the faster penetration of electric vehicles in “Ydalir, ultra-low” decreases the results from the baseline by 21%, “Ydalir + car sharing, trend path” decreases the results by an additional 12%, and “Ydalir + car sharing, ultra-low” reduces the results by an additional 10% for a total decrease of 43%. The measures taken in Ydalir to reduce the use of passenger cars to go to work and use public transportation instead reduce the overall emissions by 17%. When doubling the area of PV panels, the total emissions increase by 3% when assuming S1-NO for the emission credits and decrease by 8% when assuming S2-EU28+NO for emission credits. The reason is that PV electricity generation gives higher emissions than the average Norwegian power mix but is still well below the average European power mix. A further use of materials with low GHG intensities will reduce the overall emission by 2% only, because the building materials at Ydalir have already been chosen carefully and are mainly wood-based. The combination of different measures in the final scenario reduces the overall emission by 54%.

3.5. Paper V

“Environmental co-benefits and trade-offs of climate mitigation strategies applied to net-zero emissions neighbourhoods”

Lausselet, C., H. Brattebø. 2021. In a review process in the special issue on LCA in the Context of Decarbonization and Carbon Neutrality of the *International Journal of Life-Cycle assessment*

Rationale The ongoing climate urgency has led to GHG emissions to be the most often inventoried lifecycle indicator. But to draw comprehensive CMS, adverse potential environmental side effects and trade-offs should be assessed as well. Multi-layered CMS will be most effective. For the building sector, the energy demand should be reduced. At the same time, this sector should be decarbonised and strategies that reduce life-cycle material CO_2 emissions should be implemented (UNEP 2020).

Consequently, and in view of the stringent short- and long-term climate objectives and the need to implement them locally, the main value of this work is to conduct a comprehensive LCA on a nZEN in the early planning stages with a time dimension to (1) assess the environmental potential co-benefits and trade-offs of an nZEN in the early planning stages, (2) develop CMSs highlighting key strategic considerations and limitations around the identified technical potential, (3) compare the identified environmental reduction potential and trade-offs with what has been realised in the current project and (4) provide recommendations on when the different CMSs must be in place.

Methods We use the model developed in Papers I and II and used in Paper II. The model is further developed to (1) compute detailed annual energy balances, (2) include mobility-related infrastructure and (3) include a wider set of impact categories. Three datapoints are used (for 2021, 2030 and 2050) to dynamically develop certain parameters over time to account for increased efficiency in the production processes and an increase in the use of recycled materials. The parameters are developed linearly from 2021–2030 and 2030–2050 and kept constant from 2050 to the end of the period of analysis. The model is applied on the nZEN Ydalir.

On the basis of the recommendation by Steinmann, Schipper et al. (2016) to use four–six impact categories to cover most of the variance (84–92%) in product rankings, five mid-point impact categories are selected: Climate Change, Freshwater Eutrophication, Human Toxicity, Metal Depletion, and Terrestrial Acidification. In addition, the importance of using several climate metrics to give short-lived GHG such as methane stronger attention as it has been stressed and recommended by the UNEP SETAC task force on climate change (Cherubini, Fuglestvedt et al. 2016, Levasseur, Cavalett et al. 2016). On the basis of this recommendation, a climate metrics sensitivity analysis is conducted by evaluating Climate Change with the global warming caused in three time horizons of 20, 100, and 500 years.

CMSs are designed to test for the effect of (1) mobility patterns less based on the use of passenger cars, (2) a better use by decreasing the size of the dwellings and increasing the passenger loads by 25%, (3) increased lifetimes of buildings and passenger cars by 25% and (4) their combination. The 25% reduction level is chosen as an example, without examining whether this is either desired or achievable but to explore the potential effects of such a reduction level. By including the time dimension, the aspiration is to identify strategic choices needed at different points in time to make the necessary provisions allowing for the nZENs to deploy their full potential.

Results The yearly results (Figure 1 in Paper V) of the Baseline showed two patterns when comparing the distribution of the sub-system at the beginning and at the end of the period of analysis. The first pattern is observed for Climate Change and Terrestrial Acidification where the material-related sub-systems "M" takes over the operational sub-systems "O" induced by the electrification based on energy source of the mobility. The second pattern is valid for Freshwater Eutrophication, Human Toxicity, and Metal Depletion where the distribution patterns and order remain pretty much the same.

The cumulative results over the period of analysis are shown in Figure 8. Across the impact categories, environmental benefits of 5–20% are shown for single CMS and of 22–42% when combined. Interestingly, when stretching towards more CMSs there are co-benefits across all these impact categories, and the highest environmental co-benefits are found for Metal Depletion, highlighting the close interconnection of CMS and decreased pressure on resource use.

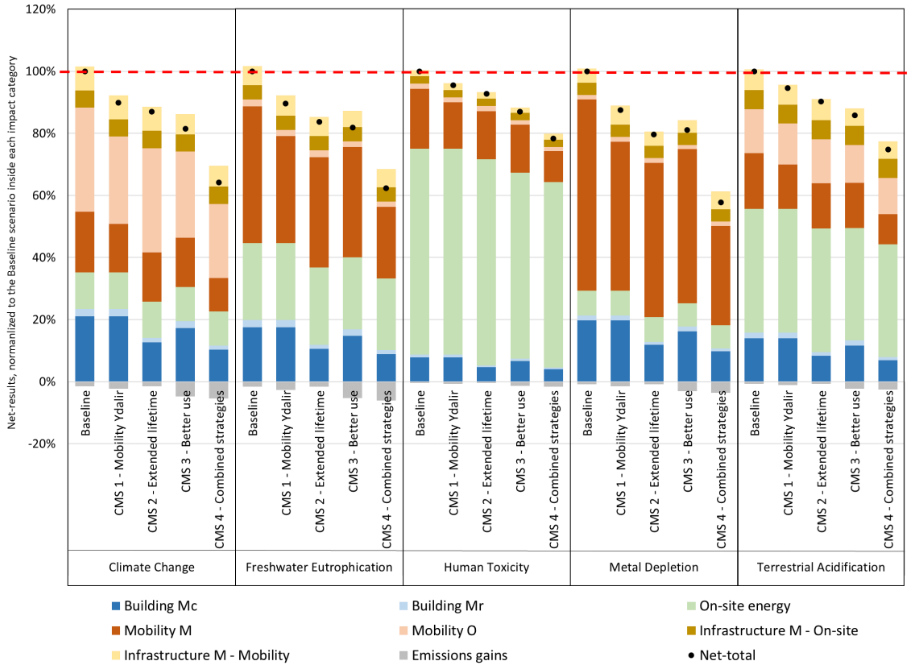

Figure 8: Cumulative results over the period of analysis, for each climate mitigation strategy (CMS) and each environmental impact category, normalised relative to the Baseline net-impact results.

Compared to using GWP100 to measure Climate Change, the cumulative results over the period of analysis vary from -2% to -4% when measuring Climate Change with a climate metric that accounts for the global warming that cumulates over a time period of 500 years (GWP500), and from 7 to 11% for GWP20, respectively. The "M" sub-systems are the most affected by use of another time horizon to measure global warming to quantify potential climate change. It is the methane released when extracting and producing the fossil fuels used in the production of those materials constituting the materials "M" subsystems that causes most of the variations. On the other hand, the operational sub-systems are less affected because they are already decarbonised through the use of renewable energy locally produced to supply the energy need of the buildings and the electric cars.

3.6. Paper VI

"Hybrid life-cycle assessment of a net-zero emission neighbourhood in Norway"

Lausselet, R. Crawford C., Brattebø. 2021. In preparation to submit to the *Journal of Cleaner Production*

Rationale Process LCA (pLCA) is a preferred method for quantifying direct and embodied building-related GHG emissions (Zhao, Zuo et al. 2019). But, whereas pLCA suffers from truncation errors due to its incomplete system boundary, top-down models such as IO or MRIO models are embedded with aggregation errors (Majeau-Bettez, Strømman et al. 2011). The truncation errors usually range between 3 and 89% (Treloar 1997, Lenzen 2000, Crawford 2008, Yu, Robati et al. 2020).

A high truncation error occurs when the pLCA results are not suited for capturing the complete upstream product inputs along the value chain. For construction products, those inputs are typically from service industries, for example, Rental, Hiring and Real Estate Services, or Wholesale Trade (Yu, Robati et al. 2020). To achieve a better system boundary completeness, the combination of top-down (IO or MRIO) and bottom-up (pLCA) approaches to form a hybrid LCA (hLCA) approach is widely recognised as more comprehensive and therefore in many cases recommended (Treloar 1997, Gibon and Schaubroeck 2017, Crawford, Bontinck et al. 2018, Agez, Wood et al. 2020).

Several hLCA techniques (tiered, path exchange (PXC), matrix augmentation and integrated) have been identified in a review by Crawford, Bontinck et al. (2018). All the hLCA techniques are complex and can be time-consuming. As a result, hLCA techniques are seldom applied outside a dedicated group of experts (Bontinck, Crawford et al. 2017).

Methods The PXC method has been introduced by Treloar (1997), validated by Crawford (2008), and formalised by Lenzen and Crawford (2009). The PXC method is applied on Ydalir, the nZEN pilot project assessed in Papers III, IV and V. The application of the PXC method to a case study is explained schematically in Figure 9.

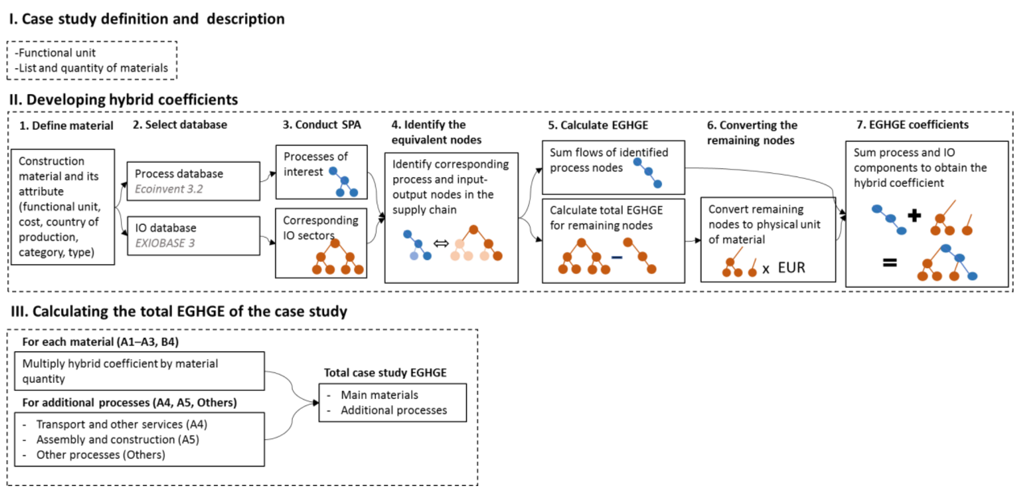

Figure 9: Description of the path-exchange (PXC) method and its application to a case study.

A hybrid GHG emission coefficient is calculated for each main construction material. These coefficients are expressed in $kgCO_2e$/unit (kg, m^2, or m^3) of material. The attributes (functional unit, cost, country of production, and type) of the materials are first defined. Ecoinvent 3.2 (Wernet, Bauer et al. 2016) is used as the pLCA database and EXIOBASE v.3 (Stadler, Wood et al. 2018) is used as the IO database. EXIOBASE is a global, detailed Multi-Regional Environmentally Extended Input Output database.

Each hybrid coefficient is then multiplied by the physical quantity of the respective material in the case study project. Then, in order to ensure a comprehensive system-boundary coverage, an additional IO remainder, which represents all inputs that are not covered by the physical material quantities, but present by cost estimates, is calculated. Please see Paper VI for more details.

Results Local hybrid embodied greenhouse gas emission (EGHGE) coefficients have been computed for all the main construction materials that are consumed in the inventory for nZEN Ydalir. Truncation errors ranging from 10 to 78% with an average of 34% and a median of 24% are found.

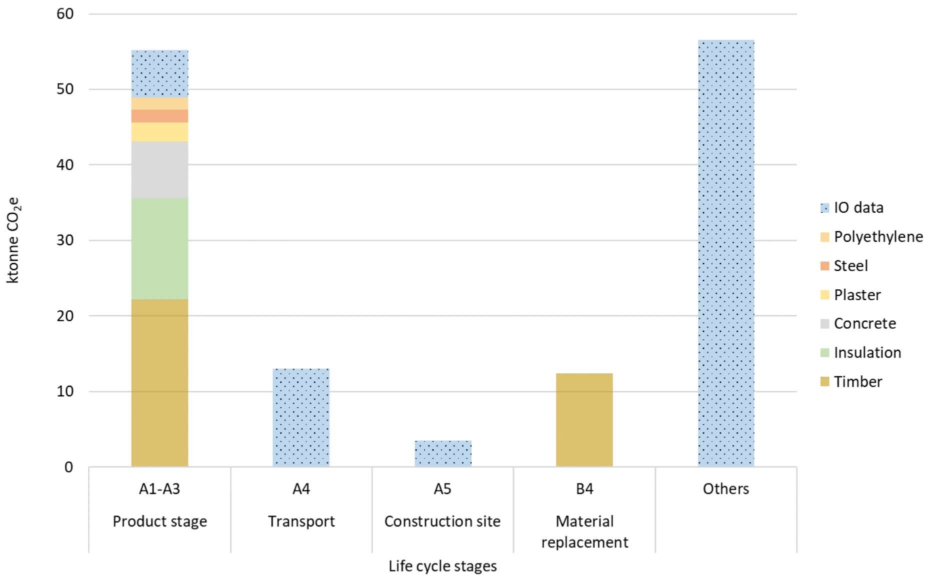

Figure 10: Life-cycle embodied greenhouse gas emissions (EGHGE) of the neighbourhood

The EGHGE of Ydalir are stemming mainly from the materials used for the construction (A1–A3) with a share of 39%. The EGHGE stemming from the transport (A4), construction site (A5) and material replacement (B4) hold shares of 9%, 3%, and 9%, respectively. Other EGHGE that do not fall into one of the defined life cycle stages account for 40% of the total. In terms of CO_2e, 55.2 ktonnes CO_2e (508 $kgCO_2e/m^2$) are emitted when producing the construction materials (A1–A3), 13.1 ktonnes CO_2e (120 gCO_2e/m^2) when transporting them to the construction site (A4), 3.54 ktonnes CO_2e (32.6 $kgCO_2e/m^2$) at the construction site (A5), 12.4 ktonnes CO_2e (114 $kgCO_2e/m^2$) when replacing them (B4) and 56.6 ktonnes CO_2e (521 for $kgCO_2e/m^2$) are allocated to Others.

Timber represents the highest proportion of EGHGEs stemming from the construction stage (A1–A3) at 40%, followed by insulation at 25%, concrete at 15%, plaster at 4%, steel at 3%, and polyethylene at 3%. The pure IO component, representing the materials that are not captured by the hybrid coefficients accounts for 11% of the total EGHGE of this stage.

IO data represents 56% of the total EGHGE.

4. Discussion and outlook

4.1. Main findings in relation to the research questions

The main findings in relation to the four research questions are presented in this section.

How can LCA be applied to examine net zero-emission opportunities in projects at the neighbourhood scale, and what are the limitations and applicability of LCA methods?

When using LCA to assess the environmental sustainability of a neighbourhood, different elements—buildings, mobility, energy systems—that evolve at very different paces are set together. Once a building is built, not too many changes occur until its renovation and eventually its destruction at the end of its lifetime. The lifetime of the transport modes (e.g., passenger cars, trains, buses) is much shorter than that of the buildings. This shorter lifetime allows for new technologies to penetrate throughout the period of analysis of the neighbourhood, which is set to 60 years in this thesis. The energy mix is a particular case; although long lifetimes are inherent to centralised energy systems, the pressure to switch from a centralised to a de-centralized energy system based on renewable and intermittent energy carriers will induce a drastic change in the carbon content of the energy mix in the coming decades.

LCA methods can capture those effects, but this requires strong and comprehensive modeling to develop time series that capture such effects over a long time period, for example, 60 years. Thus, there is no "streamlined" LCA tool yet that allows for this type of temporal relevant assessment, and in particular when examining systems with a complex inventory such as a neighbourhood. In practice, this means that several parts of the model have been developed in different software (e.g., Matlab, Python, Arda, Excel spreadsheets). The use of LCA to assess neighbourhoods over time is thus so far mainly done by a small audience of the research community.

When performing LCA in the early planning stages of a project, in this case a neighbourhood, a dichotomy between the level of details and decisions made on the form and design of the project and the availability of data needed to build accurate LCIs of the different elements emerges. In practice, it means that the detailed LCIs of the buildings I used are mainly based and adapted from previous LCIs that I deemed representative for the purpose.

There is a mismatch between the development of hourly energy profiles and their hourly emission intensity counterpart. I believe the LCA community should get more familiar with hourly energy profile in LCA databases. By getting more familiar with a higher temporal resolution, a better understanding of the temporal mismatch between energy production, use, storage, and import/export would be gained (e.g., interaction between local energy production and vehicle-to-grid technology, stationary batteries, and underground thermal storage and heat-accumulator tanks).

LCA is a bottom-up approach that can use detailed inventories. Although this approach allows for a fairly precise estimate of the environmental impact contributions of different elements of a neighbourhood, it fails to capture wider effects induced by the inhabitants of the neighbourhood, such as the carbon footprint induced by the need for health care, food, and recreational activities. A top-down approach such as proposed by IO models would be more suited to capture these kinds of wider environmental effects.

LCA results can give a snapshot on when given environmental loads happen. In reality, however, it is difficult to predict exactly when those events happen. The combination of LCA with temporal probability distribution functions for future activities, such as used in dynamic material flow analysis modelling, has proved useful to better capture the variability in timing of future material inflows and emission outflows for the neighbourhood and thereby to enable a better temporal-specific material and emission accounting.

I believe LCA is a very powerful method when aiming to plan a neighbourhood in the most environmentally sustainable way and to decrease the potential adverse environmental effects of environmental bottlenecks. LCA is also well suited to be used in the development and analysis of scenarios, with the potential to showcase which kind of intervention strategies would be the most suitable for a nZEN project. However, LCA does not capture the rebound effect, or the problem-shifting effect of the expenditure avoided by, for example, decreasing the housing cost reinvested in other goods or services that may have a heavier environmental load that the first alternative.

What would be an appropriate structure and format of inventory datasets in LCA modeling framework for neighbourhoods?

Data format and subsequent data exchange is one cornerstone in the LCA community. To allow for the exchange of information and LCA data, a common understanding is required—in this case in particular, a common framework. The ISO 14040 and 14044 standards provide an important framework for LCA but leaves a large room for interpretation of important choices that can be individually interpreted, opening the door to inconsistency and issues with reliability and comparability of the results of the assessment. The International Reference Life Cycle Data System (ILCD) is an initiative that aims to cope with this issue by providing guidance and standards for greater consistency and quality assurance in LCA.

Although the LCIs computed in this thesis have not been made directly exportable in the ILCD format, a strong focus has been set on their computational structure and transparency, in line with the ILCD format principles.

A data framework that keeps track of the different life-cycle stages, Product stage (A1–A3), Construction stage (A4–A5), Use stage (B1–B7), End-of-life stage (C1–C4), and Benefits and loads (D) as presented in the standard EN 15978: 2011 (European Committee for Standardization 2012), will ease the reuse of the LCIs by other projects. In addition, for the sub-systems of the nZENs that are classified on an element level, the LCI should follow those structures. This is the case for the buildings where buildings elements Groundwork and foundations, Outer walls, Inner walls, and so forth, are classified (Standard Norge 2009).

Ecoinvent 3.2 is the most used LCA database in this thesis; however, EPD data are also used a lot to provide more national or context-specific information. Whereas the Ecoinvent database provides the

LCI data of the unit processes on the elementary elements level, EPDs record the unit process on an aggregated level already.

The database structure should ideally be based on unit processes in elementary flows with full value chain resolution. By using this resolution level—as is the case in Ecoinvent—the resolution and traceability of results are increased and this offers the possibility to conduct structural path analyses, identify hotspots, and assess contributions from various tiers in the value chains. With this degree of resolution, the LCIs can be easily adapted according to changing key assumptions and modelling choices, such as geographic representation, technology, and time and can assess uncertainty.

I believe that, ideally, the inventories should be stored in a matrix format by a unit-process structure and given in elementary flows. A matrix format will allow for the parametrisation at different levels, from elementary flows, characterisation factors, to foreground process at the neighbourhood level.

For a wide use of LCA in the early planning stages of nZEN, potential user interests could be mapped (Skaar, Bergsdal et al. 2019). In the ZEN Centre, potential users can be found in a broad range of disciplines, for example, architects, engineers, environmental consultants, contractors, property developers, manufacturers, building products/components, LCA practitioners, urban planners, municipalities, politicians, nZEN users (mainly for interpreting results), and so forth. The needs of the users are varied and will depend on the goal and scope of their study/intention.

In my view, a very high degree of resolution in the datasets should be favoured. No LCIs should be simplified whenever stored. I do also understand that a too high degree of details may imper the use of LCA data in decision making processes, especially in the early stages of the planning. With this is mind, it is acceptable to further aggregate the data to ease the use of LCA data by a wider community. But the details of their computation should be recorded in a transparent way that allows to trace back details whenever required.

What are the critical factors, system elements, variables, assumptions, and sensitivities for LCA performance of nZEN projects over a 60 year analysis horizon?

The critical factors for the LCA performance of nZEN projects over a 60-year time horizon are the daily distance travelled by the inhabitants (Papers II, IV, and V), the dwelling size (Papers II, III, and V), the decarbonisation rate of the material production chains (Papers II and III), the emission intensity of the electricity (Papers I, II, and IV), the emissions associated with vehicle production (Papers II and IV), the choice of functional unit (Paper II), the allocation of the emission of heat production by waste incineration (Paper I), the buildings' energy load (Papers I and II), the product lifetime (Papers III and V), and the chosen time horizon of the climate metric.

Our results show the importance of the operational phases of both the buildings and the mobility at the beginning of the period of analysis and their decline over time induced by the decarbonisation of the electricity mix (Paper I, II and V).

The magnitude of the emission compensations over time depends on the decarbonisation rate. Over time, the emission compensations become marginal for a 2°C scenario and moderate for a 4°C scenario and remain significant for a 6°C scenario (Paper II).

When doubling the area of PV panels, the total GHG emissions increase by 3% when assuming a Norwegian electricity mix for emission compensation and decrease by 8% when assuming a European mix (Paper IV). The Norwegian electricity mix is based on hydropower including net import/export, and is thus already decarbonised. Therefore, emission credits are only obtained when Norway is considered as part of the European electricity market which still relies mainly on fossil fuels.

In terms of material use for the buildings, 71% of the total material are used for the construction, 13% are used for the renovation, and 16% are used for the new construction required to maintain the building-stock floor area constant over time. Concrete and timber dominate the material flows over the years, with 55 and 25% of the total, respectively (Paper III).

In terms of timing of the GHG emissions from buildings construction material, 52% of the total GHG emissions are due to the construction activities, 36% are due to the renovation activities, and the remaining 12% are due to the new constructions at the end of the period of analysis. The most dominant sources of GHG emissions are the PV panels, followed by timber and concrete (Paper III).

Across the impact categories, environmental benefits of 5–20% are shown for single CMS and of 22–42% when combined (Papers II, III, IV, and V). Interestingly, the highest environmental co-benefits are found for Metal Depletion, highlighting the close interconnection of CMS and decreased pressure on resource use (Paper V).

The material sub-systems are the most affected by the use of another time horizon to measure global warming to quantify potential climate change. The methane released when extracting, refining, and transporting fossil fuels induces those variations, highlighting the need to decarbonise not only the operational phases but the entire production chain.

The choice of functional unit is decisive, and 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 functional unit is misleading because it does not give credits to precautionary use of floor area (Paper II).

What kind of individual measure or group of measures have the largest potential for emissions reduction in nZEN projects?

To best mitigate climate change, climate-positive behaviours should be combined with energy-efficiency standards that incorporate embodied energy, and absolute threshold levels for emissions could be combined with behavioural changes. Those measures should be taken at different points in time, as explained in the following section Policy implications.

An upscaling of the electricity production from PV panels would allow for significantly reduced system-wide emissions if more surplus electricity is exported and can substitute power generated from fossil fuels or replace fossil fuels used in mobility. This is in particular valid at the beginning of the period of analysis, when considering Norway as part of a European electricity system that still mainly relies on fossil fuels and when a significant share of the Norwegian vehicle fleet is non-electric. nZENs can potentially play an important role in decarbonising the European electricity grid that is mainly based on fossil fuels by producing energy based on renewable energy carriers. But it is important to keep in mind that this is especially true today, given that the European energy market still relies highly on fossil fuels, and can potentially be less true by 2031 already.

4.2. Policy implications

The CMSs designed for nZEN presented in this thesis clearly showed the importance of **combining different measures across several layers** at different points in time to best mitigate climate change and to provide environmental co-benefits.

At the early planning stages, the focus should be set on finding incentives that will promote dwellings of reasonable sizes, the use of materials with low GHG emission intensity, and design for dismantling at the end of the lifetime. To avoid the neutralisation of those dwelling-size incentives, dwelling sizes should be measured not only by floor area per dwelling but by floor area per inhabitant. The floor area per inhabitant has a direct effect on the construction peak and related material flows and emissions. Incentives that promote the decarbonisation of the material value chains, *in-and out-land,* should be in place as well because the use of fossil fuels is still dominant.

Promising recent trends on designing buildings where part of the space is shared for given activities have appeared (Fyrstikkbakken 2021). Those initiatives should be actively promoted because they hold the potential to help pave the way for reducing the floor area per inhabitant.

Over time, a culture of car- and ride-sharing should be encouraged. Whereas the former will reduce the pressure on the use of resources mainly by diminishing the in-use stock of metals, the latter will have climate and environmental co-benefits in several other aspects such as an improved air-quality and a reduction of traffic noise and congestion. A good maintenance of the buildings will postpone the need for renovation and demolition.

A framework that allows for the accounting of the material in the different sub-systems of the neighbourhood could more easily facilitate recycling and reuse solutions. A material database would help the use of materials by their end-user to a new potential user. Efforts should be set on proactive attitudes such as preventing household waste, in light of the waste hierarchy. Overall, circular-economy strategies could be implemented in different ways, which would promote increased resource efficiency and reduced emissions.

Norwegian citizens should have climate-change mitigation potentials, at the household and neighbourhood scales, further than the ones proposed in this thesis in terms of housing and mobility needs. In particular, additional efforts should be identified to influence behavioural changes. For instance, Lekve Bjelle, Steen-Olsen et al. (2018) have shown the beneficial effect of flying less or modifying food diets. On average, households—via their consumption in terms of material, water, and land-use requirements—are responsible for more than 60% of global GHG emissions and between 50 and 80% of total land, material, and water use (Hertwich and Peters 2009, Ivanova, Stadler et al. 2016). **Households thus carry a tremendous potential to directly affect climate direction, in a beneficial way—or not.** At a neighbourhood scale, this type of household engagement could help pave the way to reduce the dwelling sizes (measured per inhabitant). Per today, there are few incentives to build smaller-sized dwellings. By asking, or building dwellings of smaller sizes, a demand and a new market niche could be created that could potentially lead to further market investment in those types of smaller dwellings.

In the same way that I combined several methods in this thesis, I believe that combining a bottom-up approach (where Norwegians will accept a certain level of behavioural change) with a top-down approach (where the Norwegian government develops energy-efficiency regulations that incorporate embodied emissions and correct energy-use thresholds for house size and use multiple functions to measure efficiency of different devices) would be beneficial.

The Norwegian electricity production mix is already highly based on renewables with a share of 95% hydropower and 2.6% wind power (Statistics Norway 2019). By further upscaling the production of renewable energy at a neighbourhood scale, nZENs may play a role in the decarbonisation of the European energy mix (1) by sending their surplus energy to the grid, with potential for export outside Norway and (2) maybe with a more direct effect domestically by liberating electricity from hydropower that can substitute the use of more carbon-rich fuels elsewhere, such as in the strive for electrification of road transport.

So far, the use of PV panels to locally produce renewable energy has been the favoured method of energy production for nZENs. Other alternative renewable-energy production pathways are available, such as exploiting local wind, biomass, and geothermal sources, and will have to be examined by local and national decision makers for their costs and acceptance. Wind energy has the advantage to be less season-dependent but has several disadvantages induced by its location, ownership, and public acceptance. PV panels can belong to one building owner whereas a wind-turbine park would require the consent of all the inhabitants. The population is in general keen to have PV panels on their roofs but less so to have wind turbines in the proximity. There is at present a strongly growing public resistance to land-based wind mills in Norway, parallel to a growing interest for PV solutions. In addition, local authorities will have to address the dichotomy between the installation of PV systems that require a large roof area and are thus more adapted to low-rise buildings such as single-family houses and the high population density needed to provide satisfactory and economically viable public-transport offers. The considered technologies are by their nature intermittent. Thus, in parallel to their deployment, energy-storage technologies such as, for example, vehicle-to-grid technology, stationary batteries, underground thermal storage, and heat-accumulator tanks, could be deployed and incentivised to better take into account the temporal mismatch between energy production, use, storage and import/export.

The results of this thesis show that for the assessed nZEN projects, as they are planned and also for other assumed scenarios, the estimated net-emissions are actually far from reaching zero, even after doubling the PV capacity and related emission gains. To reach the net-zero-emission target is even more challenging when estimating EGHGE with hLCA modeling that considers a more comprehensive system boundary.

To achieve net-zero-emission, the previously mentioned strategies (1. minimizing EGHGE through material efficient design, low-carbon materials, and passive house technology 2. sharing solutions for the mobility and buildings elements and functions and 3. upscaling of the on-site/local renewable energy generation) will most probably have to be supplemented by CO_2 removal methods (e.g., afforestation, agricultural practices that sequester carbon in soils, bio-energy with carbon capture, and storage, and direct air capture when combined with storage) in order to provide negative emissions according to the IPCC (2018).

Per today, nZENs only represent a marginal share of national building stocks that also contain buildings with less strict energy-use standards. When deploying strategies to renovate national building stocks, the opportunity to reshape dwellings into dwellings of smaller sizes should be assessed in favour of a sole focus on nZEB standards.

Another aspect is an enhanced digitalisation that would make it possible to overcome a binary relation between a single dwelling, car and PV owner to several dwelling, car and PV owners. New types of business models with smart and digital control or optimisation functions may help interconnect all the sub-elements of an nZEN and embrace a systemic approach that can allow for both the low- and high-hanging fruits to be picked when drawing CMSs.

4.3. Scientific contribution of this thesis

The work performed in this PhD thesis has helped to **advance LCA methods for use at the neighbourhood scale**. As mentioned, LCA has so far been used mainly on single systems, and combining elements from buildings, mobility, and energy systems by including a time horizon of 60 years is seldom done. Those elements evolve at different paces and are by nature different. Show-casing their combination has certainly improved the use of LCA for such complex systems.

A **holistic approach** is undertaken in this thesis. This is mainly because I consider myself as an Industrial Ecologist and see **analogies between industrial ecosystem and ecological ecosystem**, as did Frosch and Gallopoulos (1989) who saw opportunities to optimise the energy and materials consumption, reduce the waste generation, and better integrate the outputs of some processes as inputs to other processes. I believe there is no individual (or at least very few) or system that can stand by itself. We are part of something bigger, and to acknowledge that by adopting a holistic view from the start will allow for new strategic or analytical approaches to be considered. This is important in order to live a decent life within the planet boundaries.

One single method is not enough to address the complexity of the climate urgency that we are facing. The use of **cutting-edge methods** such as the combination of LCA with dynamic material flow analysis and IO analysis will, I hope, inspire other researchers to combine methods that are often used in parallel and by different types of experts.

It is often demanding to develop and use cutting-edge methods. Typically, hLCA is only used by a few researchers. In this thesis, I have contributed to a **wider use and streamlining of hLCA methods**, thereby also capturing more of the environmental impact from the background economic system than what is commonly expected to be accounted for in pLCA methods.

When undertaking a holistic approach, one has to face the dichotomy between **a high resolution in the modelling of some subsystems while at the same time keeping an overview of the**

system. In this thesis, I have proven that this is possible, for example, by using wide and top-down models such at the global MRIO Exiobase at a local scale (neighbourhood). I have also arrived at useful recommendations on the CMSs.

One output of this thesis is the environmental quantification of a set of alternative scenarios in order to best mitigate climate change. The results point towards co-benefits of CMSs across all the other impact categories examined. This indicates no serious problem-shifting consequences if CMSs are implemented, but on the contrary, there may be co-benefits of different kinds that are also very welcome. Hence, this is in support of a nZEN strategy that actually aims environmentally wider than only climate-change mitigation. In addition to the quantification of the environmental performance, the practical recommendations given at different points in time to inform decision makers early on the potential benefits but also on the adverse effects that a decision will have in the near and long terms is an added value.

4.4. Future work

Regionalised impact categories The effect of a given type of emission can vary depending on the location because of differences in background contamination levels and ecosystem vulnerability. Using impact assessment methods with a higher regional resolution on the impacts would be preferable.

Land use The construction of neighbourhoods can potentially lead to changes in land use at a scale that influences the local balance of carbon storage in soil and vegetation. This might in particular be the case when bog areas, or agricultural and forestry land are developed for urbanisation purposes. Those aspects should be better assessed when new neighbourhoods and settlements are being planned. The matching of the foreground processes (e.g, a nZEN) with the environmental stressors that are further addressed in terms of characterisation factors should be done in such a way that the full potential effects of the construction of nZEN are captured.

Potential effect of climate changes on local climate For all seasons, the projections indicate a warmer climate in Norway, with a greater projected warming for winter than for summer. Temperatures are expected to increase by 1.6–6.7°C and the number of "warm days" (> 20 °C) is expected to triple by the end of the century (Hanssen-Bauer, Førland et al. 2017). These changes will lead to a lesser need for heating in the winter and possible use of air-conditioning in the summer.

Forecasting emission intensities Decarbonising the power sector has direct implications for other sectors (Wiebe 2018). In addition to energy-efficiency improvements along the production chains, the retrofitting of the power sector in the production chains over time has to be taken into account when assessing prospective scenarios. In this thesis, we included in our scenarios some rough improvements in these demand-side technologies that reflect the shift from fossil fuels to a more circular economy based on renewable energy sources. However, a more systematic analysis of potential and expected improvements in material production, manufacturing, and transport is needed. Neglecting such improvements could result in underestimating the environmental benefits of climate-mitigation policies (Hertwich, Gibon et al. 2015).

User behaviour was addressed by introducing factors that increase or decrease some key variables in our scenarios. One should expect high uncertainties in how user behaviour 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.

Hourly energy profiles 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) or (Clauß, Stinner et al. 2018, Clauß, Stinner et al. 2019); that is, hourly impacts from grid electricity should be used to account for the temporal variation in use, production, storage and import/export of electricity. A better understanding is needed, at a neighbourhood scale, of this temporal mismatch between demand and supply, as well as of temporal emission dynamics in the electricity grid and capacity peak-shaving opportunities by energy-storage technologies, such as batteries or underground thermal storage.

Energy-storage alternatives Energy storage is likely to become a crucial element of nZEN projects because they base their energy supply on renewable energy and thus, by definition, intermittent energy sources. The potential to store, peak-shave, and thus improve the match between energy production and use, as well as the emission consequences of such measures, should be further investigated. Furthermore, BEVs may very soon represent a dominant share of the mobility fleet in a nZEN, and the opportunities to use the BEV fleet as a large battery resource to store and further re-inject electricity by vehicle-to-grid technologies should be assessed. But, to our knowledge, there are no LCA studies that use hourly energy profiles to assess the interaction between buildings and electric vehicles, in particular their battery capacity and the potential of the latter to reduce emissions at a neighbourhood scale.

Need for LCA tools in the early planning stages. As mentioned earlier, the use of LCA to assess neighbourhoods over time is a complex task and has thus mainly be conducted by a small audience of the research community or more advanced consulting firms. But the climate urgency forces us to act rapidly, especially in the course of this decade. It is therefore crucial to deploy LCA tools that can assess a neighbourhoods in the early planning stages and that can allow to avoid suboptimal solutions. The development of Område-LCA by the Norwegian consulting firm AsplanViak is one such good example (Yttersian, Fuglseth et al. 2019).

Need to follow up and benchmark values. The nZEN projects assessed in this thesis are all in the early planning stages. To follow up those nZEN projects in the years to come will provide insights on the feasibility of the assumed scenarios. Also, it will give "real-life" data that will help the assessment of other project in the early planning stages. Such data can also be important input to the validation process of new LCA tools used in early-stage planning.

Conventional energy-use standards A total of 50% of the standing Norwegian dwelling stock in 2020 is fairly young or recently renovated and will not need a natural renovation before 2050. The other 50% holds significant potentials for energy-efficiency improvements because of their expected renovation cycle. Thus, renovation of ageing and energy-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. The LCA methodology used for neighbourhoods so far only assesses newly 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 future 60 year period, because the implications of future renovation and demolition measures with respect to material consumption, energy use, and related emissions should be accounted for. Typically, dynamic segmented building-stock models have proven to be powerful tools in that context.

Better assess the uncertainty The model scenarios of future development paths can reveal how the environmental performance of a nZEN project is influenced by parameters describing alternative future developments. Predicting how such parameters will evolve has substantial uncertainty. A global sensitivity analysis such as a variance-based sensitivity analysis (Saltelli, Annoni et al. 2010) could be performed to capture such effects, and developing the LCA model to include such a method would greatly improve the uncertainty analysis compared to what is used in this thesis. Such a “global sensitivity analysis” could be based on the pedigree approach undertaken by, for example, Ecoinvent (Frischknecht, Fantke et al. 2016). In a Pedigree approach, each input and output of the LCI are assessed according to six characteristics: reliability, completeness, temporal correlation, geographic correlation, further technological correlation, and sample size. The Pedigree approach could be expanded to the foreground processes defined in the model developed in this thesis. Also, the LCIA will gain in robustness if the Pedigree approach is extended along all the life-cycle phases.

Three-dimensional model linked with geographic information system data The use of a three-dimensional model linked with geographic information system data might be helpful to derive a bill of quantity for each building, as done by, for example, Stephan and Athanassiadis (2018) or Heeren and Hellweg (2018). By developing bills of material quantities, a better understanding of the available materials in time and space will be gained and can inform potential second-hand users of these available material flows. This is required, in light of the circular economy and urban mining where a quantification and evaluation of the material and environmental flows in time and space, in order to manage the urban environment in a more environmentally—and potentially economically—sustainable manner.

Rebound effects A better material efficiency or the use of other strategies that will translate into dwellings of smaller sizes and/or a mobility pattern with shorter distances driven will have a positive environmental impact, and it will also likely reduce the budgetary spending of households who are willing to take those necessary steps. But the remaining question is how the remaining budget will be spent. Depending on how the financial left-overs saved will be spent, undesirable more adverse environmental impacts or pressure on resources could occur.

5. Conclusion

For Norwegian nZENs to play a role in restricting the global temperature increase to a safe level of 1.5°C, this thesis shows that a reduction of the following factors is crucial: (1) emissions related to material use by building floor area per house and per inhabitant, and by carbon intensity of materials, (2) emissions related to mobility, by passenger car travel distances, which can be achieved by several means, for example, commuting with public transport and/or by carpooling initiatives, (3) emissions related to operational energy use in the buildings, which are reduced by the use of the passive-house standard, and (4) emissions related to carbon intensity of the electricity mix, by on-site production of renewable energy and export of surplus low-carbon energy to compensate for actual emissions in the nZEN project.

These reductions will most likely be achieved by combining a bottom-up approach driven by positive inhabitant behavioural changes, such as reducing housing size, energy use in buildings, and travel distances, with top-down approaches in terms of energy-efficiency policies that incorporate embodied emissions as well as correct energy-use thresholds.

Climate mitigation strategies (CMSs) should be implemented at different points in time. In the planning stages, threshold values of floor area per inhabitant can be required, materials with low emission intensity should be preferred, and buildings should be designed in a way that allows for re-use of elements or recycling of materials. Over time, good maintenance of the buildings will postpone renovation needs and extend the building lifetime. Also, a culture of car- and ridesharing should be encouraged. Whereas the former will reduce the pressure on the use of resources by diminishing the in-use stock of metals, the latter will have climate and environmental co-benefits in several other aspects such as an improved air-quality and reduced traffic noise and congestion. When deploying strategies to renovate national building stocks, the opportunity to reshape dwellings into dwellings of material efficiency and smaller sizes should be assessed in favour of a sole focus on nZEB standards.

The high importance of the construction phase of a neighbourhood, in terms of material use and emissions, combined with the high uncertainty of future activities and the predicted technology improvements that will reduce the future material environmental intensity all tell us that the main priority for CMSs in nZEN projects should focus on measures that can strongly influence near-future emissions. This will also be in line with climate mitigation policy targets such as the Paris agreement, which calls for rapid emission reductions during the coming few decades.

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Paper I

Lausselet, Carine; Borgnes, Vilde Sorkmo; Brattebø, Helge. (2019) LCA modelling for Zero Emission Neighbourhoods in early stage planning. *Building and Environment.* vol. 149: 379-389

Building and Environment 149 (2019) 379–389

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

LCA modelling for Zero Emission Neighbourhoods in early stage planning

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ARTICLE INFO

Keywords:
Life cycle assessment (LCA)
Zero emission neighbourhoods
Greenhouse gas emissions
Early stage planning

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 ktons CO_2-eq over 60 years, equivalent to 1.5 tons 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° 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 [1]. 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) [2] and the Energy Efficiency Directive [3,4]. 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 [5]. 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 [6]. 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 [7–9]. LCA systematically addresses the environmental impacts of a system through its life cycle stages, from raw material acquisition, through energy and

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https://doi.org/10.1016/j.buildenv.2018.12.034
Received 26 October 2018; Received in revised form 13 December 2018; Accepted 14 December 2018
Available online 15 December 2018
0360-1323/

material production, to use and end-of-life treatment [10]. LCA studies at the building level have led to valuable insights that can now pave the way for emission reductions in the building sector [11,12].

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 [11,13,14]. 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 [15–19] [19]. 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 [19–21] [21]. 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 [22–26].

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 [27–29]. 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 [18,28].

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 [30,31], while others also consider the users' mobility [27,32–34]. The most complex LCA studies include both buildings, mobility and other elements like open spaces and networks [25,35,36]. The life cycle stages considered also vary, from only looking at the use stage, to also considering the production and end-of-life stages [18,28]. 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 [32]. 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 [25]. 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 [36]: found that indirect emissions (including, among other things, vehicle manufacturing and building roads) constituted 52% of the total emissions from transportation [27]. 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 [37], which expands the system boundaries compared to the standard EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method [38], 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 [27,28,32,36,39]. 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 [39,40]. However, in ZEN projects that involve highly energy-efficient buildings that consume only small amount of energy for heating and cooling, such a climate change effect will not be very large.

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 [41]. describe a tool called NEST (Neighbourhood Evaluation for Sustainable Territories), an LCA tool for assessing the environmental impact of urban projects, developed by Ref. [42]. 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?

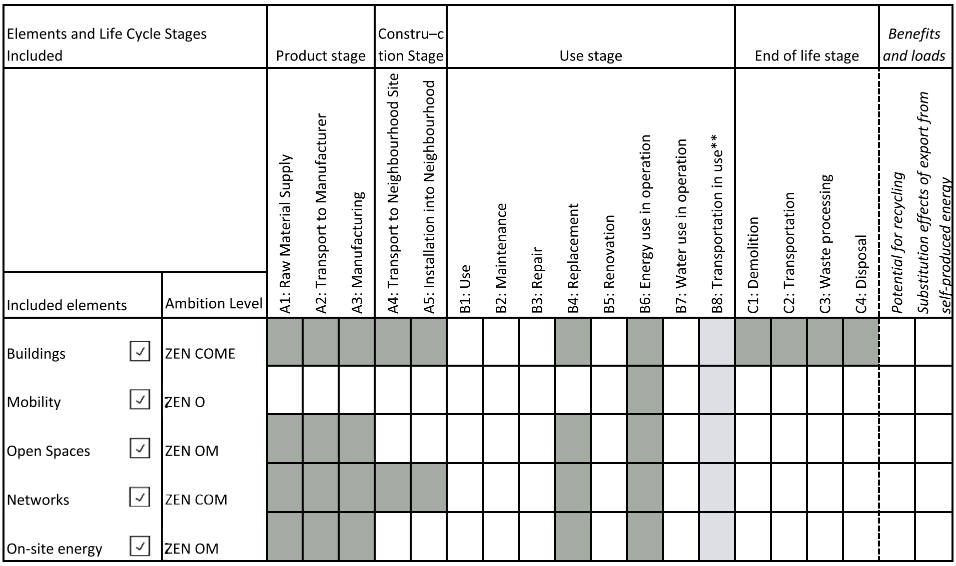

Fig. 1. Modular structure used as basis for LCA at neighbourhood level. Note: the elements and ambition levels marked in this figure are here randomly selected and serve only as an example of the use of the structure.

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 [43]. 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 Fig. 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 [44]. 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' [45]. 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 Fig. 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.

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 [44] 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 Fig. 2 represents the two scenarios as they evolve from 2015 to 2080.

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

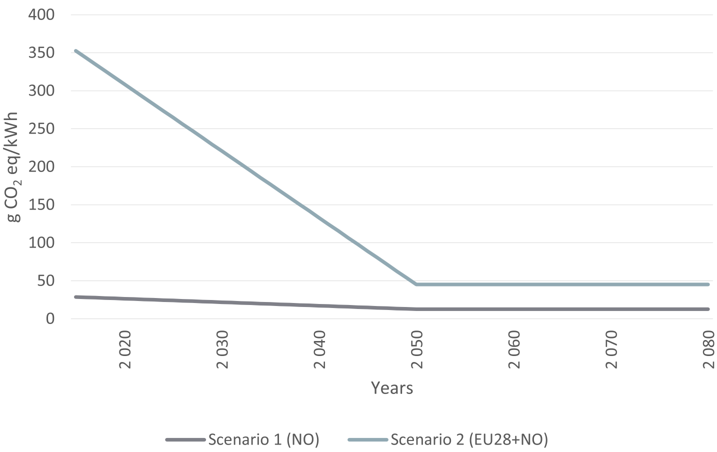

Fig. 2. Evolution of emission intensities for electricity (g CO_2-eq/kWh) 2015–2080 based on scenarios recommended in NS 3720 [44].

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 [46]. 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 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 [47], see Table 1. There will be 695 dwellings and 1340 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) [47]].

Building type	Floor area (m^2)
Terraced house	62 136
Apartment block	23 028
Total residential	85 164
Kindergarten	1061
Office	2833
Shop	2833
Underground parking	*21 657*
Total non-residential (excl. parking)	6727
Total ZVB (excl. parking)	91 891

2.2.1.1. 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).

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

$E_{mat,\,init}$ 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 consist 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 [48]. 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).

2.2.1.2. Energy use in operation. The energy use in the buildings is based on work performed by the ZEB Centre [47] where the buildings planned for the ZVB project were already estimated by IDA-ICI simulations. This gave a total thermal load of 3283 MWh and a total electric load of 3257 MWh per year, see S5.4. Fig. 3 shows the yearly load in kWh/m^2 for the different residential building types.

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

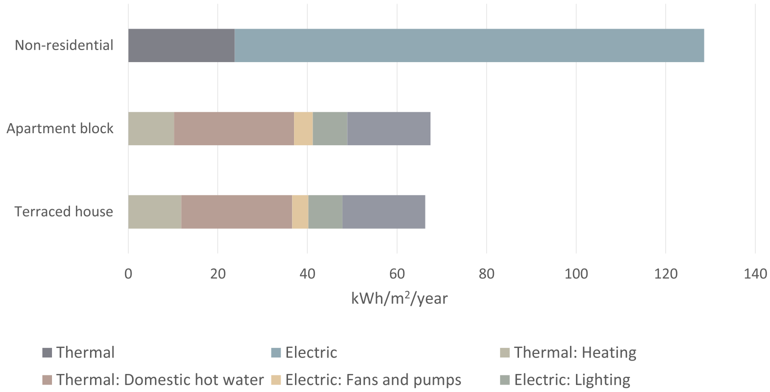

Fig. 3. Yearly energy load of residential buildings ZVB (in kWh/m2/year) (adopted from Ref. [47].

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 [43], 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 [44]. The documentation behind the results reveals large heterogeneity on data on energy use and emissions from different means of transport from previous research [49], 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 [44].

2.2.2.1. Evolution of vehicle stocks. The evolution of vehicle stocks is based on an "ultra-low emission policy scenario" developed by Ref. [50]. 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 Fig. 4). It is assumed that the use of light rail is all-electric throughout the entire period.

2.2.2.2. Product and replacement stages. The emissions embodied in the materials for mobility, $E_{m,mat}$, were calculated using Equation (2).

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

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 Ref. [49]. 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 Fig. 4.

2.2.2.3. 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 Ref. [49] were used as a starting point in 2010, see S6.4. Improvements in the fuel intensities were based on a study performed by Ref. [51]; 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. Fig. 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.

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.

2.2.3.1. 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

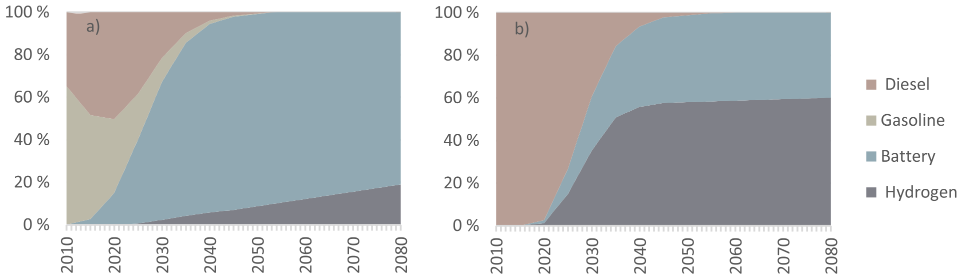

Fig. 4. Evolution of vehicle stock for a) passenger cars and b) buses by fuel type/energy carrier used in present study (See data in S6.2).

bicycle lanes. The road structure (materials and dimensions) is adopted from the work performed by Ref. [52]; 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.

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

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

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.

2.2.3.3. 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 [46]. 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.

2.2.3.4. 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 5000 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 Ref. [53]; 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.

Table 2
Open spaces in Zero Emission Village Bergen (ZVB).

Open spaces element	Length (m)	Area (m^2)
Road type 1	3700	63 640
Road type 2	4400	49 280
Sidewalk	3700	11 100
Parking	–	2900

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 Ref. [47].

2.2.4.1. Production and replacements. The panels are placed on the available roof area of the buildings, with a total PV area of 22045 m^2 [47]. 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 [54], 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 [45].

2.2.4.2. Energy use in operation. Based on available roof area,

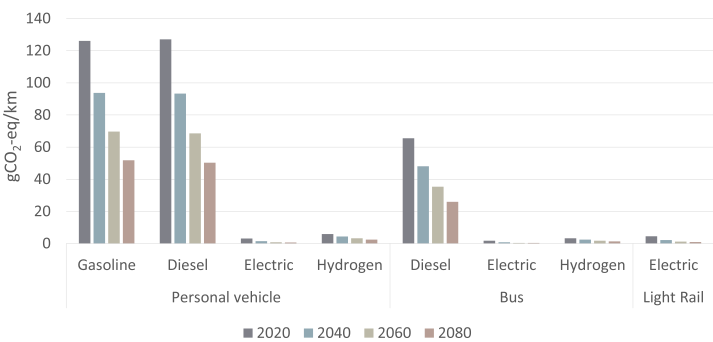

Fig. 5. Evolution of Well-to-Wheel (WtW) emissions from different modes of transport (see Table 15 in S6.5).

meteorological data, system efficiency and losses, and generation profiles, the yearly PV generation is estimated at 2941 MWh [47]. 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.

2.3. Sensitivity analysis

To address 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 ktons CO_2-eq over their lifetime. This equals 1.5 tons 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 Fig. 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 producing the photovoltaic panels.

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 thisis 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 Fig. 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.

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.

Fig. 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.

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.

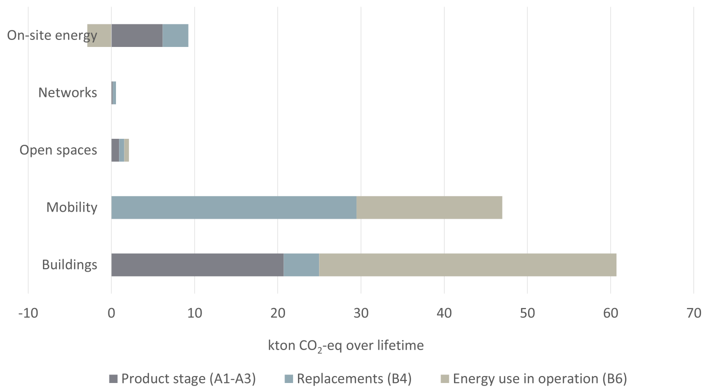

Fig. 6. Total emissions for ZVB distributed between elements and life cycle stages (see S10.1 for data).

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 Ref. [19]; 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 [55] was used. Fig. 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 Ref. [56]; '*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

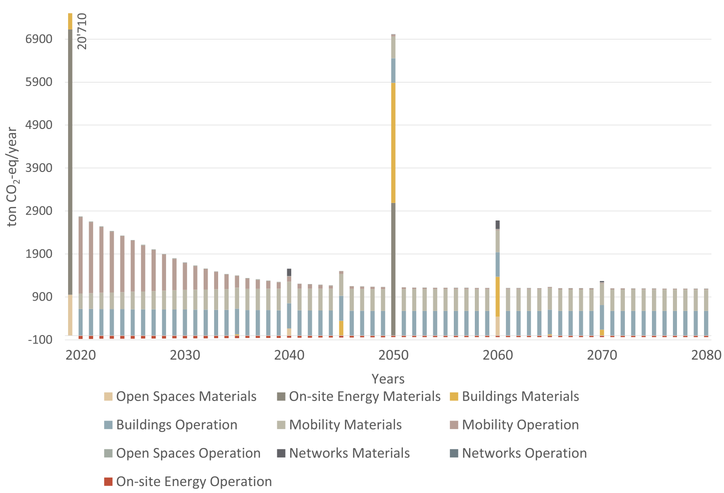

Fig. 7. Total emissions by year distributed by element and life cycle stage.

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%

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 Fig. 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 [57–59]. 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 Ref. [32]; 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 Ref. [27] 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

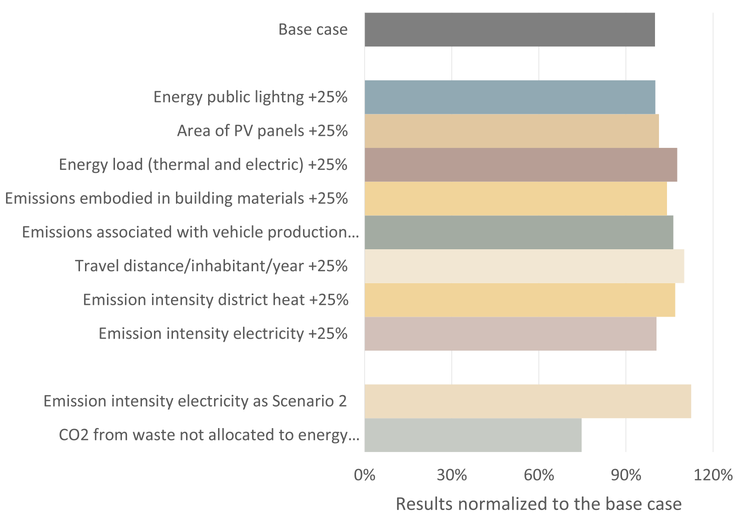

Fig. 8. Sensitivity analysis results relatively to the base case. Notice that the axis does not start at zero.

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 Ref. [49] and recommendations such as in the new NS 3720 standard [44] 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 possible effect of climate changes on local climate. In Norway, the number of “warm days” ($< 20\,^{\circ}C$) is expected to triple by 2010, and the heating season is predicted to become shorter [60]. As discussed earlier, the effect of climate changes on emissions may not be significant compared to others emissions drivers, and is therefore of less relevance in early stages planning of ZEN projects.

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 electrical 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.

Acknowledgements

The authors gratefully acknowledge the support of the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2018.12.034.

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Paper II

Lausselet, Carine; Ellingsen, Linda Ager-Wick; Strømman, Anders Hammer; Brattebø, Helge. (2020) A life-cycle assessment model for zero emission neighbourhoods. *Journal of Industrial Ecology.* vol. 24: 500-516

Corrigendum - Paper II

A corrigendum for a mistake in equations (1), (4), and a redundant mistake in equations (5) and (6) in Paper II has been sent for approval to the Journal of Industrial Ecology. Please find below the original equations below:

$$E_{B,M} = H \cdot \sum_{i=1}^{n} m_{mt} \cdot f_{mt} \cdot (1 + \frac{POA}{SL_{mt}}) \quad (2)$$

$$E_{PV} = H \cdot \sum_{i=1}^{POA} C_{PV} \cdot f_{PV,i} \left(1 + \frac{POA}{SL_{mt}}\right) \quad (4)$$

$$E_{M,M} = \sum_{vt=1}^{3} \sum_{i=0}^{POA} \alpha_{vt,i} \cdot \frac{m_{mt,vt} \cdot f_{mt,i}}{SL_{vt}} \cdot L_{tot} \quad (5)$$

$$E_{M,O} = \sum_{vt=1}^{3} \sum_{i=0}^{POA} \alpha_{vt,i} \cdot f_{vt,i} \cdot L_{tot} \quad (6)$$

Please find the revised equations below:

$$E_{B,M} = H \cdot \sum_{mt} m_{mt} \cdot \ f_{mt} \cdot \left\lceil \frac{POA}{SL_{mt}} \right\rceil \quad (2)$$

The total GHG emissions embodied in building materials $E_{B,M}$ is calculated according to equation (2). H is the total number of houses in the neighborhood, m_{mt} the quantity of material m of type mt per house, f_{mt} the CO_2 eq. emission factor f for each type of material mt, POA the period of analysis, and SL_{mt} the service life of material type mt. POA = 60 years and SL_{mt} is given for each material in the supplementary material. The ratio of POA and SL_{mt} is rounded up to the next integer.

$$E_{PV} = H \cdot C_{PV} \cdot \sum_{\substack{i \in \\ \{1,31\}}} f_{PV,i} \tag{4}$$

The GHG emissions embodied in the PVs E_{PV} are calculated according to equation (4). C_{PV} (kWh/m² floor area) is the installed capacity, $f_{PV,i}$ (CO_2 eq./kWh) the PV material GHG intensity at time i and H is the total houses in terms of floor area. $f_{PV,i}$ is of 75 g CO_2/kWh in 2018 (i=1). The PV GHG intensity is the mean value of a range of value calculated for Norwegian conditions by Kristjansdottir et al. (2016). For PV replacement at year 2038 (i=31), a 50% reduction in GHG intensity is assumed based on scenarios conducted by Gibon et al. (2017), and a value of 37.5 g CO_2/kWh is used.

A redundant minor mistake has been corrected in equations (5) and (6); $i=0$ is corrected to $i=1$. $\sum_{mt}$ is added to represent the sum over the materials in equation (5).

$$E_{M,M} = \sum_{vt=1}^{3} \sum_{i=1}^{POA} \sum_{mt} \alpha_{vt,i} \frac{m_{mt,vt} \cdot f_{mt,i}}{SL_{vt}} \cdot L_{tot} \tag{5}$$

$$E_{M,O} = \sum_{vt=1}^{3} \sum_{i=1}^{POA} \alpha_{vt,i} \cdot f_{vt,i} \cdot L_{tot} \tag{6}$$

Paper III

Lausselet, Carine; Urrego, Johana Paola Forero; Resch, Eirik; Brattebø, Helge. (2020) Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighbourhood building stock. *Journal of Industrial Ecology.* vol. 25: 419-434.

DOI: 10.1111/jiec.13049

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

RESEARCH AND ANALYSIS

Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock

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Funding information
This research was funded by the Norwegian University of Science and Technology and performed in collaboration with the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN).

Editor Managing Review: Niko Heeren

Funding information
Norwegian University of Science and Technology, Grant/Award Number: FME ZEN

Abstract

Low-energy building standards shift environmental impacts from the operational to the embodied emissions, making material efficiency (ME) important for climate mitigation. To help quantify the mitigation potential of ME strategies, we developed a model that simulates the temporal material flows and greenhouse gas embodied emissions (GEEs) of the material use in the construction and renovation activities of a neighborhood by combining life-cycle assessment with dynamic material-flow analysis methods. We applied our model on a "zero emission neighborhood" project, under development from 2019 to 2080 and found an average material use of 1,049 kg/m^2, an in-use material stock of 43 metric tons/cap, and GEEs of 294 kgCO_2e/m^2. Although 52% of the total GEEs are caused by material use during initial construction, the remaining 48% are due to material replacements in a larger timeframe of 45 years. Hence, it is urgent to act now and design for ME over the whole service life of buildings. GEEs occurring far into the future will, however, have a reduced intensity because of future technology improvements, which we found to have a mitigation potential of 20%. A combination of ME strategies at different points in time will best mitigate overall GEEs. In the planning phase, encouraging thresholds on floor area per inhabitant can be set, materials with low GEEs must be chosen, and the buildings should be designed for ME and in a way that allows for re-use of elements. Over time, good maintenance of buildings will postpone the renovation needs and extend the building lifetime. This article met the requirements for a gold-gold JIE data openness badge described at http://jie.click/badges.

KEYWORDS
building material, circular economy, decision support, industrial ecology, life cycle assessment (LCA), material efficiency

1 | INTRODUCTION

The global greenhouse gas (GHG) emission outcomes of current nationally stated mitigation ambitions as submitted under the Paris Agreement are not sufficient to limit global warming to 1.5°C. Deep emission reductions in all sectors and rapid, far-reaching, and unprecedented changes in all aspects of society are required to reach these targets (IPCC, 2018). In 2014, buildings used 32% of global final energy and were responsible for 19% of global GHG emissions. Industries were allocated 32% of global GHG emissions, with 11% as indirect emissions (Lucon et al., 2014). The bulk of these emissions are attributed to the processing of materials into products, and close to half of these emissions are due to iron, steel, and cement production, materials that are very much present in the built environment (Heeren, Jakob, Martius, Gross, & Wallbaum, 2013; Müller et al., 2013; Stephan & Athanassiadis, 2017).

GHG emissions from the construction industry are traditionally caused mainly by the energy consumed in the use phase of buildings; however, with an increased focus on highly energy-efficient building concepts, such as low-energy and zero-emission building technologies, the GHG embodied emissions (GEEs) of materials may cause as much as 60–75% of total GHG emissions over the building lifetime (Kristjansdottir et al., 2018). This calls for a stronger focus on material-efficiency (ME) strategies in future building design work.

However, the importance of material use in buildings is still overshadowed by policies focusing on energy efficiency and low GHG emissions energy supply (Scott, Roelich, Owen, & Barrett, 2018). A pluralistic ME-oriented approach that englobes stronger policy drivers for the use of low GEEs materials and increased material reuse is key for a quicker transition to low GHG emissions built environment (Pomponi & Moncaster, 2016).

ME means providing material services with less material production and processing (Allwood, Ashby, Gutowski, & Worrell, 2011). ME can be measured by quantifying material use by the total weight of materials or in service units to provide human needs such as housing or recreation as well as environmental impact-based indicators (Zhang, Chen, & Ruth, 2018) such as in strategies for climate-change mitigation (Hertwich et al., 2019). Demand-side ME strategies are complementary to those obtained through the decarbonization of our energy system and may offer substantial GHG mitigation potentials (UNEP, 2019). Better ME can be achieved through strategies such as (a) more intensive use, (b) lifetime extension, (c) light-weighting, (d) reuse of components, (e) recycling, upcycling, and cascading, and (f) improving yield in production, fabrication, and waste processing (Hertwich et al., 2019).

The potential of the building sector stands out compared to other sectors where climate-change mitigation strategies are more difficult to achieve (Edenhofer et al., 2014). ME strategies such as reusing steel, reviewing the amount of materials used in buildings and the frequency of replacement, reducing the use of cement, reusing concrete in constructions, and extending the lifespan of buildings and infrastructure, all offer tremendous climate mitigation potentials for the built environment (Eberhardt, Birgisdottir, & Birkved, 2019b; Fischedick et al., 2014; Malmqvist et al., 2018; Wiik, Fufa, Kristjansdottir, & Andresen, 2018). Planning authorities, major clients, developers, and individual designers are important to encourage innovative approaches to further reduce GEEs (Moncaster, Rasmussen, Malmqvist, Houlihan Wiberg, & Birgisdottir, 2019).

Because emissions from old building stock cohorts are dominated by operational energy use (Sartori & Hestnes, 2007), a common focus has been passive house and low-energy building concepts, such as lowering the total primary energy use below 120 kWh/(m^2·year) (Kylili & Fokaides, 2019). Passive-house design considerably cuts the building energy use, and with additional local renewable energy generation, such as with photovoltaic (PV) or heat pump technologies, to balance out the remaining energy use and life-cycle GHG emissions, nearly or net-zero energy/emissions buildings are possible (Fufa, Dahl Schlanbusch, Sørnes, Inman, & Andresen, 2016; Marszal et al., 2011; Torcellini, Pless, Lobato, & Hootman, 2010). The European Union has set into place the Energy Efficiency Directive (European Commission, 2012) and the Energy Performance of Buildings Directive (European Commission, 2010) that states that all new buildings by 2020 shall be nearly zero-energy buildings (Calwell, 2010).

According to IEA and UNEP (2018), building envelope measures and improvements in the performance of building energy systems have all helped to offset the effects of population and floor-area growth globally, but floor area has the largest influence on energy growth. As floor area increases, not only energy use but also resource use goes up, more land is occupied, and increased impermeable surface results in more storm-water runoff (Wilson & Boehland, 2005). Energy specifications shall not only be given in terms of energy efficiency but complemented by energy sufficiency in terms of a maximum amount of primary energy for a given service, for example, energy need for a building of a certain type for a household of a certain size over a determined period (Calwell, 2010).

Life-cycle assessment (LCA) is a standardized method (ISO 14040, 2006; ISO 14044, 2006) frequently used to estimate how potential environmental impacts accumulate over the different lifecycle phases and elements of a system (Finnveden et al., 2009; Hellweg & Canals, 2014). LCA is increasingly used to evaluate the environmental performance of buildings and neighborhoods (Lausselet, Borgnes, & Brattebø, 2019; Lausselet, Ellingsen, Strømman, & Brattebø, 2020; Stephan, Crawford, & de Myttenaere, 2013) and is the preferred method for quantifying direct and embodied building-related GHG emissions (Zhao, Zuo, Wu, & Huang, 2019).

Previous LCAs on residential buildings with conventional energy standards showed that the total lifetime GHG emissions are dominated by the use phase, with 80–90% of the total (Abd Rashid & Yusoff, 2015; Heeren et al., 2015; Sharma, Saxena, Sethi, Shree, & Varun, 2011). Anderson et al. (2015) attributed 15% to the embodied energy from the production of materials and only some 1% to energy from construction, demolition, and transportation stages. The magnitude of the different life-cycle phases is driven by the building's energy use, the emissions intensity of the energy carriers, and the GHG gas embodied emissions (GEEs) of construction materials (Dahlstrøm, Sørnes, Eriksen, & Hertwich, 2012). In most of the cases, buildings with low-energy-use standards, such as zero-emission buildings (ZEBs), have lower GHG emissions from the operational phase, but

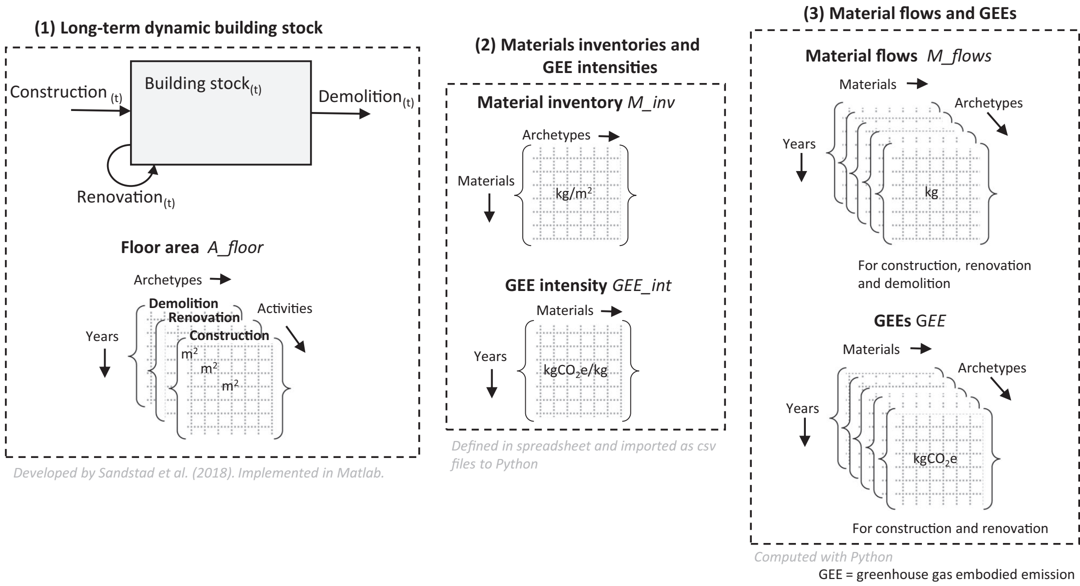

FIGURE 1 Model description

higher GEEs from building materials than conventional buildings. For ZEBs, the share of GEEs from materials is found to be from 55% to 87% of the total lifetime GHG emissions (Kristjansdottir et al., 2018; Wiik, Fufa et al., 2018).

When widening the scope from a building to the scale of a neighborhood, city, country, or region, material flow analysis (MFA) is a well-suited method to determine the material flows and stock of the built environment. Likewise, dynamic MFA (DMFA) can describe the temporal aspects of the historical (Athanassiadis, Bouillard, Crawford, & Khan, 2017; Sandberg, Sartori, Vestrum, & Brattebø, 2016) or future (Sandberg, Sartori, Vestrum, & Brattebø, 2017) evolution of a building stock, the effect of energy-reduction strategies (Ostermeyer, Nägeli, Heeren, & Wallbaum, 2018; Pauliuk, Sjöstrand, & Müller, 2013; Sandberg et al., 2016; Vásquez, Løvik, Sandberg, & Müller, 2016), future material inflow and outflow, as well as the related environmental impacts (Brattebø, Bergsdal, Sandberg, Hammervold, & Müller, 2009; Heeren & Hellweg, 2019; Müller et al., 2013; Pauliuk et al., 2013).

Although considerable efforts have been focused on understanding the energy dimension of buildings, efforts to reduce GEEs from the production of materials, construction, maintenance, and end-of-life stages of buildings require more attention (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015). Also, whereas the literature regarding building material stock and flow dynamics is rich (Lanau et al., 2019), the role of ME strategies and building-specific decisions, such as apartment size or material choice, is less understood (Heeren & Hellweg, 2019). More accurate estimates of material intensities and lifetimes can be achieved by local case studies, and cross-cutting modeling frameworks such as combining MFA and LCA can help capture the environmental impact of materials use (Augiseau & Barles, 2017). Hence, these are also promising modeling approaches to explore the temporal GHG emission power of ME strategies.

To better understand the effects of decisions taken in the early planning phase of a neighborhood, we developed a combined DMFA-LCA model that estimates the GEEs from construction, renovation, and demolition activities of a neighborhood over a 60-year time horizon. The model was applied to the Norwegian zero-emission neighborhood (ZEN) project Ydalir to answer the following questions: (a) Which materials dominate material flows during construction, renovation, and demolition activities over time? (b) Which materials contribute the most to total GEEs during construction and renovation activities? and (c) What are the GEEs mitigation potentials of selected ME strategies?

2 | METHOD

The combined DMFA-LCA model consists of three parts: (a) simulating the long-term building stock of the neighborhood by determining the amount of annual construction, renovation, and demolition activities, (b) setting up the material inventories that characterize each archetype of the building stock and determining the annual GEE intensities for each material, and (c) combining (a) and (b) to calculate the material flows and GEEs over the 60-year time horizon.

The model is conceptually illustrated in Figure 1 and explained in detail in the following sections.

2.1 | Model

2.1.1 | Long-term dynamic building stock

For the long-term dynamic building stock modeling, see part 1 in Figure 1, we use a recent model developed by Sandstad et al. (2018), which simulates the long-term dynamic development of a building stock at national or local scale such as a neighborhood. The model is based on the principles of MFA (Brunner & Rechberger, 2004) as described in Equation (1).

$$BS_{(t)} = BS_{(t-1)} + \Delta BS_{(t)} \tag{1}$$

The building stock BS at year t is equal to the stock of the previous year plus the change in building stock $\Delta BS_{(t)}$ in year t. $\Delta BS_{(t)}$ is the difference between new construction and demolition activities in year t. The model is construction-driven and has the number, type, and floor area of the different buildings to be constructed as yearly model input parameters. The building stock is categorized by archetypes defined by a building type, cohort, and renovation state, such as single-family houses (SFHs) from the 1970s after standard renovation. The timing of future renovation and demolition activities is modeled by a Normal probability distribution. During each building lifetime, demolition can occur once whereas renovation activities can occur several times.

This part of the model is implemented in Matlab with input from spreadsheets. The model output is the yearly stock of the building floor area in m^2, of each archetype stored in the floor area matrix *A_floor* with dimension (year, archetype, activity). Construction and renovation activities are inflows and have positive values. The demolition activities are outflows and have negative values.

2.1.2 | Material inventories and greenhouse gas embodied emission intensities

The second and third parts of the model are implemented in Python with input from spreadsheets. The two Python codes can be downloaded from Github (https://github.com/jpfu9/DYN_EM_MAT-Buildings). A material inventory that contains the amount and lifetime of each material is set up for each archetype. The inventories are structured according to the classification of building elements from the Norwegian standard NS 3451:2009 (Standard Norge, 2009), for example, groundwork and foundations, superstructure, outer walls, and floor structure. The life-cycle system boundary definition follows the European standard EN 15978 (European Committee for Standardization, 2012), in which life-cycle phases are divided into modules A–D, with submodules A1–A3 (production of building materials, cradle-to-gate) and B4 (replacements of building materials throughout the building lifetime/study period). Other modules related to materials in EN 15978 are not included in our model, that is, A4 (transportation of building materials to the building site), A5 (construction), C1–C4 (end-of-life management), and D (benefits outside the system).

The inventories for renovation activities are estimated from the construction inventories material lifetimes. The mass of material inventories in kg/m^2 are given in the material inventory matrix *M_inv* with dimension (material, archetype), see in Supporting Information, S1.

The material inventories contain 78 materials with data taken from environmental product declarations (EPD), which are further classified into 12 material categories: concrete, energy system, glass, gypsum, membrane, mineral, insulation from minerals, insulation from polystyrene, steel, technical, wood, and others.

Each material data point from the EPDs is assigned an equivalent from Ecoinvent (3.2 – cut-off allocation method) (Wernet et al., 2016). The exhaustive list of the 78 materials from EPDs, their Ecoinvent equivalent, and their further classification in the 12 material categories are given in Supporting Information, S3.

For the baseline scenario, Ecoinvent (3.2 – cut-off allocation method) is used for background data and Recipe v1.12 (hierarchist perspective) is chosen for the GWP100 midpoint category (Goedkoop et al., 2013). Other impact categories are not included in the present study, because it is part of the ZEN Research Centre that has its main focus on GHG emissions from neighborhoods.

2.1.3 | Material flows and greenhouse gas embodied emissions

In part 3 of the model, see Figure 1, *A_floor* is multiplied element by element by *M_inv* for each archetype to obtain the matrix of material use *M_flows* in kg/m^2 with dimension (year, material, archetype, activity), as shown in Equation (2).

$$A\_floor \cdot M\_inv = M\_flows \tag{2}$$

TABLE 1 Archetype definition according to the cohort, building type, and renovation state

Cohort	Building type	Archetype name	Renovation state	Activity	Probability distribution function
(1) 2019–2020	Kindergarten	Kind_C	Original	Construction	Not demolished
		Kind_R1	1st renovation	Renovation	N ~ (30,2)
		Kind_R2	2nd renovation	Renovation	N ~ (30,2)
	School	School_C	Original	Construction	Not demolished
		School_R1	1st renovation	Renovation	N ~ (30,2)
		School_R2	2nd renovation	Renovation	N ~ (30,2)
	SFH	SFH2019_C	Original	Construction	N ~ (60,5)
		SFH2019_R1	1st renovation	Renovation	N ~ (30,5)
		SFH2019_R2	2nd renovation	Renovation	N ~ (30,5)
(2) 2021–2025	SFH	SFH2021_C	Original	Construction	N ~ (60,5)
		SFH2021_R1	1st renovation	Renovation	N ~ (30,5)
		SFH2021_R2	2nd renovation	Renovation	N ~ (30,5)
(3) 2026–2030	SFH	SFH2026_C	Original	Construction	N ~ (60,5)
		SFH2026_R1	1st renovation	Renovation	N ~ (30,5)
		SFH2026_R2	2nd renovation	Renovation	N ~ (30,5)
(4) 2031–2080	SFH	SFH_new_C	Original	Construction	N ~ (60,5)

Abbreviation: SFH, single-family house.

The matrix of yearly GHG embodied emissions *GEE* in kgCO_2e/year with dimension (year, material, archetype, activity) is obtained by multiplying *M_flows* with the matrix of materials GEE intensity *GEE_int* in kgCO_2e/kg with dimension (year, material), as shown in Equation (3).

$$M\_flows\ GEE\_int = GEE \tag{3}$$

We decided to include the flows of demolition materials in *M_flows*, to compare their magnitude with that of the material flows from other activities. Their GEEs, however, are not accounted for in *GEE* because module C1–C4 and D are outside the system boundaries of this study, and end-of-life technologies many decades into the future are highly uncertain.

2.2 | Case study: ZEN Ydalir

Ydalir is a project currently under development, aiming to become a ZEN. A ZEN is a neighborhood aiming to reduce its direct and embodied GHG emissions toward zero over its analysis period[1] and which is powered by smart and renewable energy sources. The locally produced surplus energy is sent to the grid (Wiik et al., 2018). When examining potential GHG embodied emission reduction effects of ME strategies for Ydalir, this study uses the following functional unit: "To fulfill the housing demand in terms of residential buildings for the 2,500 inhabitants of Ydalir, including a school and a kindergarten, for a timeframe of 60 years starting in 2019."

The building stock at Ydalir, when the project is fully developed, includes a school of 6,474 m^2, a kindergarten of 2,140 m^2, and 625 SFHs, each with four inhabitants and a total floor area of 100,000 m^2. The main structural material in all the buildings is wood, and the SFHs have photovoltaic (PV) solar panels on their roofs to generate on-site renewable electricity. The school and kindergarten were built in 2019, and the SFHs are to be constructed evenly from 2019 to 2030. The buildings are identified according to their year of construction, with four cohorts: "2019 to 2020," "2021 to 2025," "2026 to 2030," and "2031 to 2080."

The combination of the cohort, building type, and renovation state results in 16 archetypes; 6 construction archetypes and 10 renovation archetypes, as defined in Table 1.

The building type SFH_new_C in cohort 4 is included to ensure a constant floor area over the 60-year analysis period, despite demolition activity toward the end of the period; hence, the yearly floor area in this cohort mirrors the amount of floor area demolished for the same year.

[1] The analysis period of a ZEN project may depend on the objective of the study. The ZEN definition referred to for Norway recommends 60 years analysis period for a ZEN project, with 60 years service life of buildings and 100 years service life of infrastructure.

The demolition activities of the SFHs follow a normal distribution with 60 years as mean service life and with a standard deviation of 5 years. The school and kindergarten are not assumed to be demolished in the studied timeframe.

The renovation activities of the SFHs are normally distributed with 30 years as a mean renovation frequency and with a standard deviation of 5 years. A shorter standard deviation of 2 years is used for the school and kindergarten because it is expected that these will be renovated close in time.

The mean value of renovation activities, 30 years, is assumed on the basis of the expected average material lifetime before replacement because of renovation, for building elements that will be replaced during a 60-year analysis period. Under these assumptions, and with renovation activities following a Normal distribution, two renovation activities can occur for a share of the buildings. The material inventories for the first and second renovations are almost similar, with some material increase in the second renovation, because of the replacement of some building materials with a lifetime greater than 30 years that are not replaced in the first renovation. See Supporting Information S1 for the complete lists and lifetime of material for each archetype.

2.3 | Material efficiency scenarios

A total of eight ME scenarios are established to examine three of the ME strategies reviewed by Hertwich et al. (2019). The two last scenarios test the uncertainty range by setting the GEE intensities to the lowest and highest possible values for each material category. The ME scenarios are described in Table 2.

3 | RESULTS

Construction and renovation activities at ZEN Ydalir mobilize a total of 116 kton of materials with 82.6 ktonCO$_2$e between 2019 and 2080, equivalent to an average material use of 1,049 kg/m^2, in-use stock of 43 tons/cap, and GEEs of 294 kgCO$_2$e/m^2. The initial construction activities drive most of the material use and GEEs. The most dominant material flow is concrete followed by wood. The most dominant source of GEEs is the PV panels, followed by wood and concrete.

In the following sections, the dynamics of the floor area, material, and GEEs flow of the building stock of Ydalir are described, followed by the results from the ME scenarios.

3.1 | Floor area dynamics

The floor area dynamics are presented in Figure 2. The initial construction activities take place during the 11 first years from 2019 until 2030. The kindergarten and the school were built in 2019, and the residential SFHs are built uniformly from 2019 until 2030.

The first renovation activities of the SFHs start in 2035 with some renovation from the first cohort. The renovation activities increase in the 2040s when the second and third cohorts come into play and peak in the 2050s. Renovations are completed by 2062 for the first cohort, by 2071 for the second cohort, and by 2076 for the third cohort. Because of the assumptions in our study, the school and kindergarten are estimated to undergo their first renovation from 2047 to 2049.

The second wave of renovation begins in the mid-2060s and overlaps with the first wave, and some renovation activity therefore occurs every year after 2035. For SFHs, it peaks around the end of the study period, and for the school and kindergarten, it occurs between 2076 and 2078. By 2080, 43% of the SFHs from the first cohort are renovated, and 32% and 12% from the second and third are renovated, respectively. In total, 32% of the neighborhood's building stock has undergone a second renovation in 2080.

Demolition is estimated to begin in 2064, for SFHs of the first cohort. By 2080, the demolished area accounts for 25,600 m^2 or 24% of the initial building stock, and the new construction is equivalent to 160 new SFHs, out of 625 SFHs in total.

3.2 | Material and embodied emissions intensities by archetype

The material intensity for each archetype and material category is shown in Figure 3a.

The construction of the kindergarten and the SFHs have a similar material intensity of 743 kg/m^2 and 731 kg/m^2. The school has a material intensity of 1,024 kg/m^2, which is 40% higher than the kindergarten and the SFHs, mainly because of higher material use in the groundwork and foundation (concrete, wood, and minerals such as asphalt). Among all archetypes, concrete and wood represent 63–89% of the material requirement in construction activities: concrete with 57–64%, wood with 18–32% followed by gypsum with 3–7%, and mineral, glass, energy system, and

TABLE 2 Material efficiency (ME) scenarios

ME strategy[a]	Scenario	Description	Single-family house size (m^2)		Building lifetime[b] (year)		Renovation rate (year)			Ecoinvent	EPD
			160	120	60	100	20	30	40		
	Baseline	Single-family house of conventional size and lifetimes according to standard	+		+			+		+	
(1) More intensive use	S1-30 m^2/cap	The SFH floor area is reduced by 25% from 160 m^2 to 120 m^2 in line with a residential floor area per capita of 30 m^2 proposed by Grubler et al. (2018). The material inventories are downscaled linearly.		+	+			+		+	
(2) Lifetime extension	S2-Ren40	The mean renovation period is set to 40 years for all the buildings. This scenario forces the renovation to happen less often, and test for the effect of a material lifetime extension.	+		+				+	+	
	S3-Ren20	The renovation rate value is decreased and set to 20 years for all building types to test for the opposite effect of S2-R40.	+		+		+			+	
	S4-Con100	The lifetimes of all the buildings are extended and set to 100 years.	+			+		+		+	
(3) Improving yield in production	S5-Ecoinvent 40%	Improving yield in production has a direct effect on the materials' emission intensities. A linear decrease of the emission intensities by 40% from 2019 to 2050 is assumed, based on technological factors proposed by Resch, Lausselet et al. (2020).	+		+			+		(+)	
	S6-EPD	Emission intensities are replaced with values from Environmental Product Declarations (EPDs) representative for Norge where the electricity mix is highly decarbonized.	+		+			+			+
Combining strategies	S7-30 m[b]/cap +Ren40	This scenario combines two ME strategies; (1) more intensive use as in S1 with (2) lifetime extension of material through increased renovation rate as in S2.		+	+				+	+	
	S8-30 m^2/cap +Ren40+EPD10%	This scenario combines all the ME strategies in addition to a decrease of 10% in the material emission intensities.		+	+			+			(+)
Uncertainty	S9-High	The material emission intensities are replaced with the highest values inside each material category	+		+			+		+	+
	S10-Low	The material emission intensities are replaced with the lowest values inside each material category	+		+			+		+	+

[a]The scope is limited to three ME strategies, but other ME strategies could have been implemented such as "light-weighting" by updating the detailed material inventories or "reuse of components" and "recycling, upcycling, and cascading" by using the annual material outflows.
[b]The standard deviations remain unchanged.

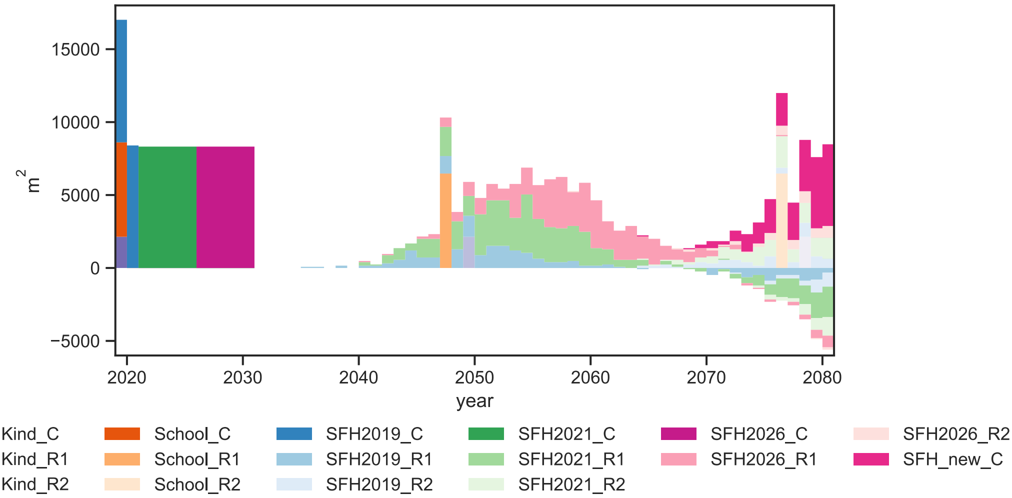

FIGURE 2 Construction, renovation, and demolition of floor area (*A_floor*) in the neighborhood over the years. Underlying data used to create this figure can be found in Supporting Information S2

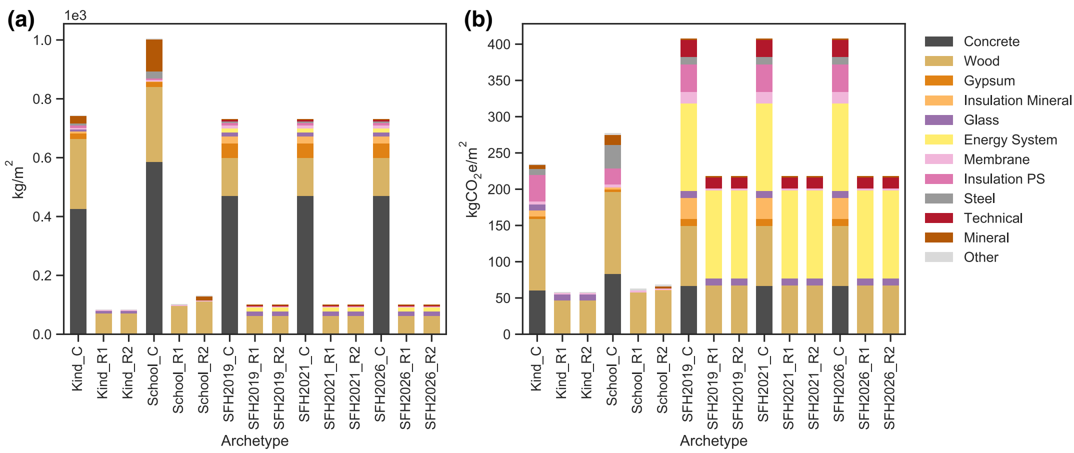

FIGURE 3 (a) Material intensity per m^2 per archetype; (b) emission intensities per m^2 per archetype. Underlying data used to create this figure can be found in Supporting Information S2

membrane with only marginal shares. The renovation of the kindergarten, school, and SFHs requires an additional 11%, 10%, and 14% of the material quantity used in the construction, respectively. Wood is the main material being replaced.

The GEE intensities of the 15 first archetypes are shown in Figure 3b. In the construction phase, the kindergarten is the least emission-intensive with 234 kgCO_2e/m^2, followed by the school with 277 kgCO_2e/m^2 and the SFHs with 408 kgCO_2e/m^2. In the renovation phases, the GEE intensities of the kindergarten, school, and SFHs are respectively 25%, 23%, and 53% of their construction.

The GEE intensities of the construction and renovation activities are highest for the SFHs because of the emission contribution of the PV panels installed on the roofs (part of Energy System), accounting for 30% of their total GEEs in the construction and 56% in the renovation.

3.3 | Material and embodied greenhouse gas emissions storylines

The neighborhood material and GEEs storylines are presented in Figure 4, expressed by their absolute (Figures 4a and 4b) and cumulative (Figures 4c and 4d) material and GEEs flows per material category.

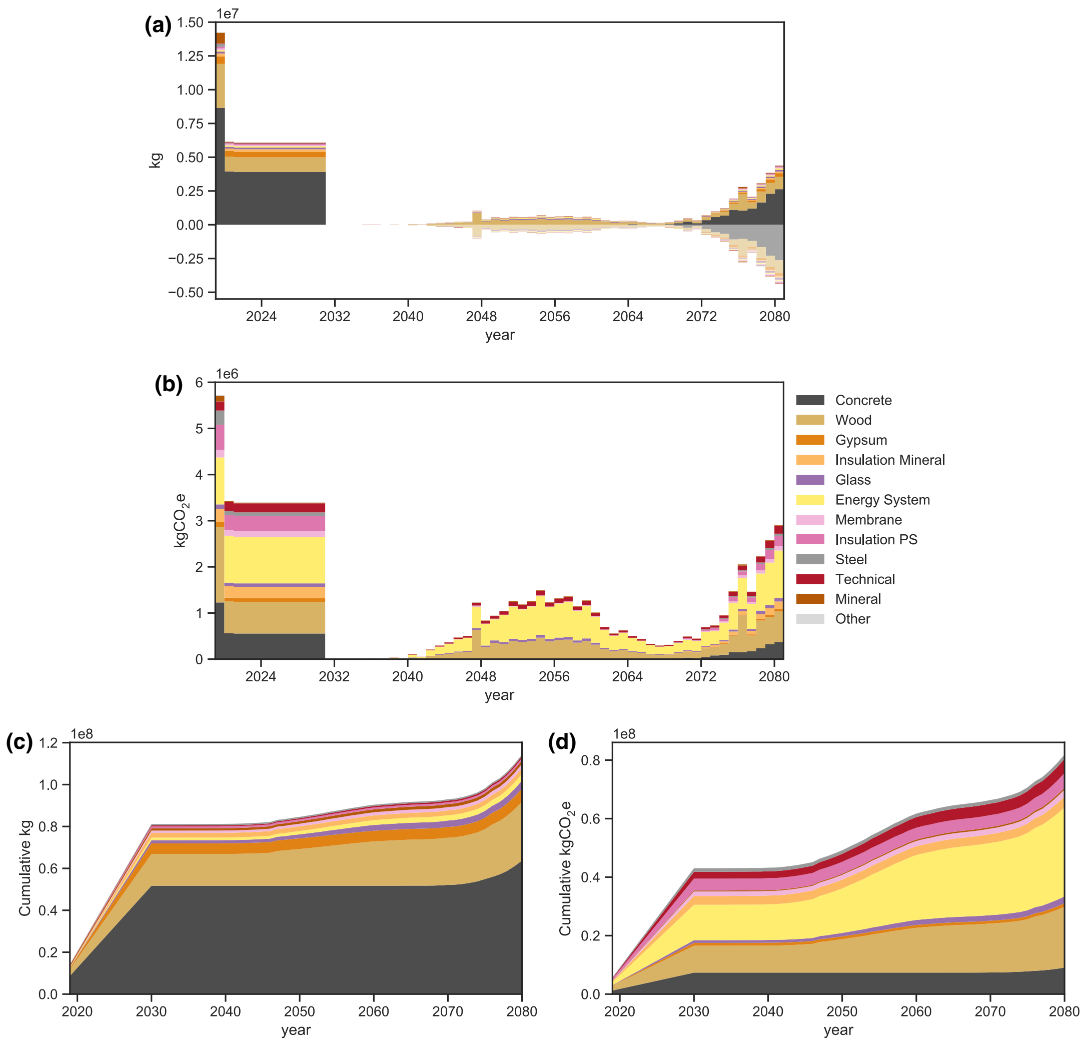

FIGURE 4 (a) Yearly material; (b) greenhouse gas embodied emissions (GEEs); (c) cumulative material flows by material categories; (d) GEEs flows by material categories. Underlying data used to create this figure can be found in Supporting Information S2

A total of 114 kton material is needed to construct, renovate, and maintain the neighborhood's building stock floor area: 71% for the construction, 13% for the renovation, and 16% for the new construction required to maintain the building stock floor area constant over time.

Rapid material stock accumulation occurs in the first 11 years. After 2030, the material stock accumulation remains almost constant until around 2045, when the first renovation activities start. The flow of concrete and wood dominates the material flows over the years, with 55% and 25% of the total material flows, respectively.

A total of 82 kton CO_2e is emitted, equivalent to 294 kgCO_2e/m^2. 52% of the total GEEs are due to the initial construction activities, 36% are due to the renovation activities, and the remaining 12% are due to the new constructions at the end of the analysis period. Although the GGEs from initial construction activities are fairly similar to those from the later renovation and new construction activities, the time window in which they occur is different. Whereas 52% of the total GEEs are spread in the first 11 years (2019 to 2030), the remaining 48% occur in a distant timeframe of 45 years (2035 to 2080). Note that the results here are for our baseline scenario, in which constant GEE intensities over time are assumed. The GEE intensities are likely to decrease during future decades, as a result of technology improvements in materials production (Gibon et al., 2015; Wiebe, Bjelle, Többen, & Wood, 2018) and low-carbon electricity generation (IEA, 2015). The magnitude of such changes is hard to predict and therefore highly uncertain. However, we explore the effects of changing GEE intensities over time in two of our ME scenarios, see results in the section below.

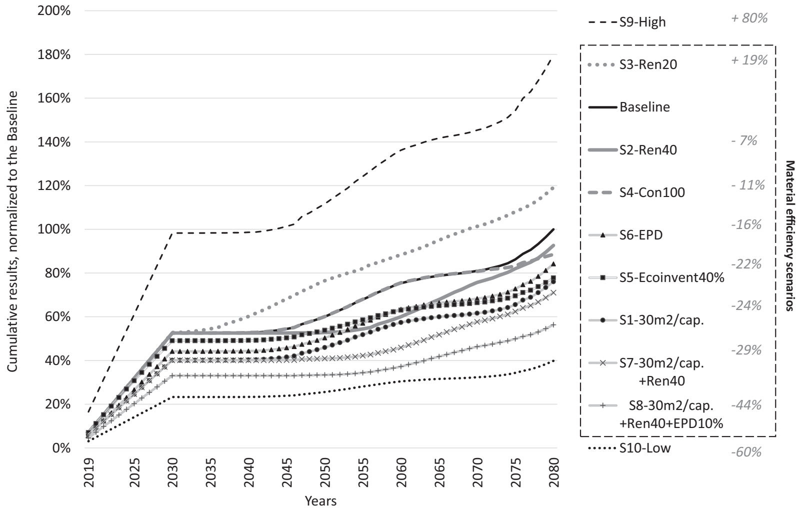

FIGURE 5 Cumulative greenhouse gas embodied emissions (GEEs) for all the scenarios. Underlying data used to create this figure can be found in Supporting Information S2

The cumulative GEEs are dominated by PV panels in the energy systems, contributing to 37%, followed by wood 30%, concrete 11%, and insulation-PS 5%. Wood takes up a third of the emissions because it is the main structural material; the results should therefore not be interpreted as wood being worse than concrete in general but as a typical current Norwegian neighborhood project consisting of wooden buildings only.

3.4 | Material efficiency scenarios

The results of the eight ME and the two uncertainty scenarios are presented in Figure 5 relative to the baseline scenario. The results of the ME scenarios show GEEs mitigation potentials ranging from 7% to 44%. The two uncertainty scenarios S9 and S10 show that the choice of another GEE intensity for the same material will largely influence the cumulative GEEs, from a 60% decrease in S10 to an 80% increase in S9.

The construction activities induce rapid GEEs increase with a peak in 2030, which accounts for about half of the cumulative GEEs for all scenarios along the study period. The magnitude of the construction peak can be reduced by 9% by implementing ME strategies that improve the yield in the production of the building materials (S6), by 13% by a more intensive use (S1) and up to 20% (S8) by combining the two aforementioned strategies.

From 2035, the GEEs are induced by renovation activities and new construction of SFHs at the end of the analysis period. Those future GEEs can be mitigated by several ME strategies. Improving the material lifetime by postponing renovation activities (S2) has a mitigation potential of 7%. The introduction of more intensive use of the buildings, by introducing a maximum floor area per capita design criterion in the neighborhood planning stage, will also have a direct multiplier effect on the stock to renovate, with a mitigation potential of 11% (S1). The same potential is obtained by increasing the building's lifetimes to 100 years, thus avoiding the need for new construction at the end of a 60-year analysis period. To factor in the improved yield in material production over time gave a mitigation potential of 18% (S5). The best mitigation potential of the GEES after 2035 is 24% and is achieved by combining all ME strategies (S8).

The combination of different ME strategies also shows the highest mitigation potential of the cumulative GEEs. Combining a more intensive use of buildings with a higher material lifetime (S7) has a cumulative mitigation potential of 29%, whereas a further combination of the former scenario with an improved yield in material production leads to further mitigation of 15% for a total of 44% (S8).

Concerning the development of the GEES over time, all ME scenarios go through a GEEs plateau after the construction peak in 2030 until the renovation activities start. The scenario with earlier renovations (S3) finishes 19% above the Baseline scenario, demonstrating the unwanted effect of high renovation frequencies. The scenario with increased material lifetime (S2) decreases its progression rate because the renovation activities are postponed. The effect of the first renovation can be seen around 2045 for the scenarios following conventional renovation times (Baseline, S1, S4, S5, and S6). The slopes of the scenarios where ME strategies improve the material production yield (S5 and S6) is less steep than the slopes of the scenarios where this type of ME is not implemented (S1 and S4).

The effect of a longer building lifetime comes into play around 2070 when the need for the construction of new SFHs to maintain the functional unit constant over the analysis period starts. For that reason, the baseline and S4 scenarios that follow the same renovation rates split at this point.

4 | DISCUSSION

4.1 | Comparison with other studies

The baseline GEE intensity of 294 kgCO2e/m^2 of the Ydalir project, with an uncertainty ranging from 118 to 529 kgCO2e/m^2, is in line with previous studies. For the same geographical context and modules A1–A4 and B4, Kristjansdottir, Heeren, Andresen, and Brattebø (2018) found GEE intensity of low-energy and zero-emission SFHs to range from 252 to 282 kgCO_2e/m^2, and Wiik, Fufa et al. (2018) reported values for seven residential and non-residential zero-emission building case studies from 282 to 918 kgCO_2e/m^2. The International Energy Agency Energy, in Building and Communities Annex 57, analyzed over 80 building case studies and found building materials GEEs to range between 20–620 kgCO2e/m^2 for construction (module A1–A3), and 20–180 kgCO_2e/m^2 for replacement (module B4). Although reported process-based LCA results went up to a value of 620 kgCO2e/m^2 for modules A1–A3, input-output based results can reach even higher up to 1,100 kgCO2e/m^2 (Moncaster et al., 2019). This is well beyond the figures we found for Ydalir and underlines the importance of regional building technologies, material choice, and system boundaries in LCAs for building stock GEE analysis.

For all scenarios, we found concrete and wood to dominate both the material flow and the GEEs. This is fully in line with what is recently reported by Resch, Lausselet, Brattebø, & Andresen (2020) and Resch, Brattebø, & Andresen (2020), for the same type of buildings in Norway. For other geographical contexts, concrete, cement, sand, and gravel are in many cases the dominant materials (Heeren & Hellweg, 2019; Huang et al., 2018).

We found a total in-use material stock of 32 tons/cap. For residential buildings, Gontia, Nägeli, Rosado, Kalmykova, and Österbring (2018) reported an in-use material stock for the city of Gothenburg in 2016 of 62 tons/cap. Wiedenhofer, Steinberger, Eisenmenger, and Haas (2015) reported 72 tons/cap for the EU25 in 2009, and Huang et al. (2018) reported 24–25 tons/cap for China. Our results are roughly half of the European results, which is expected because our buildings are wood-based and thus lighter, and slightly higher than the Chinese figures mainly because of less floor area per inhabitant in China.

4.2 | Material recycling, upcycling, and cascading

The potential to reuse and recycle materials in the building sector is well present (Augiseau & Barles, 2017; Zabalza Bribián, Valero Capilla, & Aranda Usón, 2011). For Ydalir, 13% and 16% of material flows are from renovation and demolition activities. The material outflows could be further examined regarding their mitigation potential if exposed to recycling, upcycling, and cascading ME strategies, according to the principles of a circular economy. Also, the design of buildings should consider solutions that facilitate the disassembly of materials to allow for such strategies (Eberhardt, Birgisdóttir, & Birkved, 2019a; Malmqvist et al., 2018).

4.3 | Alternative life-cycle inventory techniques

Although the use of different process-based LCA background databases (EPDs and Ecoinvent 3.2) has been tested, the use of other LCI techniques that use wider system boundaries for the inventory of materials should also be examined because this might significantly influence the results (Crawford, Bontinck, Stephan, Wiedmann, & Yu, 2018). Whereas process-based LCIs suffer from truncation errors, input-output LCIs suffer from aggregation uncertainties (Lenzen, 2000; Majeau-Bettez, Strømman, & Hertwich, 2011). The use of hybrid LCIs may provide a more comprehensive analysis of a product system, and the recent efforts by Agez et al. (2020) and Stephan, Crawford, and Bontinck (2019) to streamline hybrid LCI by automating various components will help their uptake by a wider community.

4.4 | Importance of infrastructure-related emissions

In addition to buildings, construction materials accumulate in infrastructure elements of a neighborhood, such as road networks, drinking water, wastewater, heat supply, and gas-pipe networks. Such elements can account for substantial shares of the total in-use material stock of built environment and have been reported to account for 38% and 1.3% for roads and wastewater pipes, respectively, in Gothenburg (Gontia et al., 2018), 53% for roads in the EU25 (Wiedenhofer et al., 2015) and 26%, 19%, and 8% for roads, seaports, and dams, respectively, in Japan (Tanikawa, Fishman, Okuoka, & Sugimoto, 2015). The related GEEs profile of infrastructure is region-specific and directly related to the level of economic development. Typically, it was approximately five times larger for industrialized countries compared to developing countries in 2008 (Müller et al., 2013). According to these figures, our study for Ydalir is potentially missing a significant share of the total built in-use material stock and their related GEEs, even though this project is by purpose designed with very little internal infrastructure demand.

4.5 | Strengths and limitations

The main strength of our model is its ability to combine long-term temporality in dynamic analysis of construction, renovation, and demolition activities with detailed material life-cycle inventories of buildings. The use of detailed case-specific life-cycle material inventories for individual building types reduces the uncertainty in material-flow estimates and provides more reliable results.

The model's scenarios of future development paths can reveal how GEEs are influenced by parameters describing alternative future developments. Predicting how such parameters will evolve has substantial uncertainty, which was partially explored in two uncertainty scenarios. In reality, a combination of different ME strategies will likely lead to an even larger variation in results. A global sensitivity analysis such as a variance-based sensitivity analysis (Saltelli et al., 2010) can be performed to capture such effects.

The future estimates of material flows and GEEs should not be regarded as predictions, but rather as possible paths that can be influenced. In general, the uncertainty increases into the future, and our results showed the construction peaks to release the majority of the GEEs at the beginning of the neighborhood storyline. Therefore, the main priority should be on design and ME strategies to reduce near-future emissions. Moreover, technological improvement and the decarbonization of the energy mix over that time will decrease the GEE intensity of the production of the materials (Gibon et al., 2015; Lausselet et al., 2020; Resch, Lausselet et al., 2020; Wiebe et al., 2018). We factored in the effects of technological improvements in two scenarios (S5 and S8) and found a reduction of future GEEs of 20%.

The average building lifetime in our model is set to be 60 years, in line with the Norwegian standard NS3720:2018 for the calculation of GHG emissions for buildings and the Norwegian ZEN definition (Wiik et al.,2018). Yet, it seems that a lifetime of as much as 125 years is closer to reality in Norway (Sandberg, Sartori et al., 2016). Given that the analysis period of our study is equal to the assumed building lifetime of 60 years, the implications of longer lifetimes are not fully captured. A building lifetime of 100 years, as depicted in S3, shows that new construction to compensate for demolition activities as well as the third round of renovation would not happen within an analysis period of 60 years because this will start after 2080. Lifetime estimates and renovation frequencies for buildings in a new neighborhood are unreliable and a source of uncertainty in GEEs scenario models. Our results show that different assumptions may significantly influence the annual and cumulative GEEs. A Normal distribution function is used because it is assumed that all the stock is renovated, which may not be the case when using a Weibull distribution (Sartori, Sandberg, & Brattebø, 2016). When used to estimate the building's lifetime, Normal and Weibull distributions have been proven to give similar results (Zhou, Moncaster, Reiner, & Guthrie, 2019).

The archetypes make a distinction between building types and assume the same material requirements for each building within the same building type. Although this approach is adequate for a neighborhood in the early planning phase, a bill of quantity specific to each building should be used in later planning phases, when such information becomes available. Alternatively, the use of a three-dimensional model linked with geographic information system data might be helpful to derive a bill of quantity for each building, as done by, for example, Stephan and Athanassiadis (2018) or Heeren and Hellweg (2019).

4.6 | Further work

The system boundary of our model could be expanded to follow the definition from the ZEN Research Centre, to include neighborhood elements such as mobility, road infrastructure, and energy grids, as done in a previous LCA study for another ZEN, by Lausselet et al. (2019) and Lausselet et al. (2020). To design a ZEN project with minimum GEEs, it is necessary to understand the emission drivers for each element of the neighborhood over time. An estimation of the energy demand and on-site energy generation would also give insights on how much of the GEEs can be balanced by emission credits gained by the excess on-site energy exported to external grids. Buildings and mobility can each account for 40–60% of the total GHG emissions of a ZEN, and a holistic strategy including also mobility should be embraced to help guide local design decisions to minimize GEEs.

4.7 | Strategies and policy implications

Our scenarios have shown that a combination of different ME strategies is the most efficient way to mitigate the GEEs of the assessed ZEN. ME strategies that reduce the floor area per inhabitant are very efficient to reduce the construction peak and its latter multiplier effect on future material flows and emissions. Besides, implementing guidelines that would propose an optimal GEE intensity for a given building type is an appropriate strategy to reduce GEEs of the building stock over time. This strategy will help architects keep their design options following the right GEE intensity target track. The GEE intensities and lifetimes of each material will then be balanced to stay below the recommended target limit.

The predictions of material outflows can be used to identify opportunities to reuse or recycle these resources. The anticipated knowledge of how much and what material flows out at a given time can be used to plan new construction or other activities that may take advantage of those resources. Understanding the evolution of material flows and the related GEEs of a neighborhood over time is useful to tailor strategies that can reduce the GEEs at different points in time and reuse materials on a neighborhood or regional scale.

5 | CONCLUSION

The introduction of low-energy standards in the construction sector shifts the focus from the operational to the construction phase, and this calls for attention on how and when to minimize GEEs. To quantify these GEEs, we developed a model that calculates the material flows and their associated GEEs of building stocks in neighborhoods over time by combining LCA with DMFA methods. The model is applied to the ZEN Ydalir project, in Elverum, Norway.

Scenarios are developed and tested to assess the climate mitigation potential of different ME strategies, and a potential of up to 44% GEEs reduction was found. Further reductions are possible by combining scenarios or making each scenario more aggressive, for example, by use of stronger technology improvements or lower renovation frequencies. Implementing a combination of ME strategies at different points in time will best help mitigate GEEs. In the planning stages, threshold values of floor area per inhabitant can be required, materials with low GEE intensity should be preferred, and the building should be designed in a way that allows for re-use of elements. Over time, good maintenance of the buildings will postpone renovation needs and extend the building lifetime.

The type of dynamic model that is used in this study, with detailed material and GEEs layers, can be used to plan the design of a neighborhood in a way that minimizes total GEEs by exploring the effects of different ME strategies. We found that half of the total GEEs occurs during the first 11 years. This underlines the urgency of a building-design approach that targets GEE reductions in the construction stage of a project. Moreover, with significant GEE also occurring during future decades, because of material replacement in renovation and demolition activities, it is important to avoid unexpected lock-in effects by also adopting a design approach committed to ME strategies over the total service life of buildings. The magnitude of the construction peak, the high uncertainty of future activities, and the predicted technology improvements that will reduce the future material GEE intensity all tell us that the main priority for GEEs reduction in neighborhood projects should be on measures that can strongly influence near-future emissions.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support from the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighborhoods in Smart Cities (FME ZEN).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Lausselet C, Urrego JPF, Resch E, Brattebø H. Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock. *J Ind Ecol*. 2021;*25:* 419–434. https://doi.org/10.1111/jiec.13049

Paper IV

Lausselet, Carine; Lund, Kristi Marie; Brattebø, Helge. (2021) LCA and scenario analysis of a Norwegian net-zero GHG emission neighbourhood: The importance of mobility and surplus energy from PV technologies. Building and Environment. vol. 189: 107528.

Building and Environment 189 (2021) 107528

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

LCA and scenario analysis of a Norwegian net-zero GHG emission neighbourhood: The importance of mobility and surplus energy from PV technologies

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ARTICLE INFO

Keywords:
Life cycle assessment (LCA)
Net-zero greenhouse gas (GHG) emission neighbourhood (ZEN)
Energy locally produced
Mobility scenarios
Industrial ecology

ABSTRACT

The Zero Emission Neighbourhood (ZEN) concept gives a unique chance to assess the nexus of buildings, mobility, and energy systems to limit global warming and mitigate climate change. ZENs rely on the use of passive-house technologies in combination with local renewable-energy production such as by photo-voltaic (PV) systems to meet the internal energy demand and for export of surplus energy to the external power grid.

We developed a modular LCA model that includes five physical elements: buildings, mobility, infrastructure, networks, and on-site energy. The model is applied on Ydalir, an ambitious ZEN in the early planning phases in Norway. Several scenarios were created to explore alternative mobility patterns and an upscaling of electricity production.

The results show mobility to be the major source of greenhouse-gas emissions, with 62% of the total emissions in a baseline scenario. To reduce the travel distance of the inhabitants, measures such as car-sharing or greater use of public transports are highlighted as the best options to improve the climate performance of Ydalir. An upscaling of the electricity production from PV panels would allow for significantly reduced system-wide emissions if more surplus electricity is exported and can substitute power generated from fossil fuels or replace fossil fuels used in mobility.

1. Introduction

The built environment is responsible for 40% of the total energy consumption and 30% of the total energy-related greenhouse-gas (GHG) emissions in the European Union (EU) [1]. Reducing the emissions from the built environment is thus critical to limit global warming to the 1.5 °C target and stabilize the temperature increase at a safe level [2]. In Norway, the Research Centre on Zero Emission Neighbourhoods in Smart Cities (www.fmezen.no) was launched in 2017 with the goal to develop solutions for future buildings and neighbourhoods with net-zero GHG emissions. ZENs rely on the use of passive-house technologies, in combination with local renewable-energy production such as by photo-voltaic (PV) systems to meet the internal energy demand and for export of surplus energy to the external power grid. By using the surplus energy locally produced to substitute power generated from fossil fuels, which is particularly a viable strategy for projects with power supply influenced by fossil fuels, or to replace fossil fuels used in mobility, which is particularly a promising strategy for projects with power supply dominated by low-carbon energy sources, ZEN projects will contribute to a low-carbon society [3].

Life-cycle assessment (LCA) has commonly been used to assess both individual buildings and neighbourhoods [4]. LCA systematically examines potential environmental impacts and their causes, for a given system and for each life-cycle stage of its elements, from raw-material acquisition, production of energy and materials, and usage to end-of-life processing [5]. LCA is the preferred method to assess the climate-change mitigation performance of ZENs, because it looks at the entire life span of the elements of a neighbourhood [6].

LCAs on buildings have historically shown that GHG emissions from the operational stage account for as much as 80–90% of the total GHG emissions [7,8]. More recent studies have indicated that embodied emissions from materials become the major contributor, mainly when highly energy-efficient buildings are considered [9–11]. Other aspects, such as the importance of user behaviour, construction, energy-positive buildings, and alternative and renewable materials, are also addressed in other studies [12–16].

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https://doi.org/10.1016/j.buildenv.2020.107528
Received 9 June 2020; Received in revised form 23 November 2020; Accepted 13 December 2020
Available online 14 December 2020

Buildings are commonly treated as independent objects when performing LCAs. However, when conducting LCAs on neighbourhood scale, aspects such as density, transportation, infrastructure, and consumption should be included. The interconnections between the buildings become more important when a cluster of buildings is evaluated with the same system boundaries. Although the complexity increases significantly, more opportunities regarding emission reduction are created, and innovative solutions for local energy supply, energy storage, and energy flexibility become more relevant. Whilst several tools to conduct LCA on single or several interlinked buildings have been developed [17], the literature on LCAs on neighbourhood scale that includes buildings and mobility is limited and lacks comparability because different studies are complex and largely context-dependent [18,19].

The system-boundary definition is crucial for the reliability and comparability of LCA results. Some LCA studies only assess a cluster of buildings [20], whereas others also consider the mobility of inhabitants or users [4,21]. The most comprehensive and complex LCA studies are the ones that also include several other elements, such as physical capital in networks and infrastructure, in addition to buildings and mobility [14,22,23]. There are also variations in which life-cycle stages are considered, from narrow studies that only include the use stage to system-wide studies where construction (including material production) and deconstruction are also accounted for [18,19]. Such differences often create challenges in comparing results across studies, but as mentioned below, some key points need particular attention when advancing the LCA methods at neighbourhood scale.

Previous studies have shown that the mobility needed to fulfil the transportation needs of the inhabitants and users has a significant impact on the total GHG emissions of urban areas. Nichols and Kockelman [14] found that 44–47% of the total emissions from the use stage comes from transportation, and Bastos, Batterman and Freire [21] found that mobility contributes with as much as 51–57% of the total life-cycle emissions. But studies that also include the manufacture of transportation modes lack, with a few exceptions. Stephan, Crawford and de Myttenaere [22] found that indirect emissions (including transportation supporting services such as vehicle manufacturing and building roads) from transportation represent 52% of the emissions from this element, and Anderson, Wulfhorst and Lang [4] found the same emission source to represent 22–27% depending on the neighbourhood location. In Norway, the new standard NS 3720 "Method for greenhouse-gas calculations for building" [24] is a tool to synchronize LCA studies on building at neighbourhood scale. Transportation is accounted for in a separate module (B8) in the use stage of a building.

The predictions and assumptions of future scenarios are particularly crucial when performing LCAs of systems with long service life, such as buildings and other elements of a neighbourhood. The varying service lifetime of each element of a neighbourhood, the evolution path of technologies, the temporal distribution of emissions, and long-term changes in GHG emission intensities of material and energy-carrier inputs are all key factors and have great impact on the predictions of future scenarios and thus on the final results and decision-making processes [18,21,22,25].

Accounting for the temporal variation of electricity production and use in the LCA of an energy-efficient house is crucial, and the use of an average electricity mix can lead to errors in LCA of buildings [26]. To provide a clear scientific background regarding the hourly GHG intensity of one kWh of produced electricity in order to provide a decision support tool to fully exploit the advantages of a future smart grid is crucial [27]. Hourly-based GHG emissions of electricity can be an efficient tool for households and companies to decrease their GHG emissions by changing the timing of their electricity use [28]. Hourly energy profiles have been generated widely in non-LCA studies. Lindberg, Seljom, Madsen, Fischer and Korpås [29] developed hourly electric and heat profiles for non-residential buildings for use in long-term forecasts. Furthermore, research is needed for a comprehensive view of technologies and potential for peak shavings. Luthander, Widén, Nilsson and Palm [30] indicate a higher potential for increased self-consumption with battery storage than demand side management. For load shifting, Murray, Orehounig, Grosspietsch and Carmeliet [31] predict that neighbourhoods with high renewable surpluses should consider the advantages of a hydrogen storage. On the other hand, short-term battery and thermal storage systems should be sufficient for neighbourhoods with low surpluses. Munkhammar, Bishop, Sarralde, Tian and Choudhary [32] investigated the household electricity use, electric vehicle home-charging and distributed PV electricity production. The authors found a mismatch on the household level introduced by the variability in electricity production and use, which was shown to be less prominent for large-scale scenario of an entire city. To limit average and absolute energy peak demands and almost eliminate the difference in absolute peak demands seen between fast and slow vehicle home-charging, the most successful strategy has been proven to be a combination of bi-directional battery operation, coupled with load-controlled charging and heat pump operation [33]. Yet, to our knowledge, there are no LCA studies that use hourly energy loads to assess the interaction between buildings, battery electric vehicles and the potential of the latter to temporally store and supply back the electricity produced by the buildings when appropriate.

Further LCA research in the field on ZENs is obviously required, particularly to better understand what are robust design principles, solutions, and technologies for successful mitigation of GHG emissions, critical factors for low emissions across all life-cycle stages and physical elements, and the robustness of overall performance results with respect to uncertainties, sensitivities, and assumptions over time. This insight should build the foundation in future ZEN projects, in the search for a standard to produce comparable and robust results. The benefits of LCA are fully exploited when used in the early planning phases of new neighbourhoods, and the aim of this study is to contribute the use of LCA as a decision-support tool in the early planning phases. In particular, we aim to better understand the influence of factors such as the (1) mobility patterns in terms of distances driven, choice of transport modes and penetration rate of new technologies (e.g. electric vehicle), (2) local electricity production from PV technology and (3) GHG emission benefits gained by sending the surplus electricity production to the grid in reaching a net-zero GHG emission target.

We use the model developed by Ref. [23,34], apply it on the ZEN pilot project Ydalir, in Elverum, Norway, and answer the following questions: (1) Which life-cycle stages are the most significant contributors to the global-warming potential of ZEN Ydalir, when including the elements buildings, mobility, infrastructures, networks, and on-site energy production? (2) To what extent can more ambitious solutions and assumptions for mobility reduce the global-warming potential at ZEN Ydalir? and (3) Where must improvements be implemented in order to achieve the "net-zero GHG emission ambition"?

2. Method

The LCA model previously developed by Lausselet, Borgnes and Brattebø [23] and Lausselet, Ellingsen, Strømman and Brattebø [34] has been further adapted for use in our case study, ZEN Ydalir. This project is a ZEN still in the early phases of development.

2.1. Model

The LCA model is presented in Table 1, which shows that the system boundary of the LCA study for Ydalir includes four main neighbourhood elements: (i) on-site energy production including photovoltaic (PV) panels, a co-heat and power generator, and a local district-heating network, (ii) the buildings, with a school, a kindergarten, and 1000 residential building units, (iii) a system for mobility for the inhabitants and users in the neighbourhood, including vehicles and transport activity for the modes of private cars, public busses, and light rail

Table 1
Elements of the model broken down by life-cycle stages.

	Product stage			Construction stage		Use stage								End-of-life stage				Benefits and loads	
	Raw materials	Transport	Manufacturing	Transport	Construction/ Installation	Use	Maintenance	Repair	Replacement	Renovation	Energy use	Water use	Transportation in use	Demolition	Transportation	Waste processing	Disposal	Potential for recycling	Export of surplus self-produced energy
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	C1	C2	C3	C4	D	D
Elements Buildings																			
Mobility																			
Infrastructure																			
Networks																			
On-site energy																			

transport, and (iv) a system of road infrastructure, with sidewalks and lighting. The neighbourhood is connected to external electricity and heat grids.

ZEN Ydalir is planned with the aim to meet the net-zero GHG emission ambition level "ZEN OM", which means that the neighbourhood over an analysis period of 60 years should have net-zero GHG emissions related to operation O (B6) and materials M (A1-A4 and B4).

Hence, embodied emissions from the production of materials used in the neighbourhood will have to be compensated by emission credits from on-site local energy production in surplus of what is used in the neighbourhood over the period and can be exported to the external grids in order to substitute more dirty energy production elsewhere and achieve the net-zero GHG emission balance [35,36]. The life-cycle stages, production stage [37] (A1–A3), replacements (B4), and energy use in operation (B6) were included for all elements. For the element infrastructure, construction (A5) is also included, and for the element networks, the energy use in operation is excluded.

For on-site energy, the benefits and loads (D) are included. The emission balance is calculated on a yearly basis for a timeframe of 60 years and is presented in Table 2.

The total GHG emissions of the neighbourhood are calculated with Equation (1).

$$E_{tot} = E_{b,mat} + E_{b,oper} + E_{m,mat} + E_{m,oper} + E_{inf,mat} + E_{inf,oper} + E_{en,\ prod} - E_{en,\ ben} \quad (1)$$

$E_{b,mat}$, $E_{m,mat}$, and $E_{inf,mat}$ are the GHG emissions from the materials for construction and maintenance of buildings, mobility, and infrastructure, respectively. $E_{m,oper}$ is the emissions from the energy use in operation of mobility, $E_{en,prod}$ is the GHG emissions related to on-site energy production, and $E_{en,ben}$ is the GHG emission gains from the

Table 2
Annual energy flows and resulting GHG emissions in Ydalir.

	Energy GWh/year	GHG emission factors g CO_2-eq./kWh	GHG emissions ktonne CO_2-eq.
Energy need			
Non-residential			
Heat	0.3		
Electricity	0.6		
Residential			
Heat	4.5		
Electricity	3.3		
Mobility (electricity)	0.5[c]		
Infrastructure (electricity)	0.3		
Total heat	**4.8**		
Total electricity	**4.7**		
Energy produced			
PV (electricity)	2.5	67[a], 33.5 for replacement	7561
CHP			
Heat	6.3	14[b]	2100
Electricity	2.5	19[b]	7182
District heat	5.5	24	7920
Total heat	**11.8**		
Total electricity	**5.0**		
Surplus energy sent to the grid			
Surplus heat	**7.0**	−24[b]	−168
Surplus electricity	**0.3**	S1–NO or S2-EUR28+NO[d] (see Fig. 2)	**S1–NO** From −8.4 in 2020 to −4.1 in 2080 **S2-EUR28 + NO** From-99 in 2020 to −14 in 2080

[a] From Ecoinvent 3.2.
[b] See Tables S2 and S3 in the supplementary material.
[c] The electric load varies over the neighbourhood lifetime, and we use the yearly average over the first 30 years.
[d] From Standard Norge [55].

share of on-site energy production that is exported to the external grid.

2.1.1. Buildings

Equation (2) is used to calculate the emissions from the building materials.

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

$E_{mat,\ const}$ is the embodied emissions from the buildings construction, and $E_{mat,\ repl}$ is the embodied emissions from the replacement. A represents the floor area (m^2), bt represents the building type, and i represents the year.

Equation (3) is used to calculate emissions from the energy use in operation of the buildings.

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

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

2.1.2. Mobility

Equation (4) is used to calculate the GHG emissions from the materials consumed by mobility vehicles over the 60 year period.

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

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

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

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

L_{tot} is the annual travel length for the neighbourhood, and tm and i denote the transportation mode and year, respectively. WtW represents the well-to-wheel emissions per kilometer driven and is calculated with Equation (6).

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

$Energy_{TtW,i}$ represents the propulsion energy needed per distance (MJ/vkm). I_{TtW} denotes the tank-to-wheel or direct emission intensity, and I_{WtT} is the well-to-tank or indirect emission intensity from the fuel production.

2.1.3. Infrastructure

Equation (7) describes the emission calculations for the infrastructure materials.

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

$E_{mat,\ init}$ is the embodied emissions from the initial materials in infrastructure inside the neighbourhood, and $E_{mat,\ repl}$ is the embodied emissions from the replacement materials. A represents the road area (in m^2), rt represents the road type, and i is the year. No infrastructure outside the neighbourhood is accounted for, also not such that is used for outside mobility by users in the neighbourhood. The emissions from operation of the public lighting inside the neighbourhood, such as for roads and walkways, are calculated by using Equation (8).

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

N denotes the number of lighting units, P is the power per unit in kW, and h is the hours of lighting each year. I_{el} states the emission intensity of the electricity, and i is the year. I_{el} is defined in Table S1 of the supplementary material.

2.1.4. On-site energy production

The on-site energy-production emissions include emissions due to the energy production $E_{en,prod}$ and the emission credits $E_{en,ben}$ gained by the surplus energy exported to the grid. $E_{en,prod}$ is calculated with Equation (9), and $E_{en,ben}$ is calculated with Equation (10).

$$E_{en,prod} = \sum_{i=1}^{60} \sum_{pt} Energy_{prod,pt,i} * \left(I_{en,prod}\right)_{pt,i} \tag{9}$$

$$E_{en,ben} = \sum_{i=1}^{60} \sum_{pt} \left(Energy_{prod,pt,i} - Energy_{use,i} \right) * \left(I_{en,ben}\right)_{i} \tag{10}$$

$Energy_{prod}$ denotes the energy produced by the production technology pt in year i, $Energy_{use}$ is the energy use in year i, $I_{en,prod}$ is the emission intensity of the energy production technology pt in year i, $I_{en,ben}$ is the emission intensity of the surplus energy exported to the grid, and $I_{en,ben}$ is the emission intensity of the energy mix in the external grid(s).

The new standard NS 3720 [24] recognizes the high importance of electricity-emission choices and states that at least two different energy-intensity scenarios should be used for electricity exchanges with the external power grid, namely, scenario 1 (S1–NO) and scenario 2 (S2-EU28 + NO). Scenario 1 suggests using the Norwegian consumption el-mix accounting also for domestic import or export, and scenario 2 suggests free flows of electricity between the European countries including Norway, hence using the EU28 + NO consumption el-mix. Fig. 1 illustrates the evolution from 2020 to 2080 for the two scenarios.

2.2. Ydalir

The LCA model is applied on Ydalir, a pilot project of the ZEN Research Centre, located in Elverum, Norway. Ydalir consists of one school, one kindergarten, and 1000 residential buildings. The school and the kindergarten were taken into use in autumn 2019, and the residential buildings will be built over the next 15–20 years. Yet, to simplify the assessment, we assumed all the construction to occur at the beginning of the assessment period. A map of Ydalir as it will look like when fully developed is given in Fig. 2.

The analysis period of the study is equal to the building lifetime of 60 years [38]. The functional unit is "to fulfil the housing, school, kindergarten, and mobility needs of the 2500 inhabitants of Ydalir over a 60 year time period". Ydalir has high climate-change-mitigation ambitions clearly stated in its master plan [39]. Ydalir will produce its energy locally through renewable sources, have passive-house standards or higher for all its buildings, choose wood or other materials with low GHG intensity as main building materials, and reduce and find climate-friendly solutions for the mobility of its inhabitants.

2.2.1. Buildings

The building stock in Ydalir consists of 1000 residential buildings (in total 100 000 m^2 floor area) and two non-residential buildings, a school (6474 m^2) and a kindergarten (2140 m^2), resulting in a total floor area of 108 614 m^2 [40]. An average occupancy of 2.5 inhabitants per residential building is assumed. The residential buildings will be a combination of townhouses and apartments but have not yet been designed; hence, the building ZEB 1 from a concept analysis conducted by Kristjansdottir, Houlihan-Wiberg, Andresen, Georges, Heeren, Good and Brattebø [41] has been chosen because of its resemblance with the

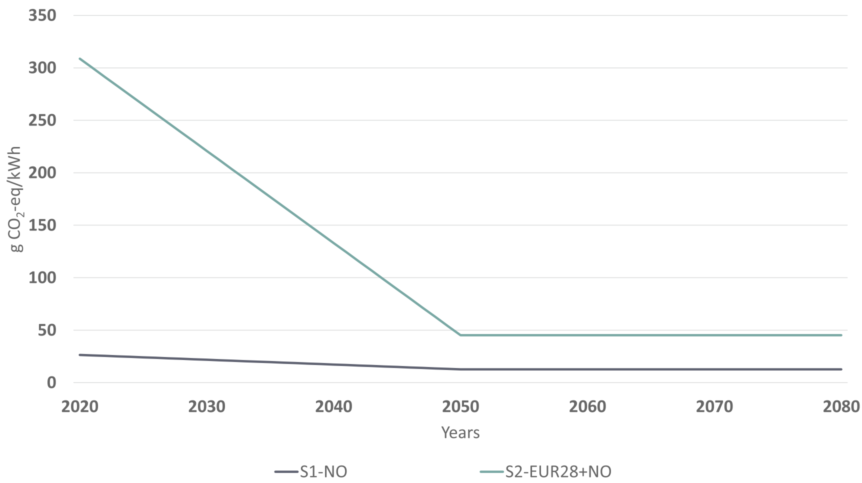

Fig. 1. Emission-intensity evolution for scenario 1 (S1) and scenario 2 (S2) based on NS 3720.

Fig. 2. Map of Ydalir. Credits to Asplan Viak and Elverum vekst.

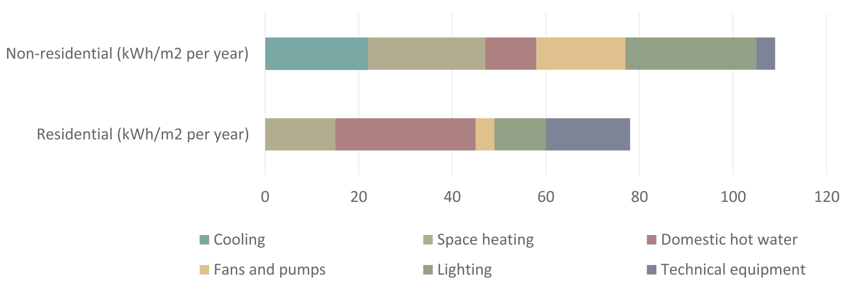

Fig. 3. Annual energy load for residential and non-residential buildings in Ydalir (kWh/m^2).

concept design of the buildings in Ydalir.

The material lists for the school and kindergarten are known and presented in Table S4 and S5 in the supplementary material. The residential buildings are assumed to have the same amount of materials per floor area as the ZEB 1 and are scaled down linearly. The embodied emissions from the non-residential buildings have been collected from Environmental Product Declarations (EPDs) and further calculated with the LCA tool One Click LCA [42].

The energy use in operation is based on Norwegian passive-house standards NS 3700 [43] and NS 3701 [44] for residential and non-residential buildings, respectively, and is 78 kWh/(m^2·year) for the residential buildings and 109 kWh/(m^2·year) for the non-residential buildings, see Fig. 3. The energy needs for space heating and domestic water are covered by heat supply, whereas the energy needs for fans and pumps, lighting, cooling, and technical equipment are covered by electricity. The average share of energy use from "technical equipment" to the total energy use in non-residential buildings is less than 10%. It is a fair value taking into consideration the relatively low operation time and low amount of technical equipment in school and kindergarten building types. A higher value for "technical equipment" would be expected if we had e.g. office buildings. The share of "technical equipment" to the total energy use in residential buildings is higher due to the domestic appliances. Lifts, alarms and control systems are not included under "technical equipment". The thermal load for the buildings in Ydalir is 4.8 GWh/year, and the electrical load is 3.9 GWh/year. Both the electrical and thermal loads are assumed to remain constant over the 60 year period.

2.2.2. Mobility

Three means of transportation are assessed: personal vehicle, bus and light rail, and walking and cycling. The travel habits of the residents in Ydalir have been based on the National travel survey [45] and further adapted to the specific measures taken in Ydalir. In order to reduce mobility needs, two measures are implemented in the design of the neighbourhood: no parking opportunities at the school and the kindergarten and limited space for cars in the shared garage that is located at the periphery of the neighbourhood. A report by the Institute of Transport Economics has been used to estimate the effects of these measures on mobility needs in Ydalir [46].

Travels by users of the school and kindergarten, which are not residents of Ydalir, are included and estimated by use of two reports by Context [47,48]. To avoid double counting of emissions, it is assumed that 40% of these emissions comes from users not living in Ydalir.

NS 3720 [24] suggests including transportation of users but does not include the methodology on how to calculate its related emissions. However, as a source for data on emissions from different means of transportation, it suggests using a project performed by the Norwegian research institute Vestlandsforskning [49]. These numbers are used as initial GHG-emission values for production of the transportation mode and the fuel/energy carriers from well-to-wheel.

The evolution of the vehicle stocks in this study is adapted to two different scenarios: a trend path and an ultra-low-emission path [50]. The trend path defines the base case in the study and is based on the development in previous years, whereas the ultra-low-emission path is an optimistic prediction of the future evolution, as illustrated in Figs. S1 and S2 in the supplementary material. Both scenarios assess the evolution of the personal-vehicle and bus stock, looking at several fuel/energy carriers. Light rail is assumed to be all-electric over the whole analysis period (see Fig. S3 in the supplementary material).

The initial emissions are collected from Vestlandsforskning [49], and future evolution of the emission intensities associated with production, replacement and operational energy use, and propulsion energy is collected from the scenario analysis by Lausselet, Ellingsen, Strømman and Brattebø [51] (see Tables S7 and S8 in the supplementary material).

2.2.3. Infrastructure

In the element infrastructure, emissions from roads, sidewalks, and lighting are included. In addition, the diesel used in the construction of the infrastructure and the associated GHG emissions have been calculated.

The area of wide roads, narrow roads, and sidewalks are defined by the plan description for the residential area B7 (16 850 m^2) [52] and then scaled up to match the size of Ydalir (350 000 m^2). This gives 20 356 m^2 of wide roads, 29 911 m^2 of narrow roads, and 26 588 m^2 of sidewalks. These numbers are associated with high uncertainties but are included to illustrate a rough estimation of the environmental impact of the on-site infrastructure. Both roads and sidewalks have crushed gravel foundations, but the roads have an asphalt pavement, and the sidewalks have a concrete pavement. The lifetime of gravel and concrete is assumed to be 60 years, and it is 20 years for asphalt. See Table S9 in the supplementary material for the life-cycle inventory.

Only the operation of the public lighting has been included. Other operation activities such as snow shovelling, road clearing, and other maintenance activities have been neglected. The operation of the public lighting has been calculated from an average of dark hours per day. See Tables S10 and S11 in the supplementary material for the life-cycle inventories.

The diesel consumption from constructing the infrastructure has been included. The total diesel consumption is the diesel consumed in the period from September 2016 to October 2018, which has been used for preparing the ground and moving masses on the construction site. The emission intensity for the diesel is 0.376 kg CO_2/l. See Table S12 in the supplementary material for an exhaustive list.

2.2.4. On-site energy production

The on-site electricity production in Ydalir consists of a district heating plant, PV panels, and 9 CHP machines fuelled by wood chips.

The length and size of the pipes are given by Eidsiva Energi and results in 7220 m of pipes. The average diameter of 100 mm and the amount of materials included have been adopted from the study done by Oliver-Solà, Gabarrell and Rieradevall [53] (see Tables S13 and S14 in the supplementary material). The emission intensity factor for the district heat is assumed to stay constant over the whole analysis period and is calculated to be 24 g CO_2/kWh (see Tables S2 and S3 in the supplementary material).

According to the Masterplan, a PV panels area of 18 m^2 per residential building results in 18 000 m^2. With an annual production of 120–160 kWh/m^2 [40], this gives 2.5 GWh electricity per year. The lifetime of the panels is assumed to be 30 years, resulting in one replacement. As suggested by Kristjansdottir, Heeren, Andresen and Brattebø [54], the emissions from the replacements will be reduced by 50% from the initial materials because of future technology improvements.

The combined-heat-and-power (CHP) machines are 9 Finnish Volter fuelled by wood chips with an electric power of 40 kW, a heating power of 100 kW, and 7000 annual operating hours. Each Volter unit will supply 280 000 kWh/year electricity and 700 000 kWh/year heat, which sums up to a total of 2.5 GWh/year electricity and a 6.3 kWh/year heat. In addition, Ydalir has signed an agreement with the local district company, who will deliver 5.5 GWh/year heat to Ydalir. The district heating company is considered inside the system boundaries, and the heat is thus locally produced. A total of 5.0 GWh/year electricity and 11.8 GWh/year heat are thus locally produced, and 0.3 GWh/year electricity and 7.0 GWh/year heat are exported, as summarized in Table 2 below.

2.3. Scenarios

In order to explore the possibility of reaching the net-zero GHG emission ambitions, several scenarios were created. Several scenarios were created to explore several mobility patterns, and other scenarios analyse the impact from energy-emission intensities, building materials, and upscaling the energy production from PV panels.

The mode of transportation distribution is based on the Norwegian National Travel Survey 2013/14 [45]. Two scenarios for the travel habits of Ydalir's residents have been created, by assuming that the average travel habits of inhabitants in Elverum, the town were Ydalir is located, is similar to the travel habits of inhabitants in the category "small towns" in the national survey. In order to best understand where the climate mitigation potentials lie, all the travels undertaken by the inhabitants are allocated 100% to the inhabitants independently of their purpose. The car-sharing scenarios reduce the daily travel distance by 50%, from 36.7 km to 18.35 km. Further, it has been calculated from the Masterplan [40] that 8% of the public transportation is done by light rail. The travel habits in Ydalir and Elverum are presented in Table 3, and the scenarios are presented in Table 4.

2.4. Sensitivity analysis

A sensitivity analysis was carried out to reveal critical parameters in the LCA model. The factors having a significant impact on the results or associated with large uncertainties were chosen and increased with 25%. The parameters analysed were mobility energy use in operation, area of PV panels, emissions embodied in building materials, emissions associated with vehicle production, travel distance per inhabitant and year, and the emission intensity of electricity. The sensitivity ratio was calculated by using Equation (10).

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

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

3. Results

Results from using the described LCA model for ZEN Ydalir with the GHG emissions associated to the included physical elements (buildings, mobility, infrastructure, networks, and on-site energy) and the selected life-cycle stages (A1–A3, B4, B6, B8, and D) are presented in this section. For the baseline scenario, the total GHG emissions from the neighbourhood over its lifetime of 60 years are 142 ktonnes CO_2-eq. and 141 ktonnes CO_2-eq. for S1–NO and S2-EUR+28, respectively. This corresponds to 0.95 tonne CO_2-eq/(capita·year) and 0.94 CO_2-eq/(capita·year), respectively. The reason for the very small difference in results, for two very different grid-electricity mix assumptions, is that Ydalir uses 94% of its electricity produced locally directly, and the surplus electricity sent to the grid is thus marginal.

Table 4
Scenario's description.

	Scenarios	Description
Mobility	Baseline	The baseline scenario analyses the effects of the personal-vehicle restriction measures taken in Ydalir. The mobility-technology development path for mobility follows the trend path. S1–NO is used for grid electricity.
	Ydalir, ultra low	Travel distance for Ydalir, but the mobility technology development follows the ultra-low-emission path.
	Ydalir + car-sharing, trend	Car-sharing (cuts the total travel distance by half) + trend-technology-development path for mobility
	Ydalir + car-sharing, ultra low	Car-sharing (cuts the total travel distance by half) + ultra-low-technology-development path for mobility
	Elverum	Distances are the same as those for the baseline, but transport-mode shares are for Elverum, the town where Ydalir is located.
Building	Wood	Exchanging traditional building materials (such as concrete and steel) for wood will reduce the total emissions from the materials significantly [56–58]. However, because the buildings materials in Ydalir have been chosen carefully, we assume a further reduction of 10% only from the building materials.
Energy production	PV-panels doubling - S1–NO	The PV-panel area and related electricity production are doubled. S1–NO is used for grid electricity.
	PV-panels doubling - S2-EU28 + NO	The PV-panel area and related electricity production are doubled. S2-EU+28 is used for grid electricity.
All	Final	The final scenario combines "Ydalir + car-sharing, ultra low" with "Wood" and "PV-panels doubling - S2-EU28 + NO".

3.1. Overall results

The results for the baseline scenario with the two electricity emission intensity scenarios are shown in Fig. 4 and given in Tables S15 and S16 of the supplementary material. Mobility contributes to the majority of the total GHG emissions with 61%, mobility operation contributes with 44%, and the embodied emissions in the mobility stock contribute with 17%. The embodied emission in the building materials contributes with 17%, and we find a similar share of 6% for the infrastructure and 4% for the PV panels. The surplus energy sent outside the Ydalir system boundary reduces the total GHG emissions by 4% for S1–NO and 9% for S2-EU28 + NO.

On the basis of the energy flows presented in Table 2, 89% of the

Table 3
Travel habits in Ydalir.

Elverum	Total		By foot		Bike		Personal vehicle		Public transportation	
	%	Km	%	km	%	km	%	km	%	km
	36.7 km/(day·capita)									
Work	19%	6.97	11%	0.77	7%	0.49	65%	4.53	17%	1.19
School	4%	1.47	29%	0.43	12%	0.18	33%	0.48	26%	0.38
Care	11%	4.04	7%	0.28	1%	0.04	89%	3.59	3%	0.12
Shopping	30%	11.01	19%	2.09	4%	0.44	74%	8.15	3%	0.33
Leisure and visiting services	31%	11.38	32%	3.64	5%	0.57	58%	6.60	5%	0.57
Other	5%	1.84	19%	0.35	4%	0.07	74%	1.36	3%	0.06
Sum	**100%**	**36.70**	**21%**	**7.56**	**5%**	**1.79**	**67%**	**24.71**	**7%**	**2.64**
Ydalir	36.7 km/(day·capita)									
	100%	36.7	32%	11.7	6%	2.0	50%	18.2	13%	4.8
Ydalir + Car sharing	18.4 km/(day·capita)									
	100%	18.4	32%	5.8	6%	1.0	50%	9.1	13%	2.4

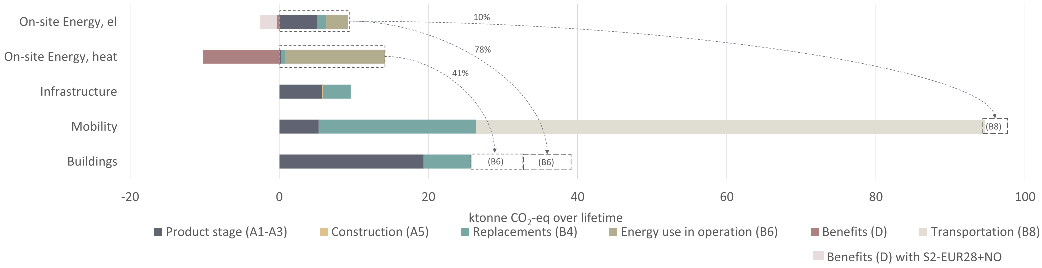

Fig. 4. Total GHG emissions over the neighbourhood lifetime for the baseline scenario and the two electricity scenarios for "Benefits (D)".

electricity produced on site is used to cover the electrical load of the buildings, and 11% is used to cover the electrical load of mobility. Only the buildings are using the heat produced on site.

3.2. *Scenario results*

The results from the scenario analysis show which measures have the most considerable impact on the results, compared with the baseline.

Fig. 5 shows the results from the scenario analysis and reveals that the mobility scenarios have the most pronounced impact on the results, as expected given the results from the sensitivity analysis. In fact, the faster penetration of electric vehicles in "Ydalir, ultra low" decreases the results from the baseline by 21%, "Ydalir + car sharing, trend path" decreases the results by an additional 12%, and "Ydalir + car sharing, ultra low" reduces the results by an additional 10% for a total decrease of 43%. The measures taken in Ydalir to reduce the use of passenger cars to go to work and use public transportation instead reduce the overall emissions by 17%.

When doubling the area of PV panels, the total emissions increase by 3% when assuming S1–NO for the emission credits and decrease by 8% when assuming S2-EU28 + NO for emission credits. A further use of material with low GHG intensities will reduce the overall emission by 2% only because the building materials have already been chosen carefully and are mainly wood-based. The combination of different measures in the final scenario reduces the overall emission by 54%.

3.3. *Sensitivity-analysis results*

The results from the sensitivity analysis are shown in Fig. 6. The two most critical parameters are related to mobility: first, the travel distance per habitant and second, the mobility energy use in operation. Next, the most important parameters are related to embodied emissions associated with vehicle production and then to the production of building materials. An increase of the emission intensity of the grid electricity influences the results significantly only in the case of S2-EUR28 + NO, because the Norwegian grid electricity is already very low in carbon emissions. An increase of the area of PV panels does increase the overall results when the emission intensity of the grid electricity is low and smaller than the emission intensity of the electricity produced by the PV panels, such as in S1–NO. On the other hand, the overall results decrease

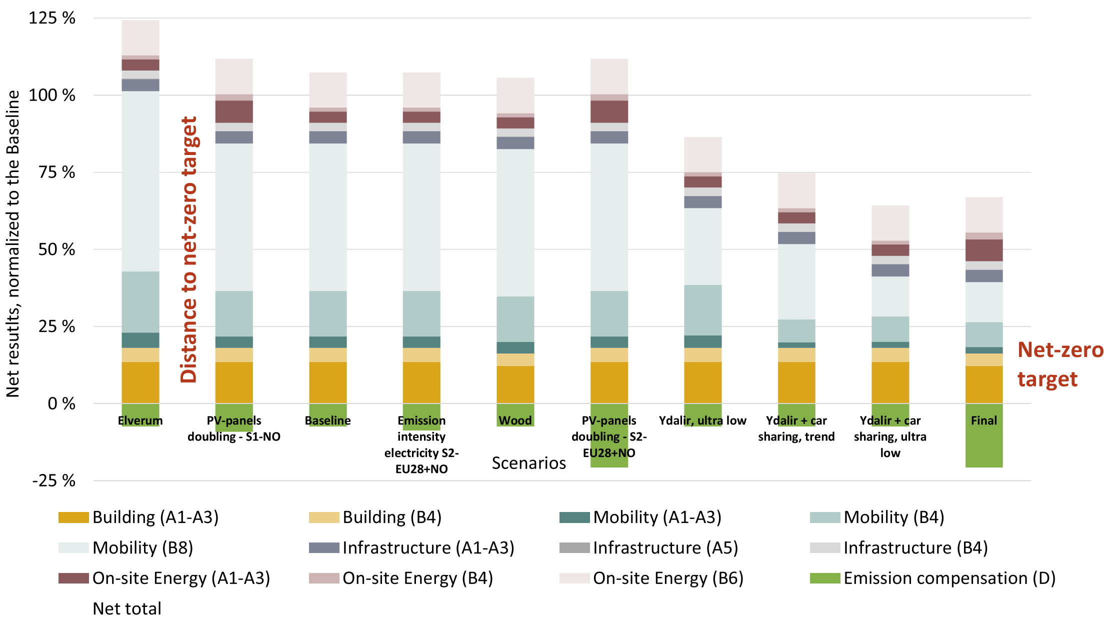

Fig. 5. Total GHG-emission results of scenario analysis relatively to the Baseline scenario.

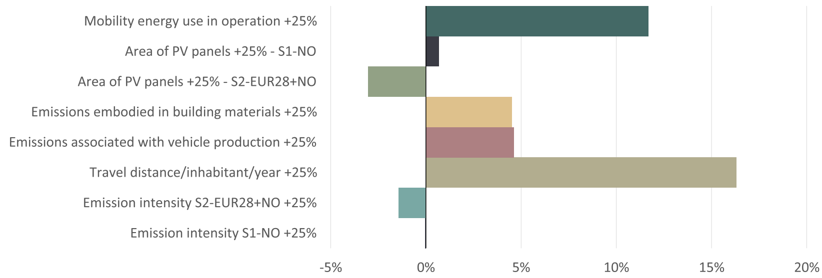

Fig. 6. Total GHG-emission results of sensitivity analysis and critical parameter relative to the Baseline scenario.

when the emission intensity of the grid electricity is high, as in S2-EU28 + NO.

4. Discussion

This section discusses the modular structure presented in this paper and its use on the ZEN Ydalir. Then, the results are discussed against the research questions, their uncertainties, and limitations. Finally, further work on the field of LCA modelling for ZENs and policy implications are suggested.

4.1. Benchmarking of the results

When expanding the LCA model from individual buildings to complex systems such as neighbourhoods, the chosen system boundary and preconditions made are crucial. The modular approach opens for the opportunity of applying different functional units and mapping the emission sources regarding both contributing elements and life-cycle stages. The modular structure also makes it simple to adjust the LCA model to different neighbourhoods.

The placement of the system boundary to decide which life-cycle stages and physical elements to include in an LCA appears to significantly influence the results. These reveal that, when all elements are included, buildings account for 27–46% of the total emissions, mobility accounts for 38–62%, and infrastructure accounts for 6–10%. Embodied emissions in materials of buildings and mobility represent 45–72%. These results are comparable with those from Wiik, Fufa, Kristjansdottir and Andresen [12], who reported the share of embodied emissions in building materials to be 55–87%. Lausselet, Borgnes and Brattebø [23] found the buildings to represent the majority of the GHG emissions with 52%. This somewhat higher share of buildings is due to the energy mix used for their study being based on district heat based on municipal solid waste. Lausselet, Ellingsen, Strømman and Brattebø [34] found buildings to account for 28–52% and mobility to account for 34–72%. The share of buildings increases with a higher emission intensity of the energy mix and construction materials. On the other hand, of course, the share of mobility decreases when active measures are taken to decrease the mobility need or when alternative transport solutions are in place.

The model considers two different scenarios regarding the emission intensity of the grid energy, as suggested by the new standard NS 3720 [24]. The total emissions from the neighbourhood decrease by only 1% when applying S2-EU28 + NO compared to S1–NO. This marginal decrease, although S2-EU28 + NO has a much higher emission intensity than S1–NO, is induced by the surplus PV-generated electricity sent to the grid being very small. Yet, when doubling the electricity-production capacity by doubling the PV area, the potential gains are a decrease of 9% with S2-EU28 + NO. The choice of emission intensity for both electricity and several other elements, such as the emission intensity of district heat, is debated a lot in LCA studies [9,59,60] and calls for a detailed description and transparency in the assumptions made.

The mobility shares of 38–62% are comparable to the results of Nichols and Kockelman [14] and Bastos, Batterman and Freire [21] who found mobility to represent 44–47% and 51–57%, respectively. The variations result from optimistic or conservative assumptions regarding the future evolutions of mobility. This is a consequence of the significant improvement in fuel/energy-carrier technologies and a shift in the share of the powertrains used. The inhabitants' travel habits in this study are based on national average numbers for travelling and are a source of uncertainty because lower values are expected for the inhabitants at Ydalir. Further studies on travel habits are recommended in order to get a deeper understanding of the importance of mobility at the neighbourhood level.

The infrastructure element includes roads, sidewalks, public lighting, and construction of the infrastructure, in addition to pipes and other network components in the district heating system. This element constitutes 6–10% of the total emissions. The estimation of embodied emissions from the materials have been highly simplified, and somewhat higher emissions from this element are therefore expected. When looking at the operation of the infrastructure, only public lighting has been considered, whereas other operational elements such as road maintenance and snow clearance have been excluded.

4.2. Limitations and future work

There are several advantages with the model approach in this study. It maps dominant drivers related to both different physical elements and life-cycle stages of a neighbourhood, and it facilitates comparability between different projects because this can be done according to a transparent and modular structure of a complex system. However, the approach has some weakening limitations and parameters that need further attention.

The ZEN Ydalir will be built over a period of 15–20 years, and improvements in production technologies in the building materials and energy-supply system, as well as changes in the Norwegian building regulations (TEK), must be expected over the neighbourhood's construction period and service life. However, this study assumes no improvement in these areas, for neither the initial construction nor the replacement of materials for buildings or infrastructure. Other temporal aspects such as technology development and increased energy efficiency of materials and fuel/energy carriers in mobility, as well as the behaviour of the inhabitants, are associated with high uncertainties. These aspects are all subject for future work.

An LCA often includes several impact categories to show a comprehensive picture of the product or process at hand. In this model, only GHG emissions have been analysed and discussed, and more environmental-impact categories should be included in order to avoid problem shifting. Data from different LCA databases has been combined, which leads to an inherent uncertainty that arises whenever combining data stemming from different sources. The number of elementary flows (i.e. materials, energy, or space that are taken directly from the environment or released directly back into the environment [61]) included in the life-cycle inventories (LCI) differs among LCA databases (from 10s to 10,000s [62]). To compute the environmental impact of a given functional unit, elementary flows are multiplied with their respective characterization factors (units of impact per unit of elementary flow). The characterization factors are given by the life-cycle impact assessment (LCIA) method. This multiplication step requires that the characterization factors from the chosen LCIA method(s) match the elementary flows of the LCI. This step is critical and can induce discrepancy in the LCIA results when several LCA databases are used because of the varying number of elementary flows included. But this effect and inherent uncertainty is minimized in this study because we focus on GHG only and GHG are usually the main elementary flows included in the LCIs. The inventory for infrastructure should be completed; this study included embodied emissions from district heating pipes, but not water pipes. Lifetime is a crucial parameter in LCA studies. A longer material lifetime postpones renovation activities and a longer building lifetime diminish the need for new buildings but might involve more renovation activities. Longer building lifetimes can induce climate mitigation potentials of 7–18% [63]. Our model does not consider the possible effect of climate change on local climate. For all seasons, the projections indicate a warming in Norway with a greater projected warming for the winter than for the summer. The temperature is expected to increase with 1.6–6.7 °C and the number of "warm days" (<20 °C) is expected to triple by the end of the century [64]. These changes will lead to a lesser need of heating in the winter, and possible use of air-conditioning in the summer. Air-conditioning need will have to be calculated according to the thermal mass of the building - wood in that case - that is lower than its concrete counterpart. Despite the limitations discussed above, the focus of this study is mainly targeting the importance of mobility and surplus energy from PV generation, and hence, the limitations are less critical to the main findings and conclusions of this study.

The results state that the daily travel distance of the inhabitants is the main challenge, and an allocation of the work travels to the workplace will significantly decrease the total travel distance and thereby the total emissions from the neighbourhood. It is, however, arguable whether such an allocation can be defended, for instance when deciding the location of a new neighbourhood. Also, road infrastructure is not included. Its inclusion will allow us to address issues such as measures to reduce traffic congestion. Moreover, the benefits of car-sharing decrease the need for additional road infrastructure.

Our mobility and PV production scenarios and our sensitivity analysis reveal how Ydalir's performance is influenced by parameters describing alternative pathways. Predicting how these parameters will evolve has substantial uncertainty, which was partially explored in the scenarios and the sensitivity analysis. In reality, a combination of different parameters may lead to an even larger variation in results. A global sensitivity analysis such as a variance-based sensitivity analysis [65] can be performed to capture such effects.

The inventory and the results in this study are derived from detailed input data, which are not likely to be available at the early planning stage of a neighbourhood. Hence, this model approach has limitations for use in such situations. In comparison, two other early-planning-stage LCA models, NEST [66] and OmrådeLCA [67], use statistically and empirically derived key numbers in their calculations and can therefore be used for early-phase decision support in neighbourhood planning. However, all three models acknowledge the significant effect preconditions and design choices have on the environmental impacts. When performing LCA at an early planning stage, the goal should be to identify the best combination of solutions that gives the lowest emissions, with a focus on the most important contributing elements and uncertainties and factors that influence these elements.

The data for energy use and local energy generation in the model is based on yearly averages rather than hourly estimates. Basically, this is the same as assuming that the external grid is part of an infinite battery, not considering when the electricity is used locally or exported to the grid. The annual resolution used is the minimal requirement imposed by the standard NS3720 and is a simplification of the reality. The standard leaves it to the user to choose a monthly, weekly, or daily resolution. But, the high share of 94% of energy locally produced and assumed to be used at Ydalir would most probably in reality be smaller if an hourly resolution energy profile had been used. An hourly energy profile consider that higher quantity of PV electricity is produced during daytime and a large part of the consumption occurs at night when there is no production. In addition, it would account for seasonal variation. But, whilst the local energy production and use profiles can be predicted with acceptable accuracy into the future, their emission intensity counterpart is embedded with high uncertainty, also in Norway that has a growing import and export exchange with the foreign power supply grid. The daily or weekly differences in the emission intensity of the production mix from the grid decades ahead is therefore highly questionable, and this is the main reason for why the current NS3720 standard requests two electricity mix scenarios to be used (one the Norwegian mix and one the EU28 + NO mix profile towards 2050). In order to avoid speculative assumptions on this matter, we decided to use annual resolution only, combined with analyzing different scenarios and overall electricity-mix alternatives. Another interesting factor that should be added to future studies is the economical perspective. The relation between imported and exported energy is commonly asymmetrical, where the price for the exported energy usually is lower than that for the imported energy. Implementing other factors such as energy storage and vehicle-to-grid concepts then also becomes relevant.

4.3. Policy implications

Regardless of the choice of emission intensity, the results in this study show that Ydalir does not achieve the goal of net-zero GHG emissions, given the solutions that are chosen for this project. Nevertheless, this study highlights the neighbourhood's promising areas of improvement. The mobility represents the highest share of emissions, and for this to decrease, more restrictions regarding the use of personal vehicles are needed. The emissions from the buildings can be reduced by increasing the use of wooden materials. Finally, an upscaling of the energy production from PV panels would allow for significantly reduced system-wide emissions if more electricity is exported and can substitute power generated from fossil fuels or shifted to replace fossil fuels used in mobility. Local authorities will have to address the dichotomy between the installation of PV systems that require a large roof area and are thus more adapted to low rise buildings such as single-family houses and the high population density needed to provide satisfactory and economically viable public transport offer. However, when examining a given neighbourhood project like Ydalir, as designed and without studying alternative building design types, density is not a variable of interest in this study. This would, of course, be totally different in other studies, where the neighbourhood design and layout are not already decided upon.

Accounting and assessing the potential of construction material-recycling solutions in the future end-of-life stage of buildings and infrastructure elements would be interesting. The recycling potential is directly correlated to the possibility to disassemble a house in a manner that allows for material separation, re-use, and recycling, and an emphasis on the design for re-use in the legislation will help in this task. However, the emission benefits of recycling will have to be handled with care, e.g.in order to avoid double counting in future studies where such potentials should be examined. Also, as Ydalir is an urban development project with ambitious goals for net-zero emissions and lifestyle changes (i.e. mobility), efforts should be put as both on materials recycling and proactive household waste prevention and reuse, which also in literature is reported to be of interest [68].

Legislations should include as well guidelines and threshold values on the embodied GHG emission in materials in addition to more strict requirements on the operational energy use per unit of floor area. So far, the use of PV to locally produce renewable energy has been the favoured method of energy production for ZENs. Other alternative renewable energy production pathways are available, such as exploiting local wind, biomass and geothermal sources, and will have to be examined by local and national decision makers for their costs and acceptance. Wind energy has the advantage to be less season-dependent, but has several disadvantages induced by its location, ownership and public acceptance. PV can belong to one building owner whereas a wind turbine park would require the consent of all the inhabitants. The population is in general keen to have PV panels on the roof, but less so to have wind turbines in the proximity. There is at present a strongly growing public resistance to land-based wind-mills in Norway, parallel to a growing interest for PV solutions.

The Norwegian electricity production mix is already highly based on renewables with a share of 95% hydropower and 2.6% wind power [69]. By further producing renewable energy on a neighbourhood scale, ZENs may play a role in the decarbonization of the European energy mix by (1) sending their surplus energy to the grid, with potential for export outside Norway, and (2) liberating electricity from hydropower that will substitute more carbon-rich electricity or fuels generated elsewhere, such as in the strive for electrification of road transport. Such an approach for avoiding emissions elsewhere in a system-wide analysis means that a consequential LCA methodology is followed, because export of surplus energy leads to technology changes elsewhere (i.e. facing out fossil fuels).

5. Conclusion

In order to highlight the dominant emission sources from the ZEN Ydalir at the early planning stages, a model based on an LCA modular structure was chosen. The following elements were considered: buildings, mobility, infrastructure, networks, and on-site energy generation. The model was adjusted to fit the specifics of the ZEN Ydalir, located in Elverum, Norway. The objective was to analyse the main contributing life-cycle stages for these elements and how different factors, assumptions, and system-boundary choices critically influence overall emissions and to find opportunities for improvements towards achieving the "net-zero GHG emission ambition", particularly with respect to solutions and assumptions for mobility. This study considered the restriction of available parking spaces at Ydalir. The results show that Ydalir can at the most cut its total emission by 54%. The dominant source of emissions is mobility with 38–62%, mainly caused by the use of personal vehicles. Our results showed that the most critical parameters for reaching the ZEN goal is the daily travel distance of the inhabitants followed by the emission intensity of the energy mix when surplus electricity from local PV production substitutes more carbon-rich power or fuels generated elsewhere.

The model is weakened by simplifications and assumptions related to technology development and evolution over the neighbourhood's lifetime, which are associated with uncertainties. Further work on the forecast of energy-emission intensity, mobility technology, materials, and habits of the inhabitants is therefore required.

The model can contribute in decision making in the early planning phase of ZEN projects, in order to explore the dominant GHG-emission contributions related to both physical elements and life-cycle stages. The modular structure makes it convenient to adapt to different neighbourhood projects and produce results that allow for comparison across projects. By exploring the possibilities of the scenario analysis, it becomes obvious that ZEN projects have to focus strongly on their mobility habits and on local PV-production capacity in order to come close to their net-zero GHG emission ambition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge the support of the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN), and Anna-Thekla Tonjer from Elverum Vekst, Ola T. Dahl from Eidsiva, and Heidi Erikstad from Eleverum Kommune for help collecting input data from Ydalir.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.buildenv.2020.107528.

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Paper V

Lausselet, Carine; Brattebø, Helge. Environmental co-benefits and trade-offs of climate mitigation strategies applied to net-zero emissions neighbourhoods. (2021) International Journal of Life-cycle assessment.

The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-021-01973-3

POLICIES AND SUPPORT IN RELATION TO LCA

Environmental co-benefits and trade-offs of climate mitigation strategies applied to net-zero-emission neighbourhoods

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Received: 6 April 2021 / Accepted: 31 August 2021

Abstract

Main purpose To limit global warming at a safe level of 1.5 °C, deep emission reductions in all sectors combined with rapid, far-reaching, and unprecedented changes in all aspects of society are required. The ongoing climate urgency has led to greenhouse gas (GHG) emissions to be the most often inventoried life-cycle indicators. But, to draw comprehensive climate mitigation strategies (CMS), adverse potential environmental side-effects and trade-offs should be assessed as well.

Methods LCA is used to assess the potential environmental co-benefits and trade-offs of a net-zero-emission neighbourhood (nZEN) in the early planning stages. CMS are designed to test for the effect of (1) mobility patterns less based on the use of passenger cars, (2) a better material use by decreasing the size of the dwellings and increasing the passenger loads, (3) increased lifetimes of buildings and passenger cars, and (4) their combination.

Results Across the impact categories, environmental benefits of 5–20% are shown for single CMS and of 22–42% when combined. Interestingly, the highest environmental co-benefits are found for Metal Depletion, highlighting the close interconnection of CMS and decreased pressure on resource use.

The use of several climate metrics has shed light on the use of fossil fuels in the production value chains of the materials used to provide the mobility services and shelters to the inhabitants of the nZEN under study. A combination of climate metrics with short- and long-time horizon should be used to give the importance that short-lived GHG such as methane deserve in the climate debate.

Conclusion To best mitigate climate change along with environmental co-benefits on a nZEN level, measures should be taken at different points in time. At the early planning stages, incentives should be in place that promote dwellings of reasonable sizes (measured per inhabitant) along with incentives to decarbonize the materials value chains, in- and out-land. Over time, a culture of car- and ride-sharing will have positive environmental benefits. When renovating, incentives that promote the reshaping of dwellings into dwellings of smaller sizes will help to shift the sole focus on nZEB standards to multi-layers strategies.

Keywords Net-zero-emission neighbourhood · Multi-layer climate mitigation strategy · Car- and ride-sharing · Smaller dwelling size

1 Introduction

Global warming induced by human activities is increasing at an unprecedent rate (IPCC 2018). In 2019, the total global final energy use of the building sector remained at the same level compared to previous years. But CO_2 emissions stemming from the final energy use (operational phase) of buildings were at the *highest level ever recorded* with a share of 28% of the total global energy-related CO_2 emissions. The continued use of coal, oil, and natural gas for heating and cooking in combination with high-activity levels in regions with carbon-intensive electricity were responsible for the increase. In addition, 10% of the total global energy-related CO_2 emissions can be reallocated from the overall industry sector to the industries devoted to manufacturing construction materials such as steel, cement, and glass (IEA 2020a).

To limit global warming at a safe level of 1.5 °C, deep emission reductions in all sectors combined with rapid, far-reaching, and unprecedented changes in all aspects of society

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Published online: 23 September 2021

are required (IPCC 2018). Time is running, and we need to move fast. Multi-layers climate mitigation strategies (CMS) will be most effective. For the building sector, the energy demand should be reduced while the energy sector should be decarbonized and strategies that reduce life-cycle material CO_2 emissions should be implemented (UNEP 2020).

Energy losses can be minimized by both renovating the existing building stock and constructing new buildings according to low-energy-use standards such as nearly-zero-energy building. According to the Energy Performance of Building Directive (European Commission 2010), a nearly zero-energy building is a "building that has very high energy performance and where the nearly zero- or very low-energy need is covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby." In Norway, the nearly-zero-energy building concept is translated in greenhouse gas (GHG) emission terms and becomes a net-zero-emission-building (nZEB) balance (Fufa et al. 2016). By undertaking a consequential approach, the GHG emissions occurring during the different life-cycle stages of a nZEB are compensated by sending the surplus renewable energy produced locally to the grid. Several nZEBs become a net-zero-emission neighbourhood (nZEN) (Wiik et al. 2018). By using the surplus energy locally produced in a nZEN to substitute power generated from fossil fuels or to replace fossil fuels used in mobility, nZEN projects will contribute to a low-carbon society.

The life-cycle material GHG emissions can be reduced by a better material efficiency that results in the same material services provided but with less material production and processing (Allwood et al. 2011). Material efficiency can be measured by quantifying material use by the total weight of materials or in service units to respond to human needs such as housing or recreation (Zhang et al. 2018). According to Hertwich et al. (2019), material efficiency such as (a) a more intensive use, (b) lifetime extension, (c) light-weighting, (d) reuse of components, (e) recycling, upcycling, and cascading, and (f) improving yield in production, fabrication, and waste processing will help to provide shelter and automotive transport with less materials and lower overall GHG emissions.

Demand-side material efficiency strategies are complementary to those obtained through the decarbonization of our energy system and may offer substantial GHG mitigation potentials (UNEP 2019). For the built environment, a combination of material efficiency strategies at different points in time will best mitigate climate change (Lausselet et al. 2020b). In the early planning stages, thresholds on floor area per inhabitant can be encouraged and materials with low environmental impact should be preferred. Over time, a good maintenance of the buildings will postpone the renovation needs and extend the buildings' lifetime. For passenger vehicles, material efficiency measures such as more intensive use by means of increased vehicle occupancy and vehicle downsizing by switching to smaller vehicles will allow for quick emission reductions (Wolfram et al. 2020). But the importance of material use and related embodied emissions is still overshadowed by policies focusing on energy efficiency and the deployment of low-carbon energy supply. Climate-change mitigation policy would benefit from a greater integration of material efficiency strategies that could significantly increase the emission coverage of existing product policies (Scott et al. 2018).

Life-cycle assessment (LCA) allows us to estimate how potential environmental impacts accumulate over the different life-cycle phases and elements of a system. LCA results provide a basis for identifying environmental bottlenecks and for comparing a set of alternative scenarios with respect to environmental impacts (Finnveden et al. 2009; Hellweg 2014). LCA is the preferred method for quantifying direct and embodied building-related GHG emissions (Zhao et al. 2019). LCA is increasingly used to evaluate the environmental performance of more complex systems such as neighborhoods that encompass several sub-systems such as the built-environment system, the mobility-fleet system, and the energy system (Lausselet et al. 2019, 2020a, 2021; Stephan and Crawford 2014; Stephan and Stephan 2016). Those studies all show (1) the shared environmental impact of the built environment and the mobility parc and (2) the importance of the embodied emissions in materials, especially when high energy-performance standards are in place. Buildings should not be analyzed as individual elements but should be contextualized to fully capture the broader impacts linked to their inhabitants and their location such as mobility patterns.

The ongoing climate urgency has led to CO_2 and other GHG emissions to be the most often inventoried life-cycle indicators. But, in order to draw comprehensive CMS, adverse potential environmental side-effects and trade-offs should be assessed as well. By including the time dimension, the aspiration is to identify strategic choices needed at different points in time to make the necessary provisions allowing for the nZENs to deploy their full potential.

Consequently, and in view of the stringent short- and long-term climate objectives and the need to implement them locally, the main value of this work is to conduct a comprehensive LCA on a nZEN in the early planning stages with a time dimension to (1) assess the environmental potential co-benefits and trade-offs of a nZEN in the early planning stages, (2) develop CMS highlighting key strategic considerations and limitations around the identified technical potential, (3) compare the identified environmental reduction potential and trade-offs with what has been realized in the current project, and (4) provide recommendations on when the different CMS must be in place.

This paper is organized as follows: Sect. 2 describes the methodology and the case study, Sect. 3 describes the main results of the analysis, Sect. 4 continues with a discussion on the results, including uncertainties, barriers, opportunities, and policy implications now and towards 2050, and Sect. 5 provides concluding remarks.

2 Methods

In this section, the different parts of the model (buildings, infrastructure, mobility, energy supply, and emission credits) and their evolution over time are described first. Then, the case study is presented, followed by a description of the Baseline scenario and the four CMS.

2.1 Model description

The model used in this study is based on the model developed by Lausselet et al. (2020a) and Lausselet et al. (2019). The model is further developed to (1) compute detailed annual energy balances, (2) include mobility-related infrastructure, and (3) include several impact categories.

If nothing else is specified, Ecoinvent (version 3.2, allocation cut-off, Wernet et al. (2016)) is used for background data. ReciPe v1.12 (with a hierarchist perspective) is chosen for the impact method (Goedkoop et al. 2013). Arda, a Matlab-routine-based program developed at NTNU (Majeau-Bettez and Strømman 2016), is used for the LCA calculations and further structural path analyses to analyze the results.

Inside each impact category i, the total environmental impacts of the neighbourhood $EI_{tot,i}$ over the period of assessment (POA) are described in Eq. (1) and are equal to the sum of the environmental impacts caused by the construction of the buildings $EI_{B(Mc),i}$, the replacement of building materials $EI_{B(Mr),i}$, the production of the transportation modes $EI_{Mob(Mc),i}$ used to fulfill the mobility needs of the inhabitants, the operational phase of those transportation modes $EI_{Mob(O),i}$, the related mobility infrastructure $EI_{Inf\text{-}Mob(Mc),i}$, the construction and replacement of the infrastructure in the neighbourhood $EI_{Inf\text{-}nZEN(Mc+Mr),i}$ as well as the production and operation of the on-site energy $EI_{En(Mc+Mr,O)i}$. Subtracted from this sum is the environmental credits $EI_{El(surplus),i}$ gained by sending the surplus electricity produced locally to the grid that replaces an average European electricity mix based on fossil fuels.

$$EI_{tot,i} = EI_{B(Mc),i} + EI_{B(Mr),i} + EI_{Mob(Mc),i} + EI_{Mob(O),i} + EI_{Inf-Mob(Mc),i} + EI_{Inf-ZEN(Mc+Mr),i} + EI_{En(Mc+Mr,O),i} - EI_{El(surplus),i} \quad (1)$$

Referring to the European Committee for Standardization (2012), *Mc* refers to the product stage or embodied emissions stemming from material production (modules A1–A3), *Mr* refers to the material replacement (B4) in the use stage, and *O* refers to the operational energy use in buildings (B6) and mobility (B8), according to the new Norwegian standard NS 3720 "Method for greenhouse-gas calculations for building" (NS 2018) that accounts for transportation in a separate module.

Each elements of Eq. (1) is further developed in the following sub-sections. Common to all the sections is the use of three datapoints in 2021, 2030, and 2050 to dynamically developed certain parameters over time to factor in a better efficiency of the production processes and an increase of the reuse and use of recycled materials. The parameters are developed linearly from 2021–2030 and 2030–2050 and kept constant from 2050 to the end of the POA.

2.1.1 Buildings

For each impact category i, the total environmental impact embodied in building materials $EI_{B(Mc),i}$ is calculated according to Eq. (2). For each building type t, B_t is the number of building types t, m_{mt} is the quantity of material m of type mt per building type t, and $Ii_{mt,2021,i}$ is the impact intensity of material mt for a given impact category i at the year of construction.

$$EI_{B(Mc),i} = \sum_t \sum_{mt} B_t \cdot m_{mt,t} \bullet Ii_{mt,2021,i} \quad (2)$$

The total environmental impact embodied in building materials because of the replacement of building materials $EI_{B(Mr),i}$ over the POA is calculated according to Eq. (3) with the help of the service life SL_{mt} of each material type mt. An overall decrease of 30% is due to an assumed better efficiency of the production processes of the main materials based on the figures provided by ESU and IFEU (2008) in addition to an increase of the reuse and use of recycled materials over time. Thus, for $y > 2021$, $Ii_{mt,y,i} = 0.7 \cdot Ii_{mt,2021,i}$. The future values of $Ii_{mt,y,i}$ are not decreased linearly from 2021 because the first renovation will not occur before 30 years.

$$EI_{B(Mr),i} = \sum_{y=2021}^{y=2080} \sum_t B_t \cdot m_{mt,t} \bullet Ii_{mt,y,i} \bullet \left(\frac{POA}{SL_{mt}} - 1 \right) \quad (3)$$

2.1.2 Mobility

For each impact category i, the total environmental impact embodied in the production of the transport modes $EI_{Mob(Mc),i}$ over the POA is determined by Eq. (4). $\alpha_{tm,y}$

stands for the share of the different transport modes *tm* (foot, bike, passenger car, bus, and train) at year *y*. $\beta_{tm,vt,y}$ stands for the distribution of each technology *vt* of transport mode *tm* at year *y*. The passenger-car parc comprises electric cars and conventional cars powered by gasoline and diesel. The buses and trains include both electric and diesel-powered engines. $Ii_{tm,vt,y,i}$ is the impact intensity for the transport mode *tm* with a technology *vt* at year *y* for the impact category *i*. L_{tot} stands for the total distance travelled yearly by the inhabitants of the neighbourhood.

$$EI_{Mob(Mc),i} = \sum_{y=2021}^{y=2080} \sum_{tm} \sum_{vt} \alpha_{tm,y} \cdot \beta_{tm,vt,y} \bullet Ii_{tm,vt,y,i} \bullet L_{tot} \quad (4)$$

$\alpha_{tm,y}$ is case-specific and is described further in this section. The technology distribution is embedded in the model and is for $tm =$ passenger cars of $\beta_{tm,electric,2021} = 13\%$, $\beta_{tm,diesel,2021} = 51\%$, and $\beta_{tm,gasoline,2021} = 36\%$ in 2021 followed by $\beta_{tm,electric,2030} = 53\%$, $\beta_{tm,diesel,2030} = 30\%$, and $\beta_{tm,gasoline,2030} = 17\%$ in 2030, and $\beta_{tm,electric,2050} = 95\%$, $\beta_{tm,diesel,2050} = 4\%$, and $\beta_{tm,gasoline,2050} = 1\%$ in 2050. Those figures are based on figures computed by the Norwegian Institute of Transport Economics (Fridstrøm and Østli 2016). The technology shares for trains represent the current situation in Norway and are, for $tm =$ train, $\beta_{tm,electric,2021} = 80\%$, $\beta_{tm,diesel,2021} = 20\%$ followed by $\beta_{tm,electric,2030} = \beta_{tm,electric,2050} = 100\%$ and $\beta_{tm,diesel,2030} = \beta_{tm,diesel,2050} = 0\%$.

$Ii_{tm,vt,2030,i}$ and $Ii_{tm,vt,2050,i}$ are assumed to be 20% and 50% lower than their respective $Ii_{tm,vt,2021,i}$ counterparts, respectively, because of a better efficiency in the production processes of the main materials based on ESU and IFEU (2008) in addition to an increased reuse and use of recycled materials over time.

$EI_{Mob(O),i}$ is calculated according to Eq. (5).

$$EI_{Mob(O),i} = \sum_{y=2021}^{y=2080} \sum_{tm} \sum_{vt} \alpha_{tm,y} \cdot \beta_{tm,vt,y} \bullet Ii_{tm,vt,y,i} \bullet L_{tot} \quad (5)$$

For electric vehicles (passenger car, bus, and train), $Ii_{tm,vt,y,i}$ is computed by multiplying the electricity use by its impact intensity inside each impact category *i*. The electricity use is of 17.1 kWh/100 km for electric cars (Ellingsen et al. 2016), of 16.4 kWh/(person·100 km) for electric trains (Ecoinvent Centre 2015), and of 18.3 kWh/(person·100 km) for electric buses (based on numbers for Norway). Electric cars are supplied by the electricity produced on-site, whereas electric trains and buses are fed by the national electricity mix. The operational energy of all the transport modes is assumed to decrease over time. $Ii_{tm,vt,2030,i}$ and $Ii_{tm,vt,2050,i}$ are decreased by respectively 10% and 20% compared to $Ii_{tm,vt,2021,i}$ on the basis of numbers from Ajanovic (2015) and Cox et al. (2018).

2.1.3 Mobility-related infrastructure

For each impact category *i*, the total environmental impact embodied in the production of the mobility-related infrastructure $EI_{Inf\text{-}Mob(Mc),i}$ is computed with Eq. (6).

$$EI_{Inf-Mob(Mc),i} = \sum_{y=2021}^{y=2080} \sum_{tm} \alpha_{tm,y} \bullet Ii_{tm,i} \bullet L_{tot} \quad (6)$$

$Ii_{tm,i}$ is the impact intensities of the infrastructure related to each transport mode *tm*. No future decreases are assumed for $Ii_{tm,i}$ because of the long infrastructure lifetime.

2.1.4 On-site infrastructure

For each impact category *i*, the total environmental impact embodied in the production of the on-site infrastructure $EI_{Inf\text{-}nZEN(Mc+Mr),i}$ is computed with Eq. (7).

$$EI_{Inf-nZEN(Mc+Mr),i} = \sum_{y=2021}^{y=2080} \sum_{e} \sum_{mt} Iel_e \cdot m_{mt,e} \bullet Ii_{mt,y,i}\left(1 + \frac{POA}{SL_{mt}}\right) \quad (7)$$

For each infrastructure element *e*, each quantity *m* of material *mt* is multiplied by its impact intensity $Ii_{mt,y,i}$. For $y > 2021$, the values of $Ii_{mt,y,i}$ are set to 50% of $Ii_{mt,2021,i}$ based on a better efficiency in the production processes of the main materials based on ESU and IFEU (2008) in addition to an increased reuse and use of recycled materials over time.

2.1.5 On-site energy production

The production and operation of the on-site energy $EI_{En(Mc+Mr,O),i}$ is computed with Eq. (8).

$$EI_{en(Mc+Mr,O),i} = \sum_{y=2021}^{y=2080} \sum_{pt} En_{pt,y} \cdot Ii_{pt,y,i} \quad (8)$$

$En_{pt,y}$ denotes the energy produced by the production technology *pt* at year *y* and $Ii_{pt,y,i}$ is the emission intensity of the energy production technology *pt* in year *y*. For photovoltaic solar panels (PV), $Ii_{PV,2050,i} = 0.5 \cdot Ii_{PV,2021,i}$ based on Gibon et al. (2017a) and for combined heat and power (CHP), $Ii_{CHP,2050,i} = 0.9 \cdot Ii_{CHP,2021,i}$. $Ii_{CHP,2050,i}$ is decreased by 10% only because this technology is already at an advanced deployment stage and little future improvements in the process efficiency can thus be expected.

2.1.6 Environmental credits

The potential environmental credits $EI_{El(surplus),i}$ are based on the annual electricity balance as depicted in Eq. (9).

$$EI_{El(surplus),i} = \sum_{y=2021}^{y=2080}\sum_{pt}\left(El_{On-site,pt,y} - (El_{use,B,y}+El_{use,el_{car},y}+El_{use,on-siteinf,y})\right)\cdot\gamma_{pt,y}\cdot Ii_{pt,y} \quad (9)$$

At year *y*, $EI_{El(surplus),i}$ is the result of the electricity produced locally $El_{on\text{-}site,pt,y}$ by each production technology *pt* minus the electricity used to cover the electricity needs of the buildings $El_{use,t,y}$, the electricity to supply the passenger cars $El_{use,el\_car,y}$, and the electricity used for the lighting of the neighbourhood $El_{use,on\text{-}site\ inf,y}$. This first convolution is multiplied by the environmental intensity of the European electricity mix computed by multiplying the share of the different energy technologies *pt* at year *y* $\gamma_{pt,y}$ with their respective environmental impact intensity $Ii_{pt,y}$ at time *y*. $\gamma_{pt,y}$ is taken from the last electricity-generation figures by source in the European Union in the Sustainable Development Scenario (< 1.5 °C target), 2019–2050 (IEA 2020b). $Ii_{pt,y}$ are taken from life-cycle inventory data for electricity generation developed and used by Gibon et al. (2017b), Arvesen et al. (2018), and Pehl et al. (2017).

2.2 Case study

The LCA model described above is applied on Ydalir, a neighbourhood in the early planning stages located in Elverum, Norway. Ydalir consists of one school (6 474 m^2), one kindergarten (2 140 m^2), and 1 000 residential buildings (of 100 m^2 each). The school and the kindergarten were taken into use in autumn 2019, and the residential buildings will be built over the next 15–20 years. Yet, to simplify the assessment, we assumed all the construction to occur at the beginning of the assessment period in 2021. The POA of the study is equal to the building lifetime of 60 years (Wiik et al. 2018). The life-cycle inventories of all the sub-systems are given in the supplementary material.

The functional unit is "to fulfil the housing, school, kindergarten, and mobility needs of the 2 500 inhabitants of Ydalir over a 60-year time period."

Ydalir has high climate-change-mitigation ambitions clearly stated in its master plan (Ydalir 2017). Ydalir will "produce its energy locally through renewable sources, have passive-house standards or higher for all its buildings, choose wood or other materials with low GHG intensity as main building materials, and reduce and find climate-friendly solutions for the mobility of its inhabitants."

The on-site electricity production in Ydalir consists of a district heating plant, PV panels, and 9 combined-heat-and-power (CHP) machines fuelled by wood chips with an electric power of 40 kW, a heating power of 100 kW, and assumed 7 000 annual operating hours. In addition, Ydalir has signed an agreement with the local district company.

On the basis of the recommendation by Steinmann et al. (2016) to use four–six impact categories to cover most of the variance (84–92%) in product rankings, five mid-point impact categories are selected: Climate Change, Freshwater Eutrophication, Human Toxicity, Metal Depletion, and Terrestrial Acidification. In addition, the importance of using several climate metrics to give short-lived GHG such as methane the attention they deserve has been stressed and recommended by the UNEP SETAC task force on climate change (Cherubini et al. 2016; Levasseur et al. 2016). On the basis of this recommendation, a climate-metrics sensitivity analysis is conducted by evaluating Climate Change with the global warming caused in three time horizons of 20, 100, and 500 years.

2.3 Climate mitigation strategies

The Baseline scenario and the four CMS are described in Table 1. The Baseline scenario depicts the situation at Ydalir without including the ambitious mobility targets. The changes made from the Baseline to each CMS are underscored in Table 1.

The first CMS (CMS 1), Mobility Ydalir, factors in the ambitions set on the mobility patterns at Ydalir. The transport-mode shares are thus changed accordingly. The next three CMS are based on the material efficiency strategies proposed by Hertwich et al. (2019) to reduce GHG emissions associated with buildings, vehicles, and electronics. CMS 2, Increased Lifetimes, is based on a material efficiency strategy that focuses on increasing the lifetime of buildings and vehicles. The building lifetime is set to 100 years and is closer to a more representative building lifetime of 125 years defined by Sandberg et al. (2016) for Norwegian buildings. The 60 years building lifetime is set according to the standard NS 3720:2018—Methods for greenhouse gas calculations for buildings (in Norwegian) (NS 2018)). The vehicle lifetime is increased by 25%. In CMS 3, Better Use, the dwelling and passenger cars are better used by means of reducing the residential dwellings size by 25% and increasing the passenger load of the passenger cars by 25%. The 25% increase or reduction levels are chosen as examples, without examining whether this is desired or achievable, but to examine the effects of such increase or reduction levels. In CMS 4, Combined Strategies, all the afford-mentioned CMSs are combined.

Please notice that, although the changes are underscored, their subsequent influence on other parameters is not

Table 1 Description of the Baseline scenario and the four climate mitigation strategies (CMS)

			Climate mitigation strategies			
		Baseline	Mobility—Ydalir	Increased Lifetimes	Better Use	Combined Strategies
	Units		**CMS 1**	**CMS 2**	**CMS 3**	**CMS 4**
Buildings						
# Residential unit	unit	1 000	1 000	1 000	1 000	1 000
# Kindergarten	unit	1	1	1	1	1
# School	unit	1	1	1	1	1
Lifetime	year	60	60	100	60	100
Residential unit	m^2/unit	100	100	100	75	75
Kindergarten	m^2/unit	2 140	2 140	2 140	2 140	2 140
School	m^2/unit	6 474	6 474	6 474	6 474	6 474
Inhabitants	pers / unit	2.5	2.5	2.5	2.5	2.5
Share inhabitants 20– 60 years	%	61%	61%	61%	61%	61%
Share inhabitants 0–19 years and 67–80 + years	%	39%	39%	39%	39%	39%
Energy use (Residential)	kWh/(m^2·year)	78	78	78	78	78
Heat	kWh/(m^2·year)	45	45	45	45	45
Electricity	kWh/(m^2·year)	33	33	33	33	33
Energy use (Non-residential)	kWh/(m^2·year)	109	109	109	109	109
Heat	kWh/(m^2·year)	36	36	36	36	36
Electricity	kWh/(m^2·year)	73	73	73	73	73
Total Heat	**GWh/year**	**4.8**	**4.8**	**4.8**	**3.7**	**3.7**
Total Electricity	**GWh/year**	**3.9**	**3.9**	**3.9**	**3.1**	**3.1**
On-site infrastructure						
Electricity	kWh/year	0.3	0.3	0.3	0.3	0.3
Mobility						
Travel distance, inhabitants 20– 60 years	km/day	36.7	36.7	36.7	36.7	36.7
Travel distance, inhabitants 0–19 years and 67–80 + years	km/day	20	20	20	20	20
Transport mode shares						
Foot	%	4%	4%	4%	4%	4%
Bike	%	10%	15%	10%	10%	15%
Passenger car	%	67%	50%	67%	67%	50%
Public transportation, bus	%	15%	20%	15%	15%	20%
Public transportation, train	%	4%	11%	4%	4%	11%
Passenger load, car	passenger/car	1.8	1.8	1.8	2.25	2.25
Electric cars, electricity use	GWh/year	0.24	0.18	0.24	0.19	0.14
Passenger cars, lifetime	km	180 000	180 000	225 000	180 000	225 000
On-site energy production						
PV panels, installed capacity	m^2/residential unit	18	18	18	18	18
PV panels, efficiency[a]	kWh/(m^2·year)	140	140	140	140	140
PV panels, annual electricity production[a]	GWh/year	2.52	2.52	2.52	2.52	2.52
CHP, electricity, Annual production[b]	GWh/year	2.5	2.5	2.5	2.5	2.5
Electricity, total annual production	**GWh/year**	**5.02**	**5.02**	**5.02**	**5.02**	**5.02**
CHP, heat, annual production	GWh/year	6.3	6.3	6.3	6.3	6.3
District heat, annual production	GWh/year	5.5	5.5	5.5	5.5	5.5
Heat, total annual production	**GWh/year**	**11.8**	**11.8**	**11.8**	**11.8**	**11.8**
Surplus energy						
Heat	GWh/year	7.0	7.0	7.0	8.1	8.1
Electricity[a,b]	GWh/year	0.6	0.6	0.6	1.4	1.5

Table 1 (continued)

[a] in 2021 followed by an efficiency increase of 20% in 2050

[b] in 2021 followed by an efficiency increase of 10% in 2050

highlighted. For instance, a reduction in the size of the residential unit in CMS 3 and CMS 4 induces a decrease of the total annual heat and electricity requirements because the energy-use intensity given in (kWh/(m^2·year)) is held constant.

The on-site production and surplus energy are snapshots taken at the beginning of the POA in 2021. Their evolution over time until the end of the POA is given in the supplementary material.

3 Results

In this section, the yearly results are first presented for the Baseline scenario in Fig. 1. Then, the cumulated results of the Baseline scenario and the four CMS are presented in Fig. 2. Finally, the results of the sensitivity of the choice of climate metrics is presented in Fig. 3. All the result datapoints are given in the supplementary material.

At the start of the POA in 2021, the shares of the different sub-systems to the total environmental impacts vary across the impact categories. For Climate Change, Mobility O comes first with 67% followed by Mobility M with 12%, Buildings M with 12%, On-Site Energy with 7%, and Infrastructure with 4% and 3% for the Mobility-Related and On-Site Infrastructure, respectively. The emission gains are of 5%. For Freshwater Eutrophication, Mobility comes first as well, but this time with Mobility M with a share of 45% followed by On-Site Energy with 23%, Building M with 16%, Mobility O with 7%, and Infrastructure

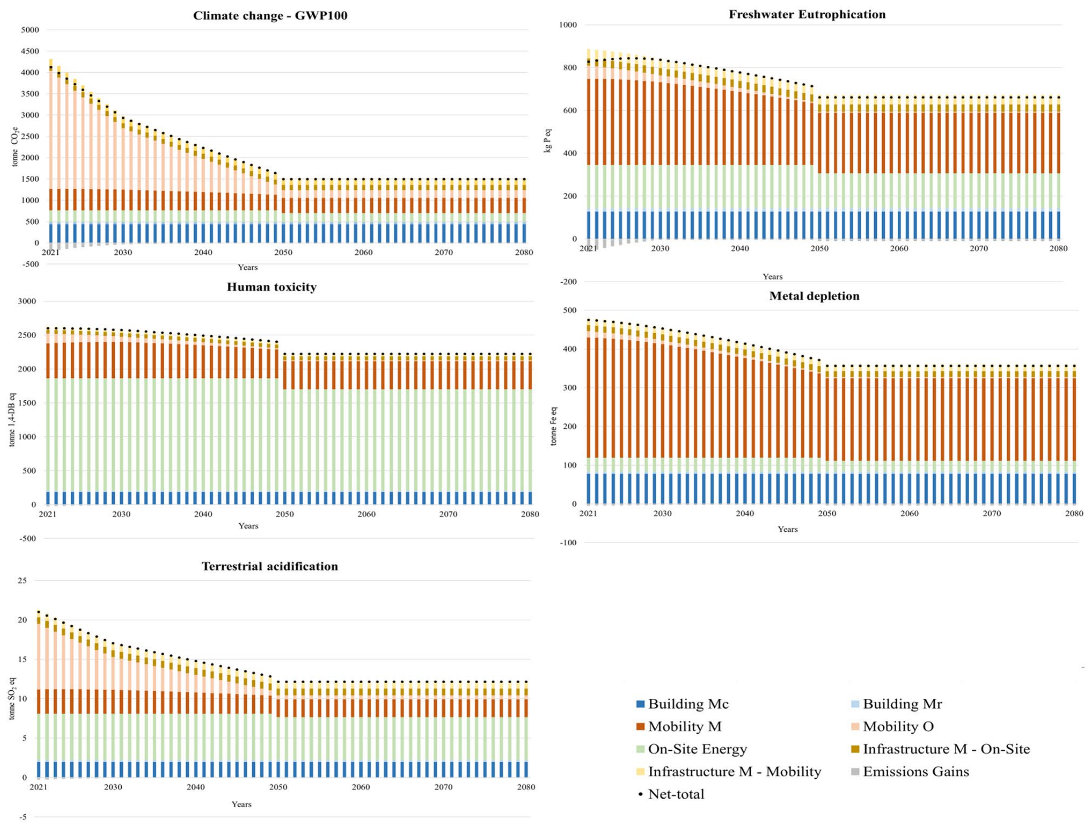

Fig. 1 Yearly environmental midpoint indicator results and their sources for the Baseline scenario

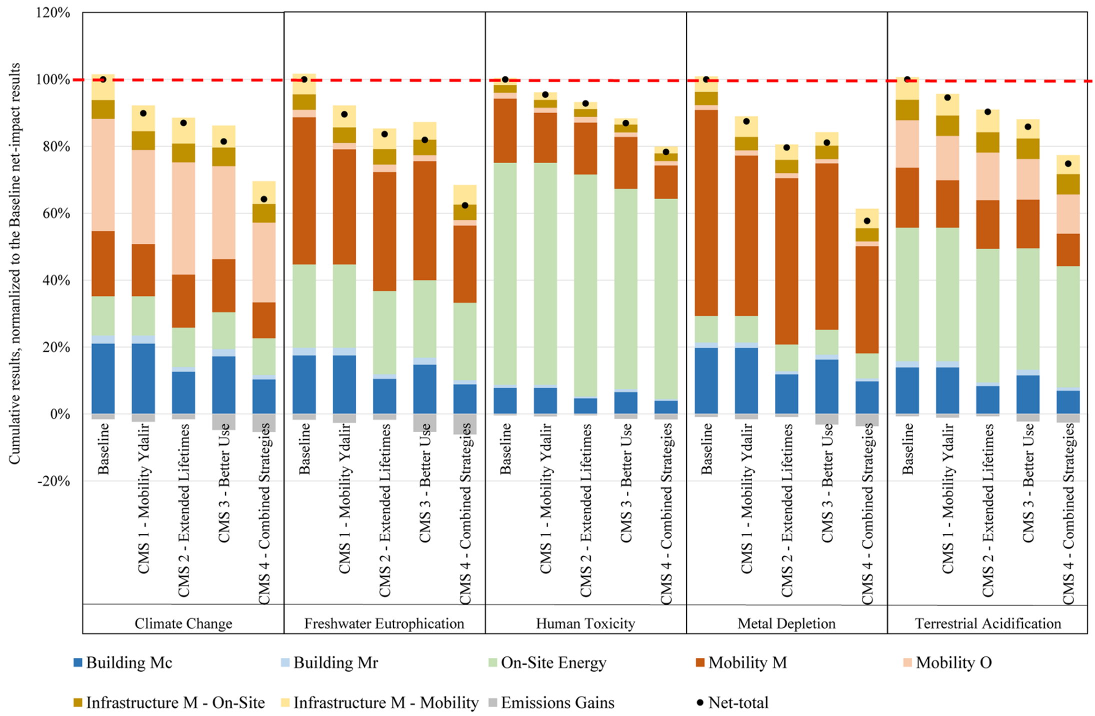

Fig. 2 Cumulative results over the period of analysis, for each climate mitigation strategy (CMS) and each environmental impact category, normalized relative to the Baseline net-impact results

with 5% and 4% for the Mobility-Related and On-Site Infrastructure, respectively. The emission gains are marginal and of less than 1%. For Human Toxicity, On-Site Energy comes first with most of the environmental impact with 64% followed by Mobility M with 20%, Building M with 8%, Mobility O with 5%, and Mobility-Related and On-Site Infrastructure both with a share of 2%. The emission gains are of 1%. For Metal Depletion, the majority of the environmental impact comes from Mobility M with a share of 65% followed by Building M with 17%, On-Site Energy with 7%, Mobility O with 3%, and Infrastructure with 4% and 3% for the Mobility-Related and On-Site Infrastructure, respectively. The emission gains are of 1%. For Terrestrial Acidification, Mobility O holds the highest share with 40% followed by On-Site Energy with 28%, Mobility M with 15%, Building M with 10%, and Infrastructure with 5% and 4% for the Mobility-Related and On-Site Infrastructure, respectively. The emission gains are of 1%.

Two patterns are observed when comparing the distribution of the sub-systems at the beginning and at the end of the POA. The first pattern is observed for Climate Change and Terrestrial Acidification where the material-related sub-systems M take over the operational sub-systems O induced by the electrification based on energy source of the mobility. The second pattern is valid for Freshwater Eutrophication, Human Toxicity, and Metal Depletion where the distribution patterns and order remain pretty much the same.

The yearly absolute environmental impacts of the end of the POA are decreased compared to the beginning of the POA in all the impact categories. The highest decrease of 64% is attributed to Climate Change followed by a decrease of 42% for Terrestrial Acidification, 25% for Metal Depletion, 24% for Freshwater Eutrophication, and 14% for Human Toxicity.

Those decreases are induced by the better assumed efficiencies in the production processes of the main materials, in addition to an increased reuse and use of recycled materials over time. Those improvements are reflected in the environmental impacts intensities that are decreased over time. The improvements explain counter-intuitive results such as Mobility M that decreases over time despite the penetration of a high share of electric vehicles that have—as per today—a higher environmental impact of 56–88% across the assessed impact categories in their production than their conventional counterparts.

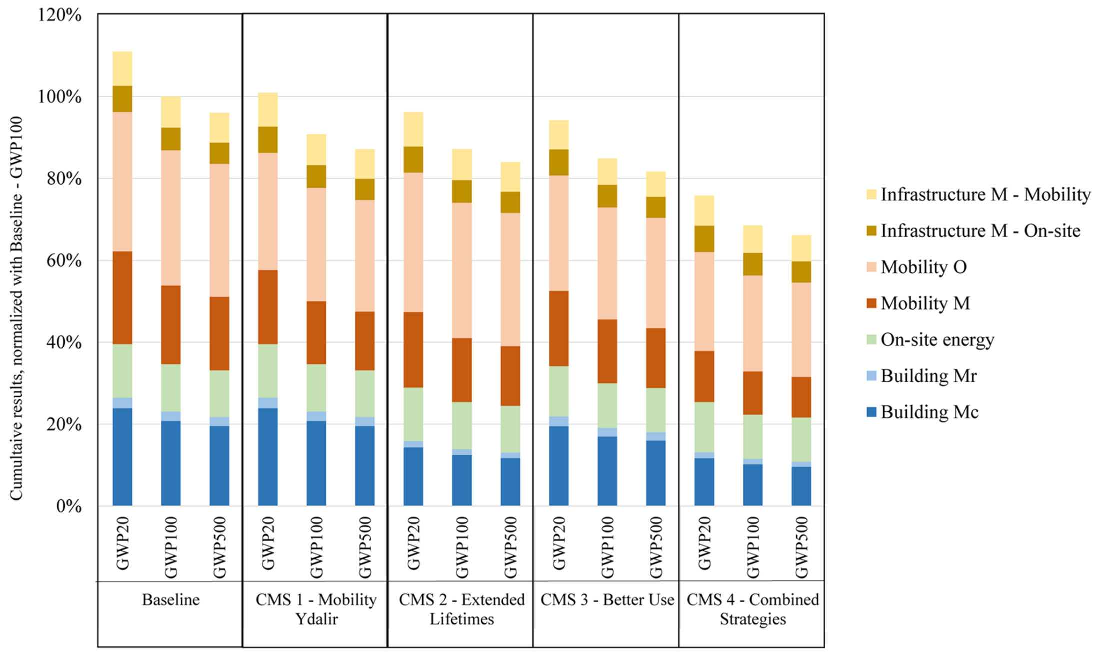

Fig. 3 Cumulative results excluding emissions gains, normalized with Baseline–GWP 100, computed with three different climate metrics with 20-, 100-, and 500-year time horizon; GWP = global warming potential

The cumulative results over the POA are presented in Fig. 2 for the Baseline scenario and the four CMS. Environmental co-benefits are shown across all the impact categories and CMS and are of 5–13% for CMS 1 Mobility Ydalir, 7–20% for CMS 2 Extended Lifetimes, 13–19% for CMS 3 Better Use, and of 22–42% for CMS 4 Combined Strategies. Interestingly, the highest environmental benefits of 42% for CMS 4 are not found for Climate Change but for Metal Depletion.

For CMS 1 Mobility Ydalir, the environmental benefits induced by the introduction of mobility patterns that reduce the use of passenger cars and promote the use of public transportation, biking, and walking can be found in all the mobility-related sub-systems. The climate and environmental co-benefits range from 4–14% for Mobility M, 1–5% for Mobility O, and 0.1–4% for Infrastructure M–Mobility. Whereas environmental benefits can be found in all the impact categories for the operational phases (Mobility O), the environmental benefits are mainly concentrated for Metal Depletion for the embodied emissions in materials (Mobility M and Infrastructure M– Mobility).

For CMS2 Extended Lifetime, the extension of the lifetime of the passenger cars and building both by 25% induces environmental benefits that can be found in the sub-systems Mobility M with 3–9% and Building M with 3–12%. The lowest environmental befits are attributed to Terrestrial Acidification and Human Toxicity. On the other hand, the highest environmental benefits are attributed to Metal Depletion for both Mobility M and Building M induced by a decrease in metal use to fulfill the mobility needs of the inhabitants over the POA as well as a discounting of the stock of metals in the building over a longer time period. High environmental benefits of 9% are also shown for Climate Change, mainly induced by a longer discounting period of the construction materials in the building due to building lifetime extension.

For CMS 3 Better Use, the reduction of 25% of the dwelling size combined with a better use of the passenger cars induced by an increase of the passenger load by 25% show environmental benefits across all the impact categories and sub-systems except for Infrastructure M–On-Site that is not affected by those measures. In descendant order, the environmental benefits are of 4–12% for Mobility M, 1–7% for On-Site Energy, 0.2–6% for Mobility O, 1–4% for Building M, 1–3% for Emission Credits, and 0.3–1% for Infrastructure M–Mobility.

The combination of the three afford-mentioned CMS leads to further environmental benefits of a total of 22–42%. As it is the case for CMS 3, environmental benefits are shown across all the impact categories and sub-systems except for Infrastructure M–On-Site that is not affected by any of those measures. In descendant order, the environmental benefits are of 8–29% for Mobility M, 4–12% for Building M, 0.1–10% for Mobility O, 1–7% for On-Site Energy, 0.1–4% for Emission Credits, and around 1% for Infrastructure M–Mobility.

The cumulative results are presented for three different climate metrics to test the influence that the time horizon of the climate metric has on the results. All the results are normalized to the results of the cumulated results of the Baseline computed with a time horizon of 100 years.

Compared to using global warming potential (GWP) 100 to measure Climate Change, the cumulative results over the POA vary by -2–(-)4% to 7–11% when measuring Climate Change with a climate metric that accounts for the global warming that cumulates over a time period of 500 years (GWP500) and 20 years (GWP20), respectively.

The M sub-systems are the most affected by a use of another time horizon to measure global warming to quantify potential climate change. It is the methane released when extracting and producing the fossil fuels used in the production of those materials constituting the materials M subsystems that causes most of the variations. On the other hand, the operational O sub-systems are less affected; indeed, they are already decarbonized because of the use of renewable energy locally produced to supply the energy need of the buildings and the electric cars.

4 Discussion

4.1 Benchmarking with previous studies

Normalized with the total number of inhabitants, our yearly results vary between 1.0–1.6 tonnes CO_2e/pers at the beginning of the POA in 2021 and between 0.38–0.60 tonnes CO_2e/pers from 2050 and until the end of the POA. Our study has the particularity to assess buildings with low-energy-use standard that are in addition fed by renewable energy. Thus, the environmental impacts stemming from the operational phase of the buildings are drastically decreased. Therefore, our result are found in the lower range of the yearly results found in the literature of 0.6–8.6 tonnes CO_2e/pers reviewed by Lotteau et al. (2015).

For similar latitudes, high-energy standards on houses and mobility stock composition, the yearly results of -0.04–2.64 tonnes CO_2e./pers (Lausselet et al. 2019, 2020a) found previously by using the model further developed in this study align well with our results. For a Swiss municipality where an average energy use in buildings is applied, Saner et al. (2013) found a yearly mean value of 4.30 tonnes CO_2e./pers, slightly higher than our results, but still in the same order of magnitude. When including the total household requirements by including, for example, food and services, Ivanova et al. (2016) found a value of 10.3 tonnes CO_2e./pers. for Norway, for a world average of 3.4 tonnes CO_2eq./pers. (in 2007).

When comparing the share of the different sub-systems, our LCA model yields results similar to those reported in the literature. The mobility shares (16–53%) are higher than the shares assigned to building (9–23%) across all the impact categories in accordance with Bastos et al. (2016) who found user transportation to account for the largest share of emissions, ranging from 51 to 57%. The shares of 5–13% of infrastructure (mobility-related and on-site) across the impact categories align well with the shares of the GHG emissions related to infrastructures 16–22% of the total found by Stephan et al. (2013).

A comprehensive overview of the potential of CMS to mitigate vehicle emissions under a vast range of conditions is presented by Wolfram et al. (2020). A more intensive use is found to yield reduction of 25% comparable to our range of 13–19% found for CMS 3 Better Use. The highest cut of 29–57% is found when combining their strategies, similar to our range of 22–42% for CMS 4 Combined Strategies. CMS are applied in order to reduce the climate impact of the buildings of a nZEN in the early planning stages by Lausselet et al. (2020b) with a better use that yields a reduction of 25% and the combination of CMS that yields the highest reduction of 44%.

4.2 Uncertainties, limitations, and future work

The use of several climate metrics has shed light on the use of fossil fuels in the production value chains of the materials used to provide the mobility services and shelters to the inhabitants of Ydalir. A recent study by Hmiel et al. (2020) showed methane emissions from fossil fuels to be 25–40% higher than earlier estimates suggested. The fossil-fueled value chains are thus likely responsible for an even larger proportion of recent climate change than previously thought. Decarbonizing the power sector has direct implications for other sectors (Wiebe 2018), and the global warming caused by short-term GHG such as methane should be fully captured. The importance of using several climate metrics to consider short-lived GHG such as methane as they deserve has been stressed and recommended by the UNEP SETAC task force on climate change (Cherubini et al. 2016; Levasseur et al. 2016). This recommendation is especially valid as long as a significant number of global value chains have not replaced their upstream use of fossil fuels by renewable-energy sources.

A yearly energy balance is used. On the other hand, a higher resolution could be achieved by using an hourly energy profile that would consider that a higher quantity of PV electricity is produced during daytime and a large part of the consumption occurs at night when there is no production. Accounting for the temporal variation of electricity production and use in LCAs of energy-efficient buildings is crucial because the use of yearly energy profiles can lead to overestimations of the surplus energy and subsequent emission credits (Roux et al. 2016). To provide a clear scientific background regarding the hourly GHG intensity of one kWh of produced electricity in order to provide a decision support tool to fully exploit the advantages of a future smart grid is crucial (Clauß et al. 2018; Messagie et al. 2014; Vandepaer and Gibon 2018; Vandepaer et al. 2019b). Implementing energy storage and vehicle-to-grid concepts then also becomes relevant (Kelly et al. 2015; Munkhammar et al. 2015; Vandepaer et al. 2019a).

Energy storage is a crucial parameter of nZENs because they base their energy supply on renewable energy and thus, by definition, intermittent energy sources. The potential to store, peak-shave, and thus improve the match between energy production and use should be further investigated. Furthermore, electric cars represent a significant share of the mobility parc in a nZEN, and the opportunities to use the electric mobile parc as a battery to store and further re-inject the stored energy by using vehicle-to-grid technologies should be assessed. But, to our knowledge, there are no LCA studies that use hourly energy profiles to assess the interaction between buildings, electric vehicles, in particular their battery, and the potential of the latter to temporally store and supply the electricity produced on-site back when appropriate.

The model scenarios of future development paths can reveal how the environmental performance of a nZEN project is influenced by parameters describing alternative future developments. Predicting how such parameters will evolve has substantial uncertainty. A global sensitivity analysis such as a variance-based sensitivity analysis (Saltelli et al. 2010) could be performed to capture such effects. Such a "global sensitivity analysis" could be based on the pedigree approach undertaken by, for example, Ecoinvent (Frischknecht et al. 2016). In a Pedigree approach, each input and output of the life-cycle inventories is assessed according to six characteristics: reliability, completeness, temporal correlation, geographic correlation, further technological correlation, and sample size. The Pedigree approach could be expanded to the foreground processes defined in the LCA model developed in this study. Also, the LCA results will gain in robustness if the Pedigree approach is extended along all the life-cycle phases, including the impact assessment phase.

Environmental co-benefits have been shown for all the CMS and impact categories. Those co-benefits are inherent to the nature of the CMS because they are based on material efficiency strategies that are deemed by their essence to reduce the pressure on the environment. The other reason is the constraint on the functional unit to be fulfilled across the CMS. If the functional unit had been "spend the money invested to fulfil the housing, school, kindergarten, and mobility needs of the 2 500 inhabitants of Ydalir over a 60-year time period," a potential rebound effect could potentially have had negative environmental co-benefits, depending on how the financial left-overs saved in CMS 1–4 would have been spent. Also, a functional unit measured in monetary terms will allow to measure the cost-effectiveness of the proposed CMSs and thus measure both their environmental and economic sustainability.

When assessing our prospective CMS, energy-efficiency improvements along the production chains have been factored in by the use of coefficients that reflect the shift from fossil fuels to a more circular economy based on renewable-energy sources. In future studies, a more systematic analysis of potential and expected improvements in material production, manufacturing, and transport is needed. The environmental impact intensities have been assessed and decreased on a model sub-system level. Ideally, the resolution should be higher and the trajectory of each material over time should be assessed and projected individually. This could be achieved by allocating an individual material coefficient to each material environmental intensity at different points in time. Neglecting such improvements could result in underestimating the environmental benefits of climate mitigation policies (Hertwich et al. 2015). Also, only current available technologies are considered. But, over the POA of 60 years considered in this study, new disruptive technologies will most probably come into play e.g. hydrogen vehicles or autonomous vehicles for the mobility sub-systems.

In the same manner that only current available technologies are considered, only current climate conditions are assumed. Climate is changing rapidly and leads to climate extremes at a frequency never seen before (IPCC 2021). The projections indicate a warmer climate in Norway for all seasons, with a greater projected warming for winter than for summer. Temperatures are expected to increase by 1.6–6.7 °C and the number of "warm days" (> 20 °C) is expected to triple by the end of the century (Hanssen-Bauer et al. 2017). Neither temperature increases over time nor climate extremes are included in the scenarios. Temperature increases will lead to a lesser need for heating in the winter and possible use of air-conditioning in the summer. In terms of modelling, climate extremes will translate in anything from shorter renovation and/or replacement periods of part of the model sub-systems to the replacement of the whole building stock, infrastructure, and vehicle fleet.

The Norwegian electricity production mix is already highly based on renewables with a share of 95% hydropower and 2.6% wind power (Statistics Norway 2019). Renewable electricity produced locally by PV has been the favored method of electricity production for nZENs. Exploiting local wind, biomass and geothermal sources are other available alternative renewable energy production pathways that will have to be examined based on their environmental profile, costs, and acceptance. But, by further producing renewable energy on a neighbourhood scale, nZENs may play a role in the decarbonization of the European energy mix by (1) sending their surplus energy to the grid, with potential for export outside Norway and (2) liberating electricity from hydropower that will substitute more carbon-rich electricity or fuels generated elsewhere, such as in the strive for electrification of road transport. This is especially true per today with a European energy system relying extensively on fossil fuels but will change over time along with the decarbonization of the European energy system.

The construction of new neighbourhoods can potentially lead to changes in land use at a scale that influences the local balance of carbon storage in soil and vegetation. This might in particular be the case when bog areas, or agricultural and forestry land are developed for urbanization purposes. Those aspects should be better assessed when new neighbourhoods and settlements are being planned. The matching of the foreground processes (e.g., a building in a nZEN) with the environmental stressors that are further addressed in terms of characterization factors should be done in such a way that the full potential effects of the construction of nZEN are captured, on-site and along the material production value chains.

4.3 Policy implications

The CMS presented in this study clearly showed the combination of different measures across several layers at different points in time to best mitigate climate change and to provide environmental co-benefits.

At the early planning stages, the focus should be set on finding incentives that will promote dwellings of reasonable sizes. To avoid the neutralization of those dwelling-size incentives, dwelling sizes should be measured not only by dwelling but also by inhabitants. As of today, dwelling sizes are not regulated. A typical case where dwelling sizes would reduce could be in an urban area where the pressure on prices is high and could constrain and decrease the dwelling sizes. For promoters to be willing to build and promote dwelling of smaller sizes, incentives should be in place to create markets for those dwellings of reduced sizes to be sold. Promising recent trends on designing buildings where part of the space is shared for given activities have appeared (Fyrstikkbakken 2021). Those initiatives should be actively promoted because they hold the potential to help pave the way for reducing the floor area per inhabitant.

Whereas the environmental impact caused by the operational phases of the buildings and mobility-fleet are drastically reduced in nZENs thanks to the use of low-energy-use standards and the production of locally renewable energy that supply the buildings and the electric passenger vehicle fleet, the use of fossil fuels along the material value chains is still highly present. Thus, incentives and standards should promote not only the decarbonization of the operational phases but also of the material value chains, *in-and out-land*. This calls for a consumer accounting perspective.

Over time, a culture of car- and ride-sharing should be encouraged. Whereas the former will reduce the pressure on the use of resources mainly by diminishing the in-use stock of metals, the latter will have climate and environmental co-benefits in several other aspects such as an improved air-quality, traffic noise, and congestion.

Per today, nZENs only represent a marginal share of national building stocks that also contain buildings with less strict energy-use standards. When deploying strategies to renovate national building stocks, the opportunity to reshape dwellings into dwellings of smaller sizes should be assessed in favor of a sole focus on nZEB standards. When deploying strategies to renovate the buildings of Ydalir, the future population demographic should be assessed, and if applicable, measures to reshape dwellings sizes could be incentivized.

Another aspect is an enhanced digitalization that would allow to overcome a binary relation between a single dwelling, car, and PV owner to several dwelling, car, and PV owners. This new type of model will allow to interconnect all the sub-elements of a nZEN and embrace a systemic approach that will allow for the high- and low-hanging fruits to be picked when drawing CMS.

Climate-change mitigation opportunities are broader than the ones proposed in this study that focus on housing and mobility needs only. For instance, Lekve Bjelle et al. (2018) have shown the beneficial effects of flying less or modifying food diets. On average, households—via their consumption in terms of material, water, and land-use requirements—are responsible for more than 60% of global GHG emissions and between 50 and 80% of total land, material, and water use (Hertwich and Peters 2009; Ivanova et al. 2016). Households thus sit with a tremendous mitigation potential.

LCA results are useful to quantify the pressure on the environment and on the resources induced by human activities. By drawing CMSs as it is the case in this study, LCA results can inform environmental policies on possible pathways to reduce the pressure on the environment and on the resources. LCA results at a certain point in time represent the current best available knowledge and practice. LCA results should thus not be seen as static, but rather evolutionary and should be updated whenever better knowledge is available (UNEP and Setac 2016). In addition, intrinsic differences exist between the boundary conditions and related assumptions between the impact assessment methods used in LCA and other frameworks. This is for example the case for human toxicity. Whereas a LCA framework focuses on the most likely range of exposure and harm for the median individual in a given human population, a human health risk assessment framework will ensure that an actual risk has not been underestimated (UNEP and SETAC 2019).

But, to achieve net-zero-emission, the previously mentioned strategies will most probably have to be supplemented by CO_2 removal methods (e.g., afforestation, agricultural practices that sequester carbon in soils, bio-energy with carbon capture, and storage, and direct air capture when combined with storage) in order to provide negative emissions according to the IPCC (2018).

5 Conclusion

Demand-side material efficiency strategies are complementary to those obtained through the decarbonization of our energy system and may offer substantial GHG mitigation potentials. To assess their combination, we use LCA to assess the environmental potential co-benefits and trade-offs of a nZEN in the early planning stages and develop CMS to come with recommendations on when the different CMS must be in place.

When deploying CMS, environmental co-benefits of 5–20% for individual CMS and of 22–42% for combined CMS are shown across the impact categories. The highest environmental benefits of 42% are found for Metal Depletion, shedding light on the close interlink between climate change mitigation and reduced pressure on resource use.

The CMS presented in this study clearly showed the combination of different measures across several layers at different points in time to best mitigate climate change and to provide the highest environmental co-benefits. At the early planning stages, the focus should be set on finding incentives that will promote dwellings of reasonable sizes, preferably around 25% smaller than the average size, measured per inhabitant. In addition, incentives to decarbonize the material value chains should be promoted, in- and out-land. Over time, a culture of car- and ride-sharing should be encouraged. Whereas the former will reduce the pressure on the use of resources by diminishing the in-use stock of metals, the latter will have climate and environmental co-benefits in several other aspects such as an improved air-quality, traffic noise, and congestion. When deploying strategies to renovate national building stocks, the opportunity to reshape dwellings into dwellings of smaller sizes should be assessed in favor of a sole focus on nZEB standards.

Future LCA studies on nZENs should better account for the temporal variation of electricity production and use by using hourly energy profiles. Also, the potential of energy storage and vehicle-to-grid concepts to store, peak-shave, and thus improve the match between energy production and use should be further investigated.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s11367-021-01973-3.

Acknowledgements The authors gratefully acknowledge the support from the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighborhoods in Smart Cities (FME ZEN).

Funding Open access funding provided by NTNU Norwegian University of Science and Technology (incl St. Olavs Hospital-Trondheim University Hospital).

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Paper VI

Lausselet, Carine; Crawford, Robert; Brattebø, Helge. Hybrid life-cycle assessment of net-zero emission neighbourhood in Norway. In a review process in the Journal of Cleaner Engineering and Technology.

This paper is awaiting publication and is not included in NTNU Open