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RESEARCH AND ANALYSIS

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

Carine Lausselet[1] | Johana Paola Forero Urrego[1] | Eirik Resch[2,3] | Helge Brattebø[1]

[1] Industrial Ecology Program, Norwegian University of Science and Technology, NTNU, Trondheim, Norway

[2] Department of Architecture and Technology, Norwegian University of Science and Technology, Trondheim, Norway

[3] Department of Applied Mathematics and Computer Science, Technical University of Denmark, Kongens Lyngby, Denmark

**Correspondence**
Carine Lausselet, Industrial Ecology Program, Norwegian University of Science and Technology, NTNU, Trondheim, Norway.
Email: carine.lausselet@ntnu.no

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## 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 kg$CO_2$e/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

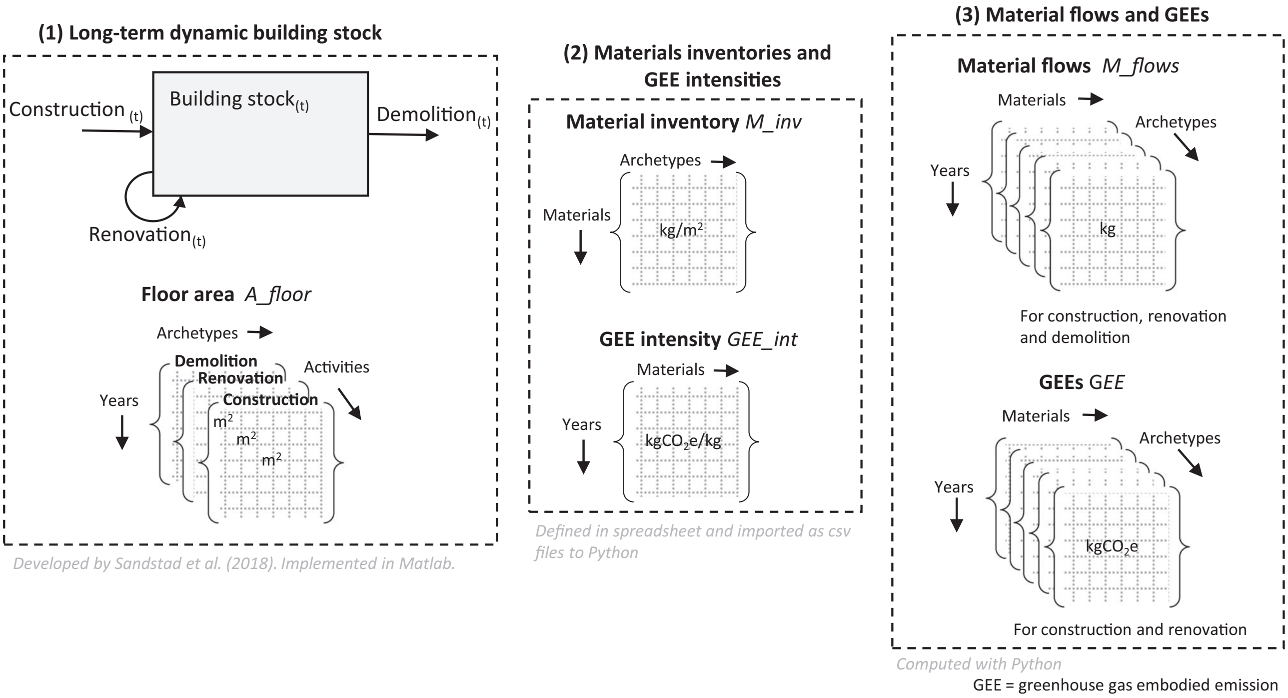


**FIGURE 1** Model description

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 kg$CO_2$e/year with dimension (year, material, archetype, activity) is obtained by multiplying *M_flows* with the matrix of materials GEE intensity *GEE_int* in kg$CO_2$e/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 kton$CO_2$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 kg$CO_2$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.

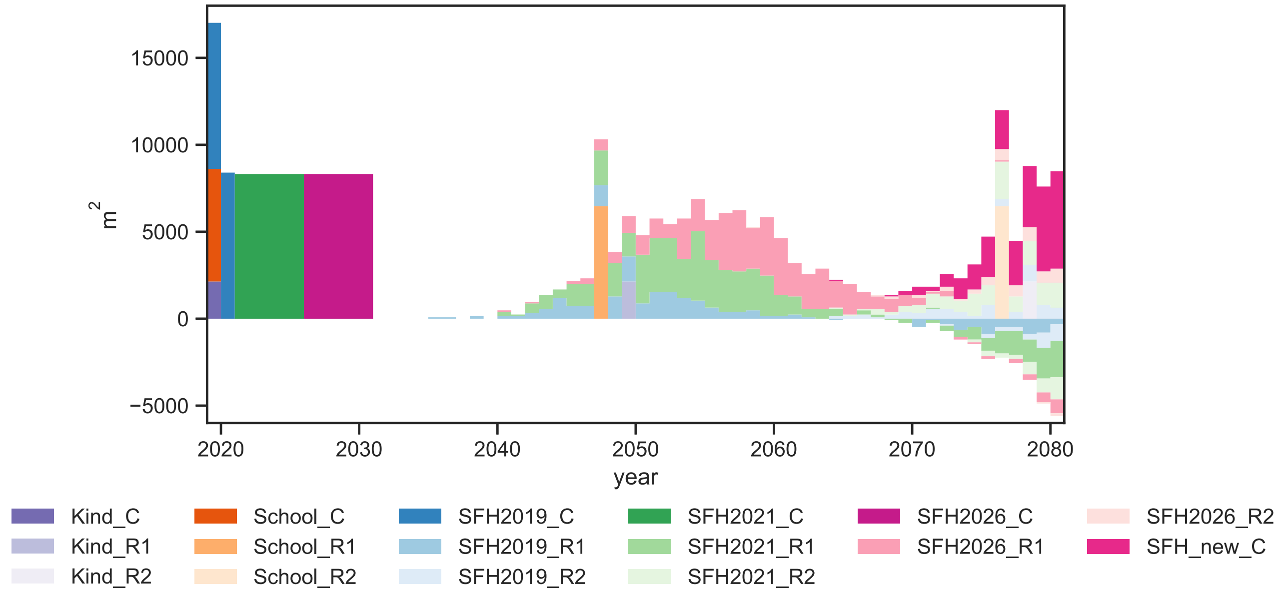


**FIGURE 2** Construction, renovation, and demolition of floor area (*A_floor*) in the neighborhood over the years. Underlying data used to create this figure can be found in Supporting Information S2

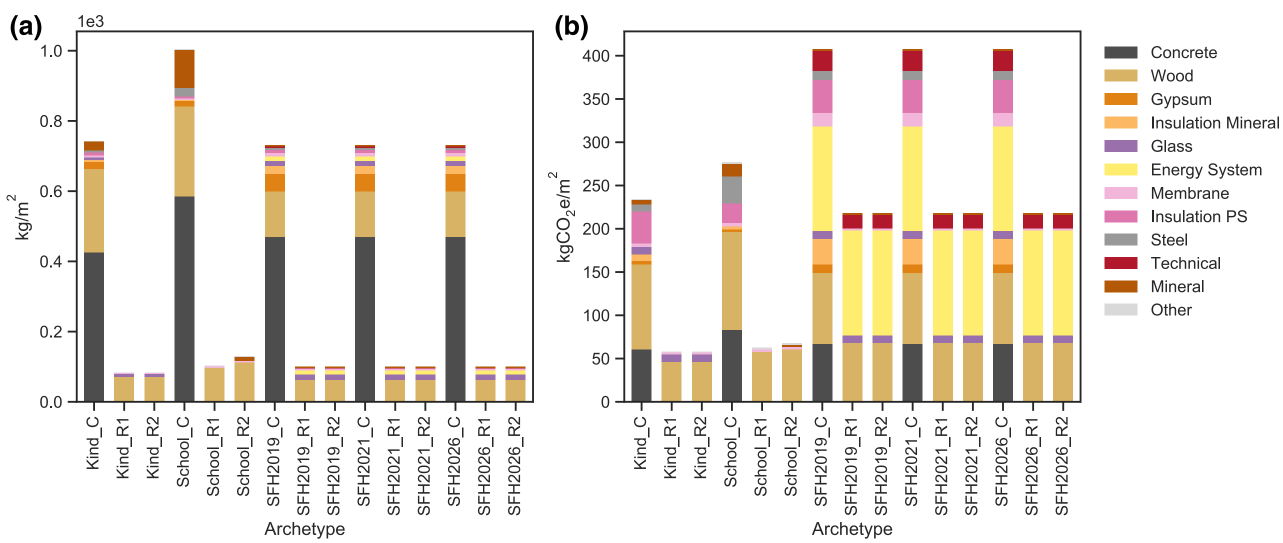


**FIGURE 3** (a) Material intensity per m$^2$ per archetype; (b) emission intensities per m$^2$ per archetype. Underlying data used to create this figure can be found in Supporting Information S2

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$_2$e/m$^2$, followed by the school with 277 kgCO$_2$e/m$^2$ and the SFHs with 408 kgCO$_2$e/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.

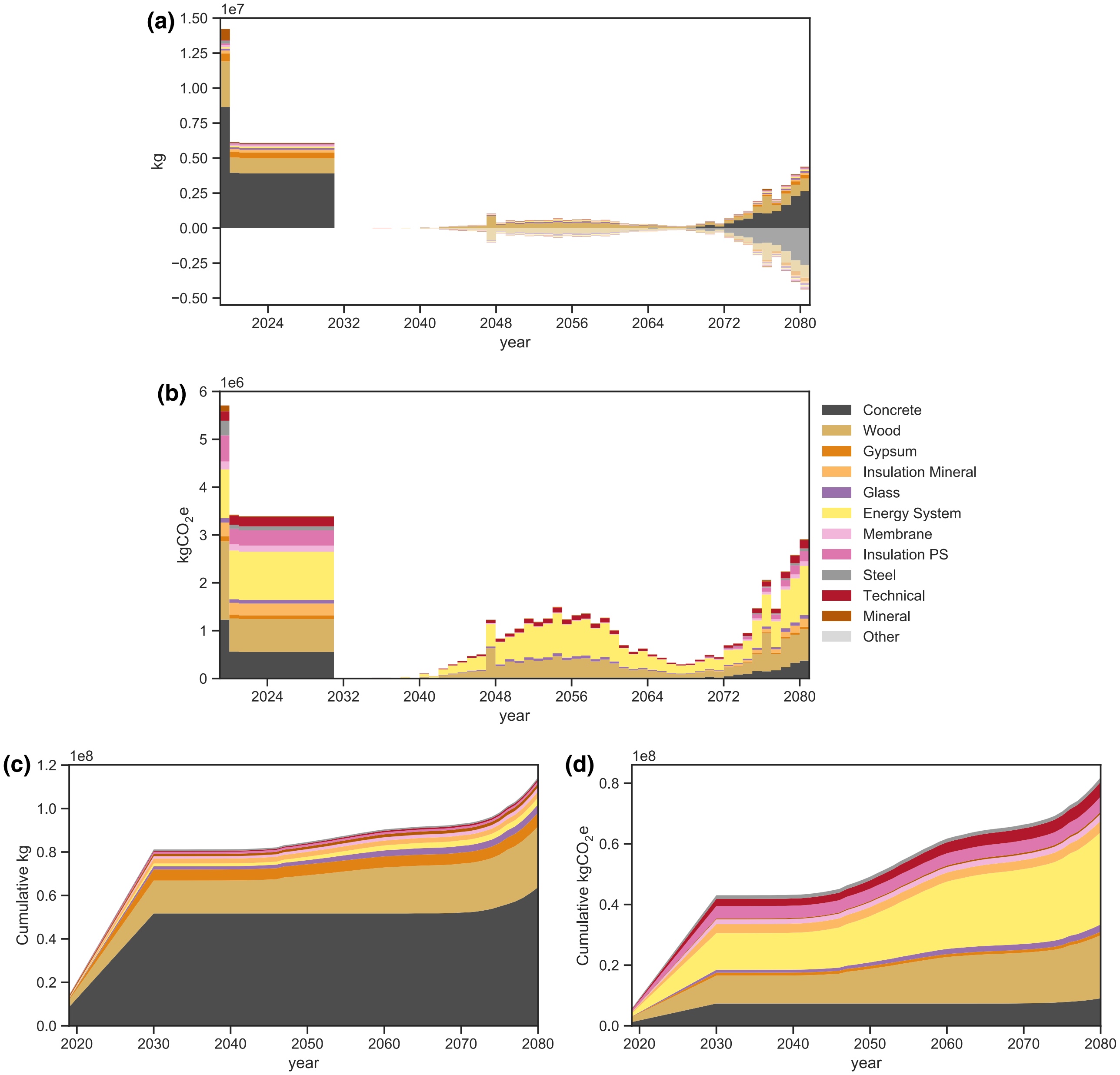


**FIGURE 4** (a) Yearly material; (b) greenhouse gas embodied emissions (GEEs); (c) cumulative material flows by material categories; (d) GEEs flows by material categories. Underlying data used to create this figure can be found in Supporting Information S2

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 $CO_2$e 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.

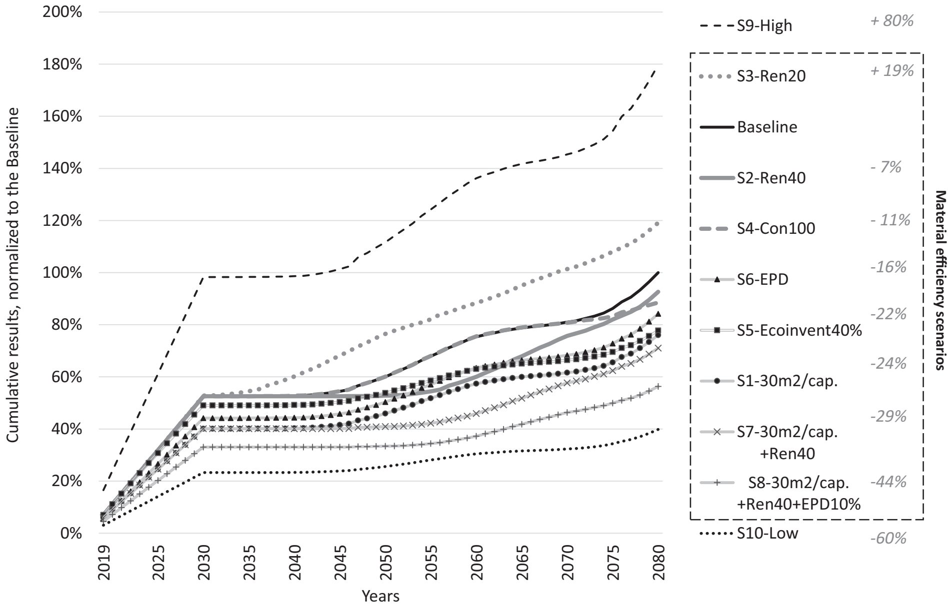


**FIGURE 5** Cumulative greenhouse gas embodied emissions (GEEs) for all the scenarios. Underlying data used to create this figure can be found in Supporting Information S2

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 kg$CO_2$e/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 kg$CO_2$e/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 kg$CO_2$e/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.

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### CONFLICT OF INTEREST

The authors declare no conflict of interest.

### ORCID

*Carine Lausselet* https://orcid.org/0000-0001-6908-2284
*Eirik Resch* https://orcid.org/0000-0002-0592-5956
*Helge Brattebø* https://orcid.org/0000-0001-8095-1663

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## SUPPORTING INFORMATION

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

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