DOI: 10.1111/jiec.13611

RESEARCH ARTICLE

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

Reducing material use and their greenhouse gas emissions in Greater Oslo

Lola S. A. Rousseau[1] | Jan Sandstad Næss[1,2] | Fabio Carrer[1,3] | Sara Amini[1] | Helge Brattebø[1] | Edgar G. Hertwich[1]

[1]Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

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

[3]Department of Forest Resource Management, Swedish University of Agricultural Sciences (SLU), Umeå, Sweden

Correspondence
Lola S. A. Rousseau, Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Høgskoleringen 5, 7034 Trondheim, Norway.
Email: lola.s.a.rousseau@ntnu.no

Editor Managing Review: André Stephan.

Funding information
Norges Teknisk-Naturvitenskapelige Universitet; Norges Forskningsråd, Grant/Award Number: 257660

Abstract

Resource efficiency strategies are key to reduce material use and help limit global warming to below 2°C in 2100. Understanding the role of such strategies at the municipal level requires a localized approach. Here we evaluate a ramp-up of resource efficiency strategies and their associated effects on car use and climate benefits toward 2050 for 19 individual subregions within the Greater Oslo region in Norway. In our scenarios, material stocks increase from 356 megatonnes (Mt) in 2022 to 361–381 Mt in 2050 driven by population growth, with low-end estimate relying on a sufficiency (SUF) scenario limiting floor area per capita and banning new single-family houses. The SUF scenario reduces total material consumption until 2050 (50.5 Mt) with 28% relative to a business-as-usual (BAU) scenario (70.8 Mt) with continuation of ongoing trends, thereby reducing greenhouse gas (GHG) emissions from material production by 21% (BAU: 11.8 $MtCO_2$-eq, SUF: 9.4 $MtCO_2$-eq). If resource efficiency strategies are combined with material production decarbonization in-line with a 2°C scenario, a 35% reduction in emissions is achievable (7.7 $MtCO_2$-eq). Car ownership rates and traveled distance per capita decrease in the SUF scenario compared to 2022 with 11%. Assuming the current relationship between settlement characteristics and transport demand, total driving distance fails to decline due to population growth. Limiting the floor-area per capita in residential buildings significantly decreases material demand. Resource efficiency strategies including densification need to be complemented with a rapid decarbonization of material supply and stronger incentives to move away from car driving to maximize climate change mitigation. This article met the requirements for a gold-gold *JIE* data openness badge described at http://jie.click/badges.

KEYWORDS
building cohorts, climate change mitigation, human settlements, industrial ecology, passenger vehicles, transport infrastructure

1 | INTRODUCTION

In-use stocks of buildings and infrastructure are “city-shapers”: their spatial arrangement is a key factor for “urban density, accessibility, transport distance and choice of transportation mode” (Pauliuk & Müller, 2014). The overall environmental impacts (e.g., due to land use, greenhouse gas emissions [GHG], and water consumption) associated with their use might be locked into patterns due to their long lifetime (IPCC, 2022; Müller et al., 2013; Saxe & Kasraian, 2020). Large amounts of materials are required to build and maintain these in-use stocks (Augiseau & Barles, 2017; Krausmann et al., 2017, 2018; Lanau et al., 2019). Construction materials comprising global transport infrastructure and building stocks amount to more than 600 Gt (Deetman et al., 2020; Wiedenhofer et al., 2024), and this number is likely to keep growing (Krausmann et al., 2017). Having access to housing and transport is essential for human well-being and good living conditions (Rao & Min, 2018). In-use stocks of products (e.g., cars, machinery, and equipment) in addition to buildings and infrastructure have been manufactured or built to provide such services (Kennedy et al., 2007; Krausmann et al., 2017; Lanau, 2020; Lin et al., 2017; Müller et al., 2013; Pauliuk & Müller, 2014).

As part of the Resource Efficiency for Climate Change (RECC) project of the International Resource Panel (IRP), material efficiency strategies for residential buildings and passenger vehicles were evaluated and quantified on a global scale (Hertwich et al., 2020; Pauliuk et al., 2021). Living in smaller and multi-family buildings as well as ride and car sharing will reduce the material demand and operational GHG emissions. However, residential buildings and passenger vehicles were modeled independently of each other, despite their synergies and interactions as reported by the IRP's Weight of Cities report (Swilling et al., 2018). Denser settlements encourage walking and cycling and provide the conditions for establishing effective public transport networks (Swilling et al., 2018), reducing the preference for passenger vehicles over active and shared mobility. This suggests the importance of analyzing and understanding how the built environment and use of passenger vehicles are linked and spatially disaggregated.

To the authors' knowledge, material stocks and flows studies encompassing both built environment components and passenger vehicles are still limited. A recent dynamic material flow analysis (MFA) study coupled residential buildings with passenger vehicles in Sweden to evaluate urban densification (Pérez-Sánchez et al., 2024). Pérez-Sánchez et al. (2024) highlight how life cycle assessment and MFA studies have, until now, provided an overview of the environmental impacts and material stocks and flows of buildings and passenger cars, but have not considered the dynamics between the sectors. Their study took a first step to fill this research gap; however, infrastructure was excluded from their scope of research. Lanau et al. (2021) calculated the carbon replacement value (CRV) for Odense, a city in Denmark, including built environment and mobile stock. Buildings contribute to 86% of the CRV, while roads and passenger vehicles (cars, buses, and motorbikes) represent 4.9% and 5.5%, respectively. Although the study focused on GHG emissions and did not offer a scenario of future stocks, flows, or emissions, it suggests that roads are as important as passenger vehicles when it comes to the CRV.

In our study, we estimate material stocks and flows of the built environment with passenger vehicles at a subregional scale for the extended Greater Oslo region. This region, the most populated of Norway, is and will be experiencing population growth (Statistisk Sentralbyrå [Statistics Norway], 2024) and presents a diversity of urban and rural areas (Statistisk Sentralbyrå [Statistics Norway], 2023b). See Sections S1 & S2 in Supplementary Information (SI) S1 for more information about the region and its population. In addition, Oslo municipality wants to reduce their indirect GHG emissions associated with consumption of construction materials (Oslo Kommune, 2023), and mapping material stocks and flows is a prerequisite. In our study, we investigate the following research questions: What is the material stock composition of the residential buildings, roads, parking, bicycle and pedestrian paths (hereafter roads and paths), and passenger vehicles in the extended Greater Oslo region in 2022? How much materials might potentially be used between 2023 and 2050 to satisfy the housing and mobility needs of the region's population? How can resource efficiency strategies and decarbonization pathways contribute to reducing material use and their GHG emissions?

We used ODYM-RECC, the open dynamic software for MFA for resource efficiency and climate change (Industrial Ecology Freiburg, 2024; Pauliuk et al., 2020, 2021). ODYM-RECC allows quantifying GHG emissions of material production (from cradle to factory gate) as well as manufacturing, use phase and end-of-life, and evaluating climate change mitigation policies. Our study makes the first application of ODYM-RECC at a local level as previous studies have focused on global or national levels (Pauliuk & Heeren, 2021; Pauliuk et al., 2021, 2024; Vélez-Henao & Pauliuk, 2025). We therefore explore the use of the model at the municipal and local scale to investigate the nexus between transport and building.

2 | METHODS

2.1 | Case study region: Extended Greater Oslo region in Norway

The extended Greater Oslo region consists of Oslo, the capital of Norway, and its surrounding counties (Østfold, Akershus, and Buskerud). The population in this region is projected to increase from 1.96 million inhabitants in 2022 to 2.32 million by 2050 (Oslo Municipality's Statistics Bank, 2023; Statistisk Sentralbyrå [Statistics Norway], 2023a). We divided the extended Greater Oslo region into 19 subregions (Figure 1). Both population density (Figure 1a) and urban land use intensity (Figure 1c) decrease as a subregion's distance from Inner Oslo increases (Figure 1b,d).

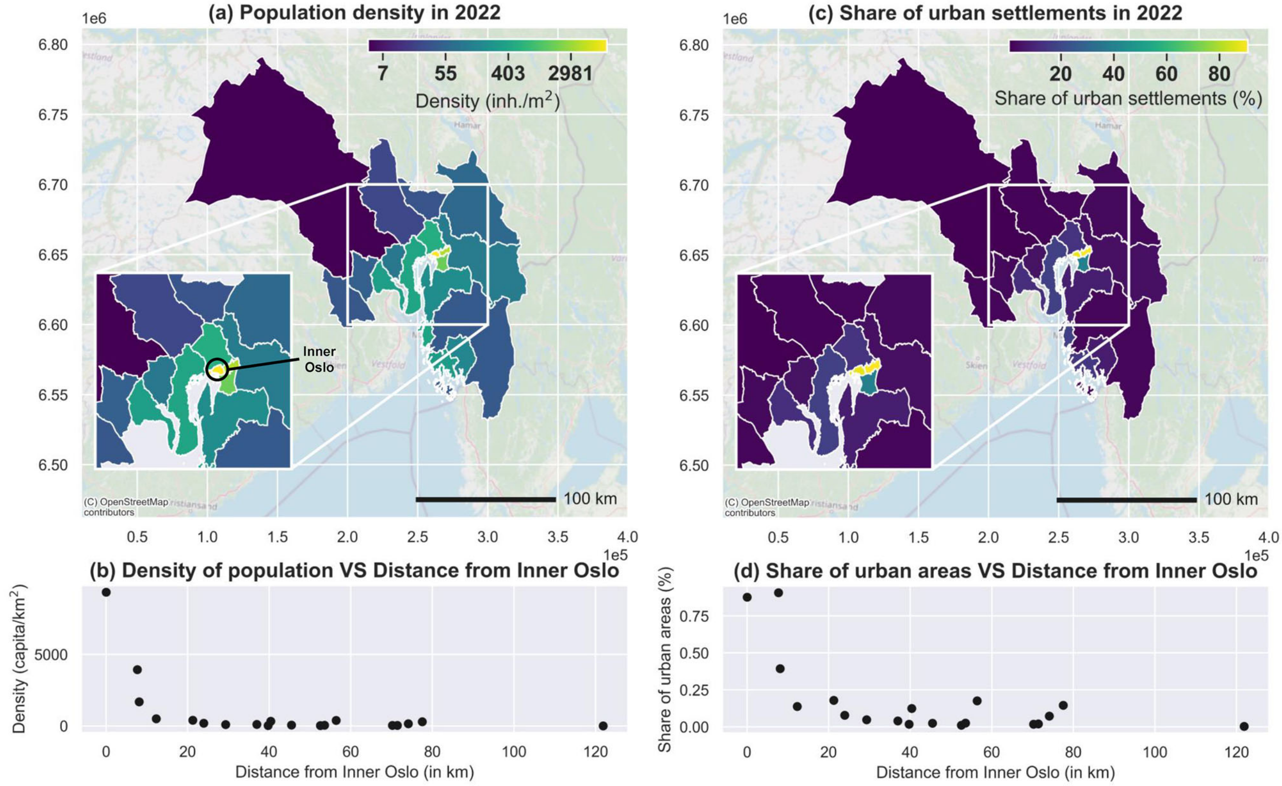

FIGURE 1 (a) Population density in 2022 in the 19 subregions with geographical location of Inner Oslo and (b) as a function to the distance to Inner Oslo (Oslo Municipality's Statistics Bank, 2023; Statistisk Sentralbyrå [Statistics Norway], 2023a). (c) Share of urban settlements in the 19 subregions and (d) as a function to the distance to Inner Oslo (Statistisk Sentralbyrå [Statistics Norway], 2023b). Underlying data for this figure can be found in Supporting Information S2, file tab "Figure 1."

2.2 | Workflow description

We investigated potential future developments of the built environment and mobility driven by the increasing population in the subregions, adapting ODYM-RECC (2024). Building upon the stock–flow–service nexus (Haberl et al., 2017), ODYM-RECC calculates in-use stocks and flows of products (e.g., single-family houses) for scenarios on population and service demand (e.g., floor area per capita [FApC] for residential buildings). Product archetypes and material cycle-related parameters (e.g., GHG emissions) are then applied to estimate material production and their impact. For documentation and parameterization, see Industrial Ecology Freiburg (2024) and the original framework (Pauliuk et al., 2020).

New capabilities were added to ODYM-RECC: (1) transport infrastructure has been introduced in addition to the existing model for residential buildings and passenger vehicles, and (2) residential buildings, infrastructure, and the car fleet were integrated into a single model relying on empirical relationships. Supporting Information (Section S7 in SI S1) provides details about the new additions to the software.

With these additions, the model comprises 128 parameters among which 70 are used in this study. SI S4 provides a list of the ODYM-RECC parameters with their description and specifies if they are region specific (e.g., population) or proxies from other regions (e.g., material intensities of passenger vehicles).

Figure 2 presents the workflow of the research: (1) combining population projections for the subregions within the extended Greater Oslo region, and two scenarios on the residential building stock based on FApC and type-split of newly constructed residential buildings, with buildings' lifetime, (2) modeling relationship between residential buildings and infrastructure to estimate infrastructure stock, and (3) modeling relationship between residential buildings, infrastructure and the distance driven by car to estimate the stock of passenger cars when combined with vehicles' lifetime, vehicle mileage, and occupancy rate. The stock of residential buildings, infrastructure, and passenger cars were combined with the other system parameters (e.g., material intensities and maintenance of infrastructure) to calculate the total material stock, the inflows of materials, and their embodied GHG emissions. Two scenarios of the materials supply chain were implemented to evaluate its decarbonization as a strategy for mitigating GHG emissions (see Section 2.4).

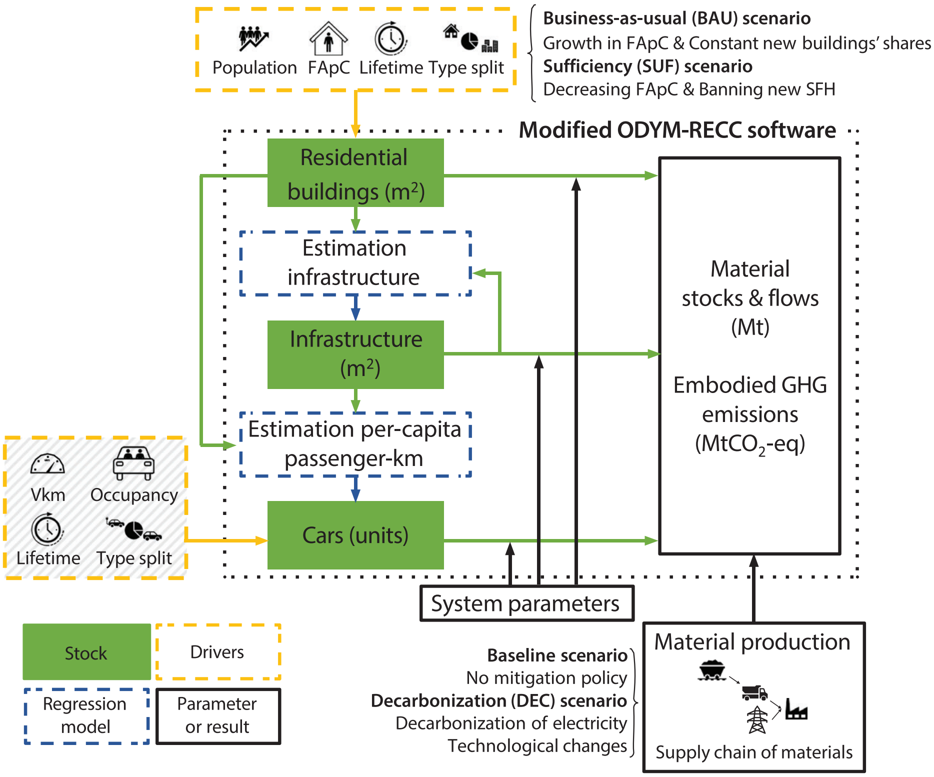

FIGURE 2 Workflow of the modified ODYM-RECC software for the purpose of this study. The box with gray stripes is for parameters which are kept constant toward 2050 and/or not involved in scenario/additional analysis.

2.3 | Description of in-use stocks

2.3.1 | Residential buildings

The number of dwellings with their characteristics (type, year of construction, and useful floor area group) shared by Statistics Norway (Statistisk Sentralbyrå [Statistics Norway], 2023c) was grouped into types (single-family houses—SFH, multi-family houses—MFH, and apartment blocks—AB) and cohorts. Dwelling numbers and characteristics were further used to estimate the residential buildings useful floor area. The type-split of new residential buildings and the future FApC toward 2050 are the scenarios described in Section 2.4.

The material composition (kg/m^2) and space heating demand (MJ/m^2) of relevant residential building types and cohorts were obtained from Amini et al. (preprint under review). Future residential buildings were assumed to have the same material composition and space heating demand as the youngest cohort (2010–2022). Since there are limited variations in material intensities for the past three cohorts, using archetypes at a single point in time is suitable to estimate future stocks and flows of residential buildings. Scenario analysis entails several uncertainties, we therefore chose to vary only the likely most significant variables. We assumed that all residential buildings are heated and that there is no cooling. A mean lifetime of 125 years was chosen for the residential buildings (Bohne et al., 2006). Some variation of lifetime is expected as the remaining lifetime of currently used buildings depends on future decisions; this variation is partially captured in ODYM-RECC using a normal distribution. See Section S3 in SI S1 for details about residential buildings.

2.3.2 | Roads and bicycle/pedestrian paths

We considered paved infrastructure for road, bicycle, and pedestrian transport (several categories of roads, bicycle/pedestrian paths, parking, and roundabouts), based on surface areas (Geodata Online, 2023a; GeoNorge, 2023).

For each type of infrastructure, asphalt and aggregates material intensities were estimated based on data from the National Road Database (NVDB, 2023a, 2023b, 2023d). The maintenance of the infrastructure was quantified for all road types and paths considering the renewal of the surface layer based on traffic volume data from NVDB (2023c) and results from Ebrahimi et al. (2022). See Section S4 in SI S1 for details about roads and paths.

2.3.3 | Passenger vehicles

The 2022 stock of passenger vehicles was estimated from the motor vehicle register and Statistics Norway data (Geodata Online, 2023b; Statistisk Sentralbyrå [Statistics Norway], 2022b). We combined the yearly average vehicle mileage (vehicle-km/year) with the yearly distance driven per capita (per-capita passenger-km/year) for 2022 to calculate the current average occupancy rate of vehicles, assumed to stay constant toward 2050 (Statens vegvesen, 2023; Statistisk Sentralbyrå [Statistics Norway], 2022a).

The new vehicles entering the stock were assumed to continue following the electrification trend. Since 2010, the share of electric vehicles in sales has increased to 82% in 2023 (Norsk elbilforening [Norwegian Electric Car Association], 2024). Data already available in ODYM-RECC were used to determine the material composition of the vehicles and the reuse of these materials when vehicles reach their end-of-life (average lifetime of vehicles is kept at 15 years). See Section S5 in SI S1 for details about passenger vehicles.

2.3.4 | Integrated residential buildings–infrastructure–car fleet model

We modeled the development of municipal roads and bicycle/pedestrian paths. We performed an ordinary least squares (OLS) multivariable regression analysis to evaluate how these two types of infrastructure are related to the residential buildings and regional roads (Section S4.2 in SI S1). The results are displayed in Table S10 (in SI S1), offering two regression equations as following:

$$\text{Road}_{\text{municipal}} = 0.38 + 0.23 \cdot \text{Building}_{\text{residential}} + 0.26 \cdot \text{Road}_{\text{regional}};\ R^2 = 0.95 \tag{1}$$

$$\text{Paths}_{\text{Bicycle/pedestrian}} = -0.02 + 0.17 \cdot \text{Building}_{\text{AB}} + 0.22 \cdot \text{Road}_{\text{municipal}};\ R^2 = 0.90 \tag{2}$$

where $\text{Road}_{\text{municipal}}$, $\text{Road}_{\text{regional}}$, $\text{Paths}_{\text{Bicycle/pedestrian}}$, $\text{Building}_{\text{residential}}$, and $\text{Building}_{\text{AB}}$ are surface and utility floor areas in m^2.

In a similar approach, we modeled how the yearly distance driven per capita could be estimated based on the built environment parameters. We again performed an OLS multivariable regression analysis (Section S5.1.2 in SI S1). Table S13 (in SI S1) shows regression results similar to the following:

$$\text{pkm}_{\text{per capita}} = 3.3 \cdot 10^3 + 1.7 \cdot 10^8 \cdot \frac{\text{Building}_{\text{SFH}}}{\text{Population}};\ R^2 = 0.78 \tag{3}$$

where $\text{pkm}_{\text{per capita}}$ is per-capita passenger-km and $\frac{\text{Building}_{\text{SFH}}}{\text{Population}}$ is m^2 of utility floor area of SFH per capita.

Regressions were used to estimate the future stock (m^2) of municipal roads and bicycle/pedestrian paths as well as the average per-capita passenger-km based on the respective residential building stock for each subregion and year toward 2050. All other types of roads and paths stocks are staying constant until 2050 and only their maintenance is modeled. We assumed the stock of infrastructure will not decrease, since infrastructure is usually not demolished (Saxe & Kasraian, 2020).

Our model and its alternatives are built upon the assumption that the relationship between driving and settlement characteristics stays constant, an assumption also found in Pérez-Sánchez et al. (2024). We stress that these relationships are not predictions, but rather an attempt at estimating some general future trends and unravelling the feasibility space of future material use and stock toward 2050.

2.4 | Scenarios analysis

We developed a set of scenarios to evaluate the effect of resource efficiency measures and energy system decarbonization (Table 1). Two scenarios of FApC and type-split of new buildings were developed to estimate the potential future stock of residential buildings: a business-as-usual (BAU) scenario and a Sufficiency (SUF) scenario. Presented in Table 1, they are further developed in the SI S1 (Sections S3.1.2 & S3.2 in SI S1). Scenarios on the type-split of new buildings influence the region's total material stock and heating demand of the residential buildings. In addition, the purpose of such scenarios was to test the integrated residential buildings–infrastructure–car fleet model developed in this paper (Section 2.3.4) and evaluate how the future development of the residential building stock might affect infrastructure, car ownership, and car use. ODYM-RECC has two scenarios (Table 1) related to the supply chain of materials: (1) a baseline scenario (Baseline scenario) with no new climate policy and (2) a scenario for GHG mitigation in materials production (DEC scenario) assuming a decarbonization of the electricity production and a shift in material production technologies (Pauliuk, 2023). These two scenarios, combined with the two scenarios on housing, resulted in four scenario combinations: BAU-Baseline, SUF-Baseline, BAU-DEC, and SUF-DEC, allowing for estimation of a range of potential future material stock, material inflows, and associated GHG emissions toward 2050.

TABLE 1 Description of the scenarios. The scenarios on residential buildings are subregion specific depending on the initial state of floor area per capita and type-split of new residential buildings in 2022. The scenarios on the supply chain of materials are from a global perspective.

Scenario	Sub-measure	Description
Scenarios on residential buildings		
BAU	BAU_FAPC	Floor area per capita increases according to historical rates.
	BAU_BT	Share of building types in new construction constant in-line with present day.
SUF	SUF_FAPC	Floor area per capita gradually decreases with 10% by 2050 instead of increasing according to historical rates.
	SUF_BT	Gradual decrease in new construction of single-family houses (reaching 0 in 2050). Shares of multi-family houses and apartment blocks increases based on initial (2022) proportions.
Scenarios on supply chain of materials		
Baseline	Baseline_ELEC	Changes in background systems occur according to a business-as-usual scenario of SSP2.
	Baseline_MAT	
DEC	DEC_ELEC	Changes in global electricity production mix according to a SSP2-RCP2.6 scenario with special emphasis on economy-driven innovation and technological solutions (“SDP_EI-26”) that limits global temperature increase to below 2°C in 2100 relative to pre-industrial times (Kikstra et al., 2024).
	DEC_MAT	Aluminum production efficiency increases, and hydrogen is introduced in steel and iron production.

To unravel the contributions of individual policy actions, we ran ODYM-RECC independently for each sub-measure considered (SUF_FAPC, SUF_BT, and DEC_ELEC, DEC_MAT). This also included testing individual modeling choices to do a sensitivity analysis: a shorter building lifetime of 100-years (-20%), increased population growth in subregions closer to Oslo (Section S2.3 in SI S1), and two alternative equations to estimate per-capita passenger-km (Section S5.1.2 in SI S1).

3 | RESULTS

3.1 | A spatially explicit analysis of the material stock in 2022

In 2022, the material stock of residential buildings (91 Mt), roads and paths (264 Mt), and passenger vehicles (1.2 Mt) in the extended Greater Oslo region added up to a total of 356 Mt with 68 Mt located in Oslo municipality. On average, the material stock is at 181 t/cap (ranging between 86.8 and 1012 t/cap) and 15.2 kt/km^2 (ranging between 4.6 and 979 kt/km^2) as displayed in Figure 3a,c.

More than half of the material stock is attributable to dwellings in Oslo, while roads and paths dominate in subregions outside Oslo. Within Oslo, the four boroughs present large differences in built environment densities and the material stock in Inner Oslo is mostly composed of residential buildings (Figure 3b,d).

The ranges of material stock per capita and per km^2 reveal the spatial disparities between the subregions, reflecting distances from Inner Oslo. On the one hand, as distance increases, the material stock per km^2 decreases for all the sectors (Figure 3e–g) with an exponential decay shape similar to the decreasing urbanization rate away from Inner Oslo (Figure 1d). On the other hand, as this distance increases, the material stock per capita presents various trends depending on the sector (Figure 3e–g). The material stock of infrastructure per capita increases exponentially, the material stock of vehicle per capita follows a logarithmic shape (with Oslo West as an outlier), and the material stock of residential buildings per capita stays relatively constant with fluctuations around 40 t/cap except Inner Oslo reaching 77 t/cap. The high share of AB in the residential buildings stock in Inner Oslo could explain its role as outlier. Regarding the material of passenger vehicles, wealthy Oslo West stands out as an outlier. Section S8.1 in SI S1 presents additional disaggregated material stock at the product level for each sector revealing the complexity of their spatial distribution in the extended Greater Oslo region.

3.2 | Material stock composition and future stock in 2050

The material stock is increasing in both scenarios, from 356 to 381 Mt (+7%) in the BAU scenario or to 361 (+1.4%) Mt in the SUF scenario. Table 2 details the material stock composition per sector in 2022 and in 2050. In both scenarios, the composition stays relatively constant with ~91% of aggregates, ~4% of wood, ~3% of cement, and 1% of steel/iron. All the other materials make, respectively, less than 1% of the stock.

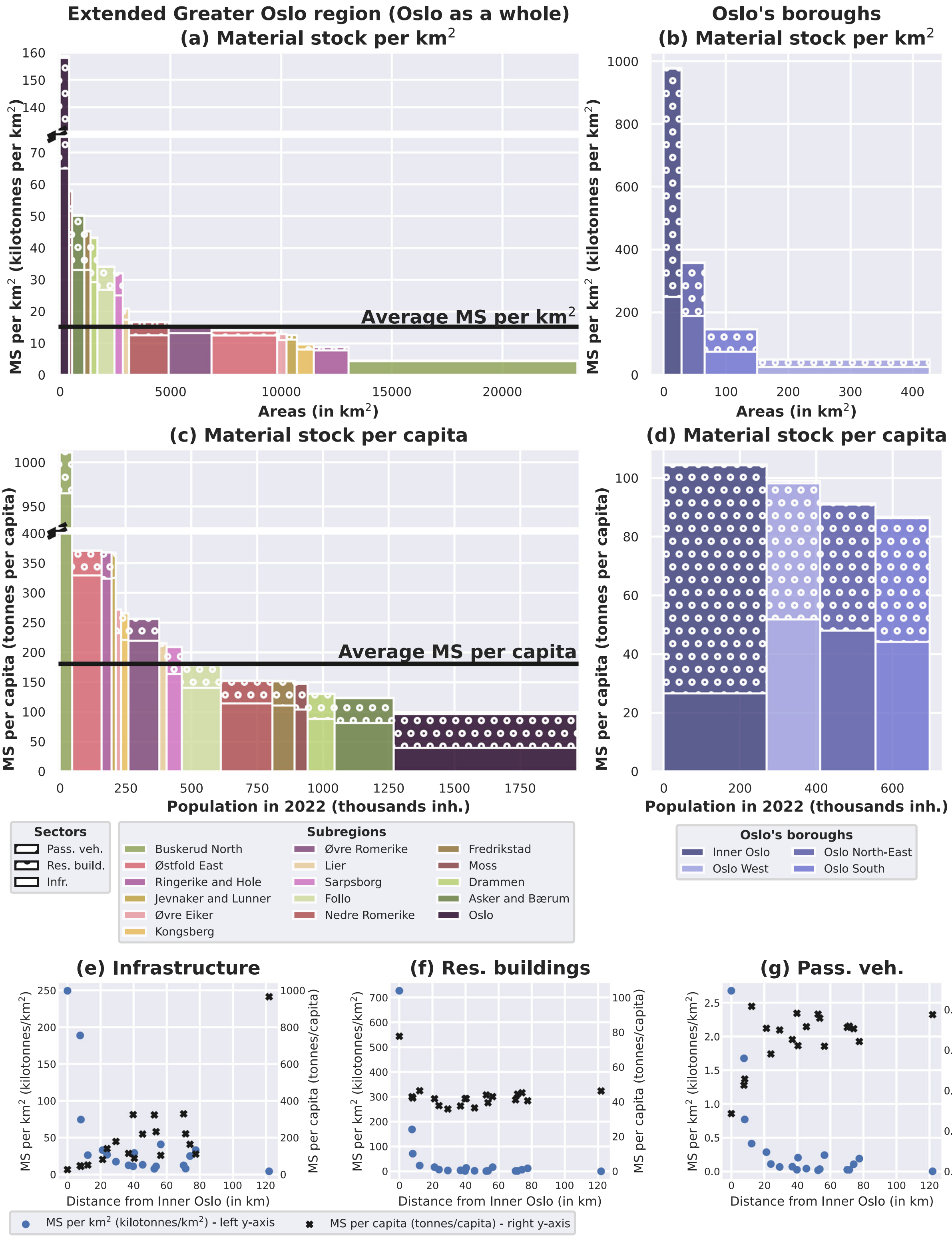

FIGURE 3 Material stock in the extended Greater Oslo region: (a) material stock per capita and (c) material stock per km^2 by subregion (Oslo's boroughs aggregated as Oslo); (b) material stock per capita and (d) material stock per km^2 for Oslo's boroughs; (e–g) Material stock per km^2 and material stock per capita as a function of the distance from Inner Oslo. The subfigures (a–d) show how the material stock is distributed between residential buildings, roads and paths, and passenger vehicles, however, passenger vehicles' material stock is not visible due to its relatively small value compared to the other stocks. The reader should note that the y-axis on charts (a) and (c) is broken for readability of smaller material stock values. Underlying data for this figure can be found in Supporting Information S2, file tab "Figure 3."

TABLE 2 Material stock comparison of 2022 and 2050 by material and sector (unit: Mt). The material stock results for 2050 are presented as a range of values [SUF scenario—BAU scenario]. Detailed data for this table can be found in Supporting Information S2, file tab "Table 2."

	2022			2050 [SUF scenario—BAU scenario]		
Material (unit: Mt)	**Res. Build.**	**Infr.**	**Pass. Veh.**	**Res. Build.**	**Infr.**	**Pass. Veh.**
Aggregates	59.9	261.9	–	[59.5–67.6]	[266.8– 273.9]	–
Cement	12.2	–	–	[12.4– 14.2]	–	–
Glass + Insulation	1.5	–	–	[1.5–1.7]	–	–
Steel + Iron	2.7	–	0.89	[2.7–3.1]	–	[0.72–0.78]
Wood	14.7	–	–	[14.9–17.1]	–	–
Bitumen	–	2.1	–	–	[2.1–2.2]	–
Aluminum	–	–	0.06	–	–	[0.07–0.07]
Copper	–	–	0.04	–	–	[0.11–0.12]
Plastics	–	–	0.19	–	–	[0.18–0.19]
Total per sector	**91**	**264**	**1.18**	**[91–103.7]**	**[268.9–276.1]**	**[1.08–1.16]**
Total	**356**			**[361–381]**		

A stock composition staying relatively constant is expected as most of the material stock is in infrastructure and the material intensities of future construction stay constant. Municipal roads and bicycle/pedestrian paths stock are estimated based on the regression analysis using 2022 stocks data. In addition, the change in material composition of the vehicle fleet is less noticeable because its material stock is relatively small compared to the built environment components.

From a spatial perspective, the material stock is growing in all subregions in the BAU scenario except in Inner Oslo where the material stock is decreasing by 8.8% mainly due to the existing residential building stock being replaced with new buildings lighter in materials. In the SUF scenario, the material stock is still increasing in most of the subregions, but the increase is limited. In both scenarios, the subregion where the material stock is estimated to grow most is Oslo North-East (+17.4% in BAU scenario, +9.1% in SUF scenario). This is the subregion with the second-largest expected population growth. In addition, apartment blocks, the most material intensive type of buildings per m^2 due to their structural elements (Amini et al., preprint under review), are predominantly built as their share of new buildings in this subregion is already nearly at 70% in 2022.

For some materials, the stock significantly increases due to the penetration of products with a different material composition such as copper (+217% in BAU scenario and +193% in SUF scenario) due to the vehicle fleet electrification. For some other materials, the stock is barely changing, such as bitumen due to limited new construction and mainly maintenance of the existing stock.

3.3 | Inflows of materials and their resulting GHGs

Accumulated inflows of materials are estimated to range between 50.5 Mt (SUF scenario) and 70.8 Mt (BAU scenario) between 2023 and 2050. The largest consumers of materials in both scenarios are Østfold East, Nedre and Øvre Romerike, Buskerud North, and Asker and Bærum. Aggregates for residential buildings and infrastructure make the largest inflows of material followed by wood and cement as displayed on Figure 4. However, aggregate production causes little GHG emissions compared to other materials. The GHG emissions from materials are dominated by emissions from steel and iron followed by cement, aluminum, and copper. Most of the metals are used to manufacture the vehicles (mostly electric vehicles) entering the vehicle fleet. Without any new climate policy implemented (Baseline scenario), the cumulated emissions due to material production until 2050 sum up to 11.8 $MtCO_2$-eq in BAU-Baseline scenario and 9.4 Mt $MtCO_2$-eq in SUF-Baseline scenario, while with a climate policy mix as described in Section 2.4 they sum up to 9.7 $MtCO_2$-eq in BAU-DEC scenario and 7.7 $MtCO_2$-eq in SUF-DEC scenario.

The reduction of material consumption between BAU and SUF scenarios, and the improvements in production technologies along with a decarbonized global electricity would reduce the total embodied GHG emissions by approximately the same amount (−21% with SUF-Baseline scenario and −18% with BAU-DEC scenario) but targeting different materials (Figure 4b). Up to 35% of GHG emissions are reduced with SUF-DEC scenarios. Major benefits are achieved in the reduction of cement use in the SUF sub-scenarios due to lowered floor area demand. In SUF, shifting new construction from SFH to AB increases material intensity, but reducing FApC leads to reduced material inflows (sheet "Individual drivers" in SI S3). Technological improvements along with a decarbonized global electricity are on the other hand targeting metals for which technological improvements have been modeled (aluminum, steel, and iron) and all materials for which electricity is used in the production (e.g., copper and cement). Both strategies are contributing similarly when independently implemented and they are reinforcing each other when combined via the greater use of decarbonized electricity in production of materials (sheet "Individual drivers" in SI S3).

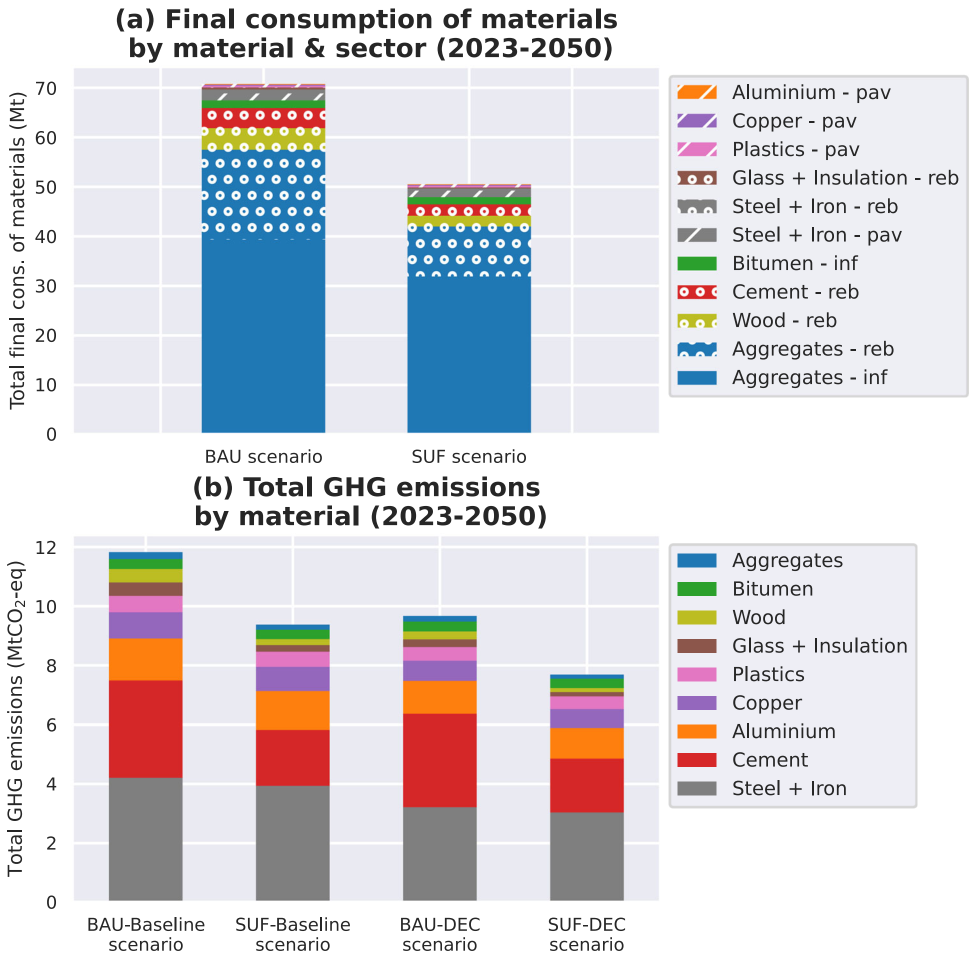

FIGURE 4 (a) Total final consumption of materials (Mt) between 2023 and 2050 by material and sector (inf, infrastructure; pav, passenger vehicles; reb, residential buildings) for business-as-usual (BAU) and sufficiency (SUF) scenarios. (b) Total greenhouse gas emissions due to the consumption of material between 2023 and 2050 by material for the four combinations of scenarios BAU-Baseline, SUF-Baseline, BAU-DEC, and SUF-DEC. Underlying data for this figure can be found in Supporting Information S2, file tab "Figure 4."

In 2023, the emissions from primary and secondary material production represent a small share (≈12%) of the total emissions comprising material production, manufacturing and waste management, use phase of passenger vehicles and residential buildings, and forest sequestration and biogenic carbon (Figure S45 in SI S1). Quantified emissions of materials represent only materials needed in the construction of new buildings (SFH/MFH/AB), construction of municipal roads and bicycle/pedestrian paths, maintenance of all the paved surfaces, and manufacture of new vehicles.

3.4 | Spatial explicit analysis of the sufficiency scenario

For the entire extended Greater Oslo region, the SUF scenario leads to a 28% reduction of total final material consumption (Figure 4). However, the extent to which the SUF scenario reduces the cumulative material flows compared to the BAU scenario depends on the subregion (Figure 5).

The distance between a subregion and Inner Oslo is not correlated with the reduction in total final material consumption from the SUF scenario. However, for the residential buildings, as the distance increases, the difference between the BAU and SUF scenario increases (Figure 5c). It is in the subregions further away from Inner Oslo where the FApC in 2022 is the largest and has had the largest increase in the past 10 years (Figures S7 and S8 in SI S1). As per our BAU scenario modeling, the continuous growth in FApC is therefore the strongest in these subregions and the difference with the SUF scenario is more significant (e.g., up to 30 m^2 difference between BAU and SUF scenario for Buskerud North). The absence of correlation in Figure 5a is due to two factors: (1) infrastructure represents a large share of the material stock (Figure 3), and (2) the SUF scenario, even though it reduces the total final consumption of material, is not correlated with the distance to Inner Oslo (Figure 5b).

The SUF scenario would also reduce the material consumption by passenger cars (Figure 5d). With the main model, passenger-km per capita changes from an average of 8029 km in 2022 to 7689 km (BAU scenario) and 7109 km (SUF scenario) in 2050. Car ownership changes from 0.47

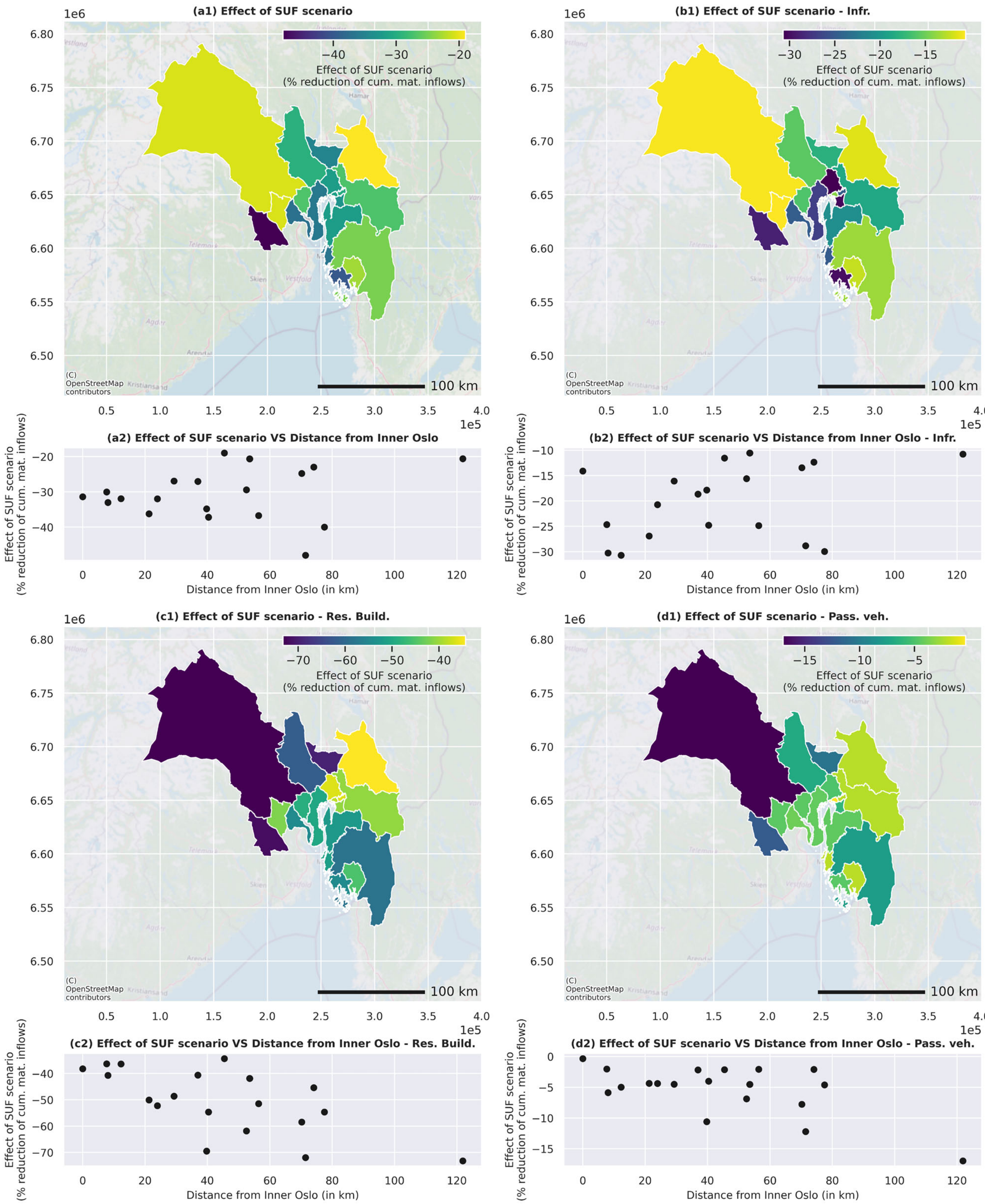

FIGURE 5 Effect of sufficiency scenario compared to business-as-usual scenario (% reduction of cumulative material inflows between 2023 and 2050) versus their radial distance from Inner Oslo for all sectors (a1, a2), infrastructure (b1, b2), residential buildings (c1, c2), and passenger vehicles (d1, d2). Underlying data for this figure can be found in Supporting Information S2, file tabs "Figure 5a", "Figure 5b", "Figure 5c", and "Figure 5d."

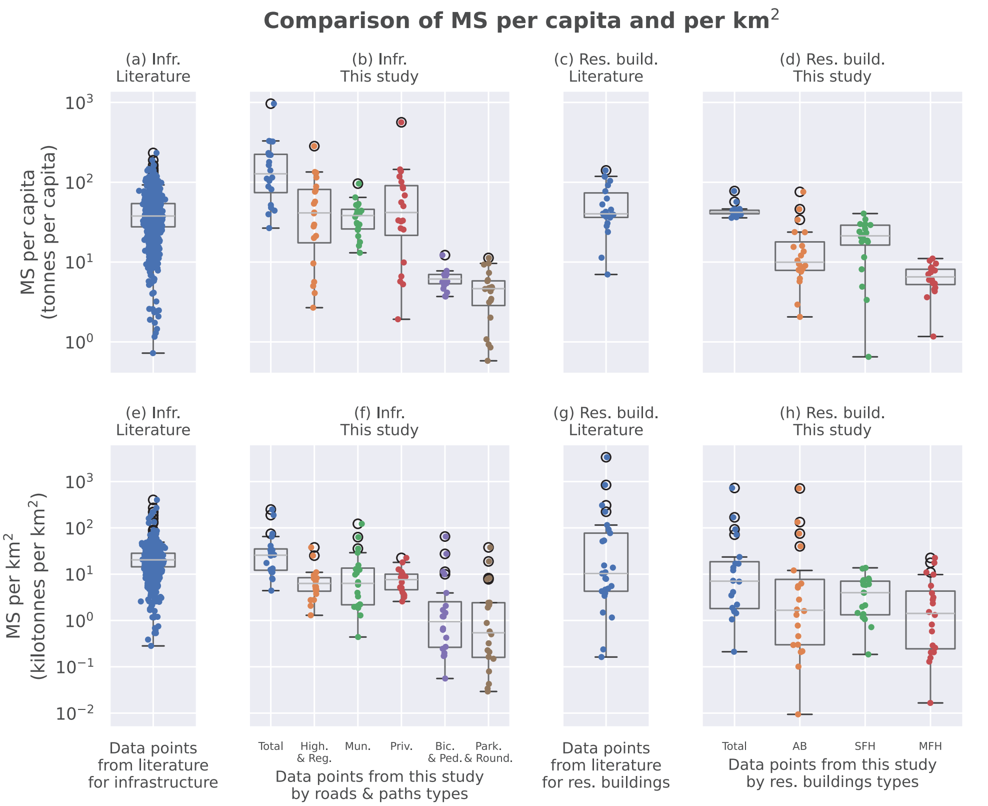

FIGURE 6 Comparison of material stock (MS) per capita (cap.) and per km^2: (a, c) MS/cap. for infrastructure and residential buildings from literature; (b, d) MS/cap. for infrastructure and residential buildings from this study; (e, g) MS/km^2 for infrastructure and residential buildings from literature; (f, h) MS/km^2 for infrastructure and residential buildings from this study. Note: The stock of residential buildings by type are divided by the total population as we are not tracking population by building type. Underlying data for this figure can be found in Supporting Information S2, file tabs "Figure 6aceg" and "Figure 6bdfh."

car/capita in 2022 to 0.45 car/capita (BAU scenario) and 0.42 car/capita (SUF scenario) in 2050. However, with the estimated passenger-km per capita, car ownership and population in 2050, the total distance driven, and total number of vehicles are higher than in 2022 (2022: 15.8 billion passenger-km and 0.92 million cars, BAU scenario in 2050: 17.8 billion passenger-km and 1.05 million cars, SUF scenario in 2050: 16.5 billion passenger-km and 0.97 million cars). It is important to note that these are affected by our modeling choices: the results of the sensitivity analysis are presented in Section S8.4 in SI S1.

4 | DISCUSSION

In this study, we mapped the material stock of residential buildings, roads and paths, and passenger vehicles in the extended Greater Oslo in 2022. We used ODYM-RECC to estimate material inflows and GHG emissions pathways resulting from transforming the residential building stock and implementing decarbonization of the material production.

4.1 | The current material stock: Comparison with literature

We compared our built environment stock results, especially stock per capita and stock per km^2, with studies encompassing buildings and/or infrastructure (roads and paths) in other high-income countries in Figure 6 (Augiseau & Kim, 2021; Deetman et al., 2020; Ebrahimi et al., 2022; Gontia et al., 2019, 2020; Haberl et al., 2021; Lanau & Liu, 2020; Miatto et al., 2017; Mollaei et al., 2021; Pauliuk et al., 2021; Rousseau et al., 2022; Tanikawa & Hashimoto, 2009; Wiedenhofer et al., 2015).

Material stock per capita in infrastructure is in the upper half of the range of findings from literature, with Buskerud North (nearly 1000 tonnes/capita) being an outlier. Low population density and private roads modeled as paved roads could explain the high values in our study. On a per km^2 basis, our values fall within the range reported in the literature. So do our estimates of material for residential buildings per capita or per km^2.

Even though our results are of similar order of magnitude as previous findings, comparisons are not straightforward due to varying scopes, buildings and infrastructure types, or materials analyzed. Important factors included the availability of construction materials (common use of wood in Norway for SFH/MFH), construction practices, socio-economic factors, climate, land availability, and spatial distribution of the built environment components (Fishman et al., 2014; Mollaei et al., 2021). In addition, the literature focused on urban areas or at the country scale, therefore not studying low-density areas such as Buskerud North.

When analyzing the spatial distribution of the stock composition, we observed similarities with previous findings. The material stock gets more dominated by infrastructure when the material stock of residential buildings per km^2 decreases (Figure S36 in SI S1), mirroring the findings in the Paris region (Augiseau & Kim, 2021). A larger material stock of infrastructure per capita and an increasing FApC associated with increasing distance from the main city center were also observed in Odense (Lanau & Liu, 2020).

4.2 | Our findings in perspective

Our scenarios for the extended Greater Oslo region show that sufficiency in residential buildings can bring down the material consumption by 30%. However, the FApC in Greater Oslo has been increasing in recent years (except Oslo as a whole), and reversing the trend could be challenging. Norwegians tend to own their home and have more residential living space than other Europeans (Eurostat, 2023). High home ownership is an intended policy outcome (Bø, 2020), but the same policies also indirectly incentivize large homes. In 2022, a public assessment of Norway's tax policy (Norges offentlige utredninger, 2022) compares taxes and tax subsidies of home ownership and finds that there are substantial net subsidies in the form of being able to offset mortgage interests against income, avoiding wealth taxation through discounts on the assessed property value, and not paying income tax on the appreciation of the value of a property. The tax commission recommends returning to a tax on the benefit of living in a self-owned property, but if this is not achieved, to eliminate offsetting mortgage interest against income and mortgage debt against wealth. While such changes in the tax system are not popular and have hence not been yet adopted, they would lead to a substantial reduction in the property investment by wealthy households with already large residences.

Policies for smaller residential units would also reduce yearly distance driven and car per capita as a consequence of reducing floor area dedicated to SFH. Even if we are not modeling densification directly, our SUF scenario points toward densifying settlements and our results support the dependency of motorized transport on settlement density, also in Nordic countries (Næss et al., 1996; Ness, 2023; Newman & Kenworthy, 1989, 2006). Still, our results show the limited impact of changing solely the residential buildings would have on mobility due to the long lifetime of buildings preventing drastic changes in the stock. We also observe that we cannot solely rely on reducing FApC and banning SFH to affect mobility patterns as the per-capita decreases are far from being sufficient to compensate the growth of population and reduce the total passenger-km driven and stock of passenger vehicles. Additional strategies are needed. Oslo municipality is working with measures to reduce car use such as providing public transport and car sharing services, increasing road tolls, making it easier to walk/bike (Oslo Kommune, 2023). However, such strategies are more easily implemented in denser areas (Camagni et al., 2002; Hjorteset & Böcker, 2020). As we have shown how slow changes can be, thinking how future housing is built should happen now (Rankin & Saxe, 2024). Moreover, driving habits are not only dependent on built environment components but could also be affected by socio-economic factors or shifts in cultural preferences (Jackson, 2005; Pérez-Sánchez et al., 2024; Thøgersen et al., 2021). Therefore, additional incentives may well be effective in reducing car use.

4.3 | Limitations and future research

Our study brings together residential buildings, some infrastructure components, and passenger vehicles. A natural next step would be to include the non-residential buildings which are an essential component of the built environment affecting the use of passenger vehicles (Rokseth et al., 2021).

We see that in the SUF scenario combined with a decarbonization of the materials supply chain, mitigation of GHG emissions from material production could be of ≈30% compared to the BAU scenario. These emissions generated from material use should be considered as a lower estimate. Only the production phase of materials is covered for most of the materials, except copper and plastics for which transport to the consumers is included. For some materials, as aggregates, the transport to the consumer site is a large contributor (Rosado et al., 2017) which is not accounted for in the model.

The emissions from material production represent a small share (≈12%) of the total emissions. Hence, strategies for mitigating emissions from the use phase of passenger vehicles and residential buildings are also crucial to the mitigation of emissions by 2050. However, we did not investigate mitigation of use phase emissions because maintenance and renovation of residential buildings was out of the scope of this research to focus on the relationships between the sectors involving mainly the construction of new buildings.

By being a python code with data stored in excel spreadsheets, ODYM-RECC offers the flexibility to be changed according to a variety of research needs. We could make use of the core of the model to evaluate how strategies reducing material production-related GHG emissions would contribute to mitigating emissions in the extended Greater Oslo. The model could be adapted to other geographic areas if the required data are collected. However, the integrated residential building–infrastructure–car fleet model developed in this study is specific to the region and is integrated in the code. A future user would need to adapt the modeling or choose to model the sectors individually by filling in the required parameters (future stock of infrastructure and distance driven by car). ODYM-RECC includes additional functionalities such as the use of lightweighting materials or introducing car sharing, which were not investigated in this study to evaluate scenarios about residential buildings services solely. However, these functionalities could be used for assessing additional development pathways reducing material consumption and mitigating GHG emissions. There are some limitations to ODYM-RECC worth highlighting: FApC is modeled independent of the type of building preventing us from making targeted scenarios such as reducing FApC specifically for SFH (additional details about that limitation are provided in Section S9 in SI S1). Moreover, the absence of constraints on how the existing residential building total floor area is distributed into individual buildings/dwellings prevents closely monitoring the composition of the residential building stock.

Downscaling the geographical scope implies that land available for construction is limited, especially in subregions already urbanized. There is therefore a need for modeling land use in the building stock model to better capture the space available for new construction and evaluate land use savings as it is done in Pérez-Sánchez et al. (2024).

5 | CONCLUSIONS

A mapping of the material stocks and flows provides an understanding of potential development pathways in the extended Greater Oslo region: where materials have accumulated, where and by how much the stock is expected to increase, and where the material inflows will be the largest with their associated GHG emissions from production.

Our findings indicate that resource efficiency measures and material supply chain measures are complementary and contribute independently to climate change mitigation. A combination of strategies is therefore recommended for effective mitigation. Policies supporting smaller residential units would be needed to achieve the modeled benefits from the SUF scenario. Shifting from SFH construction to MFH/AB construction might lead to an increase in material use if the FApC is not restricted. Global efforts and international supports to decarbonize the material supply chain is also necessary for Norway to decarbonize its own material supply when materials are imported. The total number of cars and traveled distance fails to decline due to the population growth. Car ownership and use need to be challenged by additional incentives to move away from car driving. This highlights the need to consider local, national, and international context when assessing resource efficiency strategies and material decarbonization for climate change mitigation at municipal and county levels.

ACKNOWLEDGMENTS

Lola S. A. Rousseau and Sara Amini were supported by funding from NTNU. 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, No. 257660). Some of the computations and results analysis were performed on resources provided by the Industrial Ecology Digital Laboratory at NTNU. The authors would like to thank Peter Schön (NTNU) for processing the National Transport Survey data, Stefan Pauliuk for support with ODYM-RECC, as well as Kim Rainer Mattson (NTNU) and Marthe Alnes Høiberg (NTNU) for their inputs. Lastly, the authors are thankful to the two anonymous reviewers who provided insightful comments improving the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The ODYM-RECC database (ODYM-RECC VN1.0) we have used for this study builds upon the ODYM-RECC v2.4 (https://doi.org/10.5281/zenodo.4671644) and ODYM-RECC v2.5 (https://doi.org/10.5281/zenodo.12752350). The ODYM-RECC VN1.0 database and output files of ODYM-RECC runs are available on Zenodo (https://doi.org/10.5281/zenodo.14200001). The ODYM-RECC code is made available on Github (https://github.com/LolaRousseau/RECC-ODYM) and archived on Zenodo (https://doi.org/10.5281/zenodo.14202901). Some of the data used in this study are from GeoNorge, GeoData, and Statens vegvesen. Restrictions apply to the availability of these data, which were used under license for this study. Some of the data are available at https://www.geonorge.no/ and https://www.geodata.no/. Data under the Norwegian license for public data (NLOD) made available by the Norwegian Public Roads Administration were also used in this study.

ORCID

Lola S. A. Rousseau https://orcid.org/0000-0003-2829-5376
Jan Sandstad Næss https://orcid.org/0000-0003-3166-913X
Fabio Carrer https://orcid.org/0009-0007-6432-6295

Sara Amini https://orcid.org/0009-0003-4107-1024
Helge Brattebø https://orcid.org/0000-0001-8095-1663
Edgar G. Hertwich https://orcid.org/0000-0002-4934-3421

REFERENCES

Amini, S., Rousseau, L. S. A., & Hertwich, E. G. (preprint under review). Material and Energy Use in Norway's Residential Building Archetypes. *SocArXiv Papers*. https://doi.org/10.31235/osf.io/emsa4

Augiseau, V., & Barles, S. (2017). Studying construction materials flows and stock: A review. *Resources, Conservation and Recycling*, *123*, 153–164. https://doi.org/10.1016/j.resconrec.2016.09.002

Augiseau, V., & Kim, E. (2021). Spatial characterization of construction material stocks: The case of the Paris region. *Resources, Conservation and Recycling*, *170*, 105512. https://doi.org/10.1016/j.resconrec.2021.105512

Bø, E. E. (2020). Taxation of housing: Killing several birds with one stone. *Review of Income and Wealth*, *66*(3), 534–557. https://doi.org/10.1111/roiw.12423

Bohne, R. A., Brattebø, H., Bergsdal, H., & Hovde, P. J. (2006). Estimation of the service life of buildings, and building components. In *Conference Proceedings of Towards the City Surface of Tomorrow*, Vienna, Austria, 29–33.

Camagni, R., Gibelli, M. C., & Rigamonti, P. (2002). Urban mobility and urban form: The social and environmental costs of different patterns of urban expansion. *Ecological Economics*, *40*(2), 199–216. https://doi.org/10.1016/S0921-8009(01)00254-3

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D. P., Edelenbosch, O., & Heijungs, R. (2020). Modelling global material stocks and flows for residential and service sector buildings towards 2050. *Journal of Cleaner Production*, *245*, 118658. https://doi.org/10.1016/j.jclepro.2019.118658

Ebrahimi, B., Rosado, L., & Wallbaum, H. (2022). Machine learning-based stocks and flows modeling of road infrastructure. *Journal of Industrial Ecology*, *26*(1), 44–57. https://doi.org/10.1111/jiec.13232

Eurostat. (2023). *Housing in Europe –2023 edition*. https://ec.europa.eu/eurostat/web/interactive-publications/housing-2023

Fishman, T., Schandl, H., Tanikawa, H., Walker, P., & Krausmann, F. (2014). Accounting for the material stock of nations. *Journal of Industrial Ecology*, *18*(3), 407–420. https://doi.org/10.1111/jiec.12114

Geodata Online. (2023a). *FKB Veg—FKB (Felles kartdatabase)—GeomapFKB [FKB Roads—FKB (Common Map Database)—GeomapFKB]*. https://dokumentasjon.geodataonline.no/docs/Temakart/FKB

GeoNorge. (2023). *FKB Veg—FKB (Felles kartdatabase) [FKB Roads—FKB (Common Map Database)]*. https://kartkatalog.geonorge.no/

Gontia, P., Thuvander, L., Ebrahimi, B., Vinas, V., Rosado, L., & Wallbaum, H. (2019). Spatial analysis of urban material stock with clustering algorithms: A Northern European case study. *Journal of Industrial Ecology*, *23*(6), 1328–1343. https://doi.org/10.1111/jiec.12939

Gontia, P., Thuvander, L., & Wallbaum, H. (2020). Spatiotemporal characteristics of residential material stocks and flows in urban, commuter, and rural settlements. *Journal of Cleaner Production*, *251*, 119435. https://doi.org/10.1016/j.jclepro.2019.119435

Haberl, H., Wiedenhofer, D., Erb, K.-H., Görg, C., & Krausmann, F. (2017). The material stock–flow–service nexus: A new approach for tackling the decoupling conundrum. *Sustainability*, *9*(7), 1049. https://doi.org/10.3390/su9071049

Haberl, H., Wiedenhofer, D., Schug, F., Frantz, D., Virág, D., Plutzar, C., Gruhler, K., Lederer, J., Schiller, G., Fishman, T., Lanau, M., Gattringer, A., Kemper, T., Liu, G., Tanikawa, H., van der Linden, S., & Hostert, P. (2021). High-resolution maps of material stocks in buildings and infrastructures in Austria and Germany. *Environmental Science & Technology*, *55*(5), 3368–3379. https://doi.org/10.1021/acs.est.0c05642

Hertwich, E., Lifset, R., Pauliuk, S., & Heeren, N. (2020). *Resource efficiency and climate change: Material efficiency strategies for a low-carbon future*. International Resource Panel (IRP), United Nations Environment Programme. https://doi.org/10.5281/zenodo.3542680

Hjorteset, M. A., & Böcker, L. (2020). Car sharing in Norwegian urban areas: Examining interest, intention and the decision to enrol. *Transportation Research Part D: Transport and Environment*, *84*, 102322. https://doi.org/10.1016/j.trd.2020.102322

Industrial Ecology Freiburg. (2024). *ODYM-RECC*. https://www.industrialecology.uni-freiburg.de/odym-recc

IPCC. (2022). *Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jackson, T. (2005). Live better by consuming less?: Is there a "double dividend" in sustainable consumption? *Journal of Industrial Ecology*, *9*(1–2), 19–36. https://doi.org/10.1162/1088198054084734

Kennedy, C., Cuddihy, J., & Engel-Yan, J. (2007). The changing metabolism of cities. *Journal of Industrial Ecology*, *11*(2), 43–59. https://doi.org/10.1162/jie.2007.1107

Kikstra, J., Daioglou, V., Min, J., Sferra, F., Soergel, B., Kriegler, E., Lee, H., Mastrucci, A., Pachauri, S., Rao, N., Rauner, S., Vuuren, D., Riahi, K., van Ruijven, B., & Rogelj, J. (2024). *Closing decent living gaps in energy and emissions scenarios: Introducing DESIRE [preprint v1.0]*. https://doi.org/10.13140/RG.2.2.27951.14241

Krausmann, F., Lauk, C., Haas, W., & Wiedenhofer, D. (2018). From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. *Global Environmental Change*, *52*, 131–140. https://doi.org/10.1016/j.gloenvcha.2018.07.003

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., & Haberl, H. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences*, *114*(8), 1880–1885. https://doi.org/10.1073/pnas.1613773114

Lanau, M. (2020). *Weighing the importance of urban built environment stocks for sustainability. A Danish case study* [PhD thesis]. Syddansk Universitet. Det Tekniske Fakultet.

Lanau, M., Herbert, L., & Liu, G. (2021). Extending urban stocks and flows analysis to urban greenhouse gas emission accounting: A case of Odense, Denmark. *Journal of Industrial Ecology*, *25*(4), 961–978. https://doi.org/10.1111/jiec.13110

Lanau, M., & Liu, G. (2020). Developing an urban resource cadaster for circular economy: A case of Odense, Denmark. *Environmental Science & Technology*, *54*(7), 4675–4685. https://doi.org/10.1021/acs.est.9b07749

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., & Ehlert, C. (2019). Taking stock of built environment stock studies: Progress and prospects. *Environmental Science & Technology*, *53*(15), 8499–8515. https://doi.org/10.1021/acs.est.8b06652

Lin, C., Liu, G., & Müller, D. B. (2017). Characterizing the role of built environment stocks in human development and emission growth. *Resources, Conservation and Recycling*, *123*, 67–72. https://doi.org/10.1016/j.resconrec.2016.07.004

Miatto, A., Schandl, H., Wiedenhofer, D., Krausmann, F., & Tanikawa, H. (2017). Modeling material flows and stocks of the road network in the United States 1905–2015. *Resources, Conservation and Recycling*, *127*, 168–178. https://doi.org/10.1016/j.resconrec.2017.08.024

Mollaei, A., Ibrahim, N., & Habib, K. (2021). Estimating the construction material stocks in two Canadian cities: A case study of Kitchener and Waterloo. *Journal of Cleaner Production*, *280*, 124501. https://doi.org/10.1016/j.jclepro.2020.124501

Müller, D. B., Liu, G., Løvik, A. N., Modaresi, R., Pauliuk, S., Steinhoff, F. S., & Brattebø, H. (2013). Carbon emissions of infrastructure development. *Environmental Science & Technology*, *47*(20), 11739–11746. https://doi.org/10.1021/es402618m

Næss, P., Sandberg, S. L., & Røe, P. G. (1996). Energy use for transportation in 22 Nordic towns. *Scandinavian Housing and Planning Research*, *13*(2), 79–97. https://doi.org/10.1080/02815739608730401

Ness, D. (2023). Growth in floor area: The blind spot in cutting carbon. *Emerald Open Research*, *1*(5), https://doi.org/10.1108/EOR-05-2023-0002

Newman, P., & Kenworthy, J. (1989). Gasoline consumption and cities. *Journal of the American Planning Association*, *55*(1), 24–37. https://doi.org/10.1080/01944368908975398

Newman, P., & Kenworthy, J. (2006). Urban design to reduce automobile dependence. *Opolis*, *2*(1), 35–52. https://escholarship.org/uc/item/2b76f089

Norges offentlige utredninger. (2022). *Et helhetlig skattesystem [A comprehensive tax system]*. https://www.regjeringen.no/contentassets/2dcc57a783cc4403bbdb48558514dc38/no/pdfs/nou202220220020000dddpdfs.pdf

Norsk elbilforening [Norwegian Electric Car Association]. (2024). *Statistikk elbil—Elbilbestand og markedsandel [Electric car statistics—Electric car stock and market share]*. https://elbil.no/om-elbil/elbilstatistikk/

NVDB. (2023a). *Bærelag [Bearing layer]*. https://nvdb-eksport.atlas.vegvesen.no/vegobjekter/226.csv?segmentering=true&kartutsnitt=-617776.919%2C6348628.017%2C1116199.882%2C7105888.198&typeveg=kanalisertVeg%2CenkelBilveg&inkluder=alle&api=https://nvdbapiles-v3.atlas.vegvesen.no

NVDB. (2023b). *Forsterkningslag [Reinforcement layer]*. https://nvdb-eksport.atlas.vegvesen.no/vegobjekter/227.csv?segmentering=true&kartutsnitt=-617776.919%2C6348628.017%2C1116199.882%2C7105888.198&typeveg=kanalisertVeg%2CenkelBilveg&inkluder=alle&api=https://nvdbapiles-v3.atlas.vegvesen.no

NVDB. (2023c). *Trafikkmengde [Traffic volume]*. https://nvdb-eksport.atlas.vegvesen.no/vegobjekter/540.csv?segmentering=true&kartutsnitt=-617776.919%2C6348628.017%2C1116199.882%2C7105888.198&typeveg=kanalisertVeg%2CenkelBilveg&inkluder=alle&api=https://nvdbapiles-v3.atlas.vegvesen.no

NVDB. (2023d). *Vegdekke [Road surface]*. https://nvdb-eksport.atlas.vegvesen.no/vegobjekter/241.csv?segmentering=true&kartutsnitt=-617776.919%2C6348628.017%2C1116199.882%2C7105888.198&typeveg=kanalisertVeg%2CenkelBilveg&inkluder=alle&api=https://nvdbapiles-v3.atlas.vegvesen.no

ODYM-RECC. (2024). *GitHub ODYM-RECC used in this study*. https://github.com/LolaRousseau/RECC-ODYM/releases/tag/v1.0

Geodata Online. (2023b). *Motorvognregister—Biler, anonymisert til grunnkrets [Motor vehicle register—Vehicles anonymised per basic statistical unit]*. https://dokumentasjon.geodataonline.no/docs/Temakart/Motorvognregisteret

Oslo Kommune. (2023). *Oslo's Climate budget 2023*. https://www.klimaoslo.no/rapport/oslos-climate-budget-2023/

Oslo Municipality's Statistics Bank. (2023). *Befolkningsframskrivning mellomalternativet etter år, kjønn og alder (B) [Population projection of the intermediate alternative by year, gender and age (B)]—Districts in Oslo*. https://statistikkbanken.oslo.kommune.no/

Pauliuk, S. (2023). *Documentation of the RECC model v2.5—Open dynamic material systems model for the resource efficiency-climate change (RECC) nexus*. https://freidok.uni-freiburg.de/fedora/objects/freidok:242061/datastreams/FILE1/content

Pauliuk, S., Carrer, F., Heeren, N., & Hertwich, E. G. (2024). Scenario analysis of supply- and demand-side solutions for circular economy and climate change mitigation in the global building sector. *Journal of Industrial Ecology*, *28*(6), 1699–1715. https://doi.org/10.1111/jiec.13557

Pauliuk, S., Fishman, T., Heeren, N., Berrill, P., Tu, Q., Wolfram, P., & Hertwich, E. G. (2020). Linking service provision to material cycles: A new framework for studying the resource efficiency–climate change (RECC) nexus. *Journal of Industrial Ecology*, *25*(2), 260–273. https://doi.org/10.1111/jiec.13023

Pauliuk, S., & Heeren, N. (2021). Material efficiency and its contribution to climate change mitigation in Germany: A deep decarbonization scenario analysis until 2060. *Journal of Industrial Ecology*, *25*(2), 479–493. https://doi.org/10.1111/jiec.13091

Pauliuk, S., Heeren, N., Berrill, P., Fishman, T., Nistad, A., Tu, Q., Wolfram, P., & Hertwich, E. G. (2021). Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nature Communications*, *12*(1), 5097. https://doi.org/10.1038/s41467-021-25300-4

Pauliuk, S., & Müller, D. B. (2014). The role of in-use stocks in the social metabolism and in climate change mitigation. *Global Environmental Change*, *24*, 132–142. https://doi.org/10.1016/j.gloenvcha.2013.11.006

Pérez-Sánchez, L. À., Fishman, T., & Behrens, P. (2024). Undoing the lock-in of suburban sprawl: Towards an integrated modelling of materials and emissions in buildings and vehicles. *Journal of Cleaner Production*, *451*, 141954. https://doi.org/10.1016/j.jclepro.2024.141954

Rankin, K. H., & Saxe, S. (2024). A future growth model for building more housing and infrastructure with less embodied greenhouse gas. *Environmental Science & Technology*, *58*(25), 10979–10990. https://doi.org/10.1021/acs.est.4c02070

Rao, N. D., & Min, J. (2018). Decent living standards: Material prerequisites for human wellbeing. *Social Indicators Research*, *138*(1), 225–244. https://doi.org/10.1007/s11205-017-1650-0

Rokseth, L. S., Heinen, E., Hauglin, E. A., Nordström, T., & Manum, B. (2021). Reducing private car demand, fact or fiction? A study mapping changes in accessibility to grocery stores in Norway. *European Transport Research Review*, *13*(1), 39. https://doi.org/10.1186/s12544-021-00500-7

Rosado, L. P., Vitale, P., Penteado, C. S. G., & Arena, U. (2017). Life cycle assessment of natural and mixed recycled aggregate production in Brazil. *Journal of Cleaner Production*, *151*, 634–642. https://doi.org/10.1016/j.jclepro.2017.03.068

Rousseau, L. S. A., Kloostra, B., AzariJafari, H., Saxe, S., Gregory, J., & Hertwich, E. G. (2022). Material stock and embodied greenhouse gas emissions of global and urban road pavement. *Environmental Science & Technology*, *56*(24), 18050–18059. https://doi.org/10.1021/acs.est.2c05255

Saxe, S., & Kasraian, D. (2020). Rethinking environmental LCA life stages for transport infrastructure to facilitate holistic assessment. *Journal of Industrial Ecology*, *24*(5), 1031–1046. https://doi.org/10.1111/jiec.13010

Statens vegvesen. (2023). *Den nasjonale reisevaneundersøkelsen—2022 [The national transport survey—2022] - Processed results shared through personal communication*. https://www.vegvesen.no/fag/fokusomrader/nasjonal-transportplan/den-nasjonale-reisevaneundersokelsen/

Statistisk Sentralbyrå [Statistics Norway]. (2022a). *12579: Kjørelengder, etter eierens bostedskommune [12579: Driving lengths, according to the owner's municipality of residence]*. https://www.ssb.no/statbank/sq/10082805

Statistisk Sentralbyrå [Statistics Norway]. (2022b). *13370: Registrerte kjøretøy, etter region, drivstofftype, statistikkvariabel, år og eierform [13370: Registered vehicles, by region, fuel type, statistical variable, year and form of ownership].* https://www.ssb.no/statbank/table/13370

Statistisk Sentralbyrå [Statistics Norway]. (2023a). *13600: Framskrevet folkemengde 1. Januar, etter region, år og statistikkvariabel [13600: Projected population on 1 January, by region, year and statistical variable]—Municipalities in Viken.* https://www.ssb.no/statbank/sq/10079549

Statistisk Sentralbyrå [Statistics Norway]. (2023b). Urban settlements 2022. https://kart.ssb.no/

Statistisk Sentralbyrå [Statistics Norway]. (2023c). *Dwellings in boroughs of Oslo and municipalities in Viken with their characteristics as per January 1st 2023—Shared through personal communication.*

Statistisk Sentralbyrå [Statistics Norway]. (2024). *Befolkningsframskrivinger for kommunene 2024 [Population projections for municipalities 2024].* https://www.ssb.no/en/befolkning/befolkningsframskrivinger/artikler/municipal-population-projections-2024/_/attachment/inline/ca130107-4289-477e-8761-5c012fa9854e:fb45379c08b73156b767ae8214959b58f6b86312/RAPP2024-20.pdf

Swilling, M., Hajer, M., Baynes, T., Bergesen, J., Labbé, F., Musango, J. K., Ramaswami, A., Robinson, B., Salat, S., & Suh, S. (2018). *The weight of cities: Resource requirements of future urbanization*. IRP Reports.

Tanikawa, H., & Hashimoto, S. (2009). Urban stock over time: Spatial material stock analysis using 4d-GIS. *Building Research & Information*, *37*(5–6), 483–502. https://doi.org/10.1080/09613210903169394

Thøgersen, J., Vatn, A., Aasen, M., Dunlap, R. E., Fisher, D. R., Hellevik, O., & Stern, P. (2021). Why do people continue driving conventional cars despite climate change? Social-psychological and institutional insights from a survey of Norwegian commuters. *Energy Research & Social Science*, *79*, 102168. https://doi.org/10.1016/j.erss.2021.102168

Vélez-Henao, J. A., & Pauliuk, S. (2025). Pathways to a net zero building sector in Colombia: Insights from a circular economy perspective. *Resources, Conservation and Recycling*, *212*, 107971. https://doi.org/10.1016/j.resconrec.2024.107971

Wiedenhofer, D., Baumgart, A., Matej, S., Virág, D., Kalt, G., Lanau, M., Tingley, D. D., Liu, Z., Guo, J., Tanikawa, H., & Haberl, H. (2024). Mapping and modelling global mobility infrastructure stocks, material flows and their embodied greenhouse gas emissions. *Journal of Cleaner Production*, *434*, 139742. https://doi.org/10.1016/j.jclepro.2023.139742

Wiedenhofer, D., Steinberger, J. K., Eisenmenger, N., & Haas, W. (2015). Maintenance and expansion: Modeling material stocks and flows for residential buildings and transportation networks in the EU25. *Journal of Industrial Ecology*, *19*(4), 538–551. https://doi.org/10.1111/jiec.12216

SUPPORTING INFORMATION

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

How to cite this article: Rousseau, L. S. A., Næss, J. S., Carrer, F., Amini, S., Brattebø, H., & Hertwich, E. G. (2025). Reducing material use and their greenhouse gas emissions in Greater Oslo. *Journal of Industrial Ecology*, *29*, 390–405. https://doi.org/10.1111/jiec.13611