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live (a) little: GHG emissions from residential building materials for all 400 counties and cities of Germany until 2050

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A R T I C L E I N F O

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A B S T R A C T

Germany is trying to solve the housing crisis in many of its cities with new construction. At the same time it is trying to meet its greenhouse gas emissions commitments under the Paris Agreement. This study examines how measures to tackle the housing crisis affect the climate crisis by looking at whether material emissions from the construction sector are in line with Germany's decarbonization targets. We project material demand and associated emissions from 2024 to 2050 using dynamic material flow analysis of a novel high-resolution building stock model based on synthetic population microdata. The model incorporates technological improvements in building design and material efficiency, finding that these fall short of carbon neutrality targets in 2045 and beyond. A reduction in per capita floor area is required to meet the targets. The high spatial resolution of this study allows the identification of reduction hotspots within Germany's 400 cities and counties, emphasizing the need for location-specific policy for national goals.

1. Introduction

The building sector has the largest impact on climate change, ahead of food and transport (Tukker and Jansen, 2006; Bruyninckx et al., 2024). Residential and commercial buildings account for 37% of global greenhouse gas (GHG) emissions (UNEP, 2024). Globally, about two-thirds of these emissions come from energy production for heating and cooling, and one-third from the production of building materials (IRP et al., 2019). This varies widely between countries, with higher shares in developing countries and countries with lower demand for heating (Ibn-Mohammed et al., 2013; IPCC, 2007). Mitigation of emissions from buildings has largely focused on reducing energy demand through energy efficiency and switching to renewable energy sources (Sorrell, 2015; Hertwich et al., 2019; Mastrucci et al., 2021). As a result, the share of emissions from material production is increasing as the energy system decarbonizes and buildings become more energy efficient (Röck et al., 2020). This motivates the reduction of material demand through material efficiency (Allwood et al., 2011, 2013).

Improving material efficiency requires environmental policies that focus not only on the use phase of buildings, but especially on the construction phase, where most of the material demand takes place. In Germany and in many other countries, most decisions regarding construction, such as zoning or permits, are made at the local administrative level of cities or counties (German: Landkreise). This is often necessary due to the large heterogeneity in existing housing stock, population structure, and wealth between regions, and underlines the importance of analyzing material flows and emissions at the administrative level where policy is implemented (Schiller et al., 2017). However, such high spatial resolution has been underrepresented in research (Lanau et al., 2019). Many assessments of the building stock apply material flow analysis (MFA) to provide scenarios and policy recommendations at the national level (Pauliuk et al., 2013; Huang et al., 2013; Giesekam et al., 2014; Hertwich et al., 2019; Zhong et al., 2021; Pauliuk et al., 2021), with only a few studies at the sub-national level, such as Berrill and Hertwich (2021) for US counties or Rousseau et al. (2024) for Greater Oslo. However, unlike other in-use stocks like vehicles for instance, buildings are largely immobile, so spatial resolution is fundamental to their analysis. For example, meeting housing needs requires having sufficient housing stock not just nationally, but specifically where people need it.

This type of high-resolution, comprehensive, dynamic material flow analysis of the built environment is often constrained by a lack of appropriate data. A dynamic stock-flow model requires detailed data

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on the housing stock in use and its age in order to model the future stock. These data are not available at high spatial resolution for many countries, and only recent methodological advances allow estimating building characteristics at finer scales (Peled and Fishman, 2021; Sun et al., 2021; Haberl et al., 2021; Milojevic-Dupont et al., 2023). We introduce a novel approach using synthetic population data (Többen et al., 2023) to estimate building characteristics at high spatial resolution. The dataset from Többen et al. (2023), which statistically reproduces household survey responses while matching census constraints, allows us to estimate residential building stock by age, size and type for all 400 German cities and counties.

Germany presents a critical case study for analyzing the tension between housing needs and climate targets. The German government has pledged to address the housing crisis in many of its cities by building homes cheaper and faster (BMWSB, 2022), while simultaneously committing to ambitious emission reduction targets including carbon neutrality by 2045. Previous research on the German building sector's compliance with GHG emission targets has shown that emissions exceed limits and are unlikely to decrease at the required rate (Harthan et al., 2020). These findings contributed to the 2021 decision by the German Constitutional Court mandating stronger emission reductions (BVerfG, 2021). Previous assessments typically analyzed the construction sector at a national level. By conducting 400 parallel stock-flow analyses for each city and county, this study provides a novel perspective on the spatial distribution of construction-related emissions throughout Germany. This study addresses three main research questions:

1. How do construction demand and associated emissions vary across Germany's 400 cities and counties through 2050?
2. To what extent can technological improvements in construction methods reduce emissions while maintaining current floor area per capita?
3. Are the potential reductions in line with national decarbonization targets?

2. Methodology

2.1. Model

We model construction demand in German cities and counties until 2050, and link it to the materials needed for construction and the emissions from their production. The model is adapted from the ODYM-RECC model (Pauliuk et al., 2021), which is based on the Resource Efficiency and Climate Change (RECC) model framework using the Open Dynamic Material Systems Model (ODYM) framework (Pauliuk et al., 2020a; Pauliuk and Heeren, 2020). The model was implemented for Germany by Pauliuk and Heeren (2021) with nationally specific parameters and scenarios and we regionalized the model to the city and county level. ODYM-RECC was selected because it is a state-of-the-art, open-source model that is widely used in the current literature on material flow analysis of buildings and has been adopted by the International Resource Panel (Hertwich et al., 2019; Baars et al., 2022).

Therefore, regionalization requires a resolution to the city and county level for all three data inputs:

- residential building stock
- population
- floor area per capita

Population and floor area per capita are used as input data to calculate housing demand according to Eq. (1) in yearly time steps as part of a dynamic MFA model.

$$\text{housing demand}_{year}\ [\text{m}^2] = \text{population}_{year} \times \frac{\text{floor area } [\text{m}^2]}{\text{capita}}_{year} \quad (1)$$

This stock-driven model calculates the necessary inflows (construction) to the building stock every year based on the difference between housing demand and building stock as in Eq. (2).

$$\text{construction demand}_{\text{year}}\ [\text{m}^2] = \text{housing demand}_{\text{year}}\ [\text{m}^2] - \text{building stock}_{\text{year}}\ [\text{m}^2] \quad (2)$$

The model further calculates the yearly outflows (demolition) from the building stock, based on buildings reaching their end-of-life statistically distributed around 120 years after their construction.

The model structures the housing provisioning system as three layers as shown in Fig. 1. The service layer describes the housing demand, which is taken up by the product layer. It links the demand to the necessary products (houses) and the materials these products are composed of. The model adds average material compositions to the buildings based on their type and year of construction. The model covers the materials steel, cement, plastics, copper, aluminum and wood. The impact layer lastly relates the material and energy necessary for the inflows (production) to their environmental impact. The final output of the model are greenhouse gas emissions in kilograms of carbon dioxide equivalent. Our modeling extends on this existing work by increasing the spatial resolution of the service layer significantly to individual cities and counties. The product and impact layers of the model remain unchanged due to the more regionally consistent building types and material supply. The model uses common German inventories, intensities and efficiencies for materials, energy, and GHG emissions (Pauliuk et al., 2020b). The model is constructed to run in parallel for all 400 cities and counties and allows to analyze all model results separately for individual regions. For each city the construction activity (inflows) can be further differentiated into stock additions (net increase of stock) and stock replenishment (replacing outflows) as follows:

$$\text{Stock Addition} = \max(\text{Inflows} - \text{Outflows}, 0) \quad (3)$$

$$\text{Stock Replenishment} = \min(\text{Inflows}, \text{Outflows}) \quad (4)$$

2.2. Data

2.2.1. Building stock estimation using synthetic population

The building stock over time is determined by using the in-use building stock by age cohort in a base year, and subsequent years are calculated from the balance of inflows (construction) and outflows (demolition) in a stock-flow model. Such a building stock dataset is not yet available for Germany at the level of cities and districts (NUTS3: Nomenclature of Territorial Units for Statistics). We created such a building stock dataset based on a synthetic population. A synthetic population is an artificial population whose distribution of characteristics matches the real population in a given area. Synthetic populations are widely used in agent-based modeling for disciplines ranging from sociology to epidemiology (Chapuis et al., 2022; Nicolaie et al., 2023; Hradec et al., 2022).

We use a synthetic population for Germany developed by Többen et al. (2023). They used the characteristics assessed in the household microdata of the "Income and Expenditure Survey" (German: "Einkommens- und Verbrauchsstichprobe (EVS)") conducted by the German Federal Statistical Office with a sample of about 40,000 households every 5 years. These surveys cover many characteristics, ranging from demographic information on each household member, to income and expenditure and, crucially, the size, age, and type of building for each household. Többen et al. (2023) use the data from these surveys between the years 1998 and 2018 to train a random forest machine learning model (Ho, 1995, 1998). This model statistically simulates how all households in Germany might have responded to the survey, matching the constraints of the 2011 census. The resulting dataset reproduces the same level of detail in characteristics for all 38 million households in 11 thousand German municipalities. This is the first time that such linked information on building type, size and age is available

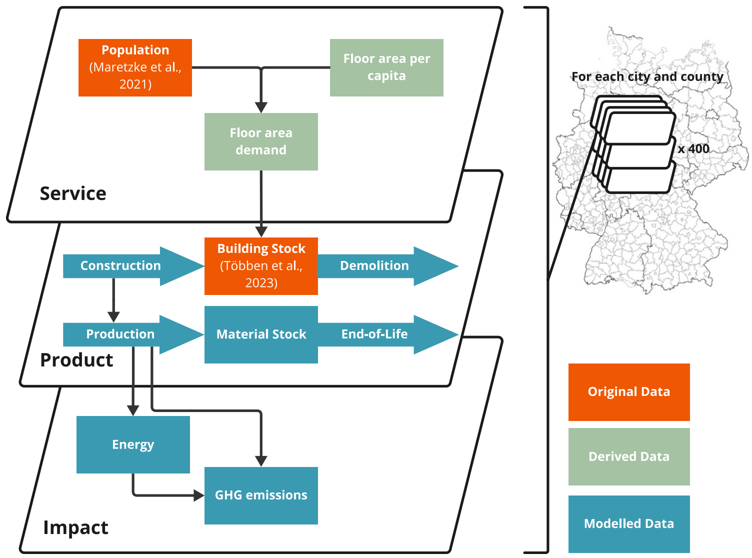

Fig. 1. Schematic overview of the dynamic material flow analysis model. Original input data in orange, derived input data in green, modeled data in blue. The model is structured according to the three layers: service, product and impact.

for the whole of Germany. For the purposes of this study, the dataset is aggregated to NUTS3 regions.

The synthetic population model enables to splice the census' sums of building ages, sizes, and types by each other. For example, an estimate of how many single-family houses (type) larger than 200m^2 (size) built between 1948 and 1990 (age) exist in Berlin (location).

The data cover the statistical building stock in four age groups (see supplementary material for detailed description). To calculate the yearly outflows based on the statistical building lifetime, we split these age groups further into annual values. For this split the buildings in each age group were evenly distributed for all years in each group from 1900 to 2012. Although there are certainly buildings built before 1900 in Germany, they would reach the statistically average lifetime of 120 years before the modeled period and are not considered significant. For the years after 2012 up to the model start year 2015, a constant age cohort of the building stock was assumed.

Building sizes are provided in 20m^2 increments from 40 to 200m^2 (see Supplementary Material for detailed description). For the middle intervals (41–200 m^2), a uniform distribution is simply assumed and the median value is used for aggregation. For the smallest interval, a uniform distribution with single square metre dwellings is unlikely. Therefore, a common s-shaped logarithmic growth function is assumed instead ($f(x) = \frac{1}{1+e^x}, x \in [-2e, 2e]$) for the interval in the range between 0–40 m^2. This results in an average dwelling size in this interval of 30 m^2.

To determine the average dwelling size in the unrestricted interval >200 m^2, all dwelling sizes in the previous intervals were added together and compared with the total residential area of Germany according to the official total housing stock in the 2011 Census (Statistische Ämter des Bundes und der Länder, 2015). The difference between the total housing stock and the number of dwellings in the interval was used to calculate the average dwelling size of 300 m^2. Building size is aggregated for each building type and year of construction.

Our building stock dataset, derived from synthetic population data by matching the census constraints, was validated against multiple existing building stock models for Germany (see Supplementary Figure S1 for detailed comparison). The close alignment with established datasets like EUBUCCO (Milojevic-Dupont et al., 2023), EU Building Stock Observatory (European Commission, 2024) and MESSAGEix-Buildings (Mastrucci et al., 2021) provides confidence in our baseline building stock estimates, while our approach offers enhanced spatial granularity necessary for regional analysis. The German building stock data are available as part of the supplementary material to this paper via a Zenodo repository.

2.2.2. Population development in Germany

The future development of the German population drives the model. As the population shifts between districts and cities, so does the demand for housing. The German government regularly produces state level population projections based on different assumptions of demographics, migration, and economic development. The most likely of these scenarios is projected for each NUTS3 region as part of the regional planning forecast 2040 (German: "Raumordnungsprognose 2040"), which was published in 2021 by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (Maretzke et al., 2021). This report presents population estimates for German districts and cities, provided at intervals of five years until 2040. We interpolated and extrapolated the values for the intermediate years until 2050 using Piecewise Cubic Hermite Interpolating Polynomials (PCHIP) (An explanation of the PCHIP method for interpolation and extrapolation and the reasons for the choice of method is provided in the supplementary material).

The population projection uses data up until 2020 and describes a German society where life expectancy continues to rise. Germany's total population remains relatively stable even as deaths outnumber births due to sustained immigration to Germany. There is a clear trend of population growth in Germany's metropolitan regions, while rural areas are experiencing a decline. Although since 2017 for the first time more people have moved from the 'old' (West) to the 'new' (East) states, the regions of the former German Democratic Republic (GDR) in the East remain structurally weaker and peripheral, with the exception of large cities such as Berlin, Potsdam or Leipzig. Of the 100 most rapidly growing regions, only 10 are in the east, while 55 of the 77 eastern regions are among the 100 most rapidly declining. Most of the change in regional population takes place before 2035, after which the projection remains largely stable (Maretzke et al., 2021).

2.2.3. Floor area per capita

The floor area per capita is influenced by both the size of homes and the number of occupants. Future reductions in floor area per capita are an important lever that directly reduces the demand for housing and

Table 1
Material efficiency (ME) strategies overview.
Source: Adapted from Pauliuk and Heeren (2021).

ME strategy	Description
Higher yields: EoL recover	Increase from current to max. realistic values
Higher yields: Fabrication yield	Increase from current to max. realistic values
Re-use	Max. 29% for construction steel, max. 27% for concrete slabs
Material substitution	Substitute concrete with wood
Lightweight design/downsizing	Lean building design

thus construction emissions (Wilson and Boehland, 2005; Stephan and Crawford, 2016; Hertwich et al., 2019). The purpose of this study is to determine if – and more specifically, where – reductions in per capita floor area are necessary. As the impact of other material efficiency measures is modeled, floor area per capita is kept stable at the current local levels.

2.3. Scenarios

The existing RECC Germany model allows to implement various material efficiency strategies, such as increased re-use of construction steel and concrete slabs, or substitution of concrete with wood (Table 1). We use them to create an optimistic scenario of improved construction methods reducing material demand and thereby emissions. This improved material efficiency scenario is used to model how much emission can be reduced by purely improving construction efficiency and increasing circularity without reducing demand.

Next to these measures reducing the environmental impact of construction there are also two measures directly targeting the demand for construction itself:

- Lifetime extension can directly reduce outflows through demolition, thereby reducing the need for new construction. However, extending the life of buildings through renovation also has a material cost, which increases short-term material demand in exchange for a long-term reduction in material demand through reduced construction.
- Reductions in floor area per capita also reduce the demand for new buildings. However, floor area per capita is projected to increase rather than decrease in the coming years (Deschermeier and Henger, 2015), mainly due to smaller household sizes and larger dwelling sizes. In societies that prioritize freedom of choice, especially with regard to consumption, reducing floor area per capita could be perceived as an infringement on personal freedoms, making it a politically difficult policy to implement. This study explores the potential need for such measures, taking into account the trade-offs between environmental benefits and preserving individual choice (Clapham et al., 2018; OECD, 2020).

The material efficiency strategies are embedded in wider assumptions about the development of the German industrial system and the decarbonization of the industries producing the required materials. These assumptions are based on widely used scenarios, the Shared Socioeconomic Pathways (SSP) (O'Neill et al., 2014). For a desirable view of a sustainable future, SSP1 and Representative Concentration Pathway 2.6 (RCP2.6) (van Vuuren et al., 2011) were selected. RCP2.6 assumes global warming to likely stay below 2 °C by the year 2100.

Two staggered scenarios are calculated both with optimistic parameters to create a lower estimation of the potential need for floor area per capita reduction. A first material efficiency scenario applies all measures from Table 1 for an optimistic look at the level of reductions in GHG emissions from material production for residential buildings possible by changing the technology used to build houses, without reducing demand for housing. A second scenario reduces demand directly by increasing building lifetimes by 90% through renovation. Both scenarios are compared to a baseline without implemented ME strategies purely based on SSP1 and RCP2.6. The scenarios allow us to investigate whether technological improvements to construction are able to reduce emissions sufficiently to stay within the bounds of the German Climate Law (Deutscher Bundestag, 2019, 2021).

2.4. Modeling system scopes, definitions, and boundaries

Hibernating stocks are not modeled explicitly. The model does not distinguish between houses leaving the stock because they have reached the end of their life or because of lack of demand. However, we were able to estimate the hibernating stock by comparing the subnational and national analyses. In the national model, available housing was allocated nationally, and lack of demand in one region was offset by growing demand in other regions. The estimate of the hibernating stock is a lower estimate because such compensation still occurs within each region, but now on a smaller scale.

The model inherits material and emission intensities for buildings from the life cycle inventories used in the RECC model. The process analysis used to determine these values typically suffers from truncation errors, which can significantly underestimate resource requirements and therefore emissions (Lenzen, 2000; Crawford, 2011; Majeau-Bettez et al., 2011; Crawford et al., 2018).

The scope of our analysis focuses on the Scope 3 emissions from six materials (steel, cement, plastics, copper, aluminum and wood) that represent the most significant mass and environmental impact in residential construction, and for which data was available in the RECC database. This material selection makes the study comparable to other analyses using the ODYM-RECC framework. Additionally, we only consider GHG emissions rather than a broader range of environmental impact categories (Torres et al., 2024).

Another major source of uncertainty are the lifetimes that drive the stock-flow modeling as part of the ODYM framework. This method is widely used in material flow analysis of very different materials and stock types. In contrast to many other regularly studied products (vehicles, appliances or electronics) buildings rarely leave the stock due to reaching their statistical end-of-life, but rather due to a variety of economic and urban planning reasons that make determining a statistical lifetime difficult. Especially in Germany were the building stock was significantly shaped by two world wars and political reunification (Ortlepp et al., 2018).

The model assessed global emissions for each material, in contrast to the German Climate law that only legislates territorial GHG emissions. However, since the aim is not to outsource production and German policy efforts target reductions both domestically and abroad, considering global emissions is reasonable. Furthermore, Germany is the largest producer of the two most environmentally impactful materials (concrete and steel) in the EU and a net-exporter of both. As bulk construction minerals are largely sourced regionally and not highly traded internationally, we can consider the emissions from material production for construction to be almost entirely territorial.

3. Results

Starting in 2024 with a residential building stock of 3.65 billion m^2 in Germany, 549 million m^2 of floor area are modeled to leave the building stock until 2050. Construction to meet the local housing demands total stock replenishments of 377 million m^2 or 87% of total construction. The remaining 13% are additions to the stock in areas with rising population.

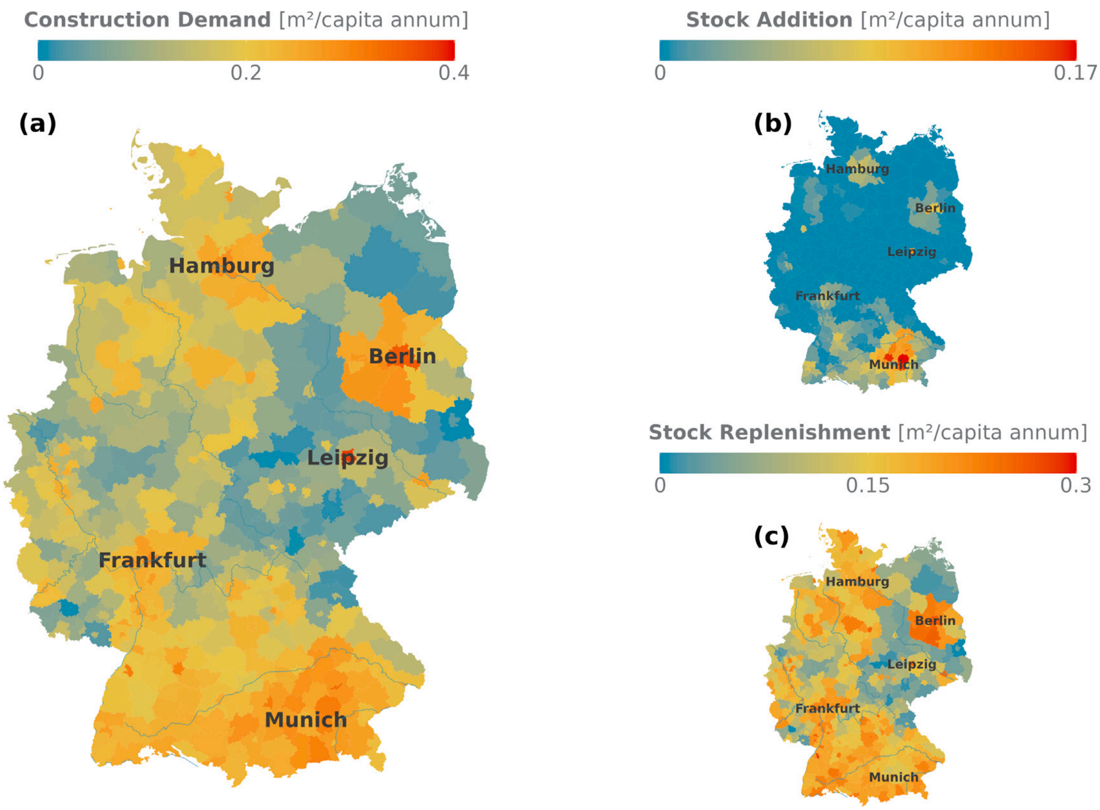

Fig. 2. Regional construction patterns in Germany's NUTS3 regions (counties and cities) showing: (a) total construction demand, (b) stock additions for growing populations, and (c) stock replenishment replacing demolished buildings. Values represent average annual demand per capita calculated as the total regional demand over 2024–2050 divided by the cumulative population over the same period.

3.1. Regional variations in construction demand and stock dynamics

Fig. 2 shows the spatial dimension of the results with the construction demand in each city and county split into demand for stock replenishment and stock additions. Whereas Fig. 3 shows the temporal dimension of the inflows over time for Germany and selected regions.

The split between stock additions and stock replenishments allows us to observe two different trends. Stock additions will decline over time nationally by 2050, while stock replenishment will be rising. Stock additions are mainly driven by population increases in major cities. These are mainly driven by internal and external migration, which the German population projection is forecasting will decline over the long term, leading to declining need for stock additions. Stock replenishments on the other hand are driven by the end-of-life outflows from the existing stock, and therefore depend on the age of the current building stock. Since most of the buildings in Germany have been built after the Second World War they only start to enter the end-of-life at the beginning of the modeling period and lead to increasing outflows and higher stock replacement in later periods.

We can assess the construction activity of individual NUTS3 regions as exemplified in Fig. 3 panels (b)–(g). We see similar trends in the three cities with the largest stock additions: Berlin (Panel 3 (b)), Hamburg (Panel 3 (c)) and Leipzig (Panel 3 (d)). Berlin and Hamburg are Germany's two largest cities and with consistently rising population. Leipzig is only Germany's 8th largest city, but faces the highest construction activity per capita nationwide due to having one of the highest population growth rates in the nation with 9% until the middle of the century. The impact of stock additions on total construction can be seen most starkly in the city of Dachau (Panel 3 (e)), where stock additions are responsible for 55% of total construction. This is due to having the highest projected population increase on the one hand with 10% until 2050 and a relatively young building stock leading to low outflows. A very different picture is visible in regions with declining populations like Dortmund (Panel 3 (g)) and Erzgebirgskreis (Panel 3 (f)). Dortmund is the largest city without any stock additions due to a declining population that is merely replacing some of the outflows but without demand to grow the building stock in the future. Erzgebirgskreis is a rural region on Germany's border with the Czech Republic. It is currently the most populous county in Eastern Germany with just over 300 thousand inhabitants. However, this county's population is projected to decline by a quarter over the next 26 years leading to a situation where the population is declining more rapidly than buildings are decaying, thus creating no construction demand at all until 2040 (Panel 3 (f)).

3.2. Technology improvements are not sufficient to reach climate targets in the housing sector

The German government has legally committed to a decarbonization pathway from reference emissions in 1990 to carbon neutrality in 2045 (Deutscher Bundestag, 2019, 2021). Emissions from 2024, the first year of our modeling, should already be reduced by 54% of the 1990 reference values. Germany has a history of falling short of its climate targets, especially for buildings (Harthan et al., 2020; OECD, 2023). As with the material efficiency strategies, we made an optimistic assumption that emission had reduced in line with the target until 2024. To meet future targets, emissions would need to be reduced by a further third by 2030, and further two thirds by 2040 compared to 2024, to reach zero emissions by 2045 and even "negative" emissions using carbon capture and storage by 2050. It should be noted that the scope of the emissions target is wider than that covered in our study, as no targets exist yet at the scale that we are investigating.

Emissions from the production of building materials are far from meeting the targets set by the German Climate Protection Act (Fig. 4),

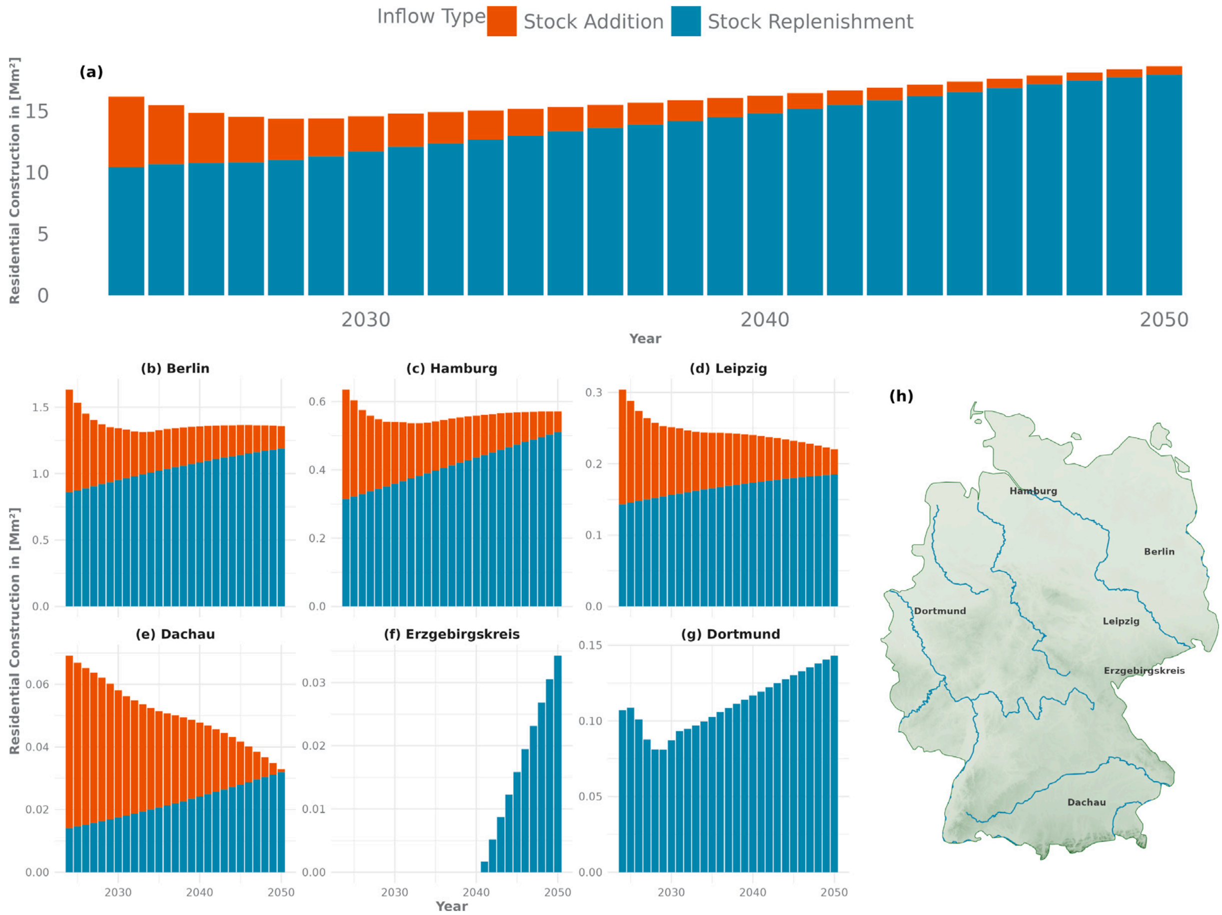

Fig. 3. Stock replenishment and stock additions for Germany's residential buildings until 2050. Rising stock replenishment is due to rising outflows, which in turn is due to the age profile of the existing building stock.

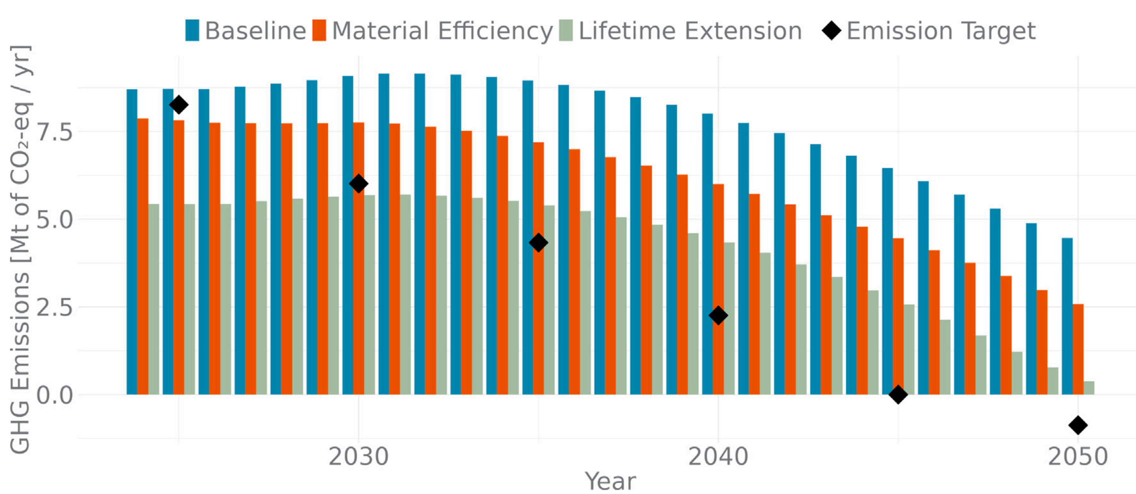

Fig. 4. GHG emissions from material production for two scenarios. A baseline scenario under SSP1 without implementing material efficiency measures. A material efficiency scenarios where all measures seen in Table 1 are implemented. A lifetime extension scenario where buildings are renovated to increase their lifetime by 50%. The reductions required by German climate protection law are shown as back diamonds. All reductions goals are set relative to the current 2024 emissions from material production for construction. Until 2030 targets for the building sector are available, afterwards targets set for the whole economy are used.

and even optimistic material efficiency measures are not enough to meet these targets. Lifetime extension is an effective method to further reduce emissions by up to 85% by 2050 compared to the baseline. However, even then the emissions reductions fall short of the carbon neutrality target in 2045 and negative emissions targeted in 2050. Technical material efficiency strategies are not sufficient to meet the climate targets set by the German government, and achieving these targets will require further reductions in per capita footprint.

Fig. 5 shows the cumulative emissions up to 2050 in all three scenarios, broken down by the materials responsible for the emissions. The main sources of emissions are cement and plastics, which currently have very low recycling and re-use rates (Pauliuk and Heeren, 2021).

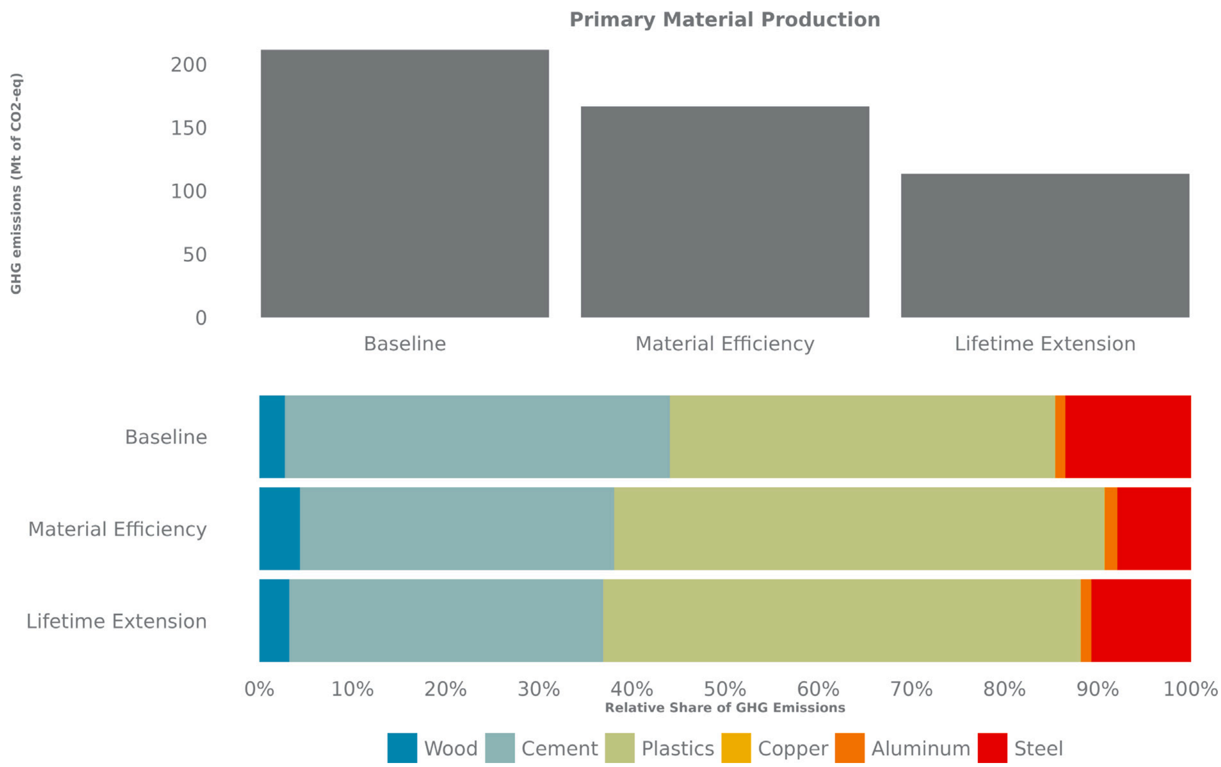

Fig. 5. GHG emissions from material production for baseline and two scenarios, split by materials.

Cement is more important in the baseline scenario with more construction compared to the scenarios with more renovation, where plastics play a bigger role.

4. Discussion

4.1. High-resolution modeling matters

The high spatial resolution of our study allows us to pinpoint regions where the conflict between housing demand and emissions reductions is most apparent. Cities experiencing significant population growth, such as Berlin, Hamburg, and Leipzig, as well as regions surrounding Munich, face the biggest challenge. In these areas, rising housing demand leads to increased construction, directly conflicting with emissions reduction targets. The hotspots are mainly determined by population development leading to stock additions. However, the majority of construction activity can be attributed to stock replenishment nationwide. The phenomenon of abandoned buildings or hibernating stock is invisible in aggregated national models where abandoned buildings in one region and unfulfilled demand in others average out. The national model can only show if there are enough houses in the whole country to house its population, but as houses are immobile it is essential to know the demand and supply in each region. The high-resolution view demonstrates that national-level policies based only on national-level assessment may be insufficient, and more targeted, locally-aware strategies are necessary.

4.2. Population dynamics and rural revitalization

While our model treats population development as an exogenous variable, it is important to consider how changes in population dynamics could affect construction demand and associated emissions. Reversing the rural exodus we currently observe through place-based policies (Neumark and Simpson, 2015) could potentially reduce construction demand in urban areas. Revitalizing rural areas to make use of existing housing stock could avoid some urban construction and its associated emissions. However, this approach presents its own set of challenges and trade-offs. Rural lifestyles generally entail higher transport and energy emissions due to increased car dependency, larger floor areas to heat in houses, and the prevalence of single-family homes with higher heating and cooling demands per square metre than houses which shared walls (Heinonen et al., 2013). These additional emissions might outweigh any reductions achieved for emissions from building materials. Future research should aim to model these trade-offs comprehensively to inform balanced policy decisions (Pérez-Sánchez et al., 2024).

4.3. Housing policy and equity

Our findings highlight the need for housing policies that go beyond simply increasing the supply. In regions experiencing population growth, policies leading to reductions in average floor area per capita become necessary, even in areas that already have some of the lowest floor area per capita in the country. This raises important questions not just about average floor area, but also how space is distributed across households, influencing housing equity. Equity is not only a concern between regions, but also within regions between rich and poor households: Between second homes on one end and overcrowding or even homelessness on the other. Unfortunately, the model is so far unequipped to model the impact of these inequalities on the housing sector. This would be an important next step to ensure that potential solutions to lower floor area per capita do not exacerbate these issues.

4.4. Technological solutions and their limitations

Even with optimistic assumptions about construction methods and industrial decarbonization, emissions from material production for the building sector will exceed targets in many areas if housing supply keeps pace with location-specific population growth dynamics. By 2050, material efficiency measures could reduce annual emissions by 40% compared to the baseline scenario, when combined with lifetime extension strategies, this reduction increases to 85%. However, these technological improvements fall short of achieving the mandated carbon neutrality already by 2045. The largest share of emissions occur during the production of cement, which is particularly hard to decarbonize (Watari et al., 2022; Müller et al., 2024).

4.5. The role of wood in construction

A leading decarbonization option for cement therefore is material substitution, the material efficiency scenario modeled increased use of wood in construction as a substitute for cement. Wood-based construction presents a potential low-carbon alternative to conventional materials like concrete and steel (Churkina et al., 2020; Pomponi et al., 2020; Pauliuk et al., 2021; Hingorani et al., 2023). It has been shown to be feasible even for multi-story buildings that use wood as the primary structural material (Mahapatra et al., 2012; Wimmers, 2017). However, the adoption of wood as a construction material faces several challenges in Germany. Administrative barriers, such as building permits and standards, as well as cultural barriers such as negative public perception, have limited its widespread use compared to other countries such as those in Scandinavia (Mahapatra et al., 2012). Moreover, the scalability of timber production for large-scale adoption is constrained by ecological barriers. Germany is already approaching the upper boundaries of its sustainable timber harvesting capacity (Egenolf et al., 2022). Mass adoption of timber for construction would exceed this capacity, leading to unsustainable land use practices and potential negative environmental impacts (Yamashita et al., 2024). While timber can serve as a low-carbon technology for necessary new construction in cities, it cannot be viewed as a panacea for reducing emissions from construction (Mishra et al., 2022).

4.6. Circular economy

Implementing circular economy principles in the building sector is a key strategy for emissions reduction. The “narrow, slow, close” approach provides a framework for categorizing and implementing various strategies to reduce material demand and associated emissions (Bocken et al., 2016; Konietzko et al., 2020). Our scenarios show that these principles can contribute significantly to emissions reduction, although they are not sufficient on their own to meet climate targets.

The effectiveness of these measures is ultimately limited by the overall demand for new construction. In regions with rapidly growing populations, the emissions reductions achieved through circular economy strategies would be offset by the volume of new construction required. This underscores the need for these approaches to be implemented alongside demand-side measures and careful urban planning (Creutzig et al., 2016; Lucassen et al., 2020).

5. Conclusion

Our dynamic material-flow analysis of the German building stock offers scenarios at the administrative level where they can have the greatest impact on housing policy. We examine the contention between Germany’s housing crisis and its Climate Protection Act and show that technological solutions alone are insufficient to meet Germany’s climate commitments in the building sector. Even with optimistic assumptions about material efficiency improvements and lifetime extension strategies, emission reductions fall short of achieving carbon neutrality by 2045.

The high spatial resolution of our modeling approach reveals significant variations in construction demand and associated emissions across Germany’s 400 cities and counties. The granular analysis shows that national-level models can misestimate emissions by failing to account for hibernating building stock in regions with declining populations, and conversely fail to account for extra stock demand in regions with increasing population. The parallel analysis of 400 regions allows for identification of specific areas where the conflict between housing demand and emission reduction targets is most acute, particularly in major cities like Berlin, Hamburg, and Leipzig.

5.1. Policy implications

Our findings have several implications for policymakers both at the local and national level:

Regions require localized policy approaches based on their specific population dynamics and existing building stock. Growing urban areas need policies focused on more efficient use of space and materials, while regions with declining population should prioritize renovation and repurposing of existing buildings.

Lifetime extension through renovation should be prioritized over new construction where possible. Local authorities should develop incentive structures that favor renovation and adaptive reuse over demolition and new construction.

In high-demand regions, policies must address floor area per capita, as technological improvements alone cannot reconcile current space consumption patterns with climate targets. This could include measures such as incentivizing more efficient housing layouts, supporting shared living spaces to increase household sizes.

5.2. Future research

Future research could extend this high-resolution approach to building modeling from just material emissions to use-phase emissions, in order to assess the full emissions profile of housing and to better investigate the region-specific trade-offs of renovation. The material investment of renovation pays a double dividend, reducing material demand and associated emissions by reducing the need for new construction, while typically improving energy efficiency at the same time. Quantifying this potential for each region could provide further motivation and guidance to policy makers in German cities and counties.

The model could also be extended to include non-residential buildings, allowing analysis of potential building reuse strategies that help to avoid construction in cities with growing populations. However, high spatial resolution data for Germany has been lacking. There is a growing need for novel methods in urban planning and climate change mitigation, including the use of new technologies and data-driven approaches to collect high-resolution data (Arbabi et al., 2022; Rankin and Saxe, 2024; Hintz et al., 2024). Future work could better disaggregate materials and building components and provide a more accurate picture of recycling and reuse potential (Stephan and Athanassiadis, 2017; Fivet et al., 2024). The integration of transport models could provide a more comprehensive view of the opportunities and trade-offs associated with different place-based policies (Creutzig et al., 2024) and allow the impact of different scenarios for population development to be explored.

The use of synthetic population data in our model opens up the possibility of more nuanced modeling of impacts on different social groups. Future studies could use this approach to explore inequality in the housing market and its relationship to GHG emissions, potentially leading to more accurate and less conservative estimates of construction demand and associated emissions.

CRediT authorship contribution statement

Jakob Napiontek: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Tomer Fishman:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Peter-Paul Pichler:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **John Heintz:** Conceptualization, Supervision, Writing – review & editing. **Helga Weisz:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resconrec.2024.108117.

Data availability

The data and code to reproduce the results can be found at https://doi.org/10.5281/zenodo.13304547, additional instructions can be found in the supplementary material.

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