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Circular strategies for building sector decarbonization in China

A scenario analysis

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Abstract

The building sector in China is responsible for 40% of total energy-related CO_2 emissions, driven by its large population, continuous economic growth, and construction boom. In addition to greenhouse gas (GHG) emissions from energy use, buildings drive significant emissions for construction activities and production of energy-intensive materials, such as steel and cement. While supply-side energy strategies have been extensively explored, a demand-side perspective that considers stock dynamics and circularity improvements is essential to assess sustainable pathways for the buildings sector. Here, we explore a set of decarbonization scenarios for the building sector in China considering a range of circular strategies and their interplay with different climate policies. The strategies include lifetime extension of buildings, switch to wood-based construction, reduction of per-capita floorspace, and a combination of all three strategies. We use the building sector model MESSAGEix-Buildings soft linked to the integrated assessment model (IAM) MESSAGEix-GLOBIOM and prospective life cycle assessment (LCA) to assess the effects of these circular strategies on building material and energy demands, and operational and embodied emissions. We find that the three strategies could reduce building material demand up to 60% on mass basis by 2060 compared to a reference scenario with continuation of current policies. This translates into a reduction of embodied and total GHG emissions of 62% and 24%, respectively, significantly contributing to achieving decarbonization targets. Integrating industrial ecology methods in IAMs, as demonstrated in this study, can provide valuable insights to inform national policy decisions on mitigation strategies accounting for both demand and supply sides.

KEYWORDS

circular economy, construction materials, industrial ecology, integrated assessment modelling, life cycle assessment, residential and commercial

1 INTRODUCTION

The building sector in China has experienced a remarkable and rapid expansion over the past two decades, although the investment for new buildings has slowed down after the COVID-19 pandemic (Han et al., 2021; Tian et al., 2021). This growth can be attributed to robust urbanization and economic developments. Between 2001 and 2020, the urbanization rate surged from 38% to 64%, and per-capita gross domestic product (GDP) witnessed an eightfold increase (NBSC, 2021). As a result of these transformative changes, the building stock doubled in size compared to 2001, reaching 66 billion square meters in 2020 (BERC, 2022). A special feature of the building stock in China is the sheer magnitude of both annual new construction and building demolitions, standing at approximately 3.3 and 1.7 billion square meters, respectively, in 2020 (BERC, 2022). These developments make the building sector in China a large consumer of energy. Buildings operation is responsible for approximately 626 million tonnes of coal equivalent (Mtce), or 23% of total final energy consumption in China (IEA, 2022). In addition, a large-scale production of building materials, such as steel and cement, drives further embodied energy use, which was around 520 Mtce in 2020 (BERC, 2022). Due to both operational and embodied energy consumption, the building sector contributes to almost 40% of China's total energy-related CO_2 emissions (BERC, 2022).

The commitment of China to achieving carbon neutrality by 2060 underscores the imperative of mitigating greenhouse gas (GHG) emissions across crucial energy consumers including the building sector. Building-related mitigations require a deep dive into the building stock dynamics which fundamentally drive energy consumption within buildings, demand for building materials, and associated carbon emissions. Circular strategies can provide key opportunities for sustainable transitions in the building sector (Norouzi et al., 2021; Van Oorschot et al., 2023); however, their wide-scale adoption is still lacking (Eberhardt et al., 2022; Meglin et al., 2022). While several studies focus on supply-side circular strategies, such as reuse and recycling of waste materials (Hu et al., 2010; Pauliuk et al., 2012; Wang et al., 2014, 2015; Wu et al., 2016), and on the decarbonization of material production (Dinga & Wen, 2022; Liu et al., 2022; Ren et al., 2023; Shao et al., 2022; Shen et al., 2021), demand-side material efficiency strategies can offer high carbon mitigation potential in the building sector (Hertwich et al., 2019; Pauliuk et al., 2021) but require methodological developments and more detailed analyses at large scales (Mastrucci et al., 2023). Previous studies have estimated the material-related GHG saving potentials for more intensive building use at 40%, lifetime extension at 40%–47%, and lightweighting design at 19%–50% (Cai et al., 2015; Hertwich et al., 2019; Milford et al., 2013; Moynihan & Allwood, 2014). Potentials can, however, significantly differ based on the regional contexts (Zhong et al., 2021). Thus, there may exist trade-offs between material efficiency and energy efficiency strategies (Hertwich et al., 2019), requiring more investigation to assess their broader effects on material demand, energy demand, and carbon emissions. We focus here on three key demand-side circular strategies with significant estimated emission reduction potential (Hertwich et al., 2019; Pauliuk et al., 2021; Zhong et al., 2021): buildings lifetime extension, switch to wood-based construction, and per-capita floorspace reduction.

Extending the lifetime of buildings can yield multiple benefits, including a reduced need for new construction and building materials. Unfortunately, the current average building lifetime in China falls notably short, hovering around just 25–30 years (EFC, 2020), in stark contrast to the originally intended 40–50-year longevity. This discrepancy can be attributed to several factors, with two primary ones being lower construction quality and frequent land use and ownership changes (Liu et al., 2014). To curtail the building material use, it becomes imperative for China to prioritize the extension of building lifetime.

The adoption of bio-based building materials, such as wood (including cross-laminated timber, glued-laminated timber, and wood frames), as substitution to conventional steel and concrete in construction, holds great potential for reducing carbon emissions associated with the building sector. Wood, as other natural materials, is renewable, reusable, and biodegradable. Therefore, using sustainably harvested natural materials in building construction is in good fit with the circular economy (Campbell, 2019; UN, 2023). Research demonstrates that wood-based buildings, particularly low- and medium-rise structures, can yield up to 30%–40% energy and carbon emissions savings compared to reference concrete buildings (Allan & Phillips, 2021; Jayalath et al., 2020; Liu et al., 2016). Wood-based buildings may provide longer-term carbon storage emphasizing the value of wood in promoting sustainability within the construction industry (Churkina et al., 2020).

Larger housing units inherently demand more energy for activities like space heating and cooling, as well as a greater quantity of building materials for their construction. In the past decades, per-capita floorspace in China has surged to about 40 and 49 square meters in 2019, for urban and rural residential buildings, respectively, reaching levels close to those of the European Union (EU)[1] (BERC, 2022; Gao et al., 2019; Guo et al., 2020; Wang et al., 2021). Continuous increase in per-capita floorspace could pose substantial challenges in meeting growing building energy and material use under climate targets. More intensive use of buildings, reduction of building vacancy, and shifts in building types, for example from single-family to multi-family housing, can contribute to significantly reducing per-capita floorspace and, consequently, both material and energy demands (Mastrucci et al., 2023).

Previous studies have delved into modeling the building sector in China, investigating either the development of building material demand, embodied energy and embodied carbon emissions, or operational energy demand and operational emissions (Hong et al., 2016; Huo et al., 2019a, 2019b; Yang et al., 2019; Yu et al., 2014; Zhang et al., 2022a; Zhou et al., 2022). The existing literature has assessed demand-side circular strategies in a number of prospective scenarios for China, including building lifetime extension (Hong et al., 2016; Hu et al., 2010; Huang et al., 2013; Wang

[1] The average floorspace of residential buildings in the EU27 is estimated at 41 m^2/cap in 2020, excluding vacant buildings, based on the EU Building Stock Observatory (BSO) available at the following website (last consulted May 29, 2024): https://building-stock-observatory.energy.ec.europa.eu/database/

et al., 2015; Zhang et al., 2022b, 2023), material substitution and lightweighting (Geng et al., 2019), and per-capita floorspace developments (Hu et al., 2010; Zhang et al., 2022b, 2023). Most of these studies have a relatively limited scope, primarily focusing on residential buildings, specific life-cycle stages, and often exploring a single emission reduction strategy, while overlooking the interplay with the operational energy of buildings and with the energy supply system. Furthermore, most studies assess the potential of circular strategies without accounting for different climate policy scenarios, which diminishes their policy relevance. Studies investigating the decarbonization of the building sector in China and accounting for both embodied and operational emissions in a consistent way are currently limited (Pauliuk et al., 2021). Linking integrated assessment modeling (IAM) commonly used to investigate climate change mitigation scenarios, industrial ecology methods accounting for materials stock and flow, and end-use sector modeling has been suggested to investigate comprehensive mitigation options accounting for energy and material aspects (Fishman et al., 2021; Pauliuk et al., 2017). However, there is still a significant gap requiring methodological advancements in linking different modeling traditions.

To address these gaps, here we develop an integrated approach that couples the bottom-up sectoral model MESSAGEix-Buildings with the IAM MESSAGEix-GLOBIOM and prospective life cycle assessment (LCA) for more comprehensive assessment of GHG emission pathways for buildings. We present a novel series of scenarios for decarbonizing the building sector in China, encompassing various demand-side circular strategies and climate policies and considering both operational and embodied emissions in residential and commercial buildings. We investigate three key demand-side circular strategies, including building lifetime extension, switch to wood-based construction, and reduction of per-capita floorspace, and their interplay with two different climate policy scenarios, and assess their potential to reduce material stocks and demand, energy demand, and embodied and operational GHG emissions of buildings in China.

2 | METHODS

2.1 | Models

MESSAGEix-Buildings is a bottom-up modeling framework to analyze climate mitigation scenarios in the building sector (Mastrucci et al., 2021). The model has a high level of granularity, enabling the accounting of key heterogeneities in the building sector, including context and climate, household types, and building and material characteristics. The model has flexibility in temporal and spatial resolution, from national to global levels.

Two main modules cover the building stock analysis: the energy demand model CHILLED (Cooling and Heating gLobaL Energy Demand model) and the stock turnover and decisions model STURM (Stock TURnover Model of global buildings). The framework is soft linked to the IAM MESSAGEix-GLOBIOM (Huppmann et al., 2019) for energy price signals and accounting of operational indirect GHG emissions.

In this study, we expand this framework to cover material stocks and demands for both residential and commercial buildings, and assess embodied and operational carbon emissions by integrating IAM scenarios and prospective LCA methods. In the representation of the building stock, we account for a set of dimensions, including urban and rural locations, climatic zones, building types (single-family houses, multi-family houses, informal houses, and commercial buildings), periods of construction and energy efficiency levels, household income, and tenure. We focus on two key stages of the buildings life cycle (CEN, 2011), namely the product stage and the use stage, accounting for the energy use for space heating, space cooling, and water heating. On-site construction activities, transportation, and end-of-life stages, generally accounting for a lower share of the life-cycle emissions of buildings (Abd Rashid & Yusoff, 2015), are beyond the scope of this paper. The following sections briefly describe the energy demand model, stock turnover and energy efficiency decision models, material accounting, and GHG emission calculations. Further details on the models and input data for China are reported in the Supporting Information. We refer the reader to previous publications (Mastrucci et al., 2021) for complete model and data description.

2.1.1 | Energy demand model

CHILLED is a bottom-up energy demand model to estimate space heating and cooling based on variable degree days (VDD) (Al-Homoud, 2001) calculated over a spatial grid. Standard degree days (DD), commonly used to assess heating and cooling demands of buildings, represent the annual sum of daily positive differences between outdoor temperature and a balance temperature, defined as the outdoor temperature at which neither heating nor cooling is required (Al-Homoud, 2001; Claridge et al., 1987; Mastrucci et al., 2021). The VDD method is different from standard DD since it analytically determines the balance temperature based on buildings thermal characteristics and occupants' behavior by using simplified thermal balance calculations, allowing for more accurate and building type-specific results. The model calculates useful heating and cooling energy and, subsequently, final energy demand by applying systems-specific heating conversion efficiency factors, which vary based on the type of heating and cooling systems and evolve over time. The equations are applied over a spatial grid at 0.5° grid resolution (approximately 50 km at the equator) for a set of building archetypes representing different types of buildings. The output of the model is energy intensity per unit of floorspace (kWh/m^2). The model aggregates the results by urban and rural locations, and climatic zones, up to the national level, weighted on the respective populations.

Water heating is calculated based on methods from the literature (Harvey, 2014), and takes into account time-series changes in energy efficiency improvements (Supporting Information, section 1.3).

2.1.2 | Stock turnover and energy efficiency decision models

STURM includes a stock turnover model to assess the future evolution of the building stock and a set of discrete choice models for energy efficiency improvement decisions. The stock turnover model is based on dynamic material flow analysis (MFA) (Mastrucci et al., 2021; Sandberg et al., 2016). The main units describing the building stock are the number of housing units and floorspace for the residential and commercial sectors, respectively. In the case of residential buildings, we calculate the total floorspace based on the number of housing units, household size, and per-capita floorspace. The model is stock-driven and determines building stock requirements based on projected population, household size (residential only), per-capita floorspace, and share of different building types. Demolitions are calculated by using Weibull distribution curves that represent the lifetime probabilities for different building types. New constructions are in turn estimated by accounting for the demolished stock and new additions to meet the stock demand for different building types.

A set of discrete choice models (Giraudet et al., 2012; Mastrucci et al., 2021) estimates the decisions of households in the uptake of energy efficiency options for new constructions and renovations in residential buildings. This involves evaluating the adoption of energy efficiency standards (standard or advanced) for the building envelope and heating systems of newly constructed or renovated housing, as well as decisions on heating fuel switches (coal, district heating, electricity, gas, oil, and solid biomass). First, the model calculates the life cycle costs (LCC) associated with different available options (i), considering investment costs (C_{inv}), operational costs (C_{op}), and intangible costs (C_{int}) using the following equation:

$$\mathrm{LCC}_i = C_{\mathrm{inv},i} + C_{\mathrm{op},i} + C_{\mathrm{int},i}$$

Investment costs for new construction, renovation, and fuel switch options are from the literature (Esser et al., 2019; Fleiter et al., 2016; Mastrucci et al., 2021). Operational costs are based on the energy demand calculations in CHILLED by energy carrier and energy price projections obtained via soft coupling with the IAM MESSAGEix-GLOBIOM, taking into account the evolution of the energy supply system. Predispositions to investment of different household types are represented by a set of discount rates applied for operational costs calculation over the expected lifetime. Intangible costs represent non-monetizable barriers toward investments that are technology specific. The market share (MS) for each option (i) is then estimated by comparing its LCC with those of all possible options (k) and applying an exogenous heterogeneity parameter ν:

$$\mathrm{MS}_i = \frac{\mathrm{LCC}_i^{-\nu}}{\sum_k \mathrm{LCC}_k^{-\nu}}$$

Renovation rates in residential buildings are endogenously calculated and constrained by region-specific boundaries. In the commercial sector, energy efficiency improvements and renovation rates are exogenously calculated based on a set of scenario-specific assumptions (Supporting Information, section 1.3).

2.1.3 | Material accounting

The model accounts for seven key construction materials: aluminum, brick, concrete, copper, glass, steel, and wood. We calculate material stocks and material demand on mass basis by using a set of material intensity coefficients representing the amount of specific materials per unit of building floorspace in kg/m^2. Material intensity coefficients are sourced from relevant literature and differentiated by building type (single-family housing, multi-family housing, and commercial buildings), period of construction, and, for new buildings, by construction type (conventional and wood based). Due to the high level of uncertainty in the material composition of informal buildings, we only account for material demands in formal buildings. We rely on material intensity coefficients specific to China whenever possible (Deetman et al., 2020; Gao et al., 2020; Huang et al., 2013; Marinova et al., 2020) and compare them with other available data from the database RASMI (Fishman et al., 2024) for consistency (Supporting Information, section 1.5). At every timestep, the material intensity coefficients are multiplied by the projected floorspace and newly added floorspace per building type to calculate the total material stock and material demand, respectively. Future changes in construction practice, such as switch to wood-based construction (section 2.2.1), are considered by applying different sets of material intensities to newly constructed buildings (see the Supporting Information, section 1.5, for the complete data and discussion on material intensity coefficients).

TABLE 1 Overview of the scenarios in this study.

Scenario Name	Abbreviation	Description
Circular strategies		
Reference	Reference	Continuation of current construction practice
Lifetime extension	Lifetime	Extension of the lifetime of buildings to average 45 years
Wood construction	Wood	Switch to wooden-based construction for up to 50% of new urban residential buildings by 2030
Floorspace reduction	Floor	Reduction of per-capita floorspace in buildings by 10% from the reference scenario
All circular strategies combined	Circular	All circular strategies combined
Climate policies		
Current policies	NPi	Continuation of current national policies (NPi) and realization of Nationally Determined Contributions (NDC)
Stringent climate policies	1.5C	Climate policies according to 1.5°C targets. Building sector interventions: improved energy efficiency of building shell and HVAC systems in new construction and renovations, increased renovation rate, electrification of heating, and phase down of fossil fuels Cross-sectoral and supply-side: carbon taxes, decarbonization of electricity and district heating, decarbonization of material production

2.1.4 | Greenhouse gas emission calculation

We calculate embodied and operational GHG emissions by using emission intensity coefficients (see the Supporting Information, section 1.6, for the complete data) applied to material and energy demands, respectively. Embodied emissions account for the production of construction materials "cradle to gate." Operational emissions include emissions from space heating, cooling, and water heating, considering both direct emissions, for example, from on-site fossil fuel burning in boilers, and indirect emissions, related to generation and distribution of electricity and district heating.

Time series of embodied emission intensity coefficients are calculated using the prospective LCA method. In this approach, life cycle inventory (LCI) databases are generated by integrating the scenario data from MESSAGEix-GLOBIOM into the cut-off version of the ecoinvent 3.9.1 database (Wernet et al., 2016), using the *premise* tool (Sacchi et al., 2022). The emission intensity results are calculated using the LCA software Activity Browser (Steubing et al., 2020). This method enables explicit accounting of future transformations on energy-intensity activities consistently with the projections provided by the IAM for different scenarios, including future electricity mixes, liquid and gaseous fuel mixes, and material production processes. We adopt the GWP over 100 years (GWP-100) values from the Intergovernmental Panel on Climate Change (IPCC) (2021) for the life cycle impact assessment (LCIA), ensuring our GHG emissions evaluation aligns with global standards for assessing long-term climate impacts. The reference processes and flows of the construction materials in ecoinvent are from the literature (Zhong et al., 2021) and consider both primary and secondary production. We estimate the future share of primary and secondary production based on the literature (Pauliuk et al., 2021). Indirect emission intensity coefficients for electricity and district heating are from the IAM MESSAGEix-GLOBIOM and depend on the configuration of the energy supply systems in different scenarios. Direct emission intensity coefficients are calculated using the guidelines for national GHG inventories of the IPCC (2006).

2.2 | Scenarios

We explore a set of forward-looking scenarios combining key demand-side circular strategies and broader climate policies to reach ambitious climate targets (Table 1). The societal development underlying all scenarios is consistent with the Shared Socioeconomic Pathway SSP2 "Middle of the road" (O'Neill et al., 2017), representing a continuation of current trends and moderate challenges to both mitigation and adaptation.

2.2.1 | Circular strategies

The Reference scenario assumes a continuation of current construction practice. The circular strategies in this study focus on upstream interventions. We investigate three key circular strategies focusing on the demand side, including extension of the lifetime of buildings (Lifetime scenario), switch to wood-based construction in residential buildings (Wood scenario), and reduction of per-capita floorspace (Floor scenario), as well as a combination of all strategies (Circular scenario).

The circular strategies are represented in the model through dedicated implementation for each scenario. The Lifetime scenario adopts a set of Weibull distributions corresponding to demolition probability of buildings with extended lifetime. In the Wood scenario, material intensity coefficients for new buildings gradually shift toward wood-based construction reaching 50% of new urban residential construction by 2030 (Churkina et al., 2020; Himes & Busby, 2020), to represent the progressive shift in construction practice. In the Floor scenario, exogenous floorspace projections are adjusted to account for a progressive reduction in average per-capita floorspace.

2.2.2 | Climate policies

We assess two climate policy scenarios, including both demand-side and supply-side policies. In the NPi scenario there is a continuation of current national policies leading to the realization of Nationally Determined Contributions (NDCs). In the 1.5C scenario, stringent climate policies are implemented with a set of sectoral and cross-sectoral interventions according to 1.5°C targets. The selected MESSAGEix-GLOBIOM scenarios were developed in the course of a model intercomparison exercise (Kriegler et al., 2023). The IAM includes process-based industrial emission mitigation options such as electrification, carbon capture of process emissions, and material recycling (Ünlü et al., 2024), which are deployed in the 1.5°C scenario. Building sector interventions include energy efficiency improvements of heating, ventilation, and air conditioning (HVAC) systems and building envelopes in new construction and renovations, for example, via building insulation, increased renovation rates, electrification of heating, and phase down of fossil fuels. In addition, carbon taxes are applied, affecting energy prices. Interventions on the supply-side tackle the decarbonization of electricity and district heating. We assume that climate policies do not change the demand and stock of construction materials considered in this study.

Building sector interventions are modeled by adding constraints to the models, including minimum energy efficiency levels in new construction and renovations, minimum renovation rates, and imposing heating fuel switches (Supporting Information, section 1.3). In addition, different sets of energy prices and indirect GHG emission intensities from the IAM MESSAGEix-GLOBIOM are used to account for different evolutions of the energy systems. Energy prices enter the LCC calculations in the discrete choice models and have an effect on the uptake of the energy efficiency options in new construction and renovations. For instance, increased fossil fuel prices support the uptake of more energy efficient options reducing operational costs, and switches to electric heating systems and heat pumps. Operational and embodied GHG emission intensities reflect changes in the supply side in different climate policy scenarios through consistent projections.

3 | RESULTS

3.1 | Material stock

Projections for the material stock of residential and commercial buildings in China are shown in Figure 1. The material stock keeps on growing in the Reference scenario, peaking around 2040, driven by increased levels of per-capita floorspace and urbanization. These trends determine larger future shares of urban buildings in the stock, in particular multi-family housing and commercial buildings (Supporting Information, Figure 3). Switching to wood construction (Wood scenario) and reducing floorspace (Floor scenario) significantly contribute to limiting the growth in the material stock, anticipating the peak to around 2030. Extending the lifetime of buildings (Lifetime scenario) does not significantly change the total material stock, but results in a different stock composition with lower share of newly constructed buildings over time. The combination of all circular strategies (Circular scenario) leads to the highest reduction in the material stock, up to 21% in residential and 10% in commercial buildings by 2060 compared to the Reference scenario. The composition of the material stock is dominated by concrete, brick, and to a lesser extent by steel, wood, and other materials. The shift in residential construction materials in the Wood and Circular scenarios leads not only to a significant decrease in the total material stock due to gradual dematerialization, but also to major reductions in the share of concrete in favor of wood. The material stock results do not change across different climate policies (NPi and 1.5C).

3.2 | Material demand

The material demand (Figure 2), after initially plateauing for the residential sector under sustained urbanization, declines as the material stock reaches a peak and starts declining in the Reference scenario. The investigated circular strategies have diverse effects on reducing the total material demand compared to the Reference scenario in 2060, with the most effective being the lifetime extension (Lifetime scenario: −45% in residential and −47% in commercial), followed by wood construction (Wood scenario: −26% in residential), and floorspace reduction (Floor scenario: −10% in residential and −17% in commercial). The reduction potential is the highest when all circular strategies are combined together (Circular scenario), reaching 60% by 2060 for the entire stock (62% in residential and 54% in commercial). For concrete and steel, all circular strategies entail reductions

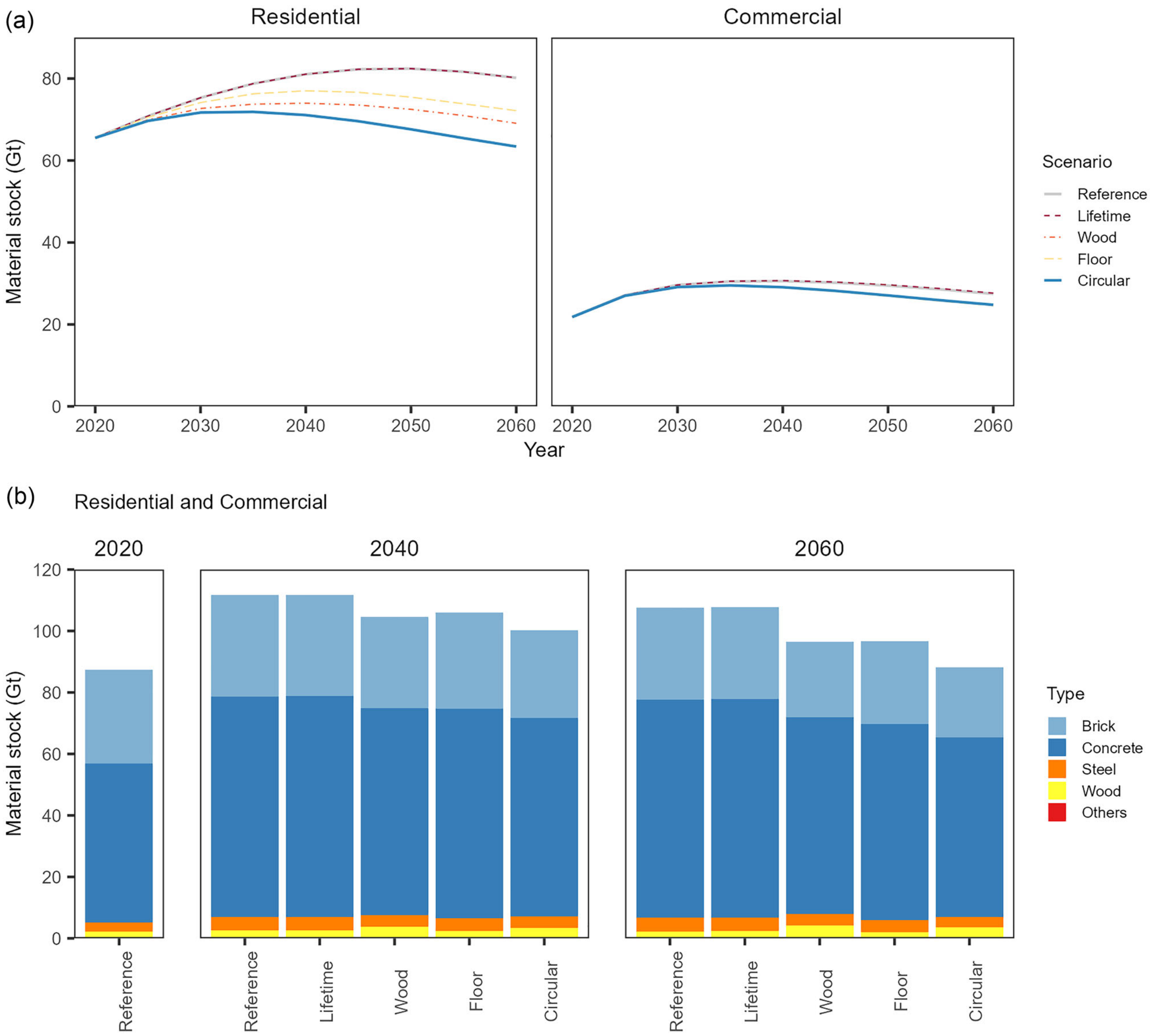

FIGURE 1 Material stock projections. (a) Total by sector. (b) Total for residential and commercial by material. Underlying data for this figure are available in Supporting Information S2.

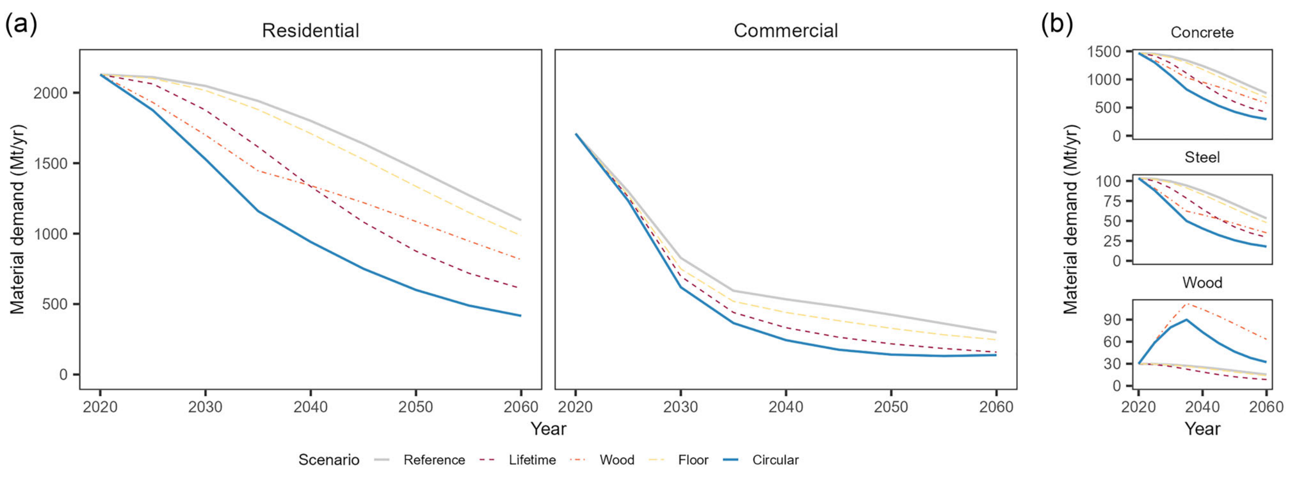

FIGURE 2 Material demand projections. (a) Total by individual sub-sectors (residential and commercial). (b) Total for all buildings, including both residential and commercial, for different materials. Underlying data for this figure are available in Supporting Information S2.

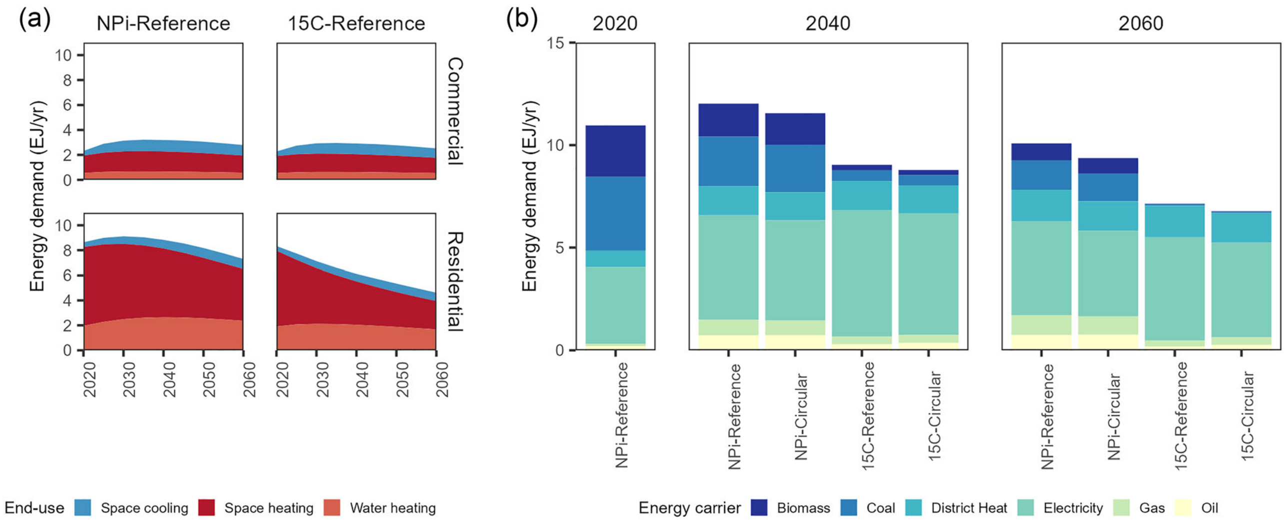

FIGURE 3 Final energy demand projections. (a) Total by sector and end-use. (b) Total for residential and commercial by energy carrier. Underlying data for this figure are available in Supporting Information S2.

in material demand. In contrast, the demand for wood increases in the Wood scenario due to material substitutions. Such increase can be reduced by combining other strategies, as shown in the Circular scenario.

3.3 | Energy demand

The energy demand of buildings for heating and cooling increases until around 2030 in the NPi-Reference scenario due to growing floorspace and more intensive operation driven by affluence, and then starts to decline under gradual energy efficiency improvements (Figure 3). Increase in energy demand stems primarily from urban residential and commercial buildings (Supporting Information, Figure 3). The investigated circular strategies affect the operational energy demand of buildings in different directions. Extending the lifetime of buildings (NPi-Lifetime scenario) decreases the uptake of new, more energy-efficient buildings. Conversely, floorspace reductions (NPi-Floor scenario) decrease the need for space heating and cooling. Switching to wood construction (NPi-Wood scenario) does not affect the energy demand under the assumption of similar energy efficiency standards of conventional buildings. Overall, the effect of these circular strategies on energy demand is relatively small. In the NPi-Circular scenario, total reductions in energy demand amount to 6% compared to the NPi-Reference scenario without stringent climate policies in 2060. The adoption of stringent climate policies (1.5C-Reference scenario) accelerates energy efficiency improvements and electrification processes and results in significantly lower energy demand (−28%). Applying the investigated circular strategies under stringent climate policies (1.5C-Circular) has similar effect as in the reference case, with a total reduction in energy demand up to 31% by 2060 compared to the NPi-Reference scenario.

3.4 | Greenhouse gas emission projections

GHG emission projections, including operational (both direct and indirect) and embodied emissions, are shown in Figure 4. In the NPi-Reference scenario, total emissions almost halve by 2060 as a result of the reductions in energy demand (Section 3.3) and material demand (Section 3.2), and partial decarbonization of the energy and material supply systems. Significant emissions, however, remain due to continuous use of fossil fuels for heating (direct emissions). Embodied emissions account for almost half of the total in 2020, and 30% of the total in 2060. By adopting all circular strategies, embodied emissions strongly decline, driven by the reduction in material demand. The GHG emission reduction potential in the NPi-Circular scenario amounts to 62% in embodied emissions and 24% in total emissions by 2060 compared to the NPi-Reference scenario. In the NPi-Circular scenario, embodied emissions account for only 15% of total emissions in 2060.

Stringent climate policies (1.5C-Reference scenario) swiftly abate direct and indirect emissions, both on the demand side, by reducing energy demand, phasing out coal, and switching to electricity-based heating, and on the supply side, by decarbonizing electricity and district heating through substantial uptake of renewable energy technologies. In this scenario, embodied emissions are only 20% lower relative to the NPi-Reference scenario in 2060, due to decarbonization of material production, and become predominant (87% of total emissions). Reductions in total embodied and operational emissions in the 1.5C-Reference scenario amount to 72% relative to the NPi-Reference scenario in 2060. Achieving

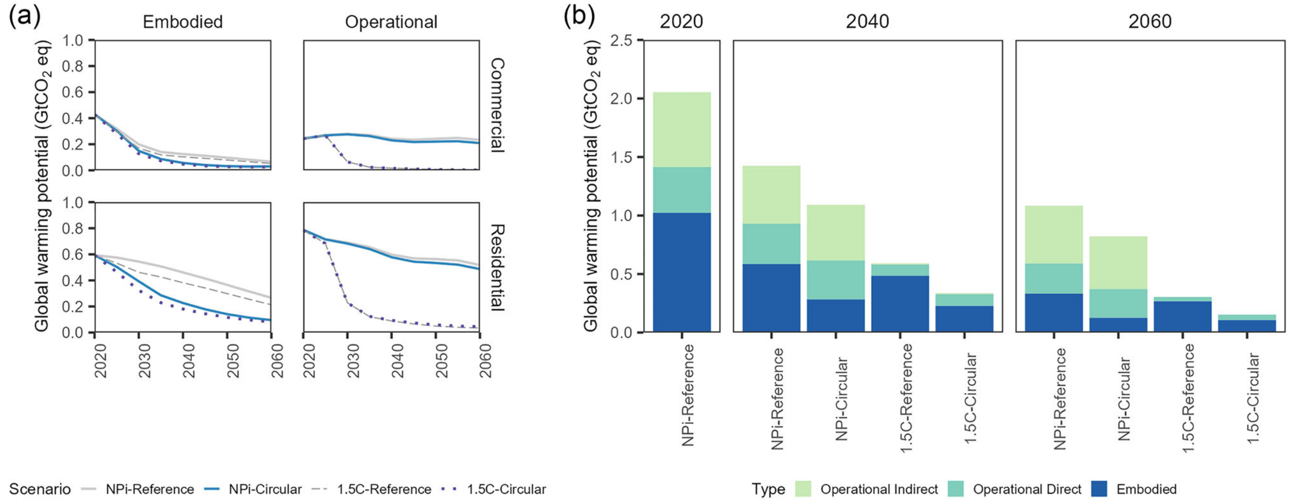

FIGURE 4 Projections of greenhouse gas (GHG) emissions. (a) Total emissions by sector and by emission type. (b) Total emissions for all buildings, including both residential and commercial, by emission type. Operational indirect emissions relate to the generation and distribution of electricity and district heating; operational direct emissions account for on-site fuel combustion; and embodied emissions relate to material production. Underlying data for this figure are available in Supporting Information S2.

more ambitious emission reductions requires further action on embodied emissions. The combination of all circular strategies and stringent climate policies (1.5C-Circular scenario) can further reduce total emissions by 86% in 2060 compared to the NPi-Reference scenario.

4 | DISCUSSION AND CONCLUSIONS

This study shows that three selected circular strategies, specifically lifetime extension, shift to wood construction, and floorspace reduction, can significantly contribute to reducing the material demand and GHG emissions of the building stock in China to achieve ambitious decarbonization targets. The reduction potentials of the three combined circular strategies in the absence of stringent climate policies (NPi-Circular scenario) amount to 62% for embodied emissions and to 24% for total (embodied and operational) emissions in 2060 compared to the reference (NPi-Reference) scenario. Under stringent climate policies in agreement with 1.5C climate targets, the three circular strategies play a key role in abating embodied emissions, that would otherwise dominate total emissions in buildings by mid-century. Overall, the total emission reduction potential including embodied and operational emissions reaches 72% with climate policy only (1.5C-Reference scenario) and 86% with combined climate policies and circular strategies (1.5C-Circular scenario). The investigated circular strategies can substantially reduce the material demand and associated emissions, but also influence operational energy demand. In particular, sufficiency measures related to floorspace reduction can contribute to lowering operational energy demand for heating and cooling. These findings are in agreement with previous studies focusing on the effect of circular strategies for decarbonization (Pauliuk et al., 2021; Zhong et al., 2021).

The analysis of the broader implications of these circular strategies and interplay with different climate policies was enabled by the integration of a bottom-up building sector model, industrial ecology methods (MFA and LCA), and IAM. This framework makes it possible to consider the broader effects of both demand- and supply-side strategies and their interactions more comprehensively and across the buildings, industry, and energy sectors. Having a detailed representation of the building sector and its service levels and heterogeneities is crucial to consider the effect of a broader set of mitigation strategies on both energy and materials demands. This study advances the assessment of circular strategies in the context of decarbonization scenarios and contributes to bridging the gap between industrial ecology and IAM highlighted in the existing literature (Pauliuk et al., 2017).

4.1 | Policy implications

This study can inform policy decision on circular strategies for decarbonizing the building sector in China, accounting more holistically for the interplay with industry and the energy system. The results confirm that the investigated circular strategies have significant potential in reducing GHG emissions from buildings in China. Thus, we have shown that under an ambitious climate change mitigation scenario, the investigated circular strategies are critical to reduce embodied emissions that would otherwise be dominating total emissions. We could obtain these results only because of the joint consideration of the buildings, industry, and energy system evolution and linkages, that are often neglected in the existing literature (Mastrucci et al., 2023). These insights can better inform more holistic decarbonization strategies that account for the interplay across sectors.

Different policy instruments could support the successful implementation of these strategies while reducing challenges in their uptake. Lifetime extension has a great potential to reduce material demand and associated embodied emissions in China (45% embodied emission reduction relative to the NPi-Reference scenario in 2060) in addition to limiting scrap release. Urban planning, land policies, and building codes can discourage premature demolitions and improve building design and maintenance to increase the functional lifetime of buildings. Shifting to strategies that promote renovation of existing buildings instead of demolition can significantly contribute to this objective. Structural renovations commonly require 80%–90% less energy compared to the energy-intensive processes of new construction (Zhang et al., 2022b). Wood construction is a promising strategy to replace emission-intensive materials and practices with nature-based solutions and dematerialization. Our results show a reduction potential of embodied emissions of 24% by switching to wood-based construction in residential buildings only relative to the Reference scenario in 2060. Building codes, subsidies and incentives could play an important role in switching construction practice. However, biomass availability constraints, competition with other uses of wood, and land-use-related impacts (Hoxha et al., 2020) should also be carefully considered. Our results show that switching to 50% wood construction in new residential urban buildings, without other demand-side measures, could result in a 2030 peak wood demand more than doubling China's total sawn wood consumption, estimated at over 110 million m^3 for 2016 (Barbu & Tudor, 2022), posing potential wood availability and upscaling challenges. Floorspace reduction can be effective in reducing material and energy demand simultaneously, but it requires important changes in lifestyles and efforts in urban planning. The reduction potential of this strategy on embodied emissions is relatively lower compared to the other two strategies in this study and amounts to 11% compared to the Reference scenario in 2060. Reduced floorspace can be achieved by promoting co-housing and co-working, switching to more compact urban form and housing types, for example, from single-family to multi-family housing. There is also potential for using vacant buildings instead of new construction. Due to the effects of urbanization, we estimate an increase in the total share of multi-family housing in residential buildings from 65% in 2020 to almost 80% in 2060 (Supporting Information, Figure 3). Since the building stock growth in China will be strongly driven by urban constructions, it is crucial to further support improved building design and city planning strategies targeting material and energy demand reductions to avoid future lock-ins.

This study highlights the importance of policies that combine these circular strategies with stringent climate policies to achieve ambitious decarbonization targets. Embodied emissions should be carefully addressed in mitigation scenarios as their contribution will be even higher (up to 87% of total emissions in the 1.5C-Reference scenario), compared to operational emissions, when adopting advanced intervention for the energy efficiency of the building sector and decarbonization of the energy system. Thus, adopting a life-cycle approach is important to inform comprehensive strategies for decarbonization and avoid burden shifting.

The results of this study show that, even when applying the three selected circular strategies and climate policies together, full decarbonization could not be achieved, though most of the emissions were abated. For a fully decarbonized building sector, the proposed strategies could be further strengthened and additional strategies could be considered both on the demand and supply sides. In particular, recycling holds an important potential, especially for metals, such as steel, that are largely used in building construction. Other nature-based solutions, alternative low-emitting materials, dematerialization, and improved building design strategies should be further addressed in future studies.

4.2 | Limitations and future developments

This study focuses on the entire building stock of a large country, encompassing material stocks and demand, energy demand, and GHG emissions. Thus, there are some limitations due to different dimensions of uncertainty and data availability. We focus here on two key life-cycle stages of buildings, holding large share of emissions and impacts, namely the product stage and use stage. We do not include other stages, such as construction, maintenance, and the end-of-life, due to data availability limitations, even though these stages commonly contribute a lower share of the life-cycle impacts (Cabeza et al., 2014; Chastas et al., 2016; Kellenberger & Althaus, 2009). For the calculation of material demand and embodied emissions we consider a set of seven key materials, in agreement with other studies (Deetman et al., 2020; Marinova et al., 2020; Zhang et al., 2022b). Future analysis may include more material types that represent minor quantity shares with non-negligible impacts, such as plastics and other insulation materials. Material intensity coefficients are associated with additional uncertainties. We compared the selected China-specific material intensity coefficients with data available in the literature to ensure consistency (Supporting Information, section 1.5). However, datasets are scarcely available for wood-based construction in China, requiring complementing the inputs with data from other regions, with higher levels of uncertainty. In this study, we employ the standard GWP-100 methodology (IPCC, 2021) to calculate GHG emission intensities for construction materials, a widely recognized approach that enables consistent and comparative analysis of their environmental impacts. Notably, biogenic carbon was not included in this analysis due to the complexities of its accounting and the need for an in-depth investigation to assess its effects on wood construction accurately (Garcia et al., 2020; Hoxha et al., 2020). Our future research will focus on a comprehensive investigation into wood construction's impact on climate change, incorporating biogenic carbon accounting to deepen our understanding of sustainable building practices.

Further developments will focus on the analysis of a broader set of demand-side and supply-side circular strategies and their synergies and trade-offs. Thus, additional strategies should be considered, including low-carbon alternatives to conventional materials, such as low-carbon concrete mixes (Elmesalami & Celik, 2022; Kim et al., 2013; Senadheera et al., 2023). Further joint analysis of circular strategies, energy efficiency improvements in buildings, and linkages with the industry and energy sectors is required for more systemic assessments. In particular, efforts are needed to better represent key dynamics in building sector modeling, for instance to consider the impact of structural renovations on extending the lifetime of buildings, and endogenously account for the effect of lifestyle changes on future buildings, materials, and energy demand (Mastrucci et al., 2023). The modeling framework presented in this study could contribute to these advancements and improve the assessment of scenarios for deep decarbonization of the building sector.

AUTHOR CONTRIBUTIONS

Alessio Mastrucci: Conceptualization; methodology; software; investigation; writing—original draft; visualization. **Fei Guo**: Conceptualization; methodology; investigation; writing—original draft. **Xiaoyang Zhong**: Investigation; methodology; writing—original draft. **Florian Maczek**: Investigation; methodology; writing—review and editing. **Bas van Ruijven**: Conceptualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article.

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SUPPORTING INFORMATION

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

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