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Abstract

China is the largest source of the growth of the global building sector. The continued construction boom across China has generated a massive flow of materials with significant associated embodied energy consumption and carbon emissions. Despite the serious implications, however, there exist a very limited number of macro-level studies on embodied energy of Chinese buildings, with even fewer exploring future scenarios. There is therefore little in the way of an evidence base to offer policy makers. We develop a probabilistic model to forecast the possible trajectories of embodied energy of residential buildings over the medium to long term in the Chinese urban context. Our results provide clear evidence to substantiate the importance of embodied energy of new construction, found to be over 0.3 times the operational energy of existing stock between 2010 and 2018. If current trajectories are followed, embodied energy is likely to peak around 2027, with a 95% credible interval ranging from 87 to 283 Mtce (61 to 198 Mtoe) and a mean of 170 Mtce (119 Mtoe). We show that building lifetime has a substantial impact on future annual and cumulative embodied energy. Our findings reinforce the need to take a whole-life perspective to formulate policies addressing building energy under China's announced overarching target of achieving carbon neutrality by 2060.

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1 Introduction

The buildings and construction sector has been identified as a primary target for the clean energy transition and emissions mitigation efforts (IPCC, 2014; Rogelj *et al.*, 2018). In 2019, the operation of buildings was responsible for 30% of global final energy use and 28% of direct and indirect energy-related carbon emissions (Global Alliance for Buildings and Construction and UNEP, 2020). Operational energy only describes part of the story. If the energy and emissions associated with the manufacturing of building materials and construction activities, as an integral part of the 'embodied energy and carbon' of buildings (Institution of Civil Engineers, 2015), are included in the accounting, the percentages would increase to 35% for energy and 38% for emissions, making buildings and construction combined the largest energy-consuming and carbon-emitting sector (Global Alliance for Buildings and Construction and UNEP, 2020).

The significant impact of embodied - in addition to operational - energy and carbon requires a whole lifecycle approach to pursuing full decarbonisation of buildings (Global Alliance for Buildings and Construction, IEA and UNEP, 2020). Some of the first steps that can be taken include cost-effective measures to reduce embodied energy and carbon, such as reducing demand for materials, promoting switches to low-energy and low-carbon materials, improving efficiency in manufacturing and construction, optimizing material usage and so on (Energy Transitions Commission, 2018), similar to those aiming to enhance operational energy efficiency in buildings.

China is a major driving force of the growth of global building stock, having the largest buildings market in the world (Yu, Evans and Shi, 2015; Global Buildings Performance Network, 2019). Over the past ten years, the floor area of new buildings constructed in China each year has remained consistently above 2 billion m^2 (National Bureau of Statistics, 2019). In 2018, new buildings amounting to 2.5 billion m^2 were constructed in China, accounting for 33.8% of the global total for new construction of 7.4 billion m^2 (IEA, 2020). In 2018, the total floor area of Chinese buildings, including residential, commercial and public buildings, reached 60 billion m^2 (THUBERC, 2020). The massive construction activity in China has generated a commensurate flow of materials, which has significantly influenced global trends in building material demand. Globally, the use of steel and cement in buildings, two of the largest sources of building material-related CO_2 emissions (World Green Building Council, 2019), increased by 4% per year from 2000 to 2015 and China's share increased from 30% to nearly 40% during this period (IEA and UNEP, 2018). The use of steel, cement and other materials to meet the demand from new construction led to a significant amount of embodied energy and carbon. In 2015, embodied energy and carbon resulting from new buildings was 0.51 billion tonnes of coal equivalent (tce) (or 0.357 billion tonnes of oil equivalent, toe) and 1.7 billion tCO_2, respectively accounting for 12% and 16% of China’s economy-wide total energy consumption and carbon emissions (THUBERC, 2018). These levels are comparable to operational energy and emissions of the total building stock in China in 2015, which were 0.96 billion tce and 2.22 billion tCO_2 respectively (THUBERC, 2017, 2018).

The impact of embodied energy and carbon of buildings is particularly high in the urban context of China, where buildings are generally short-lived for various reasons including design standards, quality of building materials, construction techniques and practices, maintenance and renovation, and massive demolition as a result of urban renewal and expansion (Huang, 2006; Yang and Kohler, 2008; Hu, Bergsdal, *et al.*, 2010; Fawley and Wen, 2013; Cai *et al.*, 2015). The short lifetime of buildings implies a high turnover rate of the residential stock (Zhou *et al.*, 2020). Old buildings at various ages are demolished, while new buildings are constructed to meet demands. Such dynamics have significant implications for stock-level energy and carbon performance from a lifecycle perspective. A high turnover rate implies lower risk of urban buildings being subject to operational energy and carbon lock-in effects, as the stock is rapidly replenished with more energy efficient buildings. Meanwhile, as the Chinese building sector is expected to continue to grow apace, new buildings will continue to be constructed to replace demolished buildings as well as meet incremental demand. However, massive construction incurs significant embodied energy and carbon. These two arguments imply a strategic trade-off from the stock-level perspective of building lifecycle energy and carbon (Zhou *et al.*, 2019). The magnitude of embodied energy and carbon, in both absolute and relative terms, clearly demonstrates that embodied energy and carbon should be taken equally as seriously as operational energy and carbon by policies and regulations. Without a parallel focus on embodied energy and carbon, both the immediate energy and carbon costs of buildings, and the savings that could be achieved, will be missed (Pomponi and Moncaster, 2018).

Despite its clear importance, embodied energy and carbon of buildings remains under-emphasised in China. Government strategies, plans and pilot initiatives relating to building energy and carbon have focused almost entirely on the operational phase of buildings (Hong, Shen and Tang, 2018). In China's energy statistics, embodied energy of buildings is accounted for under the various industrial subsectors, such as cement, steel, aluminium, etc., without explicit links to the building sector. Sector-specific design codes for energy-efficient buildings and evaluation standards for green buildings deal almost exclusively with operational energy and carbon, leaving embodied energy and carbon largely ignored (Zhu *et al.*, 2020). Similarly, there have been relatively few studies on embodied energy and carbon in Chinese buildings compared to those on operational energy and carbon (Chang, Ries and Wang, 2013; Zhu *et al.*, 2020). Amongst the former, most focus on individual case studies. There appear to be very limited sectoral studies investigating the overall characteristics of an entire building stock at the city, provincial or national level, which are much needed for policy design and evaluation (Huo, Ren and Cai, 2019; Li, Kou and Wang, 2019; Zhang *et al.*, 2019).

Against this backdrop, the objective of this study is to develop a probabilistic model to forecast the possible trajectories of embodied energy of Chinese urban residential buildings over the medium to long term. In so doing, this study can assist policymakers in better evaluating the impacts of embodied energy and addressing the strategic trade-off facing the envisioned decarbonisation of the Chinese building stock. The rest of this paper is organised as follows. Section 2 presents a review of the literature relating to embodied energy of Chinese buildings and identifies the research gap justifying the relevance of this study. Section 3 introduces the methodological framework and describes the model and data sources. Section 4 presents the results and a policy discussion. Section 5 concludes the study with a summary of key findings and policy limitations. The appendix provides further details on the model.

2 Literature review

A number of studies have quantified and analysed embodied energy and/or carbon of Chinese buildings by using different Life Cycle Assessment (LCA) methods, including process-based, input-output, and hybrid methods (Dixit, 2017). Scope-wise, these studies could be broadly categorised into micro-level studies evaluating individual cases and macro-level studies targeting a building stock at a city or national level.

Detailed assessment of individual buildings provides valuable knowledge about and insight into the drivers of embodied energy and carbon (Chen, Burnett and Chau, 2001; Aden, Qin and Fridley, 2010; Yan, 2011; Han *et al.*, 2013; Li *et al.*, 2014; Zhang and Wang, 2016, 2017; Su and Zhang, 2016; Gan *et al.*, 2017; Hong *et al.*, 2018; Yang *et al.*, 2018; Su *et al.*, 2020). However, due to case-specific factors across technological, economic, environmental and social dimensions, as well as differences in methodological and dataset choices, there exist large disparities in assessed levels of embodied energy and carbon per unit of floor area and its importance relative to the operational energy and carbon. Moreover, individual cases cannot be generalized to represent the macro-level characteristics of a sizeable building stock. Furthermore, studies based on individual cases are mostly cross-sectional, thus they cannot capture the temporal dynamics of building embodied energy and carbon as a result of trends in structural forms and material choices, advancement in technologies and practices, evolving building standards and regulations, and mounting climate impacts. Therefore, case studies have inherent limitations in providing a macro-level view needed to formulate policies targeting stock-level transition towards green buildings.

Compared to micro-level cases, studies of stock-level embodied energy and carbon of buildings in China are quite rare. At city level, Liu and Hu (2006) sampled 100 residential buildings in Beijing built in different years and of different structure types. The city-wide material consumption, energy consumption by material production, and environmental impacts attributable to residential buildings were estimated based on the samples for the historical period of 1949 to 2003. Guo and Wang (2018) used data from various national and local statistical yearbooks to calculate annual energy consumption by building material production and construction activities in Shanghai in 2015, which was found to account for 12.85% of total energy consumption of Shanghai.

At the national level, Lin *et al*. (2015) estimated the aggregated energy consumption of steel, cement and aluminium production meeting the demand of the entire building stock of China, which increased from 0.36 billion tce (0.252 billion toe) in 2004 to 0.85 billion tce (0.595 billion toe) in 2012. Extending Lin's method, Zhang *et al*. (2019) applied a process-based model to estimate the historical embodied energy and carbon of the Chinese building stock by considering the impact of different building structural types on material intensities. The total embodied energy of urban residential, rural residential, and public and commercial buildings in 2016 was found to reach 410 million tce (Mtce), or 287 Mtoe, accounting for approximately 9% of China's economy-wide energy consumption. Chen *et al*. (2017) used an input-output model to estimate the carbon emissions of the Chinese construction industry from 1995 to 2011 and found industry's carbon emissions increased by nearly 400% over this period. Indirect emissions, which were incurred by upstream activities such as material production, remained the major component of total emissions and consistently accounted for over 95%. Huo *et al*. (2019) developed a building stock turnover model to estimate the total energy consumption of urban residential buildings in China. The embodied energy, estimated using an approach highly similar to Zhang *et al*. (2019), was found to account for 30% of the stock's total energy consumption. From 2000 to 2015, the embodied energy increased moderately from 86 to 97.5 Mtce (60.2 to 68.3 Mtoe), accompanied by generally decreasing trends of material production energy intensity and construction energy intensity.

Only a very few studies have gone beyond the historical evaluation and explored the possible outlook over the next few decades. Huang *et al*. (2013) used a material flow analysis model to estimate the long-term materials demand and environmental impact from the entire Chinese building sector. They found the total embodied carbon from Chinese buildings from 2011 to 2050 would reach 56.7 billion tonnes, with a peak annual contribution of 1.49 billion tonnes reached around 2030. Employing a similar approach, Hong *et al*. (2016) modelled the stock turnover of residential and commercial buildings in China and forecast that building materials demand and the associated embodied energy would reduce by 73% and 77% respectively, from 2010 to 2050. However, both Huang *et al.* (2013) and Hong *et al*. (2016) have an inherent methodological limitation in their use of a normal distribution with pre-defined parameters to represent building lifetime distribution. This approach calls into question their forecasting results that built on the modelled building stock turnover (Zhou *et al.*, 2019, 2020).

As a noteworthy common feature of macro-level studies, the large variance in material intensity, as demonstrated by micro-level studies based on individual buildings, appears to have been overlooked in their models. The common approach taken by these macro-level studies was to apply a single average value to the intensity of a particular material in a given year. Various data sources were referred to by these studies to determine the single average values used in their calculations. The implication of this approach is strong, as evidenced by the substantial variation in the stock-level results of these macro-level studies, even for the historical period with known quantity of annual new construction. For example, the embodied energy of the national building stock in 2012 was estimated to be 330 Mtce (231 Mtoe) by Zhang *et al*. (2019), almost double the estimate of 170 Mtce (119 Mtoe) by Hong *et al*. (2016). As for urban residential stock, its embodied energy in 2015 was estimated by Zhang *et al*. (2019) and Huo *et al*. (2019) to be 150 Mtce (105

Mtoe) and 97.5 Mtce (68.3 Mtoe), respectively.

On the whole, the existing literature suggests there are three substantial research gaps. Firstly, there is a dearth of regional or national level quantification of embodied energy of the building sector. Secondly, amongst the limited national-level studies, most focus on estimating the historical amounts of embodied energy, with very few exploring future scenarios and trajectories. Thirdly, despite their importance, uncertainties associated with the material intensity, energy intensity, and future annual new construction and their propagation into stock-level embodied energy have remained largely under-researched.

This study aims to contribute to filling these gaps by developing a probabilistic model to estimate future building embodied energy trajectories. It focuses specifically on the urban residential building sector, which is an integral part of the overall building sector of China. The probability distribution of the annual embodied energy, as opposed to the point estimates produced by deterministic models of previous studies, can provide significantly richer information that can help to lower the risk of over- or under-estimation and therefore better inform policies addressing energy and environmental impacts of buildings. To the best of our knowledge, this study is a first-of-its-kind attempt to probabilistically forecast the future trajectories of the embodied energy of Chinese urban residential stock.

3 Methodology

In this section, we present the probabilistic stock-level model for tracking embodied energy and estimating its future evolution. The embodied energy modelled in this study refers to the aggregate of energy consumption incurred by building material production, transportation, on-site construction, and demolition. This boundary covers part of the product stage (A3), construction process stage (A4-5) and part of the end-of-life stage (C1) according to the building lifecycle stages defined in European Committee for Standardization CEN 15978 (CEN, 2012). The probabilistic model consists of a series of components: forecasting the possible future annual new construction in stock turnover dynamics (section 3.1); establishing probability distributions of building material intensities (3.2); estimating the trajectories of the energy intensities of producing building materials (3.3); construction and demolition of buildings (3.4); and transportation of materials (3.5). The uncertainties of these input variables are propagated using Monte Carlo simulations to obtain the probabilistic distribution of the embodied energy of new construction per year.

3.1 Annual new construction

In official statistics up to the present, annual new construction of urban residential buildings is a known statistic and therefore can be directly used to estimate annual embodied energy. For the future, it is an unknown variable which is estimated through modelling the evolution of the building stock over time. In the model, all existing buildings undergo an ageing process. Each year, a small portion of old buildings are demolished as they reach the end of their lifetimes. The rest of the buildings in the stock remain operational and become one year older. New buildings are constructed and put into use to meet incremental housing demand driven by economic growth and rising living standards. This interplay between new construction, existing stock and demolition of old buildings creates a dynamic stock turnover process. A critical factor in the turnover process is building lifetime, which decides how soon old buildings flow out from and new buildings flow into the stock. Given an estimate of building lifetime and expected future demand for housing, annual new buildings to be constructed per year can be estimated through modelling the turnover process (Zhou *et al.*, 2020).

In the Chinese urban context, there is a lack of authoritative statistics on actual building lifetime. Despite design lifetime defined by building design standards, buildings are generally short-lived due to engineering, planning, economic, and social factors (Huang, 2006; Yang and Kohler, 2008; Hu, Bergsdal, *et al.*, 2010; Fawley and Wen, 2013; Cai *et al.*, 2015; Zhou *et al.*, 2019). While the impacts of the factors differ significantly depending upon specific contexts and time, the consistent outcome is a rapid turn-over of building stock. Given the huge volume of buildings and significant heterogeneity in terms of their physical characteristics and socio-economic contexts, it is necessary to consider the uncertainties associated with the generally short building lifetime when investigating the entire urban residential stock in China. In other words, it is unrealistic to assume that a cohort of buildings, i.e. those constructed in a given year but in various cities across the country, would be in service for exactly the same period and then demolished simultaneously. Therefore, building lifetime should be taken as a profile, which can be approximated by a distribution in some form of a probability density function (PDF). The distribution recognises and represents the uncertainties associated with the factors collectively influencing building lifetime. Based on this consideration, we apply the concept of survival analysis (Allison, 2010; Liu, 2012) to model building stock turnover dynamics. The uncertainties associated with the PDF parameters and the choice of candidate PDFs are quantified and propagated to the estimate of future annual new construction. Details of this approach can be found in previous work by Zhou *et al.* (2020).

3.2 Building material intensity

This study focuses on steel, cement, aluminium and glass. Steel and cement are the most extensively used building materials in China (Zhang *et al.*, 2019), and their production also consumes significantly more energy than other materials (Zhao *et al.*, 2014). Aluminium and glass are also energy-intensive in their production process (Hong *et al.*, 2016). Collectively, steel, cement, aluminium and glass accounted for the dominant share of total energy consumption of all building materials production (THUBERC, 2019a). Building material intensity, defined as the quantity of a given building material (ton) per unit of constructed floor area (m^2), varies substantially with building characteristics as a function of cost, architectural design, structural type, heights, geological condition, climatic condition, environmental performance, etc. Such variability can potentially be characterised by a probability distribution for material intensity. Whilst a normal distribution is a plausible choice, it does not necessarily offer a good fit with the empirical data, as there could be considerable skewness of data distribution that cannot be neglected (Laner, Rechberger and Astrup, 2014; Heeren and Fishman, 2019). Skewed distributions such as Weibull or Gamma might fit the data better than a symmetrical normal distribution (Cao *et al.*, 2016; Roh *et al.*, 2019). In this study, different distributions were explored for each material and the one offering the best fit with data was used to generate random samples of material intensity for Monte Carlo simulation. The results were a Weibull distribution for steel, a gamma distribution for cement, a lognormal distribution for glass, and a normal distribution for aluminium. The dependence structure of material intensities was also captured through copula, as further elaborated in the appendix.

3.3 Energy intensity of building material production

The energy intensity of building material production refers to the energy consumed in producing a tonne of a given building material. Data from various sources shows a generally decreasing trend of energy intensities of steel, cement, aluminium and glass production driven by technological advancement and evolving sectoral policy requirements (Wang, 2001, 2013, 2016, 2019; Center for Industrial Energy Efficiency, 2014; National Bureau of Statistics, 2017; NRDC, 2019). Based on available historical statistics, this study models the possible trajectories of energy intensities in the short to medium term through Bayesian non-linear regression. This assumes a business-as-usual scenario under which the energy intensities of materials production, in the absence of disruptive technologies and/or drastic changes of policy orientation and intensity, are expected to follow the descending trends, but with diminishing potential for improvement over time. Details of modelling the energy intensities of producing the four materials are presented in the appendix.

3.4 Energy intensity of building construction and demolition

On-site building construction and demolition activities incur energy consumption that is not trivial (Moncaster and Symons, 2013; Pomponi and Moncaster, 2018). As found by Malmqvist *et al.* (2018) based on European cases reviewed under the IEA's Annex 57 project, embodied energy from the construction stage could vary between 6% and 38% of total embodied energy. However, compared to materials production, few studies have focused specifically on the construction and/or demolition stage, and empirical data is limited (Moncaster *et al.*, 2019; Zhu *et al.*, 2019). Given our interest in stock-level embodied energy from annual construction and demolition, we adopt an alternative approach by investigating key metrics of the Chinese construction industry as a whole. Firstly, historical statistics on total annual energy consumption of the Chinese construction industry are taken from the energy balance sheet provided in the Chinese Energy Statistical Yearbook (National Bureau of Statistics, 2017). Since this data is not further disaggregated into specific categories, it is used as a proxy to represent the total energy consumed by construction and demolition activities undertaken by construction enterprises. Secondly, industry-wide average energy intensity in a given year is obtained by dividing the annual total energy consumption by the total floor area under construction in the same year taken from China Statistical Yearbook (National Bureau of Statistics, 2019). Thirdly, using the pattern found in the estimated energy intensity data over 1990 to 2017, an exponential decay function is applied to model possible future trends of construction and demolition energy intensity. The parameters of the function are estimated through Bayesian inference, similar to the approach used for energy intensity for material production.

3.5 Energy intensity of materials transportation

Similar to construction and demolition energy, materials transport is an under-researched aspect of building embodied energy that needs more attention (Pomponi and Moncaster, 2018; Moncaster *et al.*, 2019). Malmqvist *et al*. (2018) pointed out that transportation should not be neglected in calculating embodied energy, as long-distance transportation of large volumes of materials, such as pre-fabricated modular building components, can have a substantial impact on life cycle embodied energy and carbon of buildings. The energy intensity of materials transportation is a function of transportation mode, vehicle loads, fuel type, and transportation distance. A common understanding in literature is that medium-duty and heavy-duty diesel trucks are the major way of transporting building materials in China (Yan, 2011; Zhang *et al.*, 2019; Hao *et al.*, 2020; Zhu *et* *al.*, 2020). As for transportation distance, there is a lack of adequate empirical data. This study refers to default values for material-specific transportation distance as given in the Standard for Building Carbon Emission calculation issued by the Ministry of Housing and Urban-Rural Development (MOHURD)(MOHURD, 2019b). In this study, the estimated energy intensities of materials transportation are assumed to be constant over the modelled period.

4 Results and discussion

4.1 Historical and future embodied energy

Based on the methodology elucidated above, the possible trajectories of the embodied energy incurred by annual new construction of urban residential buildings were modelled for the period of 2010 to 2060 (Figure 1). In each year, the embodied energy is a distribution, which quantifies its uncertainty. For the historical period, the annual new construction, the energy intensities of materials production, and the construction and demolition energy intensity are all known and therefore take fixed values. The distribution reflects the uncertainty associated with building material intensities, namely, the consumption of steel, cement, aluminium and glass per m^2 of floor area constructed. For future decades, the annual new construction is a random variable characterized by its posterior predictive distribution, which is determined by the stock turnover dynamics. Similarly, the materials production energy intensities and construction and demolition energy intensity are subject to quantified uncertainties in their respective developing trends. The uncertainties of these variables, along with those of material intensities, are propagated through the model to inform the distribution of embodied energy.

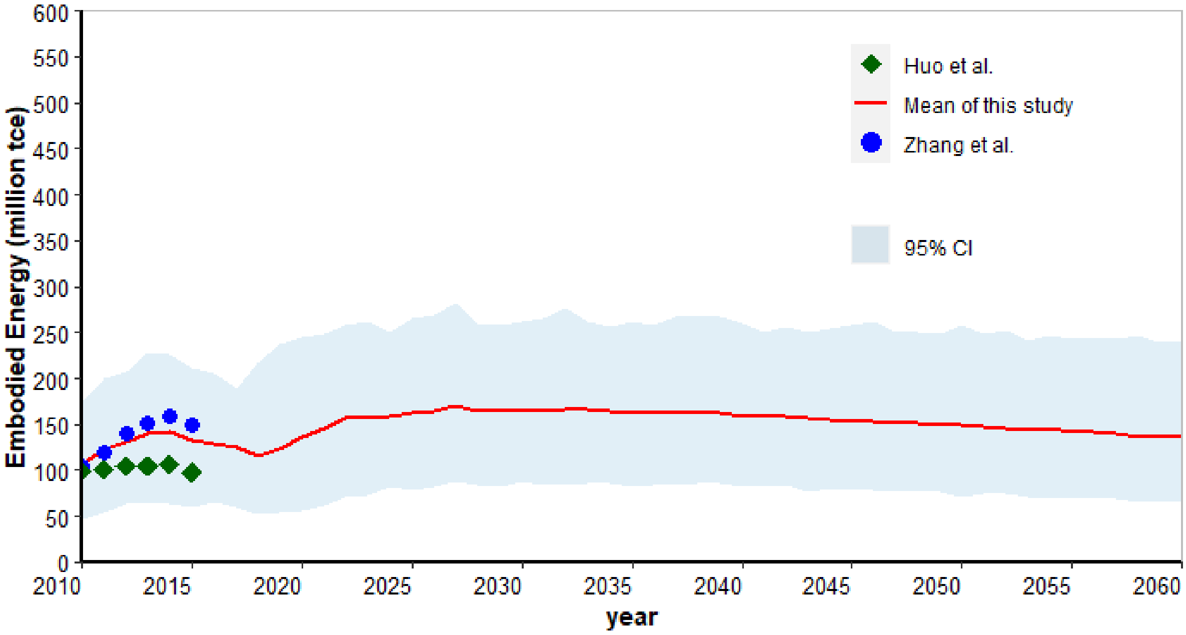

Figure 1: Possible trajectories of embodied energy of annual new residential construction

In Figure 1, the light blue belt is the 95% credible interval (CI) for embodied energy, and the red line is the mean value. The embodied energy is found to have started to increase from 2010 to 2014. It then declines gradually as a result of the decrease in annual new construction. From 2019 onwards, it starts to pick up due to expected increase in annual new construction in response to expected incremental housing demand growth (Zhou *et al.*, 2020). The trend continues but the rate slows down gradually. The peak is expected to be reached around 2027, when the 95% credible interval ranges from 87 Mtce (61 Mtoe) to 283 Mtce (198 Mtoe) and the mean value is 170 Mtce (119 Mtoe). Following the peak, the embodied energy largely plateaus until 2034, when it starts to slowly decline. By 2050, the mean value decreases to 150 Mtce (105 Mtoe). Underlying the bending of the belt is primarily the combined effect of the possible trajectories of annual new construction and the material intensities. As explained above, the energy intensities of materials production and those of construction and demolition activities are expected to have minor impacts due to the limited potential of energy efficiency improvement over time. This reflects the observed trend of decelerating energy intensity decrease implying that the 'low-hanging fruit' have been picked, as well as the assumed baseline scenario where no disruptive technologies and/or policies would emerge and improve energy efficiency significantly.

It is useful to compare the results with previous studies. As shown in Figure 1, the credible interval of embodied energy for the historical period of 2010 to 2015 presents a pattern fairly similar to the deterministic estimates of Zhang *et al*. (2019) and Huo *et al*. (2019). This pattern, featuring a continuous increase until 2014 and then a drop in 2015, is well aligned with the variation of the actual amount of annual new construction of urban residential buildings in this period. This alignment is as expected, because the annual new construction is the fundamental determinant of the demand for materials. The curve of mean value of the distribution lies between the other two studies, which referred to different sources of sample data on material intensities. As the difference between Zhang *et al*. (2019) and Huo *et al*. (2019) gets larger over time, the mean curve is consistently much closer to Zhang *et al*. (2019) than to Huo *et al*. (2019). This clearly demonstrates that, with other factors being the same or similar, the material intensities can have a significant impact on the embodied energy.

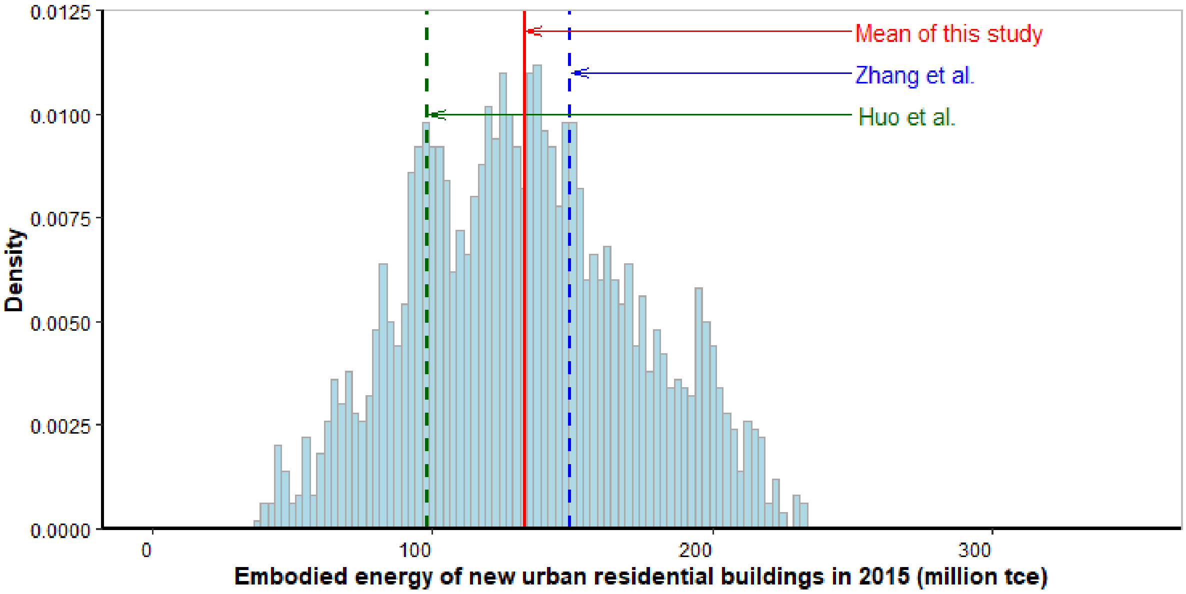

Figure 2: Estimated embodied energy in 2015 - comparison with other studies

Figure 2 takes a closer look at the situation in 2015. The minimum and maximum values of the full distribution are 37.3 Mtce (26.1 Mtoe) and 232.4 Mtce (162.7 Mtoe), respectively. The 95% credible interval is in the range of 60.3 and 211.7 Mtce (42.2 and 148.2 Mtoe). Falling into this credible interval, the estimates by Huo *et al*. (2019) and Zhang *et al*. (2019) are 98 and 149 Mtce (68.6 and 104.3 Mtoe) respectively. Using the empirical cumulative distribution function informed by the distribution in this figure, the probability of the estimated embodied energy being higher than 98 Mtce (68.6 Mtoe) and lower than 149 Mtce (104.3 Mtoe) is 45.9%. This suggests a considerable probability of over-estimate or under-estimation by taking a deterministic approach based on limited data. There is, therefore, a material risk of inaccurately interpreting the results and making less informed decisions about policy measures. In contrast, probability distributions obtained from a stochastic approach enable the quantification and communication of uncertainties, which help to mitigate the risk of over- or under-estimation and improve the robustness and reliability of the results.

4.2 Impact of building lifetime

As pointed out in previous studies, Chinese urban buildings are generally short-lived. A number of studies relating to materials demand and environmental impact of Chinese buildings take the same approach to building lifetime by representing it as a normal distribution with an assumed mean value of between 30 and 45 years (Hu, Bergsdal, *et al.*, 2010; Hu, Pauliuk, *et al.*, 2010; Hu, Voet and Huppes, 2010; Shi *et al.*, 2012; Huang *et al.*, 2013; Hong *et al.*, 2016; Shi, Chen and Yin, 2016; Huo, Ren and Cai, 2019). Some recent studies took a step forward by estimating the lifetime. For example, Cai *et al*. (2015) found that Chinese buildings had an average lifetime of 23.2 years. Zhou *et al*. (2019) used a Weibull distribution to quantify the lifetime uncertainty of urban residential buildings and found the average lifetime was 34 years. As a critical factor in the stock turnover dynamics, the short building lifetime makes it necessary to investigate how the variation in average lifetime affects the annual new construction and the associated embodied energy.

Two scenarios are modelled for comparison with the baseline scenario. The first scenario progressively extends the average lifetime by 10 years over the period of 2021 to 2040. This is modelled by shifting the lifetime distribution profile towards higher values. As specifying any one of the four representations (PDF, CDF, survival function, hazard function) allows the other three to be ascertained, shifting the lifetime distribution (PDF) results in an adjusted hazard function, which decelerates the amount of annual demolition of existing old buildings. The second scenario examines the effect of shortened lifetimes. Whilst less likely in practice than the lifetime extension scenario, it helps to demonstrate the effect of lifetime extension from the opposite perspective and the implications for stock turnover and stock-level operational energy performance justify its usefulness. Since Bayesian Model Averaging (BMA) was used to obtain the original forecast under the baseline scenario, re-modelling stock turnover dynamics under adjusted hazard functions was repeated for each of the five candidate survival models and combined through BMA. In this comparison, key variables other than lifetime, such as building material intensity, are kept the same under the two scenarios to ensure that the difference in the embodied energy of annual new construction between the two scenarios is attributable only to the variation in lifetime.

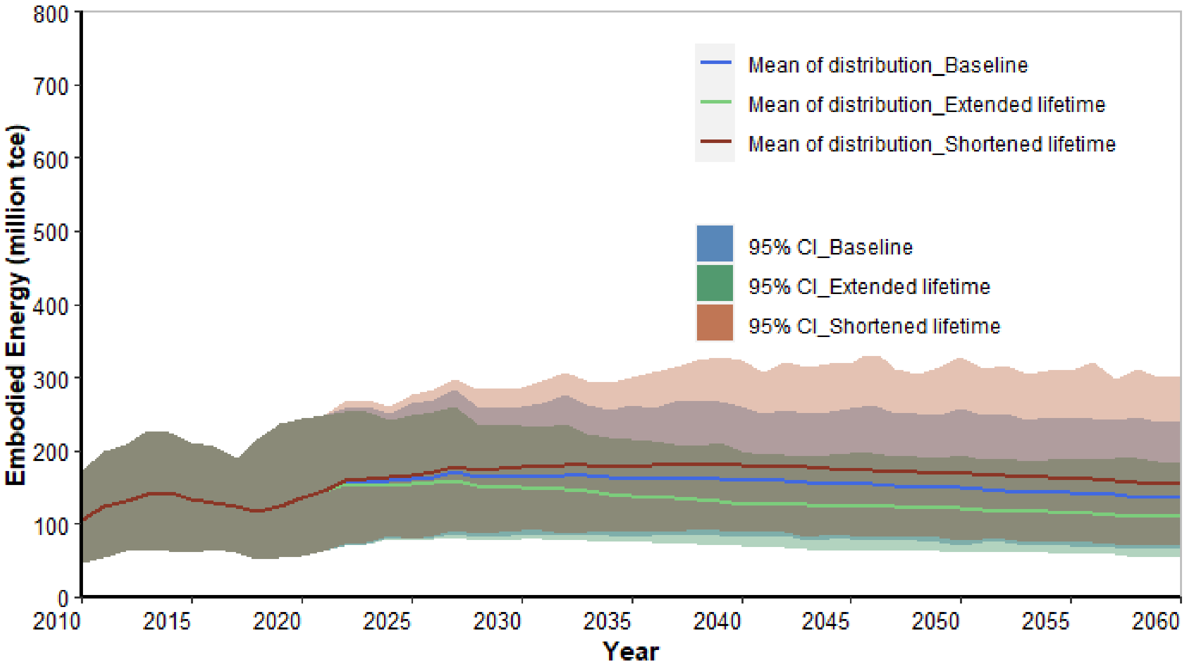

Figure 3: Impact of building lifetime on embodied energy of annual new residential construction

As shown in Figure 3, the effect of extending or shortening building lifetime is minor in the first few years since any extension or shortening is gradual, but grows over time. The belt of the extension scenario starts to bend shortly after the introduction of adjusted hazard function in 2021. It reaches a peak in 2027, when its 95% credible interval ranges from 82.9 Mtce (58 Mtoe) to 259.7 Mtce (181.8 Mtoe) and the mean value is 159.2 Mtce (111.4 Mtoe). After peaking, unlike the baseline scenario which remains stable for seven years, the extension scenario immediately starts to shift downwards. It increasingly diverges from the baseline scenario over time, because the progressively extended lifetime results in fewer existing buildings being demolished and accordingly fewer new buildings constructed. The declining trend of the extension scenario decelerates in 2040 when the extension ends. As for the shortened lifetime scenario, it keeps increasing once lifetime begins to shorten. Accelerated demolition means more new buildings need to be constructed to meet demand. This trend continues until 2039 when the peak is reached.

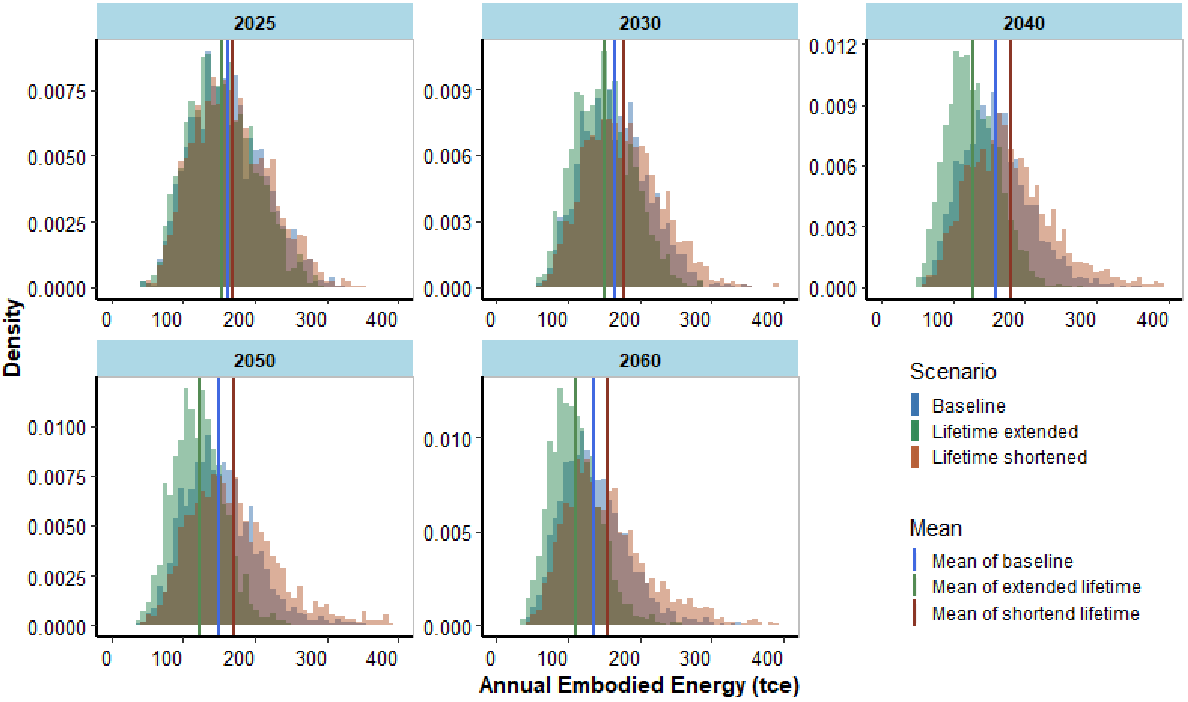

Figure 4: Distribution of embodied energy under three lifetime scenarios in typical years

The comparison of the three scenarios in typical years is presented in Figure 4 which overlays the three distributions. In 2025, the three distributions overlap almost entirely and are hardly discernible from one another. Their mean values are very close to each other. The difference between the three distributions is more notable in 2030. By 2040, when the average lifetime is no longer extended or shortened, the three distributions are most separate and so are their mean values: 127.5 Mtce (89.3 Mtoe) for the extension, 159.3 Mtce (111.5 Mtoe) for the baseline, and 179.2 Mtce (125.4 Mtoe) for the shortening scenarios, respectively. From 2041 onwards, all three belts slowly shift downwards, as the incremental demand for housing that drives the stock turnover keeps decreasing gradually towards reaching a saturation level. During this period, the difference in the three distributions remains substantial due to the 10-year difference in average building lifetime. Apart from visual inspection, the difference between scenarios can be quantitatively evaluated using the empirical CDFs. In 2030, the probability of the baseline scenario embodied energy being higher than the lifetime extension scenario is 61%, whereas the probability of the lifetime shortening scenario being higher than the baseline scenario is 54%. In 2040, these two probabilities are 71% and 60%, respectively. These numbers substantiate the effect of changing lifetime dynamics in a probabilistic setting. The above findings clearly demonstrate that increasing building lifetime will effectively reduce embodied energy in the future.

4.3 Comparison between embodied energy and operational energy

Adopting a whole lifecycle perspective enables a comparison of embodied energy (EE) and operational energy (OE) at the total stock and per m^2 levels. In practice, however, developing such estimates can be very challenging. Energy consumption by buildings is not directly recorded in the China Energy Statistical Yearbook (Wang, 2014). Overall operational energy performance of Chinese buildings is reported by the Annual Report on China Building Energy Efficiency, developed by Tsinghua University Building Energy Research Centre (THUBERC). Real data from large-scale surveys and long-time monitoring of a large number of cases are the most fundamental inputs to their model (Peng *et al.*, 2015; THUBERC, 2019b). According to recent annual reports, the operational energy consumption of urban residential buildings, including centralised heating, increased from 257 Mtce (180 Mtoe) in 2010 to 324.4 Mtce (227.1 Mtoe) in 2015, and further to 378.8 Mtce (265.2 Mtoe) in 2018 (THUBERC, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019a, 2020).

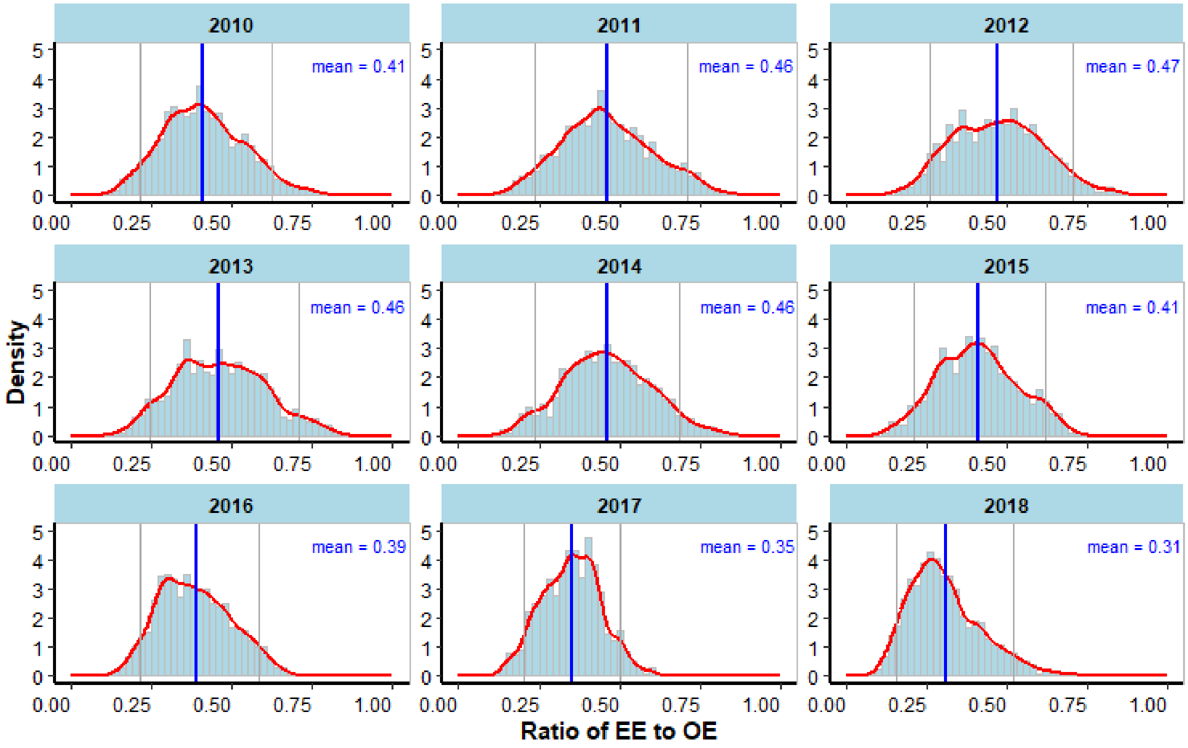

Figure 5: Distribution of the ratio of embodied energy of annual new buildings to annual operational energy of the urban residential stock

Using the THUBERC data and the estimated EE under the baseline scenario, the ratio of EE to OE in the same year is obtained for 2010 to 2018 (Figure 5). For each year, the ratio is represented by a distribution because the embodied energy follows a distribution capturing the uncertainties of material intensities. The distribution of the ratio in each year, as depicted by a histogram overlaid with a density curve, is largely bell-shaped, with some skewness. The blue line represents the mean value of distribution and the two grey lines represent the 5th percentile and 95th percentile, respectively. From 2010 to 2015, the mean value of EE to OE is in the range of 0.41 to 0.47. From 2016 to 2018, it drops but still remains above 0.3. This slightly downward trend is caused by two factors. On the one hand, there was a slight drop in annual new construction. This was accompanied by further improvement of material production energy intensities and a slight increase in average material intensity due to the evolving landscape of new building structures, which are characterised by higher shares of frame-shear and shear wall structures. The combined effect is a marginal decrease in embodied energy of new buildings. On the other hand, the overall residential stock kept growing due to continuous incoming new buildings, which far outweighed the effect of the old buildings reaching the end of their lifetime and being removed from the stock. The net increase in stock more than offset the effects of higher energy efficiency of new buildings and energy retrofit of existing buildings, thereby driving up stock-wide operational energy. However, going forward, given China's overarching climate objectives of peaking economy-wide emissions by 2030 (NDRC, 2015; Guan *et al.*, 2018) and achieving carbon neutrality by 2060 (Mallapaty, 2020; Yu *et al.*, 2020), strengthening policies on new and existing buildings will be needed to curb the increase of stock-level operational energy and emissions.

Table 1: Ratio of embodied energy intensity to annual operational energy intensity

Year	Average embodied energy intensity (kgce/m^2)	Annual operational energy intensity$^{(a)}$ (kgce/m^2)	Ratio
2010	103.3	14.2	7.3
2011	105.0	14.6	7.2
2012	103.7	14.7	7.0
2013	104.6	14.6	7.2
2014	107.1	14.5	7.4
2015	106.2	14.8	7.2
2016	107.5	14.6	7.4
2017	107.4	15.0	7.2
2018	106.0	15.5	6.8

(a) Source for annual operational energy intensity: (THUBERC, 2020)

In addition to the stock-level comparison, it is useful to compare embodied energy with operational energy per unit of building floor area, i.e., embodied versus operational energy intensity of buildings. As summarised in Table 1, the average embodied energy intensity remained stable in the narrow range of 103 to 107 kgce/m^2. In 2015, the value was 106, close to the average figures of 81 kgce/m^2 provided by Huo *et al*. (2019) and 126 kgce/m^2 by Zhang *et al*. (2019). Between 2010-2018, therefore, embodied energy intensity (of new stock) was around 7 times that of operational energy intensity (of existing stock). This result is largely consistent with Gu *et al*. (2007), who found the ratio to be 8 for urban residential buildings in Beijing. A study by the China Building Materials Academy reported that the ratio was 3, 6, and 30 respectively for steel, brick, and concrete structures (Zhao *et al.*, 2014). Overall, the comparison between embodied energy and operational energy, whether in terms of overall stock or intensity, provides strong evidence of the importance of embodied energy.

5 Conclusions and policy implications

5.1 Conclusions

This study presents one of the first attempts to model possible future trajectories of embodied energy of Chinese urban residential building stock. The annual construction of new buildings is estimated through a probabilistic dynamic building stock turnover process using various parametric survival models. BMA is applied to combine the results from individual models. Empirical data of building material intensities are fitted to probability distribution functions, with the joint distribution of steel and cement intensities captured using a copula function. Energy intensities of material production, building construction and demolition are modelled using Bayesian non-linear regression. The uncertainties of these input variables are propagated to the embodied energy of new buildings through Monte Carlo simulation.

It is found that the embodied energy of Chinese urban residential buildings is likely to peak around 2027, with a 95% credible interval ranging from 87 to 283 Mtce (61 to 198 Mtoe) and a mean of 170 Mtce (119 Mtoe). Under the current trajectory, the embodied energy is forecast to remain high at around 150 Mtce (105 Mtoe) per year through the end of the forecast period, a very substantial fraction of China's total annual energy consumption. Obvious methods towards reducing this energy in the future include reducing annual construction, or reducing material energy intensity, either through reducing the energy intensity of key materials, or moving to using materials with lower embodied energy. However, a further route which is explored and quantified here is by increasing building lifetime, which is very short in the current urban context in China. Gradually increasing this lifetime is shown to reduce embodied energy by 20% (31.8 Mtce, or 22.3 Mtoe) by 2040. Our study finally shows that over 2010-2018, annual embodied energy of new construction was between 31% and 47% of total operational energy of existing buildings. The ratio of embodied energy intensity to operational energy intensity remained around 7 throughout this period. These findings therefore provide strong evidence of the importance of considering embodied as well as operational energy.

5.2 Policy implications

Clearly, new construction in China involves high annual embodied energy so it is essential to address the issue in order to reduce national carbon emissions. This embodied energy, as has been shown, comes from the high energy intensity of common building materials, a high construction rate, and the high material intensity of that construction.

The energy intensities of producing steel, cement, aluminium, glass, and other building materials have progressively declined as a result of technological advances and sectoral policy mandates over past decades. Going forward, the potential for further improvement is expected to be limited, unless disruptive technologies and transformative policies with aggressive targets become available and assertive actions are implemented effectively. Therefore, annual new construction, and material intensities of that construction, both remain essential determinants and will have increasingly greater impacts on the embodied energy of Chinese building stock.

Construction activities are driven by market demand, which includes not only basic housing, but also upgraded housing conditions such as luxurious apartments, houses, second homes, etc. Over the past two decades, a series of policies were issued by the central and local governments to regulate the overheated real estate sector and curb the rapidly escalating demand for high-end housing. Typical examples included restricting the proportion of apartments with sizes above a certain benchmark that property developers are allowed to develop per year, imposing surcharges on transactions involving oversized properties, and restricting second and third home purchases (Asia Green Real Estate, 2019). The effects of these policies have been mixed, though. Meanwhile, in many cities across the country, high property vacancy rates have become a widely observed phenomenon. Whilst there exist various factors underlying the high vacancy such as speculative investment and excessive urban sprawl, the existence of large amount of empty properties means serious overbuilding and oversupply of residential properties, which could have been avoided, or at least partially alleviated, to free resources that could be used more efficiently in other parts of the economy (Chivakul *et al.*, 2015; Glaeser *et al.*, 2017). These issues should be addressed through strong macro-level regulation and control, and effective market-based instruments in order to support the healthy growth of the housing market. Policy measures putting an effective rein on overheated real estate market will not only generate a series of economic and social benefits, but also contribute indirectly to environmental benefits, e.g. reduced consumption of building materials and the associated energy use and carbon emissions.

Material intensities are largely dependent upon building classification and structural types. In the Chinese urban context, residential buildings have been experiencing a transition in structural type, with frame-shear and shear wall structures replacing brick concrete structure to become the mainstream (Zhao *et al.*, 2014; Zhang *et al.*, 2019). Promoted by a series of policies (MIIT and MOHURD, 2015; MOHURD, 2017), the share of steel structure residential buildings has also been increasing (Zhang *et al.*, 2019). These changes have led to new buildings becoming gradually more material intensive. In parallel with this trend, increasingly greater emphasis has been placed upon developing green buildings. The MOHURD and State Administration for Market Regulation (SAMR) jointly issued the *Assessment Standard for Green Building* in 2006, which was the first ever national standard specifically targeting green buildings (MOHURD, 2019a). Subsequently updated in 2014 and 2019, this standard sets the overall evaluation framework and specific criteria for rating potential green buildings. Whilst the standard has particular criteria concerning material saving and the use of green materials, there are no quantitative targets or indicators relating to material intensity. Likewise, the *Code for Green Design of Civil Buildings*, issued by MOHURD in 2010, sets a guiding principle of controlling building volume and reducing material consumption (MOHURD, 2010). It does not set any quantitative design requirements on material intensities but merely encourages the use of materials consuming less energy for production. In the absence of mandatory and specific requirements, it is very difficult for building material intensities to achieve substantial decrease in the short to medium term. Addressing this issue calls for quantitative design standards and performance indicators for material intensities. At the initial stage, this may involve updating existing standards for green buildings, such as the afore-mentioned code and assessment standard. The implementation of the updated standards should be supported by additional administrative and financial incentives for developers and homebuyers. Over time, mandatory requirements should be introduced and enforced in pilot cities and gradually rolled out more widely.

The lack of data has been, and still is, a major constraint on evidence-informed policymaking. Beyond existing statistics on annual new construction, it is strongly suggested that building-related statistics are expanded to cover city-wide residential stock size, which can then be aggregated to the provincial and national levels. Floor area and age of individual buildings are valuable information to obtain, possibly on a sampling basis if comprehensive data is practically difficult. A comprehensive and transparent database can provide the much-needed evidence to energy and climate policies on buildings. The same consideration applies to data on building material intensity. It is worthwhile exploring the feasibility of considering and reporting material intensities at the design and approval stages of property development. This may go hand in hand with the proposed updating of existing design code and assessment standard, to accelerate the much-needed mainstreaming of building material intensities as a key design consideration.

From the operational perspective, it is expected that buildings will become progressively more energy efficient and 'greener' over time. The *Standard for Energy Consumption of Building* was issued by MOHURD in 2016 with the view of regulating actual energy consumption of buildings. Specific quantitative operational energy consumption indicators by building type and climate zones have been set. Whilst being not yet mandatory or time-bound, the standard sends a strong signal of the envisaged transition of the design and evaluation of operational energy of buildings. Instead of focusing only on prescriptive design and *ex-ante* compliance, an increasing emphasis is being placed on performance-based and result-driven design and *ex-post* monitoring and evaluation of actual energy performance (MOHURD, 2016). Meanwhile, due to the afore-mentioned absence of quantitative limits on material intensities and also the observed evolution of building structural types, it is unlikely that embodied energy intensity of new buildings would decline substantially over the short to medium term. Rather, over that timeframe, it is more likely to increase. In fact, it has been found that the desired operational performance of green buildings was often obtained at the cost of much higher embodied energy than conventional buildings (Zhao *et al.*, 2014). With new buildings becoming more operationally efficient, the capital cost of embodied energy and carbon emissions will be more significant and should be fully taken into consideration in the decision-making process for sustainable design, construction and use of buildings.

Finally, an important and less obvious route to reducing annual embodied energy has been demonstrated in this paper – increasing the lifetime of buildings. However, this approach demonstrates the importance of ensuring that operational and embodied energy should be addressed in an integrated manner. While extending the lifetime of existing buildings will reduce embodied energy, in so doing, less efficient older buildings would be kept in the stock for longer and the construction and operation of more efficient new buildings (assuming operational standards continue to improve) would be delayed. The stock-level average operational energy efficiency would therefore not be as desirable as what otherwise would have been the case. Conversely, accelerated demolition of older inefficient buildings may be desirable from the perspective of stock-level operational energy performance, but will incur higher embodied energy for new buildings that otherwise would not have been built. These trade-offs across stock-level embodied and operational energy should be adequately recognised and analysed. It is therefore strongly recommended that a whole-life perspective should be taken in designing future strategies and policies for buildings, so as to accelerate the low-carbon transformation of buildings and contribute to achieving China's overarching climate targets of peaking its economy-wide emissions by 2030 and realizing carbon neutrality by 2060.

6 Appendix

6.1 Modelling building material intensity uncertainties

This study refers to Zhao *et al*. (2014) for material intensity data. Their data was collected through surveying over 150 urban residential buildings in different Chinese cities. These samples covered major structural types, including brick-concrete, shear wall, frame-shear and steel (Zhang *et al.*, 2019).

During the model selection process, for steel and cement, the empirical intensity data from the building samples was fitted to the following candidate distributions: Gamma, Lognormal, Normal and Weibull. The best-fit distribution was Weibull for steel and Gamma for cement, respectively. For glass, intensity data was available for less than half of the samples. Combining this data with the data given by other studies (Yu and Li, 1999; Zhu *et al.*, 2020) and performing distribution-fitting found that glass intensity was best approximated by a Lognormal distribution. Compared to glass, there were substantially fewer samples of buildings reporting their consumption of aluminium. Thus, this study assumed that aluminium intensity would follow a normal distribution, with its mean value set based on the samples as well as limited data in other studies (Hong *et al.*, 2016; Zhu *et al.*, 2020).

These univariate distributions are all marginal distributions. In reality, the intensities of these major materials are correlated to some extent, because the use of these materials in residential buildings largely follows some general pattern reflecting the typical choices of building structures and common practices of design and construction in urban context. This means the material intensities are not independent but dependent random variables. This has an important implication since drawing random samples from the fitted marginal distributions of the material intensities and then combining them to represent the materials use of a simulated building sample will likely result in a practically unrealistic combination of materials. It is therefore necessary to capture the underlying dependence structure by finding the multivariate joint distribution.

We model the dependence structure of material intensities through a copula, which by definition is a d-dimensional distribution function on the hypercube $[0,1]^d$ with standard uniform univariate margins (Schmidt, 2007; Killiches, Kraus and Czado, 2017). According to Sklar's theorem, any multivariate joint distribution can be written in terms of univariate marginal distributions and a copula which describes the dependence structure between random variables. Conversely, given a copula and univariate marginal distributions, a multivariate joint distribution can be defined. That is, a copula serves as the link of a multivariate joint distribution to its univariate margins (McNeil, Embrechts and Frey, 2015; Hofert *et al.*, 2018; Zhang and Singh, 2019). Putting this into the context of this study, a copula can be applied to form the multivariate joint distribution of steel, cement, glass and aluminium intensities. The constructed multivariate joint distribution can then be used to generate random samples of vectors of material intensities.

As the marginal distribution of glass intensity was fitted using limited data and the aluminium intensity was estimated more arbitrarily, the copula application focuses on the dependence between steel intensity and cement intensity, thereby reducing the potentially 4-dimensional multivariate distribution to a bivariate distribution. Random samples of glass intensity and aluminium intensity are drawn from their respective marginal distributions. Such a simplification has very limited impact on materials production energy consumption, which has been found to be dominated by steel and cement in literature.

This study also takes into consideration the longitudinal variation of steel and cement intensities. There has been an observed trend over the past two decades that the share of brick concrete structure in new residential buildings constructed every year has been declining steadily, whereas frame-shear and shear wall structures have become the mainstream, especially in large cities (Zhang *et al.*, 2019). Such a transition in structural types has increased the average steel intensity of new buildings (Zhao *et al.*, 2014). Buildings employing a steel structure have been particularly promoted by government policies (MOHURD, 2017). Meanwhile, the fact that residential buildings in cities have been becoming taller on average means more cement has been required for structural support (Hong *et al.*, 2016). Consequently, residential buildings have been becoming increasingly material intensive, with particular regard to steel and cement (Zhang *et al.*, 2019). Such a trend is expected to continue over the next decades, with a gradually lowering rate of intensity increase. This is modelled by gradually increasing the mean values of the marginal distributions of steel and cement intensities, while keeping their variance unchanged to reflect the substantial uncertainties associated with individual building characteristics. In this process, the original dependence structure as captured by the copula function remains unchanged due to copula's property of invariance under monotonous transformation (Hofert *et al.*, 2018). This enables the generation of random samples from the time-variant bivariate joint distribution of steel and cement intensities.

6.2 Modelling energy intensities of building material production

With a series of policy measures and technological advancement, the energy performance of the steel industry has realised continued improvement (NDRC, 2004; Center for Industrial Energy Efficiency, 2014; MIIT, 2016; China Iron and Steel Industry Association, 2019; He, Wang and Li, 2020). The average energy intensity of steel production was 1.44 tce/t in 1995. By 2010, it dropped by 34%, to 0.95 tce/t in 2010 (Wang, 2001, 2013, 2016). From 2010 to 2018, the decreasing trend remained but the rate slowed down (Wang, 2018, 2019). The generally smooth and slowing down decreasing trend of the historical values suggests a profile that could be approximated by an exponential decay curve. Thus, a three-parameter exponential decay function is applied to model the future trends of energy intensity of steel production.

$$EI_{steel} = a + (b - a)e^{c(Year - Year_0)} + \varepsilon_t \tag{1}$$

where *b* is the value of energy intensity of steel production in the initial year *Year₀*, which is 1995 in this case; *a* is the lower asymptote that the curve approaches over time, suggesting that energy saving potential will become increasingly limited and is unlikely to drop down to 0; *c* represents the relative decrease of energy intensity for a unit increase of *Year*; ε_t is the random error term assumed to be normally distributed with mean zero and unknown variance σ^2, i.e. $\varepsilon_t \sim N(0, \sigma^2)$.

Similar to the steel industry, the cement industry has made significant progress in energy saving through various structural transformation and technological measures (Center for Industrial Energy Efficiency, 2014; NDRC and MIIT, 2016; NRDC, 2019). From 1980 to 1995, the industry-wide average energy intensity decreased by 9.1%, from 0.219 tce/t (0.153 toe/t) to 0.199 tce/t (0.139 toe/t). This was then followed by a period of accelerated decrease till 2010, when the energy intensity dropped to 0.143 tce/t (0.10 toe/t). After 2010, the decrease started to slow down (Wang, 2001, 2013, 2016, 2019; National Bureau of Statistics, 2017). Given such a largely reverse S-shaped pattern, a four-parameter logistic decay model is applied to cement production energy intensity.

$$EI_{cement} = a + \frac{(b - a)}{1 + e^{(c(Year - Year_0) - d)}} + \varepsilon_t \tag{2}$$

where $Year_0$ is the initial year, which is 1980 in this case; *b* is the higher asymptote; *a* is the lower asymptote representing the lowest possible energy intensity under the business-as-usual scenario; *c* is the slope around the inflection point; *d*, together with *c* and $Year_0$, determines the *Year* value producing an energy intensity equal to the mean of *b* and *a*; and $\varepsilon_t \sim N(0, \sigma^2)$ is the random error term.

The same four-parameter logistic decay model was applied to aluminium and glass, with their respective parameters estimated using available historical data. For aluminium, the electricity intensity of aluminium electrolysis decreased substantially, from 17,100 kWh per ton (kWh/t) (1.47 toe/t) in 1990 to 13,555 kWh/t (1.17 toe/t) in 2018 (National Bureau of Statistics, 2017; Wang, 2019). For glass production, the energy intensity dropped from 0.5 tce/t (0.35 toe/t) in 2000 to 0.28 tce/t (0.196 toe/t) in 2018 (Center for Industrial Energy Efficiency, 2014; Wang, 2016, 2019).

7 References

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