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Modelling future trends of annual embodied energy of urban residential building stock in China

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The buildings and construction sector has been identified as a primary target for the clean energy transition and emissions mitigation efforts. In 2019, the operation of buildings was responsible for 30% of global final energy use and 28% of direct and indirect energy-related CO_2 emissions. 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, 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.

Given the significant impact of embodied - in addition to operational - energy and carbon, a whole lifecycle approach is required in pursuing full decarbonisation of buildings. 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, switching to low-energy and low-carbon materials, improving efficiency in manufacturing and construction, optimizing material usage and so on, which are similar to those measures needed to enhance operational energy efficiency in buildings.

China is a major driving force of the growth of global building stock, having the largest buildings sector in the world. Over the past ten years, the floor area of new buildings constructed in China each year has remained consistently above 2 billion m^2. 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. That same year, the total floor area of Chinese buildings, including residential, commercial, and public buildings, reached 60 billion m^2. 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, increased by 4% per year from 2000 to 2015 and China's share increased from 30% to nearly 40% over this period. The use of steel, cement and other materials to meet the demand from new construction has 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) and 1.7 billion tCO_2, respectively accounting for 12% and 16% of China's economy-wide total energy consumption and carbon emissions. These levels are comparable in magnitude to operational energy and emissions from the total building stock in China in 2015, which were 0.96 billion tce and 2.22 billion tCO_2 respectively.

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. The short lifetime of buildings implies a high turnover rate of the residential stock. 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, large-scale construction inevitably results in significant embodied energy and carbon. These two arguments imply a strategic trade-off from the stock-level perspective of building lifecycle energy and carbon. The magnitude of embodied energy and carbon, in both absolute and relative terms, clearly demonstrates that embodied energy and carbon should be taken as seriously as operational energy and carbon by policymakers and regulators.

Our 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. Bayesian Model Averaging (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.

We find 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 and a mean of 170 Mtce. Under the current trajectory, the embodied energy is forecast to remain high at around 150 Mtce per year through the end of the forecast period, which amounts to a very substantial fraction of China's total annual energy consumption. Obvious ways to reduce this energy in the future include reducing annual construction, or reducing material energy intensity, either through reducing the energy intensity of key materials, or shifting to materials with lower embodied energy. 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) by 2040. 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 in the policy design process.

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