A system dynamics study of lifecycle energy use in buildings in China

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Introduction

China is the largest energy user and CO_2 emitter worldwide (IEA, 2015). According to the World Energy Outlook, the final energy consumption of buildings in China increased by approximately 53% from 1990 to 2012, when China (480 Mtoe) overtook US (464 Mtoe), becoming the world's largest building energy consumer. In 2014, China's building sector consumed 529 Mtoe, representing 18% of global total energy consumption of buildings. Underlying the continued increase of building energy consumption in China are the increasing population, rapid urbanisation and consistently strong economic growth that have been driving the expansion of building floorspace and demand for energy services and thermal comfort in buildings. Over the past decade, China's building stock has been expanding at an annual rate of 1.8 to 2.8 billion m^2. By 2015, it reached 57.2 billion m^2, representing 25.6% of global total building floor area. The expansion of building stock far outpaced the rate at which the floor area energy intensity has decreased, therefore leading to continued increase in final energy consumption.

As China's social and economic growth are expected to maintain momentum, the total building stock size and the associated energy consumption will keep a generally ascending trend over the medium to long term. Energy-related emissions from buildings are also expected to rise over the foreseeable future, although the emission trajectory is sensitive to the composition of the energy used directly by buildings and to the decarbonisation of electricity and heat generation. Rising emissions from buildings present a critical challenge to China's pledge in the Paris Agreement to peak overall emissions by 2030. Strategically, China's building sector needs to undergo a transition towards low-carbon development whereby the increase of building energy consumption and emissions begins to decelerate. This urgently calls for a sector-specific policy and regulatory framework targeting both new and existing buildings and consisting of reasonably aggressive targets, sustained and effective policy instruments and assertive actions, tailored to the broader policy settings in China.

Objective and relevance

Ex-ante evaluation is an integral part of designing policies relating to energy end-use sectors such as the building sector. Modelling plays a key role in facilitating this process by allowing for the investigation of the trajectories of energy and emissions under different policy scenarios. We seek to develop insights into the complexities and dynamics associated with energy use of buildings in China by examining relevant sectoral policies. Particular emphasis is placed upon dynamic building stock evolvement and embodied energy as an integral part of lifecycle energy use of buildings. A review of the literature suggests these two distinct but inherently related aspects have not been adequately addressed in Chinese context. Their implications to energy modelling and policy analysis justify the relevance of this study.

Dynamic building stock

As capital- and carbon-intensive assets with generally long lifetimes, buildings are subject to relatively high risks of energy and carbon "lock-in". For a large building stock, its composition of buildings designed, constructed and operated to various standards will have a significant impact on the scale and strength of the lock-in effects over the medium to long term. The greater the lock-in effect, the more challenging, technically and economically, to "unlock" those suboptimal buildings and pursue a transition towards low carbon building stock.

It is therefore essential to understand the characteristics of the existing building stock and forecast plausible scenarios of the future. The key is to capture the dynamic interplay between new construction meeting incremental demand growth, existing buildings remaining in use but undergoing ageing process, and old buildings, which are either physically demolished or functionally disused. Such a time-varying complexity shall be the premise based on which building stock energy use is forecast and accordingly serves as the basis on which strategies and policy instruments are formulated and evaluated *ex ante*.

This is particularly relevant in the Chinese context where the average lifetime of buildings is as short as 25-30 years in cities and 15 years or even less in rural areas, significantly shorter than buildings in developed countries, due to various factors, including quality of buildings, design standards, construction techniques and practices, maintenance and renovation, inappropriately accelerated demolition as a result of rapid urbanisation and rebuilding, etc. This suggests a high turnover rate and great complexity and uncertainty associated with building characteristics, thereby having significant implications to stock-wide energy use and emissions over the medium to long term.

Embodied energy

Embodied energy in buildings can be defined as including initial embodied energy due to building materials production, transportation and construction activities on site, recurring embodied energy due to refurbishment and maintenance, and demolition energy due to demolition and disposal at the end of building lifetime. Whilst embodied energy of buildings has been extensively studied internationally, it remains under-emphasized in the Chinese context. Government plans and strategies relating to building energy focus almost entirely on operational energy. In Chinese national energy statistics, embodied energy of buildings is usually accounted for under various industrial subsectors, such as cement, steel, aluminium, etc., without explicit links to the building sector. Sector-specific design codes for energy efficient buildings also do not explicitly address embodied energy.

Embodied energy and carbon dioxide in construction materials is especially important in rapidly developing countries where construction rates are high. The availability of affordable low-energy and low-carbon materials used for high-performance buildings determines construction-related emissions substantially. Moreover, due to better operational energy performance, embodied energy has increased its importance in building lifecycle. Over time, as buildings will become progressively more energy efficient as a result of stronger policy intervention and continuing technology advancement, embodied energy will become proportionately more significant relative to operational energy. Such a situation remains highly relevant in China as its building sector keeps its strong momentum of development. In 2013, embodied energy in buildings in China reached 455 Mtoe, accounting for 16% of China's total primary energy consumption. Understanding embodied energy in buildings is essential to presenting a fuller energy profile of the building sector, and thus identifying opportunities and assessing potentials for energy savings and emission reductions from buildings over the medium to long term.

Methodology

The dynamics of building stock and associated lifecycle energy use under various scenarios of policy interventions are modelled at a highly aggregated level, using System Dynamics (SD). SD is a modelling paradigm focusing on dynamic complexity arising from the structure, feedbacks, non-linearity and time lags of the system in question.

The model treats building stock evolution as a continuous process of introducing new cohorts which decay over time, thereby capturing the dynamic interplay between new construction, demolition and renovation. Demolition of buildings of different categories (urban residential, rural residential, public and commercial) is modelled as a stochastic process based on hazard functions derived from Weibull or Lognormal distributions. Historical data is used to estimate the parameters of the lifetime distributions and hazard functions. For forecasting, various Weibull or Lognormal distributions featuring progressively increasing mean values and decreasing variances are attached to different cohorts of new buildings to represent building lifetime dynamics as the result of expected improvements in building quality and urban planning strategies. New construction depends upon the difference between the stock of buildings in use, which is a portfolio of buildings of different ages, and the forecasted demand for floor area. Urbanisation rate and floor area per capita are projected using Logistic model and Gompertz model respectively. Energy-related renovation takes into consideration the economic viability of renovating buildings at different ages. Different fractions and depths of renovation are experimented to model different hypothetical renovation interventions. Operational energy and embodied energy are modelled as co-flows of the building stock. Embodied energy considers initial embodied energy, recurring embodied energy and demolition energy. Since our goal is to explore the possible trajectories of lifecycle energy use of buildings, we restrict our definition of operational energy to those elements related closely to the building envelope *per se*, namely heating and cooling, so as to enable meaningful comparison between embodied and operational energy. Figure 1 shows initial embodied energy as part of the model.

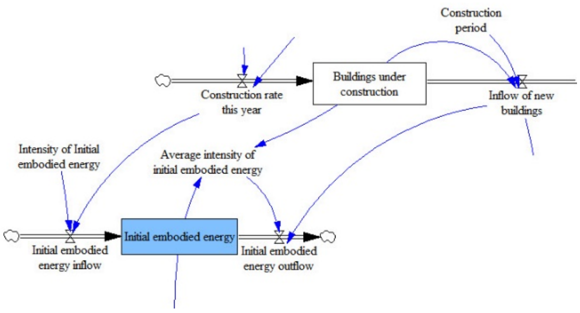

Figure 1: Initial embodied energy in the model

Expected outputs

This study is not intended to explore building energy saving potentials from building physics, technological or engineering perspectives. Rather, the overarching purpose is to add a policy evaluation perspective, with the emphasis placed on examining the importance of embodied energy relative to operational energy of the dynamically evolving building stock under various scenarios. This is realised by innovatively applying a SD approach to modelling the dynamics of building stock and its associated energy use. The interest and motivation rest on developing an enhanced understanding of the general behaviour characteristics and dynamic tendencies of the modelled building energy stock over time, which will serve to inform sectoral policy design and evaluation.

References

IEA. (2015). *World Energy Outlook 2015 Special Report on Energy and Climate Change*. OECD/IEA, Paris.