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Sustainable Scenarios in China's Buildings Sector: an analysis from the demand-side perspective

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LIST OF ACRONYMS

BF	blast furnaces
BOF	basic oxygen furnace
CO_2	carbon dioxide
EAF	electric arc furnace
GLOBIOM	**Glo**bal **Bio**sphere Management **M**odel
IAM	Integrated Assessment Modeling
LP	linear programming
MESSAGEix	**M**odel for **E**nergy **S**upply **S**ystems **a**nd Their **G**eneral **E**nvironmental Impact (ix)
MFA	material flow analysis
O&M	Operations & Maintenance
RES	Reference Energy System (RES)
SSP	Shared Socio-economic Pathway

Executive summary

Building stock dynamics play an important role on a country's primary energy use and CO_2 emissions from the energy sector, given that many key building materials are very energy intensive, like steel and cement. The buildings in China currently consume a massive amount of direct and embedded energy due to its large population, robust economic growth, and ongoing construction boom, therefore it is desired to explore the sustainable pathways of China's buildings sector from a demand-side perspective, namely sustainable building stock dynamics.

In this study, we designed three building stock related measures for China's building sector, namely, from a SSP2-based reference scenario (Shared Socio-economic Pathway No. 2), limiting the increase of per-capita floorspace (20% less in 2050 from the SSP2 reference scenario), extending building lifetime (from the current 25 years on average to 45 years) and promoting building renovating rate (increase to about 1% yearly). Based on these three demand-side measures, we developed five building sector scenarios by using the newly developed "MESSAGEix-Buildings" demand side model and explored their impacts on building stock dynamics and related building material needs. In addition, we also brought these building sector scenarios into a broader context of entire energy system by using the upgraded MESSAGEix-GLOBIOM integrated assessment modeling (IAM) tool. In this upgraded IAM tool, we combined the standard MESSAGEix-GLOBIOM model with two newly developed end-use models, "MESSAGEix-Materials" and "MESSAGE-Buildings". With such a combined modeling framework, we analyzed the impacts of building stock dynamics on the entire energy supply system.

Our building sector analysis shows that if the three designed building stock related measures are implemented, China's building stock could peak around 2030, instead of 2040 shown in a SSP2 reference scenario without these measures. In addition, our integrated assessment modeling results demonstrate that the prescribed three demand-side measures could bring down about 10.6% of final energy use in the buildings sector from the baseline scenario (which is based on SSP2 assumptions) during the period 2020-2100, and accordingly make the entire energy system consume less primary energy (2.9%) as well as emit less CO_2 from the energy supply sector (5.0%) in the same period. Regulatory and incentive policies are needed in place to implement the building stock related demand-side measures, such as stricter polices on land use for buildings, tighter building codes to use higher-quality building materials, and subsidy programs to building owners for retrofitting existing buildings and so on. Governments at different levels are expected to play a lead role in designing and implementing these demand-side measures.

1. Introduction

Different from many developed countries, whose building stock has reached saturation, the building stock in China keeps faster increase along with the country's urbanization and economic growth. In the past two decades (2001-2020), China's urbanization rate increased from 38% to 64%, and its per-capita GDP grew about eight times, from 8,700 Chinese Yuan to 72,000 Chinese Yuan (NBS, 2021). Consequently, China's building stock increased to 66 billion m^2 in 2020, doubled from the 2001 level. The net annual increase of new buildings in China was about 1.7-2 billion m^2 during the past few years (BERC, 2022). One unique feature about China's building stock is that both yearly newly added and demolished buildings are massive in China, about 3.3 and 1.7 billion m^2 in 2020, respectively.

The building sector in China consumes a gigantic amount of energy, both directly and indirectly. Currently, the buildings in China account for 23% of the country's total final energy use, about 626 Mtce (IEA, 2022). Besides the direct final energy consumption in buildings, the energy used for producing building materials (like steel and cement) is also significant in China because of the large-scale construction of new buildings every year. According to BERC (2022), such embedded energy consumption, in terms of primary energy, was estimated to be about 520 Mtce in 2020.

Consequently, the CO_2 emissions resulting from the buildings sector's direct and indirect energy use in China is enormous. BERC (2020) estimated that such CO_2 emissions account for about 40% of China's total emissions from the energy sector. China has announced to be carbon neutrality by 2060 (NDRC, 2021), therefore reducing the CO_2 emissions from the buildings and related building material production is critical for China to achieving it climate goal.

Building stock development (or dynamics) is a fundamental driver of energy use in buildings as well as needs of related buildings materials (BERC, 2021). There are three important factors that shape the building stock dynamics, namely per-capita floorspace, lifetime of buildings, and building renovation rate.

Per-capita floorspace has critical impact on both the energy use for building's operation and embedded energy consumption for producing relevant building materials. Larger housing units need more energy for space heating and cooling, and more building materials for constructing them. In 2019, the per-capita floorspace of urban and rural residential buildings in China is about 40 and 49 m^2, respectively (Wang, 2020). The per capita residential floorspace in China is already similar with those in most EU countries (BERC, 2022; Guo et al., 2020). If the per-capita floorspace in China keeps increasing, like what happened in the past years, it will be very challenging for China to provide required energy to buildings and for their construction. In other words, the future pathway of China's per-capita floorspace will play an important role in China's sustainable development and climate change mitigation.

Longer lifetime of buildings could result in less needs in new buildings and accordingly less demand for building materials. Currently, the actual building lifetime on average in China is only about 25-30 years (Energy Foundation China, 2020), which is much shorter than that it is designed to be (40-50 years), There are many reasons for the shorter building lifetime in China. Poorer quality and land use ownership change are often the main reasons. Therefore, to reduce the building sector's embedded energy consumption, it is very important for China to extending building's lifetime mainly by using higher-quality building materials for new buildings and avoiding demolishing the buildings that have not reach their end of lifetime.

Moreover, renovating existing buildings to upgrade its energy performance and extending its lifetime is also critical for reducing buildings' operation energy use and embedded energy consumption (Murtagh et al., 2021; Hasik et al., 2019; Ginks and Painter, 2017; Alba-Rodríguez et al., 2017; Assefa and Ambler, 2017). Particularly, regularly renovating buildings in cold regions by upgrading their insulation could result in less energy use for space heating. Compared to constructing new buildings, renovating existing buildings needs much less energy, about 80-90% less (Zhang, 2022).

The future pathways of China's building stock, including the buildings newly built, renovated and demolished every year, will have a significant impact on building related energy consumption and carbon emissions. Therefore, it is desired to explore the sustainable pathways of Chinese building sector from the perspective of building stock dynamics.

Several studies on scenario analysis of China's buildings stock development and embodied emissions have been conducted (Tang, et al., 2021; Wang, et al., 2015; Hong, et al., 2016; Huang, et al., 2013; Shi, et al., 2012; Hu, et al., 2010). However, these studies did not adopt a method of energy systems analysis, therefore could not provide insightes from the perspective of sectoral integration. In this research, we explore the sustainable scenarios of China's building sector based on an integrated assessment modeling (IAM) framework, the MESSAGEix-GLOBIOM model. In order to have detailed representation on buildings and building materials, two end-use sector modules, "MESSAGEix-Materials" and "MESSAGEix-Buildings", are newly developed and linked with the standard MESSAGEix-GLOBIOM model that has rich energy supply side representation. More details on modeling method are presented in the next section.

2. Modeling Approach

2.1 Models

In this study, the modeling work is conducted based on a newly developed modeling framework that combines the standard MESSAGEix-GLOBIOM model and two recently developed end-use sector modules, “MESSAGEix-Buildings” and “MESSAGEix-Materials” (see **Figure 1**). The “MESSAGEix-Buildings” module covers various end uses in both residentials and commercials, including space heating, space cooling, water heating, cooking, and plug-in appliances. The “MESSAGEix-Material” module introduces material flows into the standard MESSAGEix-GLOBIOM model by covering several energy intensive sub-industrial sectors like steel, cement and so on. The “MESSAGEix-Material” module is built into the new version of the standard MESSAGEix-GLOBIOM model, while the “MESSAGEix-Buildings” module is standalone but soft-linked with the new version of MESSAGEix-GLOBIOM that has the built-in “MESSAGEix-Material” module. A brief induction of the standard MESSAGEix-GLOBIOM model and the two newly developed end-use sector modules is presented below.

MESSAGEix-GLOBIOM model is an Integrated Assessment Modelling (IAM) framework for the comprehensive assessment of energy-environment-economy systems. It has been extensively used for developing energy scenarios and identifying socioeconomic and technological response strategies to major energy and climate challenges (Fricko, et al., 2017; Huppmann, et al., 2019).

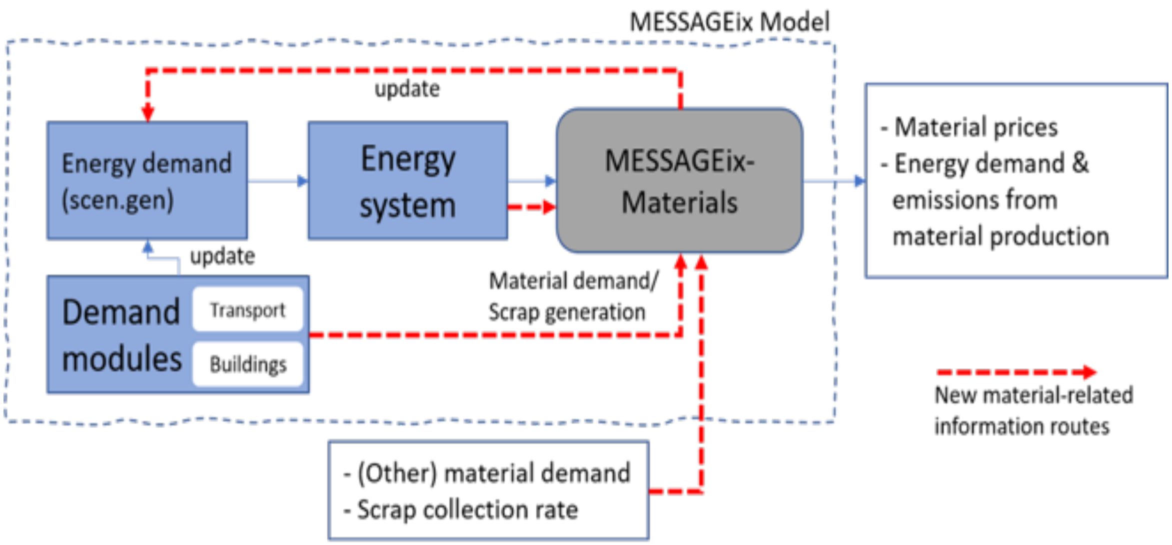
In detail, MESSAGEix-GLOBIOM model is a linked IAM of MESSAGEix (energy systems model) and GLOBIOM (land use model) by including an emulator of GLOBIOM model into the MESSAGEix model. A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a Reference Energy System (RES) that includes all the possible energy chains that MESSAGEix can access. Over the course of a model run, MESSAGEix determines how much of the available technologies and resources are used to satisfy a particular end-use demand, subject to various constraints (both technological and policy), while minimizing total discounted energy system costs over the entire model time horizon (from the first modeling year to 2110). The first modeling year in this study is 2020.

The MESSAGEix-GLOBIOM model runs for every 5 years before 2060 and every 10 years afterwards till 2110. It does this based on a linear programming (LP), optimization solution algorithm. The representation of the energy system includes vintaging of the long-lived energy infrastructure, which allows for consideration of the timing of technology diffusion and substitution, the inertia of the system for replacing existing facilities with new generation systems, and clustering effects (technological interdependence). Important inputs for the MESSAGEix model are technology costs and technology performance parameters (e.g., efficiencies, investment, fixed and variable operations & maintenance costs and lifetime). In addition to the energy system, the MESSAGEix model also tracks a full basket of greenhouse gases and other radiatively active gases—CO_2, CH_4, N_2O, NOx, volatile organic compounds (VOCs), SO_2, etc.—from both the energy and non-energy sectors (e.g., deforestation, livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning).

The MESSAGEix-Buildings module is a framework for modelling the demand for energy and materials in the buildings sector under future scenarios (Mastrucci et al., 2021; Poblete-Cazenave et al., 2021). MESSAGEix-Buildings has a modular structure with three different components, CHILLED, STURM and ACCESS. CHILLED is a bottom-up energy demand model for space heating and cooling. STURM is a stock turnover model to assess future evolution of the building stock, including new construction, demolitions and renovations, based on dynamic material flow analysis (MFA) and discrete choice models for efficiency decisions. ACCESS is a model to represent cooking energy use and electricity use by various appliances. This bottom-up framework allows detailed representation of key building and household characteristics, e.g., location, building type, vintage, energy efficiency standard, household income and tenure. The STURM and ACCESS models are soft-linked to the MESSAGEix-GLOBIOM model via energy prices generated by MESSAGEix-GLOBIOM.

The MESSAGEix-Materials is a newly developed additional module in the MESSAGEix-GLOBIOM modeling framework. It currently represents material flows of four energy intensive sub-industrial sectors, namely steel, cement, aluminum and petrochemicals (Unlu et al., 2022). For each sub-industrial sector, the life cycle of related material is represented by various technologies and processes, including the stages of material production, manufacturing, scrap recovery and recycling. As examples, in the steel sub-sector both BF-BOF (blast furnaces - basic oxygen furnaces) and EAF (electric arc furnace) processes are included, and they compete with each other in the modeling mainly based on cost optimization; for the cement, we include both wet and dry processes to make clinker, and both ball mill and vertical mill grinding technologies to make cement.

Figure 1: ***Overview of combined MESSAGEix-GLOBIOM modeling framework***



2.2 Scenario design

For the buildings sector, we run a set of scenarios to explore the effect of several demand-side (i.e., building stock related) strategies to reduce the demand of building materials (see **Table 1**), and compare the results to a reference scenario. All scenarios are generated starting from the Shared Socio-economic Pathway "Middle of the Road" (i.e., SSP2) with medium challenges to both mitigation and adaptation (O'Neill et al., 2017; Fricko, et al., 2017). The reference scenario represents a continuation of current trends in buildings construction and energy demand. The demand-side strategies analyzed in this study include: per-capita floorspace reduction; extension of lifetime of new and renovated buildings; and increased building renovation rate.

Table 1: *Scenario design*

Scenarios for the building sector modeling			Scenarios for the Integrated Assessment Modeling (IAM)
Scenario Name		**Description**	**Scenario Name**
REF	Reference	Reference scenario (SSP2)	**Baseline**
D.1	Floorspace reduction	Per-capita floorspace reduced by 20% by 2050 from the SSP2 reference scenario	n/a
D.2	Lifetime extension	Lifetime of new and renovated buildings extended from 25 years to 45 years	n/a
D.3	Renovation	Renovation rate increased to 1% yearly.	n/a
D.COMB	Strategies combined	D.1, D.2 and D.3 all combined	**LOWDEM (low demand)**

With the abovementioned soft-linkage between the "MESSAGEix-Buildings" module and the new version of MESSAGEix-GLOBIOM that includes the built-in "MESSAGEix-Materials" module, we also developed two scenarios by using the combined MESSAGEix-GLOBIOM integrated assessment modeling (IAM) framework, called "Baseline" and "LOWDEM", respectively (see **Table 1**). In this way, we could bring building sector specific scenarios into a broader context of entire energy system, and then investigate their impacts on the energy supply chains. The "Baseline" scenario is built on the buildings sector's "REF" scenario setup, while the "LOWDEM" scenario is based on the "D.COMB" scenario setup of the buildings sector. The two IAM scenarios, "Baseline" and "LOWDEM", are able to show the two extreme ends of our building sector scenarios.

3. Building sector modeling results

We report in the following sections the results for residential and commercial buildings, including projections of building and material stock, material demand and scrap release, energy demand for space heating and cooling, as well as the final energy use in the buildings sector.

3.1 Building stock results

Figure 2 shows the projections of floorspace for the set of building sector scenarios. The breakdown by building cohorts (new, renovated, existing non-renovated and informal buildings) is also displayed. In the REF scenario both residential and commercial floorspace initially increase, driven by larger per-capita floorspace, and then start declining before mid-century (around 2040) with population decrease. Existing buildings are gradually replaced by new buildings and undergoing renovation. While results are similar for the "Lifetime extension" scenario (D.2), in the scenario D.1 floorspace is significantly lower, and in the scenario D.3 the share of renovated buildings increases under higher renovation rates. The combination of all the three considered demand-side strategies (D.COMB) drives floorspace down, while increasing the share of renovated buildings. This corresponds to lower amount of material stock compared to the REF scenario (

Figure 3). The material stock is dominated by concrete - among the considered construction materials - followed by steel.

Figure 2: ***Floorspace projections under various building sector demand-side scenarios. Broken down by building cohort: buildings built after 2015 (1.new), renovated buildings (2.renov), buildings built until 2015 (3.exist), and informal buildings (4.informal)***

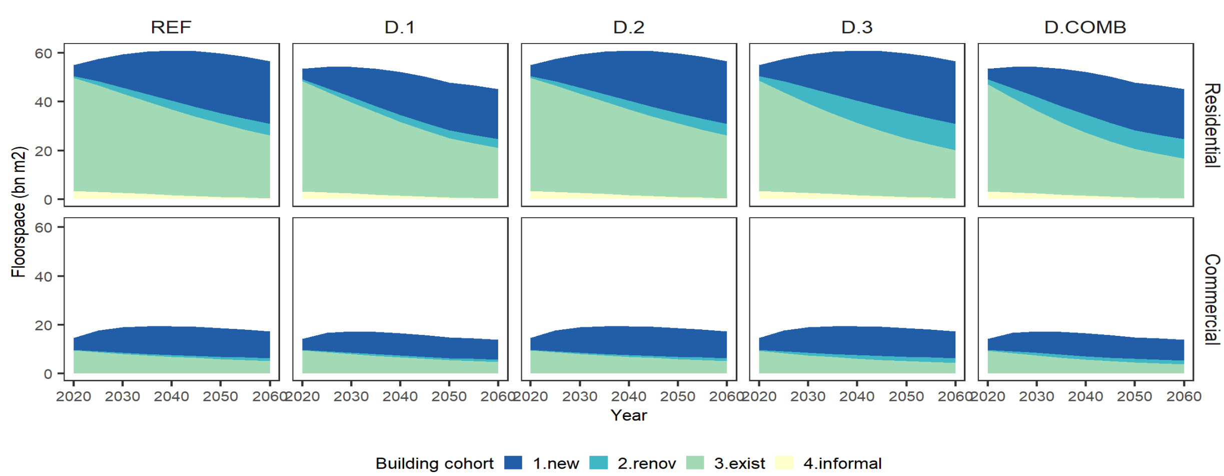


Figure 3: ***Material stock projections in the REF and D.COMB scenarios, broken down by building materials***

3.2 Material demand and scrap release

The projected material demand is expected to gradually reduce, as the construction rate for new buildings decreases over time (**Figure 4**). The decrease in material demand is steeper for commercial buildings, while plateauing for residential buildings around 2025 before declining. The highest demand is for concrete, followed by steel and wood. Implementing all considered demand-side strategies (Scenario D.COMB) entails a significant reduction in material demand into the future. Projections of scrap release (**Figure 5**) follow those for material demand with a time lag dependent on the building lifetime. In the REF scenario, scrap release initially increases and then declines for both residential and commercial buildings but peaking at a later time for commercial. In the D.COMB scenario, scrap release is both reduced and shifted over time as effect of the different demand-side strategies.

Figure 4: ***Material demand projections in the REF and D.COMB scenarios, broken down by building materials***

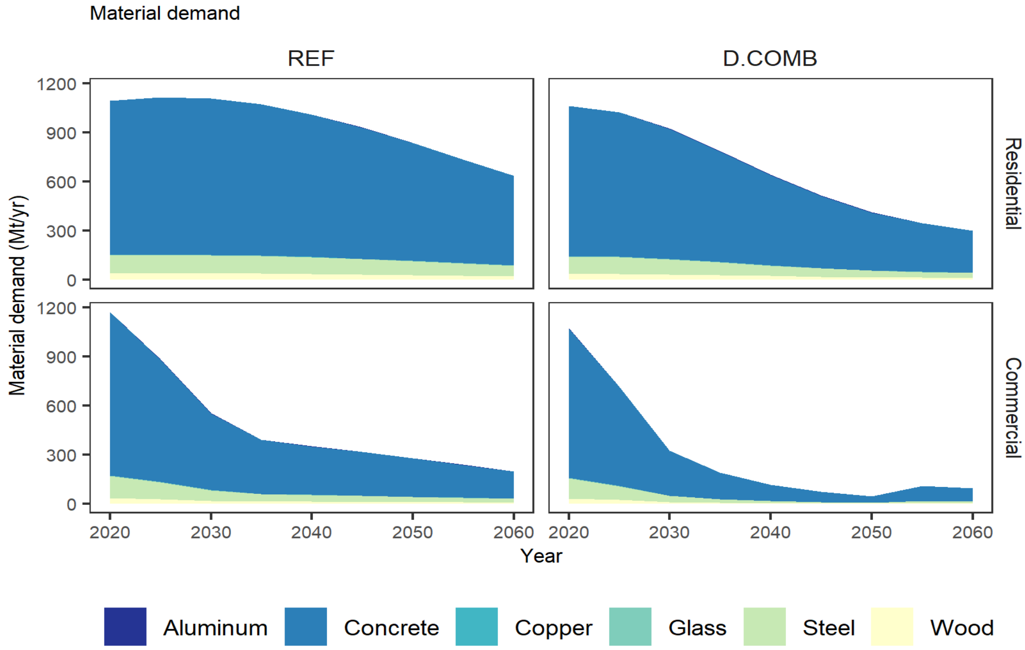
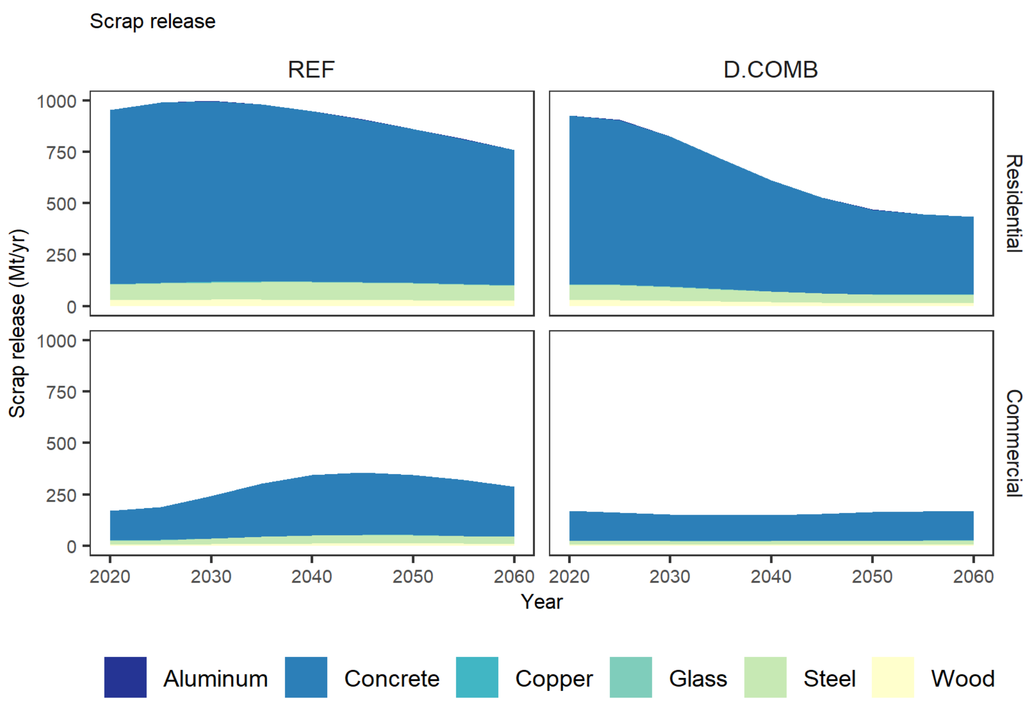


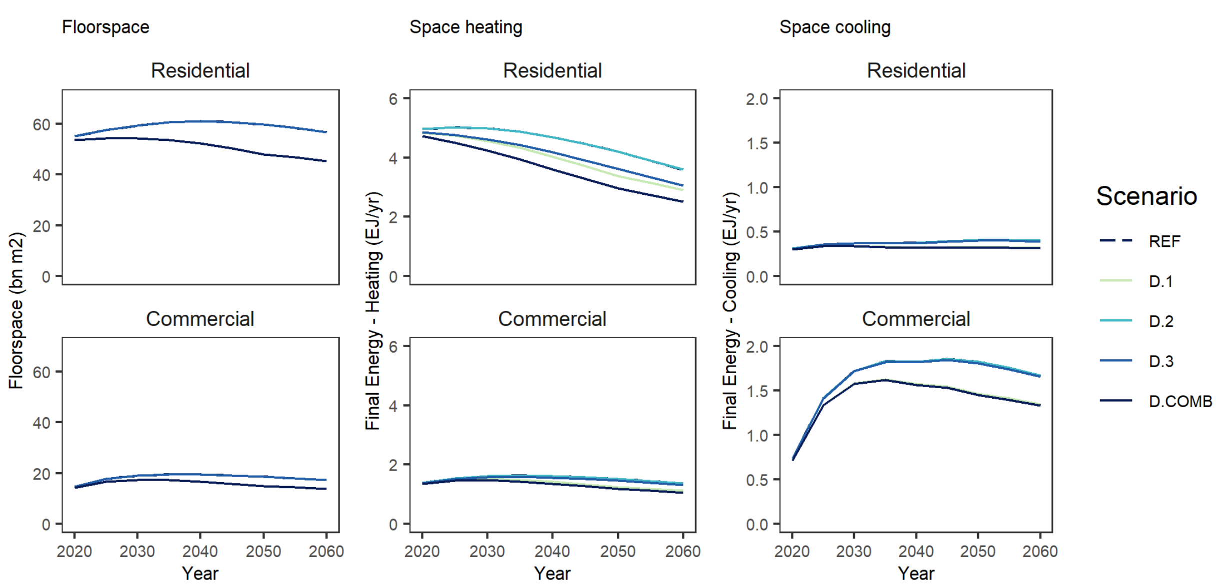
Figure 5: ***Scrap release projections in the REF and D.COMB scenarios, broken down by building materials***



3.3 Space heating and cooling demand

The considered demand side strategies also have effect on energy demand for space heating and cooling (**Figure 6**). In the REF scenario, energy demand for space heating is projected to initially increase under increased floorspace, and then decrease under gradual energy efficiency improvements of building shell and heating systems. Energy demand for space cooling increases under both larger floorspace and improved access to air-conditioning, especially for commercial buildings. Both reduced floorspace (scenario D.1) and increased renovation rate (scenario D.3) have significant effect on reducing energy demand for space heating and cooling, respectively by decreasing activity levels and improving the energy efficiency of building shell and heating and cooling systems. Increasing the lifetime of buildings (scenario D.2) has minor effects on energy demand. The combination of different demand-side strategies (scenario D.COMB) entails the largest reduction in energy demand for both space heating and cooling.

Figure 6: ***Projections of floorspace and final energy demand for space heating and cooling***



3.4 Final energy use in the buildings sector

Different from the above sub-sections, we present here the final energy use in the buildings sector of the two IAM scenarios, namely Baseline and LOWDEM, by using the new version of integrated assessment modeling framework, MESSAGEix-GLOBIOM (the new version has the built-in MESSAGEix-Materials module and also soft-linked with the MESSAGEix-Buildings module). As mentioned above, the Baseline scenario is built on the "REF" set-up of the building stock dynamics, while the LOWDEM scenario is based on the buildings sector's "D.COMB" setup, namely less per-capita floorspace (20% less in 2050 from the SSP2 reference scenario), longer lifetime of new and renovated buildings (from 25 years to 45 years), and higher yearly renovating rates (increased to 1%) than that in the "REF" buildings sector scenario set-up. The final energy use here includes all the end uses in buildings, including not only space heating and cooling, but also water heating, cooking and electric appliances.

As shown in **Figure 7,** the gap between the two IAM scenarios, using the Baseline scenario as the benchmark, is about 0.3-2.4 EJ/yr during 2020–2100. The largest gap is in 2050. The relative reduction from the Baseline scenario is presented in

Figure 8, about -6.3% and -12.5% during 2020–2040 and 2041–2060, respectively. In the entire modeling period 2020–2100, such a reduction is about -10.6%.

In summary, the final energy use in the buildings sector in China could be reduced by about one-eighth in the mid-century or one-tenth during the period of 2020-2100 by only adopting the above mentioned three building stock related measures.

Figure 7: ***Gap of final energy use in the buildings sector between the Baseline and LOWDEM scenarios***

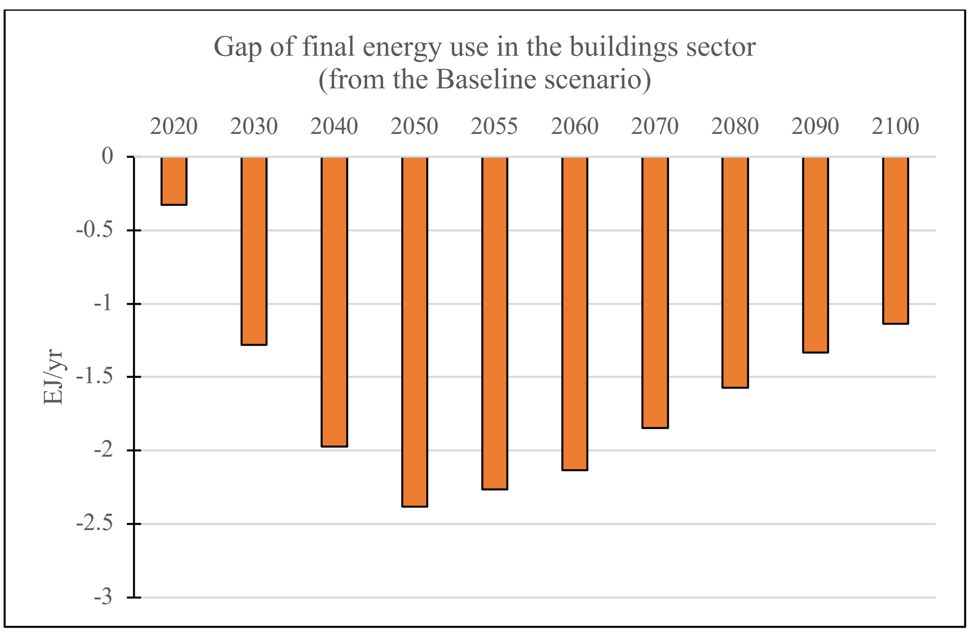
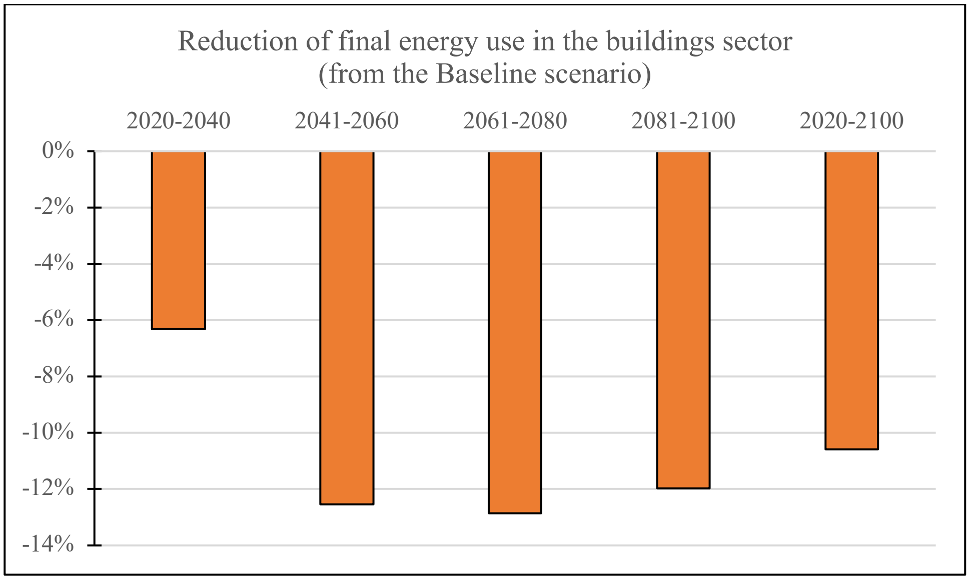


Figure 8: ***Reduction of final energy use in the buildings sector from the Baseline scenario***



4. Energy system modeling results

4.1 Primary energy use

Our integrated assessment modeling results from the combined MESSAGEix-GLOBIOM model show that the primary energy use could be reduced from the Baseline scenario by about 0.1-4.3 EJ/yr during 2020-2100 (see **Figure 9**). In 2050, the reduction is the largest. **Figure 10** shows the relative reduction of primary energy use from the Baseline scenario. The relative changes are about -1.4% and -4.0% for the period of 2020-2040 and 2041-2060, respectively, and about -2.9% for the entire modeling period 2020-2100.

In short, the three prescribed building stock related measures reflected in the LOWDEM IAM scenario could reduce the final energy use in buildings by about 10.6% during the period 2020-2100, and accordingly cause about 2.9% of primary energy use reduction in the same period.

Figure 9: ***Gap of primary energy use between the Baseline and LOWDEM scenario***

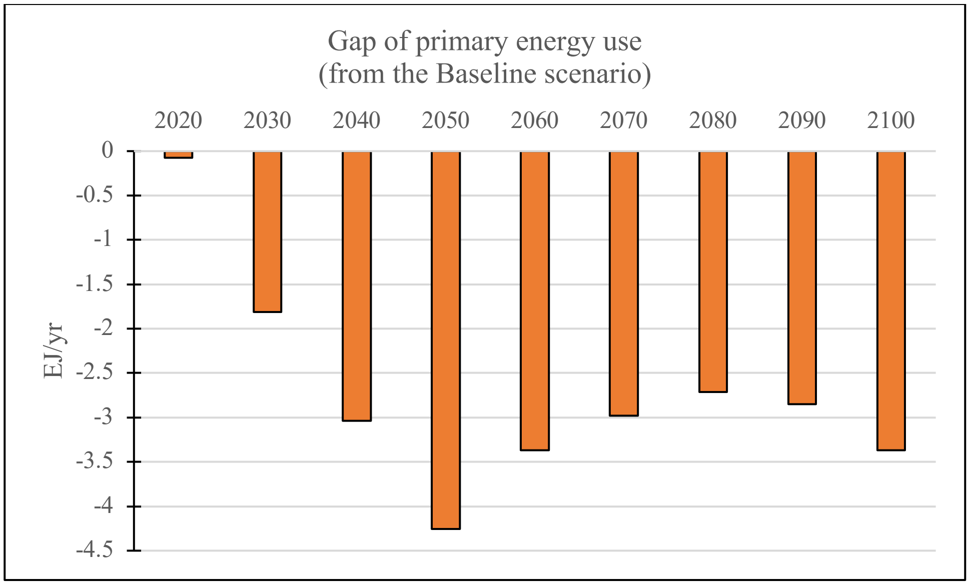
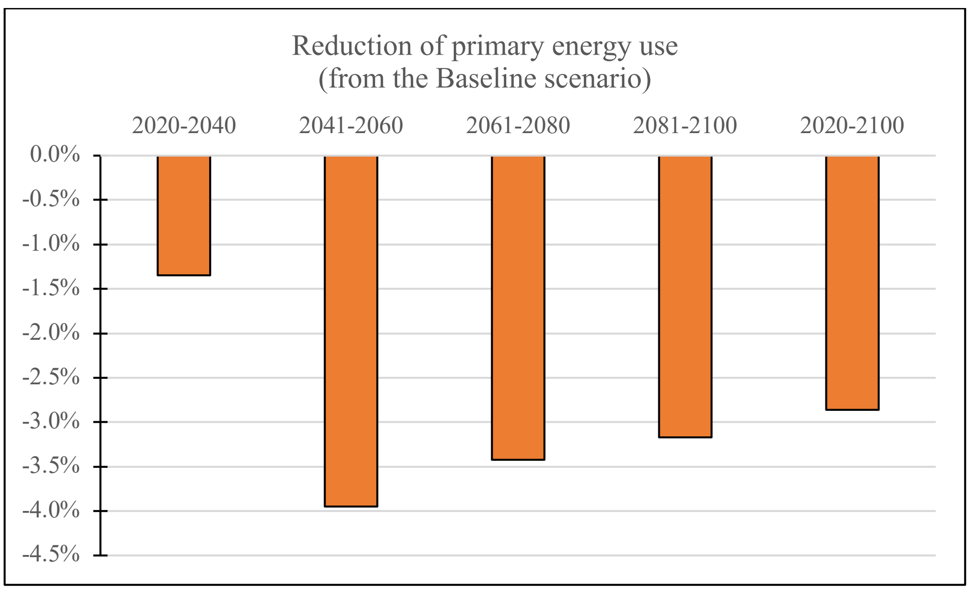


Figure 10: ***Reduction of primary energy use from the Baseline scenario***



4.2 Coal in primary energy use

As coal is heavily used for producing steel and cement, we also present here the difference of coal use in primary energy in the two IAM scenarios, Baseline and LOWDEM. **Figure 11** shows the coal consumption gap from the Baseline scenario, and we observeed that the coal consumption in primary energy could be reduced by about 0.1-3.9 EJ/yr during 2020-2100 in the LOWDEM scenario. As for the relative reduction from the Baseline scenario, it is about 0.8% and 8.1% for the period 2020-2040 and 2041-2060 respectively, and about 5.6% for the entire modeling period 2020-2100 (see

Figure 12).

Figure 11: ***Gap of coal in primary energy use between the Baseline and LOWDEM scenarios***

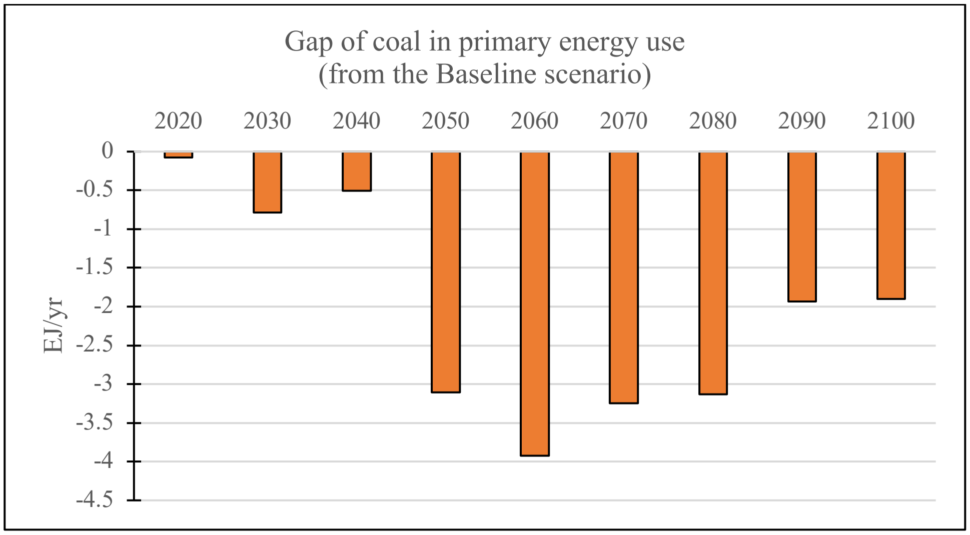
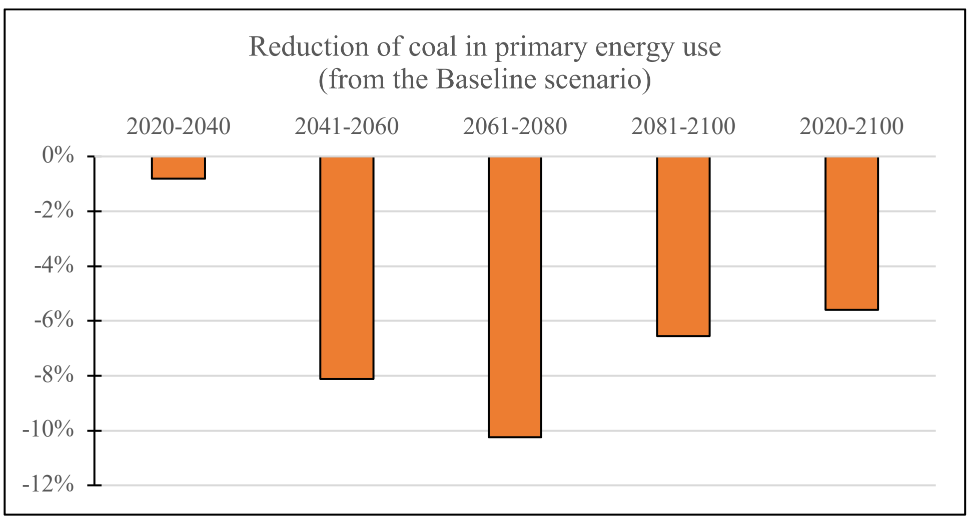


Figure 12: ***Reduction of coal in primary energy use from the Baseline scenario***



4.3 CO_2 emissions from the energy supply sector

The CO_2 emissions from the energy supply sector also show a similar trend as primary energy use. The gap of CO_2 emissions from the energy supply sector between the two IAM scenarios, Baseline and LOWDEM, is shown in **Figure 13**. It can be observed that the CO_2 emissions could be reduced by about 13-250 Mt CO_2/yr during 2020-2100. In terms of relative reduction from the Baseline scenario (see **Figure 14**), it is about 0.27% and 7.35% for the period 2020-2040 and 2041-2060, respectively. In the entire modeling period 2020-2100, the cumulative CO_2 emissions from the energy supply sector could be about 5.0% less in the LOWDEM scenario, compared to that in the Baseline scenario.

In summary, the above-mentioned three building stock related measures could bring down primary energy use by about 2.9% in the period of 2020-2100 that would cause less CO_2 emissions from the energy supply sector, about 5.0% in the same period.

Figure 13: ***Gap of CO_2 emissions from the energy supply sector between the Baseline and LOWDEM scenarios***

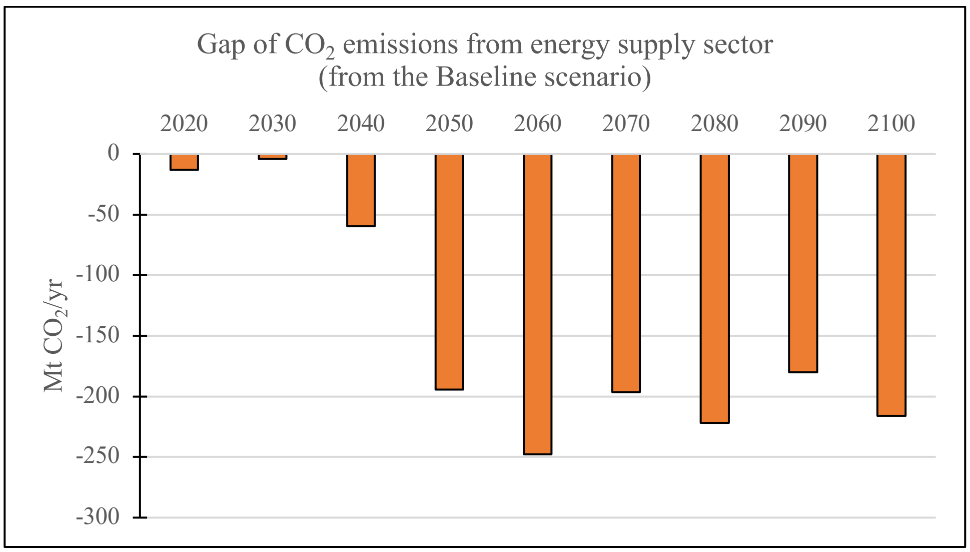
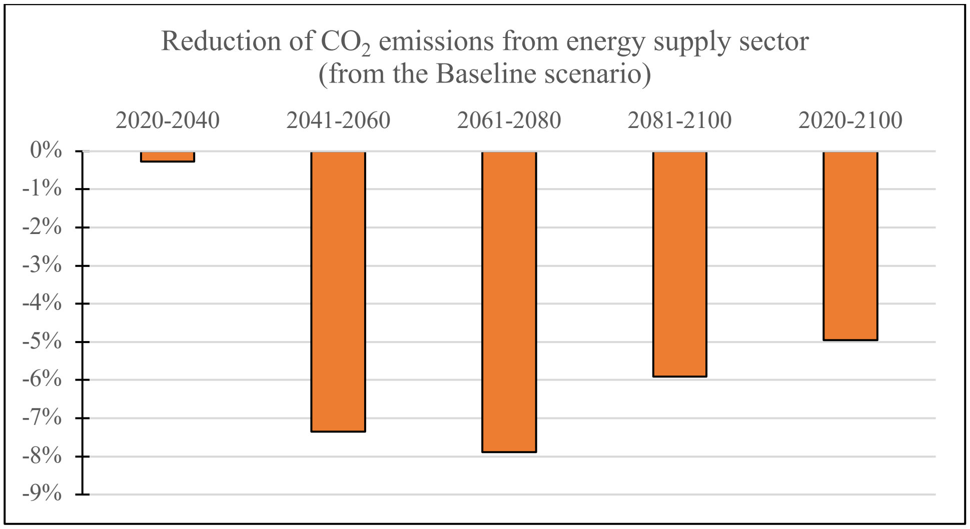


Figure 14: ***Reduction of CO_2 emissions from the energy supply sector from the Baseline scenario***



5. Discussion

Existing studies on reducing energy use in China's buildings sector mostly focused on energy efficiency improvement on the supply side, such as efficient HVAC (heating, ventilation, and air-conditioning) systems, efficient appliances (like LED bulbs, washing machines, etc.) and high performance of building insulation. However, much less studies were conducted on China's building stock itself, which is a fundamental driver of energy use in and for the buildings sector.

There are two main reasons on previous ignorance of exploring the impacts of building stock dynamics on energy use in the buildings sector in China. First, it is not very reasonable or appropriate to investigate measures of limiting the building stock development in China in the past years. This is because compared to developed countries, the per capita floorspace in China was much lower before the construction boom (about 10-15 years ago). With that background, the most important thing was improving the standard of living of Chinese people in the past years, particularly constructing larger housing units for Chinese households. Second, there is also very less similar research internationally. Different from China or other developing countries, the building stock in developed countries is very stable, and there are also no needs to conduct similar research in developed countries.

Along with China's robust economic growth in the past 1-2 decades, the standard of living of Chinese people has been substantially improved. Currently, the per-capita residential floorspace in China is almost reaching the EU level, while the yearly new buildings in China are still massive (1.7-2 billion m^2 in past few years). In other word, the construction boom continues in China. Moreover, China has pledged to peak its carbon emissions by 2030 and achieve carbon neutrality by 2060. Considering that it only gives China 30 years to go from carbon emissions peak to neutrality, significant efforts are urgently needed for the country to restructure its entire energy supply and demand system. Considering the abovementioned current development stage of China's building stock and China's pressing needs in energy transition, the deep decarbonization measures on the demand side become critical to explore. The newly published IPCC AR6 WGIII report on climate change mitigation calls for implementing SER (sufficiency, efficiency and renewable) strategies in the buildings sector (IPCC, 2022), in which sufficiency, as the demand-side indicator, is proposed to be one of the key measures for carbon emissions reduction.

This study takes a demand-side perspective to investigate the building-industry sectoral integration in energy saving and carbon emissions reduction by using a complex integrated assessment modeling tool. We find that the demand side measures related to building stock dynamics could have significant impacts on building materials needs, coal use, primary energy consumption and CO_2 emissions from the energy supply sector and so on.

Designing sustainable development pathways of China's building stock could help to achieve the country's 2060 climate goal. More further studies on demand side measures are expected from the energy and climate research community soon.

6. Summary

In this study, we designed three building stock related measures for China's building sector, namely, from a SSP2-based reference scenario, controlling per capita floorspace (20% less in 2050 from the SSP2 reference scenario), extending building lifetime (from the current 25 years on average to 45 years) and promoting building retrofitting rates (increase to about 1% yearly). Based on these three measures, we investigated five building sector scenarios (see **Table 1**) and explored their impacts on building stock dynamics and related building material needs, including steel, cement, aluminum, copper, glass and wood. Our building sector analysis shows that with the three designed demand-side (i.e., building stock related) measures combined the building stock peak could be around 2030 instead of 2040 shown in the SSP2 reference scenario without these measures. The needs of steel and concrete for new buildings will gradually decrease from now if we implement the three designed building stock related measures.

In addition, we also brought the building sector scenarios into a broader context of entire energy system by using the upgraded MESSAGEix-GLOBIOM integrated assessment modeling (IAM) tool. In the upgraded IAM tool, we combined the standard MESSAGEix-GLOBIOM model with two newly developed end-use modules, MESSAGEix-Materials and MESSAGEix-Buildings. The former one is built into the standard MESSAGEix-GLOBIOM models to represent material flows of four energy intensive sub-industrial sectors, including steel and cement, while the latter one is soft-linked with the MESSAGEix-GLOBIOM model (that has the built-in MESSAGEix-Materials module) by using the energy price generated by the MESSAGEix-GLOBIOM model. With such a comprehensive modeling framework, we could analyze the impacts of building stock dynamics on the entire energy supply system, particularly on primary energy use and CO_2 emissions.

Our integrated assessment modeling results show that the prescribed thee building stock related measures could bring down about 10.6% of the final energy use in the buildings sector from the SSP2 baseline scenario during the period 2020-2100, and accordingly make the entire energy system consume less primary energy (2.9%) (and less coal in primary energy, about 5.6%), as well as emits less CO_2 from the energy supply sector (5.0%) in the same period.

To implement the three studied building stock related measures, comprehensive regulatory and incentive policies are desired in place. It is often difficult to designing building stock related measures, as this involves various stakeholders, like governments, building owners, tenants, and business entities engaged in the construction industry (e.g., real estate developers, contractors, building material producers, project design companies, project supervision companies, etc.). Most importantly, the socio-economic status of households vary largely that makes equality a significant concern in designing and implementing such demand-side measures. However, governments at different levels play a lead role in introducing these measures.

For limiting the fast increase of total building stock and making per-capita floorspace at a decent but reasonable level, firstly the local governments need to make appropriate land use planning mainly based on local population development and economic growth, and strictly issue land use permits for constructing new buildings. This is challenging because the income from land use permits is often the main tax source for many local governments in China, and some of them may face budget difficulty if they more strictly issue land use permits of new buildings. In such cases, the support from the central government is important, for example, by transferring tax income among regions. It should be noted that controlling per-capita floorspace by regulatory land use policies should not impede the interests of low-income households. Considering that such policies may cause the rise of housing price, equality between different income groups should be paid high attention in implementing such regulatory policies. Social housing with appropriate size and affordable rent or price needs to be provided by the governments for low-income groups.

For extending the lifetime of new and renovated buildings, several critical regulatory measures should be strengthened by governments, including: 1) updating building codes regularly to promote the use of higher-quality and durable building materials, 2) improving the production criteria of building materials to remove poor-quality materials from market, and 3) implementing strict supervision in construction of new buildings to ensure their quality. Implementing these regulatory measures involve different government agencies and certain third parties (e.g., for supervision of construction projects), a close and effective cooperation among involved government agencies and third parties is essential.

For improving renovating rates of existing buildings, two things are particularly important. First, as currently a massive number of existing buildings that is in the mid-age of their lifetime is demolished every year in China, professional third parties should be established to be able to reliably assess the safety of buildings at certain points of their lifetime and provide renovation schemes. With feasible renovation schemes from such professional third parties, the demolishment of relevant buildings should not be allowed by local governments. In addition, financial support to relevant building owners for renovating their buildings should be well designed, such as subsidy programs, soft loan, etc. Renovation could not only extend building lifetime but also promote the energy performance of buildings to save energy costs for residences.

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