Climate change mitigation in Chinese megacities: A measures-based analysis of opportunities in the residential sector

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Abstract

China's commitment to the UNFCCC to peak its emissions by 2030, or sooner, signaled a long anticipated shift in China's model of development with far reaching consequences. Cities in China, and particularly the residential sector in cities, will be charged with making significant reductions in emissions growth even as rates of urbanization continue to climb. Focusing on Beijing and Shanghai, this paper carries out a measures-based economic analysis of low carbon investment opportunities in the residential sector. Results find significant opportunity: between 2015 and 2030, BAU levels of CO2 emissions could be reduced by 10.2% in Beijing and 6.8% in Shanghai with the adoption of economically attractive low carbon measures. While these headline results underline the case for low carbon investment in the residential sectors of these megacities in China, a closer analysis provides insights for understanding the economics of decarbonisation in cities more generally.

Keywords

Megacities; Climate change; Energy; Carbon; Residential buildings; Measures-based analysis

1. Introduction

China's commitment at the UNFCCC Conference of Parties in December 2015 to peak its CO2 emissions by 2030, or sooner if possible, was the latest and clearest example that the country is looking to transition to a more environmentally sustainable development path. The full consequences of a new model of lower carbon development, and the means of bringing it about, however, have yet to be fully explored.

A particular challenge may lie in 'peaking' the emissions of China's urban centers. Urban industrial agglomerations are a major component of Chinese carbon emissions, and emissions from buildings and transport are rising quickly as urbanization continues [1]. In addition to direct emissions,1 actions within cities also induce significant emissions outside of their borders. Indeed more than 70% of emissions from consumption of goods and services in Shanghai, Beijing and Tianjin (three of China's largest cities) were emitted from outside of those cities [1]. The lifestyles changes and increased affluence and consumption that often come from urban living are key drivers of emissions growth in China [1] and [2].

The scale of the challenge provides perspective on what is at stake. China's urbanization level reached 50% in 2011, and in 2015 the urban population of China was approximately equal to the population of Europe, or one-tenth of the global population. Looking forward to 2020, the Chinese government plans to raise the level of urbanization to 60% [3]. The impacts of 'business as usual' (BAU) growth in Chinese cities would be felt globally.

Both the Chinese government and the academic community have begun to focus on how to secure emissions reductions in Chinese cities. Following initial experiments in 2010, there are now 42 'low-carbon' city and province initiatives in China, including emissions targets for Beijing, Shanghai and Shenzhen that are in excess of national targets [4]. A pilot carbon-trading program that covers five cities (Beijing, Chongqing, Shanghai, Shenzhen and Tianjin) has also been operating since 2014 and will inform the development of a national program to be implemented during the 13th five-year plan [5].

In the academic sphere, a growing literature has examined cities and climate change in China. Topics that have been explored include the relationship between urbanization rates and CO_2 emissions [6], [7] and [8], the benefits of compact and connected development [9], [10] and [11], the scale of consumption emissions in cities [1] and [12], the relationship between public transit and emissions in cities [13], building energy efficiency and levels of demand for heating and cooling [14] and [15], and the effects of lifestyle changes on consumption and emissions [16] and [17]. There has also been research exploring mitigation strategies in different sectors, including power generation [18], [19], [20] and [21], industry [22], [23], [24] and [25], residential sector [12], [26], [27] and [28], commercial buildings [29] and [30], transportation [31] and [32] and waste management [33] and [34].

This body of research confirms the need for low carbon investment in Chinese cities and the opportunity that exists. However, an analysis that explores opportunities on a measure-by-measure basis, as has been completed on an international basis [35], [36], [37] and [38], has not yet been applied in China. Beijing and Shanghai are clearly not representative of cities across China as a whole; indeed, according to the World Bank [39], 2011 per capita CO_2 emissions from Beijing (10.1 tons) and Shanghai (11.7 tons) were comparable with New York (10.5 tons) and London (9.6 tons), and far higher than the average across China (7.2 tons). However, with five megacities and more than one hundred cities of more than one million people, there is much to be learnt from Beijing and Shanghai that will be of relevance to other large urban centres in China. Further, as cities in the North (Beijing) and South (Shanghai) of China, comparing these cities offers the opportunity to understand the importance of the climate on residential energy use and the options for decarbonisation in that sector.

The rest of the paper is structured as follows: Section 2 briefly introduces the methodology adopted. Results of case studies of Beijing and Shanghai are analyzed in Section 3. A comparison analysis and discussions are carried out in Section 4 and the final section provides a conclusion.

2. Methodology

To evaluate the opportunity for low carbon measures in the residential sector in Chinese megacities, an integrated measures-based assessment model was developed which built on previous assessments in other contexts [36]. This model includes four stages.

2.1. Accounting scope and baseline analysis

This study considered energy use and emissions from residential buildings2 in the metropolitan areas of Chinese megacities, including direct emissions from fuel combustion and upstream emissions from electricity generation attributable to the urban residential sector. Direct emissions included those from consumption of fuels for central heating, (independent) heating in the urban and rural3 residential sectors, and fuels used for cooking in the urban and rural residential sectors (see in Fig. 1).

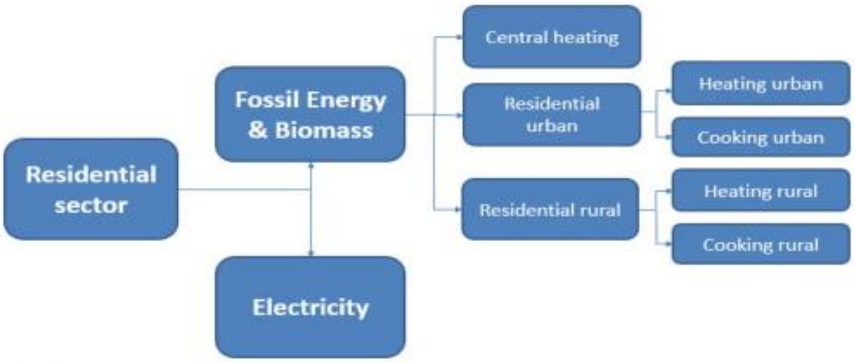

Fig. 1.
Decomposition of energy use in residential sector. (As opposed to central heating, urban and rural heating are the fossil fuels and biomass independently used for heating purpose in urban and rural households. Here, 'Electricity' denotes the electricity being used by appliances and lighting in the residential sector.)

A 'business-as-usual' (BAU) scenario for the residential sector was developed covering the period from 2000 to 2030. This scenario is not intended to predict the future, but rather to outline a possible scenario for the future given current trends and policies [40] and [41]. Data on historic energy use in the residential sector between 2000 and 2012 were collected from the Multi-resolution Emission Inventory for China (MEIC database)4 developed by Tsinghua University. This energy consumption baseline assumes the continuation of historic and contemporary trends in energy use per capita and energy structure, coupled with a projected population growth rate and urbanization rate,5 through to 2030. CO2 emissions from the residential sector were then calculated according to the IPCC Guidelines for National Greenhouse Gas Inventories methodology [42]. Apart from predictable changes in the carbon intensity of electricity generation between 2013 and 2030,6 no additional energy and climate policies were introduced in the baseline scenario. This omission is intentional as we hope this analysis can help to inform policymakers, both nationally and at the urban level, of the approaches that could help to shift current emissions trajectories towards the climate change mitigation targets.

The assumptions included in the baseline forecasts are summarized in Table A1. Data sources for background data are presented in Table A2. The resulting baselines allowed us to create a scenario of future levels and forms of energy demand as well as future energy bills and CO2 emissions. All future activities are compared against these baselines.

2.2. Identification and assessment of measures

Following extensive review of academic, policy and grey literatures, and local stakeholder consultations (see Table A3 in appendix), preliminary long lists of low carbon measures for the residential sectors in Beijing and Shanghai were compiled. Measures included those for improving the energy efficiency of appliances and lighting, behavioral measures to reduce energy consumption, measures to improve building standards and measures for the integration of small-scale renewables such as solar water heaters.

These long-lists were then shortened through a consultation process between a steering group in the UK, the research team in China and local stakeholder panels in each city. Considerations during this process included local climates, cultures and socio-economic structures. The resulting short lists were not necessarily exhaustive as some measures may have been overlooked, while others were not included in the analysis due to data limitations.

Following the completion of these lists, the performance of the shortlisted measures and the scope for deployment of all measures were then assessed with a cost-benefit analysis of each measure conducted over its lifetime. Data on capital costs, operating costs and deployment potential were drawn from an extensive literature review and stakeholder consultations. These data are then used to calculate the net present value (NPV) for each measure. Similarly, data on efficiency and energy consumption of each measure, relative to the baseline, are used to estimate the CO2 emissions saved from each measure. During the process preliminary outputs were confirmed at multiple stages with stakeholders and experts.

The NPV calculation for each measure focused narrowly on direct private costs and benefits. The NPV calculation for a higher efficiency air conditioner, for example, included the marginal cost of a more efficient air conditioner relative to the baseline model and the economic savings of running that model relative to the baseline model. This approach excludes the wider costs and benefits of certain measures, relating for example to the air quality benefits of switching from coal to natural gas for residential heating. However this modeling approach embraces the reality that a narrow economic case is an important aspect of decisions around energy use in households.

The costs of measures were held constant at 2012 prices. As each measure could be in place for many years, we modeled a 3% annual increase in real energy prices, a 5% annual discount rate and a 3% annual inflation rate between 2013 and 2030. These numbers, especially for energy prices and inflation, are conservative relative to historical trends7 in China between 2000 and 2012. Assumptions on the costs and deployment rates of each measure in each city are fully described in Table A4 for Beijing and Table A5 for Shanghai in the Appendix. The economic performance and carbon savings for each measure, are presented in Table A6 for Beijing and Table A7 for Shanghai in the Appendix.

2.3. Aggregation of potentials and assessment of opportunities

The third stage of the analysis involved aggregating potential carbon and economic savings by grouping measures into scenarios. This allows for analysis of the overall investment needs and paybacks from low carbon measures adopted across the residential sector.

Scenarios are developed by adding measures from most, to least, ‘cost-effective’ from the ‘league tables’ found in Table A6 and Table A7. The ‘cost effective’ scenario is the set of measures with the largest collective NPV, including the impacts of interactions. The ‘cost neutral’ scenario includes the largest set of measures for which the net present value of the total scenario remains greater than zero. In this scenario is it assumed that a financing mechanism is employed to re-invest the returns from cost-effective measures to pay for measures that do not independently pay for themselves (for more on financing mechanisms see Gouldson et al. [36]). The 'technical potential' scenario represents the largest possible carbon savings from measures investigated in this study with all measures being adopted to their full potential regardless of costs and benefits.

2.4. Interactions and feedbacks

In the development of the scenarios, the potential for interaction between measures needs to be considered. For example, the mitigation effects of green building standards will be affected by the efficiency of heating and air conditioning appliances. To take these interactions into account, the impact of each measure is measured independently in the league tables but with consideration for interactions included in the scenario analysis. For example, in the case above, the savings achieved by high efficiency appliances were measured for a household that has already implemented green building standards. Where measures are mutually exclusive, the measure with the greater economic return was implemented.

An additional issue concerns whether the implementation of a measure today might prevent the implementation of a more ambitious measure in the future [43]. For example, high efficiency coal heaters may discourage investment in natural gas heating. To address this issue extensive expert and stakeholder consultation was undertaken to ensure that scenarios were developed that were not locking-out future mitigation. Full details of the stakeholders and experts consulted can be found in Table A3.

3. Results and analysis

3.1. Case study of Beijing

As the capital city of China with a population of 21.5 million,8 Beijing has a unique political and economic status. In terms of the changes the city has seen over the past several decades, however, including rapid urbanization and industry-led economic growth, the city has much in common with many urban areas in China.

In recent years economic growth and CO2 emissions have shown signs of relative decoupling. The energy intensity of GDP fell by 59% between 2001 and 2010 and a further 17% decrease is anticipated during the 12th five-year plan (from 2011 to 2015).9 However continued economic and population growth are leading to rising total emissions. The population density of urban Beijing has increased from 937 people/km2 in 2005 to 1525 people/km2 in 2014, an overall increase of 62.75%. By 2030, the total population is projected to grow to 30 million.

This can be seen in Fig. 2, where energy use, energy expenditure and emissions are indexed to 2012. CO2 emissions from the residential sector grew by 127% between 2000 and 2012 and analysis here predicts that they will grow by a further 57% between 2012 and 2030 under a BAU mode of development (i.e. one where trends from 2000 to 2012 continue through to 2030). Under such conditions, total energy use, energy costs and CO2 emissions are forecast to increase by 104%, 283% and 57% respectively between 2012 and 2030. The relatively smaller increases in CO2 emissions relative to energy use and expenditure, as well as the relatively smaller increase in energy use relative to energy expenditure, are attributable to a decline in the CO2 intensity of electricity and changes in the types of energy used.

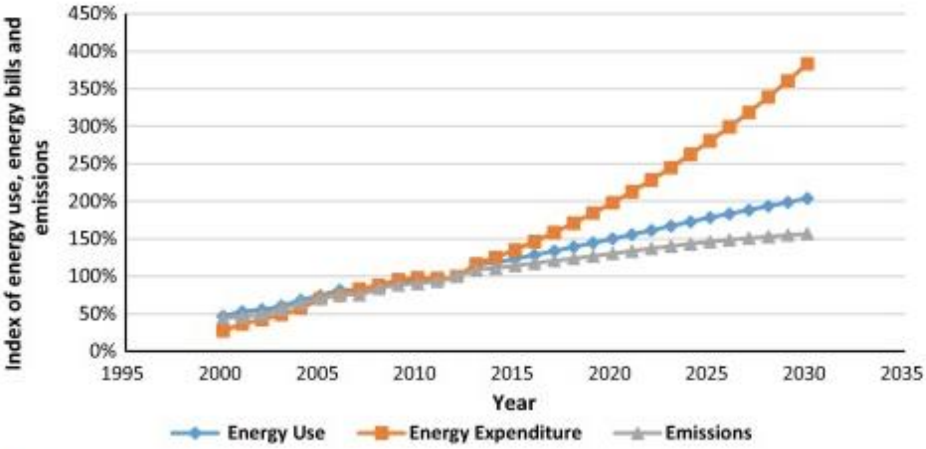

Fig. 2.

Residential sector of Beijing: Index of energy use, energy bills and emissions, 2000–2030 (2012 = 100%).

When breaking down the total emissions of the residential sector by energy sources (see Fig. 3), we can see that electricity, natural gas and coal currently contribute the most to CO2 emissions from the residential sector of Beijing. Looking forward to 2030, analysis here suggests these three energy sources will continue to dominate, however there will be a significant shift in their relative contributions. The proportion of emissions from coal is projected to decrease from 43% in 2012 to 11% in 2030, while those from natural gas and electricity are projected to increase from 19% and 27% in 2012 to 53% and 29% in 2030, respectively. This shift will be driven by various government policies; as one of the megacities in China suffering acutely from air pollution, the Beijing government has introduced tough plans to regulate coal-intensive energy use, including implementing a 'fuel forbidden area' within the six urban districts of Beijing by 2020.(10)

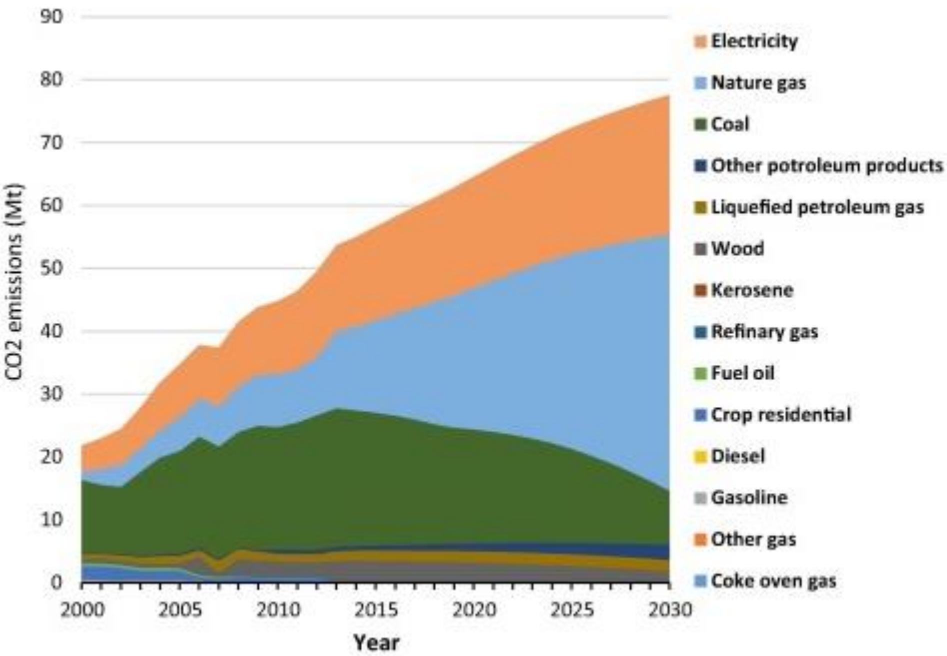

Fig. 3.

Emissions from the residential sector of Beijing by energy sources in BAU, 2000–2030.

The baseline energy scenario shows that energy use and CO2 emissions will grow significantly more slowly between 2012 and 2030 than they did between 2000 and 2012. However, to achieve China's climate change targets, further action will need to be taken. In the following, we explore the contribution that could be made through the broad based implementation of mitigation actions in the residential sector.

Comparing the different scenarios depicted in Fig. 4, we can see that significant potential exists to reduce emissions from the household sector over the period 2015–2030. Between 2015 and 2030 CO2 emissions could be reduced by:

- 10.2% with cost effective measures that would pay for themselves on commercial terms over their lifetimes. This would require investment of 35,032 RMB million (5550 USD million), generate annual savings of 4979 RMB million (789 USD million) and payback the original investment in 7.0 years but provide savings for the lifetime of the measures.
- 14.8% with cost neutral measures that would require investment of 43,439 RMB million (6881 USD million), generate annual savings of 5977 RMB million (947 USD million) and payback the original investment in 7.3 years but provide savings for the lifetime of the measures.
- 15.5% with the exploitation of all of the realistic potential of the different measures with carbon saving potential. This would require an investment of 241,939 RMB million (38,327 USD million), generating annual savings of 6255 RMB million (991 USD million), paying back the investment in 38.7 years and generating annual savings for the lifetime of the measures.

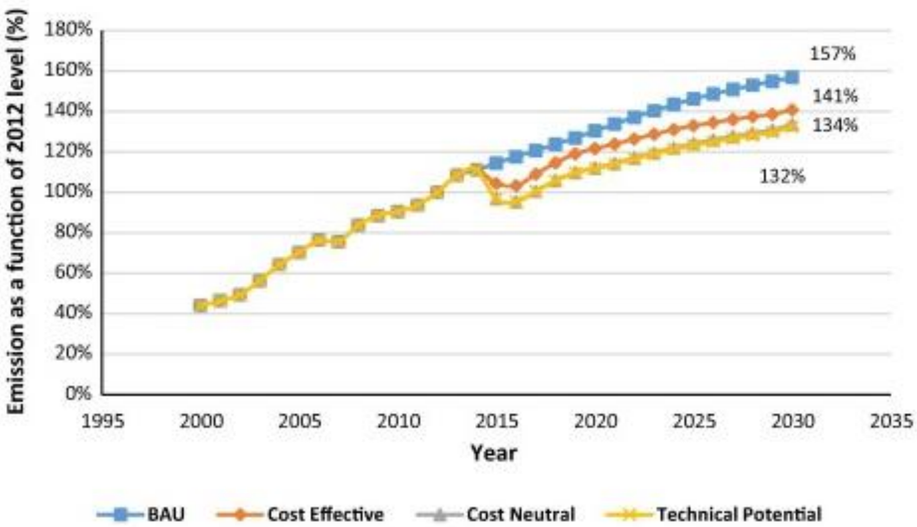

Fig. 4.
Indexed emissions from the residential sector in four different scenarios between 2012 and 2030.

With investment in all cost-effective low-carbon measures, Beijing could therefore avoid residential emissions of 97.3 MtCO2 between 2015 and 2030, or almost 2 years of annual emissions at the current level. With further investment in cost-neutral measures, Beijing could avoid emissions of 165.6 MtCO2, or more than 3 years of emissions. While these are very significant emissions reductions, they are not enough to prevent emissions growth from continuing. Indeed in 2030, the so-called TREBLE point, or the 'time to regain business as usual levels of emissions' [36] after investment in low carbon measures in the face of on-going urban, population or economic growth (even in a lower carbon form), is only 2 years in the case of cost effective measures and 3 years in the case of cost neutral measures. In order to achieve deeper and longer lasting cuts in emissions, policymakers in Beijing may need to take more aggressive actions.

This research reveals some specific measures with high potential for reducing CO2 emissions from the residential sector in Beijing. The most carbon-effective measures include gasification of heating furnaces for heating and cooking, insulation of rural households within the metropolitan area and improvements in central heating efficiency. Less effective measures for reducing CO2 emissions include improving the energy efficiency of household appliances and solar hot water heaters.

A number of measures also show significant potential for economic returns. The most cost-effective include measures to improve the efficiency of coal heating, and measures to improve the energy efficiency of household appliances and lighting. Other measures, for example insulating rural households within the metropolitan area and improvements in air conditioner efficiency do not show an economic case. However if these measures could be subsidized by the returns from cost-effective measures then CO2 emissions mitigation could be substantially increased.

3.2. Case study of Shanghai

Shanghai is the second largest city in China with a population of 24.26 million in 2014.11 Apart from its large population, Shanghai is also unique for its high density, which is more than two times that of Beijing at 3826 people/km2.

Similar to Beijing, Shanghai's economy has been becoming less dependent on energy for growth. The energy intensity of GDP fell 16.5% between 2000 and 2005 and 20% between 2005 and 2010. During the 12th five-year plan12 (from 2011 to 2015) the energy intensity of GDP is projected to fall by a further 18%. However, the population in Shanghai is projected to increase to 30 million by 2030 and economic growth continues to drive up absolute levels of emissions and energy use.

Seen in Fig. 5, CO2 emissions from the residential sector grew by 146% between 2000 and 2012 in Shanghai, and we predict that they will grow by a further 77% between 2012 and 2030 under BAU conditions. Energy consumption is anticipated to increase by 88% between 2012 and 2030 under these conditions, and due to the assumption that energy prices will increase 3% per year, energy expenditure is expected to increase by 242% in the same period.

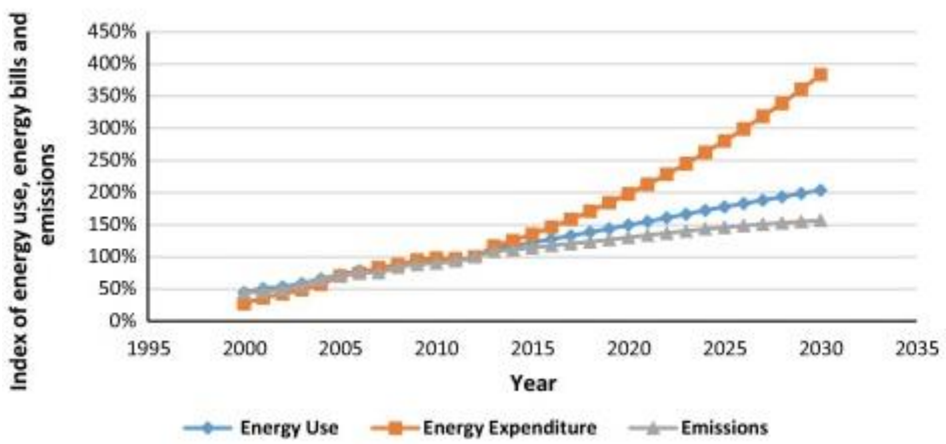

Fig. 5.
Residential sector of Shanghai: Index of energy use, energy bills and emissions, 2000–2030 (2012 = 100%).

The smaller increase in CO2 emissions relative to energy use and expenditure can be attributed to a decline in the carbon intensity of the electricity grid and changes in the types of energy that are likely to be consumed between 2012 and 2030. When breaking down total emissions by energy sources (see in Fig. 6), we can see that electricity contributed the most to CO2 emissions in the residential sector of Shanghai, followed by natural gas and other petroleum products. Electricity remains nearly constant in its contribution to emissions at around 57% in both 2012 and 2030. The emission proportions of natural gas and other petroleum products increase from 12% and 9% in 2012 to 15% and 18% in 2030, respectively. Emissions from coal consumption are forecast to decrease as a proportion of total emissions from 11% in 2012 to 5% in 2030. The lower use of coal in Shanghai compared with Beijing reflects Shanghai's warmer climate.

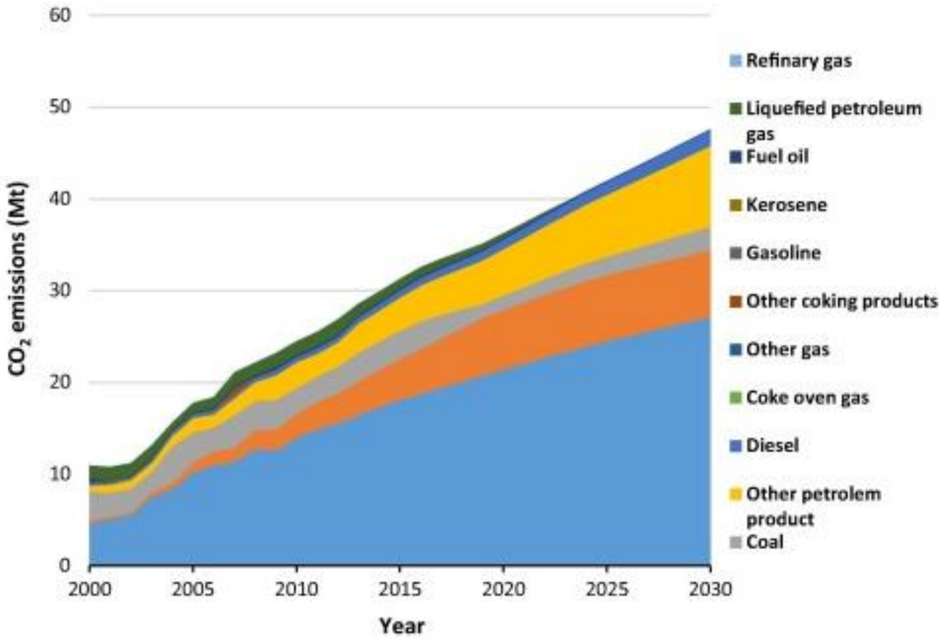

Fig. 6.
Emissions from the residential sector of Shanghai by energy sources, 2000–2030.

The baseline energy scenario shows that energy use and CO2 emissions will grow quickly in Shanghai without action to change the BAU trend. In the following discussion, we explore the effect of adopting different mitigation actions in the residential sector in Shanghai.

Comparing the different scenarios shown in Fig. 7, we can see that significant potential exists to reduce emissions from the household sector in Shanghai over the period 2015–2030. Between 2015 and 2030 CO2 emissions could be reduced by:

- 6.8% relative to BAU levels through economically attractive investments within the residential sector of city. This would require an investment of 19,758 RMB million (3130 USD million), which would generate annual savings of 3048 RMB million (483 USD million). This package of investments will be paid for in 6.5 years.
- 7.0% relative to BAU levels through economically feasible investments within the residential sector of city. This would require an investment of 27,267 RMB million (4320 USD million), which would generate annual savings of 3155 RMB million (500 USD million). This package of investments will be paid for in 8.6 years.

– 9.9% relative to BAU levels through investments to achieve the technical potential within the residential sector of city from these investments. This would require an investment of 241,228 RMB million (38,214 USD million), which would generate annual savings of 4712 RMB million (746 USD million). This package of investments will be paid for in 51.2 years.

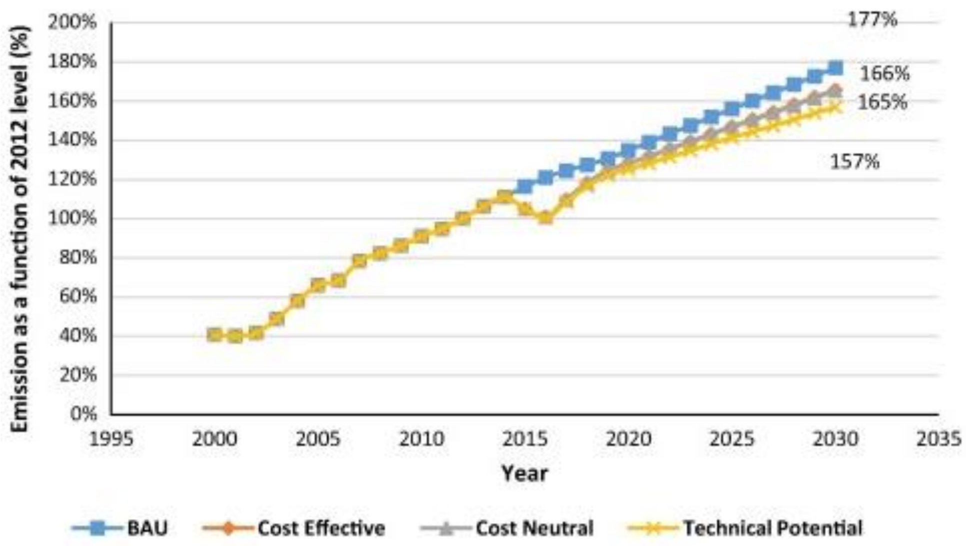

Fig. 7.
Indexed emissions from the residential sector in four different scenarios between 2012 and 2030.

Significant reductions in emissions are therefore achievable in Shanghai through measures which generate economic returns (as in the cost effective scenario), or at no net cost (the cost neutral scenario). Similar to Beijing, however, the TREBLE point for cost effective emissions is only 2 years and for cost neutral emissions is 3 years. The measures explored here will therefore need to be supplemented with more aggressive actions if policymakers wish to achieve more significant emissions reductions.

A number of measures were found to have significant potential to reduce emissions on an individual basis. The top three among these are efficiency standards for air conditioners, replacing coal with natural gas in residential cooking and adopting efficiency standards for entertainment appliances. Other measures, including energy efficiency improvements for water heaters and electric heaters and solar hot water heaters, provide the smallest CO2 savings.

In addition to the potential for emissions reductions, significant economic opportunities for low carbon investment in the residential sector of Shanghai were found. The most cost effective measures include the adoption of standby features for appliances, banning incandescent light bulbs and raising the temperature of the thermostat linked to air conditioners by 1 degree. In many cases, measures showed both a strong emissions case and a strong economic case. Such cases included replacing incandescent lights with LED lights, switching from coal to natural gas in cooking and heating and behavioral measures such as turning up the thermostat by 1 degree. In other cases, measures that were not directly economic individually could theoretically be financed by cost-effective measures. For example, savings from measures to improve the efficiency of lighting in Beijing could be used to finance retrofitting home insulation.

4. Comparison and discussion

The analysis presented above shows that absolute levels of energy use and CO2 emissions can be expected to increase rapidly in Beijing and Shanghai even though structural changes and background trends in energy efficiency are leading to improvements in energy and carbon intensities. Guided by national energy saving and emission reduction targets, local governments have goals to reduce the emissions intensity and energy intensity of GDP respectively by 17% and 18% in Beijing and 18% and 19% in Shanghai between 2010 and 2015. It is anticipated that targets will be raised further during the upcoming 13th 5-year plan in China (2016–2020).

This analysis demonstrates that, with investment, there is a significant scope for emissions reduction from the residential sector to contribute to meeting these goals. In Beijing, by 2030 residential emissions could be reduced 10.2% compared to BAU through cost-effective investments alone. While as a proportion of total emissions this may seem relatively small, Beijing's population is expected to grow steadily over this period. On a per capita basis, these measures could lead to emissions from the residential sector peaking in 2016 and falling 2.9% below 2015 levels by 2030. In Shanghai, absolute levels of residential emissions could be reduced by 6.8% relative to BAU trends by 2030. It should also be noted that the analysis here only assesses the period from 2015 to 2030 and the majority of the measures evaluated would have substantially longer lifetimes.

A number of observations can be drawn from these findings (see Fig. 8). A first observation regards the significantly larger abatement potential in Beijing relative to Shanghai. This difference can be largely attributed to climate (see comparison of backgrounds of Beijing and Shanghai in Table A8 in appendix). Energy use for central heating in Beijing was 36.4 TWh in 2012, accounting for 26.15% of the total energy consumption in the residential sector. By contrast only 0.5 TWh of energy was consumed for central heating in Shanghai, accounting for 0.7% of total residential energy use.

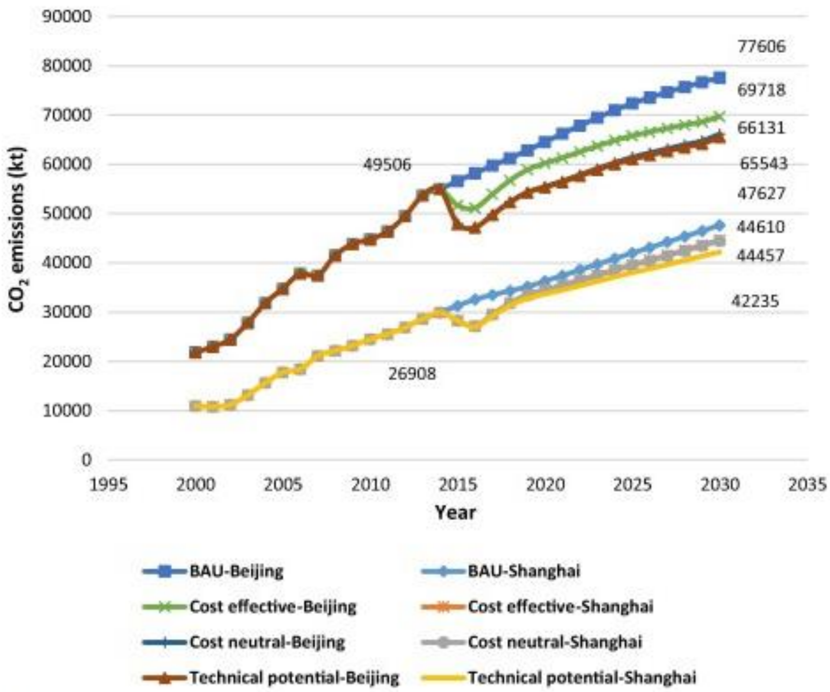

Fig. 8.

CO_2 emissions from residential sector between 2000 and 2030 under different scenarios.

While heating is a major cost and source of emissions in Beijing, analysis here also finds that it is also a source of unrealized economically attractive mitigation potential. Viewing the cost effective mitigation potential in Fig. 9, 384% of Beijing's total potential reductions arise from actions to increase the efficiency of central heating. This is followed by 37.7% of savings from non-heating electricity use (air conditioning and appliances), 12.2% from urban cooking and 11.6% from rural heating.13 In Beijing, many of the most cost-effective measures are also highly carbon effective. Examples include improved efficiency of coal burners for heating and cooking, improving the use of biomass briquettes and switching from coal to natural gas.

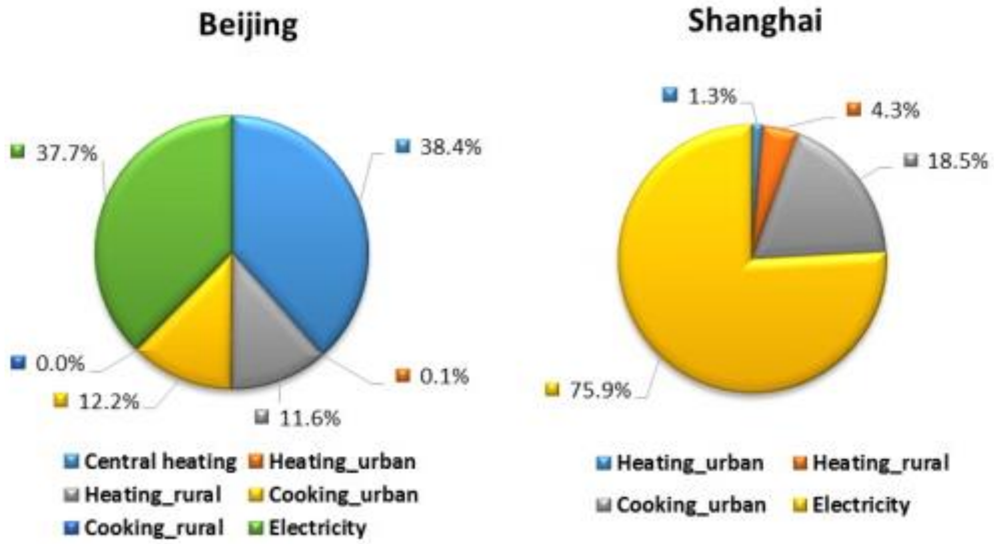

Fig. 9.
Breakdown of CO_2 reductions during 2015–2030 with cost effective options by subsectors in Beijing and Shanghai.

In contrast with Beijing, cost effective emissions savings in Shanghai largely come from higher efficiency in electric appliances and air conditioning (75.9%), with heating comprising 18.5% of savings and rural and urban heating comprising less than 6% of savings combined. Central heating is excluded, as it is uncommon in Shanghai. The most cost effective measures include the deployment of high efficiency light bulbs and raising the thermostat by 1 degree.

Raising the air conditioner thermostat in the summer by 1 °C and promoting appliance standby features fall into the top five cost effective options in both Beijing and Shanghai while measures to improve the energy efficiency of air conditioners save larger amounts of carbon in both cities. These findings suggest that the impact of weather (unsurprisingly) is only relevant for specific measures, and that for other measures affluence and lifestyle factors are better indicators of whether an intervention will be cost or carbon effective [16].

These findings are broadly consistent with other studies that have adopted a measures-based approach to explore the scope for decarbonisation in different sectors in cities in diverse contexts around the world [35], [36] and [37]. For other cities in Asia, these studies have indicated that city-scale CO2 emissions could be reduced by between 10% and 25%14 by 2030 compared to BAU levels through the adoption of cost-effective measures in the residential sector.

Numerous reports have found that low carbon initiatives for residential buildings – as well as those for commercial buildings - represent an underappreciated and often unexploited opportunity [45], [46], [47] and [48]. One of the reasons for this is that the opportunities are spread across a number of measures in a large number of households, rather than being concentrated in a particular project or opportunity. Market based approaches to climate finance and low carbon investment may depend on the consolidation of these fragmented opportunities and on the emergence of new forms of finance and new business models for delivery [36]. But investment can also be induced through various forms of policy, the political case for which can be underpinned by the presence of an economic case. For Beijing and Shanghai, and perhaps for Chinese cities more generally, our assessment strengthens the case for the adoption and application of, for example, tougher green building standards or appliance-based energy efficiency standards. Some of the requisite policies are already in place. The Energy Conservation Law of the People's Republic of China revised in 200715 for example, has been associated with significant improvements in the energy efficiency of air conditioners and appliances. But in other instances, relating for example to the retrofitting of residential buildings, government mandates need to be complemented by delivery mechanisms and new forms of engagement, and possibly also by new financing arrangements.

While this study has provided both an economic and an environmental case for action to reduce the energy use and CO2 emissions of the residential sector in Beijing and Shanghai, it is important to note the limitations of the study and the potential to refine or extend the study over time. An obvious point is that to some extent the findings rest on the quality of the available data and the methods and assumptions adopted. Although these were all reviewed through stakeholder consultations, the scope of the study is quite broad and there is a need for the findings to be triangulated or ground-truthed through finer grained research. Further, in contrast with studies carried out by Mohareb and Kennedy [49] and [50], we did not consider the impact of technological learning on the cost and performance of measures. An assumption to hold costs constant was made to ensure that estimates were robust and defensible, however an analysis including different learning scenarios would extend on this work. It is also important to note that the analysis has considered only the direct impacts of the range of measures assessed. Some potentially significant indirect or co-costs and benefits are outside of the scope of the study. This is of particular significance in Chinese megacities such as Beijing and Shanghai where hazardous levels of air pollution justify tough actions against the use of heavy fuels (specifically coal [51]) irrespective of the narrower carbon or economic case for action. Finally, this study was restricted to Beijing and Shanghai and to the residential sector. A wide analysis, including other sectors and cities would provide a more complete picture of the landscape for low carbon mitigation in urban China.

5. Conclusions

This study evaluated the environmental and economic performance of a number of low carbon measures in the residential sector in China. The cities of Beijing and Shanghai were selected as cases of large cities that – as part of a wider national strategy – are starting to make the transition towards greater sustainability. While these cities are unique, in terms of their size, recent rates of population and economic growth, aspects of their governance and location, lessons can be drawn from them that are of great relevance elsewhere in China and possibly also internationally.

The results provide clear evidence, supported by technical and economic modeling and stakeholder consultation, that the residential sector provides a significant opportunity for economically viable improvements in energy efficiency and reductions in CO2 emissions. Economically attractive low carbon measures with payback periods of 7.0 years for Beijing and 6.5 years for Shanghai could deliver carbon reductions of 10.2% and 6.8% between 2015 and 2030 when compared to BAU levels.

In per capita terms, these measures have the potential to 'peak' Beijing residential per capita emissions in 2016 and to significantly reduce the per capita growth of emissions in Shanghai.

While this evidence is directly applicable in Beijing and Shanghai, it adds to a wider evidence-base that highlights the untapped potential for decarbonisation in different cities and the social, economic and environmental benefits that could emerge from their exploitation. Unlocking these opportunities may not be straightforward – political commitment and innovative policy intervention are likely to be needed – but this study has highlighted the potential for low carbon initiatives in the residential sector in Chinese megacities to make a substantial contribution to global climate mitigation efforts.

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