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PUBLISHED ONLINE: 18 SEPTEMBER 2017 | DOI: 10.1038/NCLIMATE3373
nature climate change

Urban cross-sector actions for carbon mitigation with local health co-benefits in China

Anu Ramaswami[1]*, Kangkang Tong[1], Andrew Fang[1], Raj M. Lal[2], Ajay Singh Nagpure[1], Yang Li[3], Huajun Yu[3], Daqian Jiang[4], Armistead G. Russell[2], Lei Shi[3], Marian Chertow[4], Yangjun Wang[5] and Shuxiao Wang[3]

Cities offer unique strategies to reduce fossil fuel use through the exchange of energy and materials across homes, businesses, infrastructure and industries co-located in urban areas. However, the large-scale impact of such strategies has not been quantified. Using new models and data sets representing 637 Chinese cities, we find that such cross-sectoral strategies—enabled by compact urban design and circular economy policies—contribute an additional 15%–36% to national CO_2 mitigation, compared to conventional single-sector strategies. As a co-benefit, ~25,500 to ~57,500 deaths annually are avoided from air pollution reduction. The benefits are highly variable across cities, ranging from <1%–37% for CO_2 emission reduction and <1%–47% for avoided premature deaths. These results, using multi-scale, multi-sector physical systems modelling, identify cities with high carbon and health co-benefit potential and show that urban–industrial symbiosis is a significant carbon mitigation strategy, achievable with a combination of existing and advanced technologies in diverse city types.

Energy supply to support urban homes, businesses, industries, transportation, construction, water and waste infrastructure sectors is associated with >70% of global carbon (CO_2) emissions[1]. Further, fossil-fuel-related outdoor/ambient air pollution by fine particulate matter (<2.5 µm: PM2.5) contributes to more than 4.7 million premature deaths worldwide[2], a majority occurring in populous urban areas. Therefore, city strategies that reduce fossil fuel use have great potential to achieve both global carbon mitigation and local health protection goals. However, quantifying carbon and health co-benefits potential has been challenging for cities due to three main reasons, summarized below.

First, to quantify contributions toward global CO_2 emissions, individual cities are now including both territorial (direct) fuel use as well as transboundary CO_2 emissions embodied in supply chains that support their residential, commercial, and industrial activities through different footprinting perspectives[3]. Although CO_2 emissions footprints of several individual cities and a few city-typologies worldwide have been reported[4–6], quantifying total urban contributions toward national or global CO_2 emissions has been challenging[6], because we do not yet have energy-use and energy-supply data for all city activity sectors, for all cities in a nation, with attention to local specificity.

Second, the unique opportunities that cities provide for CO_2 mitigation through co-location of residential–commercial and industrial activities have not been fully assessed. Most CO_2 mitigation strategies modelled in global scenario models[7,8] and in individual cities[9,10] focus on energy efficiency within single sectors (for example, industry, power plants, transportation or building energy use)[8]. Although the role of urban co-location in reducing travel demand is recognized[7], uniquely urban cross-sectoral actions that advance system-wide energy efficiency by reutilizing 'waste' energy or materials across co-located homes, commercial buildings, industries and the various infrastructure sectors in cities, have not been quantified to date in energy futures models. These strategies, described by the term urban–industrial symbiosis[11,12] show much promise, particularly enhanced by recent technological innovations. Examples include advanced fourth-generation district heating/cooling systems[13,14] that enable efficient conveyance and use of presently unutilized low-grade industrial waste heat up to 30 km fence line distances[15] to heat and cool buildings in cities, energy exchanges across co-located industries[16], and strategic material exchanges such as substituting fly ash and steel slag for energy-intensive production of Portland cement used in construction[17–19]. Compact urban design and spatial urban infrastructure planning that supports district energy[15,20], along with circular economy policies[21], are essential for implementing such cross-sectoral symbiosis in cities, highlighting the unique urban nature of these strategies. Estimating fuel savings and CO_2 reductions from widespread adoption of these actions requires co-location data on homes, businesses and industry, as well as new energy- and material-exchange algorithms to estimate cross-sectoral symbiotic exchange potential in diverse cities of a nation, based on each city's unique mix of residential, commercial and industrial activities.

Third, CO_2 and PM2.5 co-benefits experienced by individual cities due to fuel-use reductions both within and outside the boundary, arising from city actions, are of interest. However, few models are available to address CO_2 and PM2.5 co-benefits at the city scale. The emerging co-benefits literature largely focuses on national-scale aggregate co-benefit estimation[22], with a few models evaluating fuel use, CO_2 and air pollution interactions at regional scales[23]. Of interest to cities is the distribution of CO_2 and health co-benefits across different cities in a nation; the exploration of transboundary CO_2 interactions from energy embodied in supply chains; and the inclusion of transboundary

[1]University of Minnesota, Twin Cities Campus, Minneapolis, Minnesota 55455, USA. [2]Georgia Institute of Technology, Atlanta, Georgia 30332, USA. [3]Tsinghua University, 100084 Beijing, China. [4]Yale University, New Haven, Connecticut 06520, USA. [5]Shanghai University, 200444 Shanghai, China. *e-mail: anu@umn.edu

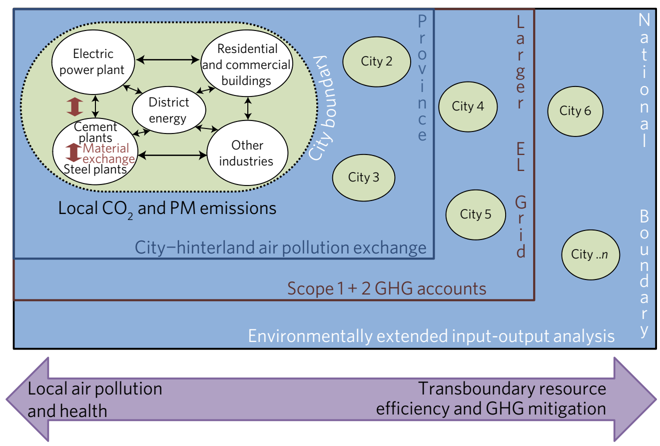

Figure 1 | Multi-scale modelling of linkages across intra-city, hinterland, provincial, grid region and national scales to assess local health and national CO_2 benefits of urban–industrial symbiosis. EL, electricity. Red arrows represent material exchange; black arrows represent energy flow linkages, including flows of electricity, heat or gas.

air pollution interactions—that is, the wind-blown transport of air pollutants between cities and their hinterlands[24].

Against this backdrop, this paper contributes by developing new data sets on all 637 cities of China, developing new algorithms to estimate symbiosis potential based on co-location data in diverse cities, and advancing multi-scale systems linkages across intra-city, city, hinterland and national scales to quantify decarbonization and health co-benefits of urban–industrial cross-sectoral interactions uniquely occurring in cities (Fig. 1). We seek to answer an often asked question—what is the individual and collective impact of city-scale actions on national decarbonization goals, and, what are the local PM2.5 pollution-related health benefits achieved in individual cities? Insights from this paper broadly inform sustainable urban designs in China and globally, where future urbanization–industrialization is expected to bring an additional 2.5 billion people to cities by 2050, primarily in Asia and Africa[25].

City-scale actions and co-benefits in Chinese cities

With China contributing ~27% of global anthropogenic CO_2 emissions, Chinese cities can be significant players in national (and hence global) CO_2 mitigation efforts. China's cities housed ~54% of China's population in 2014[26] and contributed >75% of the national gross domestic product (GDP)[27]. Further, Chinese cities are experiencing high levels of air pollution, with annual average ambient airborne PM2.5 concentrations[28] exceeding international guidelines[29], contributing to more than 4,000 pollution-related daily deaths in China[30]. China's commitments to the Paris Accord, along with clean air commitments, provide impetus for identifying urban strategies that simultaneously yield large carbon reductions and provide local health co-benefits[31].

Urban–industrial symbiosis strategies have been explored in a few recent city-scale energy-planning studies in China[14], and in the European Union (EU) wherein symbiosis-contributions toward decarbonization were found comparable to an efficiency-plus-renewables scenario that achieves 80% CO_2 reduction by 2050[32]. Urban–industrial symbiosis potential is likely to be substantial in industrial nations such as China, where 70% of national total fossil fuel use occurs in industry and power sectors that generate waste heat, compared to only 20% in the commercial–residential sectors[33] that could reuse such waste heat, maximizing exchange potential. District heating networks and eco-industrial parks that provide physical infrastructure to achieve cross-sectoral energy–material exchanges already exist in some Chinese cities[34], and can be made much more efficient. For example, low-grade heat that dominates industrial waste heat output has few applications within industry, but can effectively be used for space heating in advanced district energy systems recently implemented in the EU[13]. This strategy can beneficially apply vast amounts of low-grade industrial waste heat, presently unutilized in Chinese cities, displacing inefficient individual stoves and boilers that collectively are large PM2.5 emitters[35]. Similarly, although the adoption of eco-industrial parks has been increasing, much potential remains[17]; moreover, new technologies for cooling steel slag offer enhanced material–energy recovery pathways[36]. Thus, technology innovation and widespread implementation of urban–industrial symbiosis in China can contribute significantly to national decarbonization, while reducing fuel-related PM2.5 emissions. To quantify these impacts we implement a methodology summarized briefly below. (Details are in Methods.)

To quantify the collective contribution of urban-scale actions toward national CO_2 mitigation, we develop a new and comprehensive Chinese City Industry-Infrastructure (CCII) database that represents energy use in co-located homes, businesses and industries—for all 637 cities in mainland China in the Year 2010, in a manner that is consistent with national total energy use and CO_2 emissions (Supplementary Figs 1 and 2 and Supplementary Table 1), along with location-specific information on energy generation systems, that is, power plants and local city heating systems.

Energy-cascading and material-exchange algorithms are developed in conjunction with the CCII data set to quantify the potential for urban–industrial symbiosis in individual cities utilizing co-location data. Energy-cascading algorithms (Supplementary Figs 3 and 4) match high-, medium- and low-grade industrial waste heat[16] generated from specific industries in each of the cities (modelled after case studies noted in Supplementary Table 3a), with suitable reutilization 'sinks' available in those cities, including advanced district energy systems that reutilize low-grade heat in homes and commercial buildings[13,37]. Two dominant material-exchange pathways are also modelled wherein waste materials from steel- and power plants[17–19,38,39] displace cement use in construction, motivated by China's massive annual cement use[40]. Other potential material exchanges are not evaluated. This yields a conservative first-order estimate of cross-sectoral urban–industrial symbiosis potential in Chinese cities, beyond reuse levels already occurring in 2010 (see Tables 1 and 2). Because cross-sectoral symbiosis potential decreases when individual sectors become more efficient, urban cross-sectoral symbiosis scenario strategies (Table 2) are modelled after applying conventional single-sector efficiency actions nationwide in buildings, power plants, cement, steel, and other sectors, assuming near-term efficiency targets specified in China's Five-Year Plan (FYP 2010–2015) are achieved[41] (Table 1). This is referred to as the FYP-Efficiency-plus-Symbiosis scenario. We also evaluate cross-sectoral potential if higher levels of single-sector efficiency were to be achieved, comparable with international best practices (Supplementary Information 2; the High-Efficiency-plus-Symbiosis scenario). Both scenarios represent a What-If analysis, comparing single-sector versus cross-sector actions if implemented in the short term (2010–2015 period) across all the cities. We do not model futures because modelling each city's future population-economic trajectory is not possible. Rather, we analyse What-If scenario impacts for the Year 2010 in different city typologies[42], comparing highly industrial, highly commercial and mixed-economy Chinese cities to gain insight into the impacts of future economic transitions in cities (that is, from industrial to commercial) on symbiosis potential.

Multi-scale linked models are implemented to represent system-wide fossil fuel reductions arising from the scenario actions: applying single-sector efficiencies nationwide, and cross-sectoral urban–industrial symbiosis actions only in cities. The resulting fuel-use reductions and associated CO_2 emissions reductions occur at different geographic scales, both within and outside city

Table 1 | Reductions in China's national energy use and CO_2 emissions in the What-If FYP-Efficiency-plus-Symbiosis scenario case relative to the 2010 Base-Case: Impact of conventional single-sector strategies from China's 2010–2015 five-year plan (FYP).

Sector (production or primary energy use); tonnes of coal equivalent (tce)	China's energy use (%)	Energy intensity reduction: Base-Case to China's FYP	Resource use reduction: Base-Case to China's FYP (%)	CO_2 reduced: 10^6 metric tonnes (mt)
Steel (582 million mt crude steel and 593 million mt pig iron produced)	10	0.572 to 0.527 tce per t steel	15 electricity, 6.5 thermal energy	66.3
Power plant (3,144 TWh generated)	34	500 to 450 g coal kwh^{-1}	10	341.6
Cement (1,856 million mt produced)	4.6	0.163 to 0.15 tce per t cement	5 electricity, 10 thermal energy	44.3
Buildings energy for heating and cooking (262 million tce for heating; urban residential and commercial floor area: 29 billion m^2)	12.6 (8% for heating)		5–15 thermal energy	11.6
Industrial boiler (506 million tce)	15.9	75% to 82.5% (efficiency improved)	10 thermal energy	93
Other key industrial sectors (325 million tce)	10	Varies by industry (see Supplementary Information 3)	7–40	197
Total single-sector reductions (as a percentage of China's 2010 GHG of 8,800 million metric tonnes)				754 (8.6%)

Energy use is shown in different forms such as electricity (TWh), thermal energy and primary energy use (in unit of ton coal-equivalent (tce)).

Table 2 | Reductions in China's national energy use and CO_2 emissions in the What-If FYP-Efficiency-plus-Symbiosis scenario case relative to the 2010 Base-Case: Impact of additional cross-sector urban–industrial symbiosis strategies.

Strategies	Technology pathways and assumptions	CO_2 reduced: 10^6 metric tonnes (mt)
High-grade waste heat (>400 °C) to electricity* (generates 14.6 TWh)	Commercially available Organic Rankine Cycle (ORC) to convert high-grade waste heat to electricity at 15% efficiency[49] to displace grid electricity production	14.5
Medium-grade waste heat (100–400 °C) to other industries and district energy system (overall savings 6.2 million tce in industrial sector, 7.3 million tce in current district heating systems serving 4.4 billion m^2, and generates 12.6 TWh electricity)	Cascade 1*: Heat is first applied to food/beverage and other low temperature industries	19.6
	Cascade 2: Remaining heat is reused in current district heating system to displace heating fuel use	22.9
	Cascade 3*: Heat displaces electricity via ORC	12.5
Low-grade waste heat (<100 °C) to new district energy systems (Savings 48.3 million tce in 8.8 billion sq m floor area)	Heat is applied in new 4th generation district heating systems circulating low temperature hot water (30–70 °C) to energy efficient buildings only in the urban core of cities	152
Material exchange—fly ash from power sector to cement (avoids 54 million mt cement production†)	Fly ash reuse beyond current provincial reutilization rates (50–90%) to achieve 35% saturation of fly ash by mass in cement	9.2
Material exchange—steel slag to cement (avoided 170.14 million mt cement production[2]; generates 19.57 TWh electricity)	Steel slag from dry slag granulation reutilized to displace cement up to 25% by mass plus waste heat to electricity	39.4
Additional total cross-sectoral reductions (as a percentage of China's 2010 GHG of 8,800 million metric tonnes)		270.1 (3.1%)
Unutilized low-grade waste heat	Can displace heating fuels in future 4th generation district heating systems. Range indicates fuel displaced: coal (high CO_2 savings) or natural gas (lower CO_2 savings)	120–203

Energy use is shown in different forms such as electricity (TWh), thermal energy and primary energy use (in unit of ton coal-equivalent (tce)). *Denotes the category of heat exchange across industries in Fig. 2, which includes high-grade waste heat to electricity, medium-grade waste heat to industrial sinks and to generate electricity (Cascade 1 and 3), and yields total CO_2 reduction of 46.6 million mt. †Computed as the cement displaced at the provincial level. This strategy is assumed to be stimulated by demand for (urban) construction, where waste materials displace cement in concrete.

boundaries (see Fig. 1 and Supplementary Fig. 3). Transboundary air pollution modelling tracks air pollution dynamics between cities and their surrounding hinterland areas; both of which are impacted (although not equally) by system-wide fossil fuel reductions from single- and cross-sector urban actions. Transboundary pollution modelling is important because even if cities reduce fuel combustion and corresponding PM2.5 emissions within their boundaries, their local airborne PM2.5 concentration can be affected by wind-blown transport of PM2.5 from surrounding polluted areas into cities, and vice versa. Health benefits, that is, premature deaths avoided due to reduction in PM2.5 concentration in each individual city, are computed by applying concentration-response functions[43] to the age-distributed population of that city.

Thus, this paper develops and implements a multi-scale integrated systems modelling approach that quantitatively connects diverse human activities in cities (single sector, cross-sector, use and production) with multi-scale fuel-use reductions, carbon mitigation models, PM2.5 atmospheric transport models, and health risk

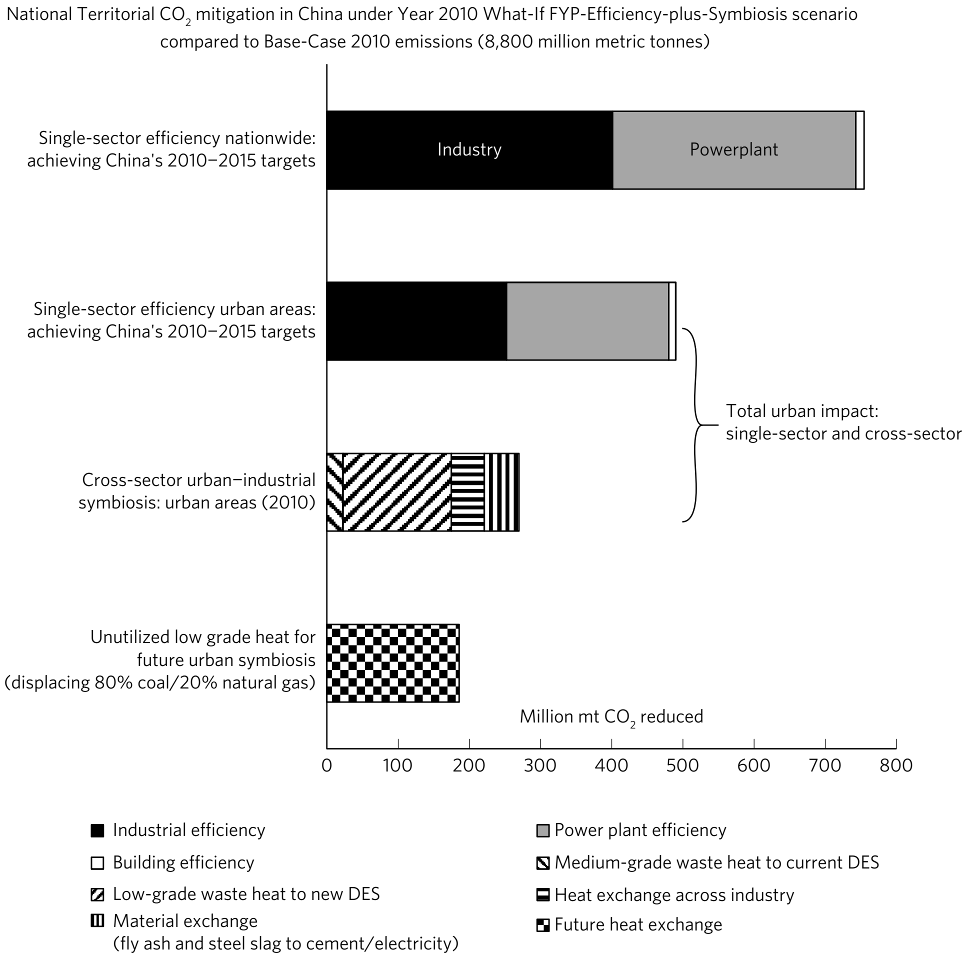

Figure 2 | National territorial CO_2 emissions reduction potential in China disaggregated by single-sector efficiency based on China's 2010–2015 FYP targets, and cross-sectoral urban–industrial symbiosis interventions, including reuse of heat in current and advanced district energy systems (DES). Note material exchange relevant to construction (assumed predominantly urban construction) is modelled to reduce cement production evenly at the provincial scale.

assessments across a large number of cities, coherent with national data. The multi-scale linked modelling (Fig. 1 and Supplementary Fig. 3) spans geographic scales from the sub-city, city, provincial, electricity grid scale to the national scale, contributing to carbon–air pollution–health nexus assessment methodologies, and to sustainable urban system science (see further discussion in Methods). While demonstrated in China, the systems approach is broadly relevant to all cities and nations, globally.

Results

The bottom-up CCII data set effectively represents co-location of energy use in multiple sectors along with energy generation systems in 637 diverse Chinese cities, consistent with China's national energy balance statistics (Supplementary Table 1). Total national CO_2 emissions for the Base Year 2010 were ~8,800 million tonnes CO_2, in the range reported by others[44].

Direct territorial CO_2 emissions (Scope 1) from the 637 cities add up to 62% of China's total CO_2. Direct CO_2 emissions of cities are correlated with city populations ($R^2 = 0.612$) and with city GDP ($R^2 = 0.611$), and hence are spatially distributed in patterns corresponding with urban population centres in China. Classifying cities by economic structure[42], 14% are highly commercial (tertiary GDP share >49.1% of total city GDP), 13% are highly industrial (secondary GDP share >64.4%), and the rest are mixed industrial–commercial cities. Industrial cities, on average, exhibit much higher direct CO_2 emissions intensity (0.37 kg-CO_2/yuan), compared to commercial (0.2 kg-CO_2/yuan) and mixed-economy cities (0.25 kg-CO_2/yuan), identifying such cities as hotspots for symbiosis interventions. Among the 637 cities, 73% are net importers of electricity, reinforcing the need for transboundary multi-scale modelling of CO_2 mitigation accomplished in this paper.

CO_2 Mitigation potential in the What-If FYP-Efficiency-plus-Symbiosis scenario is shown in Fig. 2. China's 2010 five-year plan (FYP) single-sector efficiency targets (Table 1), applied across all industries and aggregated nationally, assuming they are fully met, yield ~9.0% (754 million tonnes (Mt)) CO_2 mitigated compared to the 2010 baseline, of which 65% (490 Mt) occurs geographically within cities. Urban cross-sectoral symbiosis interventions evaluated in this paper (Table 2) contributed an additional 3.1% (270 Mt) reduction of national CO_2 emissions (Fig. 2). This represents an additional 36% (270 Mt) CO_2 emissions reductions compared to the national single-sector FYP-efficiency strategies (754 Mt), revealing co-location enabled urban–industrial symbiosis to be an important decarbonization strategy that should be incorporated into future energy models. Further, energy use for heating of residential–commercial buildings can be fully supported by co-located industrial waste heat sources in as many as 192 Chinese cities. Significant low-grade waste heat remains unutilized, available to heat/cool future new buildings. Low-grade waste heat reutilization in advanced district energy systems emerges as a dominant contributor to symbiosis (Table 2); such low-grade heat dominates industrial waste heat output[37], for which urban buildings are an ideal sink. Material-exchange contributions (Fig. 2) appear relatively small, because of the significant material exchange already practiced in China[17] (incorporated in our Methods). Additional customized inter-industry material exchanges in individual cities may offer further benefits, not quantified here.

If China were to achieve international best practice industrial efficiency (Supplementary Table 2) in individual sectors in 2010 (What-If High-Efficiency-plus-Symbiosis scenario), single-sector savings relative to the Base-Case almost double (from 754 Mt to 1,476 Mt CO_2), while the impact of urban cross-sectoral strategies decreases when compared to the Chinese Five-Year Plan (FYP) Efficiency-plus-Symbiosis scenario (Fig. 2) because less waste heat is available for exchange, although this still contributes an added 14.9% (218 Mt CO_2) mitigated relative to the single-sector savings (1,476 Mt CO_2) (Supplementary Fig. 9). Thus, going forward, even with high levels of single-sector efficiency, sufficient waste heat would be available in China to support urban–industrial symbiosis.

Individual Chinese cities showed wide variation (<1% to 37%) in direct CO_2 emission reductions in the What-If FYP-Efficiency-plus-Symbiosis scenario versus the 2010 Base-Case (Fig. 3a). Fuel reductions from heat exchange are largest in cities where sources of waste heat are balanced by sectors that can utilize the waste heat (Fig. 3b; the peak occurs where the ratio of heat sources to sinks is nearly 1 on a logarithmic scale), thus providing a heuristic to identify those cities best suited for symbiosis; this potential is also impacted by climate zones (significance level, $\alpha = 0.001$) that determine heating–cooling needs. Comparing city types, the average CO_2 reduction was only slightly higher in industrial cities (15.3% ± 5.7% (s.d.)) compared to 9.9% ± 5.5%, and 11.3% ± 5.6% in highly commercial, and mixed-economy cities, respectively, indicating urban–industrial symbiosis remains promising even with changes in the economic structure of cities in China, as are expected to occur in the future.

PM2.5 impacts and health benefits: total Base-Case annual average PM2.5 emissions from all sectors (excluding agriculture) normalized per unit geographic area ranged from <1 to 30.6 g m^{-2} yr^{-1} across cities and are in the range reported by others[45]. The modelled airborne PM2.5 concentrations (μg m^{-3}) in the Year 2010 Base-Case were within the range of those measured in Chinese cities[28], illustrating the model results are reasonable. Aggregated across urban China, the health benefits—that is, the overall reduction in premature deaths per year in the What-If FYP-Efficiency-plus-Symbiosis scenario compared to the Base-Case—are 47,230 (+10,240/−21,874) deaths per year. This estimate is probably conservative as we do not consider secondary PM2.5 formation from gaseous SO_2 and NO_x emissions from industries that would be similarly reduced by the efficiency and cross-sector (material and energy) symbiosis strategies assessed in the scenario versus Base-Case.

The spatial distribution of carbon versus health co-benefits across the individual cities yields interesting results. We find the percentage reductions in spatial PM2.5 emission intensities (PM2.5/area) across the 637 cities, in the Base-Case versus scenario case, are tightly correlated ($R^2 = 0.90$), with reductions in spatial CO_2 emission intensities in the cities, both linked to fuel-use reductions (Supplementary Information 2). Reductions in PM2.5 concentrations in air (and hence avoided premature mortality) are less correlated with reductions in PM2.5 emission intensities ($R^2 = 0.65$), because of transboundary air pollution dynamics with the rest of province (see Supplementary Table 6b). Because of such air pollution dynamics, along with differing population age structures across the 637 cities, only 175 cities experienced both above-average CO_2 benefits and above-average health benefits in our model (Fig. 4a). This is an important and counter-intuitive result, important for co-benefit analysis, that cities may achieve high

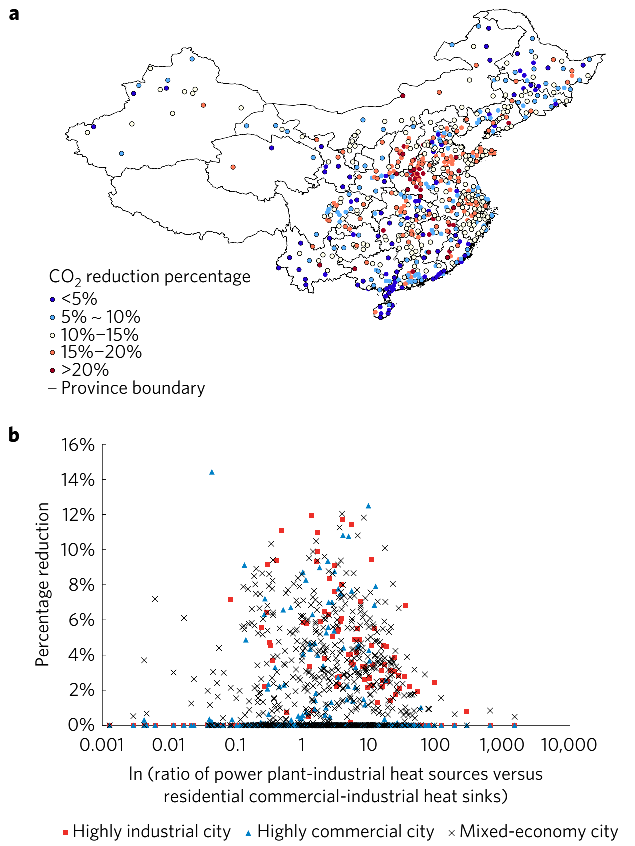

Figure 3 | Direct CO_2 mitigation potential across 637 cities in mainland China. a, City CO_2 percentage reduction in What-If FYP-Efficiency-plus-Symbiosis scenario compared with the Base-Case across cities in mainland China. **b**, City CO_2 percentage reduction by heat exchange only, for different city typologies by economic structure: highly industrial (red), highly commercial (blue), and mixed-economy cities (black). Cities with high or low ratio of heat sources versus sinks show reduced CO_2 reduction through energy exchange strategies.

levels of CO_2 mitigation (as a percentage relative to the Base-Case), but may not necessarily experience commensurate high levels of premature deaths avoided. Simplified modelling approaches such as those in this paper can help identify such dynamics.

The spatial distribution of cities with both above-average health and above-average CO_2 benefits (High–High), those with below-average health and below-average CO_2 mitigation (Low–Low), and the remaining cities (High-carbon and Low-health, and Low-carbon and High-health co-benefits), is illustrated in Fig. 4b. If the absolute magnitude of CO_2 mitigation and premature deaths avoided are of interest (rather than percentage reductions), the population centres show the highest benefits (Supplementary Fig. 8a,b)—with the megacities (>10 million in population) contributing 8.3% of the urban total CO_2 mitigation and experiencing 28% of the reduction in air pollution-related premature deaths.

Discussion

Achieving timely and deep decarbonization to meet our world's climate goal to keep warming below 1.5 °C is expected to be challenging, with several futuristic technologies for negative carbon emissions being considered[46]. Yet, uniquely urban cross-sectoral strategies that cities offer today for decarbonization, as well as local health co-benefits, have not been integrated in international assessments because their analysis requires co-location information, urban–industrial symbiosis algorithms, and multi-scale carbon, air pollution, and health risk models. Applying a novel multi-

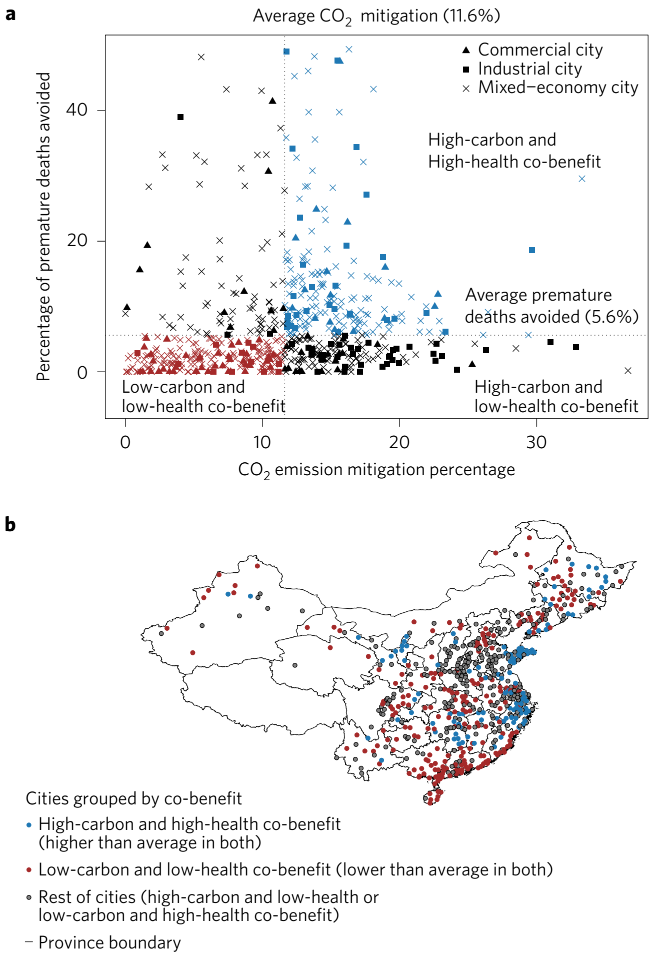

Figure 4 | Carbon mitigation and health co-benefits across 637 cities in mainland China. Cities with different levels of co-benefits in percentage reduction of CO_2 and percentage reduction of premature deaths in the What-If FYP-Efficiency-plus-Symbiosis scenario versus 2010 Base-Case: above-average co-benefit in both outcomes shown in green, below-average co-benefit shown in brown, and the remaining cities shown in black (in **a**) or grey (in **b**). **a**, Quadrants show different levels of co-benefit by percentage reductions and city type. **b**, Map of cities in mainland China showing spatial distribution of cities by co-benefit criteria. (Both maps in Fig. 3a and Fig. 4b are used as the illustration of cities in mainland China, not as the standard territorial map of China.)

scale urban systems model to a new CCII data set, we show that co-location-dependent urban–industrial symbiosis is a significant and previously unquantified pathway for CO_2 mitigation in China, achievable with a combination of existing and advanced technologies in diverse city types. The analysis highlights the importance of reutilizing low-grade waste heat in cities, and enabling key material-exchange strategies relevant to the construction sector. Urban–industrial symbiosis may complement the emerging electrification strategy for deep decarbonization in China that anticipates a renewable-electricity future[47]; more study is needed to integrate the role of heat networks in electricity and energy transitions.

We develop an algorithm to estimate the magnitude of the CO_2 mitigation arising from urban–industrial symbiosis in different cities, and a coupled city–hinterland carbon footprinting plus air pollution modelling approach to identify those cities where carbon and health co-benefits are synergistic. Given that many symbiosis strategies are commercially available and offer a relatively short return on investment[32,37], the added benefits to human health provide significant impetus to support sustainable multi-sector urban energy and infrastructure planning in cities to advance human and environmental well-being.

Implementing urban–industrial symbiosis will require urban spatial infrastructure planning that supports mixed uses and high intensity of development, that is supportive of energy and material exchanges, relevant to future cities in China, as well as other world regions where massive new urbanization and industrialization are expected to co-occur[25]. Several policies in China support such urban–industrial symbiosis and may be adapted to other world regions. For example, China's national circular economy policies promote eco-industrial parks[21], which are also reinforced in air pollution action plans[48]. Recently enacted urban planning guidelines support district energy with waste heat reutilization[20]. Additionally, policies that provide renewable energy credit for waste heat reuse in heating networks, on par with waste-to-electricity projects, can also create balanced incentives. A combination of multi-scale, multi-sector physical infrastructure systems modelling as accomplished in this paper, along with multi-level governance is critical to achieve future energy transitions that connect materials, waste, heat and electricity in unified sustainable futures models, recognizing cities as critical foci of change.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

Received 14 December 2016; accepted 25 July 2017; published online 18 September 2017

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Acknowledgements
This work was supported by a NSF Partnerships in International Research and Education grant (PIRE-1243535), Tsinghua University Initiative Scientific Research Program (No. 20121088096), and National Science Foundation of China (21625701). We thank M. Ahern and P. Bourne of Evergreen Energy (Saint Paul, Minnesota) for reviewing the district energy scenarios. We thank H. Shen for reviewing the results of air pollution modelling. We also appreciate G. Chan's comments on this paper.

Author contributions
A.R., L.S., M.C., A.F., K.T., Y.L. and D.J. designed the urban energy and material-exchange interventions; R.M.L., A.S.N. and A.G.R. implemented the air pollution and health risk models. A.R., K.T., Y.W., S.W., L.S. and Y.L. developed the city infrastructure database; L.S. and Y.H. developed the China industry waste heat case studies. A.F. and K.T. implemented scenario modelling. A.R. led the writing and data checks, and K.T. led data coordination across nations and graphics.

Additional information
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Competing financial interests
The authors declare no competing financial interests.

Methods

The methodology is implemented in five steps (a)–(e).

(a) Development of Chinese City Industry-Infrastructure (CCII) database. This database brings together detailed city-specific data on electricity use (by residential, commercial and multiple industry sectors), along with detail on energy supply and heat distribution for all 637 cities of China, including 280 city propers (Shiqu) and 357 county-level cities (Xianji Shi). The CCII data set includes location-specific, at-scale city data for a number of parameters including: (A) Economic and Demographic Data: population, number of households (including those located in the urban core of cities), city GDP categorized into primary, secondary and tertiary categories, helpful for classifying cities by economic structure, and, employment by industry two-digit and four-digit sectors from the China Industrial Enterprise Database[50–52]; (B) Environmental data: Heating/cooling degree days; (C) Electricity Use: Total use, and, disaggregated into residential and industrial use[52]; (D) Non-electricity fuel use in three key industrial sub-sectors (power plants, cement, and steel plants) along with respective combustion technologies, sourced from an air pollution database assembled by the authors[53–60], with the individual power plants and factories mapped to specific cities and to the rest of province (ROP), based on their location, to provide total fuel use in cement, steel and electricity production units in cities and in the hinterland areas for each of China's 31 provinces; (E) Non-electricity fuel use for heat supply in current local district energy systems in each city sourced from ref. 61, providing detail on the heat supply and distribution network area, and current coverage levels.

Remaining data not found at scale for the cities, such as thermal energy (non-electricity) fossil fuel use in the 13 additional key industry sectors, were downscaled from national industrial energy-use statistics[62], using local employment data from ref. 50. By comparing at-scale industrial electricity use data available for a subset of these cities (280 Shiqu) with the downscaled industrial electricity obtained from our methods, we estimate the (likely) error of downscaling thermal energy use for the 13 smaller industry sectors to be of the order of 20% (see Supplementary Fig. 1; $R^2 = 0.8$), assuming downscaling errors are the same for both electrical and thermal energy use. Likewise, household non-electricity fuel-use activities and associated technologies were also downscaled from provincial energy-use profiles provided in the Tsinghua University database[59,60]. The downscaling approach was evaluated for coherence by assessing the degree of correlation between downscaled and at-scale electricity use data available for a subset of cities, and were found to be consistent with R^2 of 0.9 for residential electricity use (Supplementary Fig. 2).

Aggregation and Coherence with National Data. Overall, the bottom-up CCII data set when added up to the national total agreed well with China's national energy balance statistics (with <1% difference in fossil fuel used; Supplementary Table 1). Differences within the sub-categories were due to different accounting categories noted also by other researchers, and representing residences of industry workers as industrial energy use[63,64]. For example, Zhou and Lin[64] indicate that the apparent sectoral discrepancy between bottom-up and China's national statistics arises because 'End-use fuel consumption in China is recorded by the sector in which the consumption occurred, not by the purpose for which it was used.' Further, 'a work unit (or, danwei) is the place of employment, and also the living quarters. Many residential and commercial energy uses associated with industrial enterprises or plants have thus been reported as industry energy use.' Their year 2000 study resulted in reallocating sectoral energy use, with commercial and residential fuel-use allocations increasing (with commercial by about 40% when comparing bottom-up with top-down) and industry decreasing, similar to what we report in Supplementary Table 1. The sectoral sub-totals therefore show apparent differences due to classification differences; the national totals are coherent across the approach we have used and the national data. Total national CO_2 emissions for the base Year 2010 in our model were ~8,800 million tonnes CO_2, in the range reported by others (for example, ref. 44).

(b) What If scenario modelling. A What-If scenario modelling approach is undertaken where it is assumed single-sector efficiencies, followed by cross-sectoral energy-cascading and material-exchange strategies (see Table 1 in main text), are applied to the year 2010 data for all 637 cities. Such an approach is taken because it is not possible to predict the future evolution of all 637 cities in terms of the mix of industries and residential and commercial sectors. However, the 637 modelled cities include industry-dominated cities, balanced cities (with both industries and commercial) and commercial-dominated cities[65]. Energy-saving outcomes for these different city typologies by economic structure in the 2010 What-If scenario provide insight into how future evolution of city economies shapes waste reutilization potential.

Two different What-If Scenarios are evaluated, the first with single-sector efficiencies modelled to achieve Chinese Five-Year Plan (FYP) targets, followed by cross-sectoral symbiosis (referred to as What-If FYP-Efficiency-plus-Symbiosis), and a second where single sectors achieve high-efficiency targets specified in international best practices for each industry (referred to as a What-If High-Efficiency-plus-Symbiosis scenario). The single-sector efficiencies in the FYP and the High-Efficiency scenarios are compared in Supplementary Table 2.

(c) Cross-sectoral symbiosis modelling though energy cascading and material exchange. Supplementary Fig. 3 illustrates the energy-cascading and material-exchange processes modelled in cross-sectoral symbiosis, demonstrating their application at different spatial scales (sub-city, city, province, grid region), and their coherence with national data.

For energy cascading, we first estimate waste heat generation as a percentage of the primary fuel inputs to each industrial sector located in a city based on the known characteristics of each industry detailed in the CCII database, and, drawing upon Chinese industry case studies collected by the authors (Supplementary Table 3a). The recoverable industrial waste heat is categorized into high-grade (>400 °C), medium-grade (100–400 °C), and low-grade (<100 °C) heat[16]. All (100%) high-grade heat, 80% of low-grade heat, and only 25% of medium-grade heat are assumed to be available for exchange due to corrosion concerns from sulfur-containing medium-grade heat (Bourne P. and Ahern M. Personal Communication Evergreen Energy, United States (2016)).

Energy cascade algorithms. These represent a series of exchanges (A–E) and associated fossil fuel displacements (see Supplementary Fig. 4): (A) high-grade heat to electricity using Organic Rankine Cycle (ORC) engines[49] at 15% efficiency, displacing coal used in thermoelectricity generation. (B) Medium-grade waste heat (100–400 °C) to four heat 'sink' industries (food and beverage, textiles, pulp and paper, chemical) as detailed in Supplementary Table 3b and displacing primary fuels. (C) Any remaining medium-grade heat (100–400 °C) to Conventional District Energy systems (DES), displacing primary heating fuels that produce steam and hot water use in existing centralized DES (see ref. 37). Any further remaining medium-grade heat waste heat was modelled to convert to electricity via ORC engines, similar to high-grade heat to electricity. (D) Low-grade waste heat (<100 °C) to Advanced Fourth-Generation District Energy Systems (DES) in the urbanized core area of cities not already covered by DES, and displacing primary fuel used in individual household stoves and boilers in the baseline Year 2010 case. (E) Unutilized low-grade heat: Any low-grade waste heat that remains is noted as being available to meet heating and cooling needs of future new residential–commercial buildings in the Chinese cities.

Material-exchange algorithms. This focused on two select material-exchange strategies across industrial and urban construction sectors: incorporating waste fly ash from power plants into the cement and/or brick-making sectors; and using dry-granulated blast-furnace slag, produced from an advanced technology recently taken to scale in the Chinese steel industry, ground up with cement clinker to produce high-performing cements[18,19,38].

Different pathways for material exchange were evaluated, without double counting the fly ash reutilization already occurring in China, summarized in Supplementary Table 4. Our What-If scenario did not count existing reutilization, that is, we assumed only (one minus the existing reutilization rate, as a percentage) was available for exchange. For the new dry ground glass granulation process, we assumed the dry slag granulation process did not occur in China in 2010, because the new technology was commercially piloted at scale in 2015[19]. We also incorporated saturation, using a conservative 25% level as the maximum percentage of waste material that can be incorporated per unit of ordinary Portland cement produced[66,67]. Therefore, in many ways, we under-estimate the potential for energy recovery and material exchange from the steel slag process—that is, the market for the steel slag could grow beyond the limited 25% reuse as a cement substitute. These pathways are unknown. We model material-exchange potential conservatively with respect to the above reuse rate and saturation constraints.

(d) Estimating reductions in fuel use, CO_2 and PM2.5 emissions at different scales. Heat exchange was modelled to yield direct reduction in fuel combustion transforming to direct (Scope 1) CO_2 and PM2.5 emission mitigation within a city boundary, with emission factors from various sources derived from refs 33,68–71. Strategies that reduce the electricity demand of a city were modelled to have an impact on the entire grid region that the city was housed in—with the percentage reduction arising from all cities within a grid region assumed to apply equally to all generators (power plants). All but one of China's six grid regions have a net electricity import–export balance <2% of internal generation[53], indicating the suitability of the grid-scale aggregation and analysis. The exchange of steel slag and fly ash was assumed to be commercially viable at the provincial scale. As a comparison, fly ash markets in the US are such that fly ash is profitably shipped from Texas to Colorado by railroad. The provincial scale in China for waste exchange thus yields a conservative estimate of symbiosis potential.

Fuel use, CO_2 and PM2.5 emissions reductions from avoided electricity are calculated based upon the grid average heat rate (450 g kWh^{-1}) after applying power sector efficiency increases described in Table 1 and Supplementary Table 2. We apply CO_2 emissions factors (2,200 g CO_2/kg coal) for coal combustion obtained from IPCC[68] and author's calculations of the average PM emission factor (0.551 g PM2.5/kg coal) across coal-fired electricity generators (>6 MW) based on each plant's coal use and technology reported in the Tsinghua data set, respectively. All PM2.5 emission factors are summarized in Supplementary Table 5a, including for power plants, steel, cement and other industries and industrial boilers. Methods used to compute fuels displaced from waste heat applied in current and advanced conventional centralized DES, displacing coal and gas used in centralized boilers, and in individual stoves/boilers, respectively, are detailed in ref. 37 for two provinces of China. In all cases, carbon and PM2.5 savings associated with direct primary fuel savings are computed using fuel combustion GHG emission factors from IPCC[68] and PM2.5 emission factors based on technology and fuel features of China (summarized in Supplementary Table 5b).

A life-cycle analysis (LCA) was conducted to assess the GHG impact of investments in new heat-exchange infrastructure (needed for the new district energy systems, DES), and was evaluated through a national-economy-wide economic input–output-based LCA (EIO-LCA), and found to be very small compared to direct fuel savings (less than 0.5% of CO_2 emissions from current fuel use for heating[37]).

We also explored the impact on fossil fuel savings due to potential seasonality of waste heat availability versus when it is used. For combined heat and power, the proportion between heat and electricity is continuously adjusted over the year, and hence the annual total incorporates this impact. For other sources of waste heat, a sensitivity analysis assumed available waste heat could be used only 40% of the year. It is found the CO_2 mitigation potential of cross-sectoral strategies in the What-If FYP-Efficiency-plus-Symbiosis scenario (Fig. 2 in main text) decreases from 270 to 243 million metric tonnes (that is, by 10%) when such seasonal effects are applied. Most of this reduction was seen in existing DES using medium-grade heat. Low-grade heat, being plentiful, is still available for reutilization should these systems be upgraded to more efficient advanced district energy systems. Thus, we retain our current estimate of the waste heat reutilization potential, recognizing it is a first-order estimate, and also a conservative estimate that does not include waste heat use in building cooling applications (found favourable in ref. 37) or industrial waste heat exchange beyond the four sink industries modelled here, or greater levels of ground-granulated steel slag substitution in cement (25% is very conservative).

(e) PM2.5 Pollution and health benefit calculations. Reductions in fuel use in the What-If FYP-Efficiency-plus-Symbiosis scenario yield direct PM2.5 emissions reductions within and across city boundaries in the Base-Case versus scenario case. Total Base-Case annual average PM2.5 emissions in the cities from all sectors (excluding agriculture) normalized per unit geographic area ranged from <1 to 30.6 $g\,m^{-2}\,yr^{-1}$ across the 637 cities. Our model uses location-specific details on the major industrial emitters—power plants, cement and steel factories—and downscales fuel combustion in the remaining smaller industrial sector activity based on employment data in the different cities; the fuel-use error for which is about 20% (see Supplementary Fig. 1). Comparisons of our modelled PM2.5 emission fluxes with those computed by other studies for 25 cities in the Yangtze river delta[45] showed fairly good agreement ($R^2 = 0.64$, slope = 0.94 in Supplementary Fig. 5). Differences in methods account for variations in estimating the industrial sectors in cities; also, our model does not include agricultural emissions as they are typically small in urban areas.

PM2.5 emission reductions within and outside city boundaries due to the efficiency-plus- symbiosis actions, along with wind-blown transport of PM2.5 to and from the rest of the province, are modelled using AERMOD[72], yielding simulated impacts on airborne primary PM2.5 concentrations in each city. AERMOD does not treat nonlinear chemistry, and we did not consider impacts from secondary PM2.5 formation, so the actual reductions are probably higher. AERMOD has an advantage over coarse-grid chemical transport models because, as a Lagrangian Gaussian plume model, it does not suffer from numerical diffusion, so it will capture fine-scale increases that would be artificially smoothed when using a grid model with horizontal grid sizes similar to or larger than the city itself (in this analysis, from ~10–100 km). Because spatial detail on the location and elevation of pollution sources (that is, boiler, factories, power plants, and roads) with respect to people within each city were not available for all 637 cities, annual average PM2.5 spatial emission intensities were applied within each city and in the rest of province (ROP) in the AERMOD approach. This approach is appropriate to explore sensitivity of primary PM2.5 concentrations to multi-scale impacts of urban actions, and to explore interaction of emissions within the city and the rest of the province (that is, the hinterland areas). With these caveats, the modelled PM2.5 concentrations in the Year 2010 Base-Case were within the range of measured PM2.5 concentrations reported in 112 Chinese cities[73]. The health benefit, that is, the premature deaths avoided due to reduction in PM2.5 concentration in the city were computed by applying concentration-response functions from ref. 43 to the age-distributed populations in each of the cities. Such infrastructure linkage to fuel-use reduction, CO_2 mitigation, air pollution, and health risk modelling helps broadly understand which cities may expect to reap the health benefits from their local carbon mitigation actions, and in which cities the carbon and health co-benefits will not be aligned and synergistic due to transboundary atmospheric dynamics.

In summary, this paper develops new multi-scale modelling methodology that quantitatively connects the human activities in cities (single sector and cross-sector) with multi-scale fuel-use reductions, carbon mitigation models, PM2.5 atmospheric transport modelling, and health risk assessment across a large number of cities. The modelled multi-scale interactions (Fig. 1 in main text and Supplementary Fig. 3) include cross-sectoral energy exchanges implemented at multiple scales—ranging from sub-city, city, provincial and electricity grid scale. Material exchange and air pollution modelling is implemented at the provincial and city scales, representing interactions among multiple cities and the hinterland. As described and applied, the multi-scale linked models developed in this paper are unique and a new contribution to urban system science. The modelling in this paper implements a Social–Ecological–Infrastructural Systems framework[74] that goes beyond currently available urban modelling ontology, that may focus on energy models, largely within a city/boundary. Here we include symbiosis with material and energy exchanges occurring across sectors at multiple scales, connect energy use systematically across city, provincial, grid and national scales, and further, connect with air dispersion modelling. Such modelling has not previously been integrated—although individual models have been used in different applications, for example, air pollution dispersion models are well known but have not been linked to multi-scale infrastructure and carbon accounting models, which in turn have not been linked with locational aspects of symbiosis potential across cities.

Data availability. The data that support the findings of this study are available from the corresponding author upon request.

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