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Coupling of carbon and energy flows in cities: A meta-analysis and nexus modelling

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HIGHLIGHTS

- A time-series dataset of 66 global urban samples is developed.
- The correlation between energy use and carbon emissions is analyzed.
- The coupling of energy and carbon flows in cities is illustrated.
- The impact of urban nexus on carbon intensity is quantified.

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ABSTRACT

Urban metabolism is a useful framework for characterizing human manipulation of energy and material flows in cities, but little attention has been paid to interactions among different flows. In this study, we examine the coupling of energy and carbon flows associated with cities. To do this, a time-series dataset of carbon and energy flows with 66 urban samples of various geographic and economic conditions is developed, dating back to 1865. We assess correlation between energy consumption and carbon emissions with consideration of urban size and population density. By focusing on Beijing and Issaquah as two case cities, we model the coupling of energy and carbon metabolism at urban scale from a network perspective. The energy-carbon nexus is evaluated for its impact on carbon intensities associated with economic sectors. We find energy-use and carbon emissions of 1865–2014 are strongly coupled, for both large and small cities of varying population densities. A closer look into the impact of the energy-carbon nexus on carbon intensities is important for emissions control. We suggest that more comprehensive and up-to-date monitoring of the nexus in urban energy and carbon flows be initiated immediately in order to search for ideal options of low-carbon pathways for cities at global scale.

1. Introduction

Over half of the world's population now resides in urban areas, and the process of global urbanization remains rapid [1]. Urbanization has made many people's lives healthier and more convenient, with advanced facilities and sophisticated services [2]. However, the rapid expansion of urban areas has exerted increasing pressure on ecosystems at both local (e.g., eutrophication, solid waste) and global (e.g., global warming) levels [3–5]. Maintaining a balance between economic growth and ecosystem health will be even more difficult in future because the projected urban population and areas in Africa, South America, and parts of Asia will see another major increase in the following decades [6].

It has been documented that 60–70% of global CO_2 emissions originate from urban areas, because of their commercial activities, industrial production, and vehicles [7,8]. Much of these carbon emissions are strongly associated with energy use in cities [9,10]. The reliance on carbon-intensive fossil fuels for powering cities and lack of low-carbon and renewable energy have produced a warming world. Therefore, the search for a low-carbon roadmap for cities is strongly correlated with reducing energy intensity (energy consumption per economic output) [11,12]. One promising means to understand energy and material flows is developed based on the framework of urban metabolism [13]. The modelling of carbon and energy metabolism is not only important for investigating urban system function, but also meets the real need for reducing carbon emissions of economic sectors. Direct flows of carbon or energy within cities have been investigated mostly through material flow analysis (MFA) or substance flow analysis (SFA) [14,15]. Indirect carbon emissions and energy consumption in trade have

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Nomenclature

MFA	material flow analysis
EFA	energy flow analysis
ENA	ecological network analysis
E	energy consumption
α	calorific value
β	proportion of energy consumption
ε	CO_2 emission factor
C	energy-related carbon emissions
MN	metabolic network connecting different sectors
I	carbon intensity
Subscripts	
i	generic economic sector
j	energy type
s	energy source
x	intermediate sector
u	final use sector

been tracked and quantified using input-output analysis [16,17], while system interactions under this indirect effect have been assessed via a network approach called ecological network analysis (ENA) [18,19]. Nonetheless, it is always a challenge to jointly model carbon and energy flows in a unified scheme of urban management [20,21]. The coupling of urban carbon emissions and energy consumption has been analyzed based on a range of techniques such as statistical regression [22,23], non-linear decomposition modelling [24,25] and land cover modelling [26,27]. However, time-series observation of cities has been lacking. Recent progress used the "nexus" concept to examine carbon-energy metabolic processes, which may be a promising step toward de-coupling economic growth from unintended emissions [28–31].

The present study presents a meta-analysis of urban energy consumption and carbon emissions in cities and the nexus between energy and carbon metabolism. We compile energy and carbon data of 66 city sample points (in different years) to analyze the correlation of carbon emissions and energy consumption from 1865 through 2014. This is the primary database for quantifying the coupling of energy and carbon flows in cities. After that, we select two cities, Beijing (China) and Issaquah (USA) as case studies for an in-depth modelling of energy-carbon nexus, involving sources and end users. Finally, we assess the impact of energy-carbon nexus among economic sectors on cities' carbon intensities, which is discussed for its potential to search ideal pathways for a low-carbon economy. By so doing, we aim to answer two questions: (1) How are energy consumption and carbon emissions coupled in cities of varying conditions? (2) How do we identify and quantify the nexus between urban energy and carbon flows using a metabolism-oriented framework?

2. Materials and methods

2.1. Model framework

The model framework for the coupling of energy and carbon flows in cities is shown in Fig. 1. In our model, a three-tier process is required for assessing the coupling of urban energy and carbon metabolism:

(A) Energy and carbon inventory. The selection of system boundary for energy and carbon inventory is dependent on the purpose of study. Direct energy and carbon process is most relevant for targeting in-city urban productions and local planning, whereas the analysis of all embodied energy and carbon consumption should track the upstream production processes outside city boundaries. The energy use database is established based on statistical reports from local government, and carbon emissions data are derived from the calculation based on IPCC recommended approach. Socioeconomic data are also needed for assessing efficiency of urban development. These data are used to match with the activities of economic sectors in cities.

(B) Construction of inter-sector flow networks. Analogous to food-web network in ecosystems, the metabolic networks associated with energy and carbon flows are constructed based on interactions between economic sectors. The supply-demand relations in energy metabolic networks can be quantified based on a MFA or life-cycle perspective. In contrast, the transfers of carbon emissions from one sector to the other are determined by the amount and type of energy use related to the supplier. The correlations of energy/carbon flow with urban population and economic outputs are also important for the forming of urban energy and carbon profile. This step is the basis for modelling energy-carbon nexus in real cases.

(C) Energy-carbon nexus modelling for a low-carbon economy. A hybrid network incorporating energy flow and carbon transfer is developed based on the individual networks constructed. In such a network, both energy and carbon related processes can be tracked simultaneously. The carbon intensities influenced by the coupling of energy and carbon flows are collectively quantified for each process between sectors. The analysis of carbon intensity is used to reflect the potential for lowering carbon emissions for one unit of energy use. A sensitivity analysis is used to identify the most influential factors for carbon intensity. This will facilitate the searching of low-carbon pathways of sectors and comparison between cities.

2.2. Energy and carbon inventory

There is surprisingly great disagreement on the definitions of urban areas in the literature [8,10,32]. This is partially because of the different objectives and types of analysis. For example, suburban areas within administrative boundaries may or may not be included in the assessment of a city's energy consumption. Another explanation is a scarcity of social and natural data at city scale. The lack of data on the "statistical urban area" (where population density reaches a certain threshold) of most cities has prevented rigorous comparison of urban attributes. For some cities (such as Osaka and Stockholm), the definition of "core city" has been applied for consistency of accounting [33]. In such cities, a rich economic dataset is generally available, including urban area, population, and GDP. For other cities (such as Beijing and Shanghai), one must use geographic boundaries as urban borders, because metabolism-related data are usually published at this scale. Although the inclusion of rural areas may somewhat impact the utility of comparison, meta-analysis has been seen as a sensible means for examining generic urban properties [4]. Based on this data framework, sector-level disaggregation of urban energy and materials becomes possible for most cities.