ARTICLE IN PRESS

Journal of Cleaner Production xxx (2015) 1–9

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Efficiency evaluation of material and energy flows, a case study of Chinese cities

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ARTICLE INFO

Article history:
Received 5 April 2015
Received in revised form
14 August 2015
Accepted 18 August 2015
Available online xxx

Keywords:
Case study
Chinese cities
Data envelopment analysis
Efficiency
Material and energy flows
Principal component analysis

ABSTRACT

The environmental impact of materials and energy is an important concern when cities and regions produce goods and services. To examine this requires an evaluation tool which can deal with the complex system of resources, energy inputs, products and wastes involved. This paper evaluates the urban material and energy flow efficiencies of 31 cities in China using a combination of the Data Envelopment Analysis model and Principal Component Analysis method. The results show that the urban flow system is composed of several input and output principal components, including energy, materials, urban capital investment, overall output, wastes, and others. In 2010, 16 cities were efficient as judged by the material and energy inputs and outputs. The remaining 15 cities were not efficient, primarily due to product shortfalls and waste excesses. Since 2000, half of the analyzed cities experienced a decline in the urban flow efficiencies, while only six cities showed a positive trend. The reasons include excess inputs of coal, coke, electricity, cement, investment, as well as output shortfalls in terms of overall output, wastes, services, agriculture and transport. We conclude that key priorities for improving urban systems with material and energy flow inefficiency are the use of urban renewable supplies, focus on sustainable endogenous development model, and improvement management of waste output, in order to increase efficiency and sustain economic growth.

1. Introduction

As the world becomes urbanized, building and maintaining sustainable cities sustainable is a paramount priority for analysts and policy makers (Elliott et al., 2000; Kennedy et al., 2012; Pijawka, 2012; Qin, 2014). In particular, recent climate events and deteriorating ecological environments have issued warnings that urban growth cannot continue at the expense of the natural environment (Dulal et al., 2011). However, in the past decades, human activities and particularly ongoing urban growth have continued to result in increasing adverse effects for the environment, such as pollution of the air, water, and land. Environmental challenges have become a key focus of sustainable development agendas (Ernstson et al., 2010; Newman, 1999; UNDP, 2014). For many countries and regions, to achieve continued economic growth while decreasing the pressure on ecological systems presents a paradox which requires a more mature set of management tools and evaluation systems.

This is particularly the case for China, which has experienced environmental distress alongside its rapid economic growth over the last three decades. Positive outcomes of its economic growth are indicated by its status as the world's largest exporter and manufacturer, with over 500 million people lifted out of poverty (United Nations, 2012). However, negative indicators are observed as China's current pattern of development has placed considerable stress on the environment—air, land, water, and natural resources. Particularly since the end of 2013, many Chinese regions have been shrouded by intense smog, caused by severe increases in air pollution. Other indicators of environmental and social crises associated with the consistent rapid economic growth have included unbreathable air, heavy metal waste, and income disparity. These have raised the question of whether the efficiencies of urban development are taking place at the expenses of resource and energy flow.

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http://dx.doi.org/10.1016/j.jclepro.2015.08.080
0959-6526/

There is a growing body of research engaged in examining material and energy flows of individual cities, and modeling urban ecosystem efficiency by a linear process, usually focusing on energy or carbon (or other material) flows of urban production process (Newman, 1999; Schulz, 2007; Warren-Rhodes and Koenig, 2001; Yang et al., 2012). Efficient use of material and energy is important for a city to produce goods and services to accommodate dwellers and support city growth; as well as reduce discharge and emission of pollutants to environment (Golubiewski, 2012; Hendriks et al., 2000). Kennedy et al. (2007) points out that the accumulation or storage of materials and energy, the growth of the city, and the generation of waste are interlocked and essential to the sustainable development of cities. However, despite the accumulated evidence from the scientific literature, there is still a need for systematic and comparative analysis on urban material and energy flows by weighting the desired outputs to support city growth vs. undesired adverse outputs to environment (Zhang et al., 2015). Such an analysis would allow for the comparison across cities to determine which cities have performed best and could be used as a point of reference for best practices in sustainable urbanism.

Therefore, this paper aims to capture a relatively complete picture of materials and energy flows in urban development; as well as compare the efficiency of materials and energy flows across 31 Chinese cities, for the purpose of improving the evaluation of urban efficiency. This study is meaningful for urban managers who must consider reconstructing urban industrial developing with more efficient material and energy flows; as well as regional scholars who aim to evaluate regional sustainable development by integrating material and energy flows analysis.

2. Conceptual framework: material and energy flows analysis of cities

By quantifying the balance of a city's inputs and outputs, Material and Energy Flows Analysis (MEFA) is a widely used and meaningful method for policy making processes (Fischer-Kowalski and Hüttler, 1998). The crux of this approach is to emphasize the efficiency with which resources are used (Golubiewski, 2012). Applications of this approach to address a city's sustainability can be found for Hong Kong (Warren-Rhodes and Koenig, 2001), Sydney (Newman, 1999), Vienna (Hendriks et al., 2000), Toronto (Sahely et al., 2003), Singapore (Schulz, 2007), and Xiamen (Yang et al., 2012). To the best of our knowledge, few studies have contributed to understanding the increasing inputs and outputs of the fast growing Chinese cities. Though the analyses are slightly different in emphasizing part or all elements of population, food, water, land, energy, emissions, waste and other inputs or outputs, they show that the MEFA is a useful approach to measure a city's load on the natural environment, and that high efficiency of material and energy flows can be beneficial to the survival of the city (Warren-Rhodes and Koenig, 2001).

In applied and policy perspectives, there is also a strong inclination to reduce or limit greenhouse gas emissions and waste discharge with the purpose of improving environmental quality (Schneider et al., 2010). This is embodied by the environmental goals set by international cooperation bodies and many countries such as United States, China, and European Countries. However, local governments within each country may exhibit reluctance to apply these goals, citing challenges in maintaining or growing economic development. The analysis of material and energy flows to some extent connects ecology and economics (Golubiewski, 2012), helping to reconcile these tensions. The key question which MEFA helps to answer is in determining which methods can be used to account for material and energy flows through the city, and whether the results can inform the optimization of these processes (Broto et al., 2012). As inefficient use of materials and energy threatens the sustainability of cities (Kennedy et al., 2007), such analysis ensures that the concept and requirement of sustainability becomes explicitly integrated into policy design.

The major limitation of MEFA is availability and accuracy of data at the city level (Sahely et al., 2003) and inconsistent interpretations of those data (Kennedy et al., 2007). Particularly, the information about resource use and waste discharge is quite scattered and needs to be synthesized (Elliott et al., 2000). Previous studies primarily focus on the linear cumulative analysis of energy use, storage processes of resources, services and urban waste dumps. The efficiency of urban resource consumption and waste production is seldom systematically evaluated, and consequently the role of cities in the national or global sustainable development is hardly defined.

Another problem of some of current studies is that “only resource inputs and economic outputs are of concern (Golubiewski, 2012)” without noticing unnecessary and unwanted imports, wastes, and exports. The amount of waste depends on inputs, which are the sum of outputs and the stock increase (Newman, 1999). Sustainability of urban ecosystem will not be evaluated if too much emphasis has been placed on the efficiency with which resources and energy are used. Urban ecosystem is an open system comprised of the community and its environment. Imports and exports of cities should be included in MEFA to capture the interchange among urban ecosystem and its environment.

From a policy perspective, MEFA should also consider social and economic conditions and values of resource use in supporting cities (Broto et al., 2012). Given the diversity of urban scenarios it is challenging to compare efficiency across cities, as they have different population sizes and distributions of socioeconomic status, in addition to complex interactions and processes of production, consumption, and waste generation. As Decker et al. (2000) point out, comparison across cities is made possible by understanding the efficiency of MEFA changes in each city, and is dependent on the status of each city's development. Therefore, there is still a need for research that systematically explores the urban material and energy efficiencies by considering energy, resources, services as well as urban waste and comparing them across different cities.

3. Data and methods

3.1. Study design

We apply the evaluation of material and energy flow efficiency to Chinese cities using a combination of methods: Principal Component Analysis (PCA) to condense and derive key variables, and Data Envelopment Analysis (DEA) approach to evaluate resources used with both concerns of cost-saving and environmental benefits. We report the main findings of the selected 31 Chinese cities, and discuss the value of the DEA approach in contributing to the main emphasis of material and energy flows analysis as Broto et al. (2012) describe as ‘comparative analyses of cities and models of urban planning in relation to their efficiency in allocating material and energy’.

3.2. Study area and context

This paper examines urban material and energy flow data in 31 Chinese cities for the years 2000 and 2010. This set of cities includes all the provincial level cities and provincial capitals, which act as the economic and political centers of their corresponding provinces in China. Provincial-level cities include Beijing, Shanghai, Chongqing, and Tianjin. Provincial capital cities include Harbin,

Please cite this article in press as: Song, T., et al., Efficiency evaluation of material and energy flows, a case study of Chinese cities, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.08.080