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Review

A review on eco-city evaluation methods and highlights for integration

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ABSTRACT

Current rapid urban development, particularly in Asian cities, is facing various challenges, such as resource depletion, environmental emissions and increasing pressures on responding climate change. It is critical for decision-makers to raise the appropriate urban development strategies so that cities can move toward sustainable development. In this regard, well-designed evaluation methods are valuable for managing environmental development and providing guidelines to improve sustainable urban development. Six well-known assessment methods for environment and sustainability assessment, namely, input–output analysis (IOA), life-cycle analysis (LCA), ecological footprint (EF), carbon footprint (CF), emergy analysis and cost benefit analysis are selected. Each method has its own advantages and disadvantages. This paper provides a comprehensive literature review on these methods and proposes an integration of different methods so that the holistic performance of one eco-city initiative can be scientifically evaluated and key problems can be identified. Such an integration can solve the problems that each single method is facing so that valuable policy insights can be identified for urban decision-makers to prepare more appropriate urban strategies.

Contents

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1. Introduction

Being densely populated, cities are major resource consumers and waste producers and account for three quarters of national energy consumption and greenhouse gas emissions (Liu et al., 2012). Moreover, resources such as energy, land and water, have become crucial for sustainable urban development. Under such a circumstance, cities have become the hot spot for addressing innovative mitigation actions and policies (Hamin and Gurran, 2009; Xu et al., 2012).

Eco-city concept was first proposed by Register in 1975, in which he raised the perspective on "rebuilding cities in balance with nature" (Register, 1993). The terms of "eco-city" and similar concepts such as "green" and "sustainable" cities, have evolved over time with the development of understanding social change and mankind's impact on environmental and economic health (Zhou et al., 2015). It has an eternal target for achieving future sustainable urban development by considering social, economic, environmental and cultural aspects through changing the production mode, consumption behavior and decision instruments based on ecological economics and systems engineering (Cao and Li, 2011; Cheng and Hu, 2010; Yu, 2014).

There are no authoritative and unambiguous definitions and descriptions on eco-city (De Jong et al., 2013). Recently, industrial and urban symbiosis has received increasing attentions in promoting eco-city development since it can effectively minimize resource consumption and waste production by encouraging "Using resources more efficiently", "Using waste as a resource", "Restoring and maintaining urban environmental quality" and "Promoting highly efficient and effective urban and industrial planning, design and management systems" (Bai and Imura, 2000; Newton and Bai, 2008). Industrial and urban symbiosis has been demonstrated to be a good strategy for eco-city transition, particularly the eco-town projects in Japan, and many studies have been done in this regard (Chen et al., 2012; Dong et al., 2014b; Geng et al., 2010a; Hashimoto et al., 2010).

Besides successful strategies, appropriate evaluation methods and models for planners and policy makers are also critical to promote eco-city transition. They can provide quantitative information on the status of the studied city and help guide policy makers to identify the key issues of their development and then prepare appropriate strategies. Particularly, due to the complex nature of urban development, no single method can provide perfect evaluation on the overall development of one city, leading to an urgent need of integrating various evaluation methods and addressing different needs of economic, environmental and social perspectives. Consequently, the objective of this paper is to conduct a comprehensive literature review on main eco-city evaluation methods and propose an integration of different methods, so that the holistic performance of one eco-city initiative can be scientifically evaluated and key problems can be identified. Then valuable policy insights can be raised for urban policy-makers so that they can prepare more appropriate urban development strategies. The structure of this paper is organized as below. After Section 1, we present our methodology in Section 2. Then we detail six main evaluation methods in Section 3, including input–output analysis (IOA), lifecycle analysis (LCA), ecological footprint (EF) analysis, carbon footprint (CF) analysis, emergy analysis and cost benefit analysis (CBA). The research boundaries, advantages and disadvantages of different evaluation methods are further compared and discussed in Section 4. Finally, concluding remarks on how to integrate different methods for different eco-city transitions are discussed and concluded so that the best solution for eco-city transition can be recognized.

2. Method

This paper is a review paper and therefore has a qualitative nature. Main methods used in bibliometrics analysis such as citation analysis and relevance analysis are adopted in order to select and analyze the most important literatures. Web of Science core collection database is the main source to collect both literatures and literature statistical data. For example, ("eco-city" OR "eco city" OR "ecological city" OR "eco-town" OR "eco town" OR "sustainable city") was set as the keywords under the "topic" option for searching eco-city related literatures in Web of Science core collection database. About 250 literatures were found and only 30–50 most important and related literatures were selected for further detailed review so that methodology integration for eco-city transition can be figured out. As for the selection of evaluation methods for further review, there are three reasons. First, ((Environment* OR sustainab* OR ecolog*) AND ("evaluation method*" OR evaluation indicator*)) was set as the keywords for analyzing environmental evaluation methods. BibExcel (Yu et al., 2014) was used to analyze the bibliometric data, and the co-word analysis showed that lifecycle analysis, ecological footprint, emergy/exergy analysis and carbon footprint/greenhouse emissions are the top four methods in this domain. Second, we further refer some review papers about existing environment assessment methods (Loiseau et al., 2012; Marchettini et al., 2007; Pulselli et al., 2008) and include input–output method because of its wide application. Moreover, according to our knowledge, all above methods are mainstream methods on environmental assessment and are useful for eco-city planning. Finally, considering the economic cost and practical feasibility in the real eco-city projects, cost–benefit analysis method was also included according to the recommendation of experts.

3. A comprehensive review on evaluation methods

3.1. Input–output analysis (IOA) method

Input–output analysis (IOA), developed by Leontief in the 1930s, is a top-down economic technique that uses sectoral monetary transaction data to account for the complex interdependencies of various economic sectors (Leontief, 1970; Munksgaard et al., 2005). IOA offers a variety of appealing features for studying environmental problems and has been used for evaluating various embodied resources, such as embodied energy (Baral and Bakshi, 2010; Yang et al., 2014), embodied/virtual water (Dong et al., 2014a) and embodied carbon emissions (Dong et al., 2013b; Jiang et al., 2015). First, this approach provides a complete description of the regional and/or inter-regional supply chain and avoids the truncation error typically encountered by those bottom-up approaches (Feng et al., 2011). Second, IOA method assigns the environmental problems to final consumption rather than intermediate consumption, which allows for assessing both direct and indirect effects from consumption perspective. However, this method is more used at macro levels, such as provincial or national levels, but less at micro levels, such as industrial parks or individual products, due to the lack of IO tables.

IOA method has been widely used for ecological footprint, carbon footprint, water footprint and energy. For example, IOA was used for water footprint study to mitigate regional water scarcity problems of Beijing (Wang et al., 2013; Zhang et al., 2011b), suggesting closer interregional trade coordination so that regional water resource utilization can be improved. Similar studies have also been done in other water scarce regions, such as Liaoning Province of China (Dong et al., 2013a). Kanemoto and

Tonooka (2009) used a multi-regional input–output model (MRIO) to calculate the CO_2 emissions embodied in Japan's international trade and found that emissions embodied in imports to Japan increased significantly. Druckman and Jackson (2009) studied the carbon footprint of UK households using a quasi MRIO model and found recreation and leisure sectors were responsible for over one quarter of CO_2 emissions in a typical UK household in 2004. Hubacek and Giljum (2003) also applies IOA for ecological footprint study and calculated direct and indirect land requirements for the production of exports from EU-15 to the rest of the world.

3.2. Lifecycle analysis (LCA) method

Lifecycle assessment (LCA) is a method used to comprehensively assess environmental effects of product choices from the generation of raw materials to the ultimate disposal of wastes, and is motivated by the desire to authoritatively determine the least-damaging alternative (Ayres and Ayres, 2002; Hertwich et al., 2000; Liamsanguan and Gheewala, 2008). LCA study dated from the late 1960s and early 1970s. The first acknowledged LCA study is the one for quantifying resource requirements, emission loadings, and waste flows of different beverage containers for the Coca-Cola Company in 1969 (Guinée et al., 2010). Since then, LCA has been applied to evaluate the potential environmental impacts from diverse aspects relating to the treatment and disposal of wastes, such as food recycle (Cellura et al., 2012), waste glass recycle (Blengini et al., 2012), waste paper recycle (Liang et al., 2012; Wang et al., 2012), PET bottle recycle (Song and Hyun, 1999) and Waste-to-Energy approach (Tunesi, 2011; Vázquez-Rowe et al., 2014). LCA is also incorporated into studies on resource recycling system and eco-cities. For instance, Singh et al. (2007) studied an agrochemical complex consisting of 13 chemical and petrochemical industries in the state of Mississippi, USA by conducting an "entry to exit" life cycle assessment (LCA) and found that LCA is an extremely useful tool for analyzing and comparing different designs of industrial ecosystems. Chen et al. (2011) modified and applied a LCA-based two-step simulation system to assess the potential environmental benefits, including the reduction of GHG emissions and saving of fossil fuels by employing various Japanese plastics recycling technologies in Shenyang, China. Different from IOA, LCA is more used at small scales such as a product or process since detailed process data are available.

3.3. Ecological footprint (EF) analysis

The ecological footprint (EF) concept was originally developed by Wackernagel and Rees in the 1990s, aiming to calculate the biologically productive land and water that a population requires to produce the resources it consumes and to absorb part of the waste generated by fossil and nuclear fuel consumption (Rees, 1992; Wackernagel and Rees, 1998; Wackernagel et al., 2002). EF was often broken down into six components: use of arable land (for food, feed and other agricultural products), use of pasture land (for animal grazing), use of forest/woodland (for timber), use of built-up land (for living etc.), use of productive sea space (for fish), and use of forest land to absorb CO_2 that was emitted due to human activities (Hoekstra, 2009). EF is widely used for evaluating environmental sustainability by comparing with bio-capacity, which is defined as the ability of an ecosystem to produce useful biological materials and to absorb carbon dioxide emissions (Geng et al., 2014). If EF is bigger than ecological carrying capacity, it means that human activities have surpassed the natural capacity, indicating an unsustainable development nature.

Ecological footprint method is a useful tool to help budget limited natural capital and can be applied to different scales, particularly for regions and cities. It is found in Wackernagel et al. (2006) that "London's EF in 1995 was 125 times the size of the city itself, indicating that in order to appropriately function, London required an area of the size of the entire productive land surface of the UK to provide all the resources the city uses and to dispose of its pollutants and wastes". Geng et al. (2014) studied and compared the ecological footprints of one city in a developing country and one city in a developed country, uncovering that cities in developing countries are experiencing rapid ecological footprint increases, while cities in developed countries have relatively stable ecological footprints. Such findings propose more collaboration between cities at different development stages through technology transfer and capacity building efforts.

3.4. Carbon footprint (CF) analysis

Carbon footprint (CF) stems from the concept of ecological footprint and has become popular since 2007 in order to respond global warming. It is defined as the amount of CO_2-equivalent emissions caused directly and indirectly by an activity (Wiedmann and Minx, 2007). Carbon footprint study has been done at different scales, such as nations, cities, households, organizations, production processes and products. Such an evaluation method can be categorized into three types, namely, IPCC (Intergovernmental Panel on Climate Change) method, life cycle analysis (LCA) method, and input–output analysis (IOA) method. LCA method is mainly used at a small scale such as organizations and products, while IPCC method and IOA method are more appropriate for evaluating regional and city level carbon footprints. A lot of studies at regional and city levels have been done. For example, Hertwich and Peters (2009) quantified greenhouse gas emissions associated with the final consumption of goods and services for 73 nations and 14 aggregate world regions by using multi-regional input–output (MRIO) model, and their results showed that national average per capita footprints vary from 1 tCO_2e/year in African countries to 30 t/year in Luxembourg and the United States. Sovacool and Brown (2010) offered a preliminary comparison of carbon footprints in 12 metropolitan areas. Xi et al. (2011) studied the carbon footprint of Shenyang city, China by using IPCC method. Lin et al. (2013) studied the carbon footprint of Xiamen City in China by integrating both IPCC method and EIOA method.

3.5. Emergy analysis method

Emergy analysis, firstly proposed by Odum in late 1980s, is defined as the sum of the available energy of one kind previously required directly and indirectly through input pathways to make a product or service (Odum, 1988, 1996). The emergy value of a resource reflects the amount of past work endeavored by natural processes to produce or regenerate it (Odum and Nilsson, 1997; Tilley and Swank, 2003). Therefore, emergy has the advantage to assign values to nature's environmental efforts and investment (e.g., solar, deep geothermal heat, and gravity) to make and support flows, materials, and services and to contribute to the economic system (Geng et al., 2013). Emergy provides a unified, self-consistent objective method for quantifying the relative value of material and energy flows in the economy and in the environment (Campbell et al., 2014) since it transforms all kinds of products (natural or man-made) to solar-equivalent Joules (sej).

Emergy analysis can provide useful insights to decision makers so that proper urban development policies can be raised (Li and Wang, 2009). In this regard, many studies have been conducted, such as urban metabolism (Huang and Chen, 2005; Huang et al., 2006; Sun et al., 2015; Zhang et al., 2011a), sustainable level evaluation (Lei and Wang, 2008), urban ecosystem health assessment (Liu et al., 2009; Vassallo et al., 2006), and urban land use (Huang et al., 2001). Moreover, different emergy evaluation

Table 1
Focus of different evaluation methods.

	Initiated year	Initiator	Conceptual root	Definition	Unit	Scale	Strengths	Weakness
IOA	1936	Leontief	/	An economic technique that uses sectoral monetary transaction data to account for the complex interdependencies of various economic sectors.	/	Macro level, such as national and regional.	- The calculation is simple, if the data were available. - The result is complete and comprehensive.	- The calculation is less detailed and less accurate. - The IO table is published every five years, therefore data is old.
LCA	1960s	/	/	A method used to comprehensively assess environmental effects of product choices from the generation of raw materials to the ultimate disposal of wastes.	/	Micro level, such as product and process.	- It can avoid burden shifting between lifecycle stages or territories. - The calculation is more detailed and accurate.	- It ignores indirect flows outside the boundary and leads to truncation errors. - It needs lots of process data and is more time and labor consuming.
CF	1997	Wiedmann and Minx	Climate change	The amount of CO_2-equivalent emissions caused directly and indirectly by an activity.	ton	From micro to macro levels.	- Effective indicator for evaluate carbon emissions from lifecycle perspective.	- Focus on only the carbon emission aspects.
EF	1992	Wackernagel and Rees	Environmental carry capacity	The biologically productive land and water a population requires to produce the resources it consumes and to absorb part of the waste generated by fossil and nuclear fuel consumption.	ha	Multi-levels, particularly regions and cities.	- It evaluates the natural capita and is easily understood by policy makers. - It allows for sustainable development analysis.	- Pollutants, and embodied energy etc. are not considered. - Work done by nature is not incorporated. - Equivalence factors and yield factors are not easy available.
Emergy	1988	Odum	Energy transfor-mation hierarchy	The energy of one type required in transformations to generate a flow or storage.	sej	Multi-levels	- It considers the natural contribution. - It transforms different kinds of energy, materials, goods and services into the same unit. - It allows for sustainable development analysis.	- It has uncertainty because it uses the same transformity for materials produced by different process.
CBA	1848	Jules Dupuit	Unit abatement cost, external cost	A technique that is used to determine options that provide the best approach for the adoption and practice in terms of benefits in labor, time and cost savings.	/	More efficient in project or technology	- Through monetizing the cost and benefit, the project managers and policy makers can easily judge the profitability and feasibility.	- It has uncertainty on the calculation of environmental external cost and social cost for pollution control.

indicators can be used to quantify different environment performances. For example, emergy yield ratio can reflect the capability of human activities to exploit local resources; emergy loading ratio can measure the pressure of human activities on local ecosystem due to excess exploitation of local non-renewable resources or investment from outside (Geng et al., 2010b). Emergy sustainability index can reflect the sustainability level of the region or city.

3.6. *Cost benefit analysis (CBA)*

Traditional cost–benefit analysis (CBA) is a systematic process for calculating and comparing benefits and costs of a project, decision or government policy (Melichar, 2009; Pearce et al., 2006). With the concerns on environmental issues and sustainable development, this method is used to quantify the losses on human health and environment caused by economic activities, and identify the most efficient way to reduce them, as well as to compare the cost of environmental damage to the cost of mitigation (Bachmann and van der Kamp, 2014; Hanley, 2013). Especially, environmental externality (Bickel et al., 2005) and social well-being (Pearce et al., 1996) are considered into the cost–benefit calculation. With its development, CBA has become a prevailing decision tool for making national and local environmental policies in EU and other OECD countries, such as urban planning (Kolosz and Grant-Muller,

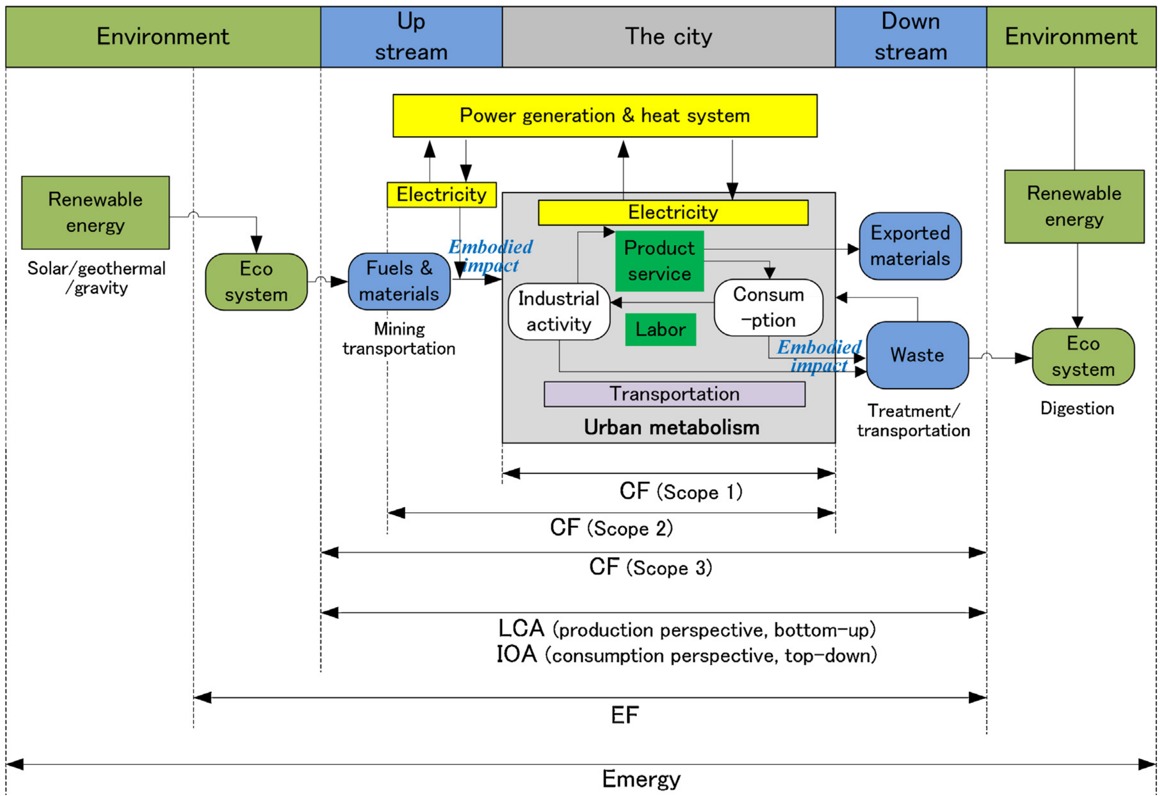

Fig. 1. Boundary differences for different evaluation methods.

2015) and mitigation policies (Bachmann and van der Kamp, 2014; Commission, 2009; Shreve and Kelman, 2014).

Several CBA approaches have been developed to monetize the environmental externality, e.g., External E (Bickel et al., 2005), willing to pay, and calculate the life cycle cost. To minimize the environmental externality, systematical approaches such as "circular economy" have been proposed by environmental economists (Pearce and Turner, 1990) and widely applied in Germany, Japan, and China (Geng et al., 2009; OECD, 2009). However, as the core of CBA is to monetization, thus it has the limitation of quantification some environmental benefit, ecosystem benefit and social benefit (Kolosz and Grant-Muller, 2015; Massiani, 2015; Söderqvist et al., 2015).

4. Comparison of different methods

4.1. Advantages and disadvantages

The six evaluation methods can be classified into three types, namely economic type (IO method and LCA method), environmental type (EF, CF and emergy) and the decision type (CBA method). Each method has its own advantages and disadvantages, shown in Table 1. For example, LCA method is a bottom-up method and can provide more specific information to decision-makers. However, it is more time-and-labor consuming since it requires a large amount of detailed data. It also suffers from a systematic truncation error due to the delineation of system boundary and the omission of contributions outside this boundary (Suh et al., 2004). The IOA method is a more comprehensive top-down approach and has a potential to solve the major drawbacks of LCA method (Crawford, 2008). It mainly uses public data from input–output tables and can reduce both time and manpower once the model is in place. However, the suitability of IOA at micro levels such as products or processes is limited because IO tables are usually available only at larger scales. Moreover, the data are often outdated and not continuous.

The environmental type methods (EF, CF and emergy) are single unit methods and are easy to be understood and accepted by the public and policy makers. Moreover, they have the advantage to appraise the sustainability degree of a region. However, they are often criticized for their inaccuracy and uncertainty (Cleveland et al., 2000; Hau and Bakshi, 2004; Parker and Tyedmers, 2012). For instance, EF and CF were criticized for not addressing technology improvement (Geng et al., 2014). In order to solve such problems, it is recommended to combine such evaluation methods with LCA and IO in a complementary way, so that more robust and detailed sustainability assessment could be achieved (Baral and Bakshi, 2010; Wiedmann and Barrett, 2010). Moreover, IOA method can be used at a large scale in order to solve some data problems during regional evaluation. The decision type method (CBA) is a classical method for giving final policies and decisions by considering the economic feasibility. However, it faces the uncertainty problem on calculating external costs (Hoogmartens et al., 2014).

4.2. Boundary issue

System boundary is an important aspect for evaluating an eco-city, and can influence the results significantly. The evaluation boundaries of these methods are illustrated in Fig. 1. The boundary of LCA method is usually based upon classic "from-cradle-to-grave" life cycle stages, which includes not only the direct production activities within the urban territory, but also impact embodied in upstream and downstream activities such as mining, fuels & materials production and transportation, waste treatment and transportation, etc. IOA method has a similar boundary to LCA method, but the difference is that LCA is from the bottom-up process perspective and IOA is from the top-down final consumption perspective. The boundary under the CF method is more flexible and can be only at the urban territory level (scope 1), or including both territory level and upstream heat & electricity (scope 2), or even the whole life cycle (scope 3) (Kennedy et al., 2010). Emergy method has the largest boundary which includes not only the life cycle boundary, but also includes the contribution of natural ecosystem such as solar energy, geothermal, rainfall and ecosystem. As for EF, its boundary includes the effect of urban territory, upstream and even the ecosystem, but usually not the downstream. Such a boundary can be extended by integrating different methods and avoid environmental responsibility shifts.

5. Concluding remarks for methods integration

Eco-city concept has been proposed with a target for sustainable urban development. However, currently there are no unanimous criteria for defining an eco-city. Each individual eco-city project has its own criteria, such as the "zero-waste and zero-carbon emissions" in Abu Dhabi Masdar City project (Palca, 2011), the "industrial symbiosis and recycling" of Japanese eco-town projects (Van Berkel et al., 2009), the "economically sustainable, socially harmonious, environmentally friendly and resource-conserving" of the Sino-Singapore Tianjin Eco-city project (Baeumler et al., 2009). In order to identify appropriate pathways toward eco-city, feasible evaluation methods should be identified. Considering the boundary differences and advantages and disadvantages of different methods, it is necessary to develop an integrated decision support method for eco-city transition and low carbon development.

First, integration of three types of methods to contribute holistic eco-city planning by analyzing both economic and environmental benefits. For example, the combination of EF and emergy analysis can provide suggestions on improving local bio-capacity and urban sustainability, while CBA can quantify the feasibility by taking into account the economic cost. The further combination of LCA and IO can provide technical and data support to make such an evaluation more accurate and reasonable. Such integration can scientifically guide the eco-city planning. However, such kind of comprehensive integration is still lack in both current eco-city research and planning, and need future application in eco-city project.

Second, integration of environmental type and economic type methods to move toward low carbon eco-city. CF is the dominate method for raising appropriate low carbon policies. However, the integration of CF with LCA and IOA methods can provide a systematic analysis from a life cycle perspective so that emission transfer problems can be avoided by tracking supply chain boundaries (Dong et al., 2013b; Matthews et al., 2008). Such a hybrid approach has already been applied in several low carbon city studies (Dong et al., 2014b, 2013c; Lin et al., 2013), but need to be further promoted.

Finally, the integration of environmental type and decision type methods is necessary in order to support final decision makings. Cost is often the decisive factor since all the decision makers need to assess the economic feasibility of one eco-city project. In this regard, CF, EF and emergy analysis should also be integrated with CBA so that corresponding environmental and ecological benefits can be quantified. Unfortunately, such integration studies have not been promoted and applied. Consequently, more innovative integration efforts should be initiated by considering the local realities so that more feasible policies toward eco-city transition can be raised.

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