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Resource Effectiveness in and Across Urban Systems

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Synonyms

Carbon emissions; Circular economy; Environment; Linear economy; Resource efficiency; Urban systems

Definition

Resource effectiveness metrics quantify city-wide material and energy efficiency. In a thermodynamic formulation of material and energetic flows within and across cities, effectiveness of resource utilization and conversion reflect the efficiency of the city as a consumer and producer, respectively. These dimensionless metrics are based on the ratios of successfully utilized (effectiveness of utilization) or exported (effectiveness of conversion) biophysical resources to the total resources extracted or imported into the city, all measured in units of exergy.

Introduction

Cities are centers of economic growth but also responsible for ever higher resource consumption and greenhouse gases emissions. Rapid urbanization due to increasing human population and resource-intensive economic activities have drawn concerns for the future of urban sustainability (Seto et al. 2017; Krausmann et al. 2017). Often described as thermodynamically open systems, cities rely on intake of resources and are heavily dependent on flows of resources and energy from their external environment to avoid stagnation (Carmona et al. 2021). This resource reliance raises a key question: how *effectively* do cities consume the resources available to them?

Main Approaches to Measurement

In the 1960s, Wolman undertook a thought experiment to estimate the material needs of a typical American city by assembling per capita resource consumption and waste generation figures using available national statistics (Wolman 1965). Drawing on ecological metaphors, he used the term *urban metabolism* in describing the resource input and waste output sustaining cities. Since Wolman, under the umbrella of "urban metabolism," a variety of methods have been developed. These facilitate the measurement and/or estimation of the quantity of materials and energy imported, exported, stocked, and consumed in

R. Brears (ed.), *The Palgrave Encyclopedia of Urban and Regional Futures*,
https://doi.org/10.1007/978-3-030-51812-7_202-1

cities. Many case studies have been undertaken over the last few decades quantifying resource flows in various cities. Table 1 summarizes the most prominent of these approaches within the academic literature.

Material Flow Analysis (MFA)

Material flow analysis as a method relies on a spatiotemporally defined system boundary across which an assessment of the flows and stocks of resources can be analyzed using a mass/energy conservation approach (Brunner and Rechberger 2004). The method is often used to track resource streams across these spatial and temporal boundaries providing a measure of the demand for resources and pace of development. Such a quantification of the inbound and outbound urban resource streams is meant to contribute towards an understanding of how the urban environmental and economic functions interact with the city's surroundings (Bancheva 2014).

Applications of the MFA can take two overall forms based on the treatment of the data used. In top-down approaches, resource flows are estimated using economy-wide, and often national, inflow and outflow statistics collected annually over a given period. For subnational system boundaries, the national statistic is often treated using appropriate population or economic scaling factors. Depending on the availability of the aggregate statistics, resource streams in MFA studies can be subcategorized based on specific economic activities for which they have been recorded. The resource intensity of these economic sectors relative to their economic output can then inform their resource productivity (Fischer-Kowalski et al. 2011).

The bottom-up methods, on the other hand, approach data collection through survey samples. Surveys allow for constructing inventories of products and tracing the stocks and streams of resources embedded in their life-cycle from extraction to their eventual disposal (Brunner and Rechberger 2004). These inventories often contain quantities of resources normalized against suitable indicators, for example, population, area, gross domestic product, etc., coded as *material intensities.* These average characteristics estimated from the survey samples can then be used to extrapolate for material embedded in flows and stocks across other systems of various sizes but similar compositions. They can also be used in more dynamic formulations of the MFA that use demand-driven models to examine past and future material use and its effects through time (Augiseau and Barles 2017; Müller 2006; Müller et al. 2014).

MFA is, however, limited by its linear and simplified nature. System conceptualization, particularly in top-down MFA, follows black-box definitions that simply estimate throughflow using the net differences in total inputs and outputs. On the other hand, bottom-up approaches can suffer from the unavailability of the intensive resources that are needed for data collection and the time it often takes. More importantly, the implementations of MFA often ignore differences in quality of the resource streams. Such quality differences are crucial when considering material transformation processes that suffer thermodynamic degradation (Barles 2010; Kennedy et al. 2007).

Input-Output Analysis (I/O)

Input-output analysis techniques date back to Leontief's formulation of an input-output model which is used to analyze industrial interdependencies in an economy (Leontief and Strout 1963; Leontief 1986). The method requires development of input-output tables, which are comprehensive adjacency matrices that contain the flows of intermediate goods and services between industries, that is, industry by industry, and their final sale and purchase within an economy (OECD 1999). Constructing IO tables requires meticulous record keeping. The method is thus most reliably used in studying national and global economic systems where data is more readily available. At lower spatial scales, however, multiregional input-output models can be assembled and have been shown to be useful tools in analyzing trade links across interconnected systems (Bruckner et al. 2012).

Most applications of I/O in urban metabolism rely on monetary flows as a proxy for the physical resources exchanged between industries within

Resource Effectiveness in and Across Urban Systems, Table 1 Broad summary of methods frequently used in quantifying resource flows in cities

Method	What it includes	What it measures	What it is lacking
Material flow analysis	Total material/energy stocked in cities and crossing urban boundaries	Material input, consumption, production, and waste emissions in kilograms of material	Linear system description, mismatched measurement units, lacks quantification of a differential in quality of resource streams
Input-output analysis	Direct and indirect interactions and interdependencies between different sectors	Impact of shocks, disruptions, and ripple effects throughout the system	Rely on monetary supply and use tables requiring large quantity of survey data to be collected frequently
Ecological network analysis	Input-output analysis with an emphasis on network structure of sectoral interactions and interdependencies	Nature of resource interactions between sectors including control and dependence relationships	
Emergy and exergy approaches	Extends the other methods providing unified units of measurement for embodied energy content or its thermodynamic quality	Unified energy content of resources in Joules	Difficult to estimate or unified conversion factors for waste and socioeconomic resource streams

the system (Bailey et al. 2004a, b). However, extensions of I/O methodology have been implemented to broaden the applications. Environmental-extended input-output is one such extension that enables evaluation of the associated environmental impacts of industrial exchanges. These include system-wide effects of the extraction of natural resources or the carbon emissions associated with industrial interactions (Kitzes 2013). The main difficulty in using I/O rests with its strict requirements for data and its format. Limitations of data that are recorded and are available at city-level often pose constraints on the applicability of the method.

Ecological Network Analysis (ENA)

Ecological approaches to urban metabolism expand on the implied analogies between urban processes and those of ecosystems. This allows for using methods originally developed to study ecosystems and food webs to model complex interactions among processes in and across cities. In doing so, parallels are made between components and their interactions in urban systems, for example, industrial sectors, and those in food webs and ecological networks, that is, various species. In an ecological paradigm, the overall behavior of the system is dictated by the complex interactions of its internal components (Bai 2016; Huang 1998; Newman 1999).

From a theoretical perspective, the ecological network analyses build on the same core concepts as the I/O analysis developed by Leontief (Hannon 1973). However, unlike I/O, the end goals are not so much in studying the ripple effects through the system but rather in the nature of the relationships between different system components as a function of their direct and in-direct interactions. ENA, additionally, allows examining the dynamics that influence the formation of these resource flows between different components in an urban resource network. Due to the background of the methods, these are often articulated as a function of hierarchical relationships between components mirroring those seen in natural ecological pyramids with apex predators towards which the majority of overall trophic resources flow (Bodini et al. 2012; Li et al. 2018, 2011, 2012).

A number of perspectives can be attained using ENA methods. Functional analysis allows the quantification of the total system throughflow much like I/O (Fath and Borrett 2006; Zhang et al. 2010, 2014). Utility analysis allows allocation of metabolic relationships to any component pairs based on their reciprocal flows (Fath and Patten 1998). These are used to determine whether different industrial sectors, or different cities when studying flows of material between cities rather than within them, exhibit competitive, exploitative, or mutually beneficial resource interactions (Tan et al. 2018). Finally, a control allocation analysis allows quantification of the degree to which different sectors exert control over the resource-input others or how different sectors depend on the resource-output of others (Chen and Chen 2015; Schramski et al. 2007).

ENA has been widely used and is considered an effective assessment toolkit for examining urban and regional resource flows (Chen and Chen 2015; Fan et al. 2017; Li et al. 2012; Yang et al. 2014). Implementing ENA, however, suffers from the same difficulties as I/O. At city-level large amounts of data are required in a similar format as is required by I/O. Additionally, studies that do not directly use monetary I/O tables as a proxy face additional difficulties in collecting granular data. The difficulties lie in sourcing data that is both measured in consistent and comparable units and meets the required format in an I/O table for flows of different resources.

Emergy and Exergy Approaches

Emergy and exergy approaches have been developed as means by which to address the problem of comparability of units used in measuring resource streams of different qualities. Emergy as a method was developed within the ecological tradition. It seeks to unify resource measurement by estimating the total *embodied energy* embedded in a resource stream in terms of the solar energy equivalent needed for its creation (Odum 1988, 1996). In principle, this would provide for directly comparable resource streams in both quantity and quality using a single objective unit of measurement. In reality, however, the method can become severely limiting as a function of prior agreement on and ease by which solar energy conversion factors can be defined and estimated for flows of complex resources outside a strictly ecosystem context (Zhang et al. 2015).

Exergy, on the other hand, has its roots in the thermodynamic principles of irreversibility and work availability. In such contexts, it is defined as “the maximum theoretical useful work obtained if a system is brought into thermodynamic equilibrium with the environment by means of processes in which the system interacts only with this environment.” (Sciubba 2001; Sciubba and Wall 2007) As such it retains not only the energetic content of resource streams, but also its thermodynamic quality. While estimation of exergy can face similar difficulties as emergy with regard to conversion factors, *chemical equivalent* conversion factors can be used to provide estimations for different resources based on their required primary energy input (Szargut 1989). In addition to industrial resources, exergy-based approaches have also been adapted for quantification of nonenergetic resources, for example, labor and direct capital flows (Sciubba 1999, 2005). In this way, exergy has been more successful than emergy in providing a unified framework. As a unit of measurement for both quantity and quality of resources, exergy can be integrated and used within the other previously mentioned approaches to urban metabolism (Ayres et al. 1998; Gong and Wall 2001; Lozano and Valero 1993; Finnveden and Östlund 1997).

As with emergy, exergetic approaches can still face difficulty when compiling data for complex systems that encapsulate a large variety of physical and energetic resources. These include the recurring concerns about the appropriateness of the conversion factors used when converting flows into an exergetic framework. More specifically, both emergy and exergetic accounting are still lacking a unified approach to the quantification of waste products (Zhang 2013).

Mathematical Description

Answering the question of how effectively cities do consume the resources available to them requires a mixed use of the reviewed approaches. Particularly helpful is the ability of the exergy-based formulation to keep track of quantity and quality of resource streams. *Exergy destruction*, as is often used in the context of describing urban processes, expresses the usefully dissipated part of a resource stream. This is in contrast with the wasted portions of flow streams that due to thermodynamic irreversibilities are not used nor can be directly recovered (Nicolis and Prigogine 1977). Resource effectiveness of urban systems can then be evaluated through comparisons of the destroyed and wasted resources to the total inflows of resources and energy into the system.

A Network Model of Urban Systems

System abstractions used in MFA and I/O to represent cities can be thought of as a directed network of N nodes and E edges. In such networks, nodes can be representative of industrial sectors within a city with edges taking the place of monetary, physical, or energetic flows between them. They can, more broadly, be stand-ins for any such similar roles depending on the context of the domain of study, for example, regional resource flows or international monetary interactions.

For each node i, F_{ij} represents the resource flow passed on from it to node j with Δ_i representing the resource in/outflows that cross the boundary of the overall system, for example, the city's boundary. X_i^U, constitutes part of F_{ij} that is successfully utilized at i, for example, exergy destroyed. Meanwhile, X_i^W denotes the portion lost to thermodynamic irreversibilities. Disutility factors, λ and ϕ, account for process efficiencies that dictate how successful a process is in using available resources and maintain the conservation of energy across the model. More specifically, λ controls the amount of exergy successfully *destroyed,* and ϕ reflects the portion that is irrecoverably lost to waste for each resource stream F_{ij}. In the majority of model formulations, these processes and their efficiencies are characteristics of the node inside which they take place (Arbabi et al. 2020; Tan et al. 2019). Figure 1 shows a schematic representation of such network arrangements.

Expanding this formulation across all nodes and edges would give the system-wise overall resources balance as

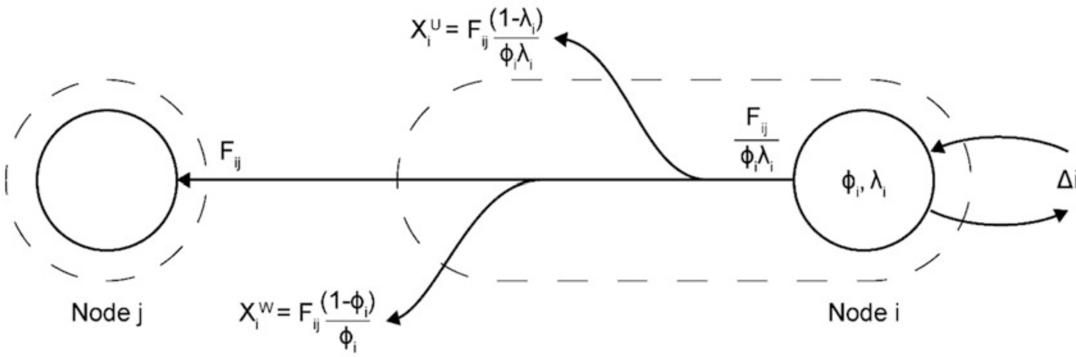
$$\sum_i^N \sum_{j,j\neq i}^N F_{ij} + \sum_i^N X_i{}^U + \sum_i^N X_i{}^W - \sum_i^N \sum_{j,j\neq i}^N F_{ji} + \sum_i^N \Delta_i = 0.$$

Overall Resource Effectiveness and Balance

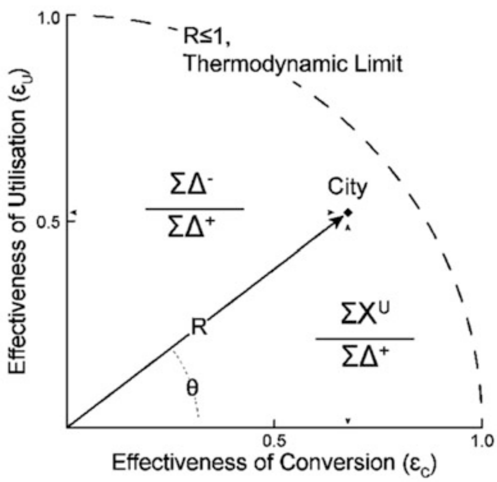
Resource effectiveness in each process and across the system as a whole depends not only on the efficiency by which the transformations are performed, that is, combined effects of λ and ϕ, but also the intended purpose of a sector. Urban systems and their processes can exhibit different behaviors and qualities when regarded as consumers of resources or their producers/transformers. For cities, the two aspects as consumers and conversion engines are captured by effectiveness of resource utilization, $\epsilon_U \coloneqq \frac{\sum_i^N X_i{}^U}{\sum_i^N \Delta_i{}^+}$, and effectiveness of resource conversion, $\epsilon_C \coloneqq \frac{\sum_i^N \Delta_i{}^-}{\sum_i^N \Delta_i{}^+}$, where $\sum \Delta^+$ denotes the incoming resources imported into the city and $\sum \Delta^-$ represents those that have been exported outside the city for use in other cities or countries.

Both metrics are dimensionless indicators of performance that measure either the successful exergy destruction or the total exergy of useful product export, inclusive of the capital funds generated in a socially extended framework, per total urban resource requirement. Close examination of the energy conservation equation reveals that the ability of cities to be efficiently self-sufficient in their consumption, that is, values of ϵ_U closer to unity, and their ability to be efficient producers, that is, ϵ_C closer to unity, are at odds. This tradeoff between the two aspects of cities is demonstrated in Fig. 2.

The overall magnitude of resource effectiveness of cities can then be captured as $R \coloneqq \sqrt{\epsilon_U{}^2 + \epsilon_C{}^2}$ measuring both producer and consumer capabilities. As such, its value provides a system-wide performance metric for using and transforming resources available. The tension between the consumer/producer behavior of the overall system can be captured as angle $\theta \coloneqq arctan\left(\frac{\epsilon_U}{\epsilon_C}\right)$, where the system is more



Resource Effectiveness in and Across Urban Systems, Fig. 1 Schematic showing a node pair and the resource flow between them broken down in exergetic terms to its utilized, wasted, and exported components. (Adapted from Arbabi et al. 2020)



Resource Effectiveness in and Across Urban Systems, Fig. 2 Effectiveness diagram showing balance between resource utilization and conversion, the overall resource effectiveness, *R*, the overall effectiveness balance, *θ*, and the city's thermodynamic limit for conservation of energy

dominantly a producer with $\theta < 45^\circ$ and is exhibiting more dominant consumer tendencies with $\theta > 45^\circ$.

Application of Resource Effectiveness in an Urban System

The main use of resource effectiveness metrics is to provide a clear understanding of the role of various economic sectors in cities and explore how this affects their needs and prospects for future growth. Such an understanding of how effective cities are in using their resources facilitates a decentralization of urban resource policy and a focus on sector-specific economic strategies and urban planning informed by the unique urban characteristics of each city (Tan et al. 2021).

Additionally, open system network models that underlie effectiveness assessment can be expanded to include nested representation of sectors in cities and their interactions across cities. Multiscale approaches, as shown in Fig. 3, would enable a thorough investigation of the cross-sector relationships and interdependencies between cities to identify the key channels of resource intake into the system and the external risks the system is exposed to. These range from disruptions due to climate change and sea level rise to changes to the infrastructure, for example, transport, facilitating resource flows. For instance, identifying the possible hazards causing disruptions to resource connections of the urban network can suggest suitable precautionary actions to secure the resource linkages in the supply chains and sustain proper functions of the urban system. Insights of this nature impact regulatory decisions on how sectors and cities connect with one another and the resource connectivity in and across cities.

Data Requirements

Understanding cities and measuring how effective they are at resource consumption are data intensive. Modeling cities as open systems within an exergetic framework that allows estimation of resource effectiveness metrics requires a minimum of the following data types to be available beforehand or capabilities in estimating such information from other available datasets.

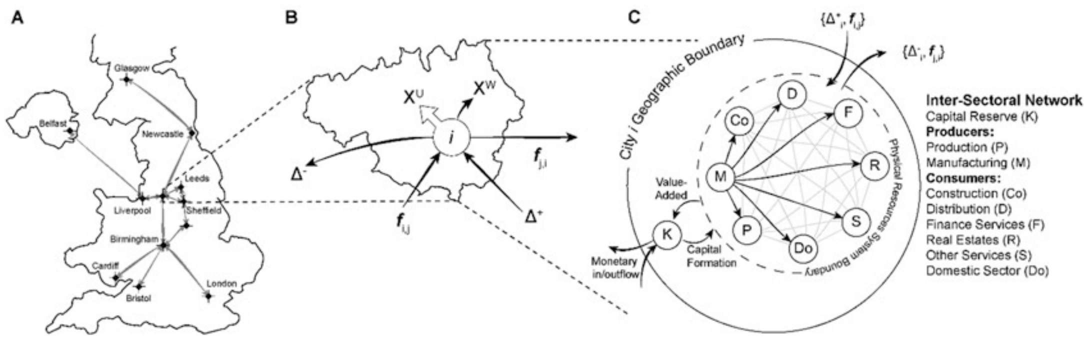
Minimum data input requirements are:

- Records of cross-boundary physical resource imports and exports in terms of their mass to estimate overall system boundary flow
- Records of virgin resource extraction through local production activities in terms of their mass or energetic content
- Monetary input-output tables and supply-and-use tables detailing the intensity of interactions between economic sectors
- Employment and labor data for industrial sectors in terms of number of employees, total hours worked, and wages
- Greenhouse gases emission intensity factors for industrial product output and domestic energy use

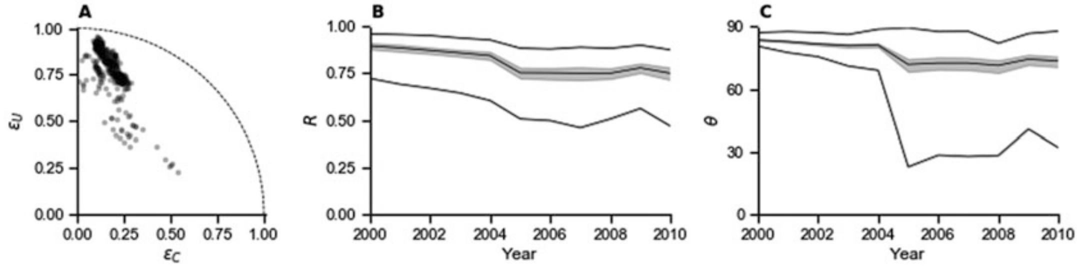
A UK Example

The example here outlines the resource effectiveness of the 38 functional urban areas building up the urban system in Great Britain. Figure 4 shows both the estimated values of ϵ_U and ϵ_C and the trajectories of R and θ between 2000 and 2010. The widespread tendency for cities to exhibit consumer-like behaviour is clear particularly on panels B and C.

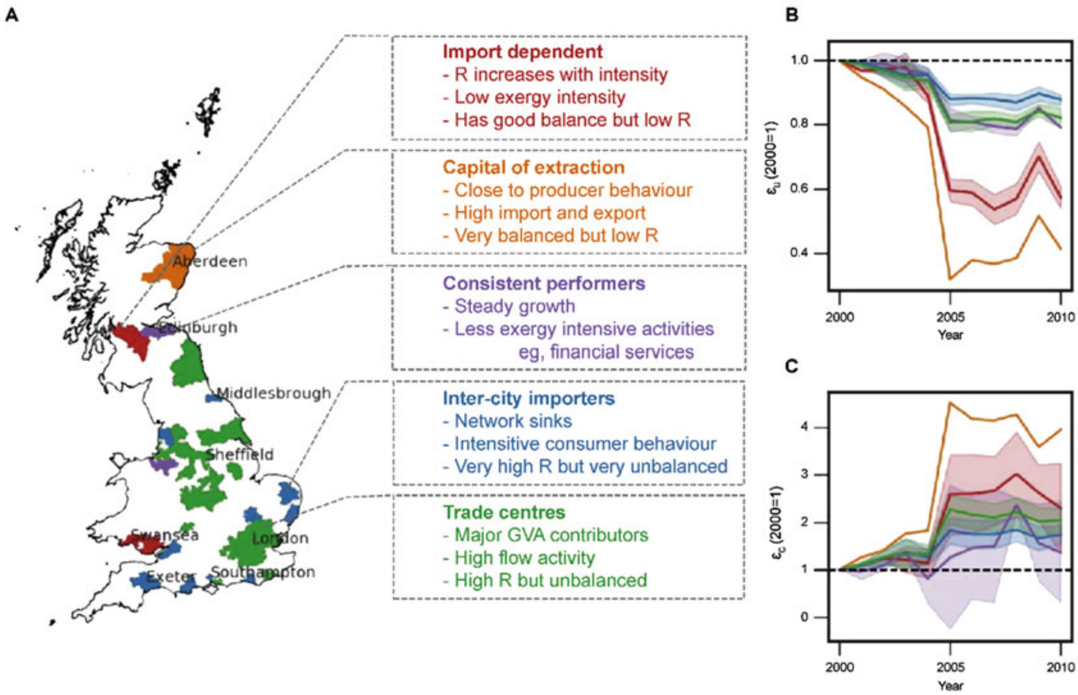
Finally, while effectiveness metrics are informative for management of individual cities, they also provide a means for the assessment of wider urban networks as a whole. Examination of clustering and similarity patterns in the resource-use behaviors across the urban system enables



Resource Effectiveness in and Across Urban Systems, Fig. 3 Schematic of an inter-urban flow network (**a**), aggregated flows over a city (**b**), and detailed inter-sectoral physical and financial flows within a city, with those of manufacturing highlighted (**c**) as a nested multiscale resource model



Resource Effectiveness in and Across Urban Systems, Fig. 4 Annual estimates of the effectiveness of resource utilization and conversion for the period 2000–2010 (**a**), annual trend showing mean and its 95% CI (shaded area), minimum, and maximum of the overall resource effectiveness (**b**), and resource balance (**c**). (Adapted from Tan et al. 2021)



Resource Effectiveness in and Across Urban Systems, Fig. 5 Map of urban clusters by resource effectiveness behavior (**a**) and indexed variations of mean ϵ_U (**b**), and ϵ_C (**c**) for each cluster with their standard deviations. (Adapted from Tan et al. 2021)

identification of common characteristics that can be addressed in system-wide resource allocation planning. For the system of cities in Great Britain as an example, the individual temporal trajectories in Fig. 4 underlie five fairly distinct consumer/producer characteristics, as shown in Fig. 5.

Cross-References

- ► Circular Cities
- ► Circular Economy Cities
- ► Sustainable Development Goals from an Urban Perspective

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