

Chapter 4

Industrial Ecology and Cities

Christopher A. Kennedy

Abstract The study of cities, or urban systems, in Industrial Ecology has a peculiar history. In the 1960s, there was a false dawn for green cities in the United States under the Experimental City project, the unfulfilled plans for which included numerous aspects of Industrial Ecology (IE). When IE eventually began to form as a discipline in the 1990s, cities or urban systems were at best a fringe topic, although their importance was recognized by thought leaders in the field. The development of research on cities as a theme within IE perhaps followed with the broadening of IE to include Social Ecology. Then the study of urban metabolism, which had its own separate literature, arguably became one of the three metabolisms within IE – along with industrial and socio-economic. In this review of work on IE and cities, a Scopus search of ISI-rated publications finds over 200 papers on the topic, many of which are in the *Journal of Industrial Ecology*. Amongst the common themes are papers on urban industrial symbiosis, urban infrastructure frameworks, transportation, waste, energy, greenhouse gas emissions, other urban contaminants, metals, phosphorus and food in cities. The great ongoing challenge for work on IE and cities remains to understand the environmental impacts related to urban metabolism and attempt to reduce them. More specific examples of possible future work include determining potentials for city-scale industrial symbiosis and uncovering how much is occurring and exploring theoretical limits to the sustainability of cities using non-equilibrium thermodynamics.

Keywords Urban systems • Urban metabolism • Industrial symbiosis • Material flow analysis • Energy • Water • Waste • Urban infrastructure

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1 A False Dawn

Between 1966 and 1973, a sustained attempt was made to initiate the construction of an experimental green city in rural Minnesota, USA (Wildermuth 2008). Promoted as a solution to the problems of inner city decay and growing concerns about environmental pollution, a site for the space age city was selected, in 1972, near the small community of Swatara, 130 miles north of Minneapolis. The vision for the city, stemming largely from its influential brainchild Athelstan Spilhaus, contained concepts that are today central to Industrial Ecology. The Experimental City would not generate any wastes, as all residuals would become useful substances. The city regulations would exclude polluting industries. Transport would be by a guideway network system, eliminating the need for cars. Furnace sewers would pump away any polluted air produced by delivery trucks in the underground service roads. Water would be completely recycled. Even buildings and infrastructure would be constructed from precast modular parts that could be adapted or reused to meet the changing needs of future generations. Energy supply for the city would be provided by a fossil-fuel-free power plant, likely nuclear, located at the city centre. No single part of the city was ever constructed – it was a utopian dream with many failings – but it was backed by powerful politicians and received hundreds of thousands of dollars in supporting grants over the 7 years of planning.

The initial instigator of the Experimental City was a scientist of the highest standing (Wildermuth 2008). Athelstan Spilhaus (1911–1998) was a South-African born geophysicist and oceanographer who is credited with developing the bathythermograph while working with the Woods Hole Oceanographic Institution in Massachusetts. The device, which provides measurements of ocean depth and temperatures from moving vessels, was important for the United States in submarine warfare during WWII and helped establish Spilhaus as a scientist of notoriety. In January 1949, at age 37, he was appointed Dean at the University of Minnesota's Institute of Technology. It was at Minnesota that his interest in future cities first began, but Spilhaus was also engaged in a broad range of scientific issues. In 1957, he began a scientific comic strip known as "Our New Age" which was published in 102 US and 19 foreign newspapers. From 1954 to 1958, he was US representative on the executive board of UNESCO and was the commissioner of a hugely successful popular science exhibit at the 1962 World Fair in Seattle. Following publication of an article on The Experimental City in *Science* magazine (Spilhaus 1968), he became President of the American Association for the Advancement of Science in 1969.

The aspects of Industrial Ecology in the Experimental City link back to Spilhaus' role as the Chair of the Committee on Pollution of the National Academy of Sciences and National Research Council. As early as 1961, Spilhaus had observed that "Waste ... is some useful substance that we don't know how to use or we don't yet know how to use economically" (quoted in Wildermuth 2008: 59). The national committee on pollution, which Spilhaus chaired from 1963, recognized that growing environment challenges in the United States were linked to increasing population and urbanization. A report by the committee published in 1967 had some bold solutions; it proposed "closed system" manufacturing, under which goods were

“designed in the first place with the return to the factory for remaking and reuse in mind” (Wildermuth 2008: 64; Committee on Pollution 1966: 06). Spilhaus’ later writings on the Experimental City recognized the dematerialization strategy of selling services rather than products: “Instead of owning things in the future, you will own the services that the things will give you” (Wildermuth 2008: 113). In an article on the Experimental City, he also notes “There are examples of industrial symbiosis where one industry feeds off, or at least neutralizes, the wastes of another...” and he provides several examples (Spilhaus 1967: 1131). Recognizing American cities to be the hot spots for pollution, Spilhaus’ committee had at first decided to conduct a case study in the highly urbanized Delaware River Basin. Getting data on pollution for the urban area proved, however, to be too challenging due to the myriad of state, county and municipal governments involved (a common challenge for urban metabolism studies). It was this experience with the frustrating institutional structures within existing cities that to a large extent encouraged Silhaus to pursue his vision of a full-scale experimental new city.

There were other powerful actors supporting the Experimental City idea (Wildermuth 2008). Back in Minneapolis, working in parallel to Spilhaus at first, newspaper executive Otto Silha had taken an interest in the idea of enclosed cities that had been popularized by Buckminster Fuller. Silha had strong connections to government and industry – including the US Vice President Hubert Humphrey, who was a former mayor of Minneapolis. Keen to see Minnesota lead the country on building new cities, Silha assembled a powerful steering committee and co-opted Spilhaus to be the front man for the project. Other members of the steering committee included a retired four-star general, a former economic advisor to President Kennedy, the personal physician of President Johnson, and further representatives from government, industry, labour unions, foundations and academia, as well as Buckminster Fuller. In May 1966, Silha’s committee received \$248,000 in federal funding to kick-start the planning of the city, with more to follow. Federal support for the Experimental City later waned, but then the state government took a stronger role. On June 4, 1971, Minnesota Governor Wendell Anderson even signed legislation to create a new state agency known as the Minnesota Experimental City Authority.

The great plans for the Experimental City came to nothing, however, due to a variety of reasons. First Spilhaus’ vision of the city was utopian, and he was inflexible with many details. The utopian aspects were not so much the ambitious technological features, although some no doubt still needed to be worked out but lay with the social and cultural dimensions. Spilhaus argued that the city should be designed for a fixed population of 250,000 people, no more or less, and that potential residents would have to be screened to achieve the right balance of required professions. Spilhaus saw the city as being a perfectible machine and ignored the aspirations of regular people. Even after Spilhaus withdrew from the implementation efforts, Silha’s committee continued to make mistakes. In choosing a possible site for the Experimental City, they failed to suitably engage environmentalists or local people, the majority of whom saw urbanization of their rural surroundings to be deplorable. Ultimately, the effort failed on both cultural and environmental

grounds. As one of the local citizen's group concluded: "the idea of relocating population masses rather than treating and solving problems of cities where they exist is just as repugnant as ... timbering without reforestation..." (Wildermuth 2008: 231). With the failure of the Experimental City project, opportunities to make progress on both green cities and Industrial Ecology were lost.

2 Formative Years of IE

When Industrial Ecology did emerge in North America around the 1990s, the subject of green cities or urban systems was at first largely absent. This can be seen from examining the contents of early books and conference proceedings in the formative years of Industrial Ecology (Table 4.1). Georg Winter's 1988 book on *Business and the Environment* considers IE from a corporate perspective; it does have advice for companies with respect to buildings, but gives no mention to cities. Contributors to a broad purview of intersections between technology and the environment (Ausubel and Sladovich 1989) mention issues of air pollution in cities and the management of municipal solid waste, but none give specific focus to cities. On May 20–21, 1991, Kumar Patel organized a colloquium on Industrial Ecology at the US National Academy of Sciences; the 23 papers from the meeting, none of which were on cities, were published in *Proceedings of the National Academy of Sciences*. A further early publication in which cities are omitted is a collection of papers edited by Brad Allenby and Deanna Richards (1994). There are also examples of IE principles being applied earlier than the 1990s outside of North America – such as in Japan in the early 1970s (Erkman 1997). The report from a US-Japan Workshop on Industrial Ecology, held March 1–3, 1993, in Irvine, California, however, has no mention of urban issues either from Japanese or American perspectives (Richards and Fullerton 1994). Of course, it may be the case that cities were considered in other early literature pertaining to IE in Japan, or elsewhere for that matter, but clearly cities were low priority.

The subject of cities did get on the agenda for the 1992 Snowmass conference on Industrial Ecology and Global Change, which was important for the development of the discipline (Socolow et al. 1994). Approximately 50 people attended the meeting in Colorado, supported by the Office for Interdisciplinary Earth Studies. One of the 32 papers in the proceedings was a study quantifying methane emissions for an American city by Robert Harris of the University of New Hampshire (Harris 1994).

In Tom Graedel and Brad Allenby's textbook on Industrial Ecology, cities are recognized in a chapter on the future of industrial activities (Graedel and Allenby 1995). The section entitled *The Ecologically Planned City* suggests that engineers might consider cities "as systems to be optimized for sustainability" (p. 336), but discussion is limited to just two paragraphs. The reason for such little detail on cities perhaps becomes apparent in Allenby's later text on policy frameworks and implementation of IE – which indicates that the science has yet to be done. Under the subtitle *Physical Models of Communities*, Allenby (1999: 20) writes:

Table 4.1 Coverage of cities or urban systems in early books or conference proceedings on industrial ecology

Book or conference proceeding	Content on cities or urban systems
Winter (1988). <i>Business and the environment: a handbook of industrial ecology with 22 checklists for practical use</i>	No chapters, or checklists, specific to cities
Ausubel and Sladovich (1989). <i>Technology and environment</i>	Cursory mention of urban air pollution and waste management
National academy of science colloquium on industrial ecology published in PNAS (1992)	No papers specific to cities
Allenby and Richards (1994). <i>The greening of industrial ecosystems</i>	No chapters or cases on cities
Socolow et al. (1994). <i>Industrial ecology and global change</i>	One paper on reducing urban sources of methane
Richards and Fullerton (1994). <i>Industrial ecology: U.S. –Japan perspectives</i>	No urban content
Graedel and Allenby (1995). <i>Industrial ecology</i>	Two paragraphs on ecologically planned cities
Ayres and Ayres (1996). <i>Industrial ecology: towards closing the materials cycle</i>	Brief mention of a proposed industrial ecosystem including a municipal waste treatment plant
Lowe et al. (1997). <i>Discovering industrial ecology: an executive briefing and sourcebook</i>	Section on applications of IE for local government
Allenby (1999). <i>Industrial ecology: policy framework and implementation</i>	One paragraph describing the need for research on physical models of communities
Ayres and Ayres (2002). <i>A handbook of industrial ecology</i>	Three chapters on: urban material flows, urban planning; and municipal waste
Bourg and Erkman (2003). <i>Perspectives on industrial ecology</i>	One chapter on urban transportation and IE

Note the list of books examined here may not be comprehensive and is influenced by availability at the University of Toronto library and online access

It is increasingly chic for some communities to call themselves “sustainable communities” yet the science to understand what such assertions really mean has yet to be done. Developing integrated models of urban communities, including small, relatively self-contained cities, larger cities with surrounding suburbs, and large megalopolises with decayed centres and most business activity decentralized throughout the suburbs will be a necessary step in achieving such an understanding. Urban centres in developing and developed nations should also be modelled and compared. Such models would include: transportation, physical infrastructure, food energy, material stocks and flows, and other systems. Both direct and embedded impacts (...) should be included. This information would facilitate identification of major sources of environmental impacts, patterns of activities that give rise to them, and potential environmentally preferable technological or mitigation options. It would also provide a necessary basis for comparing the environmental impacts of different kinds of communities, as well as creating higher level, integrated regional models.

Further recognition of the topic of cities is given in *Discovering Industrial Ecology* by Ernest Lowe, John Warren and Stephen Moran (1997). The front cover shows a night-time city panorama superimposed on to a view of Earth from Space.

Inside the authors include a city public works director in a conversation amongst six professionals about the challenges of implementing IE. A chapter on opportunities for governments in applying IE discusses the need to develop integrated models of urban communities. Several pages on local government then describe how practical applications of IE in cities can lead to waste reduction, extended capacity to local infrastructure, development of resource exchange markets and related economic development – all of which should be pursued within strategic community green planning. As part of this planning, Lowe et al. also encourage the study of urban metabolism (although they call it the industrial metabolism of the community).

In *A Handbook of Industrial Ecology* (Ayres and Ayres 2002), cities are explicitly recognized as being relevant to IE – at least to a small extent – by the inclusion of 3, out of 46, chapters relating to urban issues. The first of these, by Ian Douglas and Nigel Lawson (2002), shows sensible understating of the dominant material flow processes being entitled *Material flows due to Mining and Urbanization*. With respect to the urban end, Douglas and Lawson distinguish between the urban fabric of buildings and infrastructure with slow turnover of materials and the other materials such as food, clothing, packaging, water and energy that flow relatively rapidly through cities. They also note how, over centuries, the in situ deposition of construction and demolition waste in cities gradually raises the elevation of cities. The authors also make reference to a limited number of ecological footprint studies and urban material flow balances, but concede like others previously, that these are challenging to conduct. They resort to presenting a few measures of Earth moved or materials placed in major tunnels, airports runways or similar projects in the United Kingdom or otherwise present national level data.

In *Industrial Ecology and Spatial Planning*, Clinton Andrews (2002a) explains some of the important linkages between industrial ecology and the activities of urban planners. He begins by recognizing that geography matters because it brings details of scale and the level of analytical resolution to IE. Challenges in applying IE to cities sometime occur, however, because of misalignment between natural and political boundaries and the existence of multiple levels of government. Andrews notes the wide variation in physical characteristics of cities worldwide and also comments that planning practices are just as varied – e.g. ranging from pure regulatory roles to those who are active in shaping urban form. He then discusses several intersections between spatial planning and IE: (1) connection between urban patterns and the environmental performance of cities; (2) the significant role for planners in eco-industrial developments, which are subject to a several regulatory issues; (3) urban waste management; (4) several ways in which the design of the built environment impacts eco-efficiency; (5) the use of non-toxic, biocompatible materials in cities; and (6) the potential for industrial ecologists to study behavioural attributes of citizens, linked to policy interventions. Andrews concludes with a warning that IE should be careful to learn from some of the ill-conceived, utopian interventions that urban planners implemented in previous decades.

Like planning, prescriptive IE is in danger of cycling from hubris to despair before discovering humility and effectiveness.....Until the grand visions of IE are tempered by implementation experience they will be a poor basis for public decisions. (Andrews 2002a: 487)

A second contribution from Andrews in the *Handbook* examines municipal solid waste management through the combined lens of IE and political economy. Andrews (2002b) notes that methods of IE have been used by US waste management policy analysts since the 1970s for mass flow analysis and since the 1980s for life cycle assessment. The perspective of political economy is required to address issues beyond IE – such as trans-boundary transport, deregulation and environmental justice. Andrews provides integrative analysis of the predominant actors at each stage of the product life cycle. This leads to an examination of the basis for government intervention and a summary of lessons from implementation.

A further collection of papers on IE edited by Dominique Bourg and Suren Erkman (2003) includes one urban flavoured chapter, out of 28, this being on Urban Transportation and IE by Tom Graedel and Michael Jensen (2003). The short paper reviews the costs and benefits of automotive transportation and considers three different approaches to optimizing the net benefits. An urban system is proposed comprising trams, high-speed networks and feeder lines, with automobile restricted to low-density suburbs and new ways of handling personal cargo developed.

This review of formative literature on IE shows relatively sparing attention to urban systems, but it would be wrong to conclude that the early protagonists of IE failed to understand the significance of cities in environmental challenges. For example, both Andrews and Graedel were attendees of the Snowmass 1992 summit and were (and remain) influential within IE. Andrews was coeditor of the Snowmass proceedings and went on to become a Chair of Planning at Rutgers University, where he published several papers pertaining to IE and cities (some discussed below here). Graedel, the first Professor of Industrial Ecology, and the first President of the International Society for Industrial Ecology (ISIE), examines metal stocks and flows in cities within his wider work at other scales. Another who worked on cities was Jesse Ausubel, coeditor of a National Academy of Engineering book on *Cities and Their Vital Systems* (Ausubel and Herman 1988). Like Andrews and Graedel, he attended the formative meeting of the ISIE in 2000 and also coedited the proceeding of a National Academy of Engineering meeting on Energy and Environment (Ausubel and Sladovich 1989). A further attendee at the Snowmass meeting – and early influence in IE – was Arnulf Grübler – who had a profound understanding of the role of cities on global environmental change. In his text *Technology and Global Change* (Grübler 1998) – which arguably should be the first textbook read by students of IE – Grübler clearly describes how the phenomena of urbanization result from improvements in agricultural productivity.

3 Into the Twenty-First Century

Moving into the twenty-first century, there is the emergence of an academic research literature specifically concerned with applications of IE to cities. This can be examined through use of the search function on Scopus, although many caveats are required. A first set of search results, shown in Fig. 4.1, is for papers that explicitly

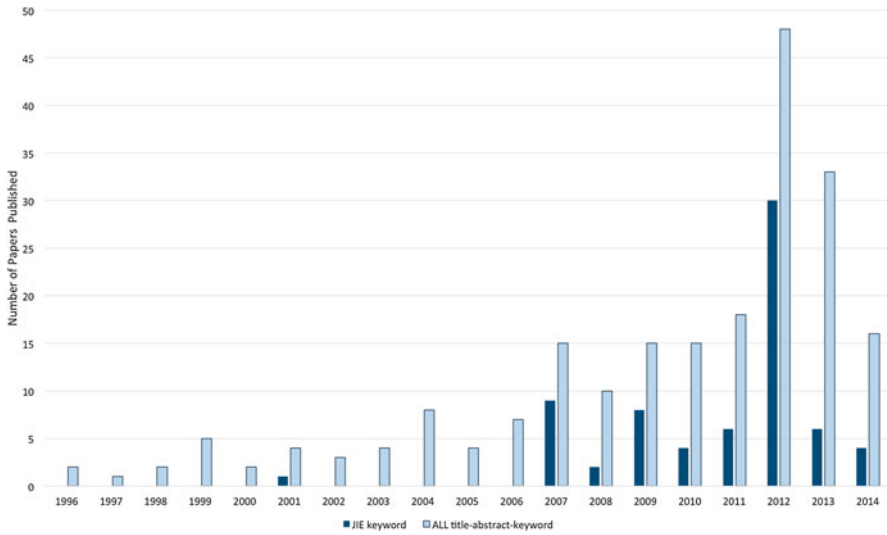


Fig. 4.1 Papers published (1996–2014) in: (1) Scopus-tracked journals including industrial ecology and cities, city, urban or urbanization in the title, abstract or keywords; (2) the Journal of Industrial Ecology, including the keywords cities, city, urban or urbanization

use the term “industrial ecology” and any one of four city-related words: “cities”, “city”, “urban” or “urbanization” in the title, abstract or keywords. The search results are modified to remove obvious anomalies as well as articles in press for 2014. Still, the search results include some papers that perhaps do not really reflect the essence of applying IE at the city scale while missing others that do. To give some examples, several of the early papers discuss eco-industrial parks as a strategy for sustainable cities, or eco-parks which just happen to be in cities, without really reflecting the idea that industrial symbiosis might be more broadly applied on a city scale. Similarly, the search picks up a few papers that are focused on household consumption within cities, which, while contributing to urban metabolism, might miss industrial and larger-scale urban processes in cities. Another scale-related problem is that a few papers are included that primarily discuss energy or material flows at national and regional levels, with only brief mention of processes at the urban scale. Of the 212 papers recorded in the first search perhaps as many as half might be rejected if the search were restricted to research at the city scale. That said, the search terms exclude a potentially large literature on energy and material flows in cities that does not use the term “industrial ecology”. Omitted papers include, for example, a material flow study of paper in a city (Leach et al. 1997) and an overview of strategies for the ecological restructuring of cities (Hahn and Simonis 1991). In more recent years, industrial ecologists have made numerous studies of greenhouse gas emissions associated with cities (e.g. Kennedy et al. 2009), or urban sustainability more broadly (e.g. Baynes and Wiedmann 2012), many of which are missed.

Most significantly, the search misses many papers on urban metabolism – now seen as central to urban IE – but also used in other fields; this will be addressed in a separate section below.

A few reoccurring themes can be observed within the Scopus-tracked papers in the first search. Starting with a paper by Robbins and Kumar (1999), several authors discuss the application of industrial symbiosis with an exchange of residuals occurring broadly at a city scale (Cerceau et al. 2014; Liu and Chen 2013; Chen et al. 2012; Giurco et al. 2011; Van Berkel et al. 2009a, b). Amongst these are two papers by Pierre Desrochers which suggest that industrial symbiosis has a long history in cities (Desrochers 2002; Desrochers and Leppälä 2010). A couple of papers analysing the use of biogas or sewage gas for transportation in Swedish cities might also be considered examples of city-scale industrial symbiosis (Fallde and Eklund 2015; Vernay et al. 2013). The topic of waste has been addressed in several papers, including work focussed on e-waste (Leigh et al. 2012), healthcare waste (Soares et al. 2013) and construction and demolition waste (Bohne et al. 2008), as well as city-specific waste studies (Murphy and Pincetl 2013; Chertow and Eckelman 2009). Urban infrastructure systems have been researched in both broad and narrow contexts. In a broad sense, several sustainable infrastructure or resource frameworks have been published (Ramaswami et al. 2012a, b; Hodson et al. 2012; Agudelo-Vera et al. 2012). Narrower sector-specific infrastructure studies include those on water systems, including drinking water, wastewater and storm water (Venkatesh 2013; De Sousa et al. 2012; Venkatesh and Brattebø 2012; Kenway et al. 2011; Pasqualino et al. 2011; Venkatesh et al. 2009). At least two papers have examined the historical use of energy in cities (Reiter and Marique 2012; Baynes and Bai 2012). Also related to energy, amongst other activities, is a large number of papers on greenhouse gas emissions for cities (Ramaswami et al. 2012a, b; Mohareb and Kennedy 2012a, b; Chavez et al. 2012; Sugar et al. 2012; Feng et al. 2012; Shi et al. 2012; Bullock et al. 2011; Kraines et al. 2010; Lebel et al. 2007; VandeWeghe and Kennedy 2007), although this is just a subset of a larger literature. Other contaminants featured include heavy metals (Batzias et al. 2011) and PBDEs (Vyzinkarova and Brunner 2013). There is also a distinct grouping of papers on the theme of metals in cities, including urban mining (Kral et al. 2014; Zhang et al. 2012; Klinglmair and Fellner 2010; Månsson et al. 2009; Drakonakis et al. 2007; Harper et al. 2006). Similarly, several papers address stocks and flows of phosphorus in cities (Ma et al. 2013; Kalmykova et al. 2012; Li et al. 2012; Fu et al. 2012), while others have addressed food more broadly (Broeze et al. 2011; Neset et al. 2006; Waggoner 2006). Over 200 papers on cities and IE are picked up in the first Scopus search, only a few of which have been mentioned here in order to demonstrate the dominant themes of the literature.

Much of the recent upward trend in publications on IE and cities is due to papers in the Journal of Industrial Ecology (JIE); it accounts in particular for the steps up in publications in 2007 and 2012 (Fig. 4.1). The second search in Fig. 4.1 is for all titles in the JIE for the keywords cities, city, urban or urbanization. In 2007, JIE had a quasi special issue on *Industrial Ecology and the Global Impacts of Cities*, edited by Xuemei Bai, with nine articles (picked up by the keyword search). Since then

there have been between 2 and 8 urban systems papers per year in JIE, with the exception of 2012 when 30 papers are recorded. This was due to the publication of a full special issue on *Sustainable Urban Systems* with Larry Baker, Shobhakar Dhakal, Anu Ramaswami and myself as coeditors.

In addition to the journal articles on IE and cities, the past decade has also seen publication of textbooks on the topic. Amongst these is *Sustainable Urban Metabolism* by Paulo Ferrão and John Fernández (2013). Another that explicitly recognizes IE is *Vortex cities to sustainable cities: Australia's urban challenge* by Phil McManus (2005).

4 Urban Metabolism

The interdisciplinary field of Industrial Ecology can today perhaps be broadly understood as the study of the three types of metabolism – industrial, socio-economic and urban. When IE first began to establish as a discipline in the 1990s, it primarily did so with an initial focus on industrial metabolism. Inclusion of urban metabolism within IE arguably only occurred once IE had broadened to include Social Ecology (Fischer-Kowalski and Hüttler 1998); urban metabolism can be seen as a scale-delineated component of socio-economic metabolism. The term urban metabolism, however, seems to predate the term industrial metabolism, which is usually attributed to Ayres (1994). Abel Wolman's influential paper on the *Metabolism of Cities* was published in *Scientific American* in 1965, while the notion that cities have a metabolism can perhaps be traced back further to Marx (Newell and Cousins 2014). Interestingly, Wolman was a member of the Spilhaus' Committee on Pollution in the early 1960s, as was Alan Kneese who co-authored the highly influential paper on material flows in an economy with Bob Ayres in the late 1960s (Ayres and Knesse 1969). So the study of urban metabolism and industrial metabolism do have some shared history.

The topic of urban metabolism nonetheless has its own literature, originally separate from Industrial Ecology. Starting from the 1970s, quantitative studies of the metabolism of actual cities have been conducted by researchers from several disciplines including civil engineering, chemical engineering, ecology and urban planning (Kennedy et al. 2007). Significant contributions to urban metabolism in the early years included works by Newcombe et al. (1978), Odum (1983), Baccini and Brunner (1991) and Girardet (1992). The first urban metabolism study to recognize the term industrial ecology appears to be Peter Newman's study of Sydney in 1999. A review of the urban literature with discussion of applications to urban planning and design is given by Kennedy et al. (2011), with an extension to include a growing number of Chinese studies by Zhang (2013). Barles (2010) explores the origins of urban metabolism in relation to sustainable urban development. More recent review papers by Broto et al. (2012) and Newell and Cousins (2014) have examined relations between studies of urban metabolism in the fields of industrial ecology, urban ecology and political ecology.

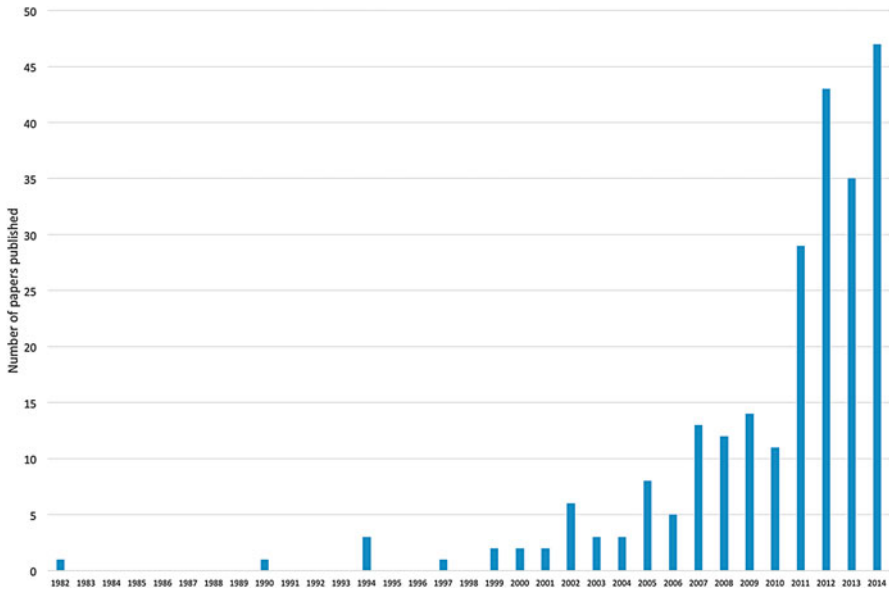


Fig. 4.2 Papers published (1982–2014) in Scopus-tracked journals including urban metabolism or metabolism of cities in the title, abstract or keywords. Wolman’s 1965 publication off the chart

A further search using Scopus shows an increasing number of publications on urban metabolism over the past 15 years or so (Fig. 4.2). Around the turn of the century, there were typically two papers on urban metabolism published each year, but the number increased to 47 in 2014. The results for early years in this search should be treated cautiously, as some works recognized today as urban metabolism studies do not register. Notably, none of the works in the 1970s, between Wolman’s paper and one by Olson in 1982, were picked up in the search. Nonetheless, it is clear that research on urban metabolism is accelerating.

5 Future Directions

The grand challenge for IE and cities is to understand the environmental impacts of the urban metabolism and pursue plans and strategies to reduce them. These aspirations are to some extent the same as those of Spilhaus and the Experimental City project 50 years ago, but necessarily tempered with large doses of practicality, as raised by authors such as Andrews. Unlike Spilhaus’ efforts, the applications of IE have to first be in today’s existing cities, many of which are rapidly growing. It might be possible in some countries or cultures that new cities are built on green-field sites, possibly on the edge of existing cities – and principles of IE might be incorporated to some degree. A small example of an experimental green city does exist in the case of Mazda, UAE; important lessons have been learnt at Mazda, such

as the cost of building a city with the pedestrian realm one storey up above a ground floor dedicated to service vehicles and personal rapid transit pods. Nonetheless, sustainable transformation of today's existing and expanding cities is where the challenge lies.

Although not complete, the study of cities in Industrial Ecology has come a long way since Allenby's (1999) observation that the science had yet to be done. Progress has been made with a combination of broad holistic analyses of urban metabolism – the scale upon which differences are measured – and more detailed studies of specific resource flows or infrastructure systems – which reveal the inner workings of the city. As more cities, hopefully, move towards greater practical application of IE, then attention to both scales will be important. There is a need for further study of material flows in cities; few studies have quantified material stocks and flows with as much detail as those in Lisbon (Niza et al. 2009) or Paris (Barles 2009). More refined understanding of material flows will be necessary to address questions in a couple of related future directions discussed below: increased application of industrial symbiosis at the city scale and examination of the thermodynamics of urban metabolism.

Just how much potential is there for industrial symbiosis to be conducted at the city scale and how much of such sharing or recycling of residuals is already taking place? Examples such as the case of Kawasaki, Japan, where 565,000 tonnes of potential waste per year are diverted through seven key material exchanges hint at significant potential for industrial symbiosis in cities (Van Berkel et al. 2009a, b). Drawing upon four examples of urban regions where waste exchange is practiced, and citing several nineteenth and early twentieth century authors, Desroches (2002) argues that urban industrial symbiosis used to be relatively common. "The fact that cities or regional economies... have probably always exhibited localized inter-industry recycling linkages seems highly plausible" (Desroches 2002: 35). He suggests that industrial symbiosis is a form of agglomeration effect that occurs due to the high volumes and close proximity of waste-producing activities in cities. As well as further empirical studies, perhaps there is potential to develop theoretical economic models that describe such agglomeration effects. Further research might also seek to determine the limits to which industrial symbiosis or other notions of the circular economy can practically be applied in cities. Some categories of materials cannot be recycled or require so much energy as to be undesirable (Ayres 1997; Allenby 1999; Allwood 2014).

A final challenging topic, which will also inform the questions on industrial symbiosis, is the development of improved theoretical understanding of the urban metabolism using thermodynamics. This is important for addressing concerns over possible limits to the notion of sustainable cities. If cities were to pursue high levels of efficiency, and greater closing of material loops through increased industrial symbiosis, what would be the repercussions, feedbacks or rebound effects? For example, if today's cities were able to cut their consumption of fossil-fuel energy use in half, might that just result in the saved fuels being used to build more cities? Nonequilibrium thermodynamics, as used by Bristow and Kennedy (2015) to understand the growth of cities, might tentatively offer insights into such questions. A

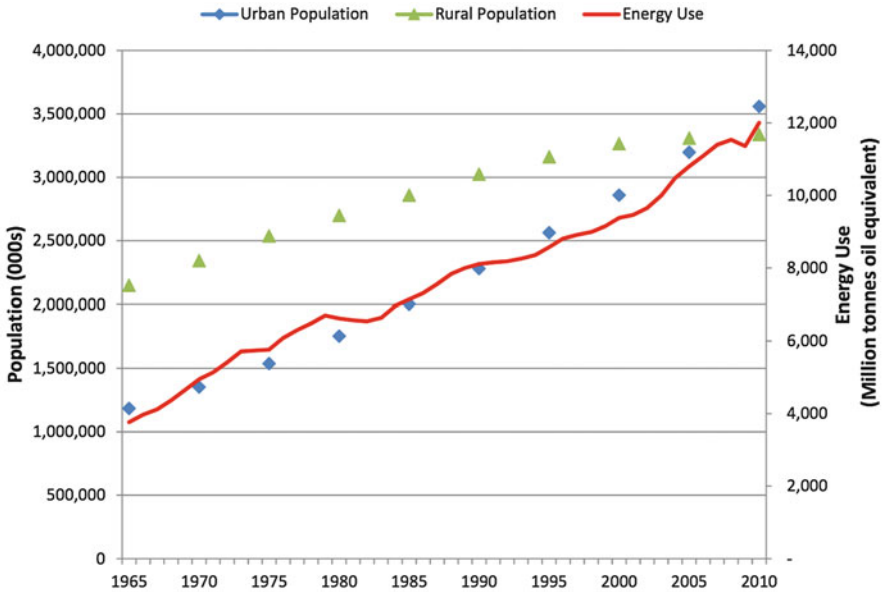


Fig. 4.3 Global energy use, urban and rural population, 1965–2010 (Figure 4.3 from Bristow and Kennedy 2015)

possibly important finding in this regard is the strong relationship showing that global energy use is directly proportional to global urban population (Fig. 4.3). Three areas for future research on the thermodynamics of cities are proposed: (1) development of nonsteady, nonequilibrium thermodynamic models specific to cities or systems of cities; (2) more studies of exergy gradients for cities; and (3) exploration of the possible intersection of thermodynamic and economic theories of urban growth (Bristow and Kennedy 2015).

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