Towards Urban Energy System Indicators

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Executive Summary

The BP Urban Energy Systems project seeks to "at least [halve] the energy intensity of cities" (Shah et al., 2006: 3) and this goal requires the creation of a set of urban energy system indicators in order to understand and measure urban energy use. Unfortunately much of the existing work on urban indicators has focused on developing measures to fulfil communication roles; the more demanding task of creating analytical indicators has been given less attention.

To address this problem, a UES indicator framework was developed based on the notion of energy services. In this model, the use of energy is seen as a thread running through nearly all aspects of the urban system. Therefore instead of selecting energy indicators according to the traditional sustainability domains or other such classifications, the proposed framework concentrates on energy consumption as a demand derived from urban activities. Metrics are accordingly chosen to represent the core stages of consumption: the drivers of activity demand, energy-using activities themselves, the resources required to meet these demands, and the impacts of resource consumption. An additional system category was added to encapsulate aggregate and technical performance measures, as well as important contextual information vital for the interpretation of the core indicators.

The framework was tested by gathering data on London's energy system from readily-available sources. A total of 110 core indicators were identified, with 39 metrics suggested as candidates for facilitating comparisons with other cities. To summarise the results, a number of methods were reviewed for creating aggregate "headline" indicators and several potential measures of system performance were also discussed. While these analyses were useful, the main goal of this case study was to assess the indicator framework and the question of indicator selection more generally. To this end, several important issues were raised. These included how to draw the boundaries of analysis, how to overcome data availability constraints, how to implement an indicator framework consistently in a multi-scale analysis environment, and the need for a clearly-defined theory of urban energy performance.

The report therefore concludes that no single indicator is likely to fulfil all requirements of UES indicators. Nonetheless it is hoped that the framework and issues presented here will help the project to develop multi-scale UES indicators that support valid analyses and ultimately facilitate engagement with urban energy system stakeholders.

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Introduction

Energy systems have been described as “the combined processes of acquiring and using energy in a given society or economy” (Jaccard, 2005: 6) but this brief definition is open to a variety of interpretations, particularly in the urban context. For example, analysts might restrict themselves to the physical flows of energy and resources within a small neighbourhood (e.g. Thomas, 2003). Alternatively, social scientists and policy makers may wish to consider how energy use is affected by “town planning, environmental goal-setting, employment policies, and so on” (Alexandre et al., 1996: 253). The BP Urban Energy Systems (UES) project will need to consider these and many other perspectives to “identify the benefits of a systematic, integrated approach to the design and operation of urban energy systems“ (Shah et al., 2006: 3) and the development of an effective set of urban energy system indicators will therefore be vital to meeting this goal.

The list of potential UES indicators is long. At the most basic level, the project has “a view to at least halving the energy intensity of cities” (Shah et al., 2006: 3) and therefore core measures of energy performance are required. However to understand how the energy performance of a city might change over time or in response to policy interventions, other indicators will be needed to describe related urban features such as economic structure, population, and environmental quality. A review of existing literature on urban sustainability and energy system indicators has therefore been conducted to assess the potential contribution of existing measures to the goals of the UES project.

The project's annual report and other publications have presented early versions or specific aspects of the indicators research (Shah et al., 2006; Keirstead, 2007; Keirstead et al., in press). However feedback from the advisory board highlighted that the indicator work needs to be integrated with other project components from an early stage. In particular, strong links between indicators and the development of the 'synthetic city' modelling platform were noted; research on energy systems innovation, consumer behaviour, urban metabolism, transport and energy networks will also shed light on the parameters that should feature in the UES indicator suite. This report therefore has the following goals:

- to provide a summary of the indicator research to-date
- to outline a proposed framework for UES indicators and demonstrate it using collected data for London
- to solicit feedback from team members on indicator issues, in particular how the indicator work might integrate with modelling efforts.

The report is divided into four major parts. First, a brief review of the literature on urban sustainability indicators is presented (Section 1) and the proposed indicator framework outlined (Section 2). In the second part, four basic indicator themes are discussed in detail (Sections 3 through 6). A wider view is taken next, considering possible techniques for developing 'headline' aggregate indicators (Section 7) and system performance indicators (Section 8). Finally, a summary of the main findings is presented along with a list of specific issues for discussion (Sections 9 and 10).

Part I: BACKGROUND

Urban sustainability literature provides the most immediate precedents for urban energy system indicators. After outlining the key features of these existing approaches, a framework for the indicator activities of the UES project is developed.

1 Urban sustainability indicators

With approximately 50% of the world's population now living in cities (UN, 2006), the sustainability of urban environments is a major issue. As centres of economic and cultural activity, cities can deliver significant quality of life improvements to both developed and developing countries. However these benefits are threatened by a range of issues including urban sprawl, sanitation and water provision, waste management, and social and economic inequalities (Starke, 2007). Nor are the effects of urbanisation confined to the city limits. Meeting the food, energy and material needs of a city will draw upon global resources and contribute to international issues such as climate change and biodiversity loss. As Agenda 21 makes clear, cities are therefore central to both local and global sustainability (UNDESA, 1992).

For many cities, addressing sustainability begins with a definition of indicators, i.e. "a parameter, or a value derived from parameters, which points to, provides information about, describes the state of a phenomenon/environment/area, with a significance extending beyond that directly associated with a parameter value" (OECD, 2003: 5). Accordingly, indicators are commonly seen as policy tools, providing 'objective' input to processes such as measuring the state of the urban environment, assessing progress against desired policy targets, or educating the public about important sustainability issues (e.g. Alberti, 1996; AtKisson, 1996). This need for trusted metrics means that, of the three indicator criteria noted by the OECD (2003), policy relevance and measurability are given priority; the validity of the metrics often has a secondary role, hence limiting their ability to provide meaningful insights into how the urban environment might be improved. When developing London's quality of life metrics for example, the Mayor's Sustainable Development Commission noted that there were a number of issues which "the Commission would like to measure, but for which there are no available data" (LSDC, 2006); as in other studies (Donatiello, 2001; Streimikiene et al., 2007), this consequently led to the use of a reduced set of metrics supported by readily-available data.

The use of sustainability indicators is not restricted to urban governments. As Table 1 shows, a variety of stakeholders have used these metrics at urban, national, and international scales. Each group has its own requirements and consequently there are a significant number of indicator frameworks, as well as individual metrics. For example, Walton et al. (2005) identified 675 urban sustainability indicator frameworks, Parris et al. (2003) mentioned over 500 efforts, and Mihyeon Jeon et al. (2005) found 186 indicators on sustainable urban transport alone. Yet despite this wealth of indicator activity – or perhaps because of it – only a limited consensus on the form of urban sustainability indicators has been reached. Indeed it has been observed that “there are no indicator sets that are universally accepted, backed by compelling theory, rigorous data collection and analysis, and influential in policy” (Parris et al., 2003: 559).

Table 1. Sample studies using (urban) sustainability indicators

Group	*Example studies*
Urban governments	(e.g. City of Cape Town, 2002; SFOC, 2004; City of Melbourne, 2005; Hong Kong SDU, 2005; LSDC, 2005; BCC, 2006; TMG, 2006)
National governments	(e.g. EEPSEA, 2000; Spalding-Fecher, 2002; LBNL, 2004; JFS, 2006; SDC, 2006)
International organizations	(e.g. IAEA, 1999; UN, 2001; OECD, 2003; EEA, 2006a)
Industry	(e.g. Good Energy, 2005; Shell, 2005; BP, 2006a; BP, 2006b; Ofgem, 2006)
Non-government organizations and think-tanks	(e.g. YCELP et al., 2005; GRI, 2006; Helio International, 2006; IISD, 2006; NEF, 2006; Sustainlane, 2006)
Academia	(e.g. Alberti, 1996; Ooi, 2005; Lee et al., 2007)

Despite the diversity of urban sustainability indicators, the review found that the emphasis on indicators as ‘objective’ policy tools did lead to some common practices. For example, great care is often taken: to clearly describe indicators, their data sources and interpretation; to arrange them according to policy goals or broad sustainability themes; and to ensure that indicator selection and use are transparent to interested stakeholders. These trust-building features of the indicator selection process are generally positive and can be adopted for our work. However, two major weaknesses of current practice also need to be acknowledged. First, indicators are not objective; evidence shows that the selection and use of indicators is very much the product of social processes and political debates (Connolly et al., 1999; Jacobs et al., 2000; Astleithner, 2003; Baker et al., 2006).[1] Secondly, the limits of data availability and participatory processes mean that the selected indicators often provide a rather superficial overview of urban sustainability; several authors have noted that more sophisticated views of sustainability issues are frequently neglected (Brugmann, 1997; Ooi, 2005). Since both of these issues arguably stem from the lack of a strong theoretical basis for indicator selection, the challenge is to re-introduce the importance of theory and analytical validity to the selection of indicators.

[1] i.e. following Marilyn Strathern’s paraphrase of Goodhart’s law, ‘When a measure becomes a target, it ceases to be a good measure.’

2 A framework for UES indicators

Although the project's energy focus unavoidably influences the way in which the above general problems are addressed, it has been argued that an energy-centric analysis of urban sustainability can offer genuine theoretical and practical advantages (Keirstead et al., in review). Theoretically, it has been noted that energy offers a good "entry-point" to a variety of urban sustainability issues (OECD, 1995) "since human activities are closely linked to energy use" (Kemmler et al., 2007: 2467). Yet despite its importance, Hammond (2000) has noted that energy issues are often poorly represented in traditional sustainability assessments; even when explicit energy sustainability indicators are designed, they can often be interpreted as extensions of the basic, data-limited indicators discussed earlier (e.g. Patlitzianas et al., ; IAEA, 2005; Mega, 2005). However there are exceptions. For example, the UK's energy sector indicators describe basic energy flows (i.e. supply and demand trends) as well as providing a complementary series of system-performance measures relating to market competition and network reliability (DTI, 2006b). Furthermore, literature from techno-economic studies (Aki et al., 2003; Giannantoni et al., 2005; Tonon et al., 2006), thermodynamics (Afgan et al., 2000; Balocco et al., 2000; Gong et al., 2001; Wall et al., 2001; Rosen, 2002; Balocco et al., 2006), and ecology (Brown et al., 1997; Haberl et al., 2004; Cabezas et al., in press) offers a variety of metrics that could prove useful in assessing urban energy systems and their links with wider sustainability debates.

So how might we develop an effective set of UES indicators? As noted above, one of the strengths of current practice is an emphasis on transparency in indicator selection. This goal can be achieved through the use of an accepted indicator selection methodology. While several alternative strategies exist (e.g. Alberti, 1996; Bell et al., 1999; Hemphill et al., 2004) Maclaren's "structured process for urban sustainability reporting" (1996) has been chosen here. As Figure 1 shows, the methodology is iterative and so the final choice of indicators will continue to evolve as the project progresses; however at present, the goal is to work through the initial stages and identify a set of indicator selection parameters to promote discussion.

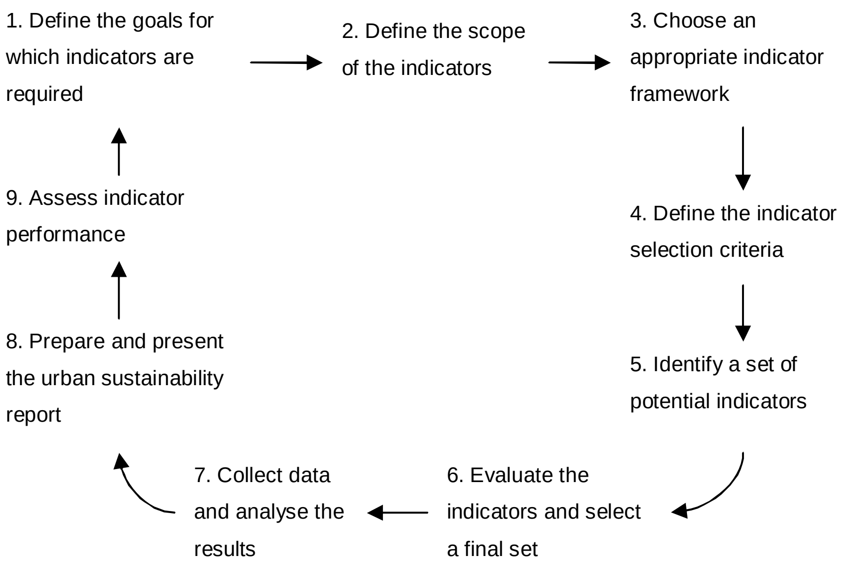

Figure 1. Methodology for selecting urban sustainability indicators (Maclaren, 1996)

In the method's first step, we identify the potential audiences for the UES metrics and their indicator requirements. During the project's early stages, it is assumed that the indicators will be used primarily for analysis and modelling. Since the project members are energy experts, this means that more advanced indicators can be used (i.e. both greater number and sophistication of metrics). In the longer term however, the project will need to share its results with decision-makers and non-expert groups. This is likely to require a modified set of indicators, emphasising communications and public engagement roles.

The initial development of indicators by experts is not uncommon and in fact it has been found to help engage wider audiences by setting a cornerstone for sustainability debates (IAEA, 1999; McAlpine et al., 2006). However for this dialogue to succeed the process must be transparent; stakeholders need to understand why particular metrics have been chosen, why certain assumptions were made and how the underlying data have been collected. This process is particularly important in Maclaren's second step, declaring the scope of the indicators. Scope accounts for the number of indicators, as well as their temporal and geographic range. For the UES indicators, there is a strong case for a large number of base indicators as a range of temporal and geographic scales will need to be represented in order to account for issues such as:

- the reliability of energy networks (evaluated on second or sub-second timescale);
- patterns of urban growth and global change (decadal); and
- urban/regional/global interactions (e.g. material and resource flows)

The third step is to select an indicator framework. A framework helps to structure the selection and use of indicators by ensuring that all relevant elements of the sustainability assessment have been considered. In other words, the framework tries to provide the theoretical foundation of the indicator set while meeting the practical goals of the stakeholders. Maclaren identifies several commonly-used frameworks, e.g. those centred on specific sustainability issues (e.g. climate change), the general domains of sustainability (e.g. social, environmental, economic), or particular causal relationships (e.g. driver-state-pressure-impact-response (EEA, 2006b)). Such approaches could be modified to incorporate energy system metrics and existing energy sustainability studies have arguably done this (e.g. IAEA, 1999). However modifying an existing approach creates a risk that energy issues are shoe-horned into a theoretical framework designed for an alternative purpose; in such cases, Maclaren notes that an appropriate response may be to create a custom indicator framework.

The indicator framework presented here uses energy as a consistent organizing principle, specifically focusing on energy-service demands and its links to energy flows and the rest of the urban system. Inspiration for the design comes from the long-standing observation that energy is a derived demand; that is, people do not want to consume kilowatt-hours of electricity or emit the associated tonnes of greenhouse gas emissions (e.g. van Raaij et al., 1983; Carbon Trust, 2006). Energy use and its impacts are largely a by-product of the demand for goods and services. The “integrated assessment” model of Ravetz (2000) provides the template for this approach and Figure 2 shows how it can be adapted for UES indicators. There are four primary indicator categories: the *drivers* of energy-service demand, service demand itself (*activities*), the *resources* required to meet these demands, and the resulting *impacts* on the urban system. As will be seen later, a *system*-level category has also been added to encapsulate important contextual information and the overall measures of system performance seen lacking in the traditional indicator frameworks noted above.

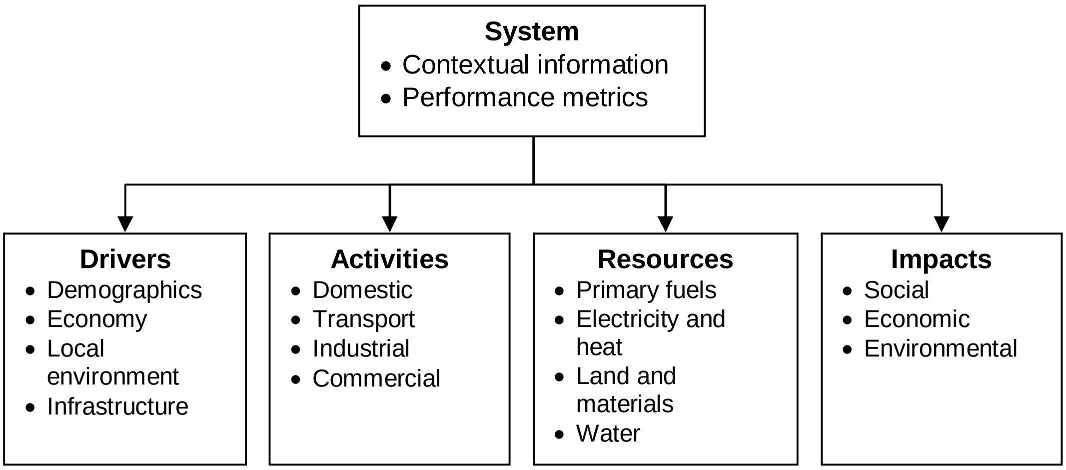

Figure 2. An service-based framework for the selection of urban energy indicators with indicative indicators (based on Ravetz, 2000)

Further notes on Maclaren’s indicator selection methodology and the assumptions made so far can be found in Appendix A. One of the themes of this discussion is that many questions of indicator selection are difficult to resolve in the abstract; concrete data are needed to explore the practical difficulties involved with developing an indicator set. Therefore the next two parts of the report apply the energy-service indicator framework to London. The goals of this pilot study are to assess the effectiveness of the framework, to determine what sources of data are readily available and to experiment with different techniques for creating system indicators.

Part II: ‘Conventional’ energy-system indicators

The indicators outlined in the UES framework above can be divided into two categories: conventional and system. In this first section we examine conventional indicators, i.e. those metrics which might be found in more traditional assessments of urban sustainability but with relevance to urban energy analyses. These indicators form the foundation of the indicator framework, providing a descriptive dataset that can be explored and expanded when creating more sophisticated system metrics.

The four primary indicator themes – drivers, activities, resources, and impacts – are considered in detail below. In each section, relevant indicators are presented for London and these have been selected on the basis of available data and consistency with the scoping criteria noted above (though a formal multi-criteria assessment has not been done). Logical sub-themes were identified within each theme and a minimum of three indicators per sub-theme selected. The text and summary tables describe the issues encountered while gathering this data and the most promising indicators are marked in **bold** as potential core metrics, i.e. those which should be gathered for other cities as well.

3 Drivers

Driver indicators describe the determinants of energy-service demand and four sub-themes were identified: demographics, economic structure, local environment and infrastructure. While these divisions are useful on their own, the metrics were primarily selected for their relevance to the major energy consumption sectors. For instance, trends in household numbers are important demographic factors on their own but their value as energy system metrics is dependent on their link to domestic energy demands (e.g. Boardman et al., 2005). Similarly the choice of infrastructure, economic and local environment indicators was driven by the desire to explain demands for transport, commercial, industrial and domestic energy services. This multiplicity of indicator classifications is a recurring theme of the framework, giving the indicators flexibility for use with a variety of stakeholders.

As Table 2 shows, the data come from a variety of sources and this raises questions about whether the data are representative of the same area. This occurs both between indicators (e.g. is the definition of London used for calculating population the same as that used for employment?) and within indicators (e.g. is the definition of London used for population statistics consistent through its 2000+ year history?). For some indicators, data were incomplete and had to be estimated; London household numbers before 1991 for example were estimated by downscaling national trends to the city level. Bearing in mind that comparability between cities is an important criterion for final indicator selection, it should be noted that many indicators are defined based on local standards (e.g. decent housing) and strictly-comparable data may not exist for other cities. This uncertainty suggests that indicators should often be presented with confidence intervals.

Table 2. Indicators for drivers of energy-service demand

Sub-theme ID	Indicator	Units	Source and notes
Demographics			
1	**Population**	# of people	UK census and historical estimates. Greater London. Do the administrative limits of London reflect its true (i.e. functional) population? The GRUMP urban-rural extents database, for example, suggests that the 2000 population is 12,766,430 not 7,237,000 (SEDAC-CIESIN, 2007).
3	**Households**	# of households	National Statistics. Greater London. Pre-1991 data are estimated by downscaling national figures based on London's population and national household trends. Longer time series to 1970 could be extrapolated using BREHOMES (BRE, 2006).
2	Life expectancy at birth	Years, average of male & female	London Health Observatory citing National Statistics. Greater London. Useful in forecasting future population change (e.g. GLA, 2006).
Economic structure			
6	**Employment**	% of working-age people in employment	National Statistics Labour Force Survey. Greater London region only.
13	CBD employment	# of people working in central business district	Transport for London 2001 annual report, though metric does not feature in all subsequent annual reports. A functional indicator of urban form and transport demand (e.g. Crampton et al., 1996).
45	Gross weekly household income	£ per week	Family Expenditure Survey. Greater London region only. Potentially useful for modelling energy demand in response to prices.
82, 83, 84, 79	**Fuel prices (wholesale)**	pence per kWh	DTI Quarterly Fuel Price statistics. Assume UK = London. Calculated separately for coal (82), gas (83), and oil (84). DTI UK Energy Sector Indicators, showing industrial energy prices, or global oil price (via Brent Crude, £ per barrel, 79) might also be used. Current prices.
34, 35, 36, 81	Fuel prices (retail)	Normalised, 1990 = 100	DTI Quarterly Fuel Price statistics. Assume UK = London. Calculated separately for coal (81), oil (36), gas (34), and electricity (35). Current prices.

40, 41, 85, 86	Competition in the energy sector	Herfindal-Hirschman index (10000 = monopoly, 0 = complete competition)	DTI UK Energy Indicators. Assume UK = London. To assess corporation innovation in generation and retail sectors. It is calculated separately for electricity generation (40), gas sales to generators (86), domestic electricity sales (85) and domestic gas sales (41).
42	**R&D investment in energy**	£ (millions)	DTI UK Energy Indicators. UK level investment only. An indicator for learning and potential technological innovation.
7	Purchase power parity	per unit GDP (USD = 1)	Penn World Table. Assume UK = London. UK-wide metric used to facilitate international comparisons.
80	Inflation	CPI (2005 = 100)	National Statistics. Assume UK = London. Could be used instead of GDP to calculate constant price values.
Local environment			
38	**Solar resource**	Sunshine hours per day	Met Office, Greenwich station. Assumed constant (over long-term). South England average irradiance approximately 1100 kWh/m^2
39	**Wind speed**	Average m/s (10m above ground)	DTI windspeed database for Greenwich (SE10 9NF). Assumed constant (over long-term).
8	Area	Square kilometres	Wikipedia, Greater London. Again there is a question of city boundary definitions: GRUMP says London is 7,723 km^2 whereas the official figure for Greater London is only 1,577 km^2
9, 10	Latitude and longitude	Degrees-minutes-seconds as decimal	Wikipedia. Assumed constant. Nelson’s Monument, Trafalgar Square.
87	Temperature	^oC	Met Office Greenwich station. Records of both long-term average (87) and daily variability (11). Similar rainfall data also available (88 long-term, 12 daily).
	These variables help to determine the requirements for heating, cooling and lighting services. They also describe energy resources and therefore other cities may add additional metrics to describe biomass, hydro, tidal, geothermal, fossil fuels or other resources (e.g. Mori et al., 2007).		
Infrastructure			
15	**Car ownership**	% of households with one or more car	Transport for London annual travel report.

16	Road length	km	Transport for London annual travel report.
17	Rail length	km	Transport for London annual travel report.
18	Rail stations	number	Transport for London annual travel report.
43	**Investment by energy industries**	£ (thousands) per head at 2001 prices	DTI UK Energy Statistics. UK indicator. Can be broken down by electricity, gas and coal sectors if desired.
23	Office space	m^2	Wikipedia and City of London. It is difficult to get consistent figures for this, both long-time series and also same area (some figures refer to the City only, others to Central London and others still to Greater London)
78	Dwellings	Number	LSE study, using National Statistics. Greater London.
89	**Thermal quality of housing stock**	Average SAP rating	DTI UK Energy Statistics, assuming England = London. An alternative metric is the % of households living in government-defined 'decent housing' (see English House Condition Survey); such a metric shows how a locally defined metric might not be directly comparable with other jurisdictions. Further measures on penetration of loft insulation, cavity wall insulation, double-glazing, draught proofing, HW tank insulation, central heating, and average heat loss (W/^{o}C) are also available (BRE, 2006)
44	Internet access	% of households with access	National Statistics. Assume UK = London, proxy for structure of economy?

It is worth noting that many important drivers of urban energy use are not included in this table as the appropriate data were not readily available. In some cases, this simply means that additional data processing is required to gather the data (e.g. developing building size distributions from the English House Condition Survey or similar data source). Other issues however may not have accepted indicator definitions, despite their importance; for example, questions of urban form and its influence on commuting patterns, transportation networks, and ecological health are often found in urban sustainability literature (Næss, 1995; Burton, 2002; Cook, 2002; Shim et al., 2006; Gusdorf et al., 2007).

4 Activities

Activity indicators are the first direct measures of energy use within the indicator framework, representing energy-consuming activities (end-uses). However to understand these metrics properly, they must be introduced within the wider context of official energy statistics. Energy consumption can be measured in three ways: primary fuel input, final consumption (supplied energy) and final consumption (useful energy) (DTI, 2006a). Primary fuel inputs and supplied energy are the most common measures of an energy system's performance (see Figure 3); however useful energy analysis is important to understand whether the inefficiencies in an overall system lie with end-use technologies or in upstream conversion and transmission processes. The activity indicators presented here attempt to describe useful energy consumption; the primary fuel inputs and delivered energy are considered mainly in the resources category.

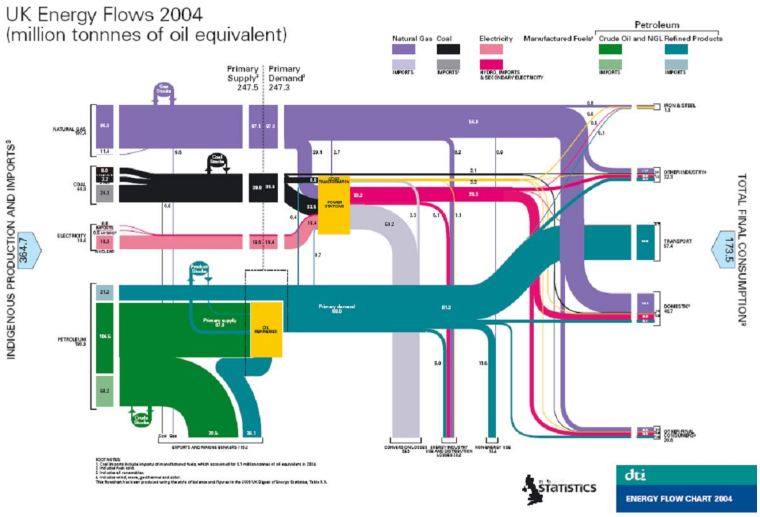

Figure 3. UK energy flows (DTI, 2004)

Correspondingly the sub-themes for activity indicators are based on the end-use sectors of official energy consumption metrics. However there can be some disagreement about how fine these divisions should be made. The IEA (2005), for example, divides total final consumption into "industry, transport, other (includes agriculture, residential, commercial and public services) and non-energy uses." Considering Figure 4, and ignoring the upstream power generation consumption, one can see that the IEA classification gives a fairly coarse aggregation with the "other" category accounting for nearly 38% of total final consumption. In contrast, DTI (2006a) introduces a domestic consumption category to provide finer detail, allowing the trends and possible policy interventions for this sector to be considered independently. Owing to the importance of the domestic sector (27% of UK final energy consumption), this finer classification has been adopted here: transport, industrial, domestic, other.

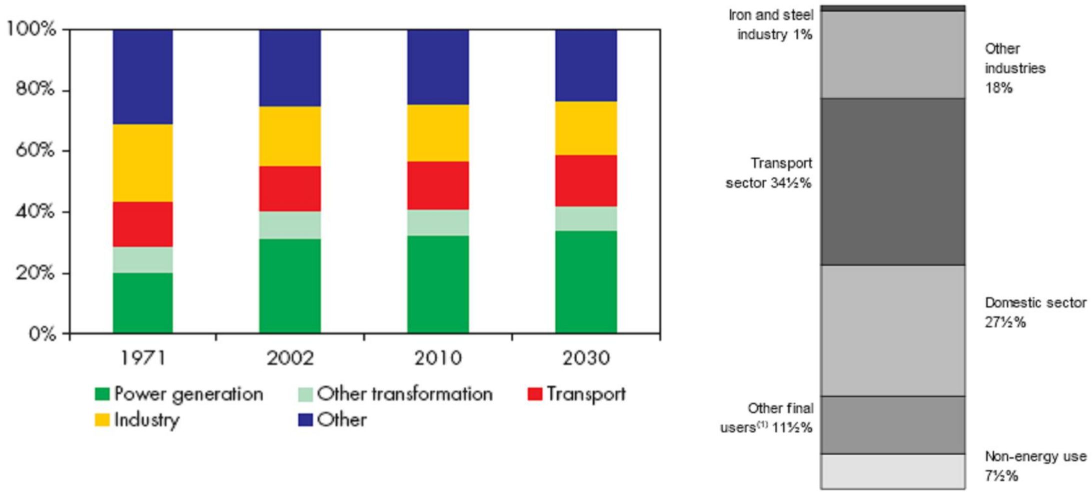

Figure 4. Sectoral shares in world primary energy demand (IEA, 2004) and UK final energy consumption (DTI, 2006a)

Unfortunately for those selecting activity indicators, "[s]tatistics on useful energy are not sufficiently reliable… there is a lack of data on utilisation efficiencies and on the purposes for which fuels are used." (DTI, 2006a: 21). As a result, activity indicators often need to be based upon proxy measures or simulations. For example, bottom-up modelling has been widely used to disaggregate national level statistics and explore the workings of each sector. The domestic sector, in particular, has a wealth of experience modelling the role of lighting, space and water heating, appliances and so on (e.g. Boardman et al., 2005; Lampaditou et al., 2005; BRE, 2006). In the transport sector, information on urban journeys can be used as a proxy for useful energy and both the modelling and proxy approaches hold promise for assessing industrial and commercial activities. Oxford's Environmental Change Institute, for example, hopes to release a model of UK building energy consumption in the non-domestic sector by December 2007; international standard industrial classification (ISIC) codes for industrial outputs might also be used to provide valuable information about likely energy-consuming processes (Nanduri et al., 2002). For the time being, only a rough proxy of commercial activity is included here (gross value added); a question for later consideration is therefore how finely disaggregated activity data must be in order to meet the project's goals.

As most of these indicators are estimates, it can be difficult developing consistent terminology for comparisons. For example, BRE's modelling work on the domestic sector uses Great Britain figures for the number of households, whereas other indicator sources use UK values (e.g. DTI sources). This creates problems when trying to downscale national figures and compare the values with results from other sources (Table 3). In general then, it would be useful to have a clear protocol for promoting consistency between indicators, for example, by using confidence intervals to demonstrate how indicators were derived and defined (i.e. are the values from official, modelled, or estimated sources?).

Table 3. Indicators of energy-service activities

Sub-theme ID	Indicator	Units	Source and notes
Domestic			
97	**Total delivered energy**	GJ per household	BREHOMES (BRE, 2006). Assume Great Britain = London. BRE report does not explicitly say whether their data represents useful or delivered energy. However since government figures are provided as delivered, and delivered figures by fuel are given later, we have assumed delivered. Further information is available about the delivered energy, rates of ownership of insulation, central heating, double-glazing and so on.
93, 94, 95, 96	Domestic energy consumption	% of total delivered energy	BREHOMES(BRE, 2006). Assume GB = London. Compiled separately for space heating (93), water heating (94), cooking (95), lights and appliances (96). Total sector estimates in PJ are available from BRE as well.
92	**Mean indoor temperature**	^{o}C	BREHOMES. Assume GB = London. A measure of comfort and heating demand.
46, 47, 48, 49, 50, 90, 91	**Total household energy expenditure**	£, constant prices	Family Expenditure Survey. London government region. Broken down by fuel (elec 47, gas 48, other fuels 49, total fuels 50) and total expenditure (46) as well. Note that BRE also estimates these values (all expenditure 90, total fuels 91) but for GB and does indicate whether they are constant or real prices.
Transport			
14	Morning rush journeys	Total journeys to CBD	TfL annual travel reports.
61, 62, 63, 64, 65, 66	**Daily average trips**	Millions	TfL annual reports. Total (61) and by mode (bus 64, car 65, tube 62, rail 63, walk or bike 66)
67	Terminal passengers at airport	Millions	DfT Regional Statistics. London government region.
68	Freight at airports	Thousands of tonnes	DfT Regional Statistics. London government region.
69	Goods moved by road	Thousands of tonnes	DfT Regional Statistics. London government region. Journeys originating in London.

98	**Fuel economy**	Litres per 100 km	DfT Transport Statistics Great Britain. Assume GB = London
Industrial			
126	**Total industrial turnover**	£ million	ONS Annual Business Inquiry. For NUTS 1 London region. Measured in constant prices? Divide between industrial and commercial end-uses has been made according to (DTI, 2006a).
Other			
70	**Total commercial turnover**	£ million	As above

5 Resources

Resource indicators measure the stocks and flows of energy, water and materials needed to meet the activity demands described above; however only energy is considered at present.

The choice of system boundaries is critical when analysing these resource flows and the trade-off is largely between data availability and urban function. On the one hand, administrative boundaries are convenient as statistics are calculated on this basis (particularly for national statistics). However when applied to an urban level, administrative boundaries are likely to underestimate or even neglect completely certain forms of consumption. London's energy demand for example would appear to be comprised largely of secondary electricity, without consideration for the associated primary energy inputs to generation facilities outside of the city limits. Alternatively, supply chains can be analysed to account for the energy embodied in different goods and services regardless of where they were produced. This approach can be seen in the material flow analysis of York (Barrett et al., 2002) and London (BFF, 2002). Rather than using geographic or administrative boundaries, these reports adopted a responsibility approach taking account for the resource demands necessitated by the behaviour of each city's occupants. Consequently London's analysis removes the consumption of visitors to the city by excluding the impact of restaurant meals and the City of London (whose financial services are meeting a global, not local, need). However it can be extremely difficult to implement this method consistently particular if the necessary data are not available. For example, London's analysis relies primarily on statistics gathered at the NUTS 1 Greater London level and despite applying the responsibility principle for visitors *to* London, no effort is made to gather data on the influence of Londoners abroad (or even in their own city – surely London's restaurants are not exclusively for the benefit of visitors?).

These boundary issues have specific interpretations in the energy context, particularly in the divide between primary and secondary energy sources. From a policy indicator point of view primary energy consumption is important largely at a national level and has relevance to debates about resource extraction, energy security, infrastructure costs and global environmental impact. In contrast secondary fuels play a greater role in the urban context, where the use of clean transformed products such as electricity helps to remove the negative impacts of fuel consumption from the local environment. The analysis of urban energy consumption must therefore account for both types of energy flow and their inter-conversion.

In the UK, the distinction between primary and secondary fuels is made as follows (DTI, 2006a):

- Primary fuels
    - Coal
    - Primary oils (e.g. crude oil)
    - Natural gas liquids
    - Natural gas
    - Nuclear electricity
    - Natural flow hydro-electricity
    - Renewable energy sources
    - Net electricity imports (from interconnectors)
- Secondary fuels
    - Manufactured fuels (e.g. coke, furnace gases, briquettes)
    - Petroleum products
    - Secondary electricity (i.e. generated from fossil fuels)
    - Heat sold

This divide largely makes sense as raw imported fuels are assigned to the primary category and converted fuels are secondary. However the treatment of nuclear electricity and net electricity imports – though consistent with international practice – is not what it appears to be at first glance. For example, kilowatt-hours of nuclear electricity are divided by the thermal efficiency of the steam turbines[2] whereas other forms of electricity, including net electricity imports, are evaluated "in terms of the energy content of the electricity produced (the energy supplied basis)". The implied logic for this practice (¶ 5.57 of DUKES) is that the heat generated by nuclear fission could be used directly as heat, in a similar fashion to the way that natural gas could be used in a central CCGT or piped into homes for direct use in a boiler. However nuclear power plants are often intentionally located far away from urban areas and so in the UK, fissile heat is generally not used for other purposes (though Russia and China have used or are exploring the possibilities (e.g. Tian, 2001)). For indicators, this

[2] 33% in the case of IEA statistics (Europe's average nuclear turbine efficiency in 1989); evaluated annually in the UK, 38.2% in 2005

means that the contribution of nuclear in primary energy statistics is approximately 3 times larger than what one might expect if it was interpreted as generating electricity alone. A similar problem can be seen when trying to analyse net electricity imports. If these flows are aggregated with other primary electricity flows (e.g. renewables and hydro), a policy maker could conclude that they have a benign impact on the environment. However for global issues such as climate change or energy security, it is not sufficient to say that net electricity imports are uniformly high-quality energy. In the UK, this electricity might be generated by French nuclear stations or German coal plants with significantly different implications for the environmental impacts of these flows (though of course policy makers cannot select only 'clean' imported electrons and must address imports as an entire class). The conclusion of this discussion then is that indicators for the various energy fuels should be presented at a disaggregated level and interpreted with great care.

Energy consumption data were gathered for both UK and London. Each jurisdiction is covered by length time-series, though the national data (DTI, 2006a) are more consistent than those of London which were collected in two separate studies (Chell et al., 1993; GLA, 2003). As discussed above, both data sets are necessary to understand the implications of energy use from primary supply through to end-use. Table 4 lists the relevant indicators; the units (thousands of tonnes of oil equivalent) are those used by the DTI, though conversion factors to SI units can be found in the DUKES report (DTI, 2006a).

Table 4. Indicators of energy resource use

Sub-theme ID	Indicator	Units	Source and notes
Energy			
120, 121, 122, **129**	**Primary energy supply**	Thousands of toe	DTI DUKES Table 1.1.2. UK values. Production (120), imports (121) and exports (122), TPES (129).
102, 103, 104, 105, 106, 107, **108**	**Final consumption by fuel**	Thousands of toe	DUKES Table 1.1.5. UK values. Coal (102), petroleum (103), natural gas (104), nuclear electricity (105), hydro electricity (106), net electricity imports (107), total primary energy demand (108, i.e. TPES – statistical changes)
110, 111, 112, 113, **136, 137, 138, 139**	**Delivered energy by end-user**	Thousands of toe	DUKES Table 1.1.5. UK scale. Industrial (110), transport (111), domestic (112), other (113) LECI (Chell et al. 1993, GLA 2003). London. Industrial (136), transport (137), domestic (138), other (139)

114, 115, 116, 117, 118, 119, **132, 133, 134, 135**	**Delivered energy by fuel**	Thousands of toe	DUKES Table 1.1.5 (i.e. after non-energy uses, transmission and energy industry uses). UK scale. Coal (114), gas (115), electricity (116), heat (117), renewables (118), petroleum (119). LECI (Chell et al. 1993, GLA 2003). London. Coal (132), gas (133), electricity (134), petroleum (135). BREHOMES also provides similar data for Great Britain from domestic modelling (56–60)

6 Impacts

Impact indicators describe the consequences of meeting activity demands with particular resource flows. Three types of impact are considered based on the traditional social, economic, and environmental domains of sustainable development; this provides a degree of compatibility with many existing indicator frameworks. Although these categories all represent some form of output from the energy system, each theme has its own specific considerations.

Social concepts, such as human well-being, are arguably the ultimate ends of urban life and sustainable development (Meadows, 1998). However converting these broad aspirations into specific indicators is extremely difficult and there have been extensive debates about the merits of different quality-of-life measures (Rogerson, 1989; Craglia et al., 2004; NEF, 2006). Owing to the project's technical focus, the indicators suggested here are less ambitious and reflect a few specific measurable social aspects of energy use. The economic sector often tries to approximate human well-being based on wealth and economic output. For example, gross domestic product (GDP) is a widely-calculated measure which therefore might provide a good basis for international comparison. However gross value-added (GVA) is used by London as a better measure of the city's output and other cities do not necessarily calculate this statistic. In addition, green economic measures such as the genuine progress indicator (GPI) and index of sustainable economic welfare (ISEW) have attempted to distinguish between 'good' and 'bad' forms of growth. Unfortunately there are some outstanding methodological criticisms of these measures which combined with their relative novelty means that extensive data sets are not widely available (e.g. Neumayer, 2000). Finally, the environmental sector includes indicators of both local and global impact, an important theme noted by many authors (e.g. Haughton et al., 2003; McGranahan et al., 2005).

Ideally the impact indicators would reflect the activities of each energy sector. In some cases, this is fairly easy to achieve; greenhouse gas emissions for example can be calculated separately for the domestic, transport, and industrial sectors. However impacts are not exclusively negative and if one considers efficiency as a measure of valuable output per unit input, it is not readily apparent how value should be measured in each sector. In the industrial/commercial sector, GVA seems appropriate and tonne-km or passenger-km might be used for the transport sector but the domestic sector is more difficult as the beneficial value of energy services represents a mix of measurable and immeasurable concepts (e.g. comfort could be measured by room temperature but quality of life is more nebulous). Table 5 therefore only provides an indicative set of indicators and, as with all categories, further suggestions are welcome.

Table 5. Indicators of energy-service impacts

Sub-theme ID	Indicator	Units	Source and notes
Social			
27	**Road accidents**	Numbers	Dept for Transport TSGB. Downscaled UK figures using some limited London figures to give a constant ratio.
28	**Fuel poverty**	Number of households spending >10% of income on fuel	DTI and SDC Regional indicators. Downscaled UK figures again using limited information on London.
123	Quality of life	% satisfied with local area	SDC Regional indicators. For London GOR.
Economic			
5	**Economic output**	Gross Value Added per capita (£)	ONS. For London GOR.
99, 100		Gross Value added (£ millions)	ONS. For London GOR. Calculated separately for industrial and commercial sectors according to DTI ISIC-split described above.
29	**Productivity**	Whole economy output per worker (2003 = 100)	ONS. For London GOR for recent data. Longer time series extrapolated using constant London productivity 25% higher than UK.
Environmental			
30, 31, 124	**Local air quality**	μg/m^3 (SO_2, NO_2, PM_{10})	London Air Quality Network. Measured at Cromwell Road (could be averaged over multiple sites if desired).

125	**Greenhouse gas emissions**	Million tonnes (carbon equivalent), CO_2 and full GHG basket	Defra. These are UK statistics adjusted to estimate London. The 2003 LECI provides London CO_2 emissions and this ratio, compared to UK emissions, was taken as a constant for longer time series of CO_2 and for GHG at large. The previous version of the LECI doesn’t include CO_2 data at length (Chell et al., 1993). The Defra statistics are disaggregated by sector as well and this could be used to estimate figures for London, though it hasn’t been done here.

Other indicators not included here that might be very useful, particularly for international comparisons, include measures of health impacts (e.g. from poor air quality) and measures of access to energy services (e.g. IAEA, 1999).

Summary

The indicators presented in this section provide the basic descriptive background for an analysis of London’s urban energy system. Using a variety of readily-available data sources, metrics were found to outline the drivers of energy-service demand, energy-using activities, the resources consumed by these activities and the resulting consequences of this consumption. The indicators presented in the tables above are by no means definitive but the core metrics in particular should be available for other cities, facilitating comparisons. However two major issues have been raised that need to be considered when selecting and applying a final indicator set.

The first concern is the comprehensiveness of the data as certain parts of the urban energy system had insufficient coverage. In particular, it was found that very little information was available on useful energy demands and this makes it difficult to evaluate the efficiency of end-use technologies. The indicators also generally reflected aggregate data and questions were raised about the extent to which disaggregate measures might be required, for example, to facilitate detailed analyses of major energy-using processes. This is particularly important from a policy perspective as not all energy-sectors are equally well-covered. The domestic and transport sectors (which account for approximately 63% of London’s delivered energy) are relatively well-described, enabling some of the major policy issues and interventions to be described (e.g. thermal performance and fuel poverty in the domestic sector). However in commercial and industrial sectors, data are scarce and proxies (e.g. output from ISIC codes) may be particularly important in order to understand the major sources of energy consumption.

The second issue pertains to the processing of the collected data. Since the indicators were gathered from many different data sets, it is difficult to ensure the comparability of indicator values: not just in anticipation of inter-city comparisons, but also when comparing different London indicators at different time-scales. The final data set contains a mix of observed, downscaled and modelled values, sometimes reflecting London's administrative boundaries and sometimes representing a more functional perspective. This could be seen in simple measures such as population as well as more complicated questions such as the interpretation of primary energy data. The challenge therefore will be to develop consistent data storage and labelling procedures so that the caveats associated with each data point are preserved where possible.

Part III: Selecting headline and system-level indicators

The indicators identified so far describe the basic features of an urban energy system but, as single isolated metrics, they have two major shortcomings. First, policy makers and non-expert groups may be unable to decipher a large number of individual metrics and instead may require a set of concise "headline" indicators. Secondly, the basic indicators arguably do not provide sufficient understanding of the city as a complex system. Further information on the system's overall performance and the links between metrics might therefore be valuable to expert groups. Both of these issues are considered below.

7 Headline indicators and aggregation techniques

In the UK sustainable development community, a headline indicator refers to a metric that provides an overview, acting as a 'barometer' for quality of life and sustainability issues (LSDC, 2005; SDC, 2006). These measures are typically drawn from a larger pool of 'supporting' indicators but the promotion of a particular metric to the headline level can be guided by uncertain motives (Tate, 2002). Fortunately well-established techniques exist for creating these aggregate headline indicators and some of these methods are reviewed below.

Key indicators ("Cherry-picking")

Key indicators are metrics selected from a pool of supporting indicators that are perceived to provide the best summary for the goals of a given measurement theme. This "cherry-picking" technique is commonly used for government sustainability indicators when a particular policy issue is clearly associated with a certain measure; greenhouse gas emissions, for example, are used to represent the UK energy policy goal of reducing the economy's carbon footprint (e.g. DTI, 2006b). Although the selection of these metrics implies some deliberation between alternatives, it is largely an informal process particularly in contrast to the more rigorous multi-criteria decision methods outlined below. Given the method's simplicity, Mitchell (1996) notes that key indicators are most effective for communicating data to non-experts and the public; scientists and expert policy makers are likely to find this approach inadequate.

Considering our data set, a hierarchical approach can be used to select key indicators. Recalling that a number of sub-themes lie within each indicator theme, we can cherry-pick an indicator that intuitively represents the main ideas of each sub-theme; for example, among the driver indicators, we might pick population as a demographic indicator, employment as an economic indicator, temperature as an environmental indicator, and car ownership as an infrastructure metric. One of these four sub-theme metrics can then be selected as that theme's overall headline indicator; population, for example, might be considered as the most important driver of urban energy use. Table 6 presents some key headline indicators from the collected data set but again, no formal assessment of the merits of each metric was made.

Table 6. Key energy system indicators

Theme	*Headline indicator*	*Sub-theme headline indicators*
Drivers	Population	Population, employment, temperature, car ownership
Activities	Mean internal building temperature	Mean internal temperature of dwellings, daily average trips, industrial turnover, commercial turnover
Resources	Total delivered energy	Delivered energy by sector
Impacts	Economic output	Fuel poverty rate, economic output (GVA), greenhouse gas emissions

MULTI-CRITERIA DECISION ANALYSIS

While the cherry-picking method offers advantages in terms of ease of use, other techniques can be used to make the trade-offs between different metrics more explicit, thus helping to build understanding between stakeholders. Multi-criteria decision analysis (MCDA) is the general term for this approach and it proceeds by identifying criteria of interest and then judging each option against these goals (Hobbs et al., 2000; DTLR, 2001; Brunner et al., 2004). For example, potential headline indicators might be scored against the goals of policy relevance and usability, analytical validity or data quality and availability (OECD, 2003) or to ensure that metrics are "scientifically sound and technically robust, easily understood, sensitive to the change that it is meant to represent, measurable and capable of being updated regularly" (DETR, 1998: 6). Weights can then be assigned to each criterion, for example, stating that analytical validity is twice as important as policy relevance or measurability. Combining these weights and scores, a ranked list of indicators can then be created with the top results forming the headline metrics.

Most authors recommend that MCDA be undertaken with a range of stakeholders so as to reflect their different priorities and concerns. This participation is required at two stages specific to MCDA. First, decision criteria should ideally be selected in response to the question "is it possible in practice to measure or judge how well an option performs on these criteria?" (Dodgson et al., 2000: 27). However not all stakeholders may be able to convert their general concerns into quantifiable criteria and some authors have therefore suggested experts should be responsible for making these translations (Rotmans et al., 2000). The second participatory stage is the selection of criteria weights. A number of formal weighting techniques exist, though not all require participatory groups; for example:

- the analytical hierarchy process (AHP) where criteria are ranked using pair-wise comparisons solicited from relevant stakeholders

- a linear programming solution to derive weights from within the data set without external input (Zhou et al., in press)
- a principal components analysis method to improve the discrimination between similar criteria (Barannik et al., 2007)

As a simple demonstration of these issues, a headline indicator for the drivers theme is now selected. First, three selection criteria are identified drawing on the OECD guidelines cited above. These general principles then need to be converted into specific measurable questions; where this is not possible, a quantifiable personal judgement has to be made (e.g. using a Likert scale). For this demonstration, the following criteria were used:

- *Analytical validity*: From 1 (least) to 5 (most), how much of a contribution do you feel this indicator makes to our understanding of urban energy systems?
- *Policy relevance:* How many times is the indicator mentioned in the LSDC QoL indicators report?
- *Measurability:* Within the collected dataset, how many annual measurements for the indicator exist between 1970 and 2005?

Thirty-six driver indicators were evaluated against these criteria and the scores normalised on a 0 to 1 scale; this gives the results in Table 7. Simple weighting scenarios were then applied in Table 8 to demonstrate how different priorities could affect the ranking of headline metrics.

Table 7. Raw evaluation scores for driver indicators

Criteria	*Top 3 results*	*Scores (max = 1)*
Analytical validity	Employment	1
	Population	1
	Car ownership (an example, tied with many other measures)	0.8
Policy relevance	# of households	1
	Population	0.71
	Employment	0.48
Measurability	Purchase power parity	0.97
	Oil price	0.83
	Households with internet access	0.77
	Note that environmental data also scores well but is assumed to be constant and therefore not shown here.	

Table 8. MCDA for driver indicators

Scenario	*Top 3 results*	*Scores (max = 1)*
Equal weighting (1:1:1)	Population	0.718
	# of households	0.683
	Employment	0.624
Analytical validity (2:1:1)	Population	0.789
	Employment	0.718
	# of households	0.712
Policy relevance (1:2:1)	# of households	0.762
	Population	0.716
	Employment	0.589
Measurability	Population	0.650
(1:1:2)	Purchase power parity	0.636
	# of households	0.575

INDICES

As an alternative to selecting a single representative indicator, headline indicators can also be chosen by aggregating supporting indicators. The most basic of these techniques is derived from the concept of an index number, i.e. converting each metric to a unitless value based on a common reference point. This reference can be picked using a widely-accepted threshold such as an acceptable pollution level (PRE, 2006a), a known performance standard (Nanduri et al., 2002), a theoretical limit (e.g. 220 lumen/watt for lighting (Ayres et al., 2003)) or a common point in time (Boardman et al., 2005); alternatively, the values (if normally-distributed) might be converted to standardised z-scores and normalised on a 0 to 1 scale (Lee et al., in press). These index scores can then be averaged together with or without weighting to create an overall headline indicator.

The technique offers two advantages. First, it enables indicators based in different unit scales to be aggregated together. In the transport sector for example, indicators might include trips (# of), passenger volumes (passenger-km), freight movements (tonne-km), and fuel economy (L/100 km). By creating a unitless metric, one avoids the difficulty of interpreting an aggregate metric with units of people-trip-tonne-km^2-litres per 100 kilometres. The second advantage is that these indices show trends very clearly. Boardman et al. (2005) for example used this approach to demonstrate how domestic energy consumption has been shaped by changes in appliance usage, appliance efficiency, and demographic trends.

However these indices pose some disadvantages as well. First, indicators must be aligned to enable aggregation and sensible interpretation. That is, a metric which decreases to show progress (e.g. energy intensity) needs to be inverted so that it can be combined with an indicator that increases to show progress (e.g. income per capita). Secondly, aggregating diverse indices implies that a change in any constituent index is equivalent to the same change in another metric. In most cases, this is over- simplistic: a 10% increase in the GDP index for example might not lead to a 10% increase in the energy consumption index owing to scale-effects. Nanduri et al. (2002) discuss these issues at length and highlight a number of techniques for weighting and aggregating indices.

Overall then, indices are perhaps best used as a brief demonstration of trends, rather than to support more meaningful analyses. Using the indicators collected above, a simple aggregate index has been created by taking the year 2000 as 100 (Figure 5). This figure demonstrates the shortcomings of the technique, as the introduction of the market competition around 1990 caused a sudden spike in the driver index.

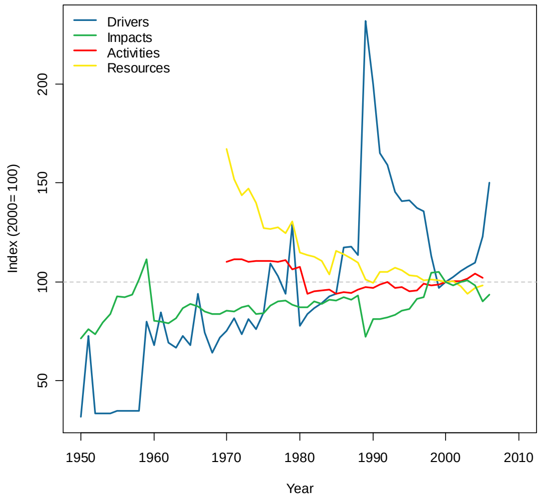

Figure 5. Trends in simple aggregate indices of indicator themes

DAMAGE FUNCTIONS

A more concrete basis for indicator aggregation can be found in the Eco-indicator 99 methodology, a life-cycle analysis technique (PRE, 2006a). Here, supporting indicators are grouped according to the type of damage they inflict, e.g. on human health, ecosystems, or resource stocks. The benefit of this approach is that each type of damage carries with it specific units. Damage to human health, for example, is measured in disability adjusted life years and this provides a common basis for amalgamating the effects of issues such as climate change, local air pollution, and radiation. The methodology also outlines a technique for aggregating these damage indicators into a single overall measure, similar to the index method described above. Damage measures are first normalised against accepted threshold levels or reference system values. Weights are then assigned to each dimensionless index to assess the trade-offs between different damage types.

The Eco99 methodology focuses on forms of environmental damage and these end-goals may not be directly applicable to the UES project, as we may wish to take a wider view of a system's impacts, for example, to include the positive impacts on economic growth arising from energy use. Furthermore, the methodology is impact-focused and does not offer a consistent basis for the aggregation of driver or activity indicators as well. While some possible grounds for aggregation can be identified within certain themes and sub-themes (e.g. people as a basis for aggregating demographic drivers or energy expenditure for aggregating activities), the diversity of indicators within these categories may necessitate other methods.

PRINCIPAL COMPONENT ANALYSIS

Principal component analysis (PCA) is a statistical technique used for data compression. Since headline indicators are intended to reduce the amount of data required to communicate important changes within a system, it is not surprising that PCA is increasingly applied to the creation of headline indicators (e.g. Campbell et al., 2001; Jollands et al., 2004; Bernard et al., 2005; Morse et al., 2005; Zhang et al., 2006b; Lam et al., in press). These studies have found that the technique can improve the quality of data presented to policy makers and help critique the assumptions used in other indicator aggregation techniques.

PCA was applied to the London indicators to identify potential headline indicators. Statistical guidelines note that there should be three times as many observations as input variables and therefore not all of the supporting indicators were analysed (only a subset of data covering 1980–2005 was used). After running the analysis for each indicator theme, the largest principal components (representing at least 95% of the total variance) were selected. A further PCA was then performed to determine which combination of theme principal components best represented the entire system of supporting indicators. These results are shown in Table 9 demonstrating that the variation in the population data set is much larger than in other variables.

Table 9. Principle component analysis of indicators

Category	*# of components*	*% variance explained*	*Component constituents*
Drivers	1	100	z_{driver} = Population
Activities	1	99.92	$z_{activities}$ = HH expenditure (all goods)
Resources	1	100	$Z_{resources}$ = Total primary energy supply
Impacts	1	100	$z_{impacts}$ = Road accidents
Overall	1	99.85	$Z = z_{driver}$ (i.e. population)

SUMMARY

As Mitchell (1996) notes, the amount of data required from an indicator set will vary from stakeholder to stakeholder. Policy makers for example may only have time for the key messages. The aggregation and headline indicator techniques presented here address this need with varying levels of complexity – from the simple choice of “cherry-picked” key indicators through to principal components analysis. However regardless of the specific technique used, all of these methods involve some degree of data compression. Policy makers and other non-expert groups therefore need to be aware of this limitation when interpreting the results of headline indicators.

For scientists and other expert groups, headline indicators are unlikely to provide the insight needed for detailed analyses. The next section therefore considers a set of more detailed system performance metrics.

8 System indicators

The indicator framework outlined in Part II provides a good overview of urban energy use but it is a fairly descriptive approach. It provides the data necessary to understand the basic trends in urban energy systems but does not attempt to explain the connections between system components or describe the system’s overall performance and complexity. Furthermore the performance and management of urban energy systems may be affected by factors that do not easily fit within the basic indicator framework; governance, composite efficiency measures and other factors may be required as well. This section therefore considers a range of possible system indicators, from technical performance measures that primarily benefit expert analysts, through to qualitative contextual data vital if policy makers are to appreciate the complexity which lies behind simplified headline indicators.

COMPOSITE INDICATORS

Composite indicators are arguably the simplest form of “emergent” system performance metric. Derived from the supporting indicators listed in Part II above, they express the efficiency of a system’s performance as a ratio of outputs to inputs. For example, one might measure physical efficiency (the amount of goods produced per unit energy, Nanduri et al., 2002), energy intensity (the amount of energy per unit of economic value), emissions intensity (emissions per unit of economic value), or standard-of-living measures (e.g. energy use per capita, Barnes et al., 2005)). However as these metrics are often used as the basis for international comparisons, the choice of normalisation unit is very important. For example, energy efficiency might be measured as delivered energy per capita. On this basis, a service-based city like London will appear more efficient than one with a larger industrial sector such as Singapore (e.g. in 2004, 75 GJ per capita versus 136 GJ per capita respectively). Yet if energy efficiency is based on economic output, the difference between the cities is smaller (London 5.3 MJ per $GVA, Singapore 5.5 MJ per $GDP). Per capita normalisations are also difficult and can be affected by boundary issues and local politics. As was shown above, London's official population may be an under-estimate and in China, urban population statistics may be even more unreliable owing to the presence of urban agriculture and debates over the status of rural-urban migrants (Girardet, 1992).

Figure 6 shows some of these basic efficiency measures for London since 1988 (GVA is the limiting factor). In this time, London has become approximately 60% more efficient per unit of economic output and 25% more efficient per capita. However as will be seen in the next section, these values may be over-estimates owing to a problem with London's transport energy consumption data between 1991 and 2003.

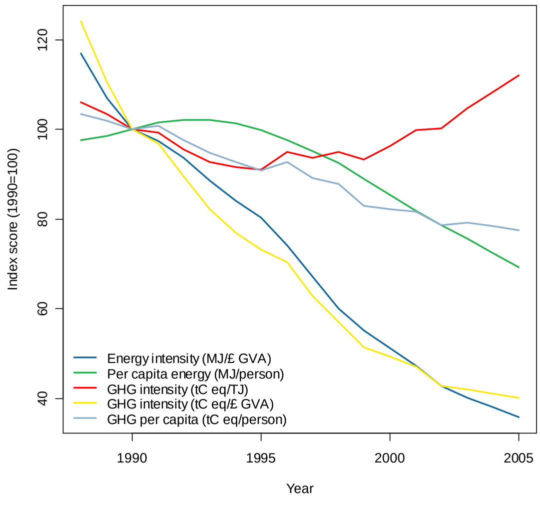

Figure 6. Efficiency of London (1988-2005)

THERMODYNAMIC EFFICIENCIES

In addition to general measures of system efficiency, thermodynamic efficiencies must be considered in order to evaluate the conversion of energy as it flows through the urban system. As a well-established science, thermodynamics also provides a series of methodologies which can help to develop comparable metrics and assess the maximum theoretical improvement potential in an urban energy system. As Hammond and Stapleton have argued

(2001), these goals are best achieved by applying both the First and Second Laws of Thermodynamics.

The First Law efficiency of an energy system is derived from the law of conservation of energy and measures the efficiency of energy conversion processes, for example, the amount of energy supplied to final consumers in comparison to the primary energy supply. In this case, the efficiency *η* would represent the performance of the upstream energy transformation, transmission and distribution systems. Since most urban areas do not have substantial local primary energy supplies *per se*, the performance of national energy systems must be analysed to determine whether the fuels consumed by the city have been efficiently generated and supplied. Figure 7 shows the first-order energy efficiency for the UK since 1970. The efficiency has been fairly constant at about 69% although there has been a slight drop in performance since 1995 reflecting an increased use of electricity (Hammond et al., 2001). The non-energy use of primary fuels is excluded from these calculations.

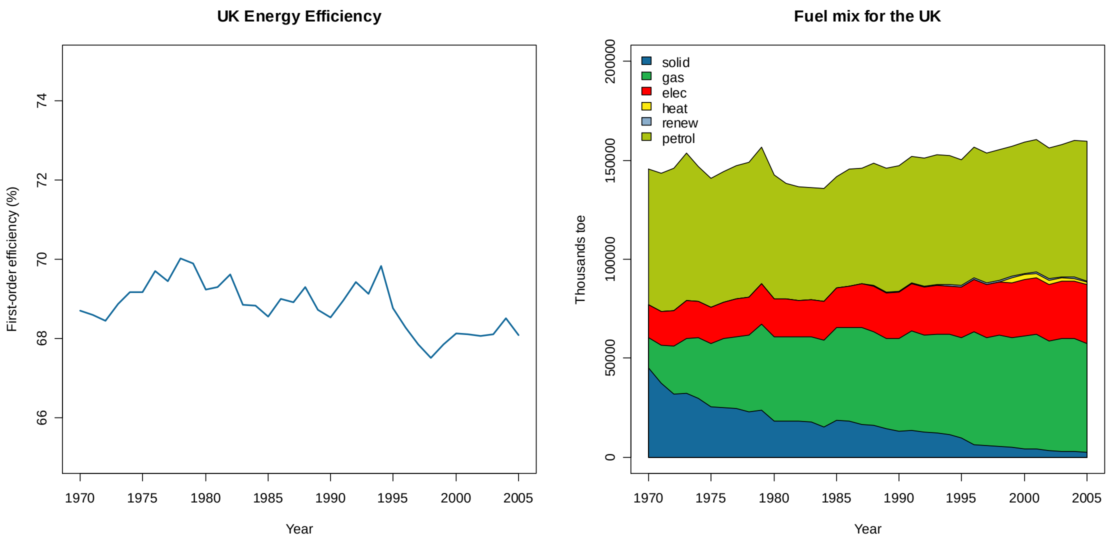

Figure 7. (a) First Law efficiency of the UK energy system (b) Delivered fuel mix in the UK (DTI, 2006a)

Although a First Law analysis is useful, it fails to discriminate between energy sources and to identify the amount of useful work that an energy flow can perform. Exergy analysis provides this additional insight, determining a system's efficiency according to the Second Law of Thermodynamics. The exergy efficiency of a system, *ψ*, is therefore measured as the extent to which the available energy within fuels is used measured against a given reference state. Hammond and Stapleton (2001) highlighted the benefit of this technique in their analysis of the UK energy system. On the supply side, they considered thermal electricity generation from both an energy and exergy perspective, showing that inefficiencies within a single process can be identified much more precisely (e.g. first law losses occur in the condenser and second law losses in the steam generator, see also Szargut et al., 1988). This leads to the conclusion that the best way to improve both efficiency measures is to use the waste heat via cogeneration. By then focusing on the demand side, the use of fuels for different tasks can be similarly analysed to maximize energy and exergy efficiency; the use of electricity for low grade heat is a particularly wasteful example.

A combination of analysis techniques – large-scale statistical analysis, disaggregated input-output analyses and close-up process level analyses – must therefore be used to fully understand the thermodynamic efficiency of the urban energy system and rationalise energy use. Unfortunately the lack of energy data means that not all of these analyses can be performed at the urban level. However these performance parameters can be estimated using a variety of data sources. For example, Figure 8 shows the fuel and sectoral mix of delivered energy use in London and this provides a good overview of energy consumption (e.g. increasing domestic consumption, a likely data anomaly with transport demand). However to determine thermodynamic efficiency properly, one needs a breakdown of the activities within each sector and the fuels used to meet these demands. For example, modelling data from the national level can provide some indication of the relative mix of domestic activities such as space heating, lighting and appliance use (BRE, 2006). Unfortunately the fuels used to meet these demands must be estimated (e.g. the mix of fossil-fuel versus electric space heating). Similarly in the transport sector, information on modal share is available but one must assume the efficiency and fuel requirements of each technology (Figure 9). This situation therefore recalls the questions discussed previously about the extent to which energy use data must be disaggregated to analyse urban energy systems.

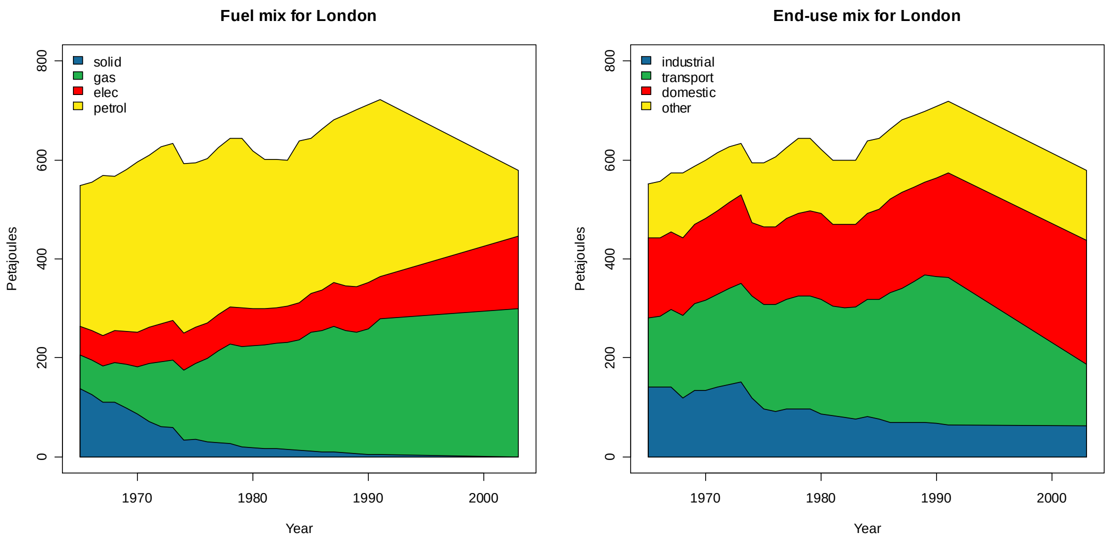

Figure 8. Energy uses in London by fuel and sector (Chell et al., 1993; GLA, 2003)

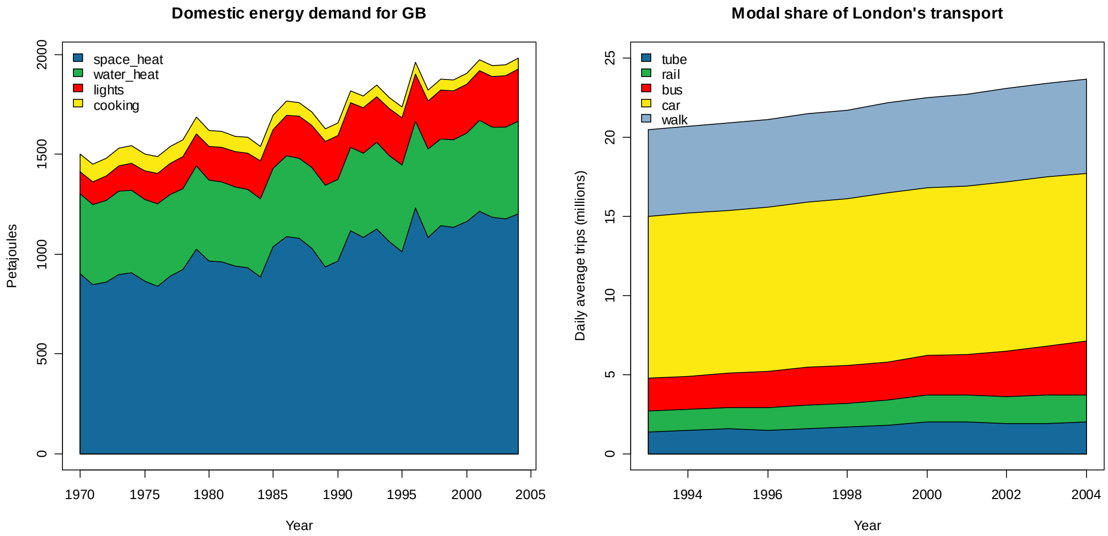

Figure 9. Breakdown of energy use in domestic and transport sectors

Following the assumptions used by Hammond and Stapleton (2001), estimations for the energetic and exergetic efficiency of the main energy sectors in London have been calculated (Table 10). Using data on the sectoral mix in London's energy consumption (Chell et al., 1993; GLA, 2003), the overall efficiencies of end-use can also be determined; this result is similar to the 30% exergetic efficiency calculated by estimating end-use processes and their operational temperatures (Shah et al., 2006). Both analyses suggest that improving the efficiency of the domestic and commercial sectors (i.e. where low-grade heat is large component of consumption) should be a priority.

Table 10. Estimated first and second law efficiencies for energy end-use in London, 1965–2003

Sector	*Energy efficiency, η (%)*	*Exergy efficiency, ψ (%)*
Domestic	62	13
Industrial	71	53
Other (commercial)	58	12
Transport	19	19
Overall	48	21

FOOTPRINT INDICATORS

One of the advantages of thermodynamic indicators is that they have a strong basis in theory. This allows them to be interpreted clearly, whereas indicators selected simply because of data availability may provide very little insight into the system's performance. Considering urban sustainability more generally, a number of theoretical principles have been identified that should be reflected in the choice of indicators. For example, in addition to the familiar concepts of inter- and intra-generational equity, the notion of trans-frontier responsibility is particularly important (Haughton, 1999). Cities exchange resources and waste products with their immediate hinterland and the wider world and while a city should not necessarily aim for complete self-sufficiency (Alberti, 1996), it is important that cities are aware of the wider impacts of their consumption.

Footprint indicators are an important tool for achieving this goal and two approaches are considered here. The most well-known method is the ecological footprint, i.e. "the total area of productive land and water required continuously to produce all the resources consumed and to assimilate all the wastes produced, by a defined population, wherever on Earth that land is located." (Rees et al., 1996: 228-229). For London, this has been calculated as 489 000 km2 (about the size of Spain) or 6.63 global hectares per person, compared with a globally-available 2.18 gha per person (BFF, 2002). While this metric does provide many advantages for communicating the environmental impact of a city to a wide audience, its usefulness and validity as an analytical indicator has been widely criticised (e.g. Costanza, 2000; Moffatt, 2000; van Kooten et al., 2000); some have gone so far as to say its use "can support unsustainable, inefficient and even immoral policy decisions." (van den Bergh et al., 1999: 71). As an energy indicator in particular, it has been noted that the ecological footprint methodology only considers the carbon dioxide impacts of fossil fuel combustion and does not account for embodied energy or other impacts (Ayres, 2000; Chen et al., 2006). In their defence, proponents of the technique have argued that it is a conservative measure which never claimed to be a comprehensive indicator of sustainability (Wackernagel et al., 2000); its main contribution should therefore be seen as a metaphor with "conceptual simplicity and intuitive appeal" (Rees, 2000: 372).

The solar footprint is a similarly accessible method for communicating the performance of urban energy systems (Shah et al., 2006). However rather than calculate the area of land required to mitigate the effects of energy consumption, the solar footprint method assesses the efficiency of the urban system and determines how much energy would be required to return the system to its original thermodynamic state. While the technologies do not necessarily exist to perform these conversions, the resulting indicator is a theoretically-consistent means of comparing urban energy efficiency that importantly can reflect local conditions. For example, given the exergetic efficiency of London above (21%) and a total delivered supply of approximately 580 PJ (in 2003), London's solar footprint can be calculated as the area required to absorb enough solar energy to replace these exergy losses. Assuming that the solar radiation available in London is on average 1100 kWh/m^2 (3.96 x 10^{-6} PJ/m^2) and a range of conversion technologies, different footprint values can be calculated as shown in Table 11.

Table 11. Footprint indicators for London

Footprint methodology		*Area (km^2)*
Ecological footprint	Total	489 000
	Energy component	48 900
Solar footprint	Theoretical, 100% efficient	116
	Silicon PV, 25% efficient	464
	Organic PV, 3% efficient	3 870
	Biomass, 4.5% efficient	2 560
Official area		1 580

INFORMATION THEORY MEASURES

Information theory is a discipline concerned with measuring the uncertainty of probabilistic events. In this context, information refers to the useful knowledge that can be gained from an event, such as a flipped coin: if the coin is fair and the odds of it landing heads is 50%, then the amount of information communicated by each flip is maximised; alternatively if the outcome of the coin toss is known in advance (p_{heads} = 0 or 1), then the information gained by flipping the coin is zero. Information therefore represents the difference between two states of uncertainty: a pre-event state and a post-event state.

When considering urban sustainability, information theory can therefore help to identify when a system deviates from an anticipated or desired state. For example, Cabezas et al. (2005) use Fisher information[3] to assess the sustainability (i.e. resilience) of an ecological system. In their model, they assume that predator and prey populations in a stable ecosystem will vary through time but demonstrate long-term stability. Fisher information is then used to measure how much the system has deviated from this idealised state at any given moment. After defining a mathematical model of this system, they then monitored the changes in Fisher information that resulted from introducing various disturbances to the system. The results demonstrated that Fisher information can provide an effective single measure of the system's performance, though the authors stressed that this metric should not be used on its own.

[3] A continuous measure of information, unlike Shannon information which is discrete.

With this precedent, it was hoped that Fisher information might be similarly applied to develop a metric for urban energy systems. However the model of Cabezas et al. assumed a periodic stability to the system and this seemed inapplicable to urban systems where a trend might be more likely (though the precise mode of growth or decline is likely depend on size and maturity of the city). Having assumed linear growth patterns for selected indicators in the London data set, an attempt was then made to derive a Fisher information metric based on the deviation of the indicator values from the anticipated linear model. Unfortunately the experiment was unsuccessful for two reasons. First, Cabezas et al. note that Fisher information can only be interpreted as the difference between two steady states. The results showed that these steady states were not achieved over the period of analysis (~20 years) and therefore extending the data set (e.g. through modelling) might be necessary. However the more important issue is that, as with any indicator, a clear theoretical understanding is needed before deriving and interpreting the metric. Instead of the simple assumptions made here, a sensible hypothesis about the desired state of the urban energy system will be needed to proceed effectively with this concept.

Other authors have also tried to apply information theory to urban sustainability. The basic principle of much of this work is that based on a local-view of sustainability, i.e. that sustainable cities minimize entropy production by importing high-quality products produced elsewhere (e.g. Dincer et al., 2004). In this context, information entropy becomes a measure of urban quality. An application of this idea can be seen Balocco et al. (2000; 2006) who consider the potential technical gains from energy-efficiency actions, as well as the extent to which local factors and actors are able to implement these changes and successfully influence a city's energy sustainability. By calculating Shannon information for a series of alternative policy strategies, this method therefore highlights those policies which provide the greatest information (i.e. moving from high urban entropy to low urban entropy). In another study, Zhang et al. (2006a) consider an urban ecosystem in China and use information entropy to provide common measures of urban development ("development degree"), ecological balance ("harmonious degree"), and urban governance ("leaning harmonious degree"). This integrative function therefore assumes that a bit of information in one field (e.g. urban development) is equivalent to a bit of information in another field (e.g. urban governance).

Unfortunately the methods outlined in these studies can be difficult to follow, making it hard for non-experts to assess their advantages and results. However parts of the techniques can be recognized from earlier discussions: for example, the problem of aggregating measures from completely different issues, the use of subjective weighting methods, and the question of how to consider energy and entropy flows between a city and its hinterland. This therefore suggests that, for the moment, the additional complexity of developing and interpreting information theory measures may not be worthwhile in a policy context. However if a strong theoretical hypothesis could be developed, some of the concepts presented here (in particular Fisher information) could be valuable in trying to quantify the dynamic performance of urban systems.

STATISTICAL ANALYSIS TECHNIQUES

Most of the system indicators described so far have attempted to capture the performance of the overall energy system in a single measure. However an important complementary approach is to understand how the individual core metrics relate to one another. Although the system is complex and non-linear, even a partial understanding of these connections might help policy makers to identify the possible side-effects of their actions and assist experts in their modelling efforts.

A variety of statistical analysis techniques can be used to achieve these aims. The most basic method is linear regression. For example, if only one dependent variable is under consideration with a direct hypothesised causal chain (e.g. greenhouse gas emissions resulting from population and economic growth), then multiple linear regression can be used to quantify the contribution of each exogenous variable. However the potential links between energy system indicators are likely to follow a more complex causal pathway, necessitating the use of more sophisticated techniques such as structural equation modelling or path analysis.

Path analysis is an ex-post analysis technique, meaning that it can confirm a researcher's hypotheses about a causal model but it cannot find the model given unstructured input data. As a simple demonstration of the technique, it was hypothesised that the indicators flow simply from one to another: the driver (id1, population) affects the activity (id90, household expenditure), which affects resource use (id129, total primary energy supply), which creates the impact (id27, road accidents). Using data from 1980 to 2005, a path diagram was calculated showing regression coefficients and error terms (drawn as double-headed arrows) (Figure 10).

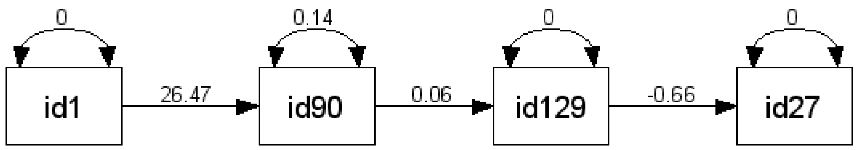

Figure 10. Initial path analysis of core indicators showing regression coefficients and errors terms

Intuitively this does not appear to be a very good model and the link between TPES (id129) and road accidents (id27) seems tenuous at best. Indeed the results of the formal path analysis provide a variety of goodness-of-fit measures, none of which suggest that the above model is appropriate. However part of the difficulty with path analysis is that large amounts of data are required; some suggest that 10 to 20 times as many observations as variables are a minimum requirement (Mitchell, 2001). According to this guideline, only two variables can be used with a data set of 26 observations. This revised analysis, using only population and road accidents, is shown in Figure 11. This model gives an excellent goodness of fit but, of course, path analysis was not required to reach this result; this is simply a basic linear regression and the regression coefficients are indeed the same for both analyses.

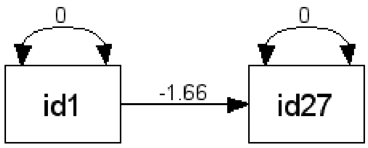

Figure 11. Revised path analysis of core indicators

Two further issues need to be considered for a valid analysis. First the data used to construct these connections represent time-series and therefore any regression models should consider autocorrelation effects (i.e. the effect of an indicator's value at *t – 1* or *t – n* on the value at time *t*). Methods such as the Granger causality test and co-integration tests are typically used. Secondly, structural equation modelling is typically used to assess the influence of latent constructs, i.e. things that cannot be measured, in the building of theory. Psychologists for example might use SEM to assess the effect of "alienation", "identity" or other immeasurable constructs in a theory of behaviour. For urban analysts, constructs might be introduced to represent the state of urban development, urban form or other concepts that are too nebulous to assess with a single observed variable. Overall then, path analysis and related statistical tools are valuable in trying to establish the connections between different elements of the urban energy system. However like many of the other techniques discussed so far, large amounts of data and a strong theoretical perspective are required in order to test hypotheses correctly.

CONTEXTUAL INDICATORS

Contextual indicators reflect issues or concepts not seen elsewhere in the indicator framework but which are necessary for correctly interpreting other measures. Both qualitative and quantitative information might be included here and three examples are considered.

The first "indicator" is a timeline describing key events in the urban energy system. In London's case, these events might include the privatisation of the electricity sector in 1980s and early 1990s or the creation of the London Mayor in 2000. While this is primarily a qualitative measure, some of the issues raised on the timeline might have quantitative equivalents elsewhere. For example, the competition measures in the driver indicators show the liberalisation of the energy sector quite clearly. For other issues though, a timeline provides an accessible and descriptive approach that will be useful for creating the greater narrative of urban energy use.

The second issue is governance. While the precise interpretation of this theme may vary, the general idea is to reflect the institutions, markets and regulations that influence the ability of the energy system to change. Again elements of governance might be seen in other parts of the indicator structure, for example, in measures of energy prices and taxes. Further metrics might also come from the World Bank which routinely measures corruption, regulatory effectiveness, political stability, accountability and other issues on an international basis (World Bank, 2006). These measures might need to be adapted for UES use though and some key areas of interest might include qualitative and quantitative measures of the market structure (e.g. competition indices, organizational charts of key institutions), key regulatory initiatives (e.g. portfolio standards, feed-in tariffs, etc.) and policy objectives (e.g. security of supply, environment or fuel poverty, measured by policy-trend/target-trend indicators (Ravetz, 2000)).

Finally qualitative measures of urban public opinion can be instructive. To gather this data quickly, Google or other internet search engines can be used to identify the adjectives that web users use to describe a particular city (Keirstead, in progress). Although these data are subject to 'digital-divide' biases and are very context-sensitive, the results for London still highlight a number of characteristics relevant to the city's energy performance which may not have been revealed elsewhere. Some of these factors are directly relevant (e.g. London as an expensive (fuel prices), visited (transport connections) and populated city), while others are indirect (e.g. London as a surveilled city suggests potential for traffic management and optimisation). Therefore while this technique does not necessarily provide explanatory insight, like the other contextual indicators, it might be help to build a more complete understanding of urban energy use.

SUMMARY

Unlike the aggregation methods presented earlier, the system performance indicators discussed here are intended largely for expert analysts. Contextual and composite metrics are perhaps the exception as these complements to the basic core indicators are relatively accessible. However measures such as thermodynamic efficiencies, information theory measures, footprint measures, and statistical analyses require a clear theoretical understanding of how the metrics are derived and interpreted. Furthermore large amounts of data are necessary to understand the individual processes behind aggregate sector-wide statistics. The challenge therefore is two-fold: first using theory to define the desired state of an urban system. Specifically, what parameters of urban energy system's performance are we seeking to optimise and improve? Secondly, as these analyses are to be applied to a number of different cities, to devise a method for collecting and storing data in a consistent manner so that sensible normalisation and inter-city comparisons can be made.

Summary

This section has highlighted some of the techniques that can be used to develop system-level indicators of urban energy performance. First, it was shown that aggregation techniques can help to select headline indicators for use primarily by policy makers and non-expert groups. However these methods unavoidably result in a loss of data richness, meaning that aggregate measures are unlikely to meet the needs of all stakeholders (Moldan et al., 1997). In particular, expert urban analysts will likely require large amounts of data and discipline-specific system performance indicators to make their assessments. These measures might range from accessible qualitative measures of urban governance through to more sophisticated quantitative techniques based on thermodynamics or statistical analysis.

The indicators presented here should not be seen as an attempt to identify a single perfect measure of urban energy system performance; indeed complexity theory and post-normal science would suggest that such a goal is inappropriate (Gasaparatos et al., 2007). These metrics instead form complements to the core indicators presented earlier and such an approach based on “methodological pluralism” is more likely to be able to meet the needs of a diverse group of stakeholders and issues (Norgaard, 1989). However a consistent theme for all stakeholders is the need for a clear theoretical basis for indicator selection so that, when combined with transparent and consistent data collection, the interpretation and comparability of the data is reliable. These points are discussed further in the next section.

Part IV: Discussion and conclusion

The previous sections have outlined the major indicator concepts that could prove useful in measuring urban energy systems and their performance. However there are undoubtedly other issues that have been missed or given insufficient coverage. The discussion below therefore considers how to take this initial work forward.

9 Discussion

Three broad issues are considered here. First, the collected London data is reviewed in order to make some initial conclusions about the effectiveness of indicators and how the city's efficiency might be improved. Secondly the completeness of the indicator set is assessed to ensure that the major concepts of urban energy systems have been given sufficient coverage. Finally, a number of general points about the use of UES indicators in analytical and policy-making environments are discussed.

The London energy system

Using publicly available data sources, 110 indicators were collected to describe the basic features of London's urban energy system. Briefly reviewing each sector, we can conclude the following:

- *Drivers*: Since the Second World War, London's population has slowly increased. More importantly however, the number of households has grown owing to national demographic trends towards fewer people per household and London's larger proportion of small households. Economically, there has been a significant increase in household incomes. Following the liberalisation of UK energy markets, energy prices fell during the 1990s but have since risen following international price signals in oil and gas markets. Regarding infrastructure, there has been an increase in the number of dwellings and their thermal performance has also improved. Car ownership rates in London seem to have steadied, after rising significantly during the 70s and 80s.
- *Activities*: Activity data is scarce but some conclusions can be drawn. In the domestic sector, household expenditure in general has risen but perhaps due to liberalisation in energy markets, spending on energy has fallen in real terms since the mid 90s. Modelling results suggest that domestic energy consumption has been fairly constant since 1970, with improved technological efficiency being offset through increased comfort (internal temperatures) and the proliferation of lights and appliances. In the transport sector, the number of daily trips in London has grown steadily since the early 90s with increased uptake of public transport (particularly buses). Commercially, the service sector continues to grow and dominate industrial activities.
- *Resources*: Since 1970, national total primary energy supply has increased by approximately 10%. However there has been a significant shift from solid fuels to gas. Data from London suggests that as in the UK as a whole, industrial demand has fallen but

transport and the domestic sectors have steadily increased (though the London transport data seems to be discontinuous between pre-1991 and 2003 data sets).

- *Impacts*: Socially, road accidents and fuel poverty rates have fallen; though in the case of fuel poverty this has been arguably been the result of direct subsidy rather than increased efficiency (DTI, 2006c); satisfaction with local area has stayed fairly constant over the past 10 years. Economically, London's output and productivity have both steadily increased. Environmentally, NO_2 and PM_{10} have decreased slightly if at all since the late 1990s; CO_2 and SO_2 have shown reductions of approximately 15% and 60% respectively over a similar time period.

While this gives a good picture of what has been happening in London over the past quarter century, system performance indicators can provide additional insight. Composite indicators for example indicate that since 1990 the city's overall energy efficiency has improved by approximately 60% when measured as energy per unit output or per unit greenhouse gas emissions; measured per capita, these improvements have been a more modest 20%. However the thermodynamic efficiency analysis demonstrates that there is still a large potential for improvement. At the end-use level, London is 48% efficient in first law terms, but only 21% in second law terms. In particular, low-grade heating is a major source of exergy losses (Hammond et al., 2001; Ayres et al., 2003) although additional data is required to fully understand the mix of cogeneration, single-use boiler, and electric heating technologies. Furthermore since the energy efficiency of primary supply has been effectively constant over the past 30 years, this suggests that local, rather than national, energy supplies should be the focus of improvement. For example, the solar footprint analysis suggests that these exergy losses could theoretically be recouped using the sunlight falling on the city's area. Unfortunately, insufficient data were available to perform an accurate assessment of the causalities between indicators and therefore the causal chains between indicators remain uncertain.

Missing concepts and other concerns

The London case study had three goals: to assess the framework's effectiveness, to determine data availability, and to experiment with system indicators. These aims have largely been met but this is not to say that the proposed framework and indicators should be adopted as is. For example, it was noted that the indicators shown here were only those based on available data, representing the major themes of the literature; other themes, such as the health impacts of air pollution and measures of urban form have not been included here but could be vital for later work. Furthermore a number of general themes have been raised that will need to be considered before selecting and using any UES indicators. The points below highlight some of these issues and give some initial thoughts on how they might be resolved.

Missing indicator concepts

- *Urban energy resources*: Locally-available energy resources are an important consideration when assessing the energy use within a city (and comparing it to that another city). The local environment metrics and solar footprint calculation give a rough idea of these resources but a more detailed accounting method would be beneficial. For example, other studies have considered the available heat in waste water and rivers (Mori et al., 2007) and created maps to facilitate the use of this information in planning decisions (Arjan von Timmeren, *pers. comm.*). With a better understanding of a city's available energy resources, a system metric might be derived that reflects whether a city has made the most of its available resources. In other words, a low-carbon city with abundant solar energy might not be as impressive as a resource-constrained city which has introduced significant system optimisations and efficiency measures. The emergy yield ratio and the notion of circular, not linear, urban metabolisms may be useful in this regard (Girardet, 1992; Ulgiati et al., 1995; Huang et al., 2005).
- *Emergent properties*: The system indicators described above gave some insight into the overall performance of an urban energy system. However the listed metrics are not exhaustive and for a system as complex as a city, any number of emergent system properties may be considered important. These could include network measures of shortest path and redundancy for energy distribution networks, as well as ecological measures of resilience (Neubert et al., 1997; Batabyal et al., 1999; Gunderson, 2000; Martin, 2004; Venkatasubramanian, 2007). Similarly other authors have suggested that measures of adaptive flexibility, i.e. the ability to respond successfully to a changing environment, are necessary to evaluate the sustainability of a complex system (Bagheri et al., 2007; Nooteboom, 2007); this clearly overlaps with policy concerns about energy security. The question is therefore a) what emergent properties are of interest to the disciplines within the UES project and b) what additional data, if any, need to be collected to allow the observation of these properties?

General indicator issues

- *System boundaries and comparability*: As demonstrated in the case of London's population, the choice of system boundaries (both geographic and temporal) can make a significant difference to the results of one's analysis. Life cycle analysis, which has not been explicitly considered here, is another example where clear and consistent system boundaries are needed, particularly to facilitate comparisons between cities. However as it is unlikely that a particular boundary will be relevant to all analyses, the challenge will be to ensure that the selected boundaries are appropriate for the desired analysis and comparison.
- *Data constraints*: Data availability is a major theme of the London case study and indicator research more generally. For example, in the framework presented here, it was noted that activity data (i.e. useful energy consumption) is particularly scarce and many analyses, e.g. exergetic efficiency, could benefit from the use of highly disaggregated data. The goal

should therefore be to provide as much data as necessary within a consistent framework so that users can get what they need without losing the relevant caveats and context. Two related strategies might be useful here. The first is to develop models that estimate disaggregated behaviour based on censuses or other detailed surveys (Druckman et al., in press); ISIC industrial output codes can similarly be used to identify the major production categories within a city and then perform detailed process analyses for each product. The second method is to back-cast from a desirable future outcome (e.g. 60% CO_2 reduction by 2050) to estimate the data requirements needed to monitor or influence progress towards this goal (Bagheri et al., 2007).

- *Optimization objective functions*: Optimization models are an important part of the UES project but the question remains what should these models be optimizing – least cost? CO_2 emissions? Resilience? For example, if efficiency was chosen as the objective function, the basis for normalization would have to be carefully chosen (e.g. energy consumption per unit output, per capita or per unit pollution) so that the optimal solution for one city can be compared with another. A related issue is whether a single objective function is appropriate. As a complex system, it might be better to optimise on multiple objectives or emergent properties though computationally this may prove difficult.
- *Theory*: Many of the issues raised throughout this report are answerable only with a clear theoretical vision of the city and its energy use. Since urban theory literature often has a social or political focus (e.g. Kotkin, 2005; Short, 2006), ecological or technical systems may provide a better basis for this debate. However the adoption of a techno-economic viewpoint needs to be balanced with an awareness of alternative perspectives, particularly if the indicators we develop are to have influence in policy-making debates (Astleithner et al., 2004).

If one theme can be drawn from these issues, it is that the analysis of urban energy systems is a multi-scale problem. Each discipline will need to situate its own sub-system within the larger context and the challenge for indicators is to ensure that information can pass accurately and freely between these different groups. These various "use-cases" might be differentiated on a four-dimensional axis: geographic, temporal, technological (centralised vs. decentralised), and behavioural (household vs. institutional). Such a framework may prove useful in ensuring that the selected indicators have an appropriate scope.

Engaging Wider Stakeholders

Although the indicators are currently being used for internal analysis and modelling work, they will eventually need to be introduced to a wider audience. However if this is not done with care, these groups – often with different technical expertise and worldviews – could return to more familiar metrics that paint a more favourable but less insightful picture of the city.

To focus discussion on this issue, it is assumed that by the end of the project a list of cities will be produced ranked according to their urban energy efficiency. Cities that come in the top of such a list would of course be quite pleased but those near the bottom would be inclined to ignore the results and continue with their existing measures. By working closely with cities on data collection and by being clear in the indicator methodology, these issues can be partly overcome. However the larger issue may be the choice of concepts that are included in this overall metric of urban energy performance, which of course will stem from the project's theoretical view. While a formal declaration of these principles has not yet been made, this indicator report has highlighted some possibilities:

- A measure of absolute sustainability (e.g. exergetic efficiency)
- A measure of local resource use (e.g. emergy yield ratio)
- A measure of adaptive flexibility or dynamic sustainability (e.g. Fisher information)
- A measure of productivity (energy consumption per unit economic output or per capita)
- A measure of impact (pollution per energy unit)

Whether or not these measures can then be fairly aggregated into a single measure is debatable. As Gasparatos et al. (2007) and others have argued, the subjectivity of sustainability concepts means that a "good" city will be different things to different people. However by clearly stating our criteria for the "best" urban energy system, alongside the background data and assumptions, we can hopefully engage with non-expert stakeholders to promote the concepts and metrics needed to improve urban energy use.

SUMMARY

Thousands of potential urban energy system indicators can be found in the literature, ranging from basic measures of population through to technical metrics derived from abstract theory. Therefore our challenge in creating effective measures of urban energy system performance is to present an appropriate range of data, both to meet our present requirements for modelling and analysis and to provide an access point for a dialogue with non-expert groups. This goal can be achieved through two practical steps: clearly stating our criteria for a good urban energy system and developing an indicator framework that can support multiple scales of analysis.

10 Conclusion

This report has provided an overview of the key issues surrounding indicators for urban energy systems. The discussion centred on three goals: summarizing the state of the art in urban indicators, outlining a framework for UES indicators and applying it to London, and highlighting issues for further consideration and research.

In this first part of the report, it was shown that the current practice in urban sustainability indicators emphasises data availability and process criteria. Their effectiveness as analytical tools is often given a secondary role due to their use in non-expert discussions and data availability constraints. Many existing urban energy indicators therefore have a descriptive role, providing basic data on the social, environmental and economic aspects of energy use within the context of a larger sustainability assessment.

It was suggested that the short-comings of this approach may be largely due to an excessively broad scope for urban indicators. It was therefore proposed that a more manageable and insightful set of indicators might be developed by focusing on energy as a cross-cutting core aspect of urban life. Specifically, an indicator framework was outlined using the concept of energy-services; i.e. tracking the drivers of service demand, the demands themselves, the resources required to meet these demands and the impacts of consumption. Data were gathered from a variety of sources and 110 indicators presented to describe these core aspects of the London energy system. However in addition to this descriptive role, the data collection phase also raised several important issues such as downscaling, system boundaries and disaggregation. These themes were also seen in the development of a series of system metrics, both aggregate measures of the core indicators and specific technical measures of performance.

The results of this review suggested that the indicator framework outlined here should be effective for the needs of the UES project. However since the project's research activities will be conducted on varying scales of analysis, it was recommended that clear and consistent procedures for data storage be developed. In addition if the indicators are to be eventually used by non-expert stakeholders, a declaration of theoretical criteria should be made so that any judgement on the merits of a particular city's energy system can be well-understood. The indicator research will therefore continue by addressing these questions and extending the methodology to other cities to gain a wider range of experience.

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Appendix A: INDICATOR SELECTION METHODOLOGY

The indicator selection methodology of Maclaren (1996) contains nine-steps:

- define urban sustainability goals;
- scoping;
- choose an appropriate indicator framework;
- define indicator selection criteria;
- identify a set of potential indicators;
- evaluate the indicators and select a final set;
- collect data and analyse the results;
- prepare and present the indicator report; and
- assess indicator performance.

While some of these issues have been discussed briefly in Section 2 above, the purpose of this appendix is to clarify the assumptions and choices that have guided the indicator work presented in this report. The following discussion is taken largely from Keirstead (2007).

1 Define urban sustainability goals for which indicators are needed

It has been suggested that three primary groups have an interest in indicators: scientists, policy makers, and the public (Braat, 1991 cited by; Huang et al., 1998). This diversity exists in urban energy systems as well and an early project workshop suggested that potential stakeholders could include Imperial College and academia, BP and other industry groups, municipal, national and international governments and civil society at large. Each of these groups is likely to have their own requirements for urban energy indicators; however at this early stage, we focus primarily on the needs of the UES project itself. The goals are therefore as follows:

- To describe urban energy systems as complex systems
- To measure and compare the performance of urban energy systems
- To support transparent debate on indicator criteria
- To support communication and decision making on UES issues

Like all steps of the methodology, these goals can be revisited later.

2 Scoping

In order to choose appropriate and relevant indicators, the scope of the investigation must be considered. Maclaren's methodology highlights three relevant tasks: choosing the approximate number of required indicators, as well as determining the temporal and spatial boundaries.

NUMBER OF INDICATORS

The number of indicators required for a project depends on the needs of the stakeholders and their ability to understand different types of data. From above, one important goal for the UES project is to develop indicators that effectively describe urban energy systems and their complexity. A large number of indicators is likely to be needed for this task and fortunately this is compatible with the expert knowledge of the primary stakeholders. However even within the project team there are different levels of expertise and therefore a reduced set of 'core' indicators would be valuable, both to share information within the project and to prepare for later engagement with other stakeholders. This suggests a hierarchy of indicators, similar to those used by the Eco 99 (PRE, 2006b) and UK energy sector indicator (DTI, 2006b) frameworks.

TEMPORAL BOUNDING

Temporal scope consists of two elements. First, the timescale must be sufficiently long to validate models against historical data (e.g. to describe Singapore's dramatic growth since 1960, Ooi, 2005) and to describe the trends relevant to future decision making (e.g. climate change over decades). The second issue is the temporal resolution of individual indicators. For example, a sustainability study in Colombia noted that not all indicators need to be measured at the same frequency: investment in renewable energy might be measured on an annual basis, while energy consumption should be observed more often to reflect seasonal or daily variation (Velásquez, 1998). The appropriate timescale and measurement frequency is therefore likely to be specific to each metric, though the overall indicator set should reflect a range of scales.

SPATIAL BOUNDING

The urban sustainability literature places a great deal of emphasis on the ability of cities to influence an area beyond their immediate boundaries (Satterthwaite, 1999; McGranahan et al., 2005). A variety of spatial scales are potentially relevant In the UES context, as energy use is connected to local quality of life and pollution issues, regional development and transportation infrastructures, and global climate and resource availability. At present, it is not clear that priority should be given to indicators at a particular scale. Therefore, indicators should be proposed to give sufficient coverage of local, regional and global scales and their interaction.

3 Choose an appropriate indicator framework

Meta-studies of urban sustainability indicators have identified hundreds of indicator frameworks that can be used to structure the selection and conceptualization of metrics (e.g. Walton et al., 2005). Maclaren (1996) summarises this diversity by enumerating the main framework types including domain-based (e.g. social, economic, environmental sustainability), goal-based, and causal (e.g. driver-pressure-state-impact-response OECD, 2003). Almost any of these methods could be applied to UES as energy use:

- influences social, economic and environmental sustainability;
- is often discussed by economic or policy sector (e.g. domestic, transport, industrial);
- affects specific issues such as fuel poverty, air pollution, or climate change;
- spans urban, regional and global scales; and
- is the result of complex interactions within urban systems.

Fulfilling these requirements does not necessarily require hundreds of indicators and a few well-chosen metrics could be effective if presented within a structure that allows them to take on various roles as necessary. The literature offers examples of such frameworks (Afgan et al., 2000; Haberl et al., 2004; Wiek et al., 2005; Cabezas et al., 2007) but the integrated sustainable city assessment method (ISCAM) (Ravetz, 2000) is chosen here because of its emphasis on service demand. If the efficiency of urban energy systems is to be improved, then it must be recognized that consumers do not buy energy for its own sake but for the services it provides.

Ravetz's framework can be modified to identify four primary indicator categories: *drivers*, *activities*, *resources* and *impacts*. Each theme can be summarised by a set of core indicators and broken down into greater detail as needed. The framework is sufficiently comprehensive to incorporate the diverse expertise of the UES researchers and hopefully the interests of future stakeholders as well; for example, one could envision adding detail on corporate innovation and alternative methods of service provision to the drivers or activities sections. However, while Ravetz noted the importance of a systems perspective in his paper (i.e. understanding a system's adaptability, resilience and robustness), no specific metrics were included within the ISCAM model framework.

This problem can be partly corrected by the addition of an explicit *system* indicators category. Here, indicators can be added to describe the links between each of the four descriptive indicator categories and the system's overall performance. However it should be noted that, even with this improvement, the framework is essentially a method for identifying the key elements of the urban energy system and ordering indicators on these topics. A theoretical understanding of how these factors work together will still be needed to select individual metrics and identify those parameters which have the greatest impact on the overall system.

4 Define indicator selection criteria

An important part of selecting indicators in a transparent manner is to define the criteria against which potential indicators will be evaluated. For example, indicators might be evaluated against the criteria identified by the OECD (2003):

- policy relevance and user utility (i.e. representative, easy to understand, comparable with data from previous studies and other regions);
- analytical soundness (i.e. based on established scientific and theoretical principles, able to link with modelling efforts); and
- measurability (i.e. data are readily available, frequently updated, affordable)

Of course these activities – selecting criteria, developing measurement scales and so on – are dependent on the goals of the evaluator. For example, national statistics agencies may choose criteria that favour an easily measured, high-precision proxy measure. In contrast, the UES project will emphasise analytical validity in its early efforts on indicators, potentially selecting simulated or estimated parameters if supported by theoretical arguments.

5 Identify a set of potential indicators

A potentially vast range of indicators could claim to be relevant to the UES project, for two reasons. First the pervasiveness of energy use in urban life means that seemingly unrelated metrics could be treated as energy proxies (e.g. the number of pedestrian accidents is an immediate indicator of public safety but it could also be linked to the design and modal share of transport networks). Secondly, a number of alternative metrics could be devised for any given topic. For example, energy efficiency could be measured as energy use per capita, energy use per unit of economic output, or energy use per unit of greenhouse gas emissions. Consequently the indicator framework outlined above cannot be used to identify potential indicators efficiently; instead some academic judgement (e.g. a theory, a model) should be used to ‘look in the right place’ for potential indicators. This report therefore takes two approaches to identify a set of potential indicators. First, a variety of potential indicators from both practical applications (e.g. London’s quality of life metrics) and theoretical literature are presented to illustrate the concepts described here (Sections 3 to 8). Secondly, the report specifically solicits reader feedback on the choice of potential indicators (Section 10) as it is hoped that while reading this report, team members will recognize how indicators from their own fields of expertise might fit within this framework.

6 Evaluate the indicators and select a final set

Once indicators and the relevant criteria have been identified, the metrics can be scored and a final set of indicators chosen. Methods such as multi-criteria decision analysis (Section 7) can be used for this purpose, enabling a variety of potential users to assign weights based on their indicator priorities. However it was felt that it was too early to perform a formal MCDA on the indicators presented here; instead the aim of this report is to demonstrate a range of metrics and the relevant issues that need to be considered. Each group within the project can then use this information to develop measures that are most effective in their disciplines. After these analyses have been completed, towards the end of the project’s initial three-year period, the entire team can discuss which metrics should form the basis for our final urban energy systems indicator set.

7 Collect data and analyse the results

8 Prepare and present the indicator report

These steps are initially fulfilled by this report. However the outputs of the other project work streams will contribute to these goals as well, demonstrating the application of additional metrics.

9 Assess indicator performance

This is an on-going task but the first formal assessment will be a workshop to discuss the findings of this report (Section 10). The goal of this meeting will be to receive feedback on the structure of the indicator framework and encourage other team members to describe their ideal indicators and indicator goals.

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