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Selecting sustainability indicators for urban energy systems

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ABSTRACT

Literature on the measurement of urban sustainability shows that no single indicator framework is appropriate for all applications. Consequently practitioners must consider the intended goals of indicator use and carefully choose metrics to maximize their relevance and effectiveness. The study of urban energy systems demonstrates these issues, as energy use is integral to many dimensions of urban sustainability and hence encompasses an array of stakeholders with potentially divergent needs. This paper therefore explores the selection of indicators for urban energy use, drawing on the previous work of Maclaren (1996) and Ravetz (2000). Potential urban energy indicators for London are presented to demonstrate the selection procedure and to highlight the challenges posed by the measurement of urban energy use. The paper concludes by suggesting that a mix of data sources, supported by a strong theoretical framework, is required to evaluate both urban energy systems and urban sustainability in general.

Key words: urban energy systems, indicators, sustainability

1 INTRODUCTION

International efforts such as the 1987 Brundtland Report and the 1992 Rio Earth Summit have helped to place sustainable development issues on international and national policy agendas. However these discussions have also demonstrated that the urban level is important to meeting the needs and aspirations of present and future generations. Indeed by 2030 the UN estimates that 60% of the world's population will live in cities, offering both opportunities and challenges when trying to achieve sustainability goals (UN, 2006). On the one hand, city planners and architects might leverage high-density urban developments to try and encourage sustainable behaviour and consumption patterns (Arendt, 2007). On the other hand, growing cities will continue to reach far beyond their local boundaries in order to fulfil resource demands. Therefore understanding the city's complexity – its "built form, government structure, production systems, consumption patterns and waste generation and management" – is integral to both local and global sustainability debates (Satterthwaite, 1999: 6).

The role of cities is recognized explicitly by Agenda 21 and its clauses on sustainable development and local government. By 1997, for example, over 6000 cities had adopted Local Agendas 21 in order to identify and address local sustainability concerns (Ooi, 2005).[1] However implementing 'sustainability' is a difficult task because of the challenges associated with measuring the state of urban capital (environmental, social and economic), defining targets and assessing progress towards these goals. Fortunately a tool exists to help with such tasks.

If chosen properly, indicators – "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) – can contribute to sustainability debates through two major roles: reducing the amount of data required to describe a situation fully and facilitating communication with diverse audiences. Indicators have been widely adopted for systematic monitoring, early warning, target setting, performance monitoring, public education and other tasks (e.g. Alberti, 1996; Brugmann, 1997), creating a large body of literature from which some general conclusions about the state of urban indicator use might be drawn (e.g. Bell et al., 1999; Walton et al., 2005). For example, studies have observed that 'sustainability' is interpreted as an extremely diverse and subjective topic, influencing the range of stakeholders and the choice of issues for which indicators are required and used. Most importantly, a common conclusion is 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).

[1] Though approximately 90% of these initiatives are in cities of developed nations, specifically 80% are European cities.

This paper considers indicators of a particular feature of the urban environment: urban energy systems (UES). This field is the focus of the BP Urban Energy Systems project at Imperial College, London, a multi-disciplinary effort which seeks "to document and understand in detail how energy, people and materials flow through a city [and] to show how the efficiency of both existing and new-built cities can be radically improved" (BP, 2006). The project, like its peers elsewhere (e.g. CMI, 2007), seeks to use a systems perspective to complement the small-scale assessments of specific energy services and technologies seen elsewhere (e.g. Aki et al., 2003; Tonon et al., 2006).

It has been suggested that energy systems might provide a useful perspective from which to analyse urban sustainability (Kemmler et al., 2007). In a similar fashion, this paper presents the development of a series of UES indicators to highlight challenges in the design of urban sustainability indicators more generally. After describing the theoretical and methodological approach, potential UES indicators for London are discussed and suggestions for better urban indicator design offered.

2 METHODOLOGY FOR SELECTING INDICATORS FOR UES

Like other aspects of urban sustainability, urban energy systems have the potential to attract a range of stakeholders. Indeed, while it has been suggested that only scientists, policy makers, and the public have a primary interest in indicators (Braat, 1991 cited by; Huang et al., 1998), urban energy system indicators are likely to engage with the commercial sector as well (e.g. energy suppliers, regulators, technology manufacturers, the public as consumers). Consequently indicators must be developed transparently if they are to occupy a trusted position within public debates and facilitate consensus-building between these groups and their diverse agendas. An important step toward this goal is therefore to identify an established method to guide the identification of indicators and their goals.

The urban sustainability literature offers several alternative strategies (e.g. Alberti, 1996; Bell et al., 1999; Hemphill et al., 2004) but for this paper, the methodology of Maclaren (1996) has been chosen. While this framework was originally proposed for the preparation of urban sustainability reports for municipal governments and other civil society organizations (e.g. initiatives like Sustainable Seattle (AtKisson, 1996)), it has the advantage that its "structured process for urban sustainability reporting" (p. 1) can be used to make explicit the academic requirements of the UES project. The full methodology is given in Table 1 below but only the first five stages of this process are considered presently.

Design stage	Scope of the present paper
1. Define the urban sustainability goals for which indicators are required	✓
2. Scoping	✓
3. Choose an appropriate indicator framework	✓
4. Define indicator selection criteria	✓
5. Identify a set of potential indicators	✓
6. Evaluate the indicators and select a final set	
7. Collect data and analyse the results	
8. Prepare and present the urban sustainability report	
9. Assess indicator performance	

Table 1: A methodology for selecting urban sustainability indicators (Maclaren, 1996)

2.1 Define goals

Given the range of potential UES stakeholders noted above, an early challenge is to solicit these diverse perspectives and incorporate their views into the design of the indicator set. Wiek et al. (2005: 593) note that this can be achieved via two methods: the participatory approach (which "enables 'affected persons', e.g. citizens or entrepreneurs, to articulate and discuss their perspectives on the city-region and its development") or the expert approach (which "is appropriate if the problem is too complex to be tackled with laypersons or requires a deeper professional insight"). As the primary goal of the project is to model and understand UES in an academic fashion, the expert approach provides a sensible starting point. Then, once this understanding has been established, the indicators can be extended to non-expert groups for feedback and discussion. Other research has similarly shown that the development of an initial selection of expert indicators can indeed be a valuable catalyst for these wider deliberations (McAlpine et al., 2006).

2.2 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. For the UES project, one of the main goals is to develop indicators which summarize and illuminate the complexity of urban energy systems. A large number of indicators may be needed for this task but 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, 2006a) and UK energy sector indicator (DTI, 2006a) 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 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 trends (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). 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 evident that priority should be given to indicators at a particular scale. Therefore, the challenge is to propose indicators that provide sufficient coverage of local, regional and global scales and their interaction.

2.3 Choose an appropriate 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) summarizes 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 but the pervasiveness of energy use suggests that a single approach is unlikely to be effective. Instead a combination framework should be developed to link key features, as energy use:

- influences social, economic and environmental sustainability;
- is often discussed by economic 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., in press) 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, it must be recognized that consumers do not buy energy for its own sake: consumers want light, warmth and mobility not kilowatt-hours or BTUs. Similarly, the impacts of energy use can also be seen as products of these service demands (Carbon Trust, 2006).

The framework shown in Figure 1 demonstrates this distinction and identifies four primary indicator categories: *drivers, activities, stocks and flows* and *impacts*. Each theme can be summarized 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 (i.e. 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 (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.

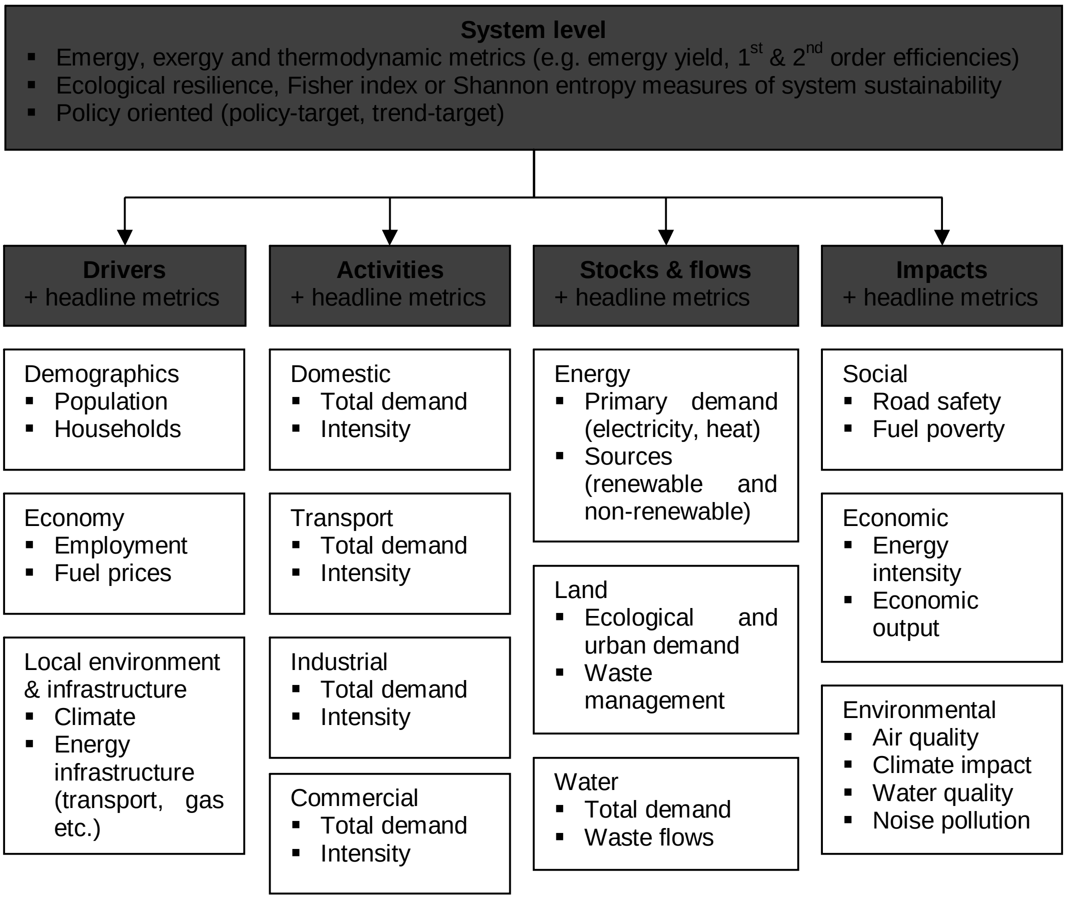

Figure 1: A framework for selecting UES indicators with indicative indicators (based on Ravetz, 2000)

2.4 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. Urban sustainability assessments often use participatory processes to establish broad definitions of evaluation criteria and experts then convert this guidance into a functioning list of indicators (e.g. Rotmans et al., 2000). 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)

Multi-criteria decision analysis suggests that individual criteria should be chosen 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 these activities – selecting criteria, developing measurement scales and so on – are arguably 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.

2.5 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, the green space within a city might be measured as a qualitative comparison to planning goals, as a percent of the overall urban area or as the total number of facilities available. 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.

2.6 Summary

The methodology described here enables the UES project to declare its interests in UES indicators and sets out its approach to indicator selection. For parts of this procedure, decisions can be taken now; for example, the indicators are to be used first to gain academic understand of urban energy systems across a range of temporal and geographic scopes. However this section has suggested that an indicator framework by itself may be of little use without strong theoretical support. To demonstrate the potential short-comings of this naïve approach, the next section presents a series of UES indicators for London selected in the 'traditional' opportunistic manner.

3 ASSESSING UES INDICATORS FOR LONDON

The culmination of Maclaren's methodology is a 'final' indicator set that can be applied, then subsequently evaluated and revised if necessary. Here, this iterative procedure is repeated in miniature, by collecting a series of possible UES indicators for London in order to shed light on the selection of potential indicators and their evaluation criteria. Accordingly the goals of the present exercise are not the same as the overall indicator selection process. For example, the comparability of indicators between cities will be an important feature of the final indicator set yet only London is considered at present. Instead, the assessment sought to address the following questions:

- What data are available for the creation of London UES indicators?
- What do the available indicators suggests about the selection criteria for the final indicator set?

The assessment began by choosing indicators in accordance with the framework outlined above. For each major theme, a number of sub-themes were identified and relevant indicators chosen. Where possible, long time-series data were selected and consequently most metrics were sourced from official government statistics; other measures were found but often only one or two years worth of data were available (e.g. London's ecological footprint, BFF, 2002). The indicators are outlined in Table 2 but, owing to the 'opportunistic' selection method, they only represent readily available London UES indicators rather than a definitive list. Indeed many flaws with the particular metrics can be found; the Met Office (2007), for example, measures the solar resource as sunshine hours, rather than irradiance in W/m^2, which would be preferable to facilitate comparisons between cities at different latitudes. The short-comings of each indicator section are now considered in detail.

Theme	Sub-theme	Indicator
Drivers	Demographics	• Population • Number of households
	Economic structure	• Energy prices (by fuel) • Employment • Competition in electricity and gas markets • Household weekly income and expenditure
	Local Environment	• Sunshine hours • Wind speed • Area • Latitude and longitude • Temperature • Rainfall
	Infrastructure	• Investment in energy industry (R&D and capital stock) • Car ownership (% households owning at least one) • Road length • Rail infrastructure (rail length, number of stations) • % of houses meeting 'decent' housing standard • Office space
Activities	Domestic	• Delivered energy demand (by function - space heating, water heating, lights and appliances) • Delivered energy demand (by fuel) • Weekly household energy expenditure (by fuel) • Total delivered domestic energy demand (electricity, other fuels)
	Transport	• Daily average trips (by mode) • Freight volumes (at airport and by road) • Airport passenger volumes • Total delivered transport energy demand (electricity, other fuels)
	Commercial	• Total commercial turnover • Total delivered commercial energy demand (electricity, other fuels)
	Industrial	• Total delivered industrial energy demand (electricity, other fuels)
Stocks and flows	Energy	• Total energy production • Total energy imports • Total energy exports • Total primary demand
Impacts	Social	• Quality of life • Road accidents • Fuel poverty
	Economic	• Economic output • Energy intensity • Labour productivity
	Environmental	• Greenhouse gas emissions • Acid rain precursor emissions • SO_2 and NO_2 emissions

Table 2: UES indicators for London identified using an 'opportunistic' selection method

3.1 Drivers

Driver indicators represent the determinants of energy services demand. Many of the indicators included here provide basic descriptions of the urban environment and consequently data are often available in long time-series which can be valuable when calibrating UES models. However the characteristics of each metric can vary significantly. For example, the location and climate of a city will change gradually (if at all) whereas energy prices and short-term weather are much more variable; both extremes are important though confirming that, while each indicator has its own ideal temporal resolution, the indicators should collectively cover short and long timeframes.

The issue of geographic scope is important to all indicators but it is particularly clear in the case of driver indicators. The concern here is that not all "London" indicators reflect the same area. Regional statistics (e.g. household income and expenditure) are gathered according to the London government office region (NUTS[2] Level 1). However other statistics, such as office space and population, are calculated on finer scales (e.g. NUTS levels 2 and 3 - Inner/Outer London; or LAU 1 – boroughs). These administrative distinctions raise important questions about the practical boundaries of a city. For example, with the introduction of the high-speed IC 125 train in 1976, London experienced the "Peterborough effect", enabling commuters to come into the city daily from over 100 miles away (Hollowood, 2006). Such changes suggest that the indicators based on administrative city boundaries may provide an incomplete picture of the drivers of energy services demand. Consequently indicators must reflect such changes to the regional, and even global, context.

3.2 Activities

Activity indicators describe services that require energy. The distinction between service demand and energy consumption is important because it enables the efficiency of service provision to be considered explicitly. Activity indicators therefore culminate in the total delivered demand (e.g. the electricity required to power the light bulb that provides the light). The indicators are divided into standard energy sectors: domestic, commercial/industrial, transport (e.g. DTI, 2006b). This provides overlap with national energy statistics and enables the indicators to be used for specific areas of energy policy; however these figures must be used with care if they are to remain valid: e.g. isolating the difference between delivered fuels (i.e. a final use of gas, coal, etc.) and delivered electricity (i.e. transformed gas, coal, etc.).

[2] The European Office of Statistics has developed this nomenclature to facilitate statistical comparisons within Europe; NUTS = Nomenclature of Units for Territorial Statistics, LAU = local administrative units.

Like drivers, activity indicators also cover a range of temporal and geographic scales. Some of the challenges here can be identified by considering potential indicators for domestic energy activities:

- Data for delivered energy demand by activity, and by fuel, are available from 1970 to 2004 (BRE, 2006). While these values cover the whole of Great Britain, they are modelled and so if sufficient data were available to parameterise a model of London's housing stock, it might be possible to simulate such data for London.

- Fuel expenditure is available for the London government region from 1990 to 2005 (ONS, 2005); however it is only a proxy for final energy consumption and, given the influence of markets and regulation on energy prices, it is difficult to determine actual energy consumption from this figure (especially over time or across jurisdictions)

- Total delivered demand by fuel is available at a UK level for 1970 to 2005 (DTI, 2006b). An alternative source of data, the London Energy and Carbon Inventory provides this data at the borough level (LAU 1) by fuel and by sector (e.g. domestic, transport, commercial) (GLA, 2003) but only for 2003. Additional long-term data might be acquired from industry (e.g. electricity and gas suppliers) but confidentiality concerns and infrequent meter readings can limit data accessibility and quality.

The introduction of modelled data demonstrates one method for overcoming the scoping issues found in official statistics. Indeed, if validated against known data, such simulations could provide valuable insights into processes at scales not covered by other data sources.

3.3 Stocks and flows

Stocks and flows represent the resources that are consumed in meeting the demand for energy services. In other words, where activities culminated in delivered energy demand, stocks and flows would represent primary energy demands (including transmission and distribution). Of course, energy need not be the only resource considered here; land and water use are also relevant in energy systems (IAEA, 1999) and could be added to the framework.

Stock and flow information is recorded primarily at national levels, which makes it very difficult to isolate the impact of one city; at most, a description of the average citizen can be gained. London, for example, has very few generating or primary fuel sources within its boundaries (National Grid, 2006) but extra-urban facilities are clearly vital to the urban energy system. Consequently energy networks themselves are an important consideration and indicators of their performance must be added here or in the system category (e.g. Watts et al., 1998; Gattuso et al., 2005; Angeloudis et al., 2006).

3.4 Impacts

Impact indicators reflect the costs and benefits of energy use. They provide the most direct correspondence with traditional sustainability indicators and are divided into social, economic, and environmental themes. Again, these indicators reflect the geographic scope of sustainability by incorporating local effects (e.g. particulate air pollution), regional effects (acid rain precursors) and global impacts (climate change).

While the UES project currently has an academic focus, it is anticipated that the results will appeal to a wider audience. However these groups may not be able to interpret the full set of indicators used for academic analysis and modelling. Consequently the framework plans to places indicators within a hierarchical structure so that detailed metrics can be condensed into headline indicators. This raises questions about how indicators might be aggregated in a sensible manner. For example, the Eco 99 methodology converts the damage from different effects into common units (e.g. disability-adjusted life years). These can then be compared to a reference system, normalized, weighted if necessary and combined into a single metric (PRE, 2006b). Yet the basis for aggregation is not always obvious as in the case of environmental damage or economic benefits (which might be measured in currency): for example, how might one combine metrics of fuel poverty and quality of life into a single social sustainability metric in any meaningful way? Furthermore, if the overall efficiency of a city's energy systems is to be quickly compared with that of another location, how might one combine bring together social, economic and environmental impacts into a single measure? Additional research in this area is required, though the literature suggests that principle components analysis (Jollands et al., 2004; Morse et al., 2005) or rank-based indices (Ooi, 2005) may be valuable.

3.5 System

The indicators presented so far might be described as 'traditional' indicators. They offer primarily a descriptive view of urban energy systems and provide little insight on the dynamic interactions between categories. However by adding a *system* indicators category, it is hoped that these links can be made explicit and offer a better understanding of the opportunities for efficiency gains. The literature suggests some potential indicators and four areas of interest have been identified:

- *Policy metrics:* Ravetz (2000) provides two policy metrics, based on progress towards desired goals and the effect of different policy scenarios, to describe the system's performance in future. Work on this theme can be extended by focusing on the uncertainty surrounding both the indicator trend and the target.
- *Ecological metrics:* Eco-footprinting is an example of a metric which attempts

to capture the impact of an entire city (Rees, 1992; Rees et al., 1996; Wackernagel et al., 1996). While the metric does have its criticisms (particularly with regard to the consequences of energy use, Ayres, 2000), it does provide a very accessible measure of the impact of urban lifestyles. Other ecological metrics – for example, of resilience and vulnerability – might also prove valuable as a way to describe the dynamics of urban energy systems (Gunderson, 2000; Villa et al., 2002; Cabezas et al., 2005; Balocco et al., 2006; Cabezas et al., in press).

- *Thermodynamic indicators:* These indicators are often derived from first principles and could be valuable to describe the opportunities for re-using energy flows of different qualities within the city. For example, early work in the UES project has suggested that London's exergetic efficiency is 30% (comparable with Hammond, 2000). Similarly a solar footprint methodology is being developed to complement traditional footprinting; i.e. how much energy (expressed as an area receiving solar radiation) would be required to return the urban system to its original energy state? Other examples of thermodynamic energy system indicators are also available (e.g. Balocco et al., 2000; Sciubba et al., 2005; Tonon et al., 2006)
- *Qualitative indicators:* Qualitative indicators could provide a valuable complement to the quantitative assessments presented so far. For example, early work has involved searching Google for adjectives that describe various cities. The results indicate that London is seen as the most "surveilled" city: one might not think of this as an energy metric yet it highlights infrastructure within London that could be used to control and optimise flows of people and goods. Precedent for mixing such quantitative and qualitative indicators can be seen, for example, in Hemphill et al. (2004) who present a method for combining disparate data sources and their uncertainty in a consistent manner.

3.6 Summary

This assessment of UES indicators for London began by selecting readily available energy indicators that fit the indicator framework outlined above. While a variety of indicators can be found to represent each of the indicator categories, these metrics are difficult to relate to one another. Differences in temporal and geographic scope, for example, mean that the link between a city-level driver indicator and a national-level stock and flow indicator is not readily apparent. However other sources of data, such as modelling results or qualitative information, may provide an important complement to 'official' data sources and help to develop a more holistic picture of the city. This suggests that measurability is less important than analytical validity as a criterion for UES indicators.

4 CONCLUSION

The paper began with the premise that urban energy systems provide a basis for the analysis of urban sustainability. It was shown that, like urban sustainability, urban energy systems are relevant to a range of stakeholders and that indicators are likely to play a key role in communicating complex data to these groups. Consequently a transparent methodology was needed to facilitate trust and the framework outlined by Maclaren (1996) provided this template.

Beginning from an academic interest in UES (as opposed to a more general communications focus), some aspects of urban energy indicators could be readily identified such as the desired temporal and geographic scope. As well, an indicator selection framework based on Ravetz (2000) was chosen to emphasise an energy services focused model of urban energy systems. However choosing a potential list of indicators and selection criteria was more difficult. To gain an understanding of the issues that might need to be considered, readily-available UES indicators for London were identified. A review of these metrics identified two important issues. First, even for a data-rich city such as London, not all desired data were available. Specifically, the boundaries that govern the collection of official statistics and other data are not always comparable and they fail to account for the full extent of a city's links with regional and global scales. Secondly, simulations or qualitative descriptions of a city offer a potentially useful complement to official statistics.

These findings suggest that urban energy system indicators, especially at the early stage of this project's research, should emphasise analytical validity over measurability. In practice, this means that a strong theoretical understanding of urban energy systems needs to be developed in order to identify potential indicators efficiently, prioritise indicator selection criteria, and provide a basis for indicator aggregation and interpretation. Such an approach should enable the use of a much wider range of data sources and analysis techniques, though the results will have to be carefully validated against a group of known metrics.

While this discussion has focused on urban energy systems, the key findings presented here are also relevant to urban sustainability indicators in general. Indeed one might conclude that urban sustainability indicators based exclusively on official statistics will rarely, if ever, provide a complete and consistent description of the urban environment. Consequently triangulation strategies should be explored using modelled and qualitative data to complement more traditional metrics. However for this strategy to be successful, a theoretical understanding of the system in question is required to guide subsequent indicator activities. The UES project will therefore continue its research on indicators by developing such a model of urban energy use and identifying complementary system-level indicators.

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