



Identifying key technology and policy strategies for sustainable cities: A case study of London

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ABSTRACT

Assuming communities in a city may formally express their aspirations for the future sustainability of their city, which technological innovations for changing the city's infrastructure and metabolism might they introduce today, as a first step towards realizing their distant aspirations? What is more, recognizing the diversity of aspirations that may never be reconciled into a consensus, might some innovations and policy interventions be nevertheless more privileged than others, in being non-foreclosing? How might we discover this? These questions are addressed through a computational case study of London. The city's metabolism is modeled as the set of interacting, cross-sectoral (water, food, energy, waste) flows of carbon (C), nitrogen (N), phosphorus (P), water, and energy. Given various degrees of target improvements in an accompanying set of metabolic performance metrics, and given four candidate technological innovations in the water sector, an inverse (or “backcasting”) analysis is implemented in order to identify the key technological, policy, social, and climate-related features determining whether the community's aspirations — through the surrogates of the metabolic performance metrics — are attainable (or not), under substantial uncertainty. From this, the paper proceeds to examine which businesses are currently marketing some of the so-identified key technological innovations. It closes with a brief review of the related status of the economic justifications and social changes that may either promote or stifle the opportunities for London to move towards a higher niveau of sustainability.

1. Introduction

Increases in resource consumption in recent decades have been driven mainly by population growth and improvements in the economic status of many countries. According to the World Bank, global GDP growth has been around 3–4% annually since 1965. Latterly, it has been propelled mostly by developing countries, notably East Asia and Pacific countries. The annual growth for developing countries was estimated to be 7.1% for 2013, while for OECD countries it was estimated at 1.2% (World Bank, 2016a). The fact that 60% of the global GDP is generated in only 600 urban centers illustrates the economic power of cities (Dobbs et al., 2011). As with these GDP increases, urbanization is experiencing a faster rate of growth in developing countries and is projected to be 1.6% annually between 2025 and 2050. This will be reflected in a two-fold urban population increase in these countries, from 2.5 billion in 2010 to over 5 billion in 2050. However, in high-income countries urban population will remain relatively unchanged,

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increasing at just 0.17% annually, from a little over 1 billion in 2015 to over 1.1 billion in 2050 (WHO, 2014; World Bank, 2016b). These urbanization growth-rates are seemingly mild in percentage terms, but they reflect an exponential growth pattern that puts pressure on the availability of resources and increases pollution. Managing such pressures effectively requires a profound change in how cities operate and, while cities do indeed set targets to reduce such pressures, the systematic means to assess the attainability of these targets are currently lacking.

Rapid urban population growth, the complexity of cities, the relative “inertia” of the built environment, and the large investment costs sunk into urban infrastructure, together represent a great challenge in managing transitions towards more sustainable and resilient cities (Beck and Villarroel Walker, 2013; Dixon et al., 2014). Scenario-based assessment is a well-known modelling approach for addressing questions about how to plan and prepare cities for the future and identify long-term consequences of strategic decision making. This approach has been in practice since it was first used for military planning in the 1960s (Chermack, 2011), but it has expanded since then to business, policy, and environmental analyses. Scenario assessment is found in exploring the human and natural influences on climate change (Iyer et al., 2013; Moss et al., 2010), energy (SHELL, 2013; Wilkinson and Kupers, 2013), in waste management (Williams et al., 2010) and in water resources management (UNESCO, 2014). Life Cycle Assessment (Heidrich and Tiwary, 2013; ISO, 2006) and Material Flow Analysis (Brunner and Rechberger, 2003; Kennedy et al., 2011) are examples of quantitative and standardized operational methods for scenario assessment in the area of environmental sustainability. We, however, will adopt a different approach in this paper.

Understanding the synergies (and antagonisms) among the various economic sectors that service the city — its access to water, energy, and food; the nexus, that is — is becoming increasingly important (Beck and Villarroel Walker, 2013; Villarroel Walker and Beck, 2012). Dealing with such intricate complexity sheds light on how scenario analysis, though sophisticated, can be limited by both the expertise of the practitioner and how alternatives are defined (Mietzner and Reger, 2005). Scenario analysis can be useful for forecasting and backcasting applications, but it does rely on the simplification of the problem and the definition of a small number of pathways towards the future (Holroyd et al., 2007; Swart et al., 2004). For this reason, scenario analysis might not necessarily account for some of the key sensitivities of the system, upon which change towards less urban sustainability, for instance, might crucially turn (Beck, 2002; Nawaz Sharif and Nazrul Islam, 1982). To succeed in this it is hard to escape the need for a computational model, and generally a more complex (as opposed to simple) model. Accordingly an approach that can help to overcome the limitations of scenario assessment is the Regionalized Sensitivity Analysis (RSA) procedure (Osidele and Beck, 2003). It explores the complex logic embedded in the assessment model and identifies which features thereof are key for achieving a certain output target. In this way, the assessment is not limited to the changes introduced a priori by the practitioner; moreover, RSA may reveal potential technological and policy interventions that would otherwise be difficult to find.

The present paper describes and applies a quantitative approach to the analysis of urban metabolism (Barles, 2009; Beck et al., 2013; Brunner, 2007; Kennedy et al., 2011; Wolman, 1965) for the Greater London area. For this it uses the Multi-sectoral Systems Analysis (MSA) framework (Villarroel Walker et al., 2014). MSA is coupled with the Regionalised Sensitivity Analysis (RSA) to investigate and reveal the technological innovations and features of an urban system that have significant potential influence in achieving sustainability targets. This analysis can be referred to as a target-oriented analysis. In our present study for London, the focus is on targets associated with energy production, water use, and nutrient recovery. For the purposes of this work, *features* are defined as those elements of the urban system that define its characteristics and behavior, such as population growth, consumption patterns, diet, efficiencies of technological processes, climate conditions, and the infrastructure in place.

The objectives of the paper can be expressed as follows:

- a. Based on a set of sustainability metrics, determine whether future targets for these metrics are attainable and how this attainability changes as these targets are made more stringent.
- b. Identify which features of the system enable or disable the attainability of future targets of direct carbon emissions, energy and water use, and resource recovery from the water sector.
- c. Establish which of these key features are associated with which aspects of the city's current metabolism, and conversely determine which are dependent on innovation, or technologies yet to be invented or brought to the market place, along with equally innovative policies that would need to depart from current conventions.
- d. Illustrate with examples which businesses or organizations have programs or technologies that are already influencing the so-identified key features.

The paper starts by describing the methodological framework, which builds upon the Multi-sectoral Systems Analysis (MSA), but crucially extends this by incorporating the Regionalized Sensitivity Analysis (RSA) procedure. This is followed by defining a set of metabolic performance metrics, with a focus on circular metabolism; these metrics are in turn used to formulate targets (in terms of energy production, nutrient recovery, and water use). The MSA/RSA framework is then employed for identifying those features of Greater London (referred to as London for the purpose of this paper) that are key for reaching the prescribed targets. The results obtained are then used to illustrate how these key features are related to facets not only of technology, but also policy and human behavior.

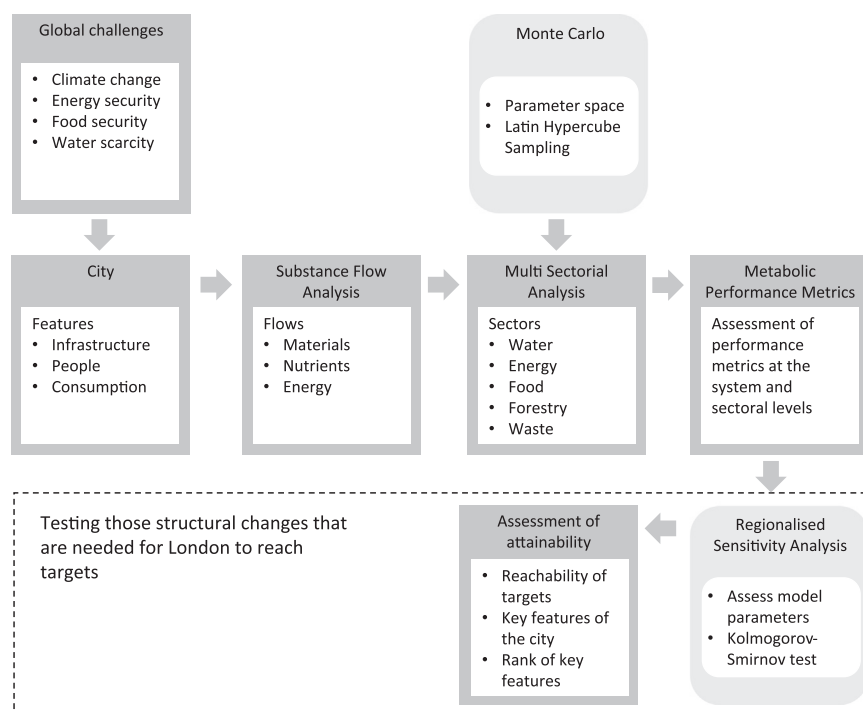


Fig. 1. Simplified flow diagram linking global challenges with the Multi-sectoral Analysis and Regionalized Sensitivity Analysis framework for assessing system-wide changes to attain city targets. Beveled boxes represent mathematical procedures.

2. Methodology of the target-oriented analysis

2.1. Multiple sectors handling multiple resource flows

A simplified diagram of the conceptual and operational framework of MSA is presented in Fig. 1. Global challenges drive the sustainability agenda of the city, hence define (in part) the performance metrics that are important for it. The people inhabiting the city and the city's infrastructure define how much material and energy are required and how these enter, exit, and move within the city. The Multi-Sectoral Systems Analysis (MSA) is built upon the methodology of Substance Flow Analysis (SFA), for tracking and quantifying the flows of energy, water, nitrogen, phosphorus and carbon through a system. The flow analysis is based on detailed flow diagrams elaborated for five socio-economic sectors: water, forestry, food, energy, and waste handling. Each sector is represented by flows and unit processes that include the main activities — human and environmental — that affect the system, also known as foreground processes. Detailed diagrams, which serve as blueprints for modeling the sectors, can be found in previous studies, where MSA has been applied to Metro Atlanta, Greater London, and Suzhou City (Jiangxue, 2015; Villarroel Walker and Beck, 2012; Villarroel Walker et al., 2014). Because MSA involves various economic sectors, it offers insight into cross-sectoral interactions, which is indispensable for overcoming the uncoordinated delivery that characterizes most of the utility and waste organizations in London (Mayor of London, 2014).

Distinctively, applying MSA in the present work involves use of the RSA procedure. It is this which enables the *target-oriented* analysis. It identifies which parameters in the MSA model are important for reaching the targets prescribed. Targets are defined as improvements in a number of metabolic performance metrics (MPM).

This application of the MSA framework focuses on the efficiency of resource use and recovery, and less emphasis is placed on environmental impact and global effects beyond the city's boundaries. Our analysis seeks to identify local technologies and policy strategies that improve the sustainability of cities by enhancing the circularity of resources and nutrients (Deelstra and Girardet, 2000), which in turn contributes to reducing the global footprint (Jones and Kammen, 2011; Shibata et al., 2016). Future work has been proposed for expanding the MSA framework to include nitrogen, carbon, energy, phosphorus, and water footprints (Galloway et al., 2014; Hillman and Ramaswami, 2010; Peters, 2010; Rees and Wackernagel, 1996; Wang et al., 2011). This expansion will allow generating analyses that trace trans-boundary implications of local decisions, and could potentially result in different conclusions.

2.2. Key features of the system

Our analysis deals with quantifying how sensitive is the attainment of a target outcome to the values assigned to the parameter vector in the model. Conventional sensitivity analysis methods for determining dominant (model) parameters have some important

limitations, since they pertain to a single point in the parameter space. This can be a severe drawback when dealing with complex systems such as cities (Keesman, 1989; Saltelli et al., 2009). A single-point approach also assumes that stakeholders or experts can develop a finalized vision of the future and its scenarios, which is not always the case (Dixon et al., 2014; Hekkert et al., 2007).

The RSA procedure has mostly been used in complex systems, such as those of the natural environment (Hornberger and Spear, 1980; Keesman, 1989; Osidele and Beck, 2003). In general terms, RSA comprises a Monte Carlo simulation and Kolmogorov-Smirnov (K-S) two-sample testing of distribution results from the simulations. RSA differs from traditional sensitivity analysis in that it explores the sensitivity of the parameters by assessing their influence over the model output to attain a prescribed domain of values (the target future behaviors) across a region (as opposed to a point) within the parameter space. RSA identifies those constituent model parameters in MSA (as representations of the system's features) that are statistically significant with respect to influencing the discrimination between model outputs (a metabolic performance metric in this case) lying above or below the prescribed threshold. The RSA procedure uses the Z_{K-S} Kolmogorov-Smirnov variate as the discrimination factor, where a larger Z_{K-S} means that the parameter is more important, while the smaller the magnitude of Z_{K-S} , the less important the parameter. The assumed cut off value for separating critical from non-critical parameters is $Z_{K-S}=1.36$, which corresponds to an alpha value of 0.05. The RSA procedure is explained in detail in the [Supplementary Material A](#).

2.3. Attainability of targets

In addition to identifying key features of the model and providing a basis for ranking the importance of these key features, RSA also offers information for exploring the ability of the system, e.g., the city infrastructure, to reach prescribed targets. In operational terms, if there are no model output values (expressed in terms of a metabolic performance metric) above the prescribed threshold, we say that the target is not attainable. The degree of attainability can therefore be expressed as follows:

$$\text{Attainability} = \frac{m}{m + n} \quad (1)$$

Attainability is calculated as the ratio between the number of occurrences when the target is reached or surpassed m and the total number of model runs in the Monte Carlo simulation. The term n represents the occurrences when the target was not reached. This ratio is referred to as the degree of attainability of the target. Attainability in this case is a measure of the technical capability of the system as represented by MSA, and does not include other factors that could influence practical attainability such as social acceptance, infrastructure lock-in, or technology maturity. A similar approach has been used for forecasting technological breakthroughs using the concept of reliability engineering (Nawaz Sharif and Nazrul Islam, 1982).

3. Testing the MSA/RSA framework for London

3.1. Study area

Greater London was established as an administrative and political entity in 1965. London is the most populous city in the United Kingdom. Greater London is under the strategic local governance of the Greater London Authority (GLA), with an administrative area of 33 boroughs, including the city of London, and a total area of 1,572 km². London's population in 2009 was 7.8 M, but this is expected to increase to about 9.0 M by 2030 (GLA, 2011b). However, that projection is likely to be exceeded since current population is already 8.6 million. The city's population growth is much larger than that estimated on average for high-income countries. It has an elected assembly, the London Assembly, and an executive head, the Mayor of London. This paper evaluates the metabolism of London for the year 2010.

Currently, some 41,720 GWh of electricity are generated within London, which is less than 30% of the city's total electricity demand. The remainder of the demand has to be imported from outside the city. The power plants at Enfield (400 MW) and Barking and Dagenham (1,000 MW) provide the city with up to 1,400 MW, producing a total of 12,200 GWh annually. However, electricity is also generated by incinerating municipal sewage at the Beckton (Northeast), Crossness (South), and Mogden (Southwest London) wastewater treatment plants. These plants treat the wastewater from over 7.1 million residents, in addition to some industrial and commercial discharges. Thames Water is currently applying about 70% of the treated sludge to surrounding land as a nutrient source. However, in the past, most of the treated sludge was incinerated (Girardet, 2006).

With regard to policy targets, London is one of the UK's best prepared cities in terms of climate change adaptation and mitigation (Heidrich et al., 2013). The city has proposed to reduce its carbon emissions by 60% by 2025, relative to its 1990 emissions (GLA, 2011a), and has developed strategies for adapting to climate change, alongside a range of other economic, social and environmental policies (Mayor of London, 2011; Walsh et al., 2013). One policy option for reducing carbon emissions across London is a requirement for at least 20% of the city's energy to come from on-site renewable sources. In addition, legislative drivers such as the Climate Act 2008 add to the motivation for adaptation. This has been further spurred by energy prices, which until recently were steadily increasing, providing thus stimulus for both businesses and the public to curb energy use at home and in the water sector. Such initiatives can also support the recovery of energy and nutrients entrained into the city's water metabolism, in particular, through the promotion of renewable energy schemes.

Table 1

Sources of data for the London case study.

Description	Source
Capacity and practices for sludge handling	Official websites or press releases of the largest treatment works in the London area: Beckton, Crossness, and Mogden (all sources accessed February 10, 2016): www.waterworld.com/articles/2012/11/thermal-hydrolysis-to-replace-ad-sludge-treatment-in-london.html http://www.thameswater.co.uk/about-us/883.htm http://www.water-technology.net/projects/mogden-sewage-treatment-works-isleworth-london/ www.waterprojectsonline.com/case_studies/2012/Thames_Beckton_Upgrade_2012.pdf
Consumption of food products	Food and Agriculture Organization of the United Nations (FAO, 2012); Department for Environment, Food, and Rural Affairs (www.defra.gov.uk)
Energy required for water and wastewater treatment	Benchmark study for the US (Carlson and Walburger, 2007),
Infiltration and inflow into the UK's sewer network	Ranges between 15–50% of average dry weather flow and about 10 – 20% of total wet weather flows (Ellis, 2001).
Metabolism of the energy-water-food nexus	Modelling of future system considering structural changes in infrastructures systems (Villarroel Walker et al., 2014)
Power generation and fuel/energy demand	UK government agencies such as www.decc.gov.uk/en/content/cms/statistics/statistics.aspx
Water abstractions	Surface and groundwater sources by purpose, and water use in agriculture from www.data.gov.uk/dataset/

3.2. Data collection

Previous work has focused on the metabolism of London (Villarroel Walker et al., 2014). Information regarding the infrastructure in place in the city, and its operation, is mostly drawn from peer-reviewed publications and technical reports. Specific data sources are listed in Table 1.

3.3. Definition of metabolic performance metrics (MPM)

Global challenges such as energy security, water scarcity, and food security (see Fig. 1), have a direct impact on urban areas, particularly rapidly growing cities, where infrastructure fails to deliver the materials and energy in a timely manner, or with the level of quality required (Hanjra and Qureshi, 2010). We propose assessing the features of London's infrastructure through the lens of a set of metabolic performance metrics (MPM), as defined in Table 2 (Villarroel Walker et al., 2014). These metrics focus on water, nutrients and energy flows. They are not absolute measures of resource use. Rather, their purpose is to gauge the extent to which flows are moving in closed loops around the city (Barles, 2010). This “circularity” of the city's metabolism has been referred to as a sustainable metabolism, i.e., one that is self-sufficient or at least less dependent on an extended hinterland for obtaining resources or disposing of waste (Baccini, 1997; Brunner, 2007). London is indeed working towards a waste management infrastructure that is suitable for a circular economy, although thus far a lack of financing mechanisms has been the main barrier to progress (Mayor of London, 2014).

MPM account for the extent to which water is used, nutrients are recovered and recycled, and energy is saved or produced. The scope of the MPM has been defined to assess city performance at two levels: on a sector-by-sector basis; and for the whole system. In this way, and for the purposes of this paper, the implementation of a strategy in the water sector — a technology, policy, or infrastructure change — can be assessed according to its impacts at both levels.

In addition, the proposed MPM are aligned with the Key Performance Indicators (KPIs) suggested in the London Plan under *Objective 5: A city that becomes a world leader in improving the environment* (GLA, 2013). Specifically, MPM relate to KPI 19 (Increase in municipal waste recycled or composted and elimination of waste to landfill by 2031), KPI 20 (Reduce carbon dioxide emissions through new development), and KPI 21 (Increase in energy generated from renewable sources). The MPM also respond to the goal of efficient local energy production, identified as key for London's decarbonization by the Office of the Mayor through the

Table 2

Definition of metabolic performance metrics (MPM).

	Water sector scope	Whole system scope
Energy	$E_w = \frac{\text{Renewable energy generation}}{\text{sector energy use}}$	$E_s = \frac{\text{Renewable energy generation}}{\text{London energy use}}$
Water	$W_w = \text{water use for public supply}$	$W_s = \text{water use in London}$
Nitrogen ^a	$N_w = \frac{N \text{ recovered}}{N \text{ in food consumed}}$	$N_s = \frac{N \text{ recovered}}{\text{Inputs of N}}$
Phosphorus	$P_w = \frac{P \text{ recovered}}{P \text{ in food consumed}}$	$P_s = \frac{P \text{ recovered}}{\text{Inputs of P}}$
Carbon ^b	$C_w = \frac{\text{Renewable C generated}}{\text{sector C emissions from energy use}}$	$C_s = \frac{\text{Renewable C generated}}{\text{London C emissions from energy use}}$

^a Inputs of N and P refer to the inputs to the system in the form of food, wood, paper, and industrial wastewater.

^b The carbon ratio assumes that all electricity is originated from natural gas.

Decentralized Energy Project Delivery Unit (DEPDU), which is funded by the European Union. The specific target is a combination of 50% locally produced energy and 50% nationally supplied by 2050. This results in more affordable energy and reduces dependence on international energy suppliers and markets.

Table 2 enables the definition of a set of targets for illustrating the application of the RSA procedure to the MSA model. These targets are expressed in terms of the metabolic performance metrics (MPM) as a percentage, as follows:

- Those MPM associated with water (W_w and W_s), energy (E_w and E_s), and carbon (C_w and C_s), are set to reach an improvement of 10% with respect to the value of the 'base case', where this base case has been calculated with a parameter vector that contains the most likely parameter values across their specified distributions.
- In the case of those MPM associated with nitrogen (N_w and N_s) and phosphorus (P_w and P_s), targets are set to attain a resource-recovery level of 30%.

Although these targets are illustrative, they are a starting point for testing the flexibility of the city's infrastructure toward achieving a degree of resource recovery.

3.4. Going beyond current infrastructure

Waste infrastructure systems should consider recoverable materials and nutrients in order to close their respective natural biogeochemical cycles (Magid et al., 2006; Verhoef et al., 2006). Moreover, integration of the multiple services that can be offered within these infrastructures (by a single business) is beginning to be seen as an opportunity for making the transition toward Multi-Utility Service Companies or "MUSCOs" (Roelich et al., 2015). Since the infrastructure assumed for London in 2010 is assumed to have no significant means to recover nutrients (in other words a base case of 0% nutrient recovery), we explore the potential influence of four candidate resource- and waste-handling technological innovations, as strategies described in Table 3. Thus this study uncovers the degree of importance of these technologies and how they *could* contribute to achieving future targets for metabolic performance at the sector and system levels. All four technologies considered can recover nutrients for fertilization purposes and, to a lesser extent, subsequent (downstream) energy production. The base case, or business as usual (BAU), scenario is assumed to be that when none of these four technologies are implemented. These candidate innovations are represented in MSA with parameters that describe their market penetration level. A complete list of parameters considered in the London case study is presented in Supplementary Material B, including their most likely value and the uncertainty range assumed.

Table 3
Description of four prospective technological innovations.

Sectors	Technology	Description
Water	Urine separation technology (UST)	Urine accounts for around 1% of the total volume of household wastewater, but up to 90% of the nitrogen, phosphorus and potassium loads passing out of the household (Lind et al., 2000). Urine-diverting toilets (Larsen and Lienert, 2007) separate urine from feces for the production of struvite and ammonium sulfate; separating urine reduces the amount of nitrogen and phosphorus in the wastewater to a level where no further nutrient removal is needed (Henze, 1997). Struvite is considered a valuable slow-release inorganic fertilizer with important economic advantages, given the fact that it is being produced from flows regarded as waste (Kirchmann and Pettersson, 1995; Shu et al., 2006).
Food, water	Consolidation and co-treatment of household organic waste (COW)	Food waste disposal units are a convenient and hygienic means to grind this waste at source and dispose of it directly to the sewer. Using food grinders, kitchen organic waste is mixed with the usual contents of household sewage, i.e., laundry and bathroom/toilet fluxes (Iacovidou et al., 2012; Malmqvist et al., 2010), and conveyed via the sewerage system to treatment at the sewage treatment works. Although the impact COW has on water consumption, the sewerage system, and wastewater treatment still needs to be determined, it has been shown that it is an effective method to reduce the amount of food waste disposed of to landfill (Iacovidou et al., 2012).
Waste, energy	Pyrolysis of separated sewage sludge (PSS)	To capture its organic matter, sewage sludge is dewatered and decomposed at high temperatures using pyrolysis, which is a process conducted in the absence of oxygen, to produce thus gas, bioliquids, and biochar (Furness et al., 2000). The thermal process of pyrolysis has been studied in detail (Werther and Ogada, 1999) and it has been shown that energy can be recovered from both municipal solid waste and sewage (Folgueras et al., 2005; Furness et al., 2000; Sánchez et al., 2007; Verhoef et al., 2006).
Water	Production of algae in wastewater treatment facilities (AWW)	Nutrients that remain in the effluent can be used to create algae. Coupling wastewater treatment with algal biofuel production has been investigated in several studies and has proven to be beneficial (Beal et al., 2012). The biomass residue after oil extraction can be utilized in the pyrolysis process (Verhoef et al., 2006) and further modified to produce yet more fuel and fertilizer.

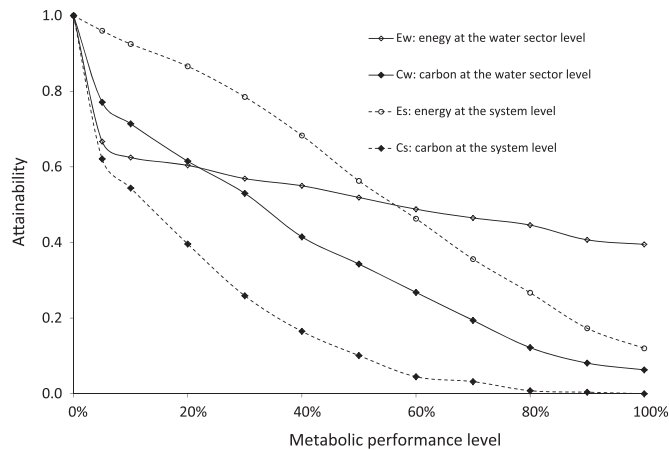


Fig. 2. Attainability (where 1 is 100% attainability and 0 is non-attainable) at various metabolic performance levels for carbon and energy.

4. Results and discussion

4.1. What is possible and what is not?

Before imposing the proposed sustainability targets in Section 3.3, it is important to assess the limitations of the current infrastructure of the city and its accompanying metabolic performance. Furthermore, as policies and sustainability targets can be expected to become ever more demanding over time, understanding their attainability (or otherwise) at various levels of achievement should be highly informative. Here, attainability is calculated as described by Eq. (1).

Accordingly, Fig. 2 offers a quick glance at the feasibility of attaining the different levels of metabolic performance associated with carbon and energy, at both the water-sector and system levels. As we should expect, as the expected metabolic performance level increases, the smaller becomes the probability of its attainability.

Achieving more ambitious metabolic performance of renewable energy seems to be easier at the system level (E_s) than at the water-sector level, up to a performance of 60% improvement. This is possibly due to the importance of the power generation industry and the electricity demand of London as a whole. The parameters describing the efficiencies of both power generation and electricity usage in MSA have a narrow range, illustrating the limitations of current technology. This narrow range results in an attainability that decays rapidly, as the expected performance becomes progressively more ambitious. In the case of renewable forms of energy at the sector level (E_w), our results are entirely different. They exhibit a much slower and more gradual decrease in attainability, as the performance levels become ever more stringent. E_w seems to be capable of continuous improvement, beyond even the 100% increase in performance, suggesting that (renewable) energy recovery in the water sector can be stretched relatively easily to reach tighter targets. In fact, a 500% improvement is possible (not pictured in Fig. 2). This is not solely a function of the generation of renewable energy within the wastewater segment of the water sector, but also a function of the potential for improving the efficiency of various features of water and wastewater treatment plant operations. Improving energy efficiency reduces the demand for energy so that, in mathematical terms, the denominator of E_w becomes smaller and a better performance is achieved. Scope for such improvement can come from opportunities for the efficient and smart distribution of potable water, savings in pumping energy, the better operation of aeration units, and effective utilization of wastewater treatment plant capacity. There are other factors that are difficult to control, such as elevation changes in the water distribution network and the Biochemical Oxygen Demand (BOD) of the wastewater.

Contrary to the findings for the energy performance metric, it appears that intervening to change the carbon (C) performance metric is less readily attainable at the system-wide scale. The respective trajectories for C_w and C_s are always below (less attainable) than their counterparts for energy, i.e., E_w and E_s . This is due to the larger carbon-energy ratio of the renewable fuels being generated in the form of sludge incineration and biofuels (pyrolysis and algae), relative to that of natural gas.

With respect to Fig. 3, the attainability of nutrient recovery for P exceeds that for N, which in turn exceeds the attainability of water use targets, which shows the steepest declines of all. This means that higher performance levels associated with P recovery are easier to attain than for N and water. However, the curves associated with water suggest that for reducing water use, at both levels (sector (W_s), whole (W_w)), a more drastic approach must be considered. Current ranges of water-use rates and efficiency are not capable of facilitating an improvement in performance any better than a 20% reduction.

The key conclusions from Figs. 2 and 3 are twofold. First, higher metabolic performance at the water-sector level is easier to attain than at the system (whole city) level. Second, and less intuitively, the attainability curves are a signal of the “structural rigidity” of a sector or the system as a whole, with respect to the performance metrics. The current infrastructure of London only allows for certain improvements, which are mostly marginal. Attaining more ambitious targets will require transformational (and possibly quite disruptive) innovations.

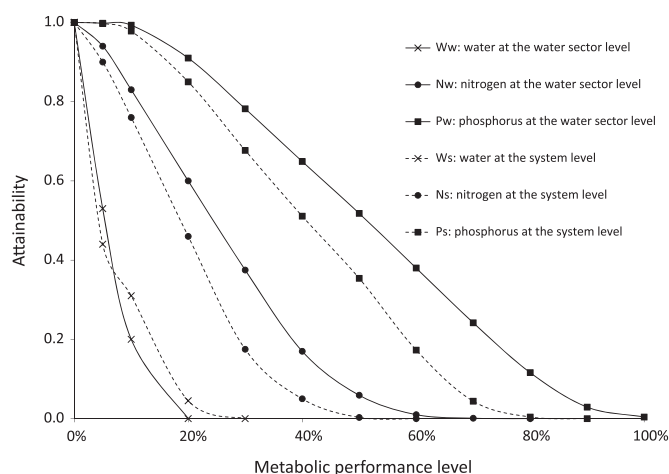


Fig. 3. Attainability (where 1 is 100% attainability and 0 is non-attainable) at various metabolic performance levels for nitrogen, phosphorus, and water.

Table 4

List of key constituent technologies and features of London's multi-sectoral metabolism for achieving targets (not necessarily ranked in order of how critical they are to attaining a given target).

Parameter	Description	Operational range in MSA	Units
P1	Energy for wastewater treatment (fixed factor)	14.8–16.9	–
P2	Energy for water treatment (flow factor)	0.32–0.68	–
P3	BOD removal and sewage sludge production	92–98	% of influent
P4	Residential water use	14–178	l/day/cap
P5	Industrial water use	51–62	l/day/cap
P6	Commercial water use	19–34	l/day/cap
P7	Leakage of the water supply system	21–25	% of supply flow
P8	Implementation of UST	0–100	% market penetration
P9	Human diet: water intake	93–96	% of water content in urine
	Human diet: nitrogen-rich food intake	15–19	% of nitrogen content in urine
P10	Implementation of PSS	0–100	% market penetration
P11	Implementation of COW	0–100	% market penetration
P12	Implementation of AWW	0–100	% market penetration
P13	Residential use of natural gas	70–85	% of residential energy use
P14	Water use for power generation	28–75	l/KWh
P15	Phosphorus removal from sewage	77–94	% of influent
P16	Cloudiness: average number of cloudy days	54–66	% of days annually

4.2. Performance-critical features of the system

RSA identifies a number of key features in London's infrastructure, as listed in Table 4. “Key” here refers to these features being key to the attainment of one or more of the target MPM improvements. This table also shows information regarding how these key features — in the form of parameters of the MSA model — need to “behave” in order to favor achievement of the target. Salient in these results is the fact that all four proposed technologies, i.e., UST, PSS, COW, and AWW, are present in the list (as features P8, P10, P11, and P12 respectively). Besides that, most key features are associated directly with the water sector, specifically with water use by various types of consumers (P4 to P6), including the energy sector (P14), and with distribution efficiency, i.e., leakage (P7). Less intuitive are the presence of features related to the sources of nutrients entering the water sector, such as population diet (P9), and the efficiency of the water sector for producing sewage sludge (P3). The only feature that has no direct connection with the water sector is that of residential use of natural gas (P13). Its significance is somewhat indirect, in the sense that natural gas, in addition to space heating, is also used for water heating.

More specifically, Table 5 shows which technological intervention or system feature is key for each performance metric. Thus, implementation of UST seems to be relevant for most metabolic performance metrics (MPM), except those for energy and carbon emissions in the water sector. Improvement at the system level in terms of carbon involves the largest number of key features, including technological innovations, such as nutrient and BOD removal from wastewater treatment, and climate conditions. Achieving improvement targets for carbon in the water sector (C_w) is a function of the energy consumed in providing pumping for wastewater (P1) and water (P2) treatment, and in the production of sewage sludge (P3), which is later converted into biogas. The addition of organic waste (rich in carbon content) into the sewage system can promote additional production of sludge. For this reason COW (P11) appears to be very close to becoming key, hence represented by a white dot in Table 5.

In general terms, it seems that intervening in the water sector with the candidate technologies is relevant at the systems level

Table 5

Key constituent technologies and features of the multi-sectoral metabolism for improving the metabolic performance metrics. White dots represent features of the system that are close to becoming key.

	Ew 10% increase	Ww 10% reduction	Nw 30% level	Pw 30% level	Cw 10% increase	Es 10% increase	Ws 10% reduction	Ns 30% level	Ps 30% level	Cs 10% increase
P1	●				●					
P2	●				●					
P3					●	●				●
P4		●				●	●			●
P5		●								
P6		●								
P7		●								
P8		●	●	●		●	●	●	●	●
P9			●	○				●	○	
P10				●		●			●	●
P11	●				○	●				●
P12						●			○	●
P13										○
P14							●			
P15										●
P16										●

across the board. There are cross-sectoral synergies that contribute to achieving some of the targets, as found for the energy performance at the system level (E_s), which benefits from initiatives that reduce residential water use (P4), as well as the four technologies implemented in the water sector. The achievement of targets in respect of N and P is almost entirely a function of technological features, specifically UST and PSS. Human diet has a less relevant role, particularly for nitrogen. The variation of phosphorus in the population diet is found to be just short of being judged as key.

4.3. Ingredients for success at different metabolic performance levels and different scales (individual sector or whole city): critical range to enable success

The analysis shows that in order to achieve prescribed targets it is necessary that the parameters representing the key technological interventions and features of the city (listed in Table 4) reach a certain value. This critical value could be interpreted, for instance, as the market penetration of the given technology, the degree of acceptance of the technology or policy, or the enforcement level of a regulation or policy. This critical value, therefore, is related to questions such as: what proportion of the population will need to adopt the urine separation technology so that the 30% target improvement with respect to N_w is achieved? The same kind of question can be expressed for other key parameters and performance metrics.

To illustrate this argument, two parameters were selected: the degree of implementation of UST (P8); and the energy required to move flows of water for treatment (P2) as potable water. A high Kolmogorov-Smirnov variate (Z_{K-S}) value results in a plot that is visually easier to interpret – because of the high differentiation between non-target-achieving and target-achieving parameter values – as it can be observed for UST (parameter P8) in Figs. 4 and 5. At the water-sector level, Fig. 4 shows that a market penetration of 50% for urine separation toilets, with the subsequent production of fertilizer, could start enabling the achievement of a 30% recovery of the nitrogen consumed in food by London's inhabitants. Although there seem to be other features of the system that play a role in achieving the target, at about 75% it becomes clearer that UST is quite the most influential.

We take advantage of the visual clarity of the results for P8 to explore this parameter's influence at the larger scale of the system level, i.e., London as a whole. Fig. 5 shows that reaching the target of 30% nutrient recovery at the system level requires a somewhat more aggressive market penetration of UST. In this case, a 60% market penetration is needed before there are any instances where the target (of 30% recovery) is attained; but the influence is not clear-cut, not even at 100% market penetration. This is to be expected, in fact, since the nitrogen that enters the entire system of London, e.g., in natural gas, food, and wood, is larger than the nitrogen that enters just the water sector. Yet the market size of UST remains the same, and so does the recovery of nitrogen. This also shows that for achieving the target of 30% at the systems level, it would be necessary to implement complementary nutrient recovery measures in addition to UST, possibly outside the water sector. Because natural gas is a large contributor to the fluxes of

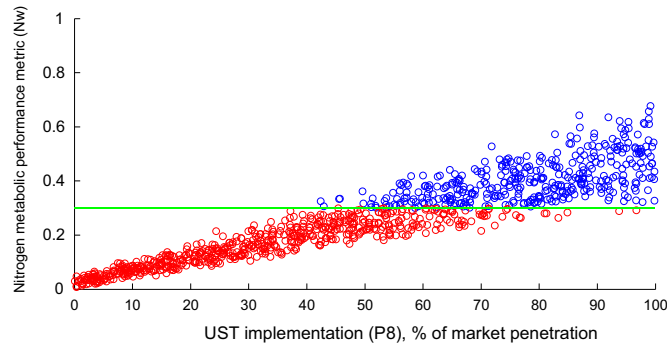


Fig. 4. The nitrogen metabolic performance metric (N_w) at the water-sector level and the UST implementation parameter (P8), where blue represents those parameter values when the target (more than 30% nutrient recovery) is achieved and red those where it is not achieved. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

nitrogen in London, one could suggest that recovering nitrogen (and carbon) from the flue gases emitted from the city's power plants should merit further evaluation.

However, not every parameter exhibits a clear visual differentiation between target-achieving and non-target-achieving values, as seen for P8 in Fig. 5. For contrast, parameter P2, for example, which describes the energy required to move flows of water for treatment (as potable water), illustrates well the kind of situation where the parameter's influence on achieving a given target is visually more difficult to interpret. Intuitively, one can imagine that reducing the amount of drinking water that needs to be pushed around the city tends to reduce the amount of energy used for this purpose. But Fig. 6 shows that it is not clear how much of the flow component, i.e., the energy needed to move a unit volume of water, will need to be reduced to achieve the target. This does not mean that parameter P2 is not key; it is simply that finding the critical range is less straightforward.

4.4. Is it key only now or forever?

After exploring the critical range over which key technological interventions and features of the city should influence the metabolic performances of the water sector and the whole system, one could ask “how lasting might be this influence?” We address this question by performing a meta-sensitivity analysis on the Z_{K-S} Kolmogorov-Smirnov variate at different metabolic performance levels. This meta-sensitivity approach, in which we test the sensitivity of the RSA results, is consistent with the idea that a complete formalization of uncertainty is impossible, referred to as the phenomenon of infinite regress (uncertainty about the uncertainty) by Funtowicz and Ravetz (1990).

We expect from this analysis that, as performance targets increase over time, because of stronger regulations and higher city expectations, the influence of a parameter will change. This is illustrated in Figs. 7 and 8 where the changes in the levels of importance of the two most key metabolic performance metrics (MPM) for nitrogen and energy at the system level, i.e., N_s and E_s , are shown.

In Fig. 7, the importance of the two most key parameters for E_s reaches a maximum as the target approaches the region of 50–70% improvement in E_s . In fact, the peaks of importance for P3 and P11 are reached at the 50% and 70% target improvements, respectively. This means that P11 (implementation of COW) is more effective when the target for E_s improvement is 50%. The same

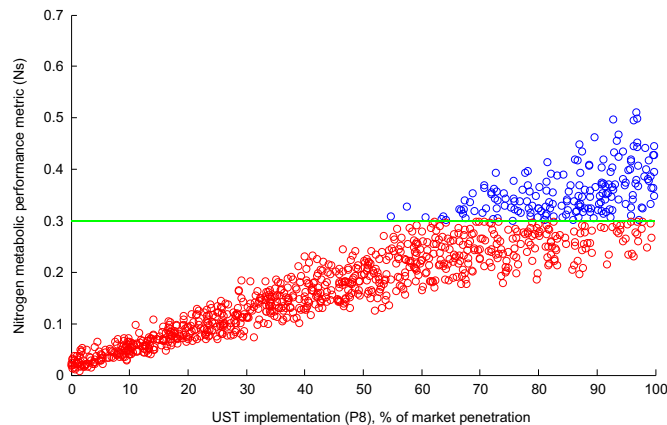


Fig. 5. The nitrogen metabolic performance metric (N_s) at the system level and the UST implementation parameter (P8), where blue represents those parameter values when the target (more than 30% nutrient recovery) is achieved and red those where it is not achieved. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

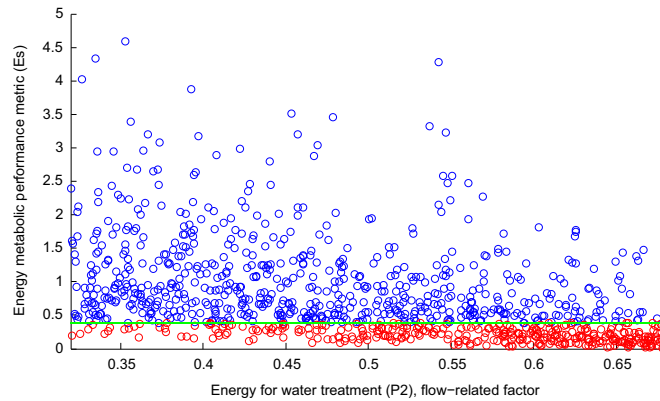


Fig. 6. The energy metabolic performance metric (E_s) at the system level and the water treatment (flow-related) parameter (P2), where blue represents those parameter values when the target was achieved (more than 10% with respect to the value of the BAU case), and red (and below the horizontal line) those when it was not. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

logic can be applied to P3 (BOD5 removal rate in wastewater treatment plants). However, beyond the 50–70% region, the importance measures of these two parameters decrease. The gap between these parameters in terms of their importance starts to get narrower as targets approach the end of the range. This is due to the fact that the importance of P3 shows an increase, i.e., from Z_{K-S} equaling 2.68 to 3.58, whereas the importance of P11 increases only from Z_{K-S} being 4.67 to its being 4.72. It is important to highlight the fact that P11 remains more important than P3 throughout the range of target levels, suggesting that focusing on collecting organic waste in sewer networks for the long run could be a more promising strategy than improving BOD removal from sewage beyond the levels currently being achieved.

Fig. 8 likewise shows that the levels of importance of key parameters P8 (UST implementation) and P9 (urine moisture content) peak (larger Z_{K-S}) at different target levels. The importance of P8 peaks at a 20% target – with respect to the nitrogen MPM at the system level (N_s) – whereas P9 peaks when at a 30% recovery target. Both parameters lose importance dramatically towards a target of 50%, where they become unimportant ($Z_{K-S} < 1.36$). If this behavior is analyzed in conjunction with Fig. 3 it is possible to explain the sudden drop of the importance curves. A target higher than 50% recovery of nitrogen (N_s) is unattainable for London. Furthermore, the meta-sensitivity analysis in Fig. 8 suggests that, as the nitrogen recovery target increases, the moisture content associated with the urine becomes all the more critical the more USTs are installed, hence its peaking towards a 30% MPM for N_s , as opposed to a peak at 20% for installation of the USTs (in the first place).

The significance of Figs. 7 and 8, therefore, lies in understanding that the level of importance of a technology or strategy varies with the level of the target to be achieved. Decision makers should consider this and cater for the fact that targets are likely to change in the future, hence be mindful of not foreclosing on the manipulation of other important key features of the city. In both cases (Figs. 7 and 8), the initially most important parameters (P11 and P8) remained the most important for the whole range of the meta-

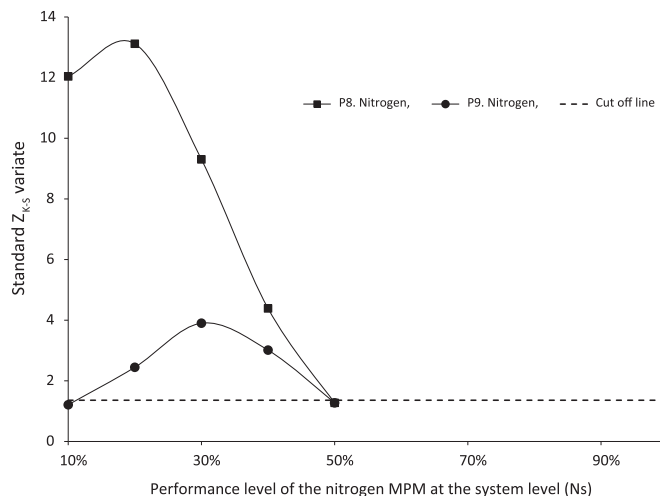


Fig. 7. Relative change of the importance (measured in terms of Z_{K-S}) of the most key parameter (■), i.e., consolidated organic waste (COW) (P11), and the second most key parameter (●), i.e., BOD removal in wastewater treatment plants (P3), for the energy MPM at the system level (E_s).

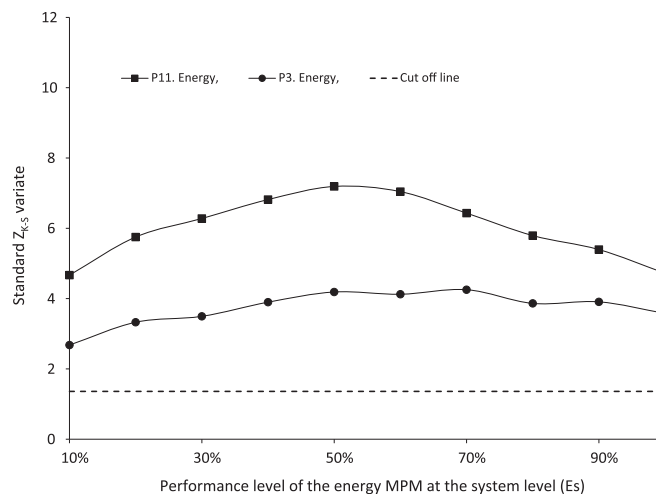


Fig. 8. Relative change in the importance (measured in terms of Z_{K-S}) of the most key parameter (■), i.e., urine separation technology (UST) (P8), and the second most key parameter (●), i.e., urine moisture content (P9), for the nitrogen MPM at the system level (N_8).

sensitivity analysis. However, we do not discard the possibility that one parameter might become more important than the other, as a consequence of prescribing higher target levels.

5. Who excels, who profits, who disrupts

The central thrust of the present work can be summarized as follows. Given a portfolio of (distant) future outcomes, expressed in the form of MPM, our analysis seeks to determine which features in the material flow model at the heart of the MSA are key — and which redundant — to attaining those outcomes. This kind of analysis complements, therefore, the more familiar “forward” analysis of scenarios, which seeks to answer the question “what if? ”, as things unfold forward into the future. Some such technological scenarios are already embedded in our analysis by virtue of the four candidate water-sector technologies being assessed. Put another way, the results from the RSA should prompt further questioning, enquiry, and exploration, in part along the lines just discussed (in relation to Figs. 4–8). More importantly, however, this inverse (backward) form of analysis should prompt questioning along the lines of the *practicalities* of beginning to move toward achieving any or all of the metabolic performance targets. Although the social component of these practicalities is not part of the scope of the present paper, [Supplementary Material C](#) offers a preliminary view on the role of society agents and governance.

5.1. Disruptive agents and technologies

[Table 5](#) has identified 16 features key in various ways to discriminating whether a specified target level of urban metabolic performance can be attained (or not) for London. In general, each of these features attaches to a flux of water, energy, N, P, and/or C into the city, around it, or out of it. The property of having been identified as key means that it matters whether the associated flux can be changed in some way, i.e., increased or decreased. The point is that manipulating these fluxes is potentially more effective in respect of attaining the target metabolic performance levels than manipulating any other fluxes. Four of these features self-evidently can be manipulated, in principle, for they represent our four candidate technological innovations. Some features, such as those associated with diet and climate, will require “manipulation” arguably more through policy instruments and changes of habits than through technological innovation (although their manipulation may well entail in due course technological innovations for altering material-energy fluxes beyond those included expressly in our MSA). Other features may signal crucial manipulations of fluxes for which businesses have yet to be started up, or technologies yet to be brought to the market place, or even invented — grand technological challenges, we might label them. Some of these are set out elsewhere in an analysis of the impact of cleantech innovations for nutrient recovery on the water-food-energy nexus ([Villarroel Walker and Beck, 2014](#)).

Directed thus by the findings of [Table 5](#), searches can be made of the state of readiness of the potentially key engineering and technical (flux) manipulations for all 16 parameters identified in [Table 5](#), as well as who exercises agency in doing the manipulating. [Table 6](#) presents results illustrative of these searches, including those for parameters P1 (energy use in wastewater treatment), P8 (UST technology), P10 (PSS technology), and P11 (COW technology). A more complete analysis of technologies can be found in the cleantech impact analysis of [Villarroel Walker and Beck \(2014\)](#).

By and large (across all 16 key parameters), agency in seeking change towards the higher levels of environmentally sustainable urban metabolic performance rests in the hands of the “utility” and/or the “household”, with “private-sector industry” in a strong third place. Manipulation of the parameters associated with the four technologies happens to be granted to the utility, although for the urine-separating toilet (UST; P8) and the insinkerator device associated with the COW option (P11; [Table 6](#)) crucial facets of agency reside in the household. Of the four candidate water-sector innovations, COW is the only one accorded (in our assessment) a

Table 6
Illustrative list of businesses and institutions providing the technologies or policies as key (model) parameters in determining whether the improved metabolic performance targets are met (or not).

Parameter	Actor-agent	Description	MPM	Feature	Technology/Policy	Maturity	Instance-company
P1	Utility	Energy use for wastewater treatment ^{a1}	E_w, C_w	Aeration efficiency and DO ^b control	Flow measurement through Thermal Dispersion Single-stage centrifugal blowers with Dual-Point Control Variable frequency drives (VFDs) Campaign for evaluating pumping systems and upgrades ^d	High Medium High Medium	Magnetrol Turbex Inc. (a Siemens Company) ABB (19% market share), Siemens (14%) ^c US Department of Energy
P2	Utility	Energy use for water treatment ^e	E_w, C_w	Pumping	Variable frequency drives (VFDs) Campaign for evaluating pumping systems and upgrades ^d	High Medium	ABB (19% market share), Siemens (14%) ³ US Department of Energy
P3	Utility	BOD removal and sewage sludge production	C_w, E_{ss}, C_s	Removal using Hydrogen Peroxide	PRI-TECH	Medium	US Peroxide
P4	Household	Residential water use	W_w, E_w, W_{ss}, C_s	Bathroom and kitchen water use Laundry water use Garden watering	High-Efficiency Toilet (HET) Rebate Program Zero-water washing machine Rainwater collection Low-flow spray rinse nozzle program	High Low High High	Bay Area Water Supply and Conservation Agency (BAWSA) Xeros Bed Cleaning KingspanWater Bay Area Water Supply and Conservation Agency (BAWSA)
P5	Industry	Industrial water use	W_w	Process water reuse ^f	Membrane bioreactor (MBR)	High	AquaSel by General Electric
P6	Commercial	Commercial water use	W_w	Lodging businesses ^g	Zero-water washing machine	Low	Xeros Bed Cleaning
P7	Utility	Leakage of the water supply system	W_w	Detection	Helium leak detection Leak noise correlation Heat pulse flow meter Infrared (thermography) Photography Ground-penetrating radar Trenchless Automated Leakage Repair (TALR) system	High High High High High Medium	Pfeiffer Vacuum SebaKMT Palmer Environmental FLIR Instruments Geophysical Survey Systems, Inc. Curapipe Systems
P8	Household	Implementation of UST	$W_{ws}, N_{ws}, P_{ws}, E_{ss}, W_{ss}, N_{ss}, P_{ss}, C_s$	Urine separation	Urine separating toilet ^h	Low	Blue Diversion Toilet, Eawag, Switzerland ⁱ
P9	Household	Human diet	N_w, P_w, N_s, P_s	Urine to fertilizer Plumbing adaptation Liquid “waste” transportation ^j Consumption of water and	Struvite process Typical plumbing material (fittings, pipes, storage tank, etc.) Vacuum trucks Human health and wellbeing	Low Low Low Low High High Low	Dubblenton, Sweden Envirosan Sanitation Solutions, South Africa Ostara Nuresys Any plumbing company Veolia Environmental Services For example, Government or NGO initiatives (continued on next page)

Table 6 (continued)

Parameter	Actor-agent	Description	MPM	Feature	Technology/Policy	Maturity	Instance-company
P10	Utility	Implementation of PSS	P_w, P_s, E_s, C_s	nitrogen-rich foods Sewage sludge pyrolysis	Pyrobustor EnerSludge	Low Low	(Marsden and Sonnino, 2012) EISENMANN GmbH & Co. KG ^s Environmental Solutions International Ltd
P11	Household	Implementation of COW	E_w, C_w, E_s, C_s	Household and Food service equipment	Food grinding	High	Insinkerator
P12	Utility	Implementation of AWW	E_s, P_s, C_s	Algae farming	Controlled eutrophication process	Low Low	Kent BioEnergy Corporation AlgaeWheel Facility
P13	Household	Residential use of natural gas	C_s	Space heating Water heating	Energy efficient furnaces Energy efficient boilers	high High	Infinity Series with Greenspeed Intelligence Bosch Greenstar Series
P14	Power generation	Water use for power generation	W_s	Cooling	Natural draft dry cooling system Air cooled condensers	High High	SPX Cooling Technologies SPX Cooling Technologies
P15	Utility	Phosphorus removal from wastewater treatment	C_s	Secondary treatment	Phosphorus filters	Low to Medium	Biotech andPhosphoReduc
P16	Climate	Water evaporation from land (cloudiness)	C_s	Tree cover	Increase or maintain tree cover	High	Greater London Authority

^a 60% of the total energy use in wastewater treatment is for aeration (WEF, 2009), while other reports attribute 80–90% of energy costs to pump and blower motors (PDPEP, 2011).

^b Dissolved Oxygen.

^c According to <http://www.marketsandmarkets.com/> (accessed February 10, 2016).

^d Pumping System Assessment Tool (PSAT) available free online at <http://www.energy.gov/eere/amo/articles/pumping-system-assessment-tool> (accessed February 10, 2016).

^e Most of the energy in water treatment and supply is for pumping (EPA, 2008).

^f Depends largely on industrial activity. As an example, the Coca-cola company (beverage industry) is used.

^g Depends largely on the commercial activity. As an example, lodging businesses and hotels are used.

^h Urinals and squatting pans not included in this analysis.

ⁱ Assumes a version of the toilet that discharges black water to the sewer network.

^j Specific to London's scenario.

^k <http://www.eisenmann.com/en/products-and-services/environmental-technology/waste-disposal/pyrobustor.html> (last accessed February 10, 2010).

high level of technological-market maturity.¹ Indeed, UST, PSS, and AWW are salient for their low level of maturity (relative to scanning across all 16 key parameters). In general (in this 16-parameter space), technical-market maturity is high for innovations addressing energy savings-renewables and water savings. By comparison, therefore, innovations having to do with recovering nutrients (N and P) and non-energy C products are not high, and mostly low, in their technical maturity. Things are on the cusp of change, however, as a recent International Water Association (IWA) position paper on resource recovery amply demonstrates (Holmgren et al., 2015).

5.2. Considerations of economics and finance

An initial portfolio of potentially relevant and applicable economic attributes, instruments, and incentives, might include the following:

Reducing costs and creating savings. Most obviously and conventionally, savings on the costs of acquiring and supplying resources and services as a result of reductions in the demand for consumption may be significant. They are typified here (for London's water and energy utilities) by their bearing down on progressive, incremental innovations and improvements in performance in respect of energy-related features, such as P2 in Table 6.

Recovered commodities, profits, and prices. Less obvious in the water sector, in particular, has been the incentive for profits to be made from the recovery and recycling of water (and renewable energy). Until very recently, it has been especially difficult to discern the profit for the entrepreneur in nutrient (P, N, and C) recovery and recycling. In London, we estimate that \$60 M annual revenues from fertilizer sales are theoretically possible, given primarily the innovations of PSS (P10), UST (P8), and COW (P11) (Villarroel Walker et al., 2014). However, fluctuations in commodity prices for the primary recovered resources of unfinished C, N, and P materials in global markets tend to be greater than for water and energy, which here are in the form of recovered, finished products, whose unit prices are both less volatile and more locally determined. Globally, i.e., beyond London (and including the food-agricultural sector as well as the water sector), it is estimated that the total market for nutrient recovery and sales could be as large as \$235B annually at current price levels (Villarroel Walker and Beck, 2014).

Attracting venture capital. Despite the arguments of some observers regarding the fate of the cleantech sector following the Great Financial Crisis (GFC) of 2008, it has continued to attract government funding for support of its undergirding science base. Cleantech, of the specific kinds of relevance herein, can be successful in attracting venture capital (take, for example, the case of Ostara Nutrient Recovery Technologies) and/or substantial support from non-governmental philanthropic foundations (e.g., the case of the Blue Diversion Toilet). Both innovations are recorded in the same row for P8 (UST) in Table 6, although they have quite distinct natural markets for their innovation. Ostara's technology is better suited to larger-scale, centralized sewerage and wastewater treatment, such as that presently existing in London (where the company would need to act in association with the water utility), whereas the BDT is well suited to small-scale, decentralized wastewater infrastructure. The town of Slough, cited in Table 6 as an instance of Ostara's technology installed in practice, is some 30 km west of London. If the much more "socially disruptive" UST technology were implemented in London, it is estimated that annual savings in water and energy consumption could be of the order of \$266 M (Villarroel Walker et al., 2014).

Asset valuation and management. For two decades, asset managers (notably Robeco SAM; www.robecosam.com) have been successfully directing investment funds into those (mature) private-sector enterprises judged to be leaders in environmental sustainability (Fussler, 2004). More recently, the threat of the market sanction of divestment has been held up to shed light on (arguably) excessively valued fossil C assets on the balance sheets of energy-sector companies (Carbon Tracker Initiative). In contrast, the C credits generated in association with the wholesale introduction into London of the four candidate technologies of this paper (above all, COW (P11) in Table 6), would currently generate the paltry permit-sales value of just \$0.8 M (Villarroel Walker et al., 2014).

6. Conclusions

In opening this paper, we asked which technological innovations for changing the city's infrastructure and metabolism might communities prepare to adopt today, as a first step towards realizing their distant future aspirations. What is more, recognizing the diversity of aspirations that may never be reconciled into a consensus, might some immediate innovations and policy interventions be more privileged than others — in being non-foreclosing? This question has its origins in the concept of adaptive community learning (Beck, 2002; Beck et al., 2002). The case study presented herein, in assessing paths towards improving London's resource metabolism, has itself been a further step in the direction of realizing that concept, following on from Osidele and Beck (2003), Villarroel Walker (2010), Beck et al. (2013), and Villarroel Walker et al. (2014). These paths can be linked to policy strategies and innovations — and the entrepreneurs that develop these innovations — that might be worthy of consideration by government and financiers. Illustrative of a candidate privileged non-foreclosing intervention, when judged according to a set of cross-sectoral performance metrics for resource-energy recovery, could be that of urine-separating technology (UST).

Communities, however, do not intuitively aspire to attaining certain quantitative rates of carbon, nitrogen, or phosphorus

¹ The COW option for London, however, is not favored by utility Thames Water, on the grounds that during low flow periods, solid waste will accumulate in the sewer system.

recovery in their city. Nor do they conceive of their distant futures — deducing the “there and then” from the “here and now” — with the aid of a computational model. Nonetheless, communities are richly creative in what they can imagine of the distant future, both their hopes and, significantly for the particular logic of our inverse analysis, their fears (Beck, 2002). The challenge, in making further progress with the kind of inverse analysis (or back-casting) employed in this paper, now rests on developing an approach that works more closely with the linguistic, qualitative ways of articulating community hopes and fears, while preserving the networks of causal logic enabling privileged, non-foreclosing policy and technology interventions to be identified.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.envdev.2016.11.006](https://doi.org/10.1016/j.envdev.2016.11.006).

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