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The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism

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ABSTRACT

Urban areas are considered net consumers of materials and energy, attracting these from the surrounding hinterland and other parts of the planet. The way these flows are transformed and returned to the environment by the city is important for addressing questions of sustainability and the effect of human behavior on the metabolism of the city. The present work explores these questions with the use of systems analysis, specifically in the form of a Multi-sectoral Systems Analysis (MSA), a tool for research and for supporting decision-making for policy and investment. The application of MSA is illustrated in the context of Greater London, with these three objectives: (a) estimating resource fluxes (nutrients, water and energy) entering, leaving and circulating within the city-watershed system; (b) revealing the synergies and antagonisms resulting from various combinations of water-sector innovations; and (c) estimating the economic benefits associated with implementing these technologies, from the point of view of production of fertilizer and energy, and the reduction of greenhouse gases. Results show that the selection of the best technological innovation depends on which resource is the focus for improvement. Urine separation can potentially recover 47% of the nitrogen in the food consumed in London, with revenue of $33 M per annum from fertilizer production. Collecting food waste in sewers together with growing algae in wastewater treatment plants could beneficially increase the amount of carbon release from renewable energy by 66%, with potential annual revenues of $58 M from fuel production.

1. Introduction

Patterns of consumption of energy, water and food in cities have conventionally been addressed independently, and so much so that their "nexus" (their inter-connectedness) is now the subject of increasing attention in research and practice (Beck and Villarroel Walker, 2013a,b; Kenway et al., 2011; WEF, 2011). The purpose of the water sector is to provide clean water to domestic, commercial, public, and industrial users, collect water-borne pollutants discharged by users, treat wastewater (remove pollutants) before releasing the resulting clean water to the environment, and dispose of separated pollutants (sewage sludge) in a safe fashion. All these processes are energy intensive, making energy a significant portion of operating expenses (Jiang et al., 2005; Olsson, 2013). Thus the water sector in general is typically perceived as a health and environmental necessity that is destined to result in continuous expenditures. For the past two decades this entrenched perception has been changing, however, from considering the removal of pollutants as the main purpose, towards the idea of resource recovery, particularly with respect to wastewater treatment (Balkema, 2003; Beck, 2011; Guest et al., 2009; Larsen et al., 2013; Lundin et al., 1999).

After water is extracted from the hydrosphere it is supplied to industrial and residential users, mainly as a waste carrier medium that is collected back in sewers. At this point, water has become entwined with substances and materials that will later need to be removed (through wastewater treatment) before the water is returned to the environment. Urban centers have been locking themselves onto this water-dependent paradigm for more than a century (Beck et al., 2010). Acknowledging that the water sector is already in place it is logical to pose the following questions: first, how should we benefit — in the business and environmental senses — from the association of the water sector with these materials and substances; and, second, how should we start untangling the water sector from technologies — such as the water closet (Beck and Villarroel Walker, 2011) — that perform functions that do not

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necessarily require water exclusively? Tackling them may also entail responding to issues related to greenhouse gases (GHG), energy, and food security (fertilizer availability) when considering the implications of the water-energy-food-climate nexus (Beck and Villarroel Walker, 2013b; Kenway et al., 2011).

Understanding and analysing the role of the water sector within the various socio-economic sectors comprising the city's fabric involve studying the flows of energy and materials (including water) that enter, undergo transformations, and then exit the city. This approach is often referred to as the study of urban metabolism (Barles, 2009; Kennedy et al., 2007; Wolman, 1965). It provides an indication of how resources are used and later discarded in the form of wastes and emissions. These input and output flows determine ultimately how the city interacts with other systems and the environment.

The paper describes and applies a quantitative approach to the analysis of urban metabolism. This reveals potential incentives that can drive water utilities towards, amongst other things, multi-utility service provision from the perspective of enhancing energy production and nutrient recovery. The present study has three objectives:

a. Estimating (under uncertainty) resource (water, nutrients, and energy) fluxes entering, leaving and circulating within the city-watershed system, as a function of behavior and consumption patterns of the city's population and its infrastructure;
b. Revealing the synergies and antagonisms amongst options for reducing water use and the recovery of energy and nutrients as a result of infrastructure changes, illustrated in this case by various combinations of four water-sector technologies; and
c. Estimating the monetary value of the additional revenue and expenditure reductions (referred to as 'benefits') that arise from implementing the four candidate technologies.

Understanding the synergies and antagonisms among the many parts of the urban system increases the scope for maximizing the benefits of a technology or policy implementation. On the other hand, ignoring these interactions can reduce the positive impact of initiatives that are implemented in an uncoordinated, isolated fashion and focused on a single technology or innovation. The paper starts by describing the methodological framework within which the Multi-sectoral Systems Analysis (MSA) is built, which is followed by analysis of the magnitude of material and energy flows entering, exiting and being transformed within Greater London. MSA is used to study synergistic interactions between sectors and flows of materials and energy while introducing various combinations of prospective technologies and infrastructure changes for manipulating these flows. By defining a set of metabolic performance metrics, with a focus on circular metabolism, a more structured comparison can be undertaken. This enables assessment of the impact of the candidate technologies on the water sector alone and on the whole city. The paper closes with an analysis of the potential additional benefits attainable under each scenario, i.e., the various possible combinations of the technologies implemented. These estimates can then be used to infer the potential market size of each alternative.

2. Multi-Sectoral Systems Analysis

2.1. Multiple sectors handling multiple materials

The Multi-sectoral Systems Analysis (MSA) framework is built upon three components. The first component is the methodology of Substance Flow Analysis (Brunner and Rechberger, 2003), the second involves the definition of metabolic performance metrics (MPM) based on material and energy flows, and the third component relies on the Regionalized Sensitivity Analysis (RSA) procedure (Hornberger and Spear, 1980; Osidele and Beck, 2003; Osidele et al., 2003). In the case of MSA, the Substance Flow Analysis (SFA) is employed to track and quantify the flows of energy, water (H_2O), elemental Nitrogen (N), elemental Carbon (C), and elemental Phosphorus (P) through 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. Unit processes are those activities that involve the mixing, separation, or transformation of flows. An important step of MSA is to define the geographic boundaries of the system under study. The socio-economic sectors are analyzed based on these boundaries and any flow entering is called an *import* while flows exiting are referred to as *exports*. Sectors are not only interconnected with each other but also with the environment, i.e., the hydrosphere, lithosphere, and atmosphere, through material and energy flows.

In general terms, the water sector includes water treatment, water supply, wastewater treatment, and those hydrological processes that affect the city, such as precipitation, evaporation, runoff, and sewer inflow and infiltration. The forestry sector involves silvicultural activities for timber production as well as urban forestry. It also covers the consumption of paper products. The food sector refers to imported or exported food, the food produced within the system's boundaries, and the fertilizer used for crop and green areas. The energy sector in MSA accounts for the demand for fuels and energy from various users, such as residential, domestic, commercial, industrial, and transport users. Power-generation users are also included; the difference between energy generated and energy demand, of a given energy form, is used to estimate the imports of energy. Lastly, MSA includes the waste handling sector, which is a generic way of grouping activities that deal with the disposal, reprocessing, and recycling of flows associated with sewage sludge and organic solid waste, including household, wood, and paper waste. The waste-handling sector interconnects the other four sectors, creating the scope, therefore, for modeling different resource and energy recovery strategies. Detailed information about the flow diagrams that organize the MSA model can be found in previous work (Villarroel Walker, 2010; Villarroel Walker and Beck, 2012) and is available as Supplementary Material Online in Figures S1 to S6.

Flows are computed as a function of the demands on the system, which are a direct result of consumption patterns (e.g., liter of water per capita per annum), their composition (e.g., nitrogen content in natural gas), and a calorific value (e.g., High Heating Value of sewage sludge). For instance, the nitrogen input in the form of food can be estimated by knowing a typical food intake per person and multiplying this by the population and the protein content of food. Similarly, total water supply can be estimated by the demands of the various users together with the amount lost through water mains leakage. The large majority of flows are computed based on the material and energy balances associated with the equations describing unit processes, e.g., biological wastewater treatment. Further details about input data, model output, and equations can be found in Tables S1 to S3, respectively, as Supplementary Material Online.

At this level of an SFA, MSA is similar to studies of the phosphorus and nitrogen flows in Finland (Antikainen, 2007), materials and money flows in the waste-handling sector in Sweden (Malmqvist et al., 2010), and phosphorus flows in the Swedish food sector (Neset et al., 2008). The capacity of MSA to analyze simultaneously more than a single material, or more than energy alone, constitutes a significant difference between it and these other studies. In particular, synergies and antagonisms between sectors can be easily identified, since the MSA is implemented within a modeling framework, i.e., Matlab®, rather than as a budgeting or accounting exercise. This modeling approach also facilitates the implementation of uncertainty and sensitivity analyses within the MSA.

Flows of resources, particularly those recovered in the form of energy, fuels, and fertilizers, can be converted into monetary revenues and expenditure reductions using the market value of these flows. This is straightforward for fertilizers and energy. For instance, a flow of recovered nitrogen (N) and phosphorus (P) in the form of a fertilizer is considered a potential revenue stream at current market value. Significantly, this flow of fertilizer is being produced via a non-conventional process, that is, different from the traditional Haber-Bosh process or the mining of phosphorus. Accordingly, there is a potential benefit stream to be derived from the difference between the emissions of greenhouse gases (GHG) associated with conventional and non-conventional means of acquiring fertilizer. These benefits will be in the form of carbon credits. In addition, where a technology reduces the need for resource, e.g., water, this can be monetized and presented as a saving in costs, which in large part amounts to the energy costs of operating the urban water system.

The second component of MSA, i.e., metabolic performance metrics (MPM), provides the practitioner with the information required to assess the change in the system's performance among scenarios. This is considered as a *change-oriented* or *forward* analysis, in which policies and technology innovations are assessed through their effect on material and energy flows, and subsequently on performance metrics.

2.2. Handling uncertainty

The large degree of speculation entailed in shaping scenarios for the future and the use of often quite imprecise or incomplete data calls for addressing issues of uncertainty in a quantitative manner, particularly if the purpose is to provide guidance for decision-making. This is achieved by the third component of MSA, the regionalized sensitivity analysis (RSA) procedure, which draws upon the use of Monte Carlo simulation — in fact, Latin Hypercube Sampling (LHS). This procedure accounts for the propagation of uncertainty through the MSA framework, from model parameters and system inputs to model (and system) outputs. The minimum number of samples, N, for adequately covering the parameter space can be estimated by $N > 0.75 \cdot p$, where p is the number of parameters of the model (Bärlund and Tattari, 2001). MSA makes use of about 400 parameters, so that the choice of $N = 1000$ simulation runs is considered large enough for the present application, while yet achieving a reasonable computing time.

In addition to ensuring a comprehensive sampling of the parameter space, it is important to define the size of the parameter space such that it adequately reflects the variability and uncertainty of the model parameters (α). In the case of absent or incomplete data, and consistent with previous studies using material flow analysis, a set of uncertainty levels based on the quality and the applicability of different sources of information is proposed (Danius and Burstrom, 2001; Hedbrant and Sorme, 2001). The uncertainty associated with each parameter is expressed as interval factors in the form $[/u_j, *u_j]$. In other words, data collected specifically for the region under study has less uncertainty, i.e., a lower value of u_j, compared with national or global averages, which are assigned higher values of u_j. For example, if the factor of $u_j = 2$ is selected, which corresponds to 'Official statistics and literature values at the regional and national levels downscaled to the local level', the parameter space is defined by the interval $[0.5 \cdot \alpha_j, 2 \cdot \alpha_j]$, where α_j is the most likely value of the jth parameter α_j.

3. Case study

3.1. Study area

Established as a geopolitical entity in 1965, Greater London (referred to as London for the purpose of this paper) is an administrative area of 33 boroughs, including the city of London, with a total area of 1572 km^2. In 2009 there was an estimated population of 7.8 M, and by 2030 it is expected to be about 9.0 M (GLA, 2011b). Land use in London has not changed significantly in recent decades. In 2010, land cover was mostly urban (63%), followed by greenspace and open areas (24%), woodlands (6%), crops (5.5%), and about 1.5% of open water. This paper evaluates the metabolism of London for the year 2010.

London has installed power-generating capacity of up to a total of 1400 MW, which is distributed in the boroughs of Enfield (400 MW) and Barking and Dagenham (1000 MW). This can be translated into an installed capacity for producing a total of 12,200 GWh annually, in support of over 3 M customers (based on average domestic consumption per household meter in 2010).[1] This however amounts to less than 30% of the total electricity demand for industrial, commercial, and domestic consumers of 41,720 GWh, the remainder of which had to be imported from outside London.

Another source of electricity is the incineration of municipal sewage, which is treated at three main facilities: Beckton (Northeast), Crossness (South), and Mogden (Southwest). Based on the population served, the total sewage produced within London is distributed among these three plants as follows: 48%, 28%, and 25%, respectively. Following European legislation on sewage sludge disposal,[2] which called for phasing out dumping at sea, the three main wastewater treatment plants in London adopted incineration with energy recovery as their disposal practice. This study assumes therefore that all the sewage generated within London is incinerated. Beckton has a sludge-based generation capacity of 8 MW of electricity. The fate of the incineration residue is assumed to be landfills.

The UK has adopted legally binding targets for emissions reduction. One of the mechanisms for achieving this reduction is the Carbon Reduction Commitment energy efficiency scheme, which is targeted at improving energy efficiency and cutting emissions in large public- and private-sector organizations, including water utilities. London has adopted a target of reducing 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 (Walsh et al., 2013). One policy 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. These legislative drivers add to the motivation, already spurred by increasing energy prices, to curb energy use in the water sector and enhance the recovery of energy from the materials (nutrients) entrained into the city's water metabolism, in particular, through the promotion of renewable energy schemes.

According to the 2008 Subnational Population Projections released by the Office for National Statistics (ONS), population in London is expected to reach the 9 M mark by 2030, a more than 15% increase compared to 2010. This has a direct effect on water and food consumption, the consequent waste and sewage generation, and the energy demand by these sectors. Significant efforts are being carried out to reduce the residential demand for water by

[1] Sub-national electricity consumption statistics and household energy distribution analysis for 2010.

[2] Article 14 (3) of Directive 91/271/EEC.

increasing the efficiency of fixtures and minimizing leakage. Water demand is not the only factor that puts pressure on water supply companies, but also leakage from water mains, currently at a rate of around 23% (DEFRA, 2009). From the current water use per capita of 160 L d^{-1}, government officials deem it possible to reduce demand down to 120 L per person per day by 2030 (DEFRA, 2008) and even further down to 110 L d^{-1} per person by 2050 (Hall et al., 2012).

3.2. Data collection

The London area has been the subject of previous city metabolism studies. Background information can be found in these from the perspective of Resource Flow Analysis and the Ecological Footprint of various sectors, i.e., energy, water, waste, and transport (BFF, 2002). A more recent analysis discusses the cross-sectoral nature of the UK's economy, including the energy, water, wastewater and solid waste sectors (Hall et al., 2012). Information regarding the infrastructure in place in London, 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 technological scenarios

To illustrate the application of MSA, the metabolism of London is studied under the influence of four resource- and waste-handling technology strategies. Our interest lies in understanding their impacts at the sector level, e.g., the water sector, and at the system's level, i.e., across all the sectors taken together as a single, integrated whole. The common theme of these technologies, although typically seen as exclusive to the water sector, is the recovery of nutrients for fertilization purposes and energy production, as described as follows:

Urine separation technology (UST): Urine-diverting toilets (Larsen and Lienert, 2007) separate urine from feces for the production of struvite ($NH_4MgPO_4 \cdot 6H_2O$) and ammonium sulfate ($(NH_4)_2SO_4$), respectively via crystallization and chemical reaction with sulfuric acid. 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 (Shu et al., 2006), with implications for agriculture and other uses, such as reconstructing declining salmon populations on Vancouver Island, British Columbia (Beck, 2011; Force, 2011).

Consolidation and co-treatment of household organic waste (COW): Using food grinders, kitchen organic waste is mixed with the usual contents of household sewage, i.e., laundry and bathroom/toilet fluxes (Malmqvist et al., 2010), and conveyed via the sewerage system to treatment at the sewage treatment works.

Pyrolysis of separated sewage sludge (PSS): Dewatered organic residues from sewage treatment are decomposed at high temperatures and in the absence of oxygen to produce gas, bioliquids, and biochar (Furness et al., 2000). The thermal process of pyrolysis has been studied as an energy recovery alternative from municipal sewage (Folgueras et al., 2005; Furness et al., 2000; Sánchez et al., 2007).

Algae production in wastewater treatment facilities (AWW): Any remaining nutrients in sewage treatment plant effluent flows are used for algae cultivation (Srinath and Pillai, 1972; Sturm and Lamer, 2011) undertaken in unit processes with the format known as "raceways" (Stephenson et al., 2010). The remaining biomass, after oil extraction, is assumed to undergo a pyrolysis process to further the production of fuels and fertilizers.

Using these four technological innovations, assuming 100% market penetration in each instance, it is possible to generate a total of sixteen scenarios, including a reference base case, i.e., no technological intervention, referred to as *Business as Usual* (BAU), see Table 2. The MSA model estimates energy requirements for water treatment and distribution, wastewater treatment, and the operation of the prospective new technologies using indicative energy consumption rates and benchmark analyses from published

Table 1
Sources of data for the London case study.

Description	Source
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)
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/
Energy required for water and wastewater treatment	Benchmark study for the US (Carlson and Walburger, 2007),
Capacity and sludge handling practices	Official websites or press releases of the largest treatment works in the London area: Beckton, Crossness, and Mogden (all sources accessed August 7, 2013): www.waterworld.com/articles/2012/11/thermal-hydrolysis-to-replace-ad-sludge-treatment-in-london.html oncomarchive.com/campaigns/mogden/mogfacts.html www.waterprojectsonline.com/case_studies/2012/Thames_Beckton_Upgrade_2012.pdf
Infiltration and inflow into the UK's sewer network	Ranges between 15 and 50% of average dry weather flow and about 10–20% of total wet weather flows (Ellis, 2001).
Electricity prices	UK Department of Energy and Climate Change (DECC) reported for industrial users for the 3rd quarter of 2012 as 9.2 pence per kWh (including a levy), equivalent to a total of 14 cents per kWh (DECC, 2012).
Biogas market price	Average prices for fuels purchased by major UK power producers, also reported by DECC in their quarterly energy prices (December 2012) as 2.25 pence per kWh (including a levy), equivalent to a total of 3.5 cents per kWh
Liquid biofuels	Assumes a commodity price similar to light crude oil at $100 per barrel
Market prices of fertilizers	US Department of Agriculture (USDA), which, in its March 2012 report, indicates that the farm price per short ton (907 kg) for Urea fertilizer (46% N) and Super Phosphate (46% PO_4) are $526 and $633 respectively
Carbon credit price	Spot price of Certified Emission Reduction units (CERs) was used at a rate of $1.4 per tonne of CO_2 equivalent for December 2012, as reported by Intercontinental Exchange (ICE).
Price of water supply and sewage collection	Thames Water: $1.90 (£1.22) per cubic meter of drinking water and $1.00 (£0.64) per cubic meter of sewage

Table 2
Definition of scenarios based on various combinations of the technologies previously described in Section 3.3.

Code	Description
BAU	Business as usual: no technology implementation
UST	UST only
PSS	PSS only
AWW	AWW only
COW	COW only
U + P	Combination of UST + PSS
P + A	Combination of PSS + AWW
A + C	Combination of AWW + COW
U + A	Combination of UST + AWW
P + C	Combination of PSS + COW
U + C	Combination of UST + COW
UPA	Combination of UST + PSS + AWW
PAC	Combination of PSS + AWW + COW
UAC	Combination of UST + AWW + COW
UPC	Combination of UST + PSS + COW
ALL	All four technologies combined: UST + PSS + AWW + COW

reports (Bleeker et al., 2010; Carlson and Walburger, 2007; Malmqvist et al., 2010; Stephenson et al., 2010).

In the following sections, the consequences of implementing these technologies are assessed in two ways: first, by investigating the synergies and antagonisms among sectors when the technologies are implemented, either singly or in combinations; second, by observing the effects of technology implementation on the Metabolic Performance Metrics (MPM).

3.4. Definition of Metabolic Performance Metrics (MPM)

Given the focus of this work on water, nutrients and energy flows, assessing and ranking of the various re-configurations of London's wastewater infrastructure can be made according to what we call Metabolic Performance Metrics (MPM), as defined in Table 3. These metrics 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). Others have signaled that the extent of *unsustainability* in a linear metabolism — one that is profoundly different from natural ecosystems and without much regard for the origin of resources and the destination and fate of wastes (Deelstra and Girardet, 2000) — can be identified by properly pricing or valuing ecosystem services (Daly, 1985, 2007). The application of the metabolism concept to cities — in the sense that urban areas should mimic the cyclical character of natural ecosystems — is now employed in urban planning and development (Kennedy et al., 2011; Mo et al., 2009).

MPMs account for the extent to which water is used, nutrients are recovered and recycled, and energy is saved or produced. The scope of the MPMs has been defined to assess the system at two levels: the water sector and the whole system. In this way, the implementation of a strategy in the water sector — technology, policy, or infrastructure change — can be assessed by its impact at both levels. In addition, the proposed MPMs 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, it relates 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).

4. Substance flow analysis of London

Model outputs are obtained in the form of a probability distribution as a consequence of the Monte Carlo simulation. Results are presented in general, therefore, on the basis of their average and the 5 and 95 percentiles of the distribution. The average value is the closest to the most likely value, while the range between the 5 and 95 percentiles represents the uncertainty of the model's output due to the uncertainty in the model's parameters and other input data.

4.1. Water

Total water withdrawals in London are estimated to average about 48 $m^3\ s^{-1}$, while the 5 and 95 percentiles are 40 and 56 $m^3\ s^{-1}$ respectively. Of the total water withdrawals, about 27% is used for electricity generation in natural gas plants and about 56% is for public water supply to residential and commercial users and, to a lesser extent, industrial customers. Fig. 1 shows the relative magnitudes of the various users of water. Leakage from water supply mains, 5.5 $m^3\ s^{-1}$, is comparable in volume to the inflow-infiltration in sewage pipes. As a consequence, the volume of water to be handled in both potable water treatment and wastewater treatment facilities is increased by nearly 25%. This has a direct effect on the energy demand for treatment. If per capita residential water use remains the same from year 2010–2050, demand for potable water (public supply) will roughly increase by 27% due to projected population increase, to a volume of between 31 and 35 $m^3\ s^{-1}$. The upper range of the estimated water abstractions for power generation is comparable to the amount of water supplied to residential users. The technology used for power generation and cooling is key in determining the amount of water required. Over 70% of the electricity generated within London is produced at Barking Power Station, which uses a Combined Cycle Gas Turbine (CCGT) technology. Typical water withdrawals associated with this process are between 28.3 and 75.7 m^3 per MWh of electricity production (Macknick et al., 2011). Barking Station reports a water use of about 1.8 million m^3 per day, which corresponds to a level of 75.7 m^3 per MWh. These values are associated with water withdrawn from the tidal section of the River Thames, most of which is returned to its source, except that volume consumed or lost via

Table 3
Definition of metabolic performance metrics (MPM).

	Water sector scope	Whole system scope
Energy	Ew = (energy generation)/(sector energy demand)	Es = (energy generation)/(London energy demand)
Water	Ww = water use for public supply	Ws = water use in London
Nitrogen	Nw = (N recovered)/(food consumed)	Ns = (N recovered)/(inputs of N)
Phosphorus	Pw = (P recovered)/(food consumed)	Ps = (P recovered)/(inputs of P)
Carbon	Cw = (renewable C generated)/(sector energy demand in C terms)	Cs = (renewable C generated)/(London energy demand in C terms)

Notes: (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 electricity is originated from natural gas.

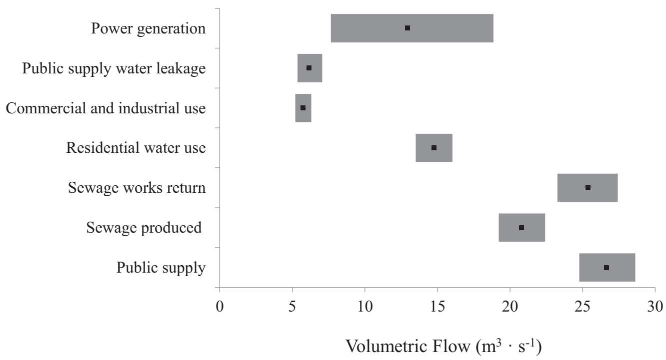

Fig. 1. Selected water and wastewater flows in $m^3\ s^{-1}$ for year 2010. The shaded bar spans between the 5 and 95 percentiles of the estimated values from the Monte Carlo simulation, while the dot represents the estimated median value.

evaporation, typically about 0.5 m^3 per MWh (Macknick et al., 2011).

4.2. Energy

Energy flows are dominated by the supply of energy for residential purposes, e.g., building heating-cooling and water heating. The fuel equivalent in natural gas terms for the total demand of electricity is the largest anthropogenic flow of energy, with a median value of about 80,000 GWh a^{-1}, as shown in Fig. 2. The largest users of natural gas are residential and commercial customers. For the former, natural gas provides mainly heating and cooking fuel. Other residential energy requirements such as appliances, electronics, and lighting are met using electricity.

The energy content of the various renewable materials used for electricity generation, i.e., sewage sludge (290–450 GWh a^{-1}) and municipal solid waste, is less significant than the flows described in Fig. 2. There is some potential for energy generation from solid waste that is otherwise sent to landfills, which in the case of the MSA model includes wood, paper, and food refuse, amounting to between 6500 and 8200 GWh a^{-1}. Currently, only about 25% of municipal solid waste is incinerated for energy purposes (producing some 670 to 900 GWh a^{-1}), while the rest is landfilled. Total food consumed, shown in Fig. 2, has an energy value of about 11,500 GWh a^{-1}. This is a mildly significant energy flow in the system and one that is eventually partly reflected in the energy content of sewage. Energy obtained from firewood, however, is more significant than that recovered from sewage, amounting to about 2000 GWh a^{-1}, but it provides just a fraction of the energy delivered by fossil fuels (as shown in Fig. 2).

In terms of energy consumption, the water sector is not significant, when compared with the system as a whole, although energy is the largest operational cost for the sector. Wastewater treatment energy use is about 390 GWh a^{-1} (ranging between 80 and 1800), while that in water treatment is 300 GWh a^{-1} (ranging between 20 and 5000). Theoretically, the estimated energy content in wastewater, 1400–1700 GWh a^{-1}, could provide a significant portion of the energy required for wastewater treatment, depending on the efficiency of the energy recovery process (Hall et al., 2012; Heidrich et al., 2011). Heidrich et al. reported that the energy content of wastewater varies from 5.6 to 16.8 kJ per liter (1.6–4.7 kWh per m^3), depending on the method for measuring energy content (i.e., oven-dried versus freeze-dried samples) and the level of domestic contributions to wastewater. The energy content value estimated in MSA varies from 6.8 to 7.2 kJ per liter (1.9–2.0 kWh per m^3) for a wastewater that is mostly discharged by residential users.

4.3. Nutrients

The flows of three nutrients are considered in MSA: those of nitrogen (N), phosphorus (P), and carbon (C). Previous studies have shown that nitrogen is the most widespread of the three (Villarroel Walker and Beck, 2012), mostly because of its presence in the energy sector as a constituent of natural gas and coal. Significant flows of nitrogen can be found in the energy, food, and water sectors. Power generation (electricity) in the area uses primarily natural gas and is responsible for an annual flow of nitrogen of about 18,000–56,000 tonnes N a^{-1}. However, the nitrogen associated with the use of natural gas for residential, industrial, and commercial purposes is much larger, amounting to between 62,000 and 190,000 tonnes N a^{-1}. Most of the nitrogen in natural gas is released into the atmosphere after combustion in the form of diatomic nitrogen (N_2) and nitrogen oxides (NO_x). This study does not discuss the potential impact of the emissions of the various forms of nitrogen but instead focuses on how nitrogen, as a valuable resource, moves into, out of, and around the system.

Water, used typically as a waste handling medium, becomes a carrier of the nitrogen exiting the food consumption and assimilation process. Fig. 3 shows that urine (22,000–40,000 tonnes N a^{-1}) contains most of the nitrogen present in food (42,000–47,000 tonnes N a^{-1}). In the diet of Londoners, meat (bovine, poultry, and swine) and cereals represent the largest intake of nitrogen (32,000–36,000 tonnes N a^{-1}), in almost equal proportions. A large portion of the nitrogen in sewage is lost to the atmosphere as elemental nitrogen during the denitrification stage in the activated sludge process (32,000–42,000 tonnes N a^{-1}). Assuming a nitrogen utilization efficiency of about 50% in crops

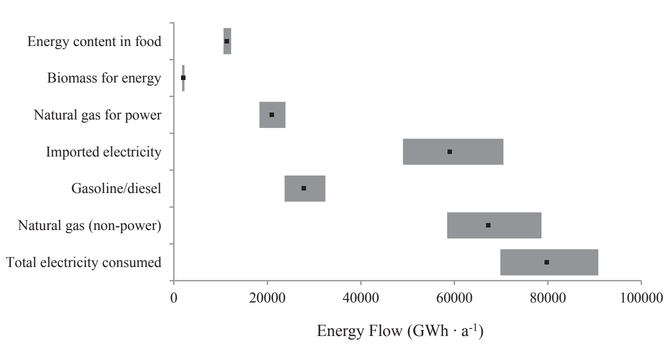

Fig. 2. Selected energy flows in GWh a^{-1} for year 2010. For comparison purposes electricity is reported in its equivalent primary energy from natural gas. The shaded bar spans between the 5 and 95 percentiles of the estimated values from the Monte Carlo simulation, while the dot represents the estimated median value.

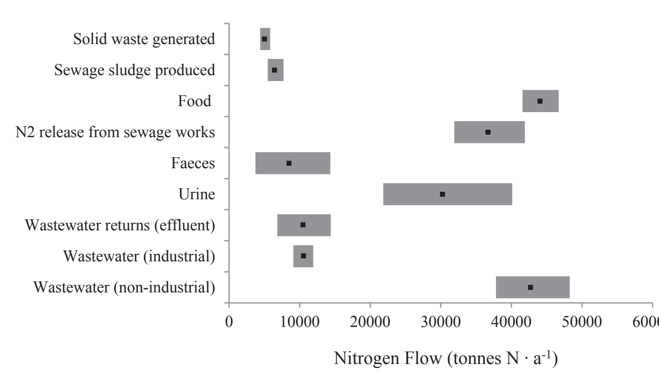

Fig. 3. Selected nitrogen flows in tonnes N a^{-1} for year 2010. The shaded bar spans between the 5 and 95 percentiles of the estimated values from the Monte Carlo simulation, while the dot represents the estimated median value.

(amount of N retained by plants from the amount of fertilizer applied (Cassman et al., 2002; Dowdell and Mian, 1982)), recovering 100% of the nitrogen currently lost as gas during wastewater treatment could supply between 32 and 46% of the demand for nitrogen for producing the food consumed in London. This is consistent with historical precedent. In 1913, 40% of human dietary N consumption in Paris was being recycled for food production (Barles, 2007a, 2007b). Today, land application of nitrogen fertilizers within the boundaries of London is much less significant than other nitrogen flows in the overall picture (2500–3200 tonnes N a^{-1}).

The energy sector plays no role in the flows of phosphorus, which are dominated by the food sector and, as a consequence, the water and waste handling sectors. Fig. 4 shows that food is the largest flow, with about 8700–9700 tonnes P a^{-1}, followed by the phosphorus in sewage sludge, 6800–8800 tonnes P a^{-1}, which includes industrial sources of about 1800 tonnes of P a^{-1}. Solid waste, which in the case of the MSA model includes paper, wood and food refuse, contains nearly 1600 tonnes of P a^{-1}. Since incineration of stabilized sewage and solid waste concentrates phosphorus in the solid residue of incineration (ashes), this phosphorus is likely to end up in landfills unless it is used for soil amendment.

Fig. 5 shows that carbon flows are closely related to energy flows because of the dependence on carbon-based energy (fossil fuels). The largest flows are those associated with the consumption of natural gas (power and non-power), gasoline, and diesel, for a total of 6.5 (5.4–7.7) million tonnes C a^{-1}. In a second tier, the flows associated with the food consumed and forestry (wood products including paper) amount to about 1.0 and 2.7 million tonnes C a^{-1}, respectively. Metabolic respiration from humans is of the same order, reaching nearly 0.8 million tonnes C a^{-1}. The carbon content in wastewater is less significant compared to fossil fuels (240–260 thousand tonnes C a^{-1}).

4.4. Cross-sectoral impacts of technology implementation

The MSA framework reveals interactions among the various sectors that arise from implementing the four candidate technologies. At the residential level, implementing urine separation (UST) reduces the demand for water for toilet flushing, which results in the reduction of demand from the public water supply from 26.7 (24.7–28.6) m^3 s^{-1} down to 24.0 (22.0–25.8) m^3 s^{-1}. This reduction in water demand has a positive effect on the energy demand in the water sector, by reducing the energy requirement by about 10% on average for water supply (a difference of 30 GWh a^{-1}) and almost 25% on the wastewater side (a difference of 100 GWh a^{-1}). The latter reflects not only the benefits of fewer toilet flushes but also

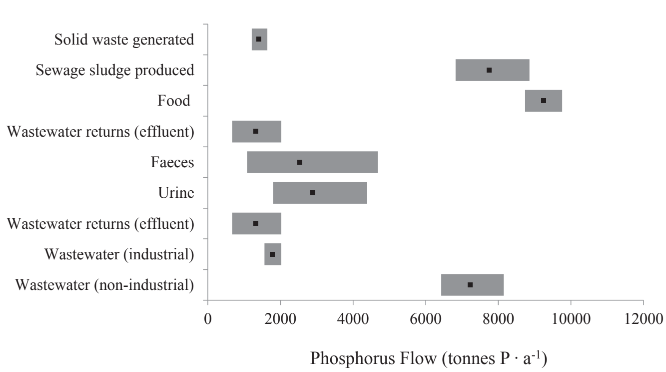

Fig. 4. Selected phosphorus flows in tonnes P a^{-1} for year 2010. The shaded bar spans between the 5 and 95 percentiles of the estimated values from the Monte Carlo simulation, while the dot represents the estimated median value.

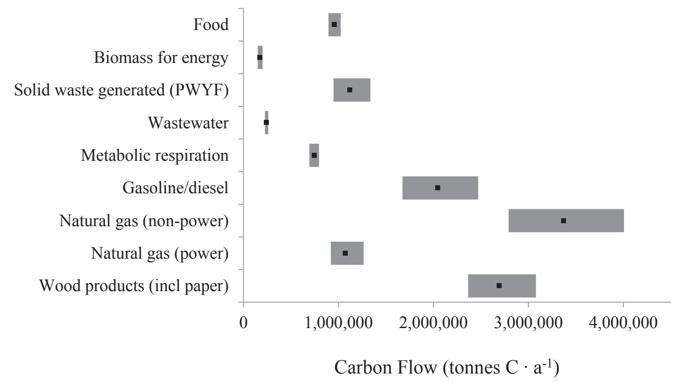

Fig. 5. Selected carbon flows in tonnes C a^{-1} for year 2010. The shaded bar spans between the 5 and 95 percentiles of the estimated values from the Monte Carlo simulation, while the dot represents the estimated median value.

the reduced amount of nutrients in sewage that require treatment. However, the process of nutrient recovery from urine does require energy, 35 (30–42) GWh a^{-1}, which estimates do not include any energy required for urine transportation and handling. In addition, fewer nutrients in sewage translates into a lower sludge and biogas production at the wastewater treatment facility. The amount of energy generated from the incineration of sewage sludge will drop from 110 (90–140) GWh a^{-1} to 90 (70–120) GWh a^{-1}, i.e., by over 15% on average. Similarly, and in proportion to the sludge being digested, the volume of the biogas generated is reduced from 410 (330–530) GWh a^{-1} to 350 (280–440) GWh a^{-1}. In tandem with the water savings, the nutrients captured before reaching the sewage stream by the UST have a fertilizer value: 2300 (1400–3500) tonnes P a^{-1} and 24,000 (17,000–32,000) tonnes N a^{-1}.

Because Pyrolysis of Sewage Sludge (PSS) is an end-of-pipe technology, i.e., implemented at the end of the water sector train of processes, it exhibits fewer synergies with other sectors in comparison with UST. The introduction of PSS generates two streams of benefits: (a) as fertilizer, 7700 (6800–8800) tonnes P a^{-1} and 1200 (900–1800) tonnes N a^{-1}; and (b) as fuel, 190 (100–300) GWh a^{-1} of biogas and 280 (130–470) GWh a^{-1} of biofuel. The recovered phosphorus is a resource that is spared from being sent to landfills, reducing the potential leaching of P towards the water table from 1300 tonnes P a^{-1} to 150 tonnes P a^{-1}. Relevant in terms of asset management, because treated sewage sludge is now diverted towards the PSS process, the installed capacity for sewage sludge incineration will be freed from its current function and could accommodate the use of other unconventional fuels, such as biomass or municipal solid waste (MSW).

The enrichment of sewage brought about by conveying organic waste in sewers (COW) has a significant effect on the contents of nutrients in sewage, i.e., N, P, and C. The amount of nitrogen and phosphorus in domestic sewage increases on average by 3600 tonnes N a^{-1} and 750 tonnes P a^{-1}, increments of 14 and 8% respectively. The enrichment of C is reflected in the energy generated from sewage sludge incineration, increasing to 185 (150–230) GWh a^{-1} from 108 (85–135) GWh a^{-1}. However, this also has a less desirable effect on the effluent side of the sewage treatment train by increasing the biochemical oxygen demand (BOD) from about 20 mg/l to 27 mg/l. Energy demand for wastewater treatment also increases to 430 (92–1970) GWh a^{-1} from 390 (86–1800) GWh a^{-1}, because of the increased organic material in the sewage. The implementation of COW does not affect the amount of P sent to landfills (on average 8600 tonnes P a^{-1}), but it does change the amount of N landfilled, which is reduced from 3100 (2700–3500) tonnes N a^{-1} down to 720 (650–800) tonnes N a^{-1}. This occurs because most of the nitrogen in the organic material sent to the sewer network is then lost through the denitrification process within the activated sludge treatment, instead of being sent to landfill as solid waste. This translates into an increase of 7% on average, from 36,700 (32,000–42,000) tonnes N a^{-1} to 39,100 (34,200–44,400) tonnes N a^{-1}, of nitrogen lost to the atmosphere. There are other effects that cannot be evaluated in detail in the present paper, such as the consequences of transporting a more viscous sewage, potential limitations of capacity of wastewater treatment facilities to handle additional organic waste, and changes in legislation. Previous studies have discussed the potential benefits and difficulties associated with the installation of food grinders (CIWEM, 2011; NYCDEP, 1997, 2008).

The implementation of algae production (AWW) has implications from the point of view of both energy and nutrients. MSA estimates that liquid biofuel can be produced at a rate of about 294 (144–470) GWh a^{-1} and biogas at 33 (15–60) GWh a^{-1}. In terms of fertilizers, the production is estimated at 730 (350–1380) tonnes N a^{-1} and 790 (400–1230) tonnes P a^{-1}. These figures are not very significant with respect to London's overall consumption of fuels and food (Figs. 3–5). AWW could provide fuel for only 1% of the demand in the transportation sector. However, within the water sector, the fuels product of the implementation of AWW could potentially cover between 15 and 20% of the energy demand for water and wastewater treatment, on average 690 GWh a^{-1} of electricity.

There are other synergies that are not fully evaluated in this paper, such as, for instance, those associated with more stringent constraints on the quality of sewage treatment plant effluents in respect of their biochemical oxygen demand (BOD) concentration. Bringing down the effluent BOD concentration to just 10 mg l^{-1} (mentioned as an "EU Elite Requirement" (Biokube, 2012)), could have a negative impact on energy demand, increasing it by about 12% (a difference of almost 50 GWh a^{-1}). However, this means that more carbon is collected via wastewater sludge, for incineration and biogas production, but the energy benefit is on average 6% and 5% respectively, which results in an energy (as fuel) gain of 6 and 10 GWh a^{-1} respectively. In other words, the gain in energy content of sewage sludge and biogas might not be sufficient to compensate for the additional energy spent on BOD removal.

4.5. Metabolic performance of the system

We now explore the impact on the metabolism of London of implementing more than a single technology at a time, i.e., according to the various combinations listed in Table 2. The impact is measured in terms of the Metabolic Performance Metrics (MPM) defined in Table 3.

To provide a simple overview of the salient MSA results, we rank the overall performance and each MPM as shown in Table 4. The best performance occurs when all technologies are implemented at the same time (scenario ALL), while the worst is the business as usual scenario, i.e., BAU. Scenario ALL performs best in terms of water and nitrogen, both at the water sector and whole system level, leaving scope for improvement, therefore, in terms of energy, carbon, and phosphorus.

The best scenarios for phosphorus recovery (P_w and P_s) are those that involve PSS. Additionally, those scenarios involving UST seem to rank poorly, reflecting the fact that there are other sources of P besides household wastewater and urine (such as industrial sewage). This suggests that it is more effective to collect phosphorus downstream, that is, where sewage sludge is treated and disposed.

In the case of nitrogen, i.e., N_w and N_s, the best scenarios are those that involve UST, while those involving PSS rank poorly. The

Table 4
Individual rankings of MPMs for each scenario, where 1 is the best ranked situation and 16 is the worst. Overall ranking assumes the same weight (importance) for each individual performance metric. For instance, to further explain how to read this table, the best scenario in terms of Ew is PAC while for Ns it is ALL.

Scenario	Overall rank	Ew	Ww	Nw	Pw	Cw	Es	Ws	Ns	Ps	Cs
ALL	1	2	1	1	3	5	3	1	1	3	6
PAC	2	1	2	9	1	6	1	2	9	1	2
UPC	3	3	1	3	5	7	6	1	3	5	9
UAC	4	5	1	5	9	1	5	1	5	9	4
P + C	5	4	2	11	4	8	4	2	11	4	7
U + C	6	7	1	7	11	3	9	1	7	11	5
P + A	7	9	2	10	2	12	7	2	10	2	10
UPA	8	10	1	2	6	14	11	1	2	6	14
A + C	9	6	2	13	13	2	2	2	13	13	1
U + P	10	13	1	4	8	16	13	1	4	8	16
U + A	11	14	1	6	10	10	14	1	6	10	12
COW	12	8	2	15	15	4	8	2	15	15	3
PSS	13	11	2	12	7	15	12	2	12	7	13
AWW	14	12	2	14	14	9	10	2	14	14	8
UST	15	16	1	8	12	13	16	1	8	12	15
BAU	16	15	2	16	16	11	15	2	16	16	11

fact that London uses advanced sewage treatment plants with biological removal of nitrogen through denitrification renders almost irrelevant any technological approach for nitrogen recovery from process streams associated with the anaerobic digestion of sludge. In other words, nitrogen recovery is more effective if implemented upstream of the wastewater treatment plant.

From Table 4 it can be concluded that performance in terms of P, N, and water does not change between the water sector and whole system, i.e., there are no significant sector-system level differences. Additional analysis has been made available as Appendix S1 in The Online Supplementary Material. How, then, can these results be interpreted by policy makers and innovators? For instance, if the goal for London is to increase the use of energy and carbon from renewable sources, then the implementation of COW could be a first step. However, this alone has a negative effect on the recovery of nitrogen. But it is not radically different from what has been happening in practice in recent years. In several London Boroughs, separated and collected food waste is today subjected to anaerobic digestion in order to produce a fuel gas and a soil amendment residue. In terms of the systems-level metabolism of London, this is roughly similar to the COW option, although operationally the two are quite different. COW utilizes the downstream wastewater treatment facilities to digest the organic material, which raises significant questions regarding the capacity of the existing sewers for handling the additional amount of solid organic material discharged from the upstream households.

The foregoing analysis is based on the rankings and scores of the Metabolic Performance Metrics (MPM). This does not account for the actual degree to which the respective performances of any two arrangements for the future are separated, including the degree of change with respect to BAU. Table 5 shows the improvement as a ratio for each scenario and performance metric. On the whole, these results corroborate those from the analysis carried out with the simple ranking. Again, ALL is the most favorable scenario at both the water-sector and the whole-system levels. Technology strategy COW appears to be the most favorable approach for increasing the energy generation from a renewable source, with an improvement of about 60% on average, followed by PSS and AWW (which offer about a 30% improvement). This is reflected in the scenarios that include COW, in particular PAC, where the amount of energy from renewable resources is doubled. Although the performance in terms of carbon (C_w) is very much linked to E_w, technology PSS does poorly in terms of carbon, since sludge incineration is substituted by pyrolysis. Therefore, the best

Table 5
Average improvement (as a percentage) of Metabolic Performance Metrics (MPM) with respect to the base case (BAU) for each scenario. In the case of MPMs associated with nitrogen and phosphorus, figures represent the actual value of the performance metric, i.e., the percentage of nutrient being recovered at the water-sector or whole-system level.

	BAU[a]	UST	PSS	AWW	COW	U + P	P + A	A + C	U + A	P + C	U + C	UPA	PAC	UAC	UPC	All
Ew	0.353	−3	30	28	60	26	54	82	18	85	64	44	107	82	90	104
Ww	26.66	10	0	0	0	10	0	0	10	0	10	10	0	10	10	10
Nw	0.00	47	3	2	0	48	5	2	48	3	47	49	5	48	48	50
Pw	0.00	19	84	9	0	78	93	9	24	91	19	84	100	25	85	92
Cw	0.717	−5	−14	11	36	−18	−3	44	5	20	38	−8	28	46	23	29
Sector	–	68	102	49	96	145	148	137	106	198	178	180	240	211	257	285
Es	0.003	−16	31	40	69	9	69	113	9	100	50	34	142	79	76	104
Ws	48.26	6	0	0	0	6	0	0	6	0	6	6	0	6	6	6
Ns	0.00	35	2	1	0	37	3	1	36	2	35	37	4	36	37	38
Ps	0.00	15	67	7	0	62	74	7	19	72	15	67	80	20	68	73
Cs	0.007	−18	−16	21	45	−30	5	66	−3	26	28	−16	47	43	11	26
System	–	22	84	70	114	84	151	188	67	200	134	129	273	184	198	247
Overall	–	90	186	119	209	229	300	325	173	398	312	309	513	395	455	532

[a] Actual value of the Metabolic Performance Metrics (MPM).

scenarios for improving the ratio of renewable carbon versus carbon used are COW and AWW, in that order.

In terms of nitrogen, UST is the clear winner, enabling the recovery of more than 40% of the N in the food consumed and more than 30% of all the inputs of nitrogen to London. In fact, UST seems to be part of all the best ranked scenarios, essentially because it addresses water, energy, nitrogen, and phosphorus. Because phosphorus remains in the liquid and solid phases of London's material flows, scenario PAC is capable of recovering the equivalent of 100% of the P in the food consumed, driven greatly by the implementation of PSS.

To summarize, sixteen alternative combinations for introducing four water-sector technologies have been assessed on two accounts: their relative rankings in respect of the city's Metabolic Performance Metrics (Table 3); and the extent to which these Metrics are altered by the introduction of any one of the future candidate interventions, relative to present-day performance, i.e., that of the BAU configuration. Moreover, ranking and performance improvement are gauged according to four Metrics at the water-sector level, four at the system-wide (city) level, and three further aggregate (overall) measures. This verges on a surfeit of assessment data, from which emerge, nevertheless, strategic pointers towards promising lines of action. If we focus, for instance, on KPI 21 proposed by the Greater London Authority, i.e., increase in energy generated from renewable sources (GLA, 2013), it is possible to draw the connection with E_w and E_s. The best technological scenario for improving these MPMs is PAC. In other words, the goal is to elevate the concentration of carbon (i.e., COW) in sewage and recover it from both the outputs of the wastewater treatment plant, i.e., in solid form (using PSS) and in liquid form (using AWW). However, the single technology strategy that exhibits the best improvement (60%) is COW, notably an alternative with an element of change upstream in the wastewater infrastructure (in households), with thus pronounced implications for their social legitimacy. In short, the thrust of our assessment so far has been about how to achieve greater "circularity" in the metabolism of the city, as one way of realizing greater environmental benignity in its behavior. Decisive, however, and in keeping with Triple Bottom Line thinking (Beck, 2011; Elkington, 1998), might be the economic feasibility attaching to each of the sixteen alternatives.

5. Economic benefits

Table 6 presents the estimated benefits from implementing the four prospective technologies. These benefits are classified into revenue and change of expenditure. The former represents a measure of the market size of the four strategies. The increase in revenue is calculated on the basis of the market values of water, fertilizer, and fuels, and the potential revenue benefit from selling carbon credits. Typically, a carbon credit is the value of either reducing a fossil-fuel-derived emission or substituting a fossil-fuel-generated emission by an equivalent emission generated by combustion of a renewable fuel. On the other hand, implementation of the technologies might result in a positive or negative effect on the overall demand for water supply and electricity in water and wastewater treatment, as well as in the operation of the technology itself. The change in demand is then expressed in monetary terms to represent an expenditure reduction or an increased cost. These changes in expenditure also need to be considered when the benefits of a technological strategy are assessed.

Three sources of additional revenue from the marketing of carbon credits are covered in the present analysis:

Table 6
Potential gross revenues and expenditure change for each scenario (in millions, US dollars).[a]

	BAU	UST	PSS	AWW	COW	U + P	P + A	A + C	U + A	P + C	U + C	UPA	PAC	UAC	UPC	All
Fertilizer	0.0	33.7	29.7	3.8	0.0	54.5	33.7	4.2	36.2	32.1	33.7	57.1	36.4	36.5	56.9	59.8
Fuels	21.9	18.3	39.5	41.9	37.0	32.7	59.9	58.8	30.9	57.9	32.8	45.8	79.6	47.2	51.3	65.9
GHG[c]	0.5	0.6	0.4	0.6	0.7	0.6	0.5	0.8	0.7	0.5	0.8	0.6	0.6	0.9	0.7	0.8
Revenue	22.4	52.7	69.5	46.3	37.7	87.8	94.1	63.7	67.8	90.5	67.3	103.5	116.6	84.6	108.9	126.5
Energy[b]	0.0	18.5	(0.9)	(12.2)	(10.7)	17.7	(13.4)	(23.0)	11.2	(12.3)	9.3	10.4	(25.2)	1.1	7.9	(0.6)
Water	0.0	248.2	0.0	0.0	0.0	248.2	0.0	0.0	248.2	0.0	248.2	248.2	0.0	248.2	248.2	248.2
Expenditure	0.0	266.7	(0.9)	(12.2)	(10.7)	265.9	(13.4)	(23.0)	259.4	(12.3)	257.6	258.6	(25.2)	249.3	256.1	247.6

[a] Values in parenthesis represent a negative value, in other words, an additional expenditure, as opposed to an expenditure reduction (a saving) or a gross income benefit.
[b] Energy is reported as the reduction (saving) or increase (due to additional demand, hence a negative value) of expenditures in respect of electricity for water, wastewater treatment, and prospective technologies.
[c] Revenues from GHG emission reductions are calculated as the carbon credit associated with: non-conventional fertilizer (only energy for production), renewable fuels produced, and electricity savings.

(a) The scope for local (non-conventional) production of fertilizer to offset greenhouse gas (GHG) emissions that would otherwise be generated during the conventional production of fertilizer via the Haber-Bosch process, for instance. Previous studies have reported that the production via struvite of fertilizer from supernatant (a side stream in the wastewater treatment process) is associated with GHG emissions five times lower than the conventional production of fertilizer (Britton et al., 2007).
(b) The scope for production of carbon-based fuels from renewable sources to offset C emissions from fossil fuels with an equivalent energy value.
(c) The savings in energy from reducing the need for electricity that is (in part) generated from fossil fuels.

Results are sensitive to market fluctuations and the various streams of revenue will need to be revised accordingly. For instance, if the value of the carbon credit were that of the fourth quarter of 2008, then the income from marketing carbon credits would range from \$5.3 M (with PSS alone) to \$13.5 M (for the UAC combination), as opposed to currently less than \$1 M.

Other factors could also play a significant part in the economic assessment of scenarios, such as tax credits and regulatory constraints. Consider, for example, the case of the Rock Creek Advanced Wastewater Treatment Facility, Hillsboro, Oregon. This facility partnered with Ostara, a company providing technology for implementing the struvite process (the same process as that of the UST option herein), to recover phosphorus from supernatant liquors generated during sewage-sludge digestion. The Rock Creek plant processes approximately 35 MGD (1.53 m^3 s) of crude sewage and has now the capacity to recover phosphorus, i.e., to produce more than 1000 metric tonnes of struvite or MAP (magnesium ammonium phosphate) fertilizer. Accordingly, the Oregon Department of Energy granted the Rock Creek facility a (one-time) Business Energy Tax Credit (BETC) of \$1.15 M to aid construction, based on the energy that would be conserved in producing fertilizer onsite compared to producing it conventionally by mining and extraction elsewhere (Hadden, 2012).

Table 6 shows that the business-as-usual-scenario (BAU) can already claim a revenue stream of \$20 M for the energy benefits of sewage-sludge incineration and biogas generated from sludge digestion and landfill. The largest revenue from implementing just a single technology is achieved with PSS, nearly \$70 M, due to the market value of the fertilizer produced (about \$30 M) and the additional renewable fuels that can be generated, i.e., biogas and liquid biofuel, which amount to nearly \$20 M (in total). In this case, the ash produced from the pyrolysis is also considered to have value as a soil amendment material and a fertilizer (only phosphorus). Not surprisingly, the scenario that generates the largest amount of revenue is when all four technologies are implemented simultaneously (ALL). However, this comes at the expense of implementing new capital works and then operating all four technologies.

The two end-of-pipe technologies, i.e., PSS and AWW, could potentially bring a gross income of about \$94 M. This would be the best figure for any combination of just two technologies. If UST is added to this pair, the figure increases to \$103 M, but with the disadvantage that significant plumbing work and adaptation would be needed at the household level. In addition, there would remain the question of the social acceptability of the urine-separating toilet (Lienert, 2013; Lienert and Larsen, 2009).

Implementing UST alone can bring an additional \$30 M in revenue compared to BAU. However, the results suggest that the interactions among UST, PSS, and AWW reduce the potential for gaining revenue from UST to a third of this, i.e., to just \$9 M. Technologies COW, PSS, and AWW (in that order) are the strongest in terms of fuels production, bringing additional revenue ranging from \$15 M to \$20 M, from each technology individually. However, the combination of all three could yield profits of over \$57 M. Since PSS and AWW are considered end-of-pipe solutions, i.e., they are implemented inside the confines of the wastewater treatment plant, they are likely to incur the least social disruption. The public's exposure to any inconvenience during their construction would be minimal; and individuals would not be being asked to accept changes either to the plumbing arrangements in their households or to their personal habits, which could be the case for UST and COW. For this reason, PSS and AWW might have a strategic advantage over COW as fuel production alternatives, given that COW involves the installation of food grinders in individual households.

With regard to reductions in expenditures, the best scenario is that including the implementation of UST, with savings on the order of \$257 M. Since less energy is required for moving water in and out of the city, direct savings of about \$8.8 M will accrue to the utility, i.e., Thames Water. The largest benefit, however, would be in the form of lowered expenses from water consumption associated with fewer toilet flushings. Utility customer bills, for both water supply and sewerage services, could be reduced by \$248 M in total. Yet this represents about \$30 per capita on an annual basis, which hardly seems a strong incentive for customers to install urine-separating toilets. The utility company might therefore need to share with its customers the benefits associated with its energy savings (pumping costs avoided) and its revenues from fertilizer production. Such arrangements could be key, since the cost for this type of toilet (a UST) currently ranges from \$900 and \$1200,[3] not including installation and plumbing materials. For comparison, the cost of a traditional low-flow toilet ranges between \$300 and \$800.

6. Conclusions

In this case study of the urban metabolism of London, interactions among the fluxes of five resources (C, N, P, water, and energy) circulating around five economic sectors (water, energy, waste-handling, food, and forestry) have been studied using the Multi-sectoral Systems Analysis (MSA). The relative proportions of these various fluxes are largely as one would expect for a metropolis the size of London, although our analysis reveals the significant extent to which N resources enter the city's metabolism in natural gas imports for purposes other than power generation. Most of the P entering the city in food ends up in the output sludge separated far downstream in London's wastewater treatment facilities.

When conducting the MSA, synergies and antagonisms among the various technological (and policy) interventions are of special interest. Significantly, for London and for the many cities with similar wastewater infrastructures, introducing facilities for nutrient (N and P) recovery upstream in the system — specifically via household urine-separating toilets (UST) — will compromise the utility of introducing unit processes downstream at the wastewater treatment plant, such as the cultivation of algae (technology AWW herein), for subsequent biofuel production.

With regard to the Triple Bottom Line framing of sustainability, our analysis reveals the following. In respect of the environment and resource recovery, UST has a cross-sectoral impact in the sense that it reduces water consumption, reduces energy consumption (for pumping), and recovers sizeable amounts nutrients, most notably N. Other technologies, however, when considered as single interventions on their own, offer greater promise in respect of P recovery (through the introduction of pyrolysis of sewage sludge;

[3] http://www.separett-usa.com/.

PSS) and renewable biofuel production, i.e., C recovery, such as the alternative of using food grinders, with subsequent conveyance of the C in waste food through the sewer network to downstream processing at the wastewater treatment plant (technology COW herein). With respect to financial benefits and savings, UST would in principle be an outstanding success, primarily because of the costs saved from the reduced consumption of water for toilet flushing. On the other hand, and in respect of the social acceptability of policy and engineering interventions, UST is likely to be the most socially disruptive option, in view of its requirements for the re-plumbing of each and every household in the city. COW, which combines elements of both upstream and downstream interventions in the city's wastewater infrastructure, should be less socially disruptive, while PSS and AWW would be even less so, since these latter are candidate technologies that can be implemented within the far downstream confines of the wastewater treatment plant.

Last, were London to seek to achieve its own Key Performance Index (KPI) 21, i.e., increasing the energy it generates from renewable sources, our MSA results indicate that the best combination of (water-sector) technological interventions would be to elevate the concentration of C in sewage upstream through COW and then recover C-based fuels downstream using both PSS and AWW — an evident synergy among the three interventions.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2014.01.054.

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