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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