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Connecting the resource nexus to basic urban service provision – with a focus on water-energy interactions in New York City

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ABSTRACT

Urban water and energy systems are crucial for sustainably meeting basic service demands in cities. This paper proposes and applies a technology-independent “reference resource-to-service system” framework for concurrent evaluation of urban water and energy system interventions and their ‘nexus’ or ‘interlinkages’. In a concrete application, data that approximate New York City conditions are used to evaluate a limited set of interventions in the residential sector, spanning from low-flow toilet shifts to extensive green roof installations. Results indicate that interventions motivated primarily by water management goals can considerably reduce energy use and contribute to mitigation of greenhouse gas emissions. Similarly, energy efficiency interventions can considerably reduce water use in addition to lowering emissions. However, interventions yielding the greatest reductions in energy use and emissions are not necessarily the most water conserving ones, and vice versa. Useful further research, expanding the present analysis should consider a broader set of resource interactions, towards a full climate, land, energy and water (CLEW) nexus approach. Overall, assessing the impacts, trade-offs and co-benefits from interventions in one urban resource system on others also holds promise as support for increased resource efficiency through integrated decision making.

1. Context

Traditionally, urban service delivery systems are planned, developed and operated in silos. While improvements in water utility operations can improve the reliability and water-quality performance of a city’s water system, more advanced water treatment typically requires more energy (Pabi, Amarnath, Goldstein, & Reekie, 2013). Further, providing this energy requires water. The use of water in hydropower production can be significant (Destouni, Jaramillo, & Prieto, 2013; Jaramillo & Destouni, 2015a). Fuel extraction and processing require water before the fuel is put into electricity production (where additional water is used for cooling purposes) or used directly for heating or industrial processes (Macknick, Newmark, Heath, & Hallett, 2012; Mekonnen, Gerbens-Leenes, & Hoekstra, 2015; Mielke, Anadon, & Narayanamurti, 2010). As a result, changes in a city’s water system may alter the city’s indirect use of both energy and water (Bazilian et al., 2011). Within the city the parallel water and energy systems have numerous interdependences (Abdallah & Rosenberg, 2014; Chini, Schreiber, Barker, & Stillwell, 2016; Kenway et al., 2015). Uncoordinated planning and management of these systems may therefore be suboptimal – with unaccounted for indirect impacts (Scott et al., 2011).

The importance of interlinkages in the supply chains of water, energy and food has been highlighted by the International Atomic Energy Agency (IAEA, 2009), among others, emphasising the need for integrated management of Climate, Land use, Energy and Water (CLEW). Howells & Rogner (2014) further argue for the need to develop quantitative frameworks to support such integrated management and policies for increased efficiency and sustainability.

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In recent years, CLEW, or *nexus*,[1] studies have started to address various geographical scales: global (United Nations, 2014), regional (Smajgl & Ward, 2013; de Strasser, Lipponen, Howells, Stec, & Bréthaut, 2016), and national (Hermann et al., 2012; Howells et al., 2013; Macknick, Sattler, Averyt, Clemmer, & Rogers, 2012; Sattler et al., 2012; Welsch et al., 2014). At sub-national level, Bartos and Chester (2014) point out missed opportunities from a lack of integrated handling of water and energy services in the state of Arizona, USA.

Available nexus literature at urban scale typically fall into one of three categories: comprehensive studies of single interactions, such as the energy footprint of a water utility's operations, or the energy and emission impacts of water conservation measures (Sanders & Webber, 2015; Stokes, Hendrickson, & Horvath, 2014; Xu, Chen, Ma, Blanckaert, & Wan, 2014); assessments of embedded resources in (and emissions of) water or energy supplies (Kenway et al., 2008; Plappally & Lienhard, 2012; Sanders & Webber, 2012; Sattler et al., 2012; Stokes & Horvath, 2010; Zhou, Zhang, Wang, & Bi, 2013) or; more general reviews of urban planning practices (Yang & Goodrich, 2014). By modelling the end-use consumption of water and energy, Rhodes et al. (2014) demonstrate the value of relevant data collection, including by use of smart meters. Other end-use focused studies regard correlated resource consumption patterns across households (Abdallah & Rosenberg, 2014) and potential economic and resource savings from shifts to high-efficiency residential appliances (Chini et al., 2016). Overall, however, as Nair, George, Malano, Arora, and Nawarathna (2014) also points out, technology-general frameworks where centralized and decentralized solutions can be assessed concurrently for integrated urban resource planning and management, are still in their infancy.

This paper contributes to the development of such a framework for linked urban *resource-to-service systems*, focusing on the urban water-energy nexus in relation to meeting urban service demands. A specific case study, based on data for New York City (NYC), is used to exemplify the concrete application of this framework. Water and energy use impacts from a limited set of urban interventions are studied, with interventions grouped into two categories: (1) shifts to more *water and/or energy efficient household appliances* and (2) expansion of selected *urban water management measures*. By analysing different types of interventions (carried out by different actors in the city, motivated by different urban needs and linked to different parts of the city's energy and water infrastructure), we explore the usefulness of a, for this work developed, *Reference Resource-to-Service System* (RRSS) for informing the analysis of interlinked urban water-energy interactions.

2. Methodology

2.1. Framework

To map how resource supply chains are intertwined in the urban space, a conceptual RRSS schematic is developed that combines elements of a reference resource system (IAEA, 2009; Weirich, 2013) and flow diagrams for urban metabolism (Newman, 1999). In the RRSS the demand side is placed at the center, in order to capture how resource flows feed into urban service provision. Similarly to its predecessor for energy system analysis (the reference energy system – or RES (Seebregts, Goldstein, & Smekens, 2002)), the developed RRSS schematic illustrates how a change in a single system link impacts other links, by simply following the arrow chains through the flowchart.

Fig. 1 presents a prototype RRSS schematic developed for the case study of the NYC water and energy resource systems. Although currently based on NYC data, this RRSS framework can – with relatively small modifications – be applied to other cities. A more comprehensive RRSS schematic can also graphically capture how impacts from a broad range of urban interventions ripple through additional resource systems, such as land-use toward various end-use sectors.

The RRSS schematic is model independent by just illustrating the key elements of each resource system and how these are linked to form a system-of-systems (SOSys). Various models can be used to quantify the RRSS elements and links, as appropriate on a case-by-case basis. The schematic thus simply maps the interactions and models used to quantify them may range over different possible simulation, optimization, and/or accounting models. The illustrative case study described in this paper uses an accounting approach, with data describing marginal impacts of the studied interventions, based on an illustrative 'snap-shot' of NYC's resource-to-service water and energy flows in the year 2010.

2.2. Case study

NYC has a population of more than 8 million people (U.S. Census Bureau, 2016) and is the center of one of the world's top ten largest metropolitan regions. In 2010, the municipal water system supplied the city with one billion gallons (3.8 million cubic meters) of water each day, while 1.2 billion gallons (4.6 million cubic meters) of wastewater were treated in fourteen in-city wastewater treatment plants (NYC Department of Environmental Protection, 2012). These volumes make the NYC Department of Environmental Protection the largest municipal water utility in the United States. The water system is characterised by mainly gravity-fed water supply and comprehensive watershed protection measures. The latter means that water filtration requirements can be evaded, thus relatively little energy is used for water treatment at the supply side (NYC Department of Environmental Protection, 2011).

At the other end of the water system, stormwater and municipal wastewater share pipes in the city's combined sewers. Heavy rains repeatedly cause the city's sewers to overflow, releasing untreated wastewater to the urban watershed. The city actively aims to reduce these overflow events as part of its comprehensive PlaNYC2030, with green infrastructure and rainwater harvesting measures being important parts of the solution (City of New York, 2007).

For electricity, NYC is connected to the United States Eastern Grid for electricity supplies. Yet, due to limited transmission infrastructure, the city is required to have an in-city production capacity of 80% of the projected summer peak demand (NYISO, 2012). This capacity is normally not fully utilized. In 2010, in-city plants produced 45% (or 86 PJ) of the total 190 PJ of electricity consumed in the city. The city's second largest fuel use (in terms of source PJ), after electricity, is direct combustion for heating. Fuel oil boilers are being increasingly replaced, primarily by natural gas-fired alternatives. In 2010, natural gas contributed 62% (or 271 PJ) of the (non-electricity) fuel use in NYC buildings (City of New York, 2012).

2.2.1. Studied water and energy interventions

Residential buildings account for close to 80% of the NYC's water use. Directly and indirectly, they account for a third of the citywide greenhouse gas emissions (NYC Department of Environmental Protection, 2012). For these reasons, our analysis focuses on interventions related to the residential sector.

The RRSS aims to be technology-independent. As such, the number of urban interventions *possible* to assess in the RRSS framework should be close to the number of possible interventions in a city (i.e.

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[1] The *nexus* refers here to the interplay and interconnections between different societal or natural systems or resources. Most commonly found to cover water, energy and food, but also found to be joined by security, eco-systems, climate, sanitation, health and/or gender (see for instance (Beck & Walker, 2013; de Strasser et al., 2016)).