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Modelling the dynamic interactions between London's water and energy systems from an end-use perspective

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HIGHLIGHTS

- End-use interactions of the urban water-energy nexus help reduce future water demand.
- Interactions at the end use limit water system expansion requirements.
- Electricity must be decarbonised by order of magnitude for CO_2 emissions targets.

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ABSTRACT

Cities are concentrations of demand to water and energy systems that rely on resources under increasing pressure from scarcity and climate change mitigation targets. They are linked in many ways across their different components, the collection of which is termed a nexus. In industrialised countries, the residential end-use component of the urban water-energy nexus has been identified as significant. However, the effect of the end-use water and energy interdependence on urban dynamics had not been studied. In this work, a novel system dynamics model is developed with an explicit representation of the water-energy interactions at the residential end use and their influence on the demand for resources. The model includes an endogenous carbon tax based climate change mitigation policy which aims to meet carbon targets by reducing consumer demand through price. It also encompasses water resources planning with respect to system capacity and supply augmentation. Using London as a case study, we show that the inclusion of end-use interactions has a major impact on the projections of water sector requirements. In particular, future water demand per capita is lower, and less supply augmentation is needed than would be planned for without considering the interactions. We find that deep decarbonisation of electricity is necessary to maintain an acceptable quality of life while remaining within water and greenhouse gas emissions constraints. The model results show a clear need for consideration of the end-use level water-energy interactions in policy analysis. The modelling tool provides a base for this that can be adapted to the context of any industrialised country.

1. Introduction

Cities have become the main loci of direct and indirect demand for water and energy services. Over half of the global population are urban and this share will increase, with the growth driven by developing countries. There, an urban dweller consumes more modern energy than a rural citizen [1]. The concentration of demand in cities is much higher than that of available supply, and this is particularly a problem for freshwater, which needs to be brought in from a large hinterland, or produced.

Water and energy are fundamental to human life, but on scales ranging from local to global the supply of these resources is posing a challenge. Freshwater stocks are being depleted faster than they are renewed due to high rates of consumption and changing water cycles [2]. Energy resource use needs to change drastically, not so much because of availability issues as because of limits on the amount of future greenhouse gas emissions if global warming is to be kept below 2 °C by the end of the century compared to the pre-industrial global average temperature [3].

Knowledge about the future development of demands for water and energy, the constraints on their supply and need for supply expansion, and the consequences of the selection of solutions is of the utmost

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importance to the planning of the infrastructure which enables the provision of these resources for activities. Infrastructure systems related to energy and water supply have long lead times for development, planning and construction, and once they are in place these characteristics are locked in for decades to come [4].

Water and energy systems are linked in many ways. On the supply side energy is used for water treatment and conveyance, and water is required for fuel processing, for cooling in thermal power plants and for pressure in hydropower. In demand, water and energy are used in conjunction for many services e.g. process heat in industry, and hot water and wet appliances in the residential and commercial sectors. Through these linkages both systems are strongly coupled, with limits in one imposing constraints on the other: water scarcity and temperature affect the potential for electricity generation [5], and power outages can interrupt the operation of water treatment plants, thereby disrupting potable water supply [6].

The set of interactions between our water and energy systems has come to be referred to as the water-energy nexus. The popularity of the term is indicative of a growing body of interdisciplinary research, with researchers in fields traditionally focussed on water looking at the energy implications (e.g. [7]), and those in energy-related fields estimating the effects on and from water systems and hydrological cycles (e.g. [5]). In almost all cases, the results are obtained by applying intensity factors to already existing data for water or energy use or conversion.

From an urban perspective, the water-energy nexus consists mainly of the energy requirements for water supply to citizens and local industry, and end-use services combining water and energy. Since electricity but also fuels are much easier to transport than water, upstream energy-related water is less of an issue for cities as energy can be sourced from places where adequate water is available.

Some have taken a comprehensive view by also taking into account upstream consumption implications [8] and even virtual water and embedded energy, the latter for Beijing [9,10] and for its broader agglomeration region [11]. However, these studies have a limited representation of end use and regard only a snapshot in time.

Studies on water and energy end use are published both in the primary but also in the grey literature. Several have disaggregated resource use by service or specific end use, for energy and for water. The former is most often electricity due to the variety of uses, e.g. [12]. When the water-energy interactions are considered they always appear to be based on energy intensities of water uses [13], most often using engineering estimates (however, in work by Beal et al. [14], energy use was based on directly measured consumption in a pilot study). What is more, the estimates at the end use are static, taken for a snapshot in time, and interest in them has traditionally come from the energy-saving side: how much electricity or gas can be saved through e.g. water-efficient dishwashers or low-flow shower heads? There is no consideration of possible feedbacks, e.g. a rebound effect in other water use due to energy saved in one service being put toward increased energy use in another service.

Hence, studies about the future cross-system interactions in the water-energy nexus are on the water-for-energy side, to a lesser extent on the energy-for-water side, and almost no research has been performed on the end-use side, despite it being the largest component in the water-energy nexus in the places where it has been studied most - predominantly the United Kingdom, the United States (and California in particular) and Australia [13]. The literature review of nexus studies at an end-use level by Nair et al. [15] confirms the latter. Since the urban water-energy nexus comprises mainly energy-for-water and end use, the dynamics of the urban water-energy nexus have not been studied extensively. This study aims to fill those gaps. By means of a system dynamics model, the hypothesis that the end-use interactions between the urban energy and water systems significantly impact urban dynamics is tested. The implications of taking these interactions into account are assessed for London as a case study. Finally, we discuss what this means for urban water security and climate policies.

1.1. Case study: London

We focus on London as a case study. It is a megacity which faces challenges both in water provision due to vulnerability of its water resources to droughts, as well as in energy use because of ambitious climate change mitigation policies and grave air pollution from fuel combustion. Carbon emissions should be reduced by 60% and 80% by the years 2025 and 2050, respectively, against 1990 levels [16, Table 1]. To remedy future water supply problems, options with a higher than current energy use have been and are being developed, e.g. wastewater reuse, bulk water transfers from other areas, or seawater desalination. Because of the scale of the infrastructure involved, these supply issues have received most attention. However, as far as water-related energy use is concerned, by far the greatest component of the urban water-energy nexus in a city such as London (i.e. a Western city in a temperate climate) is the end use: upwards of 85%, mainly for water heating purposes [13].

Furthermore, as London grows, changes at the end use may occur with strong interactions across water and energy. One example is the requirement of booster pumps for water provision at higher altitudes with densification of the population through higher buildings. Another is adoption of rainwater harvesting to reduce pressures on surface and groundwater resources as well as to mitigate runoff intensity. Both interventions in the water system increase energy end use [17,18].

On the energy supply side, Byers et al. [19] have estimated the cooling water requirements for electricity generation through 2050 for a number of pathways that are consistent with the UK's Climate Change Act from 2008. They found that although total water consumption increases across most scenarios, this is only the case for freshwater in pathways that rely heavily on Carbon Capture and Storage (CCS) because power generation can be shifted towards the coast but CCS is more location-bound. Water used in the fuel cycle for thermal power plants is much less than cooling water [20], with oil processing (e.g. for transport uses) consuming an amount of water per unit energy on the same order of magnitude as coal or natural gas [21]. Hence, upstream water for energy-related purposes is not important from the perspective of London.

Future water supply for London and in the UK has been studied extensively, not only by academic researchers but, importantly, by all water utilities. The latter are required by law, through the Water Industry Act of 1991 [22], to make management plans that look forward several decades and that should demonstrate that the water companies have resilience plans in place to ensure that demand can be satisfied at least until the plan's time horizon. Most of the water supply for London, and all of its wastewater services, are performed by Thames Water. Their management plans indicate that they expect an increase in water demand because of population growth, and they look to meet this with either or a mix of three options: bulk water transfers (imports) from other catchments, larger local storage capacity, or a greater capacity to desalinate sea and brackish water and directly treat wastewater to potable standards [23]. The assessments of the options include estimates of energy use, but these are not explicitly available.

Although the end-use water-energy nexus literature is largely limited to the residential sector and not specific to London, it is pertinent for a number of reasons. First, the residential sector is responsible for two-thirds of water use [24] and 41% of 2010 final energy use [25], more than any other sector. Second, most of the components of water and energy use in the commercial sector are also found in the residential sector (such as lighting, space heating and water heating). Third, there are no reasons to assume that average consumption patterns differ much from city to city in the UK, and the characteristics of individual uses are similar to those in the US and Australia because similar technologies are used for similar uses and lifestyles.

In the UK context, national infrastructure planning takes a scenario-