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\textsubscript{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
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 [5] 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-
based simulation approach and recognises the totality of infrastructure as a system of systems [4]. In this way, it acknowledges and takes into account the interactions and interdependencies between different systems and their infrastructure, e.g. water and electricity. Because demands are exogenous, it has a supply-side bias, and feedbacks from infrastructure performances on population and on demand and other socio-economic factors are not incorporated directly into the framework and model used. This is a shortcoming that the authors of the infrastructure study themselves recognise [4], and that this current study addresses.

2. Material and methods

Urban water and energy systems consist not only of pipes, cables, pumps and other physical infrastructure. Their planning, the demand for their services, the finance involved, among others, are all integral parts of them. Each system is complex in itself, and the combination of two even more so. It contains several feedbacks, components that operate at different time scales, and a range of drivers. Given this complexity, and in order to investigate the dynamics of the urban water-energy nexus, we use a system dynamics approach.

System Dynamics is a semi-formal method for formulating a problem and its relevant context. This modelling method was developed in the early 1960s by Jay W. Forrester and was first applied to industrial processes and supply chains [26]. Since its conception, it has been widely adopted to analyse a very diverse range of problems.

System dynamics (SD) has been applied to both [urban] water systems (e.g. by Noiva [27]) as well as energy systems (e.g. by Feng et al. [28]). Applications to the broad-water-energy nexus exist but are fewer. Zhuang [29] developed an SD model for the integrated management of water and energy resources in the Tampa area in the United States. The WorldWater model developed by Simonovic [30] takes into account cooling water requirements which are considered industrial demand for water. Sahin et al. [31] use SD to simulate the planning, construction and operation of desalination plants for urban water supply in combination with temporary drought pricing in Australia [32].

Chhipi-Shrestha et al. [33] focus on an urban water system with boundaries similar to the ones in this study. Hussien et al. [34] created an SD model to quantify future consumption in the household water-energy-food nexus under a range of scenarios determining growth rates in the model. In both studies, some water-energy interactions are modelled in one direction but feedback appears to be absent, limiting the dynamic behaviour of the model. They show plausibly what goals can be achieved but do not investigate what hurdles lie on the way there nor on what timescale the change occurs. SD models with two-way interactions at the end-use level and their inclusion in systemic feedback were not found in any of the literature studied. An SD model was developed here to test the influence of the urban water-energy end-use interactions.

We chose the geographical boundary to be the extended city, in this case the Greater London Area (GLA), except for the water supply system which may include elements outside of this boundary dedicated to delivering clean water to the consumers within the GLA.

To build the SD model we used the free software Vensim PLE [35]. With the free and open-source Python package PySD developed by Houghton and Siegel [36] we ran the different analyses due to its enhanced functionality over Vensim e.g. with respect to automation.

2.1. High-level urban water-energy system conceptualisation

A high-level Causal Loop Diagram (CLD) which contains the most important components that aggregate several more detailed variables in the final model, is shown in Fig. 1 [37]. It was built from general principles of energy systems (e.g. [38]) and from understanding shaped by the literature on energy systems, water systems and their interactions. The variables are grouped into five categories according to the subsystem they inhabit. The first of these is labelled END USE and consists of the (per capita) demand for end-use services involving water and energy. They intersect for end uses requiring both energy as well as water. The service differs from the actual per capita consumption of water and energy although they have the same units.

The degree to which services can be and are used by citizens affects their quality of life, which is grouped in the SOCIAL category of variables together with population. Quality of life represents how attractive living in the city is in terms of service provision, and it affects the demographics: if service provision is reduced, e.g. as a result of a serious shortage of water, the quality of life will decrease and people will want to leave the city. The positive polarities in the diagram indicate that services and quality of life change in the same direction, and so do the latter and population.

The group of variables labelled WATER relate to the water supply and consumption. Total water consumption depends on the use of services involving water, on the efficiency with which those services are provided in terms of consumption, on the number of people consuming water (population), and on the availability of water. The latter limits the possible water consumption in the city. Growing water consumption creates pressure to increase the amount of water that is supplied to the city, thus leading to a supply augmentation over time, which will eventually increase the availability of water. Factors such as leakage, constraints on withdrawals because of environmental laws and wastewater capacity are subsumed in these variables and not displayed in this abstracted CLD for the sake of simplicity.

When supply is augmented, it increases the effective cost per unit of water provided, due to presumed economic efficiency: if it decreased the cost, the supply option would have already been deployed. Cost increases translate into higher prices to the consumers, pressuring them to reduce their consumption. The decrease in water consumption can come about either through increasing the service efficiency with service levels constant or through a reduction in service levels. The choice depends on how much more service efficiency can be gained, and these potential gains are depleted with actual implementation of options to increase service efficiency.

The variables related to energy supply and consumption are arranged similarly to the water system components in the ENERGY group, but the supply augmentation loops are absent. The reason for this is that in cities in what are considered developed countries (and in many other countries) such as London, there is no effective physical constraint on energy supply due to the global trade in energy resources; and this is not the case for water, which is tied to local and peripheral availability. This group of variables also contains the energy use for the water supply as a supply-side component of the urban water-energy nexus, the product of total water consumption and the energy intensity of the water supply (and implicitly the wastewater system).

The CLIMATE category in this diagram is linked to the ENERGY group only, because energy use is the main contributor to anthropogenic greenhouse gas (GHG) emissions, especially in a city. Greenhouse gas emissions from wastewater sludge are not incorporated in the current version of the model because they are considered small in comparison to the energy-related GHG emissions to which the model is therefore limited. The impacts of climate change on energy and water resources are also important but are outside the scope of this study.

2.2. System dynamics model development

While the CLD is the qualitative representation of the system structure, the Stock-and-Flow Diagram (SFD) is the structure of the system as modelled by sets of differential equations.

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1 The classification overlaps with Chhipi-Shrestha et al.’s [33] for the water, energy and climate/carbon groups, to which we added a group for end-use service demand, and one for the social and demographic dynamics.
The SFD is derived from the detailed CLD but in general additional considerations need to be made in the translation. The reader is referred to appendices A and C for an elaboration on the SFD and a detailed description of the model respectively. What follows is a presentation by subsystem of the most important aspects of the SFD and the model.

2.2.1. End use subsystem

In the model, the consumption of the three resources - gas, electricity and water - is organised by end use. There are six end-use categories, representing the different ways in which resources are used separately and together. These end uses and the resources involved in them are listed in Table 1. Three of the end uses require only one resource. Water-only uses include toilet flushing and cold water use. Electricity-only uses include lighting and electronics. Gas-only uses are shown for comprehensiveness but do not play a role in the current version of the model. Hot water includes all hot water uses, either heated with electricity or gas. Heating refers to space heating, with electricity or gas. Finally, appliances refers to wet appliances such as dishwashers and washing machines.

Demand is conceived of as actual use, be it in terms of service or resource consumption. When a physical limit exists on the availability of water to be supplied, demand will decrease according to its definition in this study. This is a model design decision which sets it apart from the term ‘demand’ in other studies such as Gohari et al.’s [39], where demand is the volume of water that would be used if there were sufficient water available (and that is effectively used if enough water is available). The former is the actual volume of water, or energy in the case of electricity and gas, which is used by the consumer. Service provision is the use or service the user derives from that consumption. It is expressed in terms of equivalent consumption in a reference year. By definition, demand in terms of service is equal to the demand in terms of consumption in that reference year, but can differ at any other time.

An example illustrates this: if toilets used 30 litres per capita per day (lpcd) in 2005, but become 3 times as efficient by 2020, requiring only 10 lpcd for exactly the same function, then the demand in terms of service in 2020 will still be 30 lpcd.

For each end use and resource combination, there are up to three ways by which the resource consumption can change. The first is through a change in total consumption for that resource in response to a price change. In this case service demand is held constant if additional end-use efficiency can be implemented. The change in total consumption of a resource is determined, in absence of changes in the consumption of linked resources or substitutions, by changes in the unit price of that resource using a constant elasticity model [40]:

$$\frac{\Delta Q}{Q} = \varepsilon \frac{\Delta p}{p}$$

where $Q$ is the resource consumption per capita, $\varepsilon$ is the price elasticity of demand, and $p$ is the price per unit. This basic micro-economic
approximation was chosen because of its simple form, considered sufficient for this level of analysis.

The second way for resource consumption for a certain end use to change is through a change in service demand for a linked resource (e.g. a change in energy service demand for hot water leading to a change in water consumption). In order to investigate the effect of the end-use interactions, the effect of these changes can be fixed to zero with a ‘toggle’ variable, effectively decoupling end-use service demands for water and for energy. This enables two distinct scenarios to be studied: one with end-use ‘interactions disabled’, and one with end-use ‘interactions enabled’. In the former, a change in energy or water service demand occurs without a concomitant change in water or energy service demand, respectively.

For energy resources there is a third way by which consumption can change: long-term energy carrier substitution. When the service per unit price of electricity is cheaper than that of gas, electricity will substitute for gas in end uses for which either can be used. The rate of this substitution depends on the relative price difference per unit service.

The change in consumption of a resource is allocated among various end uses in proportion to the share in consumption of each one and depends also on the relative service benefit of the combination of the resource and end use. With a decrease in consumption, the highest relative service benefit uses will be prioritised, whereas end uses with the lowest relative service benefit will have more weight when there is an increase in consumption. This effectively tends to equalise relative service benefits. Relative service benefit is defined exactly in Section A.2.

The implementation in the stock and flow diagram is explained in more detail in Section A.1.

2.2.2. Social subsystem

The social subsystem in the model consists of demographics and quality of life.

The demographics are modelled with a simple homogeneous population model with births, deaths and migration. The birth and death rates are constants, but the immigration and emigration rates depend on a reference value and Quality of Life (QoL), a variable with a value between 0 and 1. It reflects the relative amount of service citizens enjoy. Its calculation is detailed in Section A.2. For low values of QoL, immigration must be low and emigration high, with the extreme case of an immigration rate of zero and an emigration rate of 1 for QoL equal to zero. For QoL equal to one, both rates should be equal to their reference values. A quadratic and an exponential function were chosen as they are elegant and satisfy the aforementioned requirements:

\[
\text{immigration rate} = \text{reference immigration rate} \times \text{QoL}^2
\]

\[
\text{emigration rate} = (\text{reference emigration rate}) \times \text{QoL}
\]

with migration rates expressed in persons per person per year.

2.2.3. Water subsystem

The water system comprises water distribution capacity, water supply (upstream of distribution), the finances of the water system, the availability of water for supply, and a forecast of future demand for resources planning. These are parsimoniously modelled but capture the main aspects of the water sector, with a particular focus on energy use.

**Water distribution capacity.** The water distribution system is modelled as distribution capacity (expressed in litres/day) with an average age. Leakage is conceived of in the model as being solely dependent on the (average) age of the water distribution network. This follows the finding that pipe failures are dependent on the dimensions of the pipes and their age, the latter being considered the most important factor [41]. The pressure in the network and other pipe characteristics are not explicitly modelled: the implicit assumption is that the utility maintains pressure in an optimal way considering quality of supply and leakage losses, and that the influence of the technical specifications of the pipes is negligible compared to age in determining leakage within the range of specifications for replacements. A sigmoid function was chosen to express leakage in function of the average age of the water distribution capacity, with the S-shape satisfying the constraints of very small leakage for new and young pipes, and very high, near 100%, leakage for pipes beyond a certain age:

\[
\lambda = \frac{1}{1 + e^{-\alpha (\bar{\lambda} - \lambda_m)/(\lambda_m - \lambda)}}
\]

where \(\lambda\) is the water distribution leakage rate; \(\bar{\lambda}\) is the average age of the water distribution capacity; \(\lambda_m\) is the midpoint leakage age, the average age corresponding to a leakage rate of 50%; and \(\alpha\) is a scaling factor.

The leakage level is kept at the economic level of leakage (ELL), where the costs of mitigating leakage balance the cost of supplying more water than is used and paid for by consumers. The instrument for this in the model is pipe replacement, and is explained in Section A.3.1.

**Water supply augmentation.** Water supply is augmented beyond what is available in the system at the start of the simulation in response to an expected increase in demand or an expected decrease in availability from the baseline water supply (due to a decrease in environmental flow or elevated environmental flow requirements). The energy intensity of supply increases the more augmentation is in place - reflecting the increasing energy requirements (and therefore costs) of additional water resources.

**Water system finance.** The financial side of the water system is represented in the model in order to reflect the costs of water provision and the resulting water price endogenously. They depend on the amount of supply augmentation, the mains leakage, and the price of electricity. SD has been used by Rehan et al. [42] to model the financial structure and operation of a water utility. Their model however was deemed too complex for use in this study, the main purpose of which is not to represent the water utility in great detail, but to investigate the dynamics of the interactions with the water system. Here, the cost of providing water has two components: one is operational and is proportional to the cost of the energy required to move the water around and to treat it, and the other represents maintenance and is the cost for replacing distribution capacity to abate leakage. This conceptualisation of the water sector finances does not contain capital expenditure explicitly, but we assume this to be included in a levelised form in the operational expenditure through a factor by which the electricity expenditure is multiplied.

2.2.4. Energy subsystem

The energy system has a less elaborate representation than the water system in the model because of the chosen model boundaries: there is no considerable generation of electricity or production of energy in cities similar to London, and in this study energy scarcity is not considered.

The model allows for a long-term substitution of electricity for gas for heat-related purposes in response to changing costs per unit service provided. This is explained in detail in Section A.4.

The price of gas and electricity to consumers consists of two components: the base price, and a carbon contribution. The former is an external variable and can change e.g. depending on the scenario narrative. The latter is the product of the carbon intensity of the energy carrier (exogenous) and the carbon price, which is an endogenous variable (Section 2.2.5).

2.2.5. Greenhouse gases subsystem

The consumption of electricity and gas determine the annual emissions of carbon dioxide, which is the only greenhouse gas considered in this study. A carbon price based climate policy is embedded in the model. It aims at a certain level of emissions in a target year which is still the formulation of official climate change commitments.
for London, although there is an evolution to carbon budgets on the national scale.

The carbon price increases under pressure from a discrepancy between the goal and the forecasted emissions in a target year. The latter depend on the current trend of emissions. The model implementation is explained in more detail in Section A.5.

2.3. Input data

Not all input data required in the model are measured in reality, and even if they are, they are not necessarily reported or available for the chosen geographical boundary which is the Greater London Area. In that case, approximations may be made from national-level data or from studies in similar contexts. In the current setup of the model, only initial values and parameter values are set, i.e. no full time series are specified. Instead, where longer-term time series exist over part of the period over which the model is run, they were used to fix the values of certain parameters in the calibration of the model. The input data and calibration are documented in Appendix B.

2.4. Model testing

We subjected the model to three tests. The first test is for dimensional consistency: do the units of variables in the model correspond to the units of the variables they are calculated from? This can expose modelling errors and takes the modeller through a reflection process. Vensim PLE 35 has a built-in unit check which shows that the model is dimensionally consistent. The second test is structural: does the model behave according to the rules of the part of the world it is trying to model? This cannot be checked exhaustively, but the model must satisfy the facts of the future, of which the response to extreme conditions is one: people will not live in a city where insufficient water is available. The formulation of the migration dynamics as depending on the quality of life ensures that the city population falls to zero when consumption of water or energy is insufficient or zero. Similarly, the population cannot grow infinite because the prices of resources would grow so high as to limit consumption to undesirable levels, inducing people to leave the city.

The third test is historical consistency. This is achieved by the calibration procedure: the historical data agree with the simulation for all indicators shown in Fig. 2 as well as for population. Water consumption observations exhibit more variability due to the lack of actual measurement, but the last point is not an outlier: with increasing meter penetration, water consumption has decreased.

2.5. Sensitivity analysis

How much will the conclusions in this study depend on the accuracy of the model? A sensitivity analysis is often used to answer this question. Because of the multitude of variables and parameters, and the assumptions made in setting values and formulating functional relationships, it is of the utmost importance to investigate the sensitivity of the model results to variations in the structure and parameter settings. In the functional relationships, values were not hard-coded but instead fed by separate parameters, hence a sensitivity analysis on parameters alone also covers the structure. We test the sensitivity of the difference between the two scenarios (one with ‘interactions disabled’, the other with ‘interactions enabled’) using per capita water consumption (a ‘downstream’ variable) and water distribution leakage rate (an ‘upstream’ variable) as response variables, with each quantified for the year 2050. Parameter values were varied by 10% in each direction.

3. Results

The model was run over the period 2005–2050 with a time step of 3 months (0.25 years) which proved to be sufficiently small for model stability while being long enough to reduce computational effort and time. In this present study, the basic scenario corresponds to the parameter values as documented.

3.1. Simulation results

Fig. 2 shows per capita resource consumption for the two scenarios as explained in Section 2.2.1, together with historical observations. Differences are perceptible almost only for water consumption. This happens immediately after 2005, with the ‘interactions-enabled’ scenario being closer to the latest observed water consumption. The standard model referred to hereafter has the interactions enabled.

Water demand decreases until 2020–2030 in both scenarios, and stabilises at lower levels in the end-use ‘interactions enabled’ scenario. Gas demand is on a steady decline to be phased out almost completely by 2030. Electricity substitutes for gas in space heating and water heating uses and therefore electricity consumption per capita increases sharply from 2020 onwards after an initial decline. A more moderate but still upward trend persists after 2035.

The effect of end-use interactions on the upstream water system (including wastewater services) is illustrated in Fig. 3. With end-use interactions enabled, the leakage rate is higher. This is by design, as the leakage rate is kept at the economic level of leakage: the reduced need for more energy-intensive supply expansion, because of lower water demand (Fig. 2), limits electricity intensity and therefore the water cost. The latter is the value of saved water and is hence lower, so leakage mitigation is less important.

Distribution capacity initially increases because of population growth. It then remains stable for one and a half decades as water demand per capita is reduced by an energy demand reduction. Distribution capacity increases again as water demand levels off but population still grows. Without the effect of energy demand on water demand, the required capacity would increase monotonously.

The price trajectories for water, electricity, gas and carbon are shown in Fig. 4. All increase up until 2030, after which the electricity price per unit sets on a downward course, followed by the water price because of its dependence on electricity. The decrease in electricity price towards the end of the period occurs despite a continuous increase in the carbon price, as they become decoupled due to extreme decarbonisation of the electricity system.

Fig. 5 shows the trajectories of the per capita consumption for the three resources and of the quality of life variable for lower rates of decarbonisation, reducing them by up to 75% compared to the standard model. In the lowest decarbonisation scenario, minimal services as defined in the model cannot be provided, seriously lowering the quality of life. This is due of the high price of electricity as a consequence of the carbon price. The modelled quality of life is reduced by more than half compared to 2005 for the lowest decarbonisation rate, affecting the population dynamics with increased emigration and reduced immigration.

3.2. Sensitivity analysis

The analysis of the sensitivity of the effect of the end-use interactions results in Figs. 6 and 7. They show the effects of those parameters the 10% variation of which lead to the 10 largest deviations in either direction. The response variables are the differences between the ‘interactions enabled’ and the ‘interactions disabled’ scenarios, evaluated in the year 2050, for the variables total per capita water consumption and leakage rate, respectively.

For each of the variables the largest variations are caused by the gas demand price elasticity, the initial gas demand for space heating and the ultimate maximum obtainable efficiency for electric water heating. The reference value chosen for the gas demand price elasticity is $-1.2$ through calibration, which is beyond normal ranges ($-0.57$, $-0.2$) (Section B). With such a large value the model is sensitive to the
Fig. 2. Simulation results for 3 variables: (a) water, (b) gas and (c) electricity consumption per capita per day; with end-use energy-water interactions disabled (dashed line) and enabled (solid line). Observations are shown as points for comparison and validation.

Fig. 3. Simulation results for 4 upstream variables: (a) water distribution leakage rate, (b) water supply capacity expansion, (c) water distribution capacity, and (d) annual electricity use of water supply (including wastewater services); with end-use interactions disabled (dashed line) and enabled (solid line).
parameter.

Fig. 6 only shows 5 input parameters, as because of the relatively symmetric response, they represent the 10 largest deviations in absolute value. The response changes are all less than 15% in either direction.

The sensitivity of the end-use interactions effect on water distribution leakage (Fig. 7) is greater. We notice that apart from the top two, the deviations are skewed towards an increase in the end-use interactions effect.

4. Discussion

4.1. The importance of end use

The model results confirm the need to account for the end-use component of the urban water-energy nexus: taking the effects of changes in the demand of an energy resource on that of water and vice versa into account alters the prospect of demand for resources and especially of that for water, which is the least elastic. Water is also the most critical resource on an urban scale as its supply is more dependent on local and peripheral circumstances than energy, be it electricity or gas.

On the upstream side of the water system, the effect of the interactions is even more pronounced. This is the part of the water system which is extensively planned and regulated in a centralised manner, to ensure adequate water provision to citizens and therefore urban water security, with time horizons several decades into the future. The differences in Fig. 3 show that there is a risk of overdimensioning if the end-use interactions with the energy system are ignored, both in terms of distribution capacity as well as augmentation of supply. This indicates that planning approaches for infrastructure expansion and upgrades should duly consider the effects on water demand and water prices from the energy system in addition to population dynamics.

The results apply specifically to London as a case study but the insights can be generalised to all cities with similar characteristics: consumption demand-determined rather than supply-constrained, urban demand dominated by the residential sector, the water-energy nexus dominated by the end-use level in magnitude, and a large and growing population. These characteristics are exhibited by the cities studied in

Fig. 4. Prices for water (in GBP per 10 m³), electricity (in pence/kWh), gas (in pence/kWh) and carbon dioxide (in pence per kg carbon dioxide) in the standard model run.

Fig. 5. Simulation results for 4 variables: (a) water, (b) gas and (c) electricity consumption per capita per day, and (d) quality of life, varying the future decarbonisation rates from 25% to 100% of the original rates.
much of the urban water-energy nexus literature cited here, in countries such as the United States, Australia, the United Kingdom and Western Europe, as well as China.

4.2. Price impacts

As demand for gas decreases under price signals from the resource itself but also due to the increasing carbon price (Fig. 4), the long-term substitution of electricity for gas commences, with the price per potential unit service of electricity falling below that of gas. However, because of the limited efficiency of gas heating, the service provision is reduced, especially for hot water, before gas is substituted sufficiently by electricity. The negative effect on the quality of life persists until falling electricity prices (due to decarbonisation and a high but eventually stable carbon price) allow for an increase in electricity consumption and a corresponding increase in service provision. Despite the large available efficiency for electric heating of space and water, the service initially lost with gas is not entirely recovered with the substitution by electricity. The implicit assumption is that citizens over time become accustomed to a drop in service demand or provision, and in the absence of price signals do not, on average, actively seek efficiency improvements. In the United Kingdom this is consistent with a relative lack of insulation and energy-efficient retrofitting [43] despite the benefits to heating service provision. Efficiency recovery could be introduced into the model as a function of available efficiency and reference and minimum service demands, as an alternative to the current implementation.

4.3. Policy implications

The mechanism of a carbon price is one of several to force emissions down. In the model it is an effective approach by construction: the price increases as long as goals are not on track to being achieved. This policy can probably not translate fully into the real world, and the model results are not proof that such a policy would even be effective as one that permits a decent quality of life. However, carbon-intensive activities will need to be curbed, and low or zero carbon activities promoted. For such policies, a carbon price could be used as a proxy, and the model can be adapted by any user with a different formulation for the setting of that price. Therefore, the emissions policy in the model is representative of what will likely be implemented in reality.

The effects on the quality of life are extreme in the case when the rate of decarbonisation is only a quarter of the reference rate (Fig. 5). Because of the constraints of the model, in which demands only change through price signals which force compliance with emissions targets, quality of life is the only variable which can give. However, this will not be the case in reality: new innovations (with efficiencies beyond the realistic potentials adopted in the model) or adaptation to resource conservation through forced, induced or voluntary behaviour are two ways by which a quality of life, and therefore an urban population, can be maintained at high levels. The extreme situation in Fig. 5 therefore indicates infeasibility of achieving targets with the model assumptions, and does not predict a mass evacuation. It does indicate that decarbonisation (and electrification of heat) must be sufficiently strong and must be a priority of national and international policy.

The results show that pressure on energy demand limits water demand as well as the expansion requirements for the water system. This is the mirror image of the well-known ‘saving energy by saving [hot]
water’. An important implication is that water-demand reduction sce-
arios can piggy-back on already existing energy demand scenarios
consistent with acceptable levels of climate change, such as the global
Low Energy Demand (LED) scenario consistent with 1.5 °C global
warming as well as many of the Sustainable Development Goals (SDGs)
[44].

4.4. Sensitivity and limitations

The sensitivity analysis shows that the model is sensitive to para-
eters related to demand. The most influential of these - the price
elasticity of gas demand - was determined by the calibration procedure
and the resulting value was found to be larger (in absolute terms) than
would be expected from the literature. The only mechanism for demand
to change in the model is in response to price changes, and needs to
cause what in reality may also have in part been a consequence of
regulation. This is all part of the modelling process and highlights the
approximations that must be made to devise a manageable model.
However, these sensitivities do not detract from the validity of the
answers to the questions the model was designed to answer: do the
interactions between a city’s water and energy systems matter sig-
nificantly, both upstream as well as downstream, at the end use; and
how do those systems react under scarcity? The robustness of the an-
swer to the first question is supported by the low sensitivities in Figs. 6
and 7, the latter of which shows that varying 5 out of the 7 most in-
fuential parameters has an increasing rather than decreasing influence
on the effect of the end-use interactions.

Lastly, it is important to bear in mind the simplifications necessarily
made in the model. An important one relates to the time scale. All
variables represent annual averages and thus the model neglects intra-
annual variability, for example with respect to the water system. There,
seasonal variability is important in reality, and water resource planners
work on sub-annual timescales. The simplification here implicitly as-
sumes that there is sufficient storage capacity to level out these varia-
tions, which is not actually the case. In addition, the formulation of
water availability implicitly assumes surface water rather than
groundwater. The financial side of the water system is also very much
simplified. Finally, averages are used for the residential demand for
water and energy: even if the services modelled are demanded by most
citizens, this obscures the heterogeneity in residential consumption of
both energy and water. Nonetheless, given the scope and purpose of the
model, we consider these simplifications acceptable and justified.

5. Conclusions and future work

A system dynamics model was developed to study the dynamics of the
interactions between urban water and energy systems with respect to
the residential sector. It was applied to the case study of London over the
period 2005–2050.

The model is centred around demand for end-use services, from
which the demand for resources follows. Through this approach, it is
the first dynamic model which explicitly integrates the end-use inter-
actions of the urban water-energy nexus. Interactions at the level of the
water supply and wastewater system are also included through the
electricity intensity of its operation. In the model, scarcity of water
resources drives the development of water supply augmentation which is
more energy intensive than the system which is already in place.
Compliance with London’s climate change mitigation commitments is
ensured through a carbon price which is added to energy (electricity and
gas) baseline prices.

The model results show first and foremost that there are consider-
dable differences when taking the end-use interactions into account,
mostly on the water demand and supply side. Per capita water demand
is lower, so that less supply augmentation is required. There is also a
substitution of electricity for gas through electrification of space and
water heating, driven by the lower price of electricity and the greater
efficiency of electric converters. The lower price compared to that of
gas is a consequence of a carbon price in line with urban greenhouse gas
emissions targets, combined with a sharp decarbonisation of electricity
which is exogenous to the model. With low rates of decarbonisation, the
model indicates that quality of life as formulated cannot be maintained at
an acceptable level; conversely, with a decent quality of life but low
decarbonisation of electricity, emissions targets cannot be met in the
urban residential sector.

The model passes three essential tests: historical consistency for
main variables, dimensional consistency, and structural consistency.
However, the sensitivity of the model to certain variables cannot be
neglected, and the results should be interpreted with this sensitivity in
mind. Nonetheless, the qualitative outcomes of this study are robust
even to changes in the most influential parameters: end-use interactions
have an important effect, and electrification of heating and dec-
arbonisation of electricity are necessary to comply with climate change
mitigation ambitions and water availability constraints.

In future work, the model should be expanded to cities in emerging
economies, where there is more stress on the local water system and the
configuration of the end use is different as local storage is required to
cope with an intermittent water supply. A consequence of this is that
operational energy use for water supply is distributed among suppliers
and users who must provide pressure themselves. In addition, the ap-
lication of the model to large cities instead of megacities such as
London can yield insights regarding the influence of scale on the urban
water-energy nexus.

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Appendices A–C. Supplementary material

Supplementary data associated with this article can be found
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