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A Review of Urban Water-energy Linkages in End-use: A Call for Joint Demand Studies

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Authors' contributions

Author SDS performed the literature review. The manuscript was written by author SDS with contribution from both co-authors. The work presented is a part of SDS's PhD that is supervised by authors AM and JK. All authors read and approved the final manuscript.

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ABSTRACT

Aims: A literature review to show the importance of combined water and energy demand end-use studies and to illustrate techniques that can be applied for these analyses.
Study Design: A review of energy-related water end-use and water-related energy end-use studies.
Place and Duration of Study: Cited studies on urban water/energy use are mainly based on the work done in the UK, Australia or the US, which has been completed over the course of the past decades but mainly in recent years.
Methodology: An overview included studies focused on the different energy and water end-uses in cities, their quantification and methods for estimating those end-uses using aggregate indicators such as total energy or water use. Particular focus was given to the estimation of water-related energy and energy-related water.
Results: Up-to-date research has been focused on the disaggregation of the actual end-use for energy and for water separately, estimating the corresponding water/energy use. There is considerable uncertainty about the joint end-use of water and energy, and the implications of this linkage for the overall water and energy supply at the city level.
Conclusion: Combined water/energy end-use is an important end-use component. Water and energy end-uses have been studied extensively in isolation using empirical approaches. However, there is a need for empirical studies of the combined water/energy end-uses that can greatly reduce the uncertainties on the feedbacks between the two systems, and benefit both utilities and end-users.

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1. INTRODUCTION

Cities are centres of the human capital, where the demand for services is highly concentrated. An important part of these services, crucial to modern urban living, requires energy and/or (clean) water. Illumination, hygiene, comfort, hydration, information, mobility are some examples. Vast infrastructure exists within the city and far beyond its borders to enable the provision of those services, and the area from which resources are drawn is much greater than that of the city.

With increasing population and urbanisation, the demand for services is on the rise. This is putting freshwater resources under pressure in many parts of the world. On the other hand, we ourselves are putting pressure on the energy system, as it is widely recognised that limits need to be imposed on the amount of fossil fuels that are burnt or converted in order to avert dangerous levels of climate change (with a high probability) [1].

In this context, water and energy resources are linked in many ways. Thermoelectric and hydroelectric power generation reduce the availability of water for other uses: e.g. in the United States, in 1995 cooling water alone represented 3.3% of all consumptive uses, and over one fifth if agriculture is excluded [2,3]. Of the United States' primary energy use, 12.6% is estimated to be related to direct uses of water (including end-uses and treatment) [4]. Urban water systems require energy to pump water and in wastewater treatment and distribution, as well as for supply expansion through e.g. imports or desalination. Global warming is changing the hydrological cycle, increasing the intensity of both droughts and floods. In turn, these changes can decrease electricity generation potential [5] and have effects on the broader energy system [6].

The combined water and energy use in cities represents a considerable share of national energy and water supply in countries such as Australia and the United States. Water-related direct electricity and gas use in Australian cities are estimated to constitute 13% and 18% respectively of average national use on a per-capita basis, and 9% in terms of primary energy [7]. In the United States, in 2010, 57% of public water supply went to the mainly urban - 82% of the population was urban [8] - domestic sector, corresponding to (in terms of withdrawal/flow) about 7% of all water uses (including also the commercial sector, industry, mining, thermoelectric cooling, irrigation and livestock uses) [9].

The linkages between water and energy on the supply side of each are significant and can be great for a single unit such as a nuclear power plant or a pump in the ring main system of London. At the end-use level, the linkages for a typical unit (such as a residential boiler) are orders of magnitude smaller in absolute terms. However, when the end-use services are aggregated, the linkages turn out to be far greater than those at the supply stage. Several studies have found this on the water side, with end-use being responsible for 86% of direct water-related energy (energy consumed for water-related purposes such as pumping and water heating) for all sectors in Australian cities [7] and 89.1% in South East Queensland [10], and 96% in UK homes [11].

The same holds on the energy side: energy-related water in end-use (the water used at the end-use in conjunction with energy e.g. for a hot bath, for laundry in a washing machine, for warm cooking) is larger in aggregated volume than the water consumed in the supply chain (from primary to final energy) to deliver the amount of energy. A simple example from the domestic sector illustrates this: bringing a litre of water to boil from 20ºC requires about (100-20)*4.186 kJ = 335 kJ = 0.093 kWh. Assuming an end-use efficiency of the water kettle of 85%, a (consumptive) water intensity of wholesale electricity of 1.02 L/kWh [12], and transmission and distribution losses equal to 20%, the cooling water consumed to boil the litre of water in the UK would on average be 0.14 L. Cooling water consumption is the greatest component in the water consumption of the electrical energy supply chain making up over 80% of it [13]. As most energy-related water in domestic end-use requires less energy per unit volume, and as the water intensity of fuel (such as natural gas) supply chains is generally lower than electricity's, this illustrates the significance of the domestic end-use component of the energy-related water.

Several studies have estimated the magnitude of the supply-side linkages, both for the water intensity of energy supply [14–16] as well as for the energy intensity of (municipal) water supply [16–18]. Although there is considerable variation among the estimates for different locations, these can be largely quantified and explained by local circumstances. However, the end use, and residential end use in particular, is much more granular. Even though the technological characteristics are likely less site-specific than for the upstream linkages, the differences in behaviour and modes of operation create variation and uncertainty of a different nature, and therefore make the end-use linkages less quantifiable and explicable.

There is, however, a disconnect between the importance of water-energy linkages at the end-use and the knowledge about them. This disconnect is also apparent when energy or water are regarded separately: end-use is the main leverage point for systemic efficiency in each of those systems, yet it is the most difficult to measure because of its granularity. When looking at the two systems in isolation at the end-use stage, the essence of end-use is ignored: water and energy are in demand because of the services they enable. Many of those services are neither a purely water nor purely energy service, but combined services with crucial cross effects. Knowledge of only water consumption by service or only energy use by service is not sufficient to understand the demand for all water and energy services. The aim of this study is to review the current understanding of water and energy at the end-use, as well as their linkages, and to highlight the importance of and potential approaches for linking both research streams.

The scope of this paper is limited to the residential sector, for the reasons that it represents the largest demand category in urban settings, that the services demanded are similar to those in the commercial sector, on which less has been published, and that there has been little comprehensive research on end-use linkages in the industrial sector [4,7,10], although they have been estimated [4]. The industrial sector is also much more heterogeneous in terms of users and therefore does not lend itself to a general approach. The context of a developed country, with full access to piped water, is implicit.

Fig. 1 is a conceptual representation of the problem. On the left and the right are the actual water and energy uses on a household scale, with their actual interactions indicated as arrows between them. Both are determined by contextual factors such as the environment of the household, their behaviour, the technical configuration of the local water and energy system, socioeconomic variables, etc. Both water use and energy use can be measured and estimated with some level of accuracy, symbolised by the dashed box slightly offset from the actual use. The offset indicates that the quantification and characterisation are not perfect. From the measured/estimated use of one resource, with parameters abstracted from the estimated end use context, the use of the other resource can be estimated with water/energy end-use models. However, the resulting estimate will be less accurate than it would have been had it been measured as well. This is indicated by the larger offset of the modelled estimates.

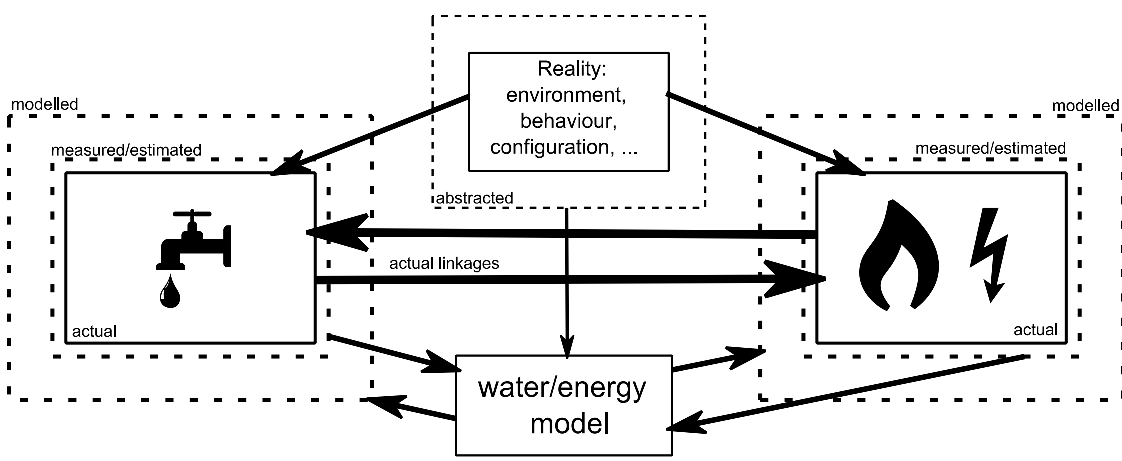

Fig. 1. Water-energy interactions in reality and in modelling

As long as the use of one resource (water or energy) is modelled from a measurement or estimate of the other, there is necessarily an amplified uncertainty about the actual linkages. Reducing this uncertainty is imperative for creating models that are fit for detailed scenario modelling.

Section 2 reviews the understanding about energy end-use and the methods involved. Section 3 discusses this for water demand. Finally, section 4 highlights what has been done so far to understand water-energy end-use linkages, and demonstrates the importance of this area for future water-energy urban nexus analysis.

2. ENERGY DEMAND

Commercial energy is used for a broad range of applications in the modern urban household. Natural gas is used for cooking, for space heating and to heat water for consumption. Oil is also used sometimes for the latter two. Electricity is a highly versatile energy carrier and apart from straightforward heating applications, is used to power electronics and provide information, to illuminate, and to provide mechanical power for several tools and appliances.

However, to both end-users and the utility companies it is quite unclear what fraction of energy consumption is used for which service, and when the energy consumption for this service occurs. Fuels are used mainly for heating, but how much for heating food, for heating shower or tap water, and for heating the space is a guess in most cases. The attribution of electric energy to end-use services is even more problematic because of the myriad of uses.

With the traditional system of monthly billing based on monthly or annual readouts of meters, information about energy consumption is highly aggregated, over time, uses and users: there is little or no more precise information on when energy was used, what for and by whom. Therefore, the potential of this information to inform end-use efficiency decisions is very limited. Estimates are possible but they require additional information about the appliance stock, environment and behaviour.

The importance of having more resolved, disaggregated information on energy end-use, particularly in the residential and commercial sectors, is widely recognised [19]. There are benefits to all actors involved: utility companies can target efficiency programs better, end-users are more aware of how their behaviour affects their energy use through appliance use or thermostat settings [19], and the energy modelling community has better data for calibration [20].

At the level of a single end-user entity such as a household, three main techniques exist to infer the energy consumption by end-use [19]:

- Surveys of the appliance stock and usage patterns by end-users. Combining this information with that from other households allows rough estimates of consumption by end-use.
- Distributed direct sensing: appliances are individually monitored for their consumption. This method is costly but highly accurate.
- Single-point sensing: the total consumption over time is measured, and additional attributes inform the break-down by appliance.

With increasing computational capacity and high-resolution measurement devices, the last method has gained a lot of attention most recently, with data from the first two methods informing the algorithms. Single-point sensing is also referred to as Non-Intrusive Load Monitoring (NILM), inspired by George Hart for electricity consumption [21]. NILM for electricity is the deduction of which appliances are drawing or not drawing current, from the aggregate electric power signal. By extension, NILM is used to derive energy consumption over time of different appliances, and can thus be used to attribute energy to the different uses.

NILM has received most attention with respect to electricity as electric smart meters are diffusing into more households and are allowing electricity use to be monitored at high temporal resolution. Several algorithms exist that differ in the quantities measured (potential, current, active/reactive power), the sampling frequency and the method to identify active appliances [19]. A toolkit called NILMTK (NILM Toolkit) has been developed to compare the different approaches on accuracy [22]. Classification accuracies for single-point sensing upward of 80-90% have been achieved [19].

In the residential sector, (natural) gas is the other major energy carrier. Natural gas is mainly used for heating, but through several methods (such as an open flame for cooking, a fireplace for space heating, or enclosed in a boiler system), the relative consumption of which cannot be derived from monthly or annual readings. Apart from directly measuring each fixture, NILM methods also exist for gas consumption, e.g. based on sound waves with a reported accuracy of over 90% [23].

These energy disaggregation methods can be used to obtain information on how much energy is related to water use at the single household level. Water-related end-use energy is a considerable fraction of the total household energy consumption, with estimates ranging from 14% to 50% for water heating alone (excluding pumping in dishwashers and washing machines) in different studies cited by Vieira et al. [24]. In the UK, the fraction is estimated to be 18% [25], or about 16% in monetary terms as a fraction of the combined energy bill [26]. However, the energy use in itself does not provide complete information on water-energy services. Without knowledge of the volume of water in each service, it is not possible to gauge service efficiency and gain a proper understanding of the effect on energy consumption of water efficiency or conservation measures.

3. WATER DEMAND

Similar to the energy end-use disaggregation, there is a lot of interest in water use disaggregation. Like electricity and natural gas consumption, water use is metered with monthly or yearly intervals, or not at all, which is still the case for about half of the households in the United Kingdom [27].

In the water sector, end-use disaggregation is better known as micro-component analysis [28]. Over the past decades several studies have been performed on consumption by micro-components in samples of households, based on surveys and diaries, measurement of water consumption over time, and recognition of the consumption signatures of the different micro-components [29–33]. New methods for NILM of water consumption are being developed, e.g. based on pattern recognition in pressure waves [34] or in vibrations of the piping [35]. Micro-component studies are becoming more important as water companies are encouraged to perform them in order to have a proper understanding of what water is used for [29]. The advent of so-called water smart meters, which allow the monitoring as well as the relaying of water consumption data at high temporal resolution and at the household scale, and their growing deployment, offer possibilities to better understand how water savings can be achieved through insights into behavioural and other drivers [33]. Cominola et al. studied the benefits and challenges associated with water smart meter use based on a comprehensive review [33].

The aforementioned studies have provided a detailed overview of household water use. For the average UK household, a main water use is toilet flushing, comprising almost a third of domestic consumption [28]. About 50% of the total water end-use was reported to be linked to the energy use through showers, baths, dishwashers, washing machines, and cooking or washing (kitchen sink) [28]. A similar breakdown was found for Australian households in East Queensland, where the share of toilet flushing is however about half that in the UK study [30]. In a California study, indoor water use breaks down roughly the same but with a larger share of perceived leakages (including part of swimming pool filling water) at almost 20%; and general outdoor water use (with which little or no end-use energy is associated) is much larger, on the same order of magnitude as indoor use [31], although this result is for the entire residential sector and outdoor use will be smaller for the more central areas of cities.

The water-energy linkages at the end-use are clearly very important from both the water and the energy perspectives. In the literature there is a significant amount of information about useful indicative reference values for energy intensities of different water uses, especially for the residential sector, as shown by several studies and reviews [18,36,37]. Through their Water Energy Calculator, the Energy Saving Trust have estimated water-related energy in UK households based on self-reported household characteristics and behaviour, and on a set of assumptions regarding e.g. temperature and volumes [26]. However, exact energy consumption does not appear to be empirically determined in studies based on empirical micro-component analysis [30,38,39]. The energy for hot water is estimated using relatively simple relationships based on the water volume, inlet, outlet and air temperatures, system type, and estimated losses. Mechanical energy uses for water are not considered in many studies. Although the energy models applied to the water end-use data will estimate the energy consumption with some level of accuracy, household-specific and behavioural variables are expected to have significant influence on the actual energy consumption through e.g. thermostat settings, heat losses or faulty operation such as a circulation pump which is constantly on instead of being thermostat-controlled [19]. These factors add to the variation and uncertainty on the energy intensity of different water uses due to modelled technical specifications alone, estimated at between 20% and 50% in an Australian study [30].

4. JOINT ENERGY-WATER DEMAND

The lack of actual water end-use data in energy end-use studies, and conversely of actual energy end-use data in water micro-component studies, contrasts with the importance of the end-use linkages between energy and water (one study does consider the temporally resolved demands for electricity and water, but does not link them across uses [40]). The arising uncertainty in end-use estimations has adverse effects on planning, e.g. efficiency measures in new developments might not materialise as expected so that jurisdictions may miss climate change mitigation goals [30]. As water use is a determinant of energy use and vice versa through these linkages, it is also logical that both be combined in end-use studies. This section discusses the benefits of having more linked end-use data on water and energy consumption, instead of separate data for energy and water. Obviously, disaggregated water or energy use information in itself already has great value as demonstrated in the previous sections.

Detailed linked data avail both end-users as well as utilities. For residential customers, the benefits include an increase in awareness of the effect of their behaviour on water and energy use, and more accurate operational cost prediction. A study showed that feedback on shower use leads to a statistically significant reduction in water consumption only when the energy consumption is also reported in addition to water use [41]. Linked end-use data also allow customers to obtain total operational cost data of the actual service. It can put a precise price on the service of hygiene through showers, just as most end-users know the cost of individual mobility by petrol station costs, thus incentivising them to save on mobility. Finally, it can highlight abnormally high energy or water consumption for a particular water/energy service, such as a thermostat set too high or a faulty one, which may not have been noticed from the end-use energy breakdown itself.

For utilities, reducing uncertainty on the end-use linkages enhances the existing benefits of integrating water and energy demand side management. Successful programmes exist in the United States that integrate water and energy management through collaboration between energy and water utilities, by pooling the costs (e.g. one in-person visit for water and energy readouts or installation) as well as the savings (from direct and indirect water and energy savings) [42,43]. Empirical water-energy end-use data reduce the uncertainty on estimated savings, and therefore the risk and total cost of the project. This is also very important with respect to planning to meet future demand, as costs from headroom and excess capacity can be reduced.

Moreover, joint energy and water end-use data can be used to derive quality aspects of the water such as the temperature. By considering the energy and water balances of a household over time, and given accurate information of the relevant water- and energy-related appliances and their configuration, the temperature of the water leaving a household could be determined within bounds. This can inform developers of the potential of heat recovery either in the household or in the broader system. For example, the information could be integrated in the water source heat map layer of the National Heat Map of the UK Department of Energy and Climate Change (DECC), to estimate the local and distributed heat from non-natural discharges which is currently not included (in addition to estimating water heating demand) [44]. Payback times have been estimated from 2 to 7 years for heat recovery from domestic showers and dishwashers, and 5.8 years for one municipal project [45]. As energy becomes more expensive, it is expected that more of the heat recovery potential will be utilised, with wastewater temperature estimates benefiting the development process.

Finally, as mentioned in the Introduction, a benefit of combined empirical water and energy end-use studies is the potential to improve water/energy models. This is useful e.g. in cases where modelled energy and water reductions have not materialised in new low energy/carbon houses in part because of behaviour and hot water demand [40]. With more comprehensive models for estimating linked end-use, scenario-based models would provide greater confidence in the modelled demand for both energy and water, e.g. when one or the other resource is constrained.

5. CONCLUSION

This paper presented the current understanding of water and energy consumption in end-use for the urban residential sector, and the important linkages between them. So-called smart metering of both systems is slowly becoming more commonplace, allowing for real-time estimation of individual uses through non-intrusive load monitoring (NILM). Research in NILM focuses mainly on electricity, but extends into gas and water consumption applications. Though energy and water use disaggregation by themselves have merits, combining them can reveal the actual linkages and can inform energy-for-water models. Household-level water-energy information can raise awareness and induce savings in end-users. For utilities, it highlights where savings are possible, and reduces the risk in planning. It can also inform the estimation of other quantities, e.g. relating to water quality. Finally, the improved models benefit the quality of future demand estimations and scenario analyses.

Key messages from this review are:

- Innovative ways are being developed for non-intrusive load monitoring for both water and energy consumption.
- There is a need for simultaneous studies of water and energy end-use to reveal the actual linkages.
- Water and energy demand side management is more cost-effective when utilities collaborate.
- Empirical data on end-use water-energy linkages reduce uncertainty for planning and investment in efficiency or demand side management.
- Information about water quality (temperature) can be derived from detailed energy and water data.
- Combined demand data inform better end-use models for improved scenario analyses.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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