The connection between water and energy in cities: a review
S. J. Kenway, P. A. Lant, A. Priestley and P. Daniels

ABSTRACT
We have only rudimentary understanding of the complex and pervasive connections between water and energy in cities. As water security now threatens energy and economic security, this is a major omission. Understanding the water-energy nexus is necessary if we want to contribute to solving water and energy issues simultaneously; if we want to stop moving problems from one resource dimension to another. This is particularly relevant in the Australian context where energy use for water supplies is forecast to rapidly escalate, growing around 300% from 2007 levels, by 2030. This paper presents a literature review with an aim of characterising the research to date with a particular focus on cities, the major centres of consumption and growth. It systematically analyses a wide range of papers and summarises the diverse objectives, dimensions, and scale of the research to-date together with knowledge gaps. There are many major gaps. These include energy use associated with water in industrial and commercial operations as well as socio-political perspectives. A major gap is the lack of a unifying theoretical framework and consistent methodology for analysis. This is considered a prerequisite for quantitative trans-city comparisons.

Key words | water energy nexus, review, urban metabolism, cities

INTRODUCTION
Substantial impacts from climate change are being felt in Australia due to altered reliability of urban water supplies, longer droughts and increased flooding (Howe et al. 2005; Bernstein et al. 2007). In 2006–2007, Australian capital cities alone spent $2 billion for new water infrastructure to mitigate climate change. This is twice the previous record for capital works expenditure in the last 100 years and represents a quantum change in approach. Over the next 5–10 years at least a further $30 billion (nearly $2,000/person) will be spent upgrading to more diverse and climate-resilient supplies (WSAA 2008).

Most new sources of water, including desalination, reuse and rainwater tanks are significantly more energy intensive than traditional sources. Energy use by water utilities in Australian capital cities is anticipated to grow between 130 and 200% above existing levels by 2030. This assumes a 25% population growth to this point in time, and that residential water consumption rates remain at 225 L/(cap*d) (Kenway et al. 2008). However, if water use returns to around 300 L/(cap*d), and existing yields diminish (WSAA for example suggested a 25% reduction by 2030) then energy use could grow by up to 600% above 2006–2007 levels. This is because the volume lost in reduced yields, and the volume required for additional consumption, would need to be provided from new sources which are likely to be far more energy-intensive.

While Australia is yet to commit to a firm greenhouse gas emissions reduction target other governments have goals of reducing emissions by 80% by 2050. If Australia adopted this, a 25-fold gap could exist between the trajectories of water-related energy use (growing say 500%) and desired emissions to 2050. Clearly this creates a problem for a water sector eager to contribute to greenhouse gas abatement efforts and will require significantly more effort than purchase of green energy alone. Understanding the links between water and energy, particularly in urban systems, will help the water sector make a wider contribution to minimising urban systems energy use. Despite the significance of the connection, many current water policy positions and water strategies ignore energy issues entirely, as energy strategies likewise ignore water issues (Marsh 2008).
What is the water-energy nexus?

Despite its common usage, definitions of the ‘water-energy nexus’ are scarce. A suggested broad definition is that the water-energy nexus addresses the interconnection or cause–effect relationships between water and energy. That is, a change in one leads to a change in the other. For example, energy is typically required to provide water, and water is typically required to produce energy. An increase in water use requires more energy, both to supply the water and treat the wastewater, but also often in the ‘use’ itself, for example for heating shower or tap water. The demand for more energy in turn requires more water.

There are also often connections between water and energy through other products which require large amounts of water and energy to produce such as food and fibre. A change in food consumption patterns leads to changes in water and energy consumption, and hence production. Because water and energy pervade every aspect of ecosystems, human systems and economic activity, the connections between water and energy are everywhere: energy is a ‘universal link’ in nature and society (Smil 2008).

Why focus on the connections within urban systems?

Knowledge of the links between water and energy in cities will help find solutions which address the root cause or the drivers of consumption. Such understanding will help us ensure that in addressing a problem (e.g. water supply) we do not simply shift a burden to another resource dimension (e.g. energy use).

Quantifying the diverse links between water energy is necessary for us to understand the implications of investment decisions and actions. Knowing the relative impact of different strategies, including the cause-and-effect chain will help identify solutions that simultaneously reduce water and energy use.

Understanding the links between water and energy also identifies important research and development directions and opportunities for technological and management innovation (Proust et al. 2007). Where should we invest in technology development to help address water and energy at the same time? Individual solutions that achieve this, yet stimulate economic growth, will foster the technologies and help find solutions that will work into the future.

Method adopted

Literature search and review was the method used to prepare the paper. Particular effort was invested in seeking papers of broad scope such as other literature reviews (e.g. in Thesis related to the topic), relevant book chapters and national or state-level assessments of the connections between water and energy. An effort was also expended to try to identify studies which quantified the connection between water and energy. While it is unlikely that all studies were identified, the review is thought to have a reasonably representative sample from the perspective of connections between water and energy in cities. Given that the author's background is from the water sector, a potential blind spot is in the consideration of studies from the energy sector. In a partial effort to address this weakness, additional references from an energy-side literature review and analysis (Marsh 2008) were included.

A literature review by Marsh (2008) used integral theory to identify that a wide range of objectives and dimensional foci have been applied in water-energy research. Similarly, studies covering a range of scales from the micro to the macro have been undertaken (e.g. Retamal et al. 2009). These perspectives were developed into a structure against which the nexus could be considered, then used to consider the various studies.

RESEARCH UNDERTAKEN AND GAPS IDENTIFIED

Substantial research on the water-energy nexus has been undertaken internationally (Table 1). In the United States there has been a particular drive from energy suppliers and related interests to understand the impacts of water supply and use on energy consumption and security. Klein et al. (2005) note that the total ‘water-related’ consumption of energy in California is large: 19 and 32% of state-wide electricity and natural gas use respectively together with over 80 million gallons of diesel. This amount includes a wide definition of ‘water-related’ energy. It covers all energy used to transport and treat water and wastewater to all users including, residential, industrial, commercial and agricultural purposes.

Australia has also been very active. However, the work has been driven more from a water-security rather than energy-security perspective. Studies have also been undertaken in Europe and Asia however not as many. It appears likely that studies on the inter-connection between water and energy have been driven by locally specific circumstances such as energy or water crises. Now that global energy (carbon) markets are emerging, and water-resources limits being reached, the drivers for combined analysis of water and energy are strengthening.
<table>
<thead>
<tr>
<th>Objective of the research</th>
<th>Dimension of the research</th>
<th>Scale of research</th>
<th>Number of Papers</th>
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<tbody>
<tr>
<td>Water/wastewater infrastructure impact on energy use</td>
<td>a,b,c,d,k,o,w,t, v,x,y,ab,ac, aa,ae</td>
<td>o,x,ad</td>
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<td>Water use:</td>
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<td>• residential impact on energy use</td>
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<td>m,s,x,z</td>
<td>13</td>
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<tr>
<td>• agricultural impact on energy use</td>
<td>g,h,l,c</td>
<td>c,i,j,z</td>
<td>8</td>
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<td>• industrial/commercial impact on energy use</td>
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<td>Energy infrastructure impact on water use or flow</td>
<td>o,e,x</td>
<td>o,e</td>
<td>4</td>
</tr>
<tr>
<td>Number of Papers</td>
<td>24</td>
<td>18</td>
<td>9</td>
</tr>
</tbody>
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Generally well studied | Isolated studies | Major research gap

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d: Cohen et al. (2004b) (San Diego, Scenario Analysis, in Marsh 2008).
h: Cohen et al. (2004c) (Westlands Water, USA, Deterministic Model, in Marsh 2008).
m: Hansen (1976) (Denmark, economic/elasticity).

The objective, dimension and scale of the various research efforts have varied considerably as shown in Table 1. These factors are now explored together with the main themes emerging from the work.

**Objective of the research**

A large number of studies have considered the influence of water or wastewater infrastructure on energy use, primarily with a focus at the scale of water system, building or city. Even more studies have considered energy aspects of water system components (e.g. energy recovery from wastewater or hydro-power) however these are not discussed here due to the focus of the analysis. Another major focus was on the influence of residential water use on energy consumption; however this was generally at a smaller spatial scale such as individual buildings or appliances (e.g. clothes washers or rain-water tanks). A consistent message emerging from these studies is that energy for operating conventional water systems is significantly higher than the provision of water and wastewater services (Cohen et al. 2004; Klein et al. 2005; Arpke & Hutzler 2006). Consequently, hot water conservation can have significant energy implications.

A major gap is evident with regard to the influence of industrial and commercial water use on energy flows. This is particularly relevant considering Klein et al. (2005) observed that energy associated with industrial and commercial water use comprises a significant proportion of total ‘water-related energy’. Additional weight for research in this area is that Kennedy et al. (2007) identified that that industrial process improvements led to increased efficiencies in the metabolism (water, energy and materials use efficiency) of Toronto. The lack of detailed studies in this area may be due to issues of complexity, non-uniformity and commercial sensitivity of the data, processes and technologies involved.

A small number of studies were observed addressing the agricultural impact of water use on energy use. These were typically undertaken at catchment, state or national level. The movement of virtual (embedded) water, e.g. in agricultural products, could also be considered to analyse the water-energy nexus in part. Only a few of the reviewed studies focused on this issue. Understanding the water-energy balance with food-producing systems at a range of scales from cities through to households is a major gap.

Fewer studies considered the influence of energy infrastructure on water use. Most of these considered the influences at a state-wide level. Very few studies considered the nexus from more than one perspective.

**Dimension of the research**

Various studies have considered one or more dimension in relation to the nexus (Marsh 2008). These include the influence of technology (e.g. what happens when our water or energy infrastructure changes?), the environment (e.g. what are the in-stream or air quality implications of options?), economics (e.g. how does pricing affect consumption patterns?), social influences (e.g. how are stakeholders affected?) and political or legal factors (e.g. what are the institutional constraints to moving forward?).

Because these diverse factors can influence water and energy use, they also influence the linkages at any particular point in time or space. For example, Hansen (1996) identified that energy price has more impact on water conservation practices than does water price, particularly when water use is primarily indoors. Social factors including demographics, income levels and household expenditure all influence energy and water consumption (Lenzen et al. 2004). Legal and political factors and reporting boundaries influence incentives for utilities to conserve water and energy. For example, Klein et al. (2005) concluded that nearly all the 2006–2008 energy and demand reduction goals of the California Energy Commission could be achieved by simply allowing energy utilities to realise the value of energy saved for each unit of water saved (e.g. to co-invest in water use reduction). Considering this and Hansen’s analysis (1996), the influence of combined water and energy legislation and governance appears a substantial and challenging knowledge gap. How do we plan for least cost water and energy strategies? Do we consider only the perspective of utilities? Consumers? The wider community? Consideration of these dimensions helps identify and quantify the cause-and-effect chain of water and energy interactions.

The majority of studies focussed on technological aspects of the water-energy nexus. Different technologies for energy production and water production abound. They also use water and energy at different rates (Diaper et al. 2007; Marsh 2008; Retamal et al. 2009). Technologies which use water (e.g. clothes washers, dish washers, steam cleaners) almost always use energy too. Continued consideration of the influence of technologies is warranted because (1) changes in technologies will change the connections...
and (2) understanding these linkages will help us achieve desirable changes by design.

Many technologies are now explicitly being designed to reduce energy use. Examples include low flow shower heads and efficient appliances (Sydney Water 2006), air-cooled, rather than water-cooled (waterless) Wok Stoves used in the Asian food industry (Kenway et al. 2007), connectionless steamers which are used in the food preparation industry and do not use and discard hot water as steam (Larabee & Ashktorab 2007). Technologies which help cities reduce water and energy simultaneously could offer tremendous scope for uncoupling the water-energy nexus in cities. They also appear to offer significant business opportunity in a carbon and water constrained world.

The environmental dimension has been reasonably well covered in water-energy nexus studies. However, economic implications are considered by only a handful of studies. This is a major gap considering the significant financial implications of water and energy linkages mentioned in the introduction. There is an even bigger gap in studies which consider the social, political or legal dimensions of the nexus. The brave-hearted could consider such a study in the industrial or commercial arena.

**Scale of the research**

With regard to spatial scale, the reviewed studies appear to be distributed more evenly than they are with regard to objective or dimension. A range of studies have considered water and energy interconnection in appliances, households, buildings, facilities, catchments, cities, states and nations. No specific global studies have been found with the exception of studies assessing the impact of climate change on water resources.

Very few studies address, or even mention, the issue of temporal scale, when considering the water-energy nexus. Possible exceptions are studies addressing water-resource allocation for power provision optimisation, and meeting other user needs (Tonkes 2009). There is anticipated to be vast substantial work needed in this area considering influences at the sub-daily through to decadal scales.

The omission of temporal studies is substantial considering the significance of peak load to energy pricing and sizing of infrastructure. Small shifts in peak electricity demand can lead to rapid and major increases in the prevailing price of energy supplied to the grid. For example, a relatively small (500 MW) shift in energy demand can lead to a price rise in energy supply to the grid from $1,000/MWh to over $10,000/MWh (Tonkes 2009). Shortages of water have affected power supply reliability in Australia (Marsh 2008), France and the United States (Hightower & Pierce 2008). Water scarcity also contributes to increased baseline electricity costs. It is increasingly clear that water security underpins energy and ultimately economic security.

**Collaboration between the water and energy sectors would help**

Marsh (2008), Retamal et al. (2009) and Cammerman (2009) all observed the lack of, and need for, water and energy sector co-involvement in nexus studies. This would help design studies which spanned multiple objectives. There appears to be significant opportunity for cross-over of data, skills and knowledge. Involvement of both sectors simultaneously may help identify interdependencies as well as help address peak load issues which are obviously critical to both sectors. In particular potential savings on peak loads of water and energy (around which much of the infrastructure for both sectors is designed), could also prove fertile research ground. Such analysis is likely to be necessary to enable optimisation of infrastructure for water and energy simultaneously.

Many water-energy studies focussed predominantly or solely on electricity rather than the full spectrum of energy sources (e.g. gas, diesel, petrol). Similarly, many studies did not take analysis through to fuel-related greenhouse gas emissions and/or fugitive greenhouse gas emissions. This has an obvious bearing on the comparability of analysis results.

**Combined governance**

Water utilities often provide energy too. While some are energy providers in their own right (e.g. Los Angeles Power and Water, San Francisco Public Utilities Commission and ACTEW AGL in Canberra, Australia) many smaller water utilities have hydropower plants or methane-driven co-generation at wastewater treatment plants. Klein et al. (2005) noted that water utilities have the capacity to move substantial load outside peak periods if they view their water storages as an energy resource. He also indicated that peak energy load could be reduced from demand periods in some systems if greater storage of treated water was practiced. This is because it would minimise the need for energy for water treatment during peak periods.

No studies were identified which considered variability in energy consumption of urban water systems over time, for example in response to drought conditions or diminishing groundwater supplies. Part of the reason could be data
availability. This is because pipes need to be sized to carry peak flow (largely for fire-fighting), even if it is only for short durations. Consequently, from the perspective of managing the combined infrastructure, approaches which reduce peak energy or water demand may have additional reasons for uptake. While the opportunities for co-managing water and energy through their temporal variations appear numerous, no study was found that considered this in any detail.

**Urban metabolism provides a guiding theoretical and analytical framework**

Urban metabolism appears to provide a, if not the, conceptual framework necessary to organise our understanding of urban systems (Decker et al. 2000). At its simplest, the concept considers the mass balances of all materials, water and energy of urban systems (Sahely et al. 2005). Water is the dominant material moving through cities even when river and stream flows and virtual water are excluded. For example, in 1965 Wolman identified that centralised flows of water comprised more than 95% of the mass balance of cities followed by fuels and food. It is possible that water analysis, concepts and modelling may help define the urban boundary. For example, the population connected by a reticulated water network could comprise a relatively definite boundary.

Others have identified the relevance of the urban metabolism concept to water management generally (Tambo 2004; Pamminger & Kenway 2008). The conceptual model offers benefits to studies of cities by providing a powerful, unified and holistic viewpoint to encompass all activities backed up with rigorous mass-balance principles. The model also has enormous practical applications. For example, Newman (1999) articulated that cities must reduce throughput of resources, while maintaining or improving liveability (e.g. health, employment, income). However, urban systems definitions are not yet sufficiently developed to enable valid comparisons of population (e.g. Satterthwaite 2008) let alone their metabolic performance (e.g. Kennedy et al. 2007).

**Other research needs**

There is some consensus that improved understanding of the links between water and energy is a priority (Cohen et al. 2004; Proust et al. 2007; Lenzen 2008; Retamal et al. 2009). To date, there has been no systematic description of the multiple points of connection within cities or within urban landscapes more generally. Further, there has been no consistent discussion or classification the range of connections including direct and indirect linkages.

Few studies have quantified linkages, or identified the key causal factors of change, even within the generally well researched areas of water and wastewater infrastructure impacts on energy use or residential water use on energy use. For example, only one study used multivariate analysis to identify the major driving factors of energy consumption within water and wastewater systems (Carlson & Walburger 2007). No such studies were observed in any other water-energy nexus studies. Very few studies have yet expressed any form of confidence interval in results. Much research has been constrained to the consideration of ‘hypothetical’ cities, facilities or water systems. This has often been necessary to circumvent lack of access to data. It is possible that greater co-involvement from the water and energy sectors could help quantify results, to mutual benefit.

While there is good understanding at the ‘water system’ or utility level, there is a need to deepen the analysis within these areas, particularly with regard to city-scale and building-scale processes. How significant are factors ‘outside’ the water system compared to factors under the control of water utilities? For example how does urban form or land use configuration influence utility energy use?

The sometimes lengthy cause-and-effect chains connecting water and energy represent a particularly problematic, but worthy, research topic. The myriad of other complex indirect impacts remain largely unstudied. For example, connections through the supply chain of food and products to cities. How does urban water policy (and pricing) influence urban agriculture, and consequently regional water and energy balances?

Perhaps because of the lack of understanding of ‘the system’ or its boundary, or possibly just due to the sheer complexity, no optimisation studies were observed. All studies were seeking simply to understand or model. Far more work is necessary to develop our knowledge of the system and necessary objective functions before optimisation work is likely to be sufficiently clear. This does not mean that work now on this topic is not warranted, rather it is likely to be challenging and necessarily broad-brush.

The methodologies observed being used for understanding the water-energy nexus included deterministic, mechanistic modelling and systems-dynamic modelling, lifecycle analysis, input-output modelling, optimisation analysis, monitoring, systems dynamic modelling, scenario analysis, elasticity analysis and household expenditure analysis (Table 1 footnotes). A more comprehensive and systematic methodological framework is required to capture the
multiple water-energy links, their various dimensions and implication. Ultimately, a standard method will be required, however significant work and comparison of alternatives would be required before that would become a possibility.

Finally, given the all-pervading nature of water and energy, and the lack of definitions observed, it is likely that further work defining the nexus in different contexts is warranted. Ideally this would capture the multiple facets articulated in this paper.

CONCLUSIONS

There appears to be far more gaps than solid footing, with regard to knowledge of the connections between water and energy in cities. Existing studies address individual aspects of the problem. Many have been swayed to the particular perspective under consideration. Viewed collectively, the research today is a rich hotchpotch that paints an incomplete picture.

There is very little guidance in the literature which addresses the overall problem that is emerging, particularly from the perspective of water suppliers with rapidly increasing energy use. While some areas have addressed the connection from the perspective of energy security, others have approached it from the angle of water security. Both ultimately impact on economic security. Consequently in a water and carbon-constrained future, those cities that understand the connections between water, energy and other related materials, will be more likely to design for efficiency with regard to both simultaneously.

The lack of application of a consistent theoretical framework and method is a major gap; however this is not to be unexpected given the infancy of the overall research effort. A consistent framework however would have a tremendous impact on our understanding of the linkages of relevance. A well developed theoretical framework may help to classify and energy, and the lack of definitions observed, it is likely that further work defining the nexus in different contexts is warranted. Ideally this would capture the multiple facets articulated in this paper.

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