Water-Energy Nexus: A Critical Review Paper

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Abstract: The interdependency between the world's two most critical resources: water and energy, is receiving more and more attention from the academia as well as the general public. A comprehensive and in-depth understanding of the water-energy nexus is essential to achieve sustainable resource management. Following the structure of hierarchy of knowledge, this paper reviewed the evolution and progress of information, methodology, knowledge, and wisdom that have grown out of this field throughout the past 40 years. By synthesizing previous work, the paper identified existing knowledge gaps, as well as directions and challenges for prospective research. System dynamics, featuring framing, understanding, simulating, and communicating dynamic behaviors within interrelated social, managerial, economic, and ecological systems over time, is proposed to be a promising research approach that could facilitate our understanding in the field of water-energy nexus in the future.

Key word: water-energy nexus, critical review, hierarchy of knowledge, system dynamics

"There are tradeoffs between energy and water. It may be… that an increase in water use for certain kinds of fuels is a good thing if you're reducing greenhouse gas emissions and dependency on oil. Understanding the relative numbers in terms of water use and greenhouse gas emissions is part of the dynamic that all of us need to engage in. It's the first step, and I don't think that has happened." (Peter Gleick, quoted in a 2008 Nature article)

1. INTRODUCTION

1.1. Water and Energy Problems

Water and energy are two critical natural resource issues facing most parts of the world today. World primary energy demand is anticipated to increase by a third in the next 25 years in the next 25 years (IEA 2011). Fossil fuels, which will still reign in 2035 (USEIA, 2011), are finite and far from environmentally friendly, responsible for 94.6% of CO2 emissions in the United States (USEPA 2011). Although worldwide, renewable energy technologies are gaining more and more attention, especially under an ever-increasing pressure of greenhouse gas emission reduction, considerable economic barriers are still expected.

Unlike energy, there are hardly any new supplies or substitutes for water resources – only 100,000 km^3 of water resources is available every year for the whole world (Gleick 1994). Due to continuing population growth, contamination caused by human activities, new technological demand, as well as the impacts of climate change, water crisis is aggravating globally (UNESCO 2009). Even under non-drought conditions, 36 states in the water-abundant United States are expected to experience local, regional, or statewide water stress by 2013 (USEPA 2008). More than 400 U.S. counties will have to deal with extremely high water shortage risks by 2050 (NRDC 2010).

1.2 Water-Energy Nexus

After water and energy experts trying to solve their own problems separately for several decades, more and more of them begin to realize that the two fundamental resources are not independent from each other. The interconnections between them, called water-energy nexus (Figure 1), are key for both of them to achieve sustainable outcomes. The *Energy Policy Act 2005*, requesting U.S. Department of Energy as well as other relevant agencies to address water and energy related issues together (Section 979), is regarded as the first formal commitment of U.S. federal government in water-energy nexus (WRRC, 2010). The resulting *Report to Congress on the Interdependency of Energy and Water* concluded that: "energy and water are essential, interdependent resources" (USDOE, 2006).

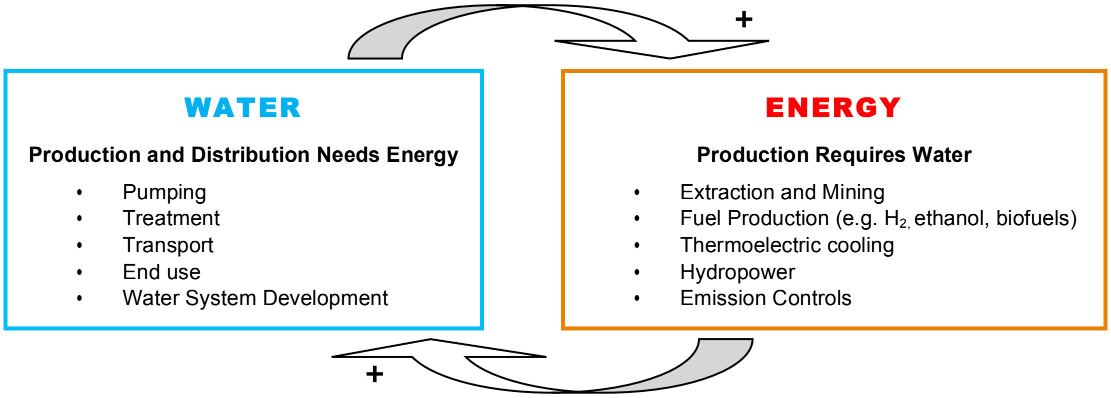


Figure 1 Water-Energy Nexus: the interrelationship between water and energy use (Adapted from Newmark, 2010)

There constraints between water and energy are becoming ever more evident (Schnoor 2011). Energy plays an important role in water supply. It is common that half of a city's energy demand is caused by water supply and wastewater treatment (Stillwell 2009). 75% of municipal water processing and distribution costs come from electricity consumption (Glassman 2011). Most non-traditional water sources and new technologies to treat more impaired water, such as desalination and thermal treatment systems, tend to be more energy intensive than traditional methods (Gleick 1994).

Water is also an integral part of energy production. Thermoelectric power is the largest water user in the United States, accounting for 49% of the country's total withdrawal (Barber 2009). Although only 3 percent of the water is considered as consumptive use, a significant increase of thermoelectric water consumption is expected as old once-through cooling systems are replaced by new recirculating cooling systems (Barber 2009, Feeley et al. 2005). In order to generate electricity continuously, at any one moment, the large amount of non-consumptive water has to be reserved for power plants and thus unavailable for other uses. Moreover, some renewable energy technologies, such as biofuel, hydrogen, and concentrated solar power (CSP) could be more water intensive than fossil fuels (Newmark 2010, Tellinghuisen and Miford 2010). Potential climate policies regarding carbon capture and sequestration (CCS) will induce substantially more water consumption by thermoelectric power plants (USDOE 2007, Mielke 2010). That is to say, policies that aim to solve one resource problem can have unintended impacts on the other resources.

Although water and energy are constraint for each other, there are opportunities that co-benefits can be achieved through an integrated resource management approach. For example, water conservation has been widely recognized as an effective approach for energy saving and thus climate adaptation (IPCC 1996, Cohen et al. 2004, Kenway et al. 2008, Maas 2009).

1.3 Overview of Literature Review

As a relatively new subject, there is a lack of systematic understanding of the interrelationships between water and energy. The limited understanding further prevents any efforts to optimize the nexus for sustainable outcomes. Two previous review papers provide some insights on the status and development of this field: Firstly, existing research have covered a wide range of dimensions: technology, environmental, economic, social, and political/legal and research scale ranges from a single appliance to a nation (Kenway

2011); secondly, few links are quantified and causal factors are not well identified (Kenway 2011); in addition, a systematic framework to guide future research is most desired for future research (Retamal 2008, Kenway 2011).

This review paper is based on over 70 publications, including published academic literatures, state and federal government agency reports, and non-governmental organizations' reports on the topic of water-energy nexus since 1979. In order to track the field's evolution and progress, the paper is organized based on "the hierarchy of knowledge" (Figure 2). "Data and information" collection is usually where any research field starts to evolve, which lays the foundation for the field's further development. In the first part of the review paper, available data and information on water-energy nexus that was extracted from existing literatures were organized into a dataset. As the most comprehensive water-energy data bank, the dataset should be helpful for future research in relevant field. "Knowledge and understanding" grow out of sufficient data and information but are generally more synthesized. Methodologies are designed and applied to facilitate reaching more comprehensive and in-depth understanding on this level. In the second part of the review paper, strengths and weaknesses of main research methodologies adopted by existing literatures examined. Preliminary understanding and knowledge in the water-energy nexus field are also discussed in this part. Wisdom of research can lead to more advanced insights and makes system optimization possible. The paper ends up with a discussion of future research framework that can help push forward to that higher end.

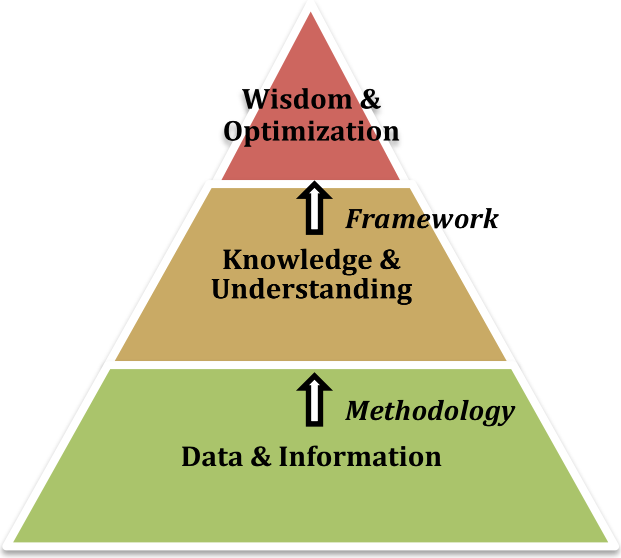


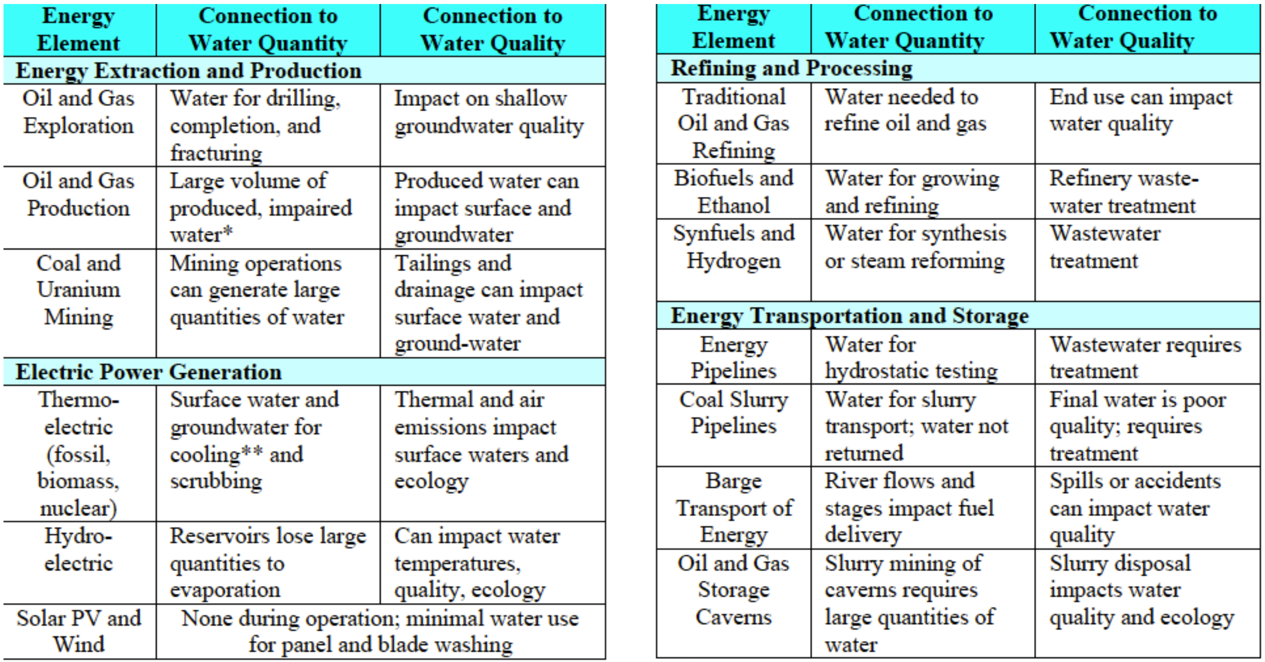
Figure 2 Hierarchy of Knowledge (the roadmap of literature review)

2. DATA & INFORMATION

2.1 Qualitative data & information

Discussion on water-energy nexus started as early as about 40 years ago. The criticality of water constraint on energy production and supply was recognized. Potential competition between energy and other activities for water resources was predicted and discussed (Bishop and Mirayanan 1979). Scholars also predicted that water would become a crucial factor on political agendas as long as people had to deal with agriculture, energy, and other economic issues that are unavoidably related with water (Weatherfold and Ingram 1984).

Several decades later, the U.S. federal government became aware of the critical interdependency between water and energy, while facing increasing water and energy stresses and possible worse scenarios caused by climate change. The connections between energy production and water resources are explained and documented in a more comprehensive way (USDOE 2006 Figure 3). Recently, water-energy nexus has attracted large media exposure and raised public attention and debates at a series of high-level international conferences (Cammerman 2009).



Energy Element	Connection to Water Quantity	Connection to Water Quality
Energy Extraction and Production		
Oil and Gas Exploration	Water for drilling, completion, and fracturing	Impact on shallow groundwater quality
Oil and Gas Production	Large volume of produced, impaired water*	Produced water can impact surface and groundwater
Coal and Uranium Mining	Mining operations can generate large quantities of water	Tailings and drainage can impact surface water and ground-water
Electric Power Generation		
Thermo-electric (fossil, biomass, nuclear)	Surface water and groundwater for cooling** and scrubbing	Thermal and air emissions impact surface waters and ecology
Hydro-electric	Reservoirs lose large quantities to evaporation	Can impact water temperatures, quality, ecology
Solar PV and Wind	None during operation; minimal water use for panel and blade washing	

*Impaired water may be saline or contain contaminants

Energy Element	Connection to Water Quantity	Connection to Water Quality
Refining and Processing		
Traditional Oil and Gas Refining	Water needed to refine oil and gas	End use can impact water quality
Biofuels and Ethanol	Water for growing and refining	Refinery waste-water treatment
Synfuels and Hydrogen	Water for synthesis or steam reforming	Wastewater treatment
Energy Transportation and Storage		
Energy Pipelines	Water for hydrostatic testing	Wastewater requires treatment
Coal Slurry Pipelines	Water for slurry transport; water not returned	Final water is poor quality; requires treatment
Barge Transport of Energy	River flows and stages impact fuel delivery	Spills or accidents can impact water quality
Oil and Gas Storage Caverns	Slurry mining of caverns requires large quantities of water	Slurry disposal impacts water quality and ecology

**Includes solar and geothermal steam-electric plants

Figure 3 Connections between the energy sectors and water availability and quality (US DOE 2006)

2.2 Quantitative information

Data availability and quality are a common and critical issue for almost all types of research. Several researchers pointed out that in order to produce more robust water-energy nexus research, high-quality data that is collected in a consistent manner will be essential (Macknick et al. 2011, Stillwell et al. 2010, Retamal 2008). U.S. federal agencies are now working collaboratively to improve the data availability and quality (Macknick et al. 2011).

Acknowledging the importance of valid data for research, this paper tried to organize available data and their sources extracted from existing publications into a dataset, in hopes of smoothening the process of data exploration by future researchers. None of the data presented is manipulated except for necessary unit conversions. For each parameter, the minimum and maximum values are documented in the dataset, but data sources for all the available values are provided. They are then grouped and graphed to facilitate analysis and comparison.

The reasoning for selecting the minimum and maximum values is that they represent the range of possible values. Therefore, they can well meet the needs of generic research, whose result is not going to be one numeric value but a range of values that indicates the every possibility that is bordered by the best and worst scenarios. Even for research that has very specific local physical and socioeconomic settings, the low and high values can provide insights for scenario analysis and sensitivity analysis. Given the dynamic features of natural and human systems, further analysis using the two extreme values in most local and regional studies actually makes a lot of sense.

2.2.1 Energy footprint of water

The dataset demonstrates that substantial but various amounts of energy resources are consumed by water and wastewater utilities, as well as water end uses (Appendix 1, Table A1).

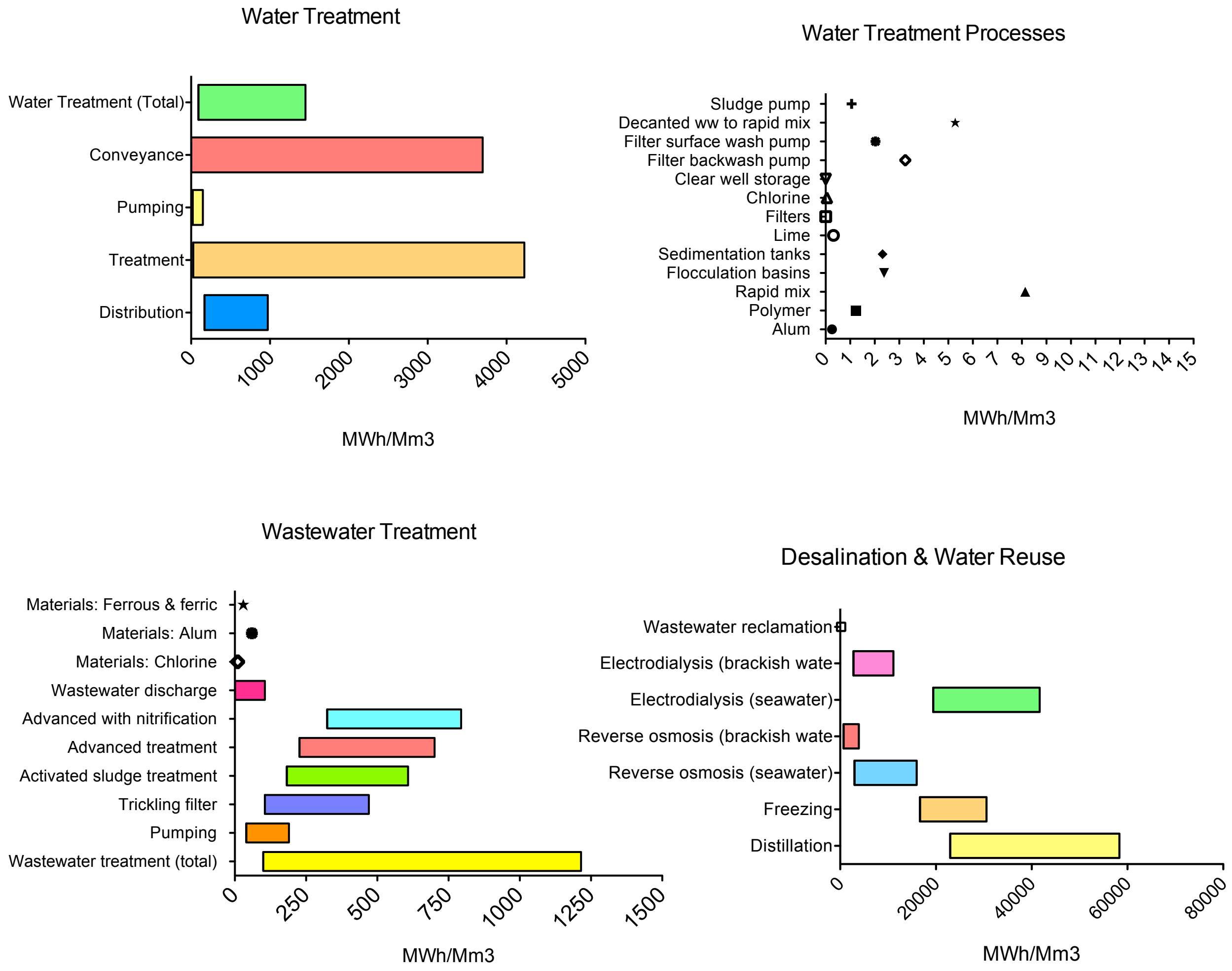


Figure 4 Energy use by water/wastewater sectors (based on data in Table A1)

The graphs above indicated that energy intensities of both water and wastewater treatment processes are highly variable, probably due to various topographies that water has to travel through, different qualities of water influents, as well as distinct processes required by different water and wastewater treatment standards (Klein 2005, Kenway et al. 2008, Kneppers et al. 2009, Stillwell 2010). Energy demand by water conveyance has become an important concern for almost all water utilities, even when they are only dealing with modest water projects. The water transportation costs can be so large that normally water efficiency measures turn out to be more economically favorable for utilities in order to meet their supply demand (Gleick 1994). The data also showed that during treatment processes, most energy is consumed at operational phases (Stokes and Horvath 2005, 2009). Treatment chemicals have negligible energy footprints, though they may cause other environmental impacts (Kenway et al. 2008).

Desalination is generally much more energy intensive (Gleick 1994, Stokes and Horvath 2005, Marsh 2008). Comparatively, wastewater reclamation needs much less energy, but extra pumping in some cases could be very energy intensive (Lim 2009). Water conservation is widely believed as the least energy-intensive technology and a better approach to deal with future water and energy stress (Cohen et al. 2004). In addition, changes of energy efficiency demonstrate economies of scales: the larger the utility is, the less energy the utility tends to consume in order to generate one unit of energy. (Maas 2009, Klein et al. 2005)

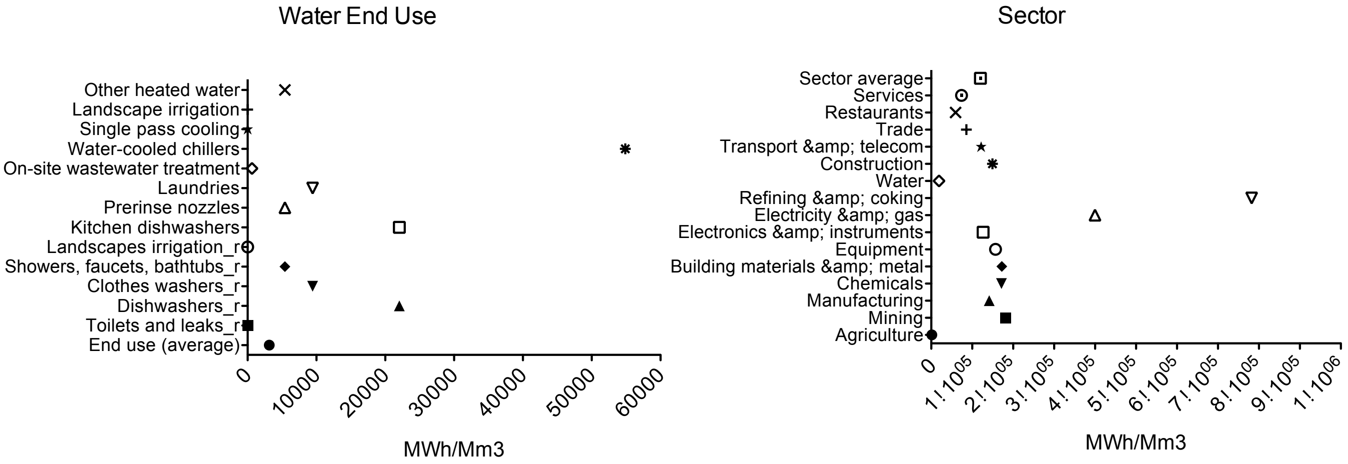


Figure 5 Energy use by end uses and sectors (based on data in Table A1)

Comparing with water/wastewater sectors, end uses (especially chillers and dishwashers) have larger energy footprints, which indicate more potential for future energy savings (Arpke and Hutzler, 2006). The results further suggest that demand-side management can be more important and effective than supply-side management in terms of improving efficiency and savings, thus deserves more research and policy attention (Marsh 2008). Unfortunately, most research now focus on energy uses by water provision and treatment sectors not by end uses (Kenway 2011).

In addition, energy consumption data by economic sectors are available from China. The much higher magnitude of energy consumption values might be explained by generally low efficiency levels in China. It is quite likely that the magnitudes will be quite similar in many other developing countries, which would suggest that water-energy research can help developing countries save bigger on both energy and water with relatively lower costs – the “low hanging fruits” are untouched. However, there is not enough data to prove it, since few water-energy nexus research has been carried out in developing countries (Kumar

2005). In general, data from industrial, commercial and agricultural sectors are scarce worldwide (Kenway 2011), which could significantly affect our understanding of the water-energy nexus and ability to quantify and mitigate the impacts.

2.2.2 Water footprint of energy

Data on water footprint of energy has been divided into two parts: water consumption by energy extraction/processing (primary energy) and water consumption by electricity generation (secondary energy) (Appendix 2, Table A2). Conventional, unconventional, and renewable energies and technologies are covered by the dataset. Water footprint of energy can be greatly affected by geographic features, e.g. climate conditions for hydropower's water footprint, sources of water supply (groundwater v. surface water), etc. (Macknick et al. 2011). Comparing with "energy footprint of water", there is much less public and research interests in "water footprint of energy", mainly due to the underestimated water value (Schuck and Green 2002). However, water has become a critical constraint to power plant siting and economic costs of energy shortages due to drought or water unavailability can be as high as several million U.S. dollars (Sovacool and Sovacool 2009, Gleick 1994). The two sides of the nexus are as equally important and deserve at least the same amount of attention from academia, government, industries and the general public.

Energy extraction and processing (Figure 6)

Water is indispensible for fossil fuel extraction and processing (Alcamo 1983, Mielke et al. 2010). However, people would generally assume renewable energies (including hydropower and nuclear) are more environmentally favorable than conventional energies. However, in terms of water footprint, not all types of renewable energies have advantages over their fossil fuel compartments, or in some cases, can be more water-intensive than conventional energies. Irrigation-fed biofuels can be extremely water-intensive (Mielke et al. 2010). Some non-irrigation biofuels, such as algae, can be also water-intensive due to high water demand for processing the fuel (Murphy and Allen 2011). Future large-scale adoption of biofuels in transportation could significantly affect water availabilities for other activities in some local areas or even on a national scale (Scown 2011, US DOE 2006). Unconventional fossil fuel energies, which have gigantic reserves but also largely unknown environmental implications now widely regarded as crucial and strategic energy resources for sustaining future energy supply (Hagood 2008). The development of some of them has been proved to demand substantial water resources. Oil shale, for example, is notoriously known for large water demand and causing nearly irreversible impacts on local water quality (Hightower 2006, Kargbo 2010).

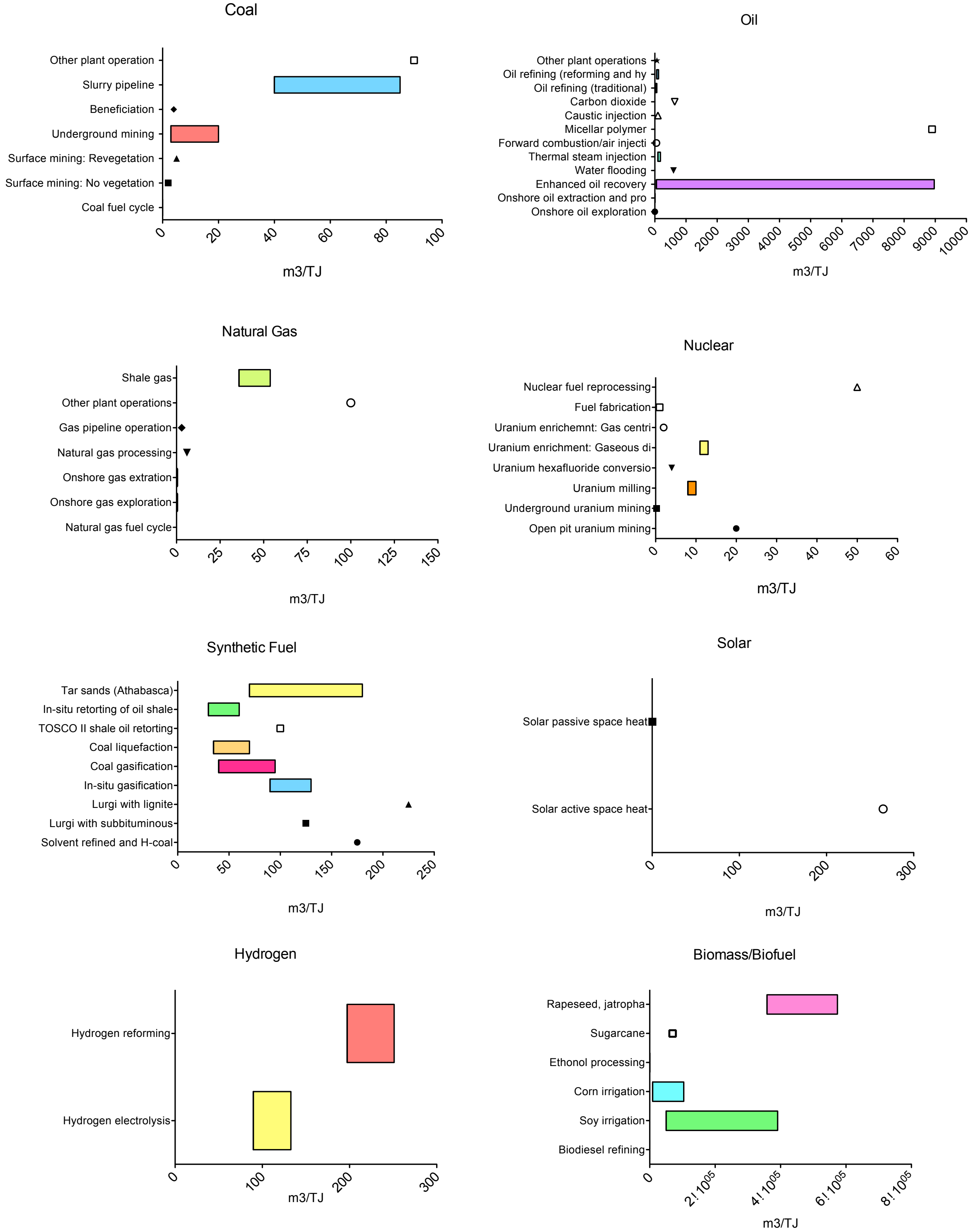


Figure 6 Water consumption by conventional, unconventional and renewable energy extraction and processing (based on data in Table A2)

Electricity generation

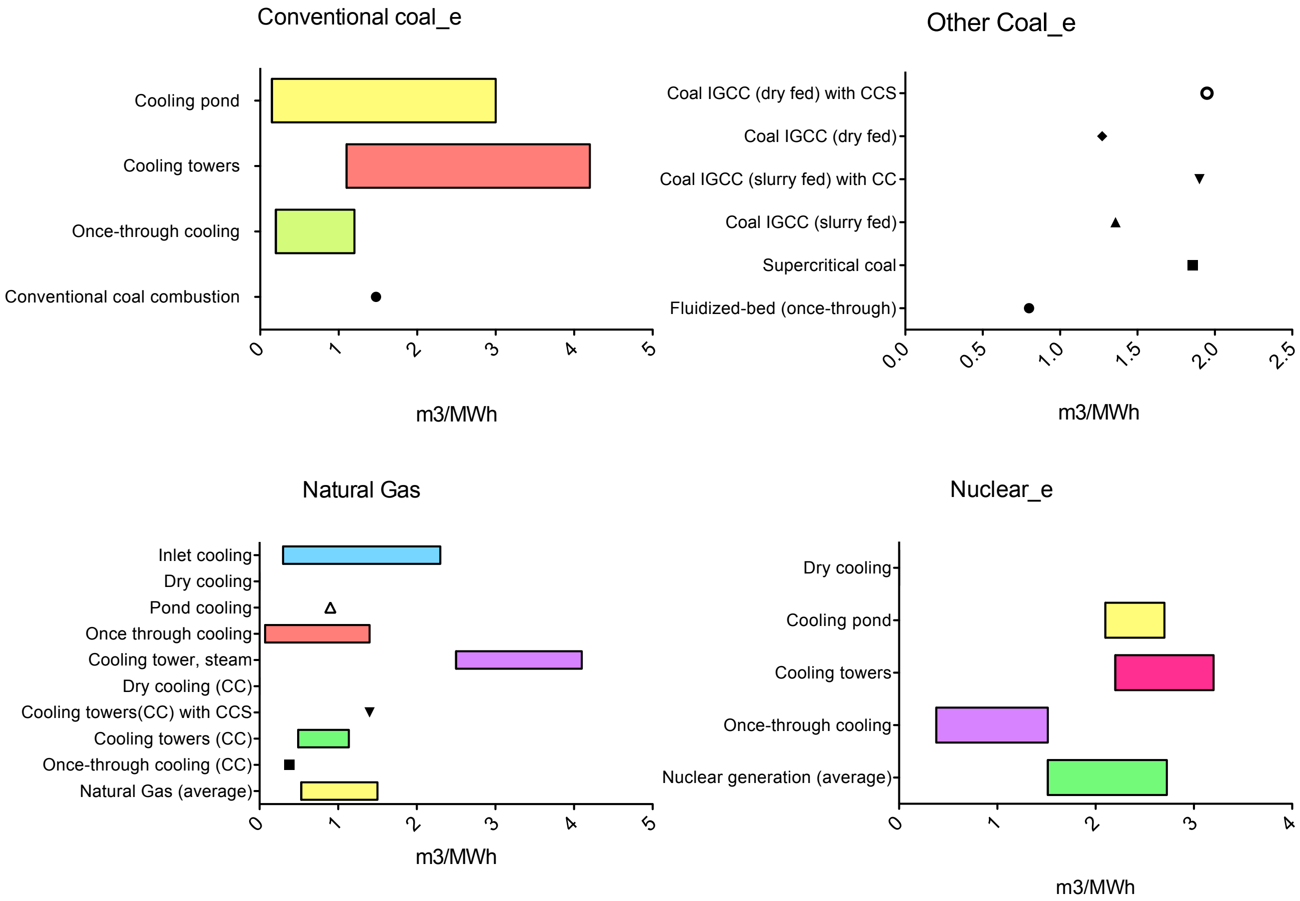


Figure 7 Water consumption by electricity generation out of fossil fuels and nuclear energy (based on data in Table A2)

For electricity, the selection of cooling technologies can significantly affect water footprints of electricity generation (Torcellini et al. 2003, Feeley et al. 2005): once-through cooling systems withdrawal much more water with little water consumption; cooling towers (recirculating systems) withdrawal less water but end up consuming a lot more; dry cooling system has very small footprints but cannot work efficiently during hot weather and is currently much more expensive than most utilities would be willing to pay or be able to afford. To protect aquatic ecosystems, new power plants in the United States and many European countries are banned from adopting the once-through system, thus many more cooling towers have been built. It is predicted that by the year of 2030, 3.3 billion gallons more water will be consumed every day if new power plants continue to use the recirculating cooling system than 1995 (Hoffman et al., 2010). Technological feasibility and reliability of using municipal wastewater for power plant cooling are being explored. Possible infrastructure corrosions and sufficiency of water quantities are two major technical concerns (Li et al. 2011). Furthermore, the tradeoffs between emission control (carbon capture and sequestration) and water consumption have been well aware and reported (e.g. Gold and Bass 2010, Cohen et al. 2004, Mielke et al. 2010).

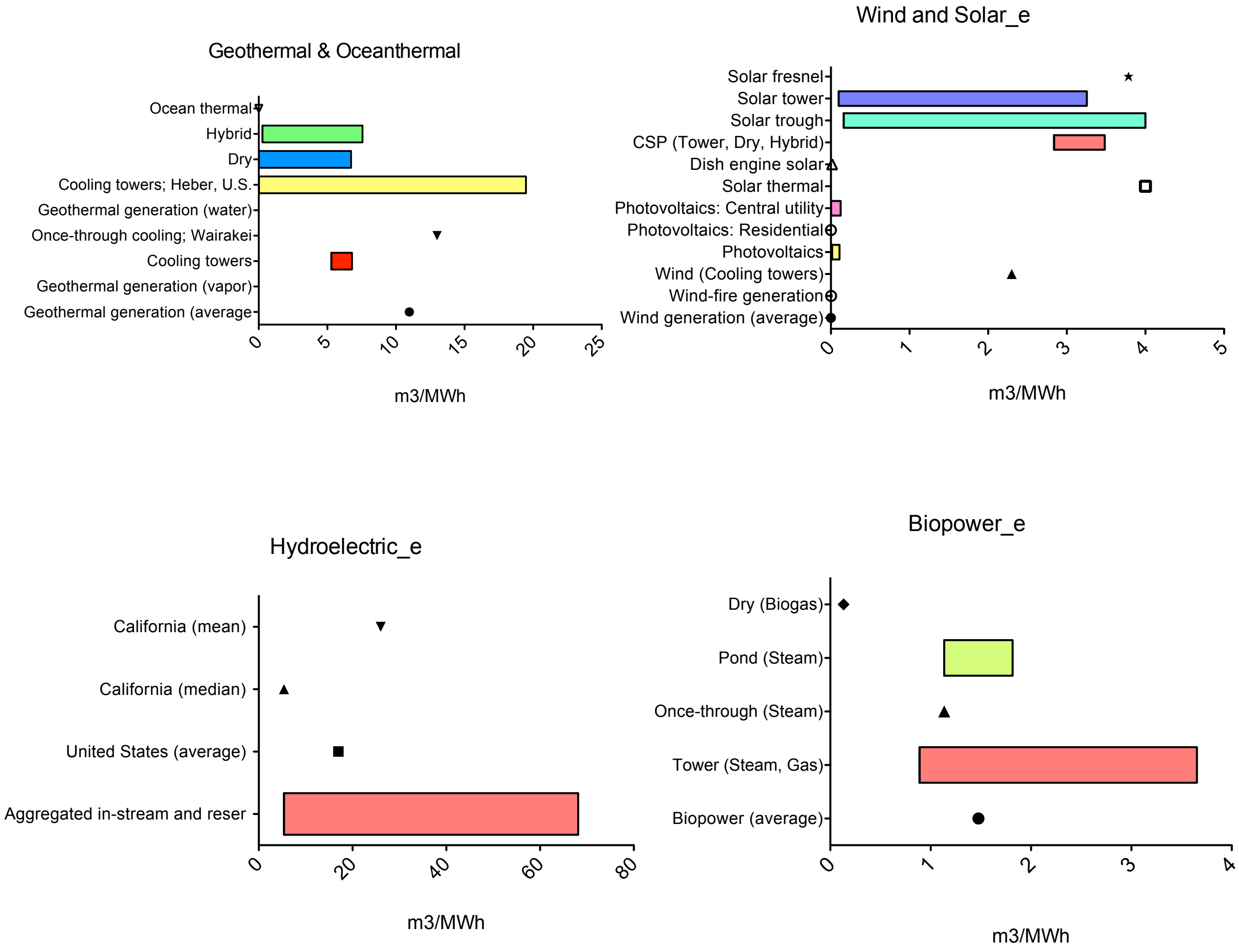


Figure 8 Water consumption by electricity generation out of renewable energy (based on data in Table A2)

Similar to conventional energies, water intensities of renewable energies are greatly influenced by the specific technologies applied. Although in most cases solar and wind consume very little water, concentrated solar power (CSP) can be even more water-intensive than most thermal powers, due to its large cooling demand (USDOE 2006, Newmark 2009, Mielke et al. 2010). Hydropower with reservoirs that have enormous water surface areas will consume a lot more water through evaporation. By providing 6% of electricity in the United States, 12 billion gallons of water is consumed every day (Torcellini et al. 2003). However, larger hydropower plants tend to consume less than smaller ones (Gleick 1993). Non-thermal renewable energies, such as PV and wind have the smallest or negligible water demand.

2.2.3 Future work on data and information collection

In order to improve our understanding on the water-energy nexus, availability of high-quality data monitored and collected in a consistent manner is critical. Geographic features, which will greatly affect parameter values, should be well documented and information should be normalized for comparative studies. Short-term temporal features (e.g. diurnal, seasonal, and annual) as well as long-term temporal features (e.g. planning period) need to be considered (Cheng 2002) to account for data variability. Definitions of key parameters need to be clarified, e.g. water withdrawal and water consumption, primary, secondary, final, and useful energy, and types of water resources (e.g. groundwater or surface water, brackish water or seawater). Since some typos have been found during the reviewing processes, researchers are always recommended to track all the way down to the original data sources to verify data. Moreover, a lot of data that is widely cited and used in existing literatures are from Gleick's 1993 paper, which is likely to be quite outdated given the relatively fast technology turnovers in both water and energy sectors. Efforts are needed to provide the most updated data in order to carry out a more robust research today.

3. KNOWLEDGE & UNDERSTANDING

Based on good data and information, knowledge and understanding of a research field will be able to grow. Normally, well-designed methodologies are needed to facilitate this evolution. By reviewing the water-energy nexus research during the past several decades, seven major approaches have been identified and examined by this paper (Table 1). In summary, each method has its own strengths and weaknesses. Accounting and case study are the mostly adopted methods. As a comprehensive and systematic environmental assessment methodology, LCA is getting more and more popular.

Preliminary understanding and knowledge from different perspectives are growing rapidly in this relatively new area. Based on case studies in California, a life cycle assessment research further revealed that different life cycle phases dominate energy consumption by different water supply sources: conveyance for imported water (56%-86%), treatment for desalination (~85%), and distribution for recycled water (61%-74%) (Stokes and Horvath 2006). Gold and Bass (2010) pointed out that water conservation is not omnipotent – adverse third-party impacts can be caused for those who “live on” the inefficiencies.

Multiple case studies concluded that coordination among stakeholders is crucial for integrated water and energy management (Gold and Bass 2010, Kenway 2011). The suggestion of combined governance is grown out of case studies in both United States (California) and Australia. Some legislative responses have also grown out of this evolution (Carter 2010). Best management practices are suggested and designed based on information, data and experience gained from case studies (Klein et al. 2005, Griffiths-Sattenspiel and Wilson 2009).

What else are missing besides data/information?

As mentioned before, high-quality data and information will be critical to push the continuing growth of knowledge and understanding. But what else are missing? Most of the literatures reviewed in this paper focused on only one side of the nexus: either energy footprint of water (e.g. Vycius 2002, Malik 2002, Dimitriadis 2005, Carlson and Walburger 2007, Kenway et al. 2008) or water footprint of energy (e.g. Sovacool and Sovacool 2009, Batlles et al. 2010, Mielke et al. 2010). A few covered both of the two sides (e.g. Maas 2010, Kenway 2011, Perrone et al. 2011). None of them has explored the dynamic interactions: the feedback relationships between the two resources, without which the nexus is never going to be fully understood and appreciated.

System dynamics modeling

Therefore, system dynamics is recommended here to be an effective tool for the water-energy nexus research. System Dynamics (SD) is an important aspect of system theory and a branch of control theory. As a methodology and computer technique, system dynamics modeling was developed by Professor Jay Forrester at the Massachusetts Institute of Technology in the mid-1950s. This computer-aid approach is effective in framing, understanding, and simulating complex behaviors of natural, social, and managerial systems for the purpose of policy design and analysis. Feedbacks, stocks and flows, and time delay are the most essential components of system dynamics modeling, which make it well suited for understanding how systems respond to change (Sterman, 2002). System dynamics modeling usually begins with conceptualizing dynamic problems, followed by mapping and modeling stock and flow variables, as well as the feedback relationships, and finalizes with model validations and policy implications. Mathematically, the simulations are based on a system of coupled, nonlinear, first-order differential (or integral) equations (System Dynamics Society, 2011).

Causal Loop Diagrams (CLD) are usually used to identify relationships between system variables as well as depict feedback loops that regulate the system. Causal loop diagrams provide an overview of the main system structure as well as facilitate understanding of the overarching system trends and behaviors, prior to modeling the more intricate system details (Nasiri et al., 2010). Direct relationships between variables are depicted by arrows that link them with each other. A "+" or "-" sign at the head of each arrow indicates a positive or negative causality between the linked variables. Polarity of each feedback loop is indicated by "R" or "B" in the loop center, indicating a reinforcing relationship or a controlling (balancing) relationship.

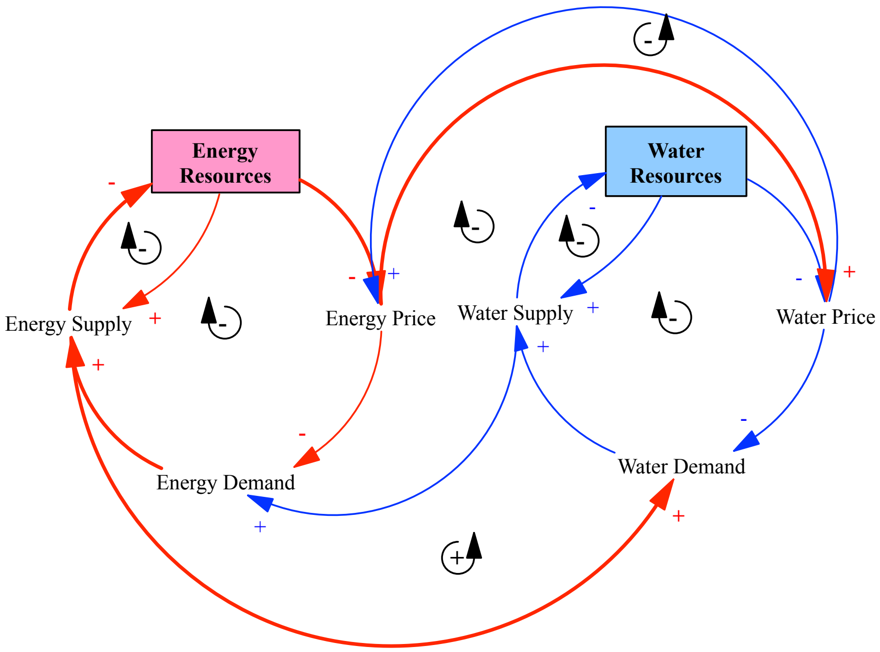


Figure 9 Causal loop diagram with the major feedback relationships within the water-energy nexus

Figure 12 Existing water-energy nexus research distribution in the context of CO2 emissions

Figure 13 Existing water-energy nexus research distribution in the context of GDP

The four maps above demonstrate the influences of energy demand and economic development for water-energy nexus research, which matches previous conclusions that energy perspective has a dominant impact within this nexus. The influence of economic development status could be an indirect influence through energy demand or a direct one, for

R&D capacities are strongly related with economic development status. Although water shortage doesn't seem to be a strong incentive for research on water-energy nexus, more research and attention are needed in areas with water problems. Again, unlike energy, available water resources are very much likely to stay constant if not decreasing. It is hard to find a substitute for it. Even though the price signal does not work very well for now, more attention needs to be called up on the water issues.

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Appendix I

Table A1. Energy consumption by water (MWh/Mm3)

	Low	High	Reference
Conveyance	0.00	3698.42	Klein et al. 2005; Cohen et al. 2004; Kneppers 2009; Maas 2009; Kenway et al. 2008; Navigant Consulting, Inc. 2006
Pumping	20.00	150.00	
Treatment	26.42	4226.77	
Distribution	170.00	972.86	
Water supply (total)	93.06	1449.56	NRDC 2004
Alum	0.26	0.26	Klein et al. 2005
Polymer	1.24	1.24	Klein et al. 2005
Rapid mix	8.14	8.14	Klein et al. 2005
Flocculation basins	2.38	2.38	Klein et al. 2005
Sedimentation tanks	2.32	2.32	Klein et al. 2005
Lime	0.32	0.32	Klein et al. 2005
Filters	0.00	0.00	Klein et al. 2005
Chlorine	0.05	0.05	Klein et al. 2005
Clear well storage	0.00	0.00	Klein et al. 2005
Filter backwash pump	3.25	3.25	Klein et al. 2005
Filter surface wash pump	2.03	2.03	Klein et al. 2005
Decanted washwater to rapid mix	5.28	5.28	Klein et al. 2005
Sludge pump	1.06	1.06	Klein et al. 2005
Wastewater collection and treatment	100.00	1215.20	Klein et al. 2005; NRDC 2004; Kneppers 2009; Maas 2009; Kenway et al. 2008; Navigant Consulting, Inc. 2006; Cheng
Pumping	40.00	190.00	
Trickling filter	105.39	470.21	
Activated sludge treatment	182.41	608.04	
Advanced treatment	227.00	701.27	
Advanced treatment with nitrification	324.29	794.50	
Wastewater discharge	0.00	105.67	
Wastewater treatment (total)	462.11	462.11	Cohen et al. 2004
Chemicals for wastewater treatment	56.00	56.00	Klein et al. 2005
Chlorine for wastewater treatment	10.00	10.00	Klein et al. 2005
Alum for wastewater	60.00	60.00	Klein et al. 2005
Ferrous & ferric for wastewater	30.00	30.00	Klein et al. 2005
End use	3161.79	3161.79	Cohen et al. 2004

Residential end use			
Toilets and leaks	0.00	0.00	Cohen et al. 2004
Dishwashers	22051.43	22051.43	Cohen et al. 2004
Clothes washers	9444.82	9444.82	Cohen et al. 2004
Showers, faucets, and bathtubs	5431.79	5431.79	Cohen et al. 2004
Landscapes irrigation	0.00	0.00	Cohen et al. 2004
Commercial, industrial, and institutional			Cohen et al. 2004
Kitchen dishwashers	22051.43	22051.43	Cohen et al. 2004
Prerinse nozzles	5431.79	5431.79	Cohen et al. 2004
Other kitchen use	na	na	Cohen et al. 2004
Laundries	9444.82	9444.82	Cohen et al. 2004
On-site wastewater treatment	648.57	648.57	Cohen et al. 2004
Water-cooled chillers	54885.36	54885.36	Cohen et al. 2004
Single pass cooling	0.00	0.00	Cohen et al. 2004
Landscape irrigation	0.00	0.00	Cohen et al. 2004
Other heated water	5431.79	5431.79	Cohen et al. 2004
Other unheated water			Cohen et al. 2004
Hot water (electric)	73000.00	73000.00	Cohen et al. 2004
Hot water (natural gas)	103000.00	103000.00	Cohen et al. 2004
Total estimated residential end uses	3161.79	3161.79	Cohen et al. 2004
Kitchen dishwashers	22051.43	22051.43	Cohen et al. 2004
Prerinse nozzles	5431.79	5431.79	Cohen et al. 2004
Other kitchen use	na	na	Cohen et al. 2004
Laundries	9444.82	9444.82	Cohen et al. 2004
On-site wastewater treatment	648.57	648.57	Cohen et al. 2004
Water-cooled chillers	54885.36	54885.36	Cohen et al. 2004
Single pass cooling	0.00	0.00	Cohen et al. 2004
Landscape irrigation	0.00	0.00	Cohen et al. 2004
Other heated water	5431.79	5431.79	Cohen et al. 2004
Other unheated water	na	na	Cohen et al. 2004
Wastewater reclamation and distribution	105.67	1000.00	Cohen et al. 2004, Dimitriadis 2005
Distillation	23000.00	58333.33	Gleick (1993) in Gleick (1994), US DOE 2003
Freezing	16666.67	30555.56	Gleick (1993) in Gleick (1994), US

			DOE 2003
Reverse osmosis (seawater)	3000.00	25000.00	Gleick (1993) in Gleick (1994), US DOE 2003, Dimitriadis 2005
Reverse osmosis (brackish water)	700.00	3888.89	Gleick (1993) in Gleick (1994), US DOE 2003, Dimitriadis 2005
Electrodialysis (seawater)	19444.44	41666.67	Gleick (1993) in Gleick (1994), US DOE 2003
Electrodialysis (brackish water)	2777.78	11111.11	Gleick (1993) in Gleick (1994), US DOE 2003
Agriculture	1388.89	1388.89	Kahrl 2007
Mining	182222.22	182222.22	Kahrl 2007
Manufacturing	141666.67	141666.67	Kahrl 2007
Chemicals	171388.89	171388.89	Kahrl 2007
Building materials & metals	172222.22	172222.22	Kahrl 2007
Equipment	157222.22	157222.22	Kahrl 2007
Electronics & instruments	126666.67	126666.67	Kahrl 2007
Electricity & gas	399722.22	399722.22	Kahrl 2007
Refining & coking	782222.22	782222.22	Kahrl 2007
Water	19166.67	19166.67	Kahrl 2007
Construction	149444.44	149444.44	Kahrl 2007
Transport & telecom	121944.44	121944.44	Kahrl 2007
Trade	85833.33	85833.33	Kahrl 2007
Restaurants	59444.44	59444.44	Kahrl 2007
Services	74166.67	74166.67	Kahrl 2007
Average	120277.78	120277.78	Kahrl 2007

Appendix 2

Table A2. Water consumption by energy

Energy production (Consumptive use, m3/TJ)	Low	High	Reference
Coal fuel cycle			
Surface mining: No vegetation	2	2.00	Gleick 1993
Surface mining: Revegetation	5	5.00	Gleick 1993
Underground mining	3	20.00	Gleick 1993
Beneficiation	4	4.00	Gleick 1993
Slurry pipeline	40	85.00	Gleick 1993
Other plant operation	90	90.00	Gleick 1993
Nuclear fuel cycle			
Open pit uranium mining	20	20.00	Gleick 1993
Underground uranium mining	0.2	0.20	Gleick 1993
Uranium milling	8	10.00	Gleick 1993
Uranium hexafluoride conversion	4	4.00	Gleick 1993
Uranium enrichment: Gaseous diffusion	11	13.00	Gleick 1993
Uranium enrichemnt: Gas centrifuge	2	2.00	Gleick 1993
Fuel fabrication	1	1.00	Gleick 1993
Nuclear fuel reprocessing	50	50.00	Gleick 1993
Oil fuel cycle			
Onshore oil exploration	0.01	0.01	Gleick 1993
Onshore oil extraction and production	3	8.00	Gleick 1993
Enhanced oil recovery	50.23	8970.00	Gleick 1993, McMahon & Price 2011
Water flooding	600	600.00	Gleick 1993
Thermal steam injection	100	180.00	Gleick 1993
Forward combustion/air injection	50	50.00	Gleick 1993
Micellar polymer	8900	8900.00	Gleick 1993
Caustic injection	100	100.00	Gleick 1993
Carbon dioxide	640	640.00	Gleick 1993
Oil refining (traditional)	25	65.00	Gleick 1993
Oil refining (reforming and	60	120.00	Gleick 1993

hydrogenation)			
Other plant operations	70	70.00	Gleick 1993
Natural gas fuel cycle			
Onshore gas exploration	0	0.00	Gleick 1993
Onshore gas extration	0	0.00	Gleick 1993
Natural gas processing	6	6.00	Gleick 1993
Gas pipeline operation	3	3.00	Gleick 1993
Other plant operations	100	100.00	Gleick 1993
Shale gas	35.88	53.82	Gleick 1993
Synthetic fuels			
Solvent refined and H-coal	175	175.00	Gleick 1993
Lurgi with subbituminous	125	125.00	Gleick 1993
Lurgi with lignite	225	225.00	Gleick 1993
In-situ gasification	90	130.00	Gleick 1993
Coal gasification	40	95.00	Gleick 1993
Coal liquefaction	35	70.00	Gleick 1993
TOSCO II shale oil retorting	100	100.00	Gleick 1993
In-situ retorting of oil shale	30	60.00	Gleick 1993
Tar sands (Athabasca)	70	180.00	Gleick 1993
Solar			
Solar active space heat	265	265.00	Gleick 1993
Solar passive space heat	0	0.00	Gleick 1993
Hydrogen			
Hydrogen electrolysis	89.7	132.76	US DOE 2006 (estimate)
Hydrogen reforming	197.34	251.16	US DOE 2006 (estimate)
Biomass/Biofuel			
Biodiesel refining	15.0696	15.07	US DOE 2006
Soy irrigation	50232	391092.00	US DOE 2006, McMahon & Price 2011

Corn irrigation	8970	104052.00	US DOE 2006, Chavez-Rodriguez et al. 2010
Ethonol processing	46.644	520.26	US DOE 2006
Sugarcane	70000	70000.00	McMahon & Price 2011, Chavez-Rodriguez et al. 2010
Rapeseed, jatropha	358800	574080.00	McMahon & Price 2011
Electricity production (m3/MWh)			
Conventional coal combustion	1.48	1.48	US DOE 2006
Once-through cooling	0.2	1.20	Gleick 1993, McMahon & Price 2011
Cooling towers	1.1	4.20	Gleick 1993, McMahon & Price 2011
Cooling pond	0.15	3.00	McMahon & Price 2011
Fluidized-bed coal combustion			
Once-through cooling	0.8	0.80	Gleick 1993
Supercritical coal	1.86	1.86	US DOE 2006; NETL 2009
Coal IGCC (slurry fed)	1.36	1.36	US DOE 2006; NETL 2009
Coal IGCC (slurry fed) with CCS	1.90	1.90	US DOE 2006; NETL 2009
Coal IGCC (dry fed)	1.27	1.27	US DOE 2006; NETL 2009
Coal IGCC (dry fed) with CCS	1.95	1.95	US DOE 2006; NETL 2009
Oil and natural gas combution			
Once-through cooling	1.1	1.10	Gleick 1993
Cooling towers	2.6	2.60	Gleick 1993
Natural Gas	0.53	1.50	US DOE 2006, McMahon & Price 2011
Once-through cooling (CC)	0.38	0.38	US DOE 2006
Cooling towers (CC)	0.49	1.14	Macknick et al. 2011, US DOE 2006, McMahon & Price 2011
Cooling towers(CC) with CCS	1.40	1.40	McMahon & Price 2011
Dry cooling (CC)	0.00	0.00	US DOE 2006, McMahon & Price 2011
Cooling tower, steam	2.50	4.10	McMahon & Price 2011
Once through cooling	0.07	1.40	McMahon & Price 2011
Pond cooling	0.90	0.90	McMahon & Price 2011
Dry cooling	0.00	0.00	McMahon & Price 2011

Inlet cooling	0.30	2.30	McMahon & Price 2011
Fossil/biomass/waste			
Once-through cooling	1.14	1.14	US DOE 2006
Cooling tower	1.14	1.82	US DOE 2006
Cooling pond	1.82	1.82	US DOE 2006
Dry cooling	0.00	0.00	US DOE 2006
Nuclear generation	1.51416	2.73	Gleick 1993
Once-through cooling	0.38	1.51	US DOE 2006, Gleick 1993, McMahon & Price 2011
Cooling towers	2.20	3.20	Gleick 1993, McMahon & Price 2011
Cooling pond	2.10	2.70	US DOE 2006, Gleick 1993, McMahon & Price 2011
Dry cooling	0.00	0.00	US DOE, Gleick 1993
Geothermal generation	10.98	10.98	US DOE 2006
Geothermal generation (vapor dominated)			
Cooling towers	5.30	6.80	US DOE 2006, Gleick 1993
Once-through cooling; Wairakei, New Zealand	13	13	Gleick 1993
Geothermal generation (water dominated)			
Cooling towers; Heber, U.S.	0.02	19.48	Gleick 1993
Dry	0.00	6.73	Gleick 1993
Hybrid	0.28	7.57	Gleick 1993
Wind-fire generation	0.00	0.00	US DOE 2006
Cooling towers	2.3	2.3	Gleick 1993
Solar			
Photovoltaics	0.02	0.11	Gleick 1993, McMahon & Price 2011, N 2002
Photovoltaics: Residential	0	0	Gleick 1993
Photovoltaics: Central utility	0	0.12	Gleick 1993, Macknick et al. 2011
Solar thermal	4	4	Gleick 1993

Dish engine solar	0.02	0.02	NREL 2002
CSP (Tower, Dry, Hybrid)	2.83905	3.48	
Solar trough	0.16	4.00	US DOE 2006, Macknick et al. 2011
Solar tower	0.10	3.26	US DOE 2006, Macknick et al. 2011
Fresnel	3.79	3.79	US DOE 2006, Macknick et al. 2011
Wind generation	0	0.00	US DOE 2006, Macknick et al. 2011
Ocean thermal	0	0	US DOE 2006, Macknick et al. 2011
Hydroelectric systems			
Aggregated in-stream and reservoir	5.39	68.14	Gleick 1993, Macknick et al. 2011
United States (average)	17.03	17.03	Gleick 1993, US DOE 2006
California (median)	5.4	5.4	Gleick 1993
California (mean)	26	26	Gleick 1993
Biopower	1.48	1.48	US DOE 2006
Tower (Steam, Gas)	0.89	3.65	Macknick et al. 2011
Once-through (Steam)	1.14	1.14	Macknick et al. 2011
Pond (Steam)	1.14	1.82	Macknick et al. 2011
Dry (Biogas)	0.13	0.13	Macknick et al. 2011