Water-Energy Nexus: *Solutions to Meet a Growing Demand*

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Abstract

Water and energy are vital to the prosperity of the United States. We describe the intimate but easily overlooked connections between the two resources: energy production relies on enormous amounts of water, and developing and delivering water supplies consumes large amounts of energy. As demand for both water and energy is expected to increase with population growth, we describe the challenges to addressing limited water and energy supplies. Obstacles exist at all scales and demand involvement of stakeholders, experts, and policymakers. In particular, we argue that because of the ubiquitous nature of the nexus between water and energy, a large-scale or system view is required to address both resource supplies together. Water and energy managers, stakeholders, and consumers can benefit greatly from enhanced data coverage, improved coordination between stakeholders and government agencies, investments in technology, anticipated supply changes from climate change, and policies to encourage suitable utility and consumer practices. These actions require federal support and can help America maintain a prosperous future while minimizing the risk of catastrophic scarcity of water and energy.

1. Introduction

Water and energy are linked resources in high demand. Water is required for energy production, and energy is necessary for water supply. Thus, shortages of one can limit the availability of the other. This colimitation has impacted communities nationwide. It is especially obvious in cases where a shortage of water has required power plants to curb energy generation or where high electricity costs prohibit the feasibility of desalinization plants. The relationship between water and energy is no longer an emerging issue. It begs the attention of citizens, energy and water managers, and policymakers to ensure that both water and energy supplies remain reliable for the immediate and distant future.

Scope and terminology

To facilitate discussion of water use, it is necessary to clarify a few common terms. *Withdrawal* describes the amount of water that is removed from a source (usually expressed in gallons per day), but it does not indicate the amount that is returned to the source after use (or any possible effects on its quality). Water that is withdrawn and not returned to the source is *consumed* (also expressed in gallons per day); consumption is a better indicator of how much an activity impacts remaining supplies. Consumption usually occurs by evaporation or incorporation into crops and products; degradation of quality may also be considered consumption in some cases. Finally, the term *water use* can sometimes be vague and misleading without proper context to clarify whether it refers to withdrawal or consumption. We will avoid using the term *water use* to refer to such measurable quantities and instead use it to mean simply the sectors or purposes of water demand, such as agriculture or mining.

Like many previous discussions of the water-energy nexus (WEN), we focus primarily on freshwater availability. Freshwater supplies are finite, many are depleted, and the already high demand for them from many competing uses is expected to increase [*U.S. Department of Energy* (*USDOE*), 2006]. Water quality is important as well; energy generation significantly increases the temperature of water before returning it to the source [*USDOE*, 2006]. Extraction and refining of fuels, however, can degrade other aspects of water quality while also withdrawing and consuming large volumes of water. We recognize some of these water quality issues but generally emphasize freshwater as a resource that is becoming sensitive to high demands because its supply is limited.

On the other side of the WEN, we will discuss the consumption of energy for the development and use of water resources. Energy resources and supplies are a subject of exhaustive debate, and increasing energy demand only exacerbates the conversation. We largely limit ourselves to assessing the quantity of energy used by water, treating energy as a resource that can be subject to high demand, scarcity, and colimitation by water resources.

2. Current State of the Issue

2.1. Water for Energy: Thermoelectric Cooling

To the layperson, the association of “water” and “energy” together often evokes images of hydroelectric dams; the water-for-energy side of the nexus, however, is more complex. Hydroelectric dams are one way water is used for energy, but because water withdrawals are nonconsumptive, most water is returned to the river (although the altered timing of withdrawals can significantly impact downstream flows and aquatic ecosystems) [*Kenny et al.*, 2009]. When hydroelectric dams store water in reservoirs, they increase the surface area of the water and thus losses by evaporation. Nevertheless, these losses are dwarfed in comparison to those of thermoelectric power plants, which withdraw and consume enormous amounts of water to cool their steam turbine systems. Thermoelectric plants consume fuels to produce steam by heating water; the steam then exerts pressure to spin a turbine and generate electricity. To continue operation, the steam must be cooled, condensed, and recycled. Usually, water is the coolant: it is effective and plentiful in many places, and it has a high specific heat capacity and is often cold, making power generation more efficient [*USDOE*, 2006; *National Energy Technology Laboratory* (*NETL*), 2010; *Pate et al.*, 2007].

Freshwater withdrawals for thermoelectric cooling have increased slightly along with total freshwater withdrawals since the 1980s (Figure 1). Thermoelectric cooling competes with other water uses, and its share of total freshwater withdrawals has also been increasing. It exceeds even agriculture as the largest freshwater withdrawal category: in 2005, thermoelectric cooling accounted for 41% of total freshwater withdrawals (143,000 million gallons per day (Mgd) out of 349,000 Mgd).

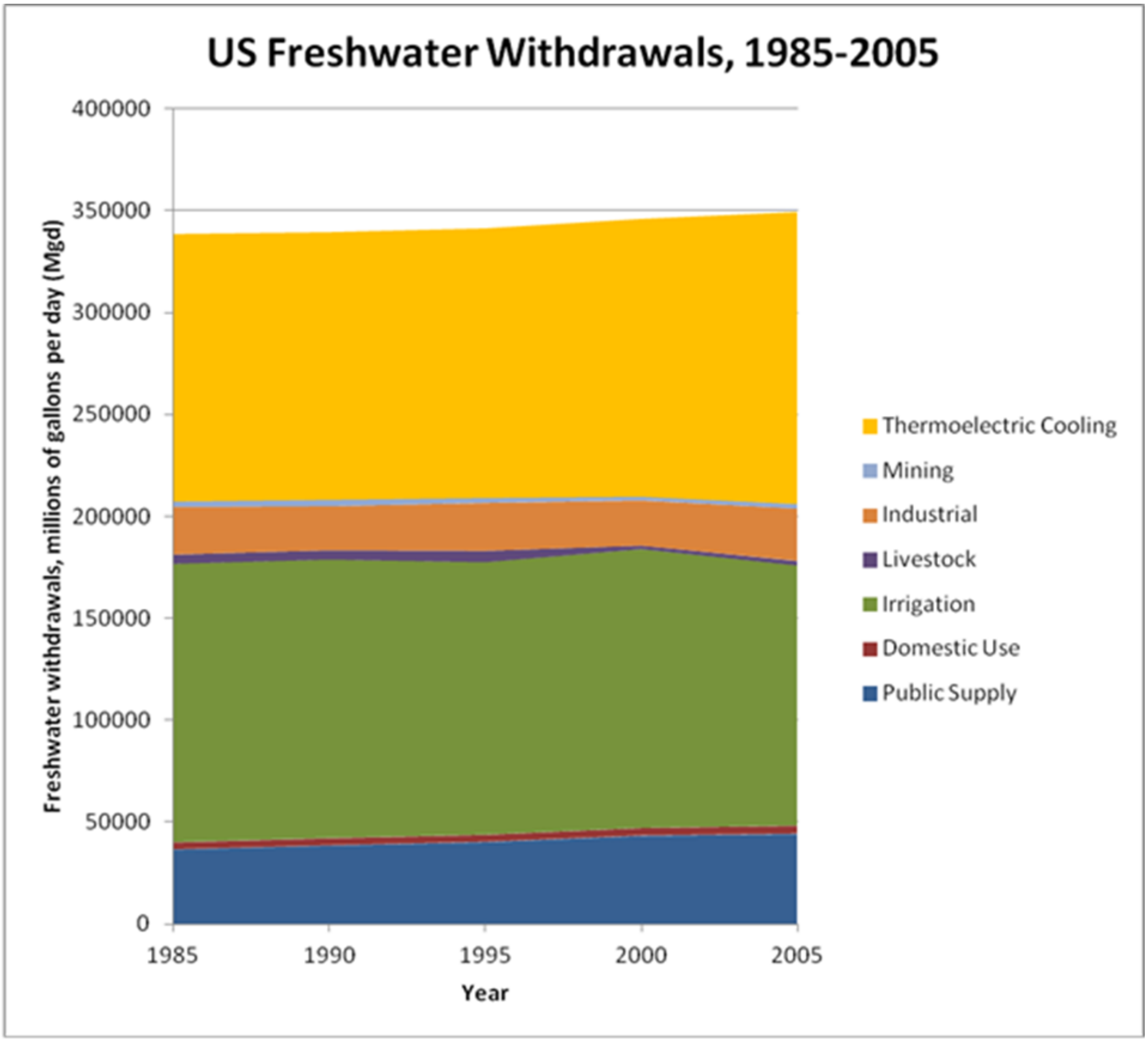

Figure 1. US Freshwater Withdrawals, 1985-2005. Total withdrawals have increased slightly since 1985. Much of this increase has come from increasing demand for public supplies and thermoelectric cooling [*Kenny et al.*, 2009].

In terms of consumption, thermoelectric cooling consumes significant volumes of water, but much less than it withdraws. It also makes up a much smaller portion of total consumption. In 1995 (the most recent year for which USGS consumption data are available), the thermoelectric sector consumed 3310 Mgd of freshwater, about 3.3% of the total 100,000 Mgd consumed by all uses (the *Atlantic Council* [2011] notes that some have estimated that thermoelectric cooling consumed about 4000 Mgd in 2005). Irrigation dominates consumption, making up 81% of the total, but thermoelectric cooling consumes about 17% of the water not used for irrigation [*Solley et al.*, 1998].

2.2. Water for Energy: Beyond Thermoelectric Cooling

In addition to cooling, water is often needed for extracting, transporting, processing, and refining fuels, as well as for electricity transmission [*Perrone et al.*, 2011]. Withdrawal and consumption requirements vary by fuel type, quality, and processing needs. Coal mining in the U.S. requires anywhere between 70 and 260 Mgd of water. On the other hand, oil and gas extraction often actually produces low-quality water from wells during drilling, which is mostly reused for enhanced oil recovery (EOR). As natural gas production has recently increased in the U.S., more water has been used; the USGS, DOE, and EPA have been charged with producing a report to better quantify water supply issues from hydraulic fracturing operations.

Withdrawals for fuel refining and transport are relatively small compared to those for thermoelectric cooling but are still significant [*Pate et al.*, 2007]. Oil refineries consume about 880 Mgd of water (about 1 gallon of water for each gallon of oil refined), and natural gas refining and pipeline transport consume about 400 Mgd. *Pate et al.* [2007] estimate that all aspects of energy production, from extraction to generation, together account for 25% of America's freshwater consumption (although this estimate does not seem to agree with *Solley et al.* [1998], so the issue may require further study).

Other emerging energy sources, which will fuel the transportation sector as an alternative to conventional oil, also have significant water requirements. Oil shale development, while facing high development expenses and concerns over carbon emissions, may also require as much as 2–5 gallons of water for each gallon of oil extracted. This could severely limit operations, especially since the largest oil shale supplies are found in the arid regions of Utah, Colorado, and Wyoming. Alternative waterless extraction methods are being developed, but they are energy intensive, which may limit their use and profitability [*USDOE*, 2006].

Biofuels, while a growing sector of the energy market, have potentially high water requirements. If grown in arid or semiarid regions, feedstock for biofuels can consume 1000 times more water through irrigation than through refining. This can compete with irrigation and land use needs for food crops [*USDOE*, 2006]. Other emerging fuels such as synfuels from coal and hydrogen fuel cells need up to three times as much water as petroleum refining [*USDOE*, 2006]. Detailed tables of the water required for transportation and electricity fuels extraction can be found in the Appendix.

2.3. Projections of Water for Energy Requirements

The Energy Information Administration (EIA) projects that electricity generation in the U.S. is expected to rise almost 25% over the next 25 years, from about 4100 billion kWh to 5100 billion kWh. Thermoelectric plants will be responsible for about 85–90% of total production [*Energy Information Administration* (*EIA*), 2011]. As new electricity plants replace old ones, there may be slight increases or decreases in water withdrawals through 2030, but overall, there should be little change [*USDOE*, 2006].

Consumption, on the other hand, is likely to increase. By 2030, the thermoelectric sector may double its 1995 consumption rates to about 6.6 Bgd (equivalent to the domestic consumption of 50 million people), depending on the efficiency of new cooling systems [*USDOE*, 2006]. More recent estimates are lower: the *National Energy Technology Laboratory* [2010] projects a rise of 24–39% by 2035, while the *Atlantic Council* [2011] expects a 63% increase by 2030. Nevertheless, even if current consumption rates remain constant, the rates may be unsustainable in the future, as seen in areas where water tables are declining [*USDOE*, 2006].

2.4. Energy for Water

Developing water supplies requires large amounts of energy to extract, transport, treat, distribute to end users, use by end users, and transport and treat resulting wastewater. Energy costs alone can account for about 75% of the processing and distribution cost of municipal water [*Pate et al.*, 2007]. In many cities, between 30 and 50% of the municipal energy budget is consumed by water supply processes, yet few cities have sought ways to curb this expense through upgraded technology or conservation [*American Water Works Association (AWWA)*, 2011].

Water supply contributes to a host of other energy demands in the face of scarce and expensive energy supplies [*Voinov and Cardwell*, 2009]. In 2002, approximately 4% of U.S. energy consumption was for water supplies (*USDOE*

[2006] from GAO and Electric Power Research Institute (EPRI)). This share of energy consumption is also expected to increase in the future as water supplies are depleted; it takes more energy to transport and process water from lower depths in shrinking aquifers and surface waters [*Pate et al.*, 2007].

The energy requirements of water supplies can vary regionally based on the water source (surface or groundwater), distance and elevation differences between the source and places of use, and climate. In some areas, heating water for domestic use can use more energy than supply and treatment. In California, where water is moved long distances by pumping, transport alone can be the most energy intensive process. The extent of water use for irrigation is usually the most important difference between regions, since watering crops can require large amounts of energy depending on water sources, climate, and crop varieties [*USDOE*, 2006].

2.5. Projections of Energy Use for Water

In the future, per capita energy demand for providing water, including transport and treatment, is not expected to increase much in most water use sectors (although total energy demand will increase as the population grows). In the industrial and agricultural sectors, per capita energy demand is expected to triple by 2030 [*USDOE*, 2006]. These types of projections usually assume current laws, regulations, and supply quality and quantity will stay the same. Predictions of the amount of energy that water will demand are likely a bit low in the face of anticipated stricter water quality standards, depleted supplies, and treatment of alternative or lower-quality supplies (e.g., desalination) [*Pate et al.*, 2007].

2.6. The Reach of the WEN Extends Beyond Water for Energy and Energy for Water

Both water and energy impact nearly every aspect of American livelihood, from food supply to transportation to industry. Even simple life cycle assessments of the sources of energy and water, their production and transmission, and their end uses show that the WEN extends far beyond the intersection where energy and water are used for each other. Growing water demands for energy production can impact supplies for competing water uses such as agriculture and public supply. The integrated and interconnected networks for both resources can lead to unexpected constraints on the ability to produce or access the resource. For example, the national energy grid operates as a network composed of thermoelectric, nuclear, hydroelectric, and alternative source facilities. Hydroelectric facilities are often used for energy demand peaking, but instream environmental flow requirements can limit the rates of ramping up (or down) of turbine releases. The timing of water withdrawals by one facility (or other water users) may temporarily limit water available to a downstream facility when it would be beneficial to produce energy at that facility. A recent study has found minimum streamflow requirements to be a significant constraint on the ability to accommodate wind power in a northeast energy grid [*Fernandez et al.*, 2012]. The extent of these conflicts is poorly understood at present. Addressing the critical connections between water and energy, and their implications for social and economic welfare, however, faces a number of challenges in a web of complex relationships.

3. Challenges

3.1. Data and Monitoring

At the national scale, the Energy Information Administration (EIA) provides detailed information from individual energy suppliers, while USGS monitors water supply and use. States also track and publish their own energy and water data, with varying degrees of quality, comprehensiveness, and accessibility. However, it is still difficult to find and synthesize information concerning the intersection of water and energy.

From the energy side, data are needed for regional electricity demand, energy production (including information on fuel and cooling systems used), water use by utilities, and projected electricity generation. From the water side, data are needed about the quantity and quality of available water, water withdrawals, water demand, and nonconsumptive flows returned to the system. Much of these data are publicly available through state and federal resources, but they vary greatly in their quality: large collections of data are outdated or have been too far aggregated to county, state, regional, or national scales for appropriate use. In addition, the areas and time periods covered by different sources do not line up [*Goldstein et al.*, 2008].

Congress took initial steps to address these needs in the Energy Policy Act of 2005. In the face of limited energy and water supplies and with the realization that the energy sector is a dominant water use and that water supply is a major energy use, Congress ordered the DOE to report on the water-energy nexus. The DOE submitted a report to Congress in 2006 [*USDOE*, 2006] and soon began work on an Energy-Water Research and Development Roadmap with regional assessments to approach WEN issues for release in 2007 or 2008 [*Pate et al.*, 2007]. Although the Roadmap was prepared for release, the DOE has withheld it since 2007 [*Schneider*, 2010]. In the meantime, the 2006 report has contributed to increased awareness of the WEN. Concerned stakeholders, researchers, and government agencies have continued to call for data, models, and, ultimately, policy.

One of the most glaring gaps in national-level data is the absence of any up-to-date nationwide water supply assessment. According to a *General Accounting Office* (*GAO*) [2003] report, there has been no comprehensive national-scale assessment of water availability since 1978. USGS recently conducted a pilot study for the Great Lakes Region in anticipation of a National Water Census, but no national census has yet been completed. This is particularly concerning since most state water managers surveyed in the GAO report expected local water shortages in the near future, and some even anticipated statewide or regional shortages. In addition, the most recent national water consumption data come from the USGS water use report in 1995 [*Solley et al.*, 1998], so there is uncertainty in the sustainability of supply depletion rates [*USDOE*, 2006].

Without sufficient federal information resources, state planning efforts to deal with WEN issues are also inadequate. Only nine states have statutes that explicitly address WEN issues: Arizona, California, Colorado, Connecticut, Nevada, South Dakota, Washington, West Virginia, and Wisconsin. A handful of others have generally included energy impacts in the definition of "environmentally sound" practices around water resources but do not yet have policies that directly address the WEN [*National Conference of State Legislatures*, 2009; *Atlantic Council*, 2011].

3.2. Coordination Problems Between the Energy and Water Communities

Poor coordination between energy and water managers and other stakeholders is often at the root of data issues. Data collection at regional and national scales is dependent upon cooperation from a diverse array of utilities that vary in ownership, authority, management, and geographic jurisdiction. Both energy and water utilities can be owned by private investors or by the public, and their planning and operations are influenced by a host of government agencies at state and federal levels, including coastal commissions, the EPA, Corps of Engineers, Bureau of Reclamation, Federal Energy Regulatory Commission, and so on. In addition, some utilities manage both water and energy for multiple states (e.g., the Tennessee Valley Authority), while others are limited to a few municipalities and individual resources in their authority and ownership of infrastructure (e.g., Tucson Electric Power Company or Tucson Water). The differences in water and energy utility ownership alone imply that there can be many possible relationships at a regional level. This can make WEN data collection by state and federal governments difficult [*Goldstein et al.*, 2008].

Data sharing has additional obstacles, whether they are between utilities or between utilities and government agencies. Different utilities have their own standards and use different software, data formats, and modeling methods, so there is no common platform for data sharing. The data currently available lack consistency in both the areas and time periods they cover. Jurisdictional boundaries between water and electric utilities rarely align and further complicate data synthesis. Even when complete data sets are available, there are often proprietary limitations. Competition between private utilities makes utilities reluctant to share data, in spite of protective federal data sharing provisions [*Goldstein et al.*, 2008].

3.3. Visibility and Valuation

The perception of the value of water and energy can further influence WEN issues. If energy and water resources are plentiful, they will remain inexpensive even if they are in fairly high demand. A major difference between water and energy is that energy is priced competitively and responds to changes in supply and demand. However, water is typically a natural monopoly, supplied by a single water utility that sets prices according to a number of factors, often including politics. For example, many cities subsidize the cost of municipal water supplies, which keeps water prices low but conceals the economic cost of supplying the water. As a result, water consumption if often greater than it would be if prices were set competitively. Raising water prices, while politically unpopular, encourages conservation [*AWWA*, 2011; *Atlantic Council*, 2011]. As water supply issues continue to emerge, the economic cost of supplying water will rise, which will increase the need to raise water prices. The high cost of water is becoming apparent as more water managers find it cost effective to utilize expensive wastewater reclamation and desalination projects as traditional high-quality supplies grow scarce [M. Hightower, personal communication, 2012].

3.4. Competing Demands and Changing Supplies

Energy and water availability will be subject to changes in both supply and demand. As population grows, so will energy and water demand, and the magnitude of changes will vary regionally [*Atlantic Council*, 2011]. The Southwest will see an 81% increase in thermoelectric generation capacity (compared to a 6% increase nationally) to satisfy the nation's most rapidly growing population [*NETL*, 2010]. Already scarce water supplies will be further strained, which will limit energy production if the Southwest remains largely dependent on thermoelectric power (there are many cases in the U.S. in which power plants have had to temporarily limit their operation due to insufficient water supplies) [*Goldstein et al.*, 2008]. The Southeast, the High Plains, California, and the western shore of Lake Michigan may experience similar situations. Although these places are not generally as arid as the Southwest, their withdrawals already exceed replenishment by precipitation. Water tables and reservoir levels have dropped considerably, and droughts have limited energy production [*Pate et al.*, 2007]. A map of anticipated population growth and available water supply can be found in the Appendix.

Perhaps the most compelling reason for addressing the water-energy nexus is the broad reach of both the water and energy sectors. Water and energy supplies feed many competing municipal, industrial, agricultural, and recreational uses, each essential to social and economic well-being. Competitive uses of water extend beyond those monitored by USGS. Withdrawal options for power plants can be limited by state or federal regulations (e.g., section 316(b) of the Clean Water Act) to support instream water uses like recreation and wildlife protection [*GAO*, 2003]. Future demands may add to the list of competitive uses. If carbon capture and storage (CCS) is mandated or incentivized for fossil fuel power plants, these facilities will have to produce more energy for carbon sequestration, with corresponding increases in water withdrawals and consumption. Estimates of increased water consumption are uncertain, ranging between 20 and 100% [*Pate et al.*, 2007; *NETL*, 2010; *Lyons*, 2012; *Atlantic Council*, 2011]. The interdependencies between water and energy supply systems are only partially understood and may produce surprises that constrain the ability to produce reliable supply of one or both of these resources.

Impacts from climate change will doubtless influence water and energy availability as well. Long-term shifts in water and energy supply will be subject to already emerging changes in precipitation, seasonality and timing of snowmelts, and temperature patterns, among other factors [*USDOE*, 2006; *Pate et* *al.*, 2007]. Effects will vary by region but will be of particular concern in arid and semiarid places with high energy demands [*USDOE*, 2006; *Pate, et al.*, 2007]. The combination of an intricate and far-reaching network of influence, population and resource demand increases, and impacts from climate change makes the WEN a central but complex issue that requires the attention of the entire community of social and economic stakeholders, administrators, and policymakers.

4. Solutions

4.1. Approaches to Improve Data Collection and Management

Improvement of data collection and monitoring is frequently cited as the first and one of the most important steps that should help in addressing WEN issues at the national and state level. State water managers have listed improved water availability and use data from USGS and EIA as one of the most important priorities to help them manage their water supplies [*GAO*, 2003]. Data collection by EIA and USGS could benefit greatly from better coordination and funding [*GAO*, 2009].

Data collection can ultimately benefit from better communication and coordination between energy and water utilities and managers, as well as from the inclusion of stakeholders. Water quantity regulations are largely managed by state water law, but national-scale support is necessary to assist state efforts. State water managers have suggested that the federal government can lend assistance in data collection and financing to upgrade water infrastructure, while also asking for improved coordination from the many federal agencies that are involved with water management. A few of their top priorities are more flexibility in implementing environmental regulations, better coordination when managing interstate and international water rights agreements, and better and more frequent consultation on federal and tribal water rights [*GAO*, 2003]. Improved federal involvement in data collection and coordination can be as simple as developing personal, working relationships between utility or agency managers [*Goldstein et al.*, 2008]. Proprietary issues and other barriers to trust arise less frequently when stakeholders are personally familiar with each other. An understanding of the purpose of data collection to address WEN issues may help as well. Introducing natural resource planning organizations invested in both water and energy supplies and integrated data collection can also help by bringing forward groups whose interests span both water and energy sectors [*USDOE*, 2006].

Support for data collection can also include promoting the use of evaluation mechanisms such as the WEN tool developed by *Perrone et al.* [2011]. The WEN tool utilizes basic information available to municipalities and their utilities to reveal the nature and magnitude of WEN issues a community faces. The tool ultimately incorporates these basic data into a life cycle assessment (LCA), which recognizes the true energy and water costs of each step from a resource’s origins to its final use, including extraction, transport, treatment and refining, transmission, and end use consumption. Many of these external processes may go unaccounted for in many sustainability assessments but are critical for thorough LCAs, which will be specific to each municipality's geography and demands. Communities can then use the WEN tool to identify more water- and energy-efficient resources and make improvements to infrastructure, regulation, and conservation efforts to enhance their independence and sustainability. Introducing an assessment method can raise awareness at the community level and perhaps even help lead to the development of a standard for data collection and use.

With the large variation in community resource portfolios and the diversity of potential relationships between stakeholders, WEN policies should be formed carefully to consider the sensitivity of both local and regional systems [*Atlantic Council*, 2011]. A path forward may be to address the WEN at local scales with large-scale support (perhaps by providing communities improved data from federal sources along with a means of applying it). This approach would allow customized state and local control while facilitating guidance at the regional level, ensuring organization and coordination between multiple states and stakeholders within watersheds. Finally, better datasets will lead to better modeling and forecasting of WEN interdependencies, which will in turn lead to better understanding of the risks and opportunities for managing the resources productively.

4.2. Expanding Supply

In the context of the WEN, much of the literature vigorously discusses expanding water supplies, since water is often a limiting factor in power generation. Although freshwater supplies are finite and declining on a per capita basis, supplies for power plants may be augmented with lower-quality water, using saline ground or surface waters or recycled wastewater. The financial and energy costs of treating low-quality water to a level acceptable for use may prevent immediate application, but some plants have already begun to use saline waters as coolant [*USDOE*, 2006]. If water becomes more expensive, it may be cost effective to invest in reclaimed wastewater.

4.3. Demand Reduction Through Efficiency

Another approach to managing energy and water resources is to reduce demand. The most popular approaches on the national scale tend to promote efficiency through development of technology. These options are attractive because the federal government already invests in research and development, and technological solutions often do not require end users to change consumptive behaviors. The National Energy Technology Laboratory (NETL) has a research program of Innovations for Existing Plants (IEP) in place to develop several technologies that, alone or together, reduce water consumption in thermoelectric cooling systems, potentially by as much as 50 to 70% at a relatively low operating cost. NETL also studies the use of nontraditional water sources, water reuse, and improved water treatment to lower water withdrawals and consumption [*Feeley et al.*, 2008].

The amount of energy used for water can be reduced as well. Installing more efficient pumps and motors in municipal water systems can cut energy use by 5–30%, particularly when enhanced by supervisory control and data acquisition. Even more basic strategies such as colocating power and water treatment plants can curb energy and water demands—for instance, biogas from water treatment can be used to produce power, and if power and water treatment plants are colocated, then the cost of transporting biogas fuel is very low [*USDOE*, 2006]. These types of improvements, however, can be very expensive and take a few decades to pay off [*AWWA*, 2011]. Since water and energy are intimately linked at the WEN, any reduction in the consumption of one resource will likewise reduce consumption of the other.

4.4. Demand Reduction Through a Changing Fuel Portfolio

Existing fuels can be replaced with less water intensive ones. Natural gas combined-cycle (NGCC) plants use gas combustion in addition to steam generation to power turbines and so use half the water of traditional coal plants [*NETL*, 2010]. Given that the EIA expects the share of energy generation from natural gas to increase from 24 to 27% of total production in the U.S. by 2035, NGCC plants may be a viable option to reduce water withdrawals and consumption as long as natural gas is relatively cheap [*EIA*, 2012; *NETL*, 2010].

Alternative energy technologies can offer energy production with little to no water consumption. Solar photovoltaic and wind power both have this capability but need to be supplemented with other fuels because of poor energy storage capacities. In addition, some hydroelectric dams have relatively low water consumption since water stays instream but have a host of other impacts on river ecology and recreational uses [*NETL*, 2010]. The Appendix contains figures with a more detailed comparison between the water uses of different fuel types for power generation.

Transportation fuels also vary in their water demands. Although any of them can be fairly water intensive, biofuels in particular should be considered with caution. Refining and processing of biofuels is comparable to that of traditional fuels, but if irrigation is required to grow feedstock for biofuels, their consumption of water can be extremely high (see Table A-2 in the Appendix).

4.5. Demand Reduction Through a Changing Cooling System Portfolio

The type of cooling system is usually the primary factor that determines the water intensity of a thermoelectric plant [*Macknick et al.*, 2011]. Plants have a few options for cooling, and each method differs in how much water it withdraws and consumes:

- *Open-loop* (or once-through) systems withdraw large quantities of water and then return it to the source at much warmer temperatures. As a result, open-loop systems lose less than 3% of their withdrawals to evaporation, but they can have profound temperature impacts on surrounding waters. About 43% of thermoelectric power plants in the U.S. use open-loop cooling.
- *Closed-loop* (or wet recirculating) systems withdraw smaller quantities of water, cool the water by evaporation in cooling ponds or towers, and then reuse it as coolant a few more times before it is discharged. Over 60% of the water they withdraw is consumed by evaporation, but they withdraw

only 5% of the water that open-loop systems do. About 56% of thermoelectric power plants in the U.S. use closed-loop cooling.

- *Dry recirculating* systems use air as a coolant, so little, if any, water is needed. Less than 1% of thermoelectric power plants in the U.S. use dry cooling (platts.com from *Feeley et al.* [2008]).

Table 1 shows common approximate water requirements for different cooling systems. For ease of comparison, the "water intensity" of different power plants and cooling systems is expressed as the volume of water withdrawn or consumed per unit energy produced (gallons per megawatt-hour, or gal/MWh). Typically, dry cooling systems have the lowest withdrawals and consumption. Open-loop systems have the highest withdrawals and closed-loop systems have the highest consumption, but open-loop systems consume only moderately smaller volumes of water. Values vary between plants depending on fuel, design, ambient conditions, and water source.

Table 1. Cooling System Water Intensities

Cooling system	**Withdrawal (gal/MWh)**	**Consumption (gal/MWh)**
Open-loop	7,500-60,000	100-300
Closed-loop	230-1,100	180-920
Dry	0	0

Adapted from USDOE [2006]

Although dry cooling systems withdraw and consume essentially no water, they are expensive to construct and are hindered in hot, arid climates. Compared to closed-loop cooling, dry cooling can penalize plant efficiency by 2–25%, resulting in 2–16% higher costs [*USDOE*, 2006]. Closed-loop systems can be advantageous in areas lacking abundant water supplies to support high withdrawals. Unfortunately, these are also often the same places where the higher consumption of a closed-loop system can be more devastating to declining water levels and reduce the water available to competing uses. These trade-offs are meaningful to power plant developers, and water intensity and availability can sometimes be major factors that influence a developer's decision on where to site a plant and which cooling system to use [*GAO*, 2009]. Upgrading power plants to more water-efficient systems can be very effective, but some plants may benefit greatly from cost-effective alternative efficiency technologies.

4.6. Demand Reduction by Customer Conservation

Conservation can also be driven by consumers changing their behavior and end uses to reduce consumption of both resources. Behavioral changes include installing water-efficient showers, faucets, washing machines, and toilets, which reduce water use, the energy required to heat hot water, and the embedded energy required to extract, treat, and deliver the water to the point of use. Interestingly, installing dishwashers poses an energy-water trade-off as dishwaters require additional energy to conserve water. Additionally, installing efficient hot water heaters, and tankless hot water heaters, changing the energy source for the hot water heater, and lowering the temperature of dispensed hot water reduce the energy required to heat hot water.

Suggestions for demand reduction by conservation sometimes go overlooked in the WEN literature but vary depending on the directives and foci of the publications. Management of demand is largely neglected in practice, even though demand in part determines the available supply [*Howe et al.,* 1971; *Vickers,* 2001; *Inman and Jeffrey,* 2006; *Kampragou et al.,* 2011]. *Voinov and Cardwell* [2009] maintain that "curbing demand is cheaper, faster, and ultimately more beneficial to individuals than increasing supply."

Conservation of either energy or water will reciprocate conservation of the other resource. Promotion of conservation in this context can be difficult since energy and water resources are often managed separately: power utilities often have programs in place to promote conservation of energy but have no authority to also promote conservation of water in an effort to conserve energy [*USDOE,* 2006]. Nonetheless, there are basic steps to improve conservation, even without explicit recognition of WEN issues. State water managers have indicated that the federal government may be able to best support these efforts by providing financial assistance to help upgrade and expand water infrastructure [*GAO,* 2003]. This could be particularly helpful where a great deal of water and energy is lost due to leaks in aging water infrastructure [*Pate et al.*, 2007]. Conservation can also be promoted by using regulation to price water to reflect its economic value when in short supply, and to account for the cost of treating low-quality supplies [*Atlantic Council*, 2011]. However, urban water demand tends to respond slowly to price changes, and the political barriers to price increases are significant. Along with other strategies, conservation can be included in policies that address the WEN to effectively ensure reliable and affordable water and energy supplies for the future prosperity of the United States.

5. Conclusion

The relationship between water and energy is intricate, strong, and far-reaching. Americans depend heavily on reliable supplies of both water and energy for their social and economic well-being. These codependent resources are in high demand from many competing uses, which restricts their availability. Demand for both is expected to increase in the near future, which will further limit their supplies for an increasing population. Areas like the Southwest, where water availability is low and energy and water demands are high and rising, are increasingly vulnerable to shortages. Scarcity will be further exacerbated by the growing influence of climate change on both demands and supplies. Despite these challenges, America has the foresight and resources to begin resolving the issues related to the water-energy nexus on a national scale. The federal government can play a major role by providing enhanced data, better coordination and communication between stakeholders, investing in technology, and offering financial support to resource managers to improve infrastructure, develop alternative supplies, and encourage conservation. The water-energy nexus spans the nation and yet has unique features at the community level.

There are roles to address water and energy issues together at all scales of influence, from municipalities to the federal government.

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Appendix

Table A-1. Water Consumption for Transportation Fuels

Fuel Type and Process	Relationship to Water Quantity	Relationship to Water Quality	Water Consumption	
			Water consumed per-unit-energy [gal/MMBTU]†	Average gal water consumed per gal fuel
Conventional Oil & Gas -Oil Refining	Water needed to extract and refine; water produced from extraction	Produced water generated from extraction; Wastewater generated from processing	7 – 20	~ 1.5
-NG extraction/Processing			2 – 3	~ 4
Biofuels -Grain Ethanol Processing	Water needed for growing feedstock and for fuel processing	Wasterwater generated from processing; Agricultural irrigation runoff and infiltration contaminated with fertilizer, herbicide, and pesticide compounds	12 – 160	~ 4
-Corn Irrigation for EtOH			2500 – 31600	~ 980*
-Biodiesel Processing			4 – 5	~ 1
-Soy Irrigation for Biodiesel			13800 – 60000	~ 6500*
-Lignocellulosic Ethanol and other synthesized Biomass to Liquid (BTL) fuels	Water for processing; Energy crop impacts on hydrolic flows	Wastewater generated; Water qulaity benefits of perennial energy crops	24 – 150 [‡][∫] (ethanol) 14 – 90 [‡][∫] (diesel)	~ 2 – 6 [‡][∫] ~ 2 – 6 [‡][∫]
Oil Shale -In situ retort	Water needed to Extract/Refine	Wasterwater genergated; In-situ impact uncertain; Surface leachate runoff	1 – 9 [‡]	~ 2 [‡]
-Ex situ retort			15 – 40 [‡]	~ 3 [‡]
Oil Sands	Water needed to Extract/Refine	Wasterwater generated; Leachate runoff	20 – 50	~ 4 – 6
Synthetic Fuels -Coal to Liquid (CTL)	Water needed for synthesis and/or steam reforming of natural gas (NG)	Wastewater generated from coal mining and CTL processing	35 – 70	~ 4.5 – 9.0
-Hydrogen RE Electrolysis			20 – 24 [‡]	~ 3 [‡]
-Hydrogen (NG Reforming)			40 – 50 [‡]	~ 7 [‡]

[†] Ranges of water use per unit energy largely based on data taken from the Energy-Water Report to Congress (DOE, 2007)

[*] Conservative estimates of water use intensity for irrigated feedstock production based on per-acre crop water demand and fuel yield

[‡] Estimates based on unvalidated projections for commercial processing; [∫] Assuming rain-fed biomass feedstock production

Table A-1. A comparison of water consumption demands from various transportation fuels by *Pate et al.* [2007]. Since vehicles engines are not steam turbines that require water withdrawals, there are no water cooling demands for these fuels. Water intensity is indicated by the amount of water consumed to produce a given amount of energy from a fuel, in gallons per million British thermal units (gal/MMBTU). Water intensity is also indicated by the amount of water consumed for a given amount of fuel, in gallons of water per gallon of fuel. Note that estimates for biofuels are based on the potential for high irrigation requirements. If biofuel feedstock is grown where irrigation needs are low, consumption can be significantly reduced. In addition, the ranges seen here reflect the variable amounts of water needed for specific locations and fuel sources.

Table A-2: Water Intensity of Power Plant Fuels and Cooling Systems

		Water Intensity (gal/MWh$_e$)			
Plant-type	**Process**	**Steam Condensing**		**Other Use**	
Steam		**Withdrawal**	**Consumption**	**Withdrawal**	**Consumption**
Coal	Mining				5 – 74
	Slurry			110 – 230	30 – 70
Fossil/biomass/waste	OL Cooling	20,000 – 50,000	~ 300	~ 30 **	
	CL Tower	300 – 600	300 – 480		
	CL Pond	500 – 600	~ 480		
	Dry	0	0		
Nuclear	Mining and Processing				45 – 150
Nuclear	OL Cooling	25,000 – 60,000	~ 400	~ 30**	
	CL Tower	500 – 1,100	400 – 720		
	CL Pond	800 – 1,100	~ 720		
	Dry	0	0		
Geothermal Steam	CL Tower	~ 2000	~ 1400	Not available	
Solar Trough	CL Tower	760 – 920	760 – 920	8**	
Solar Tower	CL Tower	~ 750	~750	8**	
Other					
Natural Gas	Supply				~11
Natural Gas CC	OL Cooling	7,500 – 20,000	100	7– 10**	
	CL Tower	~230	~180		
	Dry	0	0		
Coal IGCC*	CL Tower	~250	~200	7 – 10 + 130 (process water)**	
Hydroelectric	Evaporation				4500 (ave)

OL = Open loop cooling, CL = Closed Loop Cooling, CC = Combined Cycle
*IGCC = Integrated Gasification Combined-Cycle, includes gasification process water
Other Use includes water for other cooling loads such as gas turbines, equipment washing, emission treatment, restrooms, etc.
**References did not specify whether values are for withdrawal or consumption

Table A-2. A review of water intensities for various power plant fuels and cooling systems by *USDOE* [2006]. Cooling needs typically outpace the demand for fuel extraction and refining. Note that the variability in values depends on the specifics of plant design, ambient condition, and fuel and water sources.

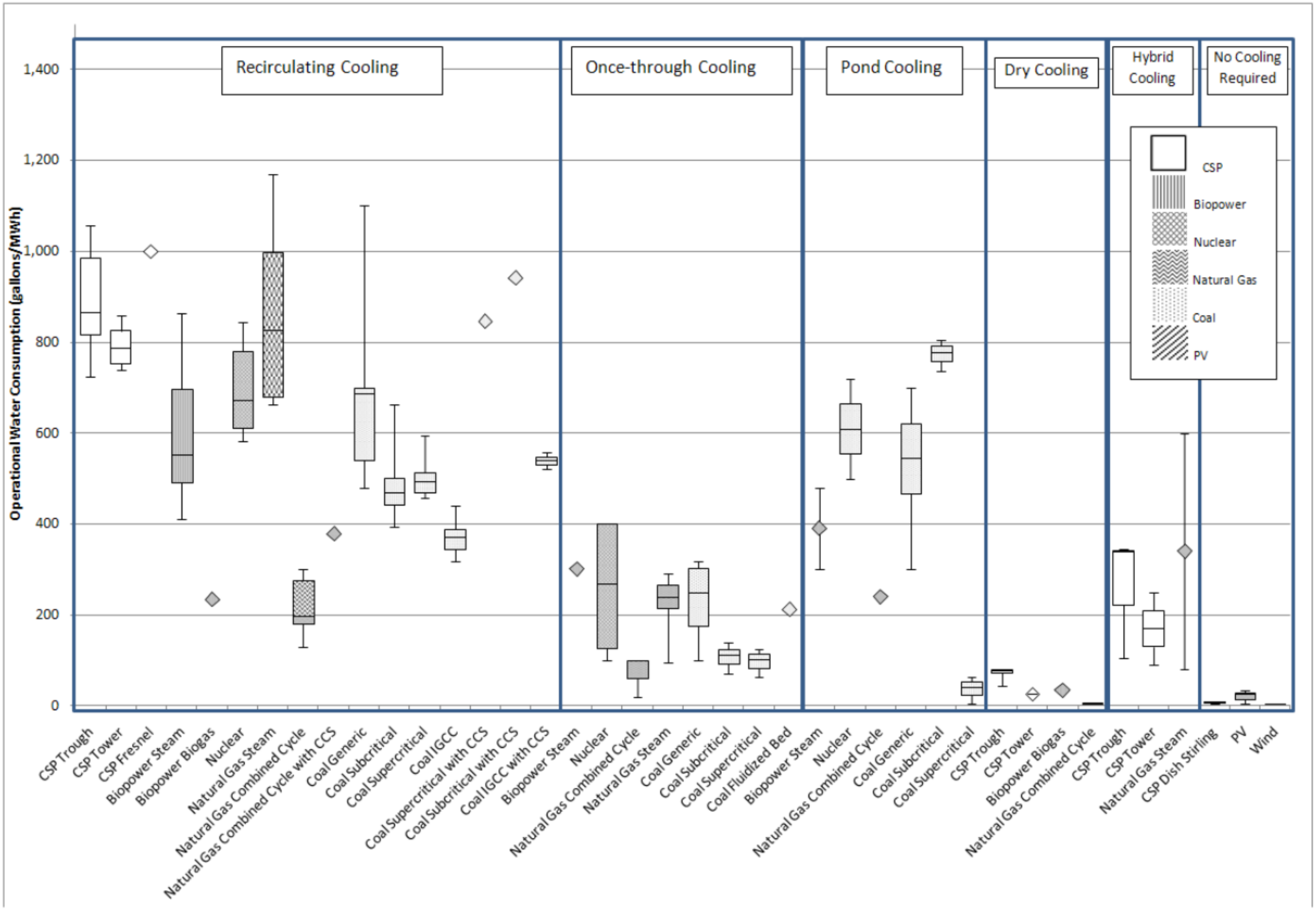

Figure A-1. Operational water consumption factors for electricity generating technologies. IGCC: Integrated gasification combined cycle. CCS: Carbon Capture and sequestration. CSP: Concentrating solar power. Whisker ends represent maxima and minima. Upper and lower ends of boxes represent 75th and 25th percentile, respectively. Horizontal lines in boxes represent medians [Macknick et al. 2011].

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