Section I. Energy for Water

INTRODUCTION

The water use cycle is relatively uniform and consistent among developed countries. Beginning with a water source, water is extracted and conveyed, moving directly to an end use (e.g., irrigation) or to a treatment plant, and from there it is distributed to customers. Once it is used by the end users, water then moves through a wastewater collection system to a treatment plant and is typically discharged back into the environment, not always to the same place from which it was originally extracted. In some limited cases, water may leave the treatment plant to be used again before eventually being discharged. Every step along this cycle involves energy inputs, outputs or both. The section explores the body of literature looking at the energy intensity of water at each point from extraction to end use.

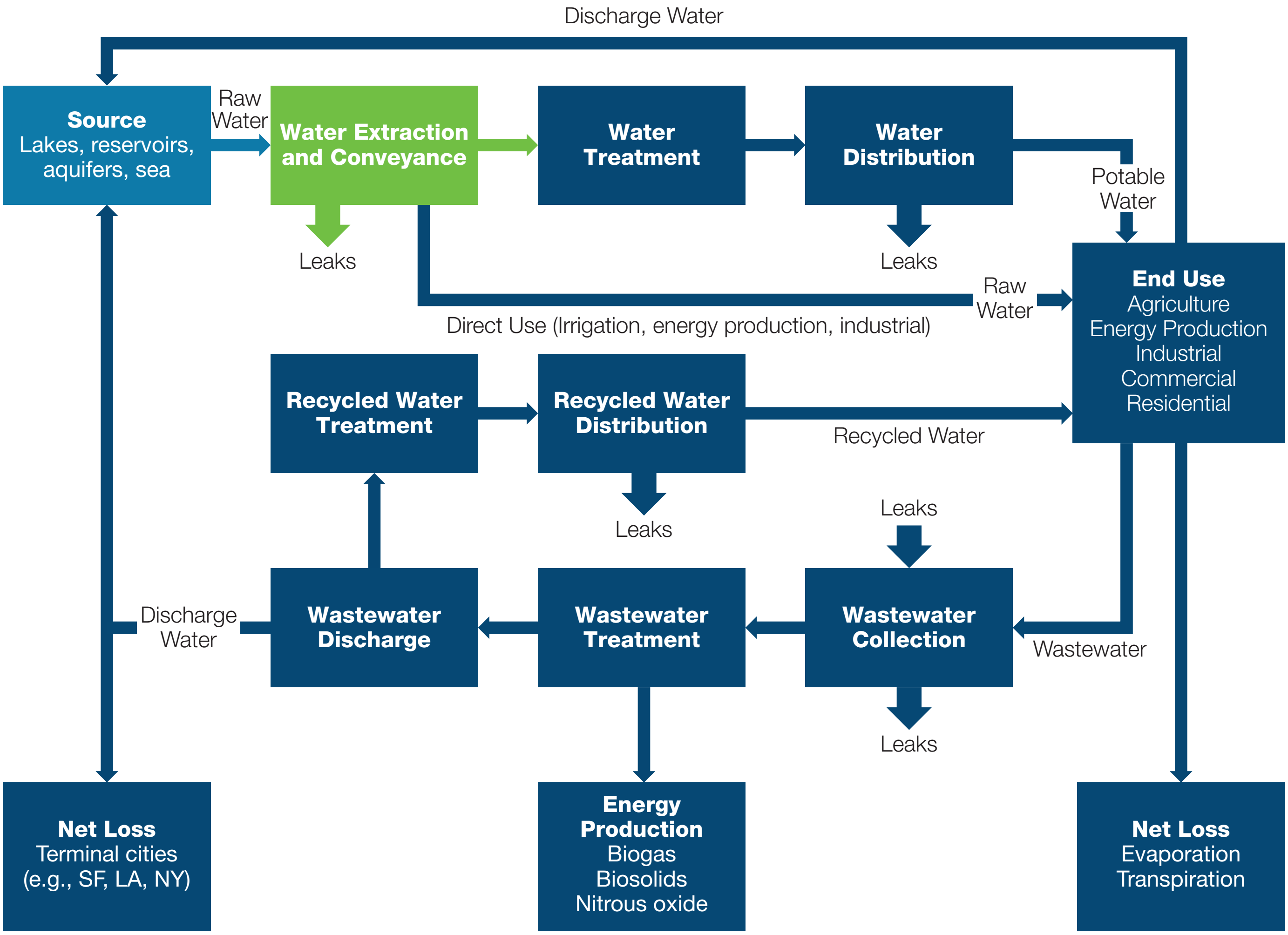
ENERGY FOR WATER EXTRACTION

More than three-quarters of the United States freshwater supply comes from rivers, lakes and streams, which collect rainfall and snowmelt (U.S. Geological Survey, 2005), although sources can be highly variable. Groundwater aquifers provide about 22 percent of U.S. freshwater and up to 30 percent in California (Wolff et al., 2004). Water supplies also tend to vary widely according to season.

While desalination is a fairly insubstantial contribution to water supply nationally, it is a source being considered and, in a few places, used by communities around the country, tapping sources such as brackish water or seawater (Wolff et al., 2004). The extraction (or taking) of water from these different sources can require anywhere from modest to extreme amounts of energy.

This section explores and evaluates the literature around the energy use of water extraction (Figure 1). Most papers and reports come from and are centered on California, which has been very engaged in the water-energy nexus and water and energy conservation (Gleick, 1994; CEC, 2005; Cooley et al., 2008; Cooley & Wilkinson, 2012; Bennett et al., 2010 a&b), but there have been other studies done in Texas, New York, Wisconsin and parts of the Intermountain West.

Figure 1. Water Flowchart (Highlighting Water Extraction and Conveyance)



Source: Adapted from Wilkinson, 2000

1. Surface Water

According to U.S. Geological Survey (USGS) data, 22 billion gallons per day (BGD) of surface freshwater and 13 BGD of surface seawater are withdrawn in the U.S. (USGS, 2005; Smith, 2011). Typically, little to no energy is required to "make" surface freshwater into a supply (Bennett et al., 2010a; Table 1). Most of the freshwater withdrawn goes to agriculture and thermoelectric generation, while virtually all the seawater goes to thermoelectric generation.

Most studies do not separate surface water extraction from conveyance, a topic we address in a separate section. It is to be noted, however, that the U.S. Environmental Protection Agency (EPA) regulates water intakes for thermoelectric cooling, which might also offer regulatory innovation to garner the multiple benefits of water, energy and wider environmental goals. For example, Section 316(b) of the Clean Water Act requires that the location, design, construction and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact at the time of construction or major revision.

Table 1. Observed Energy Intensities for Different Supply Sources in California (kWh/MG)

				Range of Energy Intensities Observed (kWh/MG)				
	Functional Component	Primary Energy Drivers	Energy Intensity From Prior Studies	Northern & Central Coast	Central Valley	Southland	Desert	Statewide
Supply	Local Surface Water	Pumping		152 – 1,213				152 – 1,213
	Groundwater	Pumping	537 – 2,272	1,712 – 2,924	906 – 1,990	1,415 – 2,552	2,169 – 2,652	906 – 2,924
	Brackish Desalination	Treatment	1,240 – 5,220			1,415 – 1,824		1,415 – 1,824
	Recycled Water	Incremental Treatment	300 – 1,200	1,072 – 2,165		1,153 – 3,410		1,072 – 3,410
	Seawater Desalination	Reverse Osmosis	13,800					

Source: Bennett et al., 2010a

Surface water can come from lakes and rivers or from man-made drinking water reservoirs, which enable water storage and management over seasons or years. Although dams and reservoirs tend to have very long life expectancies, important energy inputs are required for the construction and eventual demolition of these structures in a life-cycle analysis. Moreover, evaporation and seepage losses are issues that limit the ability of the reservoir to provide relief over severe or extended drought conditions. It is a positive feedback loop where less water in the reservoir results in more evaporation when the water is needed most. Another problem is the sedimentation of reservoirs, which reduces reservoir capacity and can only be remedied through the manual time-, money- and energy-intensive removal of accumulated sediment.

2. Groundwater

While a lot is known about the energy used by specific pumps, little is known about how much groundwater Americans withdraw, the specific types of pumps they use, what fuel they use and whether they treat the water they pump. Moreover, the dynamics of groundwater flow and recharge, the limits of groundwater supply, and the presence and migration of contaminants are all still improperly understood.

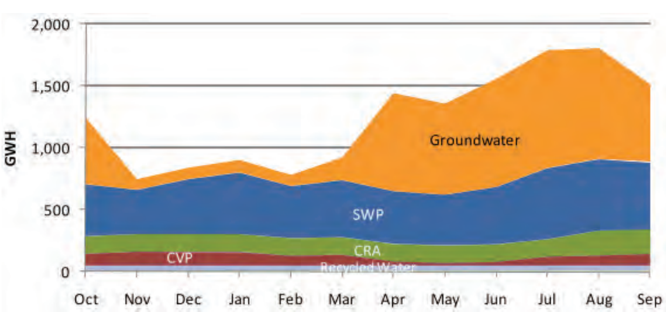
State law governs groundwater use in the U.S., and practices for managing groundwater vary. On one end of the spectrum, Texas generally allows anyone to drill a well and pump an unlimited amount of groundwater until the aquifer is exhausted. While California has not traditionally regulated groundwater pumping and does not track withdrawals, there is increased state attention to this issue, with a new program requiring elevation monitoring in groundwater basins to track seasonal and long-term trends (California Statewide Groundwater Elevation Monitoring [CASGEM], 2009). Most pumpers, especially in the agricultural sector, are individuals rather than cooperatives or public entities, which further exacerbates the data availability problem (Dinar, 1994). Even if users were responsible for better reporting, tracking groundwater use would still be fairly complex.

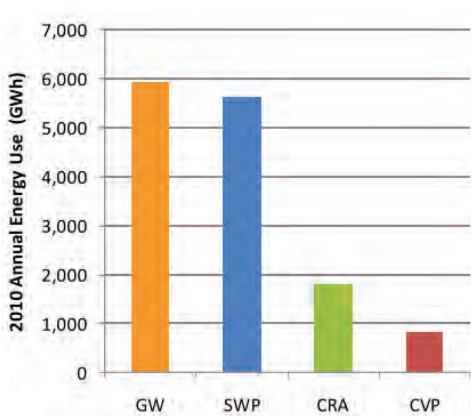
2.1 Groundwater Use in the U.S.

Working to compensate for this lack of data, estimates indicate that Americans pump approximately 80 billion to 85 billion gallons of groundwater per day, and our dependence on groundwater is increasing (Alley, 2010; Smith et al., 2011). Worldwide, up to 2 billion people depend on underground aquifers for their drinking water; however, in the U.S., two-thirds of the groundwater pumped is used for irrigation.

Of equally critical importance to our investigation is the energy intensity of groundwater pumping, and the fairly sparse literature on this topic has not estimated how much energy is expended in groundwater pumping at the national level. In a study done for the California Public Utilities Commission, Bennett et al. (2010a) reported the monthly electricity requirements of groundwater pumping in California (Figure 2). They show that the amount of energy used for groundwater is substantial, particularly during the summer months, where it exceeds the combined energy requirements of the State Water Project, the Colorado River Aqueduct and the Central Valley Project combined.

Figure 2. Electricity Consumption in 2010 by Major California Water Supplies





Source: Bennett et al., 2010 a&b

According to the U.S. Geological Survey (USGS), nationwide groundwater withdrawals in 2005 amounted to 80 billion gallons per day (BGD) for freshwater and 1.6 BGD for saline groundwater (USGS, 2005; Smith, 2011). Burton (1996) estimated electricity consumption for groundwater systems at about 1,800 kilowatt-hours (kWh) per million gallons (MG) of water for public supply systems. While this national-level estimate is coarse, a finer-resolution estimate on the amount of energy used by these systems will depend on the groundwater elevation, the volume pumped and the efficiency of the pumps.

The Santa Clara Valley Water District estimates that farmers in the San Francisco Bay Area in California use about 1,000 kWh/MG for groundwater pumping. Wolff et al. (2004) estimate that groundwater extraction for agriculture requires 540 to 2,300 kWh/MG. Bennett et al. (2010a) estimate groundwater withdrawals to require 900 to 2,900 kWh/MG. About 10 percent of groundwater is used for other purposes such as mining, aquaculture and thermoelectric cooling. Based on the literature, the energy required for groundwater extraction is estimated to be 30,000 to 50,000 gigawatt-hours (GWh), or roughly 1 percent to 2 percent of total U.S. electricity production. Bennett et al. (2010a) estimate that California used 7,000 GWh of electricity on groundwater extraction in 2010.

The amount of energy devoted to groundwater pumping depends on a) how far the water must be pumped before reaching the surface, which can change seasonally; b) the volume of groundwater pumped; and c) the types of pumping devices water rights holders choose to use (e.g., age, efficiency, fuel type). A well's necessary depth varies widely across regions and is often in flux, especially in aquifers where the water table is depleting rapidly. Changes in water table elevation and clogged well screens can cause groundwater pumps to run less efficiently, thus increasing the amount of energy needed to pump groundwater (Bennett et al., 2010b). And there is also a great deal of variation in types of groundwater pumps, ranging from solar-powered pumps (Van Pelt et al., 2008) to dated electric or diesel-powered pumps (Robinson, 2002). High diesel prices have forced the shutdown of several pumps on the Ogallala aquifer (Gleick, 1994; Zhu et al., 2007). In California, improving air quality has been a main driver for replacing diesel pumps with natural gas or electric pumps.

2.2 Next Steps

In the absence of more data about actual groundwater use, researchers could approach this question from another angle and begin their inquiry with the pumps themselves. The literature does not identify the kinds of pumps that are used and whether those pumps are the most energy efficient available. Bennett et al. (2010 a&b) identified that better (and more granular) water energy data on groundwater is necessary at the state and federal level. It could give not only a better idea of the state of aquifers in the country, but also of the energy requirements for groundwater in the U.S. With this information, public-sector energy-efficiency programs could more readily capture the full potential for energy savings from groundwater-pump optimization. Some utilities already offer free pump testing and rebates on old and inefficient pumps.

Still another approach would be to model the relative costs of energy needed to pump groundwater and the cost of buying wholesale surface water. While groundwater has historically been an inexpensive resource for agricultural producers, especially in states like Texas that do not limit groundwater use, increasing energy prices may become a substantial problem for farmers. (For a model – albeit somewhat outdated – that captures portions of this suggested analysis, see Dinar, 1994.)[1] However, there is no indication that rising energy costs have historically triggered a decrease in groundwater pumping (Zhu et al., 2007). In addition, wholesale surface water is often heavily subsidized, which makes it difficult to determine the energy price point that forces switching from ground to surface water.

3. Desalination

More saline water sources such as brackish groundwater and seawater can be converted into usable water supplies by reducing the contents of total dissolved solids (TDS) or salt and minerals. Brackish water is a mixture of freshwater and seawater, being more saline than freshwater and less saline than seawater. In 2005, roughly 2,000 desalination plants larger than 0.3 MGD were operating in the U.S. with a total capacity of 1,600 MGD, and constituted less than 0.4 percent of total water use in the U.S., (Carter, 2011). The energy intensity of desalted water depends primarily on the volume of the water being desalted, the quality (i.e., saltiness) of the source water supply and the technology used to desalt the water (Bennett et al., 2010).

Brackish water has much lower TDS than ocean water and therefore takes much less energy to desalt (Tables 1 and 2), with energy intensities ranging from 1,400 to 1,800 kWh/MG (Bennett et al. 2010a). Energy intensities for seawater desalination vary greatly from one technology or one study to another (Chaudhry, 2003; California Energy Commission [CEC], 2005; Younos & Tulou, 2005; Cooley et al., 2006; Cooley & Wilkinson, 2012; National Research Council [NRC], 2008; Bennett et al., 2010a). However, multiple efforts are under way to increase the energy efficiency of desalination through improved membranes, dual pass processes and additional energy recovery systems such as Combined Heat and Power (CEC, 2005).

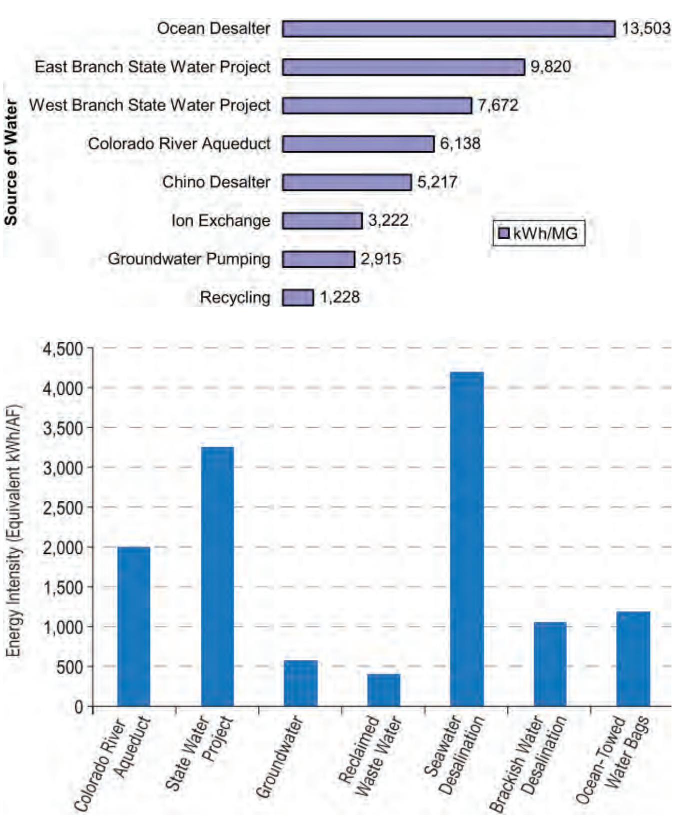
1 The Dinar study is only one example of a series of hypothetical models that shine some light on future energy use for groundwater pumping. For another example, see California Public Utilities Commission, Appendix G: Groundwater Use (2011).

Table 2. Salt Concentrations of Different Water Sources

Water Source or Type	Approximate Salt Concentration (grams per liter)
Brackish waters	0.5 to 3
North Sea (near estuaries)	21
Gulf of Mexico and coastal waters	23 to 33
Atlantic Ocean	35
Pacific Ocean	38
Persian Gulf	45
Dead Sea	~300

Source: Cooley et al., 2006

Figure 3. Energy Intensity of Inland Empire Utility Agency and San Diego (Calif.) Water Supply Options



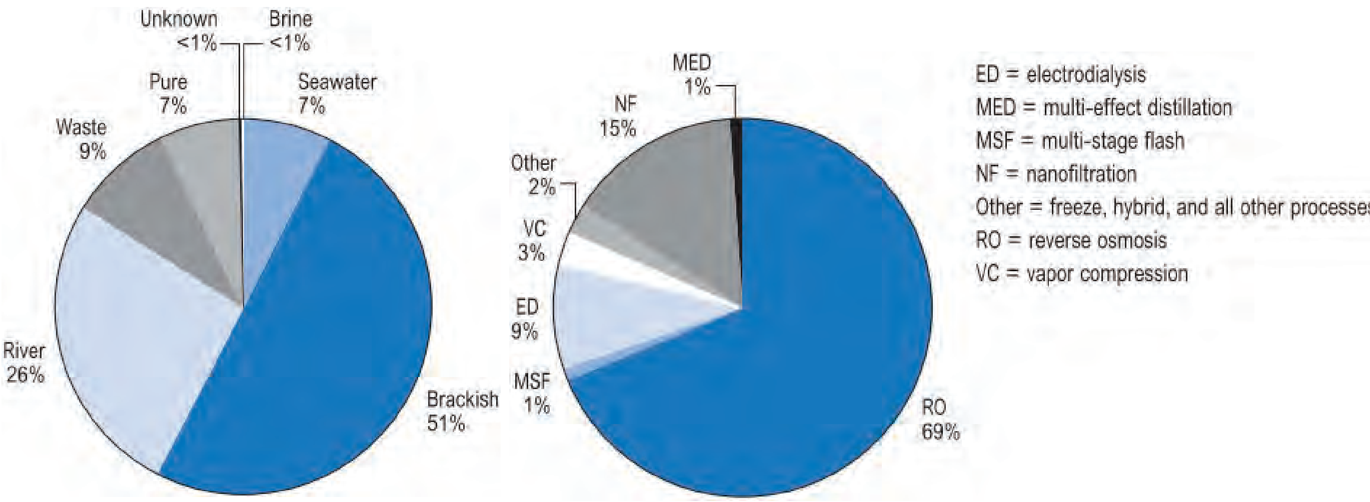
Source: CEC, 2005 and Cooley et al., 2006

Desalination is often the most energy-intensive water option for utilities, as shown by Figure 3 for the Inland Empire Utility Agency and San Diego, both in California. However, particularly in the arid West, the abundance of seawater and brackish groundwater is enough to make desalination a recurrent debate. Subsidies and incentives for desalination have the tendency to mask the true cost of providing water, avoiding issues such as overpopulation and overuse (Cooley et al., 2006; NRC, 2008). Therefore, it is important to account for the energy intensity in regional water supply portfolios as part of determining the cost effectiveness of developing particular water supplies in any given region relative to a region's marginal water supply, or the last increment of supply in a particular region, be it surface water, recycled water, groundwater or desalinated water.

3.1 Desalination Technologies

There are several different technologies for desalination, which can be divided into two major categories: thermal and membrane processes. The choice of the technology is based on operation and maintenance considerations, location, energy intensity, capital costs and water quality. In the U.S., most of the installed capacity for desalination is for brackish water and uses reverse osmosis (OS) technology (Figure 4). Seawater plays a very limited role (7 percent of installed capacity), but is likely to have a much larger role in the future, particularly in southern California, Texas and Florida.

Figure 4. U.S. Desalination Capacity by Source Water and Technology in 2005

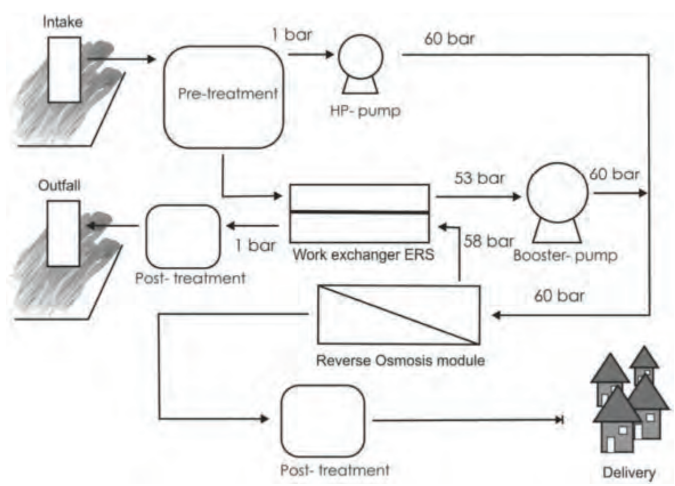


Source: Cooley et al., 2006

i. Reverse Osmosis (RO)

Semi-permeable membranes are used to retain salts and solids and let water through. This technology requires a pressure difference to be maintained across the membranes (Figure 5). All membrane processes require heavy treatment of the water prior to desalination because of fouling issues. The salt concentration will directly determine the energy requirements for RO. The operating pressures for brackish water desalination range from a pressure of 15 to 30 bar and for seawater from 55 to 70 bar. The theoretical minimum amount of energy required for the desalination of seawater is about 3,000 kWh/MG (Cooley et al., 2006). Current technologies require 1,400 to 2,000 kWh/MG for brackish water (Bennett et al., 2010a); 9,500 to 38,000 kWh/MG for seawater (NRC, 2008; Charcosset, 2009); and 8,700 to 22,000 kWh with combined heat and power (CHP) (Younous and Tulou, 2005).

Figure 5. Simplified RO Scheme With Energy Recovery System



Source: Fritzmann et al., 2007

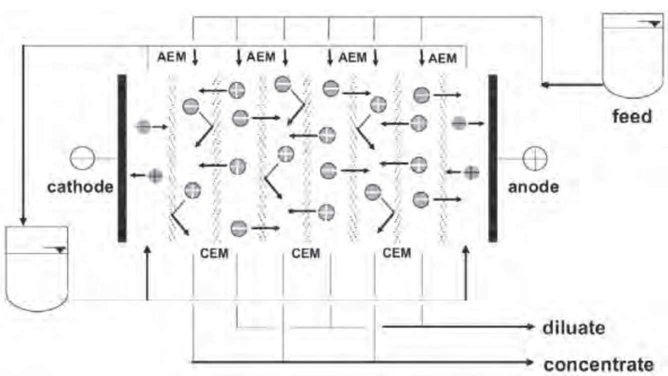
ii. Nanofiltration

Nanofiltration (NF) is a membrane process very similar to reverse osmosis, but it uses lower operating pressures. NF is used primarily for brackish water treatment and water softening. An NF plant typically requires 3,500 kWh/MG for operations (NRC, 2008).

iii. Electrodialysis (ED)

Electrodialysis (ED) is a method that uses membranes which are selectively permeable to ions (either cations or anions). This technology is most commonly used for the desalination of brackish water. Usually brackish water is pumped at low pressure between flat, parallel, ion-permeable membranes, and an electric current pulls ions through the membranes (Figure 6). Like reverse osmosis, the energy cost of ED rises with the concentration of the salts in the water. Yonous and Tulou (2005) report that desalination of brackish water with ED has an energy intensity of 6,400 kWh/MG, while the NRC (2008) reports an energy intensity of 1,900 kWh/MG, which seems more consistent with the findings of Bennett et al. (2010a; Table 1), who report 1,400 to 1,800 kWh/MG in California for brackish water desalination. These different findings could reflect the rapid changes in industry practices.

Figure 6. ED Process Principle



Source: Fritzmann et al., 2007

iv. Multistage-Flash Distillation (MSF)

Unlike the other three desalination methods discussed so far, multistage-flash distillation (MSF) is a thermal process. MSF produces high-quality freshwater with very low salt concentrations. A typical MSF system consists of several evaporation chambers arranged in series. Each has lower pressures and temperatures that cause flash evaporation of the feedstock (Figure 7). The vapor is then followed by condensation on cooling tubes at the top of each chamber. These thermal systems are extremely energy intensive and require 100,000 to 260,000 kWh/MG (Gleick, 1994; Sandia National Laboratories, 2003; NRC, 2008), but can be as low as 18,000 kWh/MG using combined heat and power (Younos and Tulou, 2005). The largest MSF plant in the world is in the United Arab Emirates and has a total capacity of 120 MGD, using seawater (Cooley et al., 2006).

v. Multiple-Effect Distillation (MED)

This is one of the oldest and most efficient desalination methods and relies on evaporators and condensers in series (Figure 8). MED takes place in a series of vessels and reduces the ambient pressure. This seawater undergoes multiple boilings without supplying additional heat after the first vessel (Cooley et al., 2006). Like all thermal processes, this technology requires a lot of energy: NRC (2008) reports that 150,000 to 400,000 kWh/MG are required in the form of both thermal and electric energy.

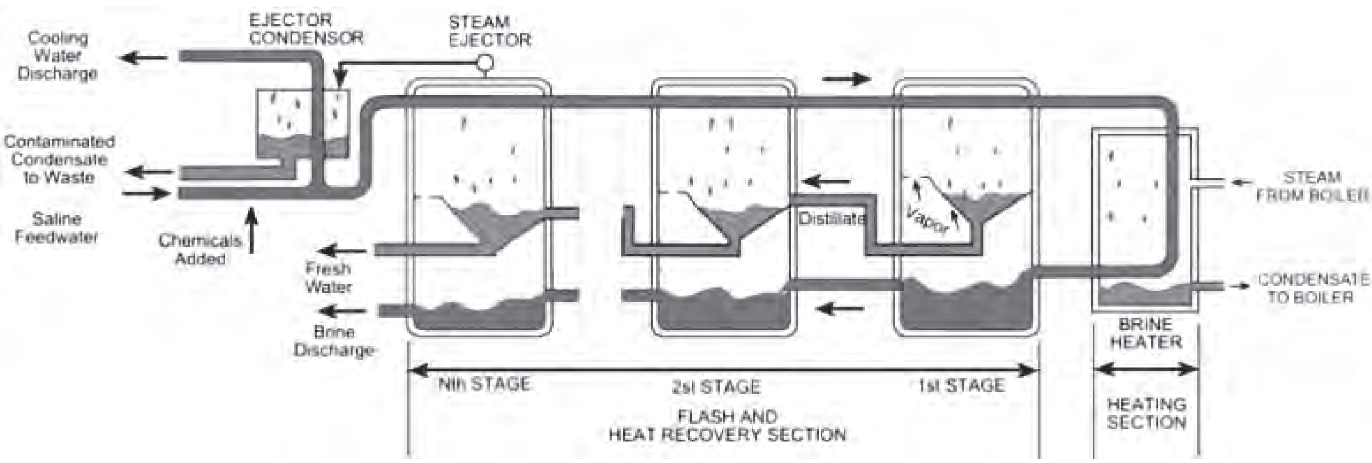
vi. Vapor Compression

Vapor compression is a thermal process that is typically used for small seawater units in tourist resorts, small industries and remote sites (Cooley et al., 2006). These units take advantage of the principle of reducing the boiling point temperature by reducing ambient pressure and condense water by raising pressure (Figure 9). These plants require 30,000 to 60,000 kWh/MG (Younos and Tulou, 2005; NRC, 2008).

vii. Membrane Distillation (MD) or Hybrid

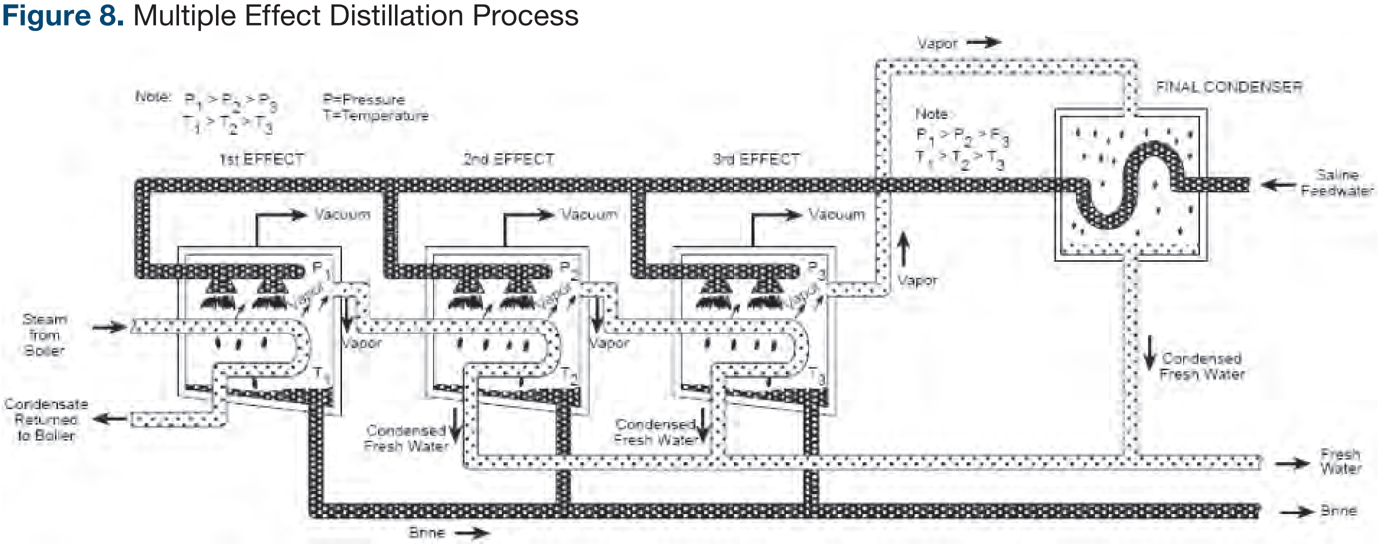
Membrane distillation combines the use of both thermal distillation and membranes. This technology has had little commercial success so far due to high capital costs, but it can have interesting applications with CHP (Cooley et al., 2006). One approach is to have two parallel plants and to blend the product water from both, enabling the membranes to operate with higher permeate TDS, substantially reducing their replacement costs (NRC, 2008). These facilities can also optimize water production and energy costs when electricity has seasonal or peak-demand variations in prices. The energy requirements for these facilities will depend strongly on its configuration (percentage of flow using MSF or reverse osmosis).

Figure 7. Simple MSF Distillation Process Scheme



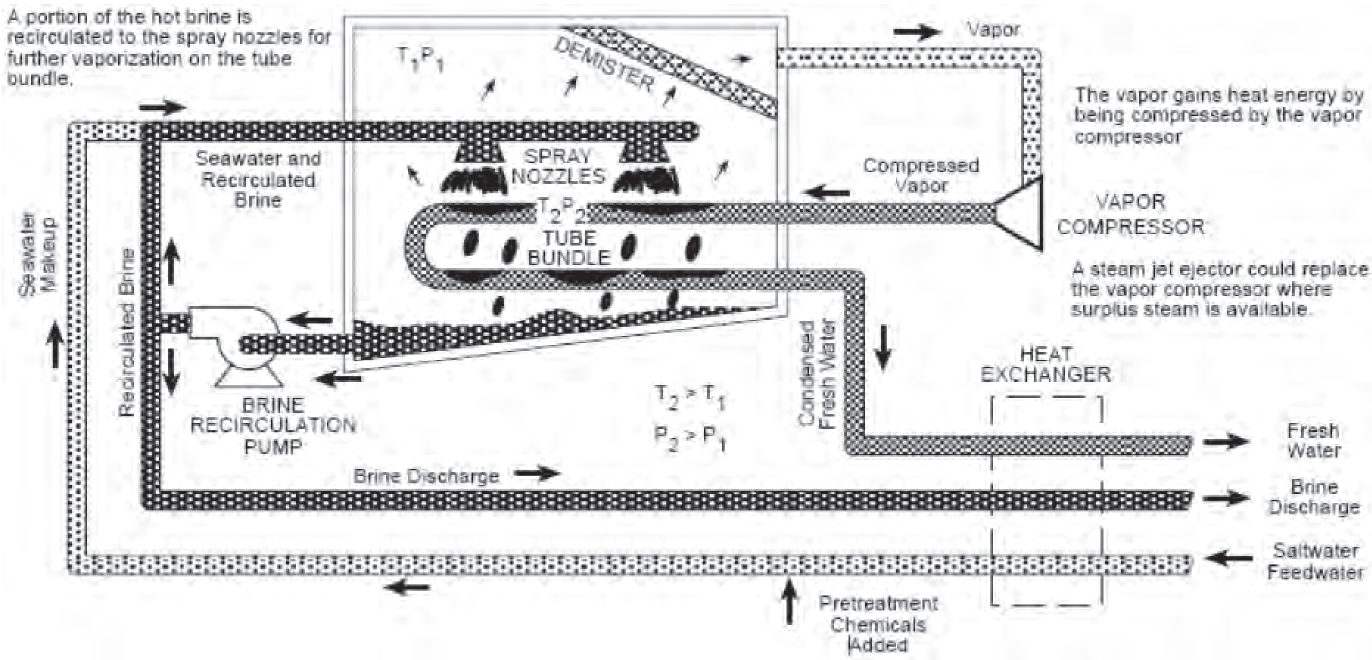
Source: Fritzmann et al., 2007

Figure 8. Multiple Effect Distillation Process



Source: NRS, 2008

Figure 9. Vapor Compression Process



Source: NRS, 2008

3.2 Energy Costs and Efficiency

The economics of desalination are tied to the cost and quantity of energy used for the process, as energy is the largest single variable cost for a desalination plant. Technologies range from 1,000 kWh/MG to 500,000 kWh/MG, often making desalination the most energy-intensive water option, although new desalination technologies and processes are lowering the energy intensity of desalination over the long run. The energy cost varies from one-third to more than one-half the total cost of desalinized water (Chaudhry, 2003). In addition, the volatility of energy prices will greatly impact water prices: a 25 percent increase in energy cost could potentially raise the cost of produced water by 11 percent and 15 percent for reverse osmosis (RO) and thermal plants, respectively (Cooley et al., 2006).

One of the ways to reduce the energy cost would be to develop a dedicated power plant along with the desalination plant, but federal (and California) utility laws prohibit existing power plants, which are co-located with other facilities, from selling power at a preferential rate to those facilities (CEC, 2005). Another framework for reducing energy costs is by looking for well-matched feedwaters that reduce overall energy intensity and combining with alternative energy sources such as waste heat.

There are many energy improvements to be made to reduce the energy footprint of desalination. For membrane process involving mechanical energy (RO, nanofiltration), the most promising advances so far have been in energy recovery devices. These systems (reverse pumps, pressure or work exchanger) recover a part of the energy contained in the concentrate streams (Younos and Tulou, 2005; NRC, 2008). Other efforts focus on new, more efficient or fouling-resistant membranes, taking advantage of breakthroughs in nanotechnologies. These new membranes often allow lower operating pressures, reducing power requirements. Feedwater characteristics can also help reduce energy use if chosen appropriately. There are several reports on the potential role of renewable energy for desalination

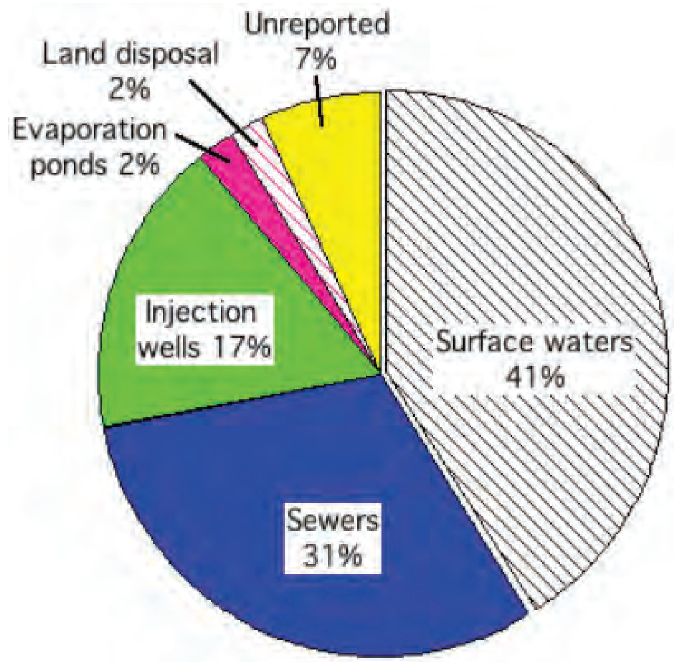
(Younos and Tulou, 2005; Mathioulakis et al., 2007; Charcosset, 2009). Renewable energy may not reduce the energy footprint, but it may reduce the environmental footprint of the energy use.

3.3 Energy Costs of Disposal

A key energy, water and environmental issue with desalination is the handling and disposal of brine, the concentrate resulting from extracting salts and minerals from the feedwater. Management of brine is key to the success of a project. The brine salinity (and its environmental impact) depends on the initial salinity, the technology used, and the recovery rate (how much of the original water is processed into potable water). With recovery around 50 percent, brine typically has double the salt of the feedwater. However, desalination also concentrates constituents found in seawater and groundwater such as manganese, lead and iodine, and chemicals introduced via urban and agricultural runoff, such as nitrates (Cooley et al., 2006). The corrosion of the desalination equipment also leaches heavy metals, such copper, lead and iron, into the waste stream.

Concentrate and residuals management involves waste minimization, treatment, beneficial reuse, disposal and conventional concentrate management (NRS, 2008). Each approach has its own set of costs, benefits, environmental impacts and limitations. Numerous brine disposal options are used (Figure 10), each presenting its set of advantages and limitations, costs and environmental impacts. Coastal desalination plants often discharge their brine out at sea (at high pumping costs), but also use evaporation ponds, confined aquifers or saline rivers. Inland disposal of brine offers fewer options, but these include deep-well injection, pond evaporation, and injection to a saline aquifer or sink (Cooley et al., 2006).

Figure 10. Brine Disposal Options for Desalination Plants in the U.S.



Source: Mickley, 2006 and NRS, 2008

The Clean Water Act regulates all point-source discharges, but states such as California also have their own regulations, requiring permits or compliance. In particular, state regulations may limit the concentrate management practices available at any individual site. For more on regulations regarding desalination and discharge, see Mickley (2006). As a whole, 41 percent of plants discharge brine to surface water, 31 percent of plants discharge into municipal sewers, 17 percent discharge into deep wells, and 2 percent dispose of concentrate in evaporation ponds (Figure 10; Mickley, 2006). The long licensing procedures and public reticence has spurred emerging technologies including zero-liquid discharge (ZLD), which involves processing concentrate into dry salts (Mickley, 2006). However, these technologies are more energy intensive and still require the disposal of solids to a landfill.

4. Conclusion

There is a substantial lack of data on the current state of the nation's groundwater. Little is known about the amount of groundwater withdrawn, with the exception of adjudicated groundwater basins. In California, only 23 groundwater basins are adjudicated. Tracking and reporting of groundwater pumping by users would enable a better understanding of the energy costs associated with groundwater extraction. There are no indications that rising energy costs equated to a decrease in groundwater withdrawals. A study of the additional energy cost of aquifer overdraft is needed.

The Embedded Water Studies (Bennett et al., 2010 a&b) showed that in California, the extraction of groundwater in summer months is substantial, supplanting the combined electricity requirements of the State Water Project, the CRA and the Central Valley Project. Estimates show that about 1 percent of U.S. electricity production is consumed for groundwater extraction. Because of the energy demands from groundwater pumping, individual states need to track groundwater more closely. A better knowledge of the pump population (age, type, number, fuel, etc.) could help regulators and agencies plan for peak load and energy reductions.

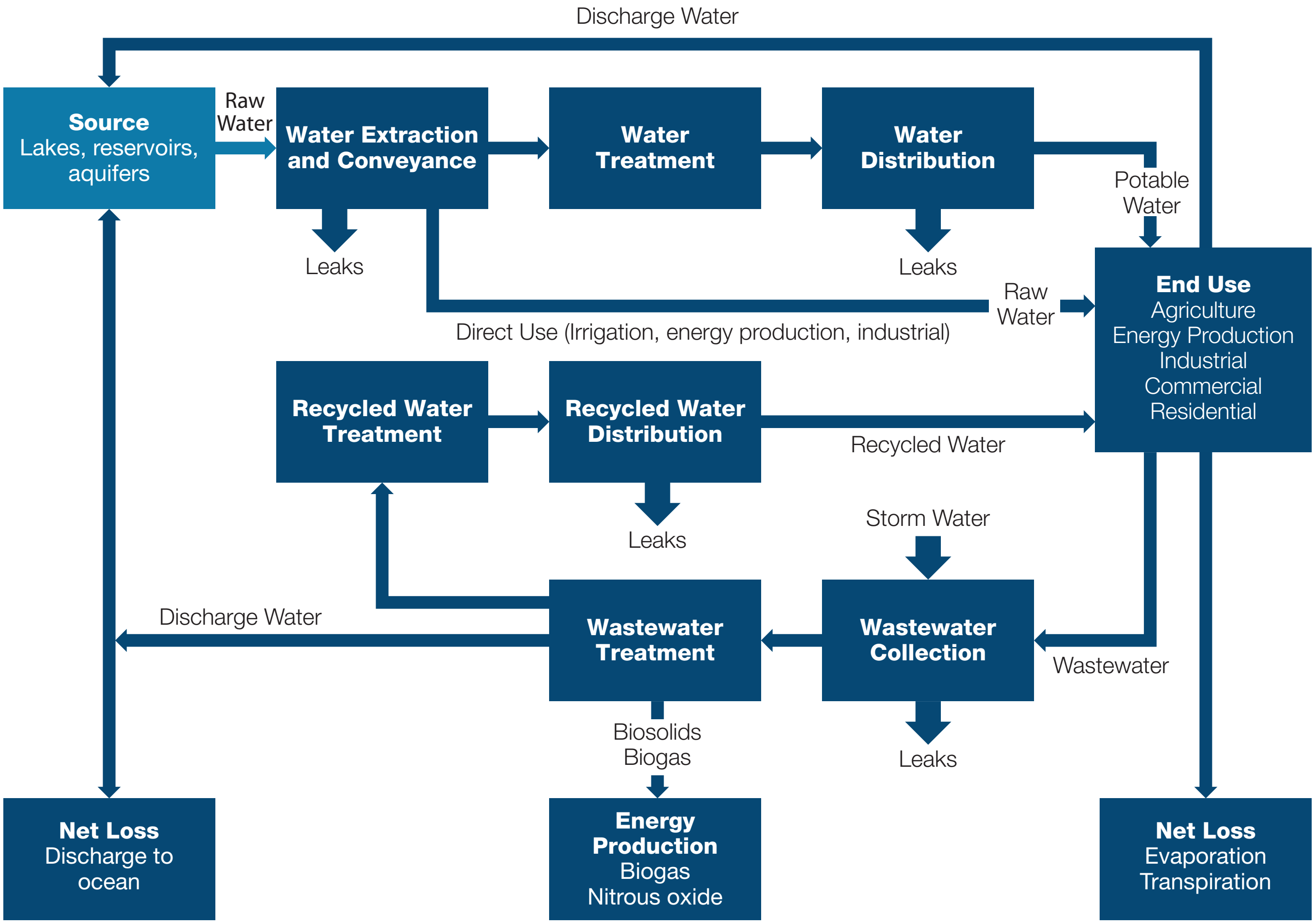
In order to calculate the avoided energy in California's water supply, there is a need to investigate the short-, mid- and long-term marginal water supply in California. Some investigators posit that the embedded energy of desalination is a logical proxy (GEI, 2012). Desalination requires much more investigation of topics, such as the co-location of power plants and desalination facilities, less energy-intensive processes, brackish water over seawater and environmental issues of brine discharge. In addition to the discussions above on surface water, groundwater and desalination, more research on water efficiency, reuse and recycling as less energy intensive options for meeting future water supply demands would broaden management options in terms of avoided energy cost.

ENERGY FOR WATER CONVEYANCE

Water is extremely heavy. At 8.35 pounds per gallon, the weight of water requires a significant amount of energy to lift. For much of history, both people's use of water and the location of their communities have been limited by their proximity to clean, abundant supplies of water. Thus, people have had to rely upon human power, animal power or gravity to convey water from its source to where it is used. Romans, Mayans and other organized civilizations developed intricate systems of water conveyance, including reservoirs, canals, pipes and aqueducts, and leveraged gravity to move the water from source to end use.

In contrast, modern societies have the ability to harness large amounts of cheap energy to move water long distances. These projects usually involve high energy investments. To lift 100 cubic meters of water per minute to a height of 100 meters requires more than 1.5 MW of power if the pumps are 100 percent efficient (Gleick, 1994). This section evaluates the literature and research on the energy use of our water conveyance system, as well as the energy intensity of traditional water distribution systems. The metric for this chapter will be kilowatt-hours per million gallons (kWh/MG). Note that conveyance is defined as moving raw water from source to water treatment or to direct uses in agriculture, energy production or other uses that do not require water treatment (Figure 11). Distribution, on the other hand, refers to moving treated water to customers that require high quality water (e.g., residential, commercial or industrial users).

Figure 11. Water Flowchart (Highlighting Source)



Source: Adapted from Wilkinson, 2000

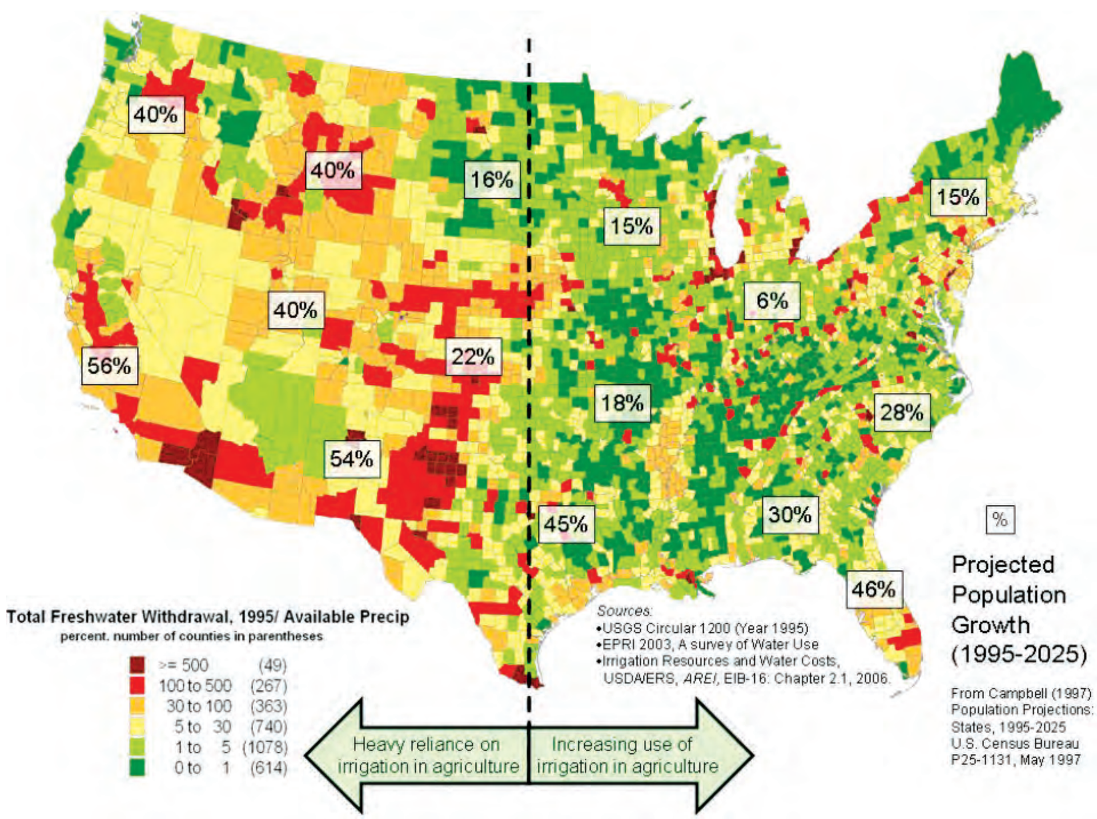
1. Water Conveyance

Research on the energy use of water conveyance clearly reveals that U.S. water conveyance systems – the networks of canals, pipes and pumps that carry water from one place to another – are in some places energy intensive, while energy producing in others. One of the fundamental determinants of the energy intensity of any particular water supply is the relationship between the elevation of where water is sourced and where it is used. Water volume and the distance the water travels are other key factors. As population expands into places where water must be imported, water supplies become more energy intensive. Most water-transfer systems, which are used to import water to these areas, have both pumps and generators to get water up and over hills and mountains and do allow for the recapture of some energy lost in pumps. Whether a system is a net consumer or producer of energy depends upon the relationship between geographical characteristics, e.g., elevation, and a particular system's ability to both utilize and capture energy (Bennett et al., 2010a&b; GEI, 2012; Gleick, 1994). As the climate changes, altered precipitation patterns could affect water conveyance and storage infrastructure, as their original locations may no longer be where the needs are.

1.1 Large Water Transfers

The problem of water conveyance as a net energy sink is especially pronounced in the West, where a large and growing portion of the population resides in the arid areas (Figure 12). This problem will be exacerbated by the current demographic trends in the U.S. To meet Southern California's demand, water is pumped through the 4,800 kilometers of pipelines, tunnels and canals (Stokes et al., 2009) of the Central Valley Project (CVP), the State Water Project (SWP), the Colorado River Aqueduct and others. These aqueducts must convey water up and over hilly terrain. The State Water Project pumps water more than 3,000 feet over the Tehachapi mountain range (CEC, 2005) adding to the energy bill of this water. The SWP provides water equally for agriculture and municipal uses, whereas the CVP provides 90 percent of its water for agriculture and 10 percent for municipal uses (Cooley et al., 2008). It is worth noting that the SWP and CVP have some shared infrastructure. As discussed in depth elsewhere in this Review (cf. section on "Potable Water"), water for municipalities requires treatment to water quality standards approved for potable use, thus adding to the energy intensity of delivered water. Water for agriculture will be delivered "as is" as long as the source water is suitable for application to the food chain and does not get contaminated en route. San Diego, the terminal city for the SWP, has an energy intensity of 9,200 kWh/MG for imported water (end use not included; Gleick, 2008; Sanders et al., 2012), while farmers in the Central Valley receive water with an energy intensity of 1,300 to 3,100 kWh/MG (Wolff at al., 2004).

Figure 12. Emerging Water Stress and Projected Population Growth

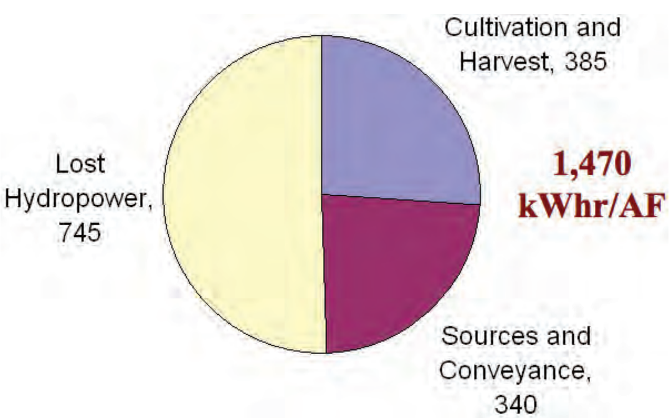


Source: Pate et al., 2008

Populations in the Colorado and Columbia River Basins also rely on imported water for most of their supplies. The Central Arizona Project (CAP) is a 541 km-long diversion canal bringing water from the Colorado River to the cities of Tucson and Phoenix, Ariz. The pumping alone requires an intensity of 5,000 to 10,000 kWh/MG (to Phoenix and Tucson respectively; Scott et al., 2011). The Columbia Basin Project is an irrigation project requiring water to be pumped down the canyon and several hundred feet up the canyon wall from behind Grand Coulee Dam to irrigate farmland through 5,800 miles of canals, drains and waterways in the arid region of Eastern Washington.

Through this particular system, the delivered irrigation water has an energy intensity of 1,040 kWh/MG (Wolff et al., 2004). While irrigation is typically a higher priority than hydropower, given that hydropower is in high demand, a life cycle examination of irrigation water requires a consideration of the opportunity cost of lost power generation. A report prepared by the National Resources Defence Council (NRDC) and the Pacific Institute (Wolff et al., 2004) investigated the lost hydropower due to the diversion of about 6 percent of the Columbia's flows for agricultural purposes (Figure 13).

Figure 13. Energy Intensity of Water in Potatoes, Columbia River Basin



Source: Gleick, 2008

Pumps are the most energy-intensive devices in most conveyance systems (CEC, 2005), rendering the California State Water Project alone "the largest single user of energy in California. Similarly, the CAP is Arizona's largest electricity user (Scott et al., 2011). In the process of delivering water from the San Francisco Bay-Delta to Southern California, the project uses 2 [percent] to 3 percent of all electricity consumed in the state" (Wolff et al., 2004). This number does not include California's other conveyances, such as the Colorado River Aqueduct and other regional and local distribution networks. Bennett et al. (2010 a&b) recalculated values of the energy intensity of conveyance and distribution from CEC (2005) as shown in Table 3 and demonstrated that water supply, conveyance and distribution consume 7.1 percent of California electricity requirements or nearly 17 terawatt hours (TWh) (92 percent of the water sector requirements). California is among the only states (including Texas and others) with estimates for the total amount of energy expended in its water sector, particularly for its conveyance systems (Sanders et al., 2012; Stillwell et al., 2010). The work of Sanders et al. (2012) in evaluating the energy consumed for water use in the United States has enhanced knowledge of the water-energy nexus on the national level.

1.2 Distribution Networks

The water system's superhighways – the conveyance system – that transport water long distances are not the system's only energy consumers, as the water equivalents of residential streets and driveways – the distribution system – require large amounts of energy, too. Water is conveyed from the source to the water treatment plant, and from there, it is distributed to customers.

One California study estimates that city water agencies use about 1,150 kWh/MG just to deliver water from the treatment plant to their customers (CEC, 2005). Energy requirements are highly dependent on topography, the size of the municipality and the distances that water must travel. Water within regional distribution networks cannot stagnate, so operators must perform regular systemwide flushes in order to prevent oxidization. Water distribution is discussed in greater detail in the "Energy for Water Treatment and Distribution" section of this Review.

Table 3. Water Sector Electricity Use in California in 2001, GWh

<table>
<tr><th>Segment of the Water Use Cycle</th><th>CEC Study 2005</th><th>CEC Study 2006</th><th colspan="2">Bennett et. al. 2010 a&b</th></tr>
<tr><td>Supply</td><td rowspan="4">10,742</td><td rowspan="4">10,371</td><td rowspan="2">15,786</td><td rowspan="2">172</td></tr>
<tr><td>Conveyance</td></tr>
<tr><td>Water Treatment</td><td></td><td>312</td></tr>
<tr><td>Water Distribution</td><td></td><td>1,000</td></tr>
<tr><td>Wastewater Treatment</td><td>2,012</td><td>2,012</td><td></td><td>2,012</td></tr>
<tr><td>Total Water Sector Electricity Use</td><td>12,754</td><td>12,383</td><td colspan="2">18,282</td></tr>
<tr><td>% of Total Statewide Electricity Requirements</td><td>5.1%</td><td>4.9%</td><td colspan="2">7.7%</td></tr>
</table>

Note: Excludes estimates of electricity consumption for water end uses.

Source: CEC, 2005; Bennett et al., 2010

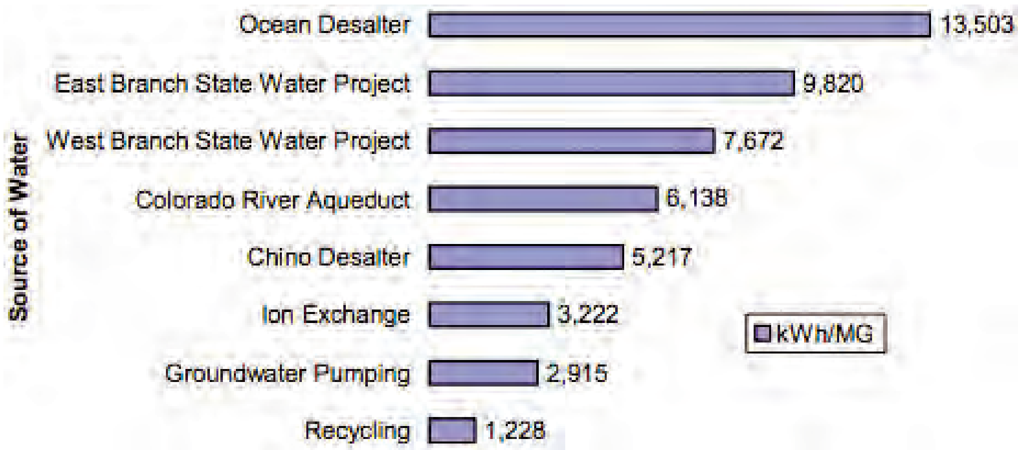
2. Policy

There is little existing law regulating water conveyance. In order to discourage waste, state laws often require that private conveyances – usually those that carry water from a source to irrigable agricultural land – conform to local customs[2] and "reasonable use." Large water conveyances were regulated as water projects and depended on state and federal funding, so they were subject to state and federal laws and regulations, with policymakers playing a central role in their design and operation.

Different recommendations exist for reducing the energy intensity of regional water supplies. Some studies suggest that one way to conserve the energy Americans now spend in water conveyance is to simply convey less water, and substitute more local sources such as water recycling and getting maximum use from local water supplies (Wolff et al., 2004). In fact, water recycling is California's fastest-growing new water source (CEC, 2005; Bennett et al., 2010a). As portrayed by Figure 14 in a case study of the Inland Empire Utility Agency (IEUA), water recycling is often the least energy-intensive option and a "local" source of water, as we discuss in the "Wastewater Treatment" section. In California, energy needed to treat wastewater to levels required for safe discharge under state and federal regulations does not contribute to recycled water energy intensity accounting. It should be noted that local water supplies such as groundwater aquifers can be rapidly depleted (e.g., groundwater withdrawal) and use should be carefully monitored. Figure 14 also supports the findings of most studies, which agree that looking to desalination to replace long-distance conveyance would not save energy (e.g.., Stokes et al., 2009). Proponents of seawater desalination as a new local water supply hope that the energy intensity and capital costs of desalination will drop in the coming decade, as we discuss the Extraction section of this Review. End-use efficiency and leak reductions are other ways to save on energy.

2 E.g., Tulare Irrigation District v. Lindsay-Strathmore Irrigation District, 2 Cal.2d 489 (1935); "conformity of a … method of diversion of water with local custom shall not be solely determinative of its reasonableness, but shall be considered as one factor to be weighed." Cal. Water Code § 100.5.

Figure 14. Energy Intensity of IEUA Water Supply Options



Source: CEC, 2004

Power Arbitrage: Making a Profit Off Subsidies

The schemes enabled by subsidized power rates can be seen in the Bureau of Reclamation's Columbia Basin Project (CBP). The project sells power to irrigators for less than 4 percent of the market rate. To take advantage of this cheap power, some water districts in the CBP have added low-head hydropower generators to their water canals. The cheap energy used to pump water into the canals is then used to help generate hydropower that the irrigators sell at a substantial profit on the open market. According to a report by the Committee on Natural Resources, this practice reduces water conservation incentives even further because every drop of water added to the canals provides more hydropower profits for the district. By allowing what is essentially a power arbitrage scheme, the Bureau of Reclamation has created an incentive for intensive pumping, leading to excess water and energy use and unnecessary environmental impacts, all at the taxpayers' expense (Wolff et al., 2004).

The nature of the regional system determines energy intensities of the water supply. Shrestha (2010) found that it required more energy to distribute treated water (65 percent) than to convey water from the source to treatment plants (35 percent). In Nevada, where Shrestha conducted her study, water demand and use is currently much closer to the source than it is in California, where these two energy components are not mutually exclusive in the water supplies in the southern part of the state. This could very well change, as the Southern Nevada Water Authority is currently laying the ground work for building a pipeline to move water from the north of the state for use in southern Nevada.

Another important factor in conjoined resource inefficiency in the water-energy nexus is the role of federal and state subsidies in large water transfers, particularly for irrigation in the West under Bureau of Reclamation projects. Energy and water subsidies help drive the cycle of inefficient and energy-intensive water use by hiding the true resource costs (Wolff et al., 2004). Therefore, policies should be aligned with appropriate financial signals to show the true value of water and energy, as well as to mitigate the effects of climate change by reducing the greenhouse gas emissions embedded in state, regional and/or national water supplies.

Federal power remains close to the cheapest power in any region of the country. For the Central Valley

Project, for example, energy charges vary widely, but a representative estimate was a charge of 1 cent per kWh, when the price of electricity in California is usually around 10 cents per kWh (Wolff et al., 2004).

3. Energy Savings Potential

3.1 Pumps and Pipes

As noted previously, pumps are the main consumer of energy used for conveyance. More than 6 percent of electricity used in California is used solely for pumps transporting water (GEI, 2012). There are many ways to reduce the energy and costs of water conveyance. Replacing older pumps with variable speed drives (VSD) can substantially improve pump performance by 5 percent to 50 percent, particularly when functioning at lower loads, as pumps are more efficient closer to full load (Wolff et al., 2004; U.S. Government Accountability Office, 2011). It is also very important to perform required repairs and maintenance, since aging electric motors are responsible for important phase shifts (when current and voltage are no longer in phase), which causes problems on the grid and leads to heavy fines from the public utilities. Well-maintained pumps used at their correct duties can help to easily avoid these fines. The goal of the CPUC "Embedded Energy in Water Pilot Programs" was to help water utilities optimize pumping, but the pilot led to disappointing results and further investigation is recommended (ECONorthwest, 2011). One best practice in agency-specific engineering studies is optimizing groundwater pumping on a well-field basis (rather than one well at a time), which can accrue energy savings.

There are other energy improvements available for energy efficiency improvements, such as increasing pipe diameter to reduce friction losses and the requisite pumping requirements, installing a parallel pipe system, and changing pump impellers and lining pipes to reduce friction losses (CEC, 2005). Moreover, net energy use is only part of the problem. Peak load is a major issue, and switching pumping loads to off-peak is also a major goal for public utility commissions. Micro-pumped storage activities such as pumping at night to upgradient storage to be released at peak use with in-conduit hydropower generation is one option for energy savings. It is estimated that total maximum water-related electric demand might be as high as 4,000 MW in California annually (GEI Consultants, 2012). This shows that there are probably no other sectors that have as much potential to reduce summer peak demand. Experts are calling for more dual fuel pumps (natural gas and electricity) and increased surface storage capacity to this goal (Park and Bower, 2012). An estimated 1,000 MW could be avoided in peak power from increased storage in urban areas (CEC, 2005).

3.2 In-Conduit Hydroelectricity

Power can be generated from water flowing in a canal, ditch, aqueduct or pipeline. This power, called conduit hydroelectricity, has been used historically, but there is more potential for gain. Major water transfer projects already use in-conduit hydroelectricity. Many water systems, such as the Hetch Hetchy and the Central Valley Project, provide potable water and also produce electricity through traditional hydropower facilities. Although we visit the traditional hydropower arena in a separate section of this Review, additional opportunities to develop new or retrofitted generation in California's existing water systems warrant mentioning here. The potential ranges for new or retrofitted generation in the latter systems vary from small, e.g., 1 or 2 kW, to about 1 MW (CEC, 2005). The CEC study estimates that with the potential roughly evenly split between municipal and irrigation district systems, about 255 MW of additional generation could be installed in California with an annual production of approximately 1,100 GWh. The most promising technology is through the replacement of pressure-reducing valves (PRVs) with a "reverse pump" which can reduce the pressure in a water system while simultaneously generating electricity. PRVs are used in water supply systems and industry to reduce the buildup of fluid pressure (Campbell,2010). Several companies like Community Hydro, with the motto "There's power in your pipes," are already offering solutions to water utilities to take advantage of this power generation.

In some situations, regulations prevent development of in-conduit hydropower, although this is changing. See CEC (2005), House (2010), GEI Consultants (2012) and the National Water Resources Association (NWRA) website for more information.

In most states, the regulatory context is still not favorable for self-generation. Most produced power, such as in-conduit hydro, cannot be directly connected to an existing load; it must be sold into the wholesale bulk power market. Some members of Congress want to provide further support for small hydropower and nonfederal hydropower at federal sites (Bracmort et al., 2012). For example, the House of Representatives passed the Bureau of Reclamation Small Conduit Hydropower Development and Rural Jobs Act of 2012 (H.R. 2842). This act would amend the Reclamation Power Act of 1939 to authorize the Secretary of the Interior to contract for the development of small conduit hydropower (1.5 MW or less) at Reclamation facilities and exempt small conduit hydropower development from the National Environmental Policy Act of 1969 (NEPA), among other things (Bracmort et al., 2012).

3.3 Losses

When conveyance systems leak, the energy embedded in that water, including the energy expended in its conveyance and/or treatment, is also lost (Chakravorty et al., 1995). Most of the literature agrees that water losses in conveyance systems are around 10 percent in the U.S., with highs over 50 percent and lows of less than 5 percent. Water utilities have primarily reacted to water leaks rather than take preventative measures. Conveyance systems can be difficult to repair. Many are critical conduits without redundancy, so it is a long process to take the system out of service for repairs. In addition, much of it is buried underground, making it challenging to find leaks and very expensive to excavate and repair.

Wolff et al. (2004) report that neither the State Water Project nor the Central Valley Project (CVP) have done an analysis of conveyance losses, but both estimate these losses to be 5 percent (conveyance losses for evaporation and seepage). Note again the shared infrastructure between these two projects. In their update to the CEC 2005 study, Bennett et al. (2010 a&b) incorporate losses to their calculations, estimating that losses are of about 10 percent. They call for more research on the issue of losses, particularly in state or federal large water conveyance projects. As the CVP accounts for 20 percent of freshwater used in California, this represents a sizable amount of water, and therefore energy, embedded its conveyance.

The "Embedded Energy Water Pilot Programs" showed that the most efficient programs for both water and energy savings were those focused on leak detection and repair, conducted conjointly by investor owned electric utilities and public water utilities (ECONorthwest, 2011). Reducing water losses is one of three main strategies in the "Pathways to implementation," particularly for Southern California by GEI (2012). The other strategies are reducing the energy intensity of the water supply portfolio in California and reducing summer pumping loads. Among the options recommended are covering water storage, detecting and repairing pipeline breaks and leaks, and lining reservoirs and canals to reduce seepage. Large-scale leak detection of conveyance systems would offer substantial water and energy savings.

4. Conclusion

Although this is hardly a new field of study (e.g., Blaisdell et al., 1963), more research on the total amount of energy water conveyance systems consume is needed and called for. For example, Rothausen et al. (2011) published a review indicating that the literature is dominated by government agency, private-sector and nongovernmental organization reports, or gray literature. The same paper calls for more holistic studies of the water sector's carbon footprint.

Perhaps the most obvious gap in the quantitative literature is that surrounding conveyance construction. There are various rough estimates of the energy required to maintain a conveyance system, but the research completely overlooks the energy expended in building these intricate systems.[3] In California, where large portions of the populations live in dry regions, conveyance is an expensive undertaking from an energy perspective, so other relatively energy-intensive processes, like recycling, become cost effective. Meanwhile, for agricultural land, or even for some urban users near a surface water source, conveyance can rely on gravity to carry water from the source to demand instead of energy. While there is some information available about the California Water Project's energy use, few other states or regions have mapped out the energy spent on conveyance in detail (Bennett et al., 2010 a&b). Such a map would aid with planning and help weigh the cost of transporting more water against other options for meeting future demand.

The CEC study (2005) is often cited by researchers and has proven valuable for water energy nexus efforts in California. While Stillwell et al. (2010) have done similar work for Texas and Sanders (2012) for Texas and nationwide, other states could benefit from higher-resolution analysis in this field. There is a strong need to examine the efficiency of California's Renewable and Distributed Energy Programs and find ways to simplify the programs when possible. Opportunities for using public-private partnerships to achieve desired goals could be explored.

ENERGY FOR WATER TREATMENT AND DISTRIBUTION

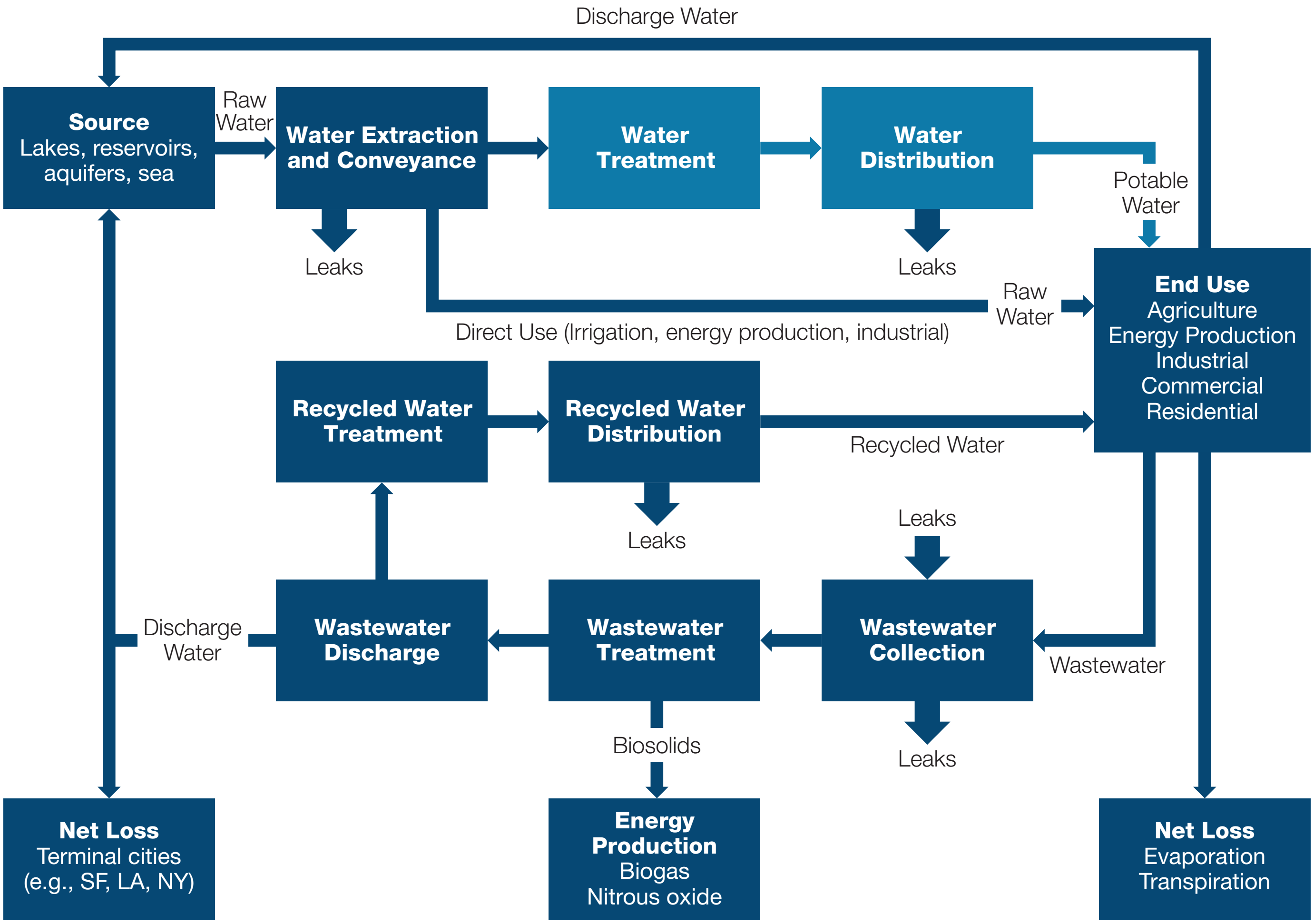
This section explores the literature that evaluates the energy used to treat and distribute potable water (Figure 15). While few studies explicitly address this nexus, there are myriad articles about individual processes and techniques that have wide-reaching implications for energy use. The bulk of the literature points to a report commissioned by EPRI in 1996 (Burton, 1996). This report relies upon model treatment plants, best management practices (issued by state or federal agencies or institutions such as the American Water Works Association) and engineering handbooks. Because the water industry is often slow to incorporate what may be costly, yet cost-effective, changes over the long term, the 1996 findings may still accurately describe many of today's treatment plants. Although the U.S. Environmental Protection Agency (EPA) offers energy audit support, it does not collect information the way the Energy Information Administration does. A survey of water treatment plants to analyze differences between industry practices at treatment plants around the country and available expert findings on the benefits of, and processes and technologies for, achieving greater energy efficiency in the nation's water sector is needed. This represents a fairly significant gap in the research in this arena.

Water supply treatment is the process of removing contaminants from water, making it clean enough for its desired use, most often to drinking water standards. This chapter does not investigate wastewater treatment, which is covered in the next section. The metric used for the energy intensity of water in this section is kWh per million gallons (kWh/MG).

According to the EPA (2012b), there are a number of threats to drinking water: improperly disposed-of chemicals, animal waste, pesticides, human threats, wastes injected underground and naturally occurring substances. Water supply treatment can be achieved through a combination of physical, chemical and biological processes; however, because contaminants vary across water sources and by seasons, there is no single standard treatment process. Since most municipal distribution systems do not have separate infrastructure for drinking water and water put to other uses (e.g., irrigation, toilet flushing), treatment plants are almost all designed to produce potable water.

3 Table 1 in Stokes et al., 2009, suggests that the energy requirements for construction are significantly smaller than those for maintenance but does not numerically estimate the size of that use.

Figure 15. Water Flowchart (Highlighting Water Treatment and Water Distribution)



Source: Adapted from Wilkinson, 2000

After water undergoes the necessary treatment, it is distributed directly to end users through a system of closed pipes, storage tanks and pumps. Approximately 90 percent of Americans get their potable water from one of the 170,000 privately or publicly owned public water systems (PWS), and the remainder use private groundwater wells (EPA, 2012). Public water systems represent 11 percent of freshwater withdrawals in the U.S. (two-thirds from surface water and one-third from groundwater), and private systems use nearly 5 percent of groundwater withdrawals (USGS, 2009). Distributing water requires pressurizing the network to keep the water moving almost continuously, and the networks must be flushed regularly to avoid corrosion. Once carried through the pipes, the water reaches end users of all types, and, once used, most indoor water drains into a series of sewage pipes, which usually carry it to a wastewater treatment facility.

Treating and transporting potable water to end-users can be extremely energy and money intensive. In particular, several studies have shown that water conveyance and treatment consume 4.9 percent to 7.7 percent of electricity use in California (see Table 3, CEC, 2005; Bennett et al., 2010). The 2005 CEC findings were used for California's overall efforts to reach its mandated greenhouse gas emissions reduction goals. Specifically, reducing the energy intensity of the state's water supplies through conservation and water use efficiency measures, as well as through water systems optimization to reduce leaks, were included in the 2008 Scoping Plan for implementing the California Global Warming Solutions Act of 2006. More recently, in May 2012, the California Public Utilities Commission (CPUC) requested that regulated Investor Owned Energy Utilities include water-energy projects in their energy-efficiency programs portfolios where cost effective for the 2013-14 program cycle. The CPUC is further examining the possibility of allowing for the investment of future energy-efficiency program dollars to reduce the energy embedded in the state's water supplies through projects to save water and energy in the water utility and end user sectors (Bennett et al., 2010; GEI, 2012).

1. Water Treatment

1.1 Water Treatment Standards

At the federal level, the Safe Drinking Water Act of 1974 (SDWA)[4] sets federal standards for drinking water treatment. The EPA's ensuing National Primary Drinking Water Regulations more specifically define the maximum contaminant level (MCL) of more than 90 potentially harmful compounds in drinking water. When capping contaminant levels, the EPA considers health risks of the contaminant concentration for humans, as well as the available technology and cost of meeting the MCL (Rideout, 2011). But, as recently as the early 1990s, more than 36 million Americans were drinking water that violated SDWA standards (NRDC, 1993), pushing Congress to amend the SDWA in 1996 to implement additional disclosure requirements, among other changes. However, *The New York Times* reported that 20 percent of public water systems across the country still violated SDWA standards between 2004 and 2009, and few offenders faced fines or other penalties (Duhigg, 2009).

There is literature highlighting the SDWA's failure to address the contaminants of emerging concern such as trace pharmaceuticals and personal care products increasingly found in drinking water in the U.S. (Congressional Research Service, 2010). In fact, the Congressional Research Service, the U.S. Geological Survey and the U.S. Government Accountability Office have repeatedly recognized a lack of research on the extent of the problem and its potential impact on human and animal health (CRS, 2010; Associated Press, 2009; GAO, 2011). Congress has made several fleeting attempts to mandate such research but has taken no decisive action (e.g., H.R. 1145 and H.R. 1262).

States have also started to address this problem. In California, the State Water Resources Control Board (SWRCB) issued a Recycled Water Policy report in 2009 by the CEC Advisory Panel, which, among other efforts, attempted to include the most current scientific knowledge on CECs into regulatory policies for use by various state agencies. This report provides guidance for developing monitoring programs that assess potential CEC threats from various water practices (SWRCB website). Thus, although nanofiltration and reverse osmosis technologies can remove pharmaceuticals from water sources with increasing effectiveness (Redjenovic et al., 2008), public water systems seldom use them in traditional water treatment facilities. These systems are also extremely energy intensive, requiring high pressure (EPRI, 2002).

Naturally, when potable water comes from a cleaner source, far less treatment – and far less energy investment in such treatment – is necessary, so one of the primary ways to save energy on water supply treatment is to protect sources from being contaminated in the first place. There is a great deal of literature describing regulatory efforts to accomplish this goal, including detailed EPA records (EPA, 1999) and various policy reviews (Turner, 1994; Rideout, 2011). The Safe Drinking Water Act (SDWA) works to protect underground water sources by regulating five classes of injection wells and funding "comprehensive analysis of geology,

4 42 U.S.C. §300(f) et seq. (1974).

hydrology, land uses and institutional arrangements impacting public water supply wells" (Roy & Dee 1989), and prohibiting federal funding for projects that could contaminate a community's sole or principal drinking water source. These efforts and Clean Water Act (CWA)[5] provisions to cap the amount of pollution discharged into surface water sources[6] result in significant energy savings, as they avoid intensive treatment processes altogether (Messina, 1995; White et al., 2006; Matamoros et al., 2007).

1.2 Treatment Plants

i. Surface Water Treatment

The Safe Drinking Water Act and its set of federal standards for drinking water shaped the plethora of water treatment facilities existing today in the United States. Figure 16 shows the typical sequence of operations for treating drinking water. Raw water is initially screened to remove large debris. Traditionally, water was pre-oxidized with chlorine to kill pathogens and break down organics. However, with better understanding of disinfection byproducts (DBP), either this step is omitted or chlorine is replaced by ozone. Alum, iron salts and/or polymeric materials are added for flocculation and coagulation.

Under rapid mixing and with coagulants, smaller particles agglomerate and settle faster in the sedimentation tanks. Water passes through rapid sand filters, usually composed of gravel and sand combined with anthracite (coal), to avoid clogging and head loss. These systems are regularly backwashed to remove filtered particles and pathogens. Sludges and impurities removed from the sedimentation basins and the filter are concentrated (dewatered) and discarded. Another disinfection step kills any remaining pathogens using ultraviolet (UV) light, ozone, chlorine or a combination of these. Usually, a disinfectant residue is required to prevent the growth of bacteria in the system. Clearwell storage allows contact time for disinfection and provides capacity to meet peak demand.

Potable water is distributed to consumers by high-pressure pumps. This step is the most energy intensive, in California consuming about 83 percent to 85 percent of the electricity embedded in potable water (CEC, 2005; Bennett et al, 2010b). (There are exceptions, such as when a water treatment plant is located at a higher elevation than the water users.) This explains small economies of scale for water treatment plants from 1 to 100 MGD. Small water facilities consume only 150 kWh/MG and large facilities about 80 kWh/MG just for treatment (Burton, 1996). Figure 17 shows water treatment energy intensity from the CEC 2005 study and is an attempt to characterize a model 10 million gallons per day (MGD) water treatment plant using data derived from Burton (1996). Bennett et al. (2010b) found that water treatment facilities used 50 to 750 kWh/MG by surveying utilities.

ii. Groundwater Treatment

Groundwater usually requires much less processing, consisting primarily of pumping water to the surface and chlorinating for disinfection and removal of odor or taste. The treated water is then pumped to the distribution system or storage tanks before distribution. About 55 percent of groundwater systems report using disinfection only, versus only 11 percent of surface water plants (ICF International, 2008).

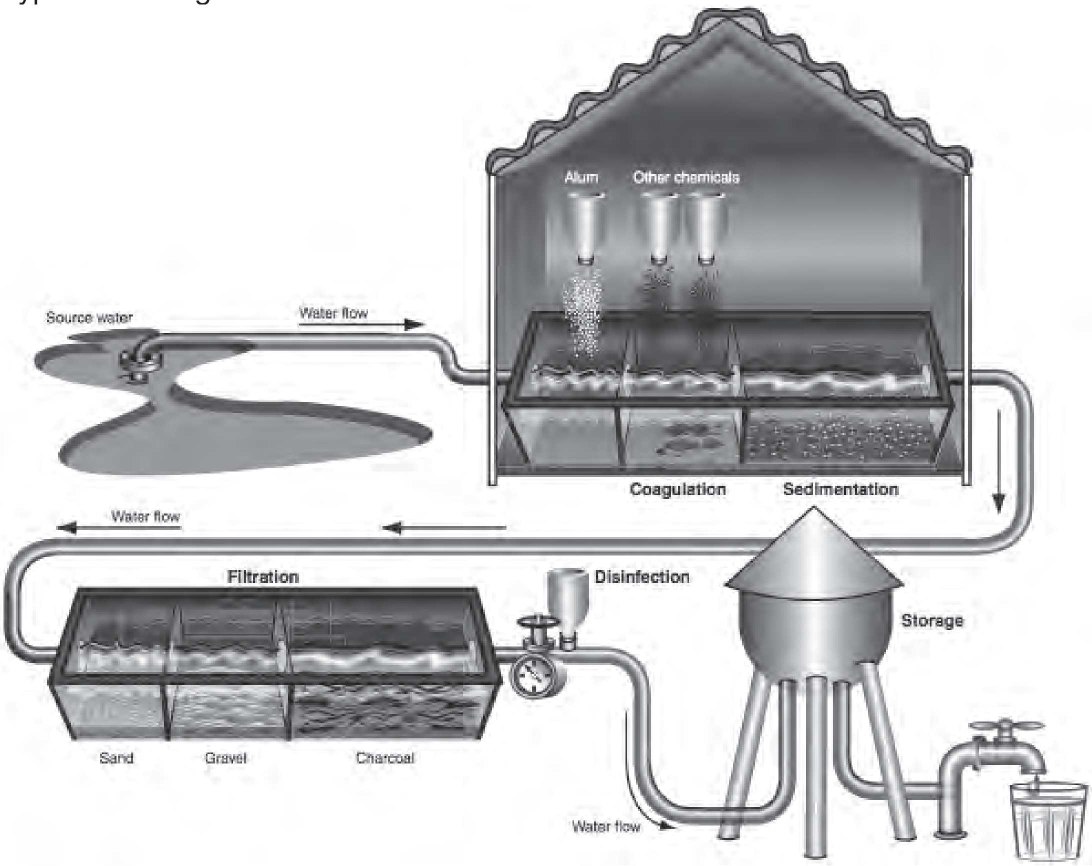
iii. Trends

Since varying circumstances dictate which of the many treatment processes must be used to meet legal standards, it is difficult to calculate how much electricity treatment plants typically consume. Moreover, every treatment plant is unique in its design and technology. Using surveys and available industry or EPA data is a way to investigate the differences between model plants and real industry practices.

5 33 U.S.C. §1251 et seq. (1972).

6 Other related federal legislation controlling water contamination includes the Resource Conservation and Recovery Act; the Comprehensive Environmental Response, Compensation and Liability Act; the Federal Insecticide, Fungicide and Rodenticide Act; and the Toxic Substances Control Act (Cotruvo, 1985).

Figure 16. Typical Drinking Water Treatment Process



Source: U.S. GAO, 2011

Figure 17. Water Treatment Energy Intensity

	Surface Water Treatment		
	Typical 10 mgd facility		kW/MG
Public Supply	Conveyance	Raw Water Pumping	120.5
	Treatment	Alum	1.0
		Polymer	4.7
		Rapid Mix	30.8
		Flocculation Basins	9.0
		Sedimentation Tanks	8.8
		Lime	1.2
		Filters	0.0
		Chlorine	0.2
		Clear Well Storage	0.0
		Filter Backwash Pump	12.3
		Filter Surface Wash Pump	7.7
		Decanted Washwater to Rapid Mix	20.0
		Sludge Pump	4.0
		Treatment Subtotals	**99.7**
	Distribution	High Service Pumps	1,205.5
		Total	**1,425.7**

Plant Size (Million Gallons per Day)	Energy Intensity (kW/MG)
1	1,483
5	1,418
10	1,406
20	1,409
50	1,408
100	1,407
Average	**1,422**

Source: CEC, 2005

Beginning around 2000, the State of California began to acknowledge the importance of the water energy nexus to energy-efficiency efforts after the state's energy crisis. This process formally began with the 2005 study by the California Energy Commission, which concluded that "[d]espite extensive data searches, staff found only a few studies that attempted to determine the exact electricity use for water treatment facilities" (CEC, 2005). Subsequent California state studies in 2008 and 2010 have built upon this work, as has the implementation of the state's water-energy greenhouse gas emission reduction measures called for as part of the state's Global Warming Solutions Act of 2006.

Estimates from several different studies (Burton, 1996; EPRI, 2002; Elliot et al., 2003; CEC, 2005 and 2006; Bennett et al., 2010) suggest that water supply treatment consumes 1,400 to 1,800 kWh per MG, representing 0.8 percent of the nation's energy, the caveat is of course that this is very location specific (source of water, quality of the water, etc.). With evolving legislation requiring more treatment and a switch from chlorine to UV and ozone disinfection, the energy intensity of these treatment plants will most likely increase. As new regulations are implemented, water supply treatment will involve more energy-intensive processes (such as ozone and UV light) and will therefore consume more energy, though none of the literature attempts to quantify this.

To the authors' knowledge, electricity costs may become an increasingly important factor in the EPA's regulatory cost calculations, especially since approximately 80 percent of municipal water processing and distribution costs are for electricity (EPRI, 2002). The EPRI study estimated in 2002, based on engineering data, foreseeable regulations and population forecasting, that the energy use of public water systems is expected to double by 2050 (Table 4). Questions include how new treatment requirements would affect the current water treatment system (e.g., would this be for new facilities, existing facilities or both?) and thereby, its energy needs.

Table 4. Electricity Consumption Projections for Water Supply

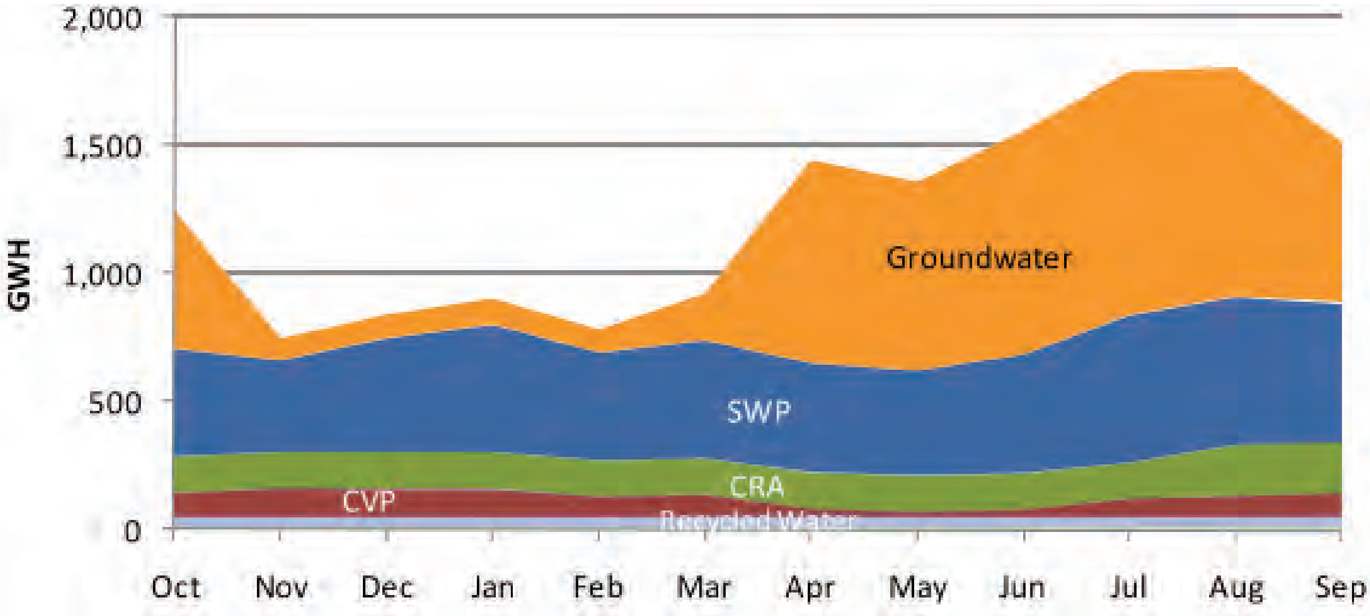
Year	Public Water Supply and Treatment (Million kWh)
2000	30,632
2005	31,910
2010	33,240
2015	34,648
2020	36,079
2050	45,660
Approx. % Increase 2000–2050	50%

Source: EPRI, 2002

However, these estimations and averages are generalized, as energy consumption varies widely from plant to plant. For example, treatment facilities that draw water from cleaner sources use substantially less electricity. Exemplifying this point, Sonoma County, Calif., uses approximately 2,600 kWh to pump and treat 1 million gallons of water, while the San Francisco East Bay area – which gets higher-quality water via aqueduct from the Mokelumne River – needs only 425 kWh per million gallons (CEC, 2005).[7] Likewise, though up to 30 percent more electricity is devoted to groundwater use, only 0.5 percent of that spent on groundwater is used for treatment (EPRI, 2002) in large part because groundwater is generally cleaner than surface water (EPA, 2012; GAO, 2011). Thus, states that obtain much of their drinking water from underground sources likely spend less energy on water treatment (Austin, 2008). However, as an aquifer gets depleted, more energy is required to pump water from deeper depths (see Water Extraction section of this Review). Moreover, supplies can depend on the time of year, as portrayed in California by Figure 18, requiring much more energy in the summer when demand is high and surface water supplies become scarce.

7 However, some of the difference between these two figures must be attributed to differences in the distribution systems. The East Bay's distribution network is gravity fed, while Sonoma relies almost entirely on pumps (CEC, 2005).

Figure 18. Monthly Energy Consumption in 2010 by California Water Supplies



Source: Bennett, 2010

1.3 Energy Conservation

Some reports suggest that there are enormous opportunities for conservation in water supply treatment. Studies on this topic were prominent in the early 1990s, including research by EPRI and HDR Engineering that promised 880 million kWh or 30 percent in savings if treatment plants would engage in "load shifting, variable frequency drives, high-efficiency motors and pumps, equipment modifications and process optimization with and without Supervisory Control and Data Acquisition (SCADA) systems" (CEC, 2005). Then, during the energy crises in 2000 and 2001, various California water agencies joined an energy and conservation campaign and, by employing some of these techniques, reduced their energy use by up to 15 percent in the course of one year (Flex Your Power). Energy-saving techniques included adjusting operation schedules, increasing water storage, utilizing generators, optimizing cogeneration and installing efficient water system equipment, variable frequency drives (VFDs) and advanced equipment controls (CEC, 2005).

Updating pumping technologies is likely the most straightforward conservation option, since pumps are responsible for substantial energy use (CEC, 2005; GAO, 2011). According to CEC (2005), water and wastewater utilities have demonstrated that significant reductions in energy consumption could be achieved by employing interim storage to shift processing to off-peak periods and balance processing loads among multiple plants to optimize plant efficiencies. A report by ICF International for the U.S. EPA (2008) estimates that water and wastewater treatment plants can save up to 15 percent to 30 percent electricity by installing high-efficiency motors and pumps. Lastly, while techniques like reverse osmosis may require spending more energy on the freshwater treatment process, these newer applications of existing technologies, as well as new technologies, may eventually lower the energy intensity of desalination (GAO, 2011).

Very little of the literature discusses the possibility of cities having separate water distribution systems for potable water and for water intended for uses other than drinking. In this case, municipal water supplies would require far less water treatment and less energy. Water for landscaping and sanitation does not need to be as clean as the water we drink, but cities must treat it as thoroughly because they often do not have sufficient infrastructure to separately deliver the two distinct water supplies. Recycled water, which is discussed in another chapter, is the fastest-growing new source of water in California (ICF International, 2008), particularly for large users in industry (refineries, agriculture) and in commercial irrigation facilities (golf courses). Building new water distribution systems is extremely expensive, with large capital and operations and maintenance costs. There have not been any studies on the life-cycle analysis of recycled water, investigating whether the energy saved in treatment would result in net savings despite the energy needed to build, maintain and operate a new distribution system.

1.4 Green Infrastructure

Building or improving treatment plants is not the only way to deliver potable water. There is a fairly large body of literature establishing that protected areas can be maintained to avoid significant costs and associated energy demands of traditional treatment works (White et al., 2006; Matamoros et al., 2007). In fact, New York City (Catskills region), San Francisco (Hetch Hetchy) and Portland, Ore. (Bull Run), all rely almost exclusively on watershed protection and management for their potable supply treatment (EPA, 2002). Of course, natural ecosystems clean water without using any energy and are therefore by far the most energy-efficient "treatment" process. These systems can provide net energy gains provided that distribution systems are comparable. This is the case of the San Francisco Hetch Hetchy system, which does not treat water except for the introduction of chloramine and generates revenues from hydropower within the system. Another category of green infrastructure worth mentioning is groundwater recharge zones, which will be further discussed in the Wastewater Treatment chapter.

2. Water Distribution

Energy used in distribution is a somewhat less controversial topic, generating less policy-based literature to complement the wealth of technological articles. One large body of literature questions municipal water systems' rate structures (Renzetti, 1999). Literature on volumetric sales of water and the rates charged to retail water customers are often not aligned with the energy intensity of that water. The literature also discusses privatization, another significant trend in the water utilities sphere (Gassner et al., 2009), but it unfortunately does not evaluate the potential implications that private ownership of distribution networks might have on incentives to upgrade infrastructure and employ management strategies to conserve energy. Instead, these studies evaluate the effects on employment, price, low-income consumers, the number of residential connections to the network and other elements of service quality (Gassner et al., 2009).

2.1 Water Distribution Regulations

State and local entities are primarily responsible for regulating water distribution networks, but very little of this regulation governs energy use. The bulk of the law caps the rates utilities can charge consumers and lays out infrastructure planning processes (e.g., the Water Resources Planning Act). In fact, many water utilities look to the American Water Works Association and other nongovernmental organizations, rather than to lawmakers, to set minimum standards (EPA, 2009; Olson, 2009). The absence of integrated regulatory approaches to water and energy, while perhaps creating more flexibility, also inhibits the coordinated management of water and energy resources. But, since the federal government has recently offered financial incentives to support green water supply treatment and distribution infrastructure, some state and local governments are becoming engaged in distribution-related policy discussions. For example, the state of Texas received $160.7 million under the

American Recovery and Reinvestment Act, at least 20 percent of which was allocated for green distribution infrastructure building (Combs, 2012).

2.2 Water Distribution Networks

There are few case studies on the energy performance of individual water distribution systems. However, rough national estimates indicate public water systems use about 1,200 kWh/MG to deliver water to their customers (CEC, 2005). The energy required for distribution pumping is mainly driven by size, elevation, system age and configuration of the system. Pressure system pumps account for the bulk of the power consumption: the survey done by Bennett et al. (2010) with California water utilities shows maintaining constant pressure in the system requires 360 to 2,500 kWh/MG. This study also attempted to break down the energy cost of booster pumps according to topography: 40 to 60 kWh/MG for flat terrain, 50 to 1,000 kWh/MG for moderate terrain and 400 to 1,600 kWh/MG for hilly terrain.

Unlike water treatment plants, water distribution systems often do not have the luxury of moving the bulk of their load off-peak. Not only must pumps maintain constant pressure within the network, but it is the end user who ultimately determines when the system bears the most load, much like with electrical power grids. Better knowledge of demand and the use of storage tanks and water towers can help remedy these difficulties. In California, water and wastewater treatment requires approximately 3GW of electricity at peak load; this peak load could be reduced by as much as 30 percent from increased water storage in urban areas (CEC, 2005).

2.3 Reducing Embedded Energy

i. Infrastructure Upgrades

There are several clear energy-efficiency and demand-management opportunities in the water/wastewater sector. Pumps account for up to 95 percent of the energy used to distribute drinking water (CEC, 2005; GAO, 2011), so any management technique that can enhance pump efficiency could have significant impacts on distribution's energy consumption. For example, many distribution systems rely on gravity to propel water into and through the pipe network. Systems that do not have such beneficial topography can employ algorithms to create temporal rules dictating when a pump should be turned on or off to maximize energy efficiency (Boulos, 2002). All of these distribution systems still require regular system flushes, which account for significant energy consumption and pump use (CEC, 2005), so minimizing the need to flush the system is likely an effective conservation strategy. For example, changing the pH of the water or adding corrosion inhibitors slows pipe degradation.

Similarly, changing old piping can be helpful. Traditionally pipes were made out of iron, which corrodes and degrades over time, thereby weakening their structure and leading to leaks and ruptures. As pipes age, they are prone to a mineral build up inside the tube, a process known as tuberculation. This increases friction and causes unnecessary head loss, requiring extra pumping (EPRI, 2002). Moreover, these aging systems can have significant losses. There is on average 8 percent and up to 20 percent of unaccounted for or "non-revenue" water in distribution systems (CBO, 2002). It is, however, to be noted that unaccounted for water is not necessarily due to leaks, but also includes accounting errors, unauthorized connections, malfunctioning meters and distribution systems, reservoir leakages, reservoir overflow and authorized unmetered water use. Switching to PVC pipes, which are smoother, not prone to corrosion and protect against bacteria growth, and following best management practices of the American Water Works Association could solve some of these problems (AWWA, 2001; WSO, 2009; Baird, 2011). Other significant improvements include leak detection sensor technologies for new installations and retrofits, or pipe lining (e.g., epoxy coating) to repair aged systems. Generally, a system audit is recommended before conducting specific leak detection and pipeline replacement activities.

Up to one-third of water utilities in the U.S. are not adequately maintaining their distribution assets and likely lack the funding to correct this problem (GAO, 2002). The average pipe is more than 40 years old (EPA, 2009). Given a lack of regulatory requirements for updates and a lack of government funding, utilities undertake water pipeline rehabilitation work when direct and indirect costs of these leaks become unbearable. The economic benefits of asset management with systematic replacement can be large – generally it is four times more expensive to replace parts at failure. Energy costs may play a small role in this formula, but are likely not a sufficient impetus for change. Indeed, ratepayers largely bear the burden of passed-through power costs, which further causes water utilities to operate with energy cost neutrality.

Moreover, water price structures are generally so low that water lost to leaks does not incent leak remediation to save either energy or water, as shown by the inaction of water utilities when it comes to leaks. The Congressional Budget Office (2002) and the U.S. EPA estimated that between $220 billion and $250 billion were needed over 20 years, just under the current capital spending of $10 billion (ICF International, 2008). However, these estimates could be grossly undervalued, as there is a very poor knowledge of the current state of distribution systems.

ii. Leak Management

In a study on California's water distribution system, WSO (2009) estimated that about 0.9 million acre-feet (MAF) of water are lost per year in leakage. This is about the amount that Southern California will need in the next decade. According to WSO, about a third of this lost water, or 0.35 MAF, is economically recoverable. This corresponds to water for roughly 2 million people or 5 percent of the population of California. It is also 20 percent of the "20 by 2020" goal set by former Gov. Arnold Schwarzenegger, and would be responsible for 1 billion kWh in energy savings. Still, according to WSO, for every million dollars invested, there is a return of $2.8 million in savings and the creation of 22 jobs. Extrapolated to the U.S., with the caveat that California is quite unique in water and energy use, leaks could account for 5 MAF, with 2 MAF that could be recoverable, an economy of $1.7 billion per year.

The "Embedded Energy Water Pilot Programs" showed that the most efficient programs for both water and energy savings were those focused on leak detection and repair, conducted conjointly by investor-owned electric utilities and public water utilities (ECONorthwest, 2011). Reducing water losses is one of three main strategies in the "pathways to implementation," particularly for Southern California, by GEI Consultants (2012). The other strategies are reducing the energy intensity of the water supply portfolio in California and reducing summer pumping loads. Among the options recommended are covering water storage, detecting and repairing pipeline breaks and leaks, and lining reservoirs and canals to reduce seepage.

iii. In-Conduit Hydropower

Perhaps the largest unanswered question in this area stems from the possibility that water distribution systems can be energy generators rather than energy consumers. Installing micro-hydro technologies – discussed in more detail in the "Conveyance" chapter of this Review – in the larger pipes can convert energy from the pressure and flow into electricity (Alexander et al., 2008 and 2009). These systems could be an energy-producing way to regulate pressure rather than using pressure valves. However, the literature has not yet revealed how micro-hydro would work in a domestic water supply system rather than in larger conveyances. While the continuous movement would likely result in continuous generation, unlike in dams and other conveyances, there may be other mitigating factors. For example, the pipes may be too small for current technologies or may generate too little power to be economically effective and power transmission from the point of in-conduit hydro generation may not be easily accomplished unless the systems are located in proximity to transmission lines.

3. Conclusion

Most of the literature relies on the work done in 1996 by the EPRI (Burton, 1996). Other work includes the "Embedded Energy Studies" done by the CPUC in California (Bennett et al., 2010 a&b) and the Sanders (2012) work on Texas and nationwide. There are limited available federal data on water and wastewater treatment plants to be able to distinguish discrepancies between real industry practices and engineering handbooks. Much useful information could be gained for further research if the U.S. EPA conducted surveys of the water and wastewater utilities, as the Energy Information Administration does for electric utilities.

Efficiency is one of the highest priorities, in the author's perspective. Other areas include research to determine how much energy cutting-edge treatment techniques (such as nanofiltration and reverse osmosis) consume, and how these technologies could affect projections for energy spent on water supply treatment in the future. How much additional energy will advanced treatment require to remove emerging contaminants? What new technologies look most promising for reducing that energy burden, and what stands in the way of their development? The potential impact on the energy performance of water treatment plants and wastewater treatment plants has not been sufficiently investigated for contaminants of emerging concern (including pharmaceuticals and personal care products).

Another way to reduce embedded energy is through green infrastructure and watershed protection. However, is it possible to calculate green infrastructure's value in terms of avoided treatment costs and to develop proxies? Can we optimize the best places for cities to invest in watershed management to avoid treatment costs? How do watershed investments yield benefits in other areas (e.g., flood control, habitat)?

Research questions also arise on the future role of separate water distribution networks for non-potable water: Would the reduction in treatment result in net energy savings despite the energy required for the added distribution and the energy cost of construction and retrofitting?

There is a dearth of literature about local water distribution policies that might incentivize energy conservation. Do governments regularly consider municipal water distribution systems eligible for energy savings grants? If so, to what effect? More work needs to be done on the issue of bifurcated regulation. There are regulatory hurdles to using energy ratepayer dollars to save water. This is due to statutes against cross-subsidization unless there are demonstrable cost-effective direct energy savings. The California administration is currently considering methodologies to account for the energy embedded in water supplies so that it becomes possible to assign values to the embedded energy in conserved water.

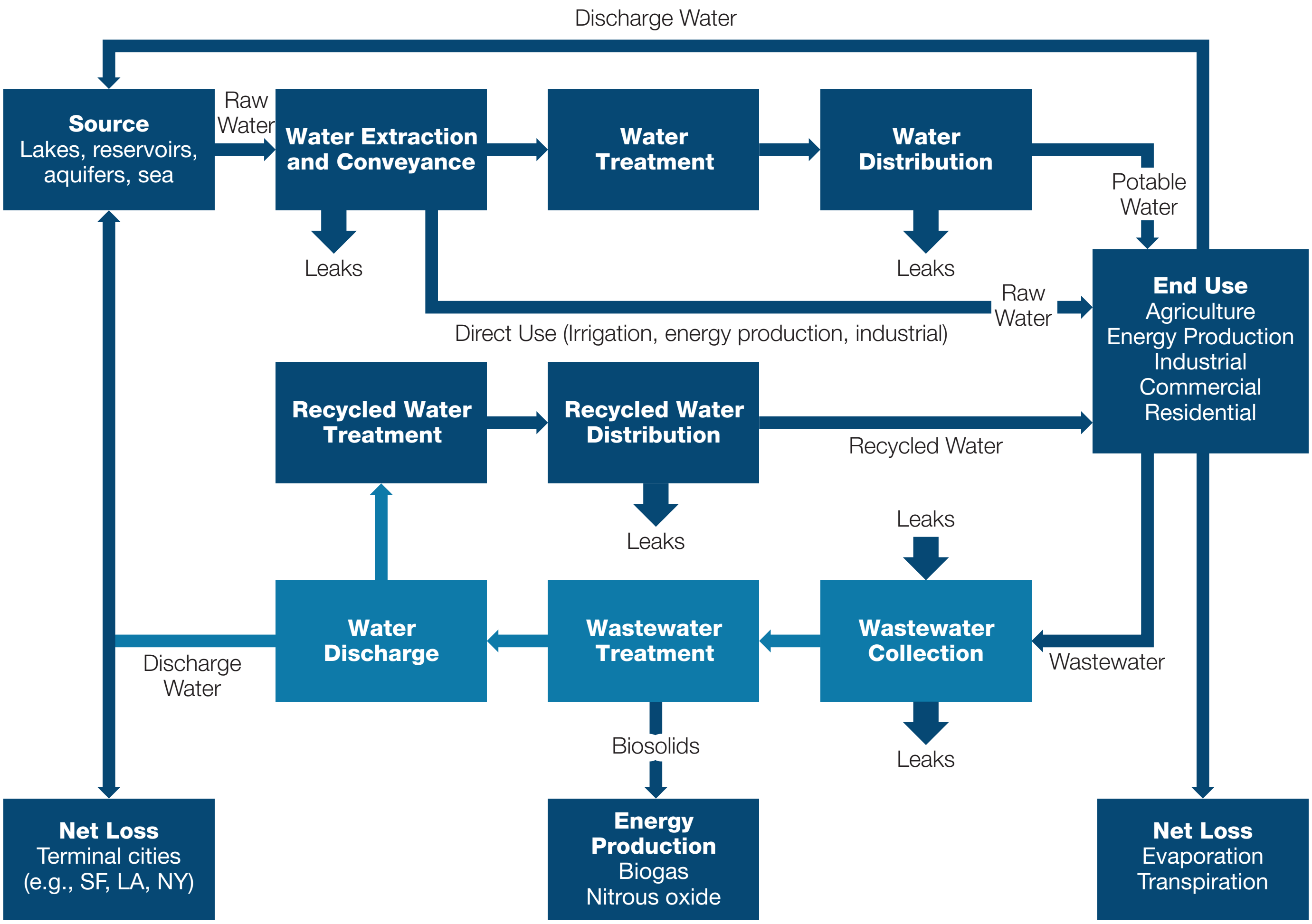
ENERGY FOR WASTEWATER TREATMENT

Wastewater management and treatment has long been considered an important instrument for public health and the control of pathogens. It took some time, however, to recognize its importance for water quality and environmental protection. Rapid economic development in the Eastern U.S. and a demographic boom following World War II greatly altered the quality of water, particularly in the Great Lakes Region. By the 1970s, water pollution had reached spectacular levels, fish kills and dead zones were current, and the nation was brutally reminded of the dire condition of American rivers during the infamous river fires in Ohio. Concomitantly, the environmental movement picked up speed in the wake of Rachel Carson's *Silent Spring*.

The Clean Water Act in 1972 started to regulate wastewater discharge, spurring the wastewater treatment plant (WWTP) growth spurt. Considerable progress has been made since the 1970s, although this has come at a high expense to municipalities due to the capital and energy intensity of the processes. Indeed, this section will detail how wastewater consumes electricity in three stages: collection, treatment and discharge (Figure 19). The metric used for the energy intensity of water production is kWh per million gallons (kWh/MG).

The few studies addressing the water and energy nexus in wastewater management all point to the same report, commissioned by the Electric Power Research Institute (EPRI) (Burton, 1996). This report relies on model treatment plants and engineering handbooks to quantify the energy intensity of wastewater processes. Some have expressed concern (GAO, 2011) that the values presented in this report are largely outdated due to technology advances and new industry practices. For instance, there is a large new body of literature on energy conservation management and best management practices now available for plant operators and managers. Government agencies such as the EPA and nongovernmental associations such as the American Water Works Association (AWWA) have published a great deal of this guidance. While EPRI's report and its methods have been valuable, the approach is somewhat limited.

Figure 19. Water Flowchart (Highlighting Water Collection, Treatment and Discharge)



Source: Adapted from Wilkinson, 2000

In California, water and wastewater treatment requires approximately 3GW of electricity at peak load; this peak load could be reduced by as much as 30 percent from increased water storage in urban areas (CEC, 2005). More electric and water utilities should partner to take advantage of energy resources of water and wastewater treatment plants, as many already do.

1. Wastewater Collection

The first stage of wastewater treatment consists of a network of sewers collecting wastewater and transporting sewage from the customer to the wastewater treatment facility. This requires on average about 150 kWh/MG to pump water depending on topography, system size and age (CEC, 2005). Wastewater pumps are intrinsically less efficient (than water pumps) because they pump both liquids and solids, and therefore have greater clearances between the pump impeller and the casing, allowing much of the pumped water to return to the intake plenum (CEC, 2005). Ideally, agencies should place potable water treatment facilities upstream and at a higher elevation from their customers, with the wastewater treatment facilities downstream and at a lower elevation, to harness gravity where possible to cut back on pumping and treatment costs. Moreover, water intakes are often placed above wastewater outfalls on rivers.

While the majority or households are connected to sewers and are served by publicly owned treatment works (POTW), a considerable minority uses on-site wastewater treatment systems such as septic tanks, cesspools or chemical toilets (Figure 20). The U.S. Census American Housing Survey for 2001 reports that 21 percent of the 105.4 million year-round occupied households used on-site wastewater treatment, this number shoots up to about 51 percent for seasonally occupied housing units (ICF International, 2008).

Aging wastewater collection systems result in additional inflow and infiltration (I/I), leading to higher pumping and treatment costs. Moreover, infiltration, particularly along coastlines, leads to deterioration of water quality from increased total dissolved solids and poses problems for wastewater reuse. The EPA estimated in the early 2000s that $54.1 billion was needed in investment for wastewater collection and conveyance systems, primarily sewer improvements (ICF International, 2008). In combined sewer systems where sewers collect storm water, all of it goes to the water treatment plant, increasing the treatment energy loads.

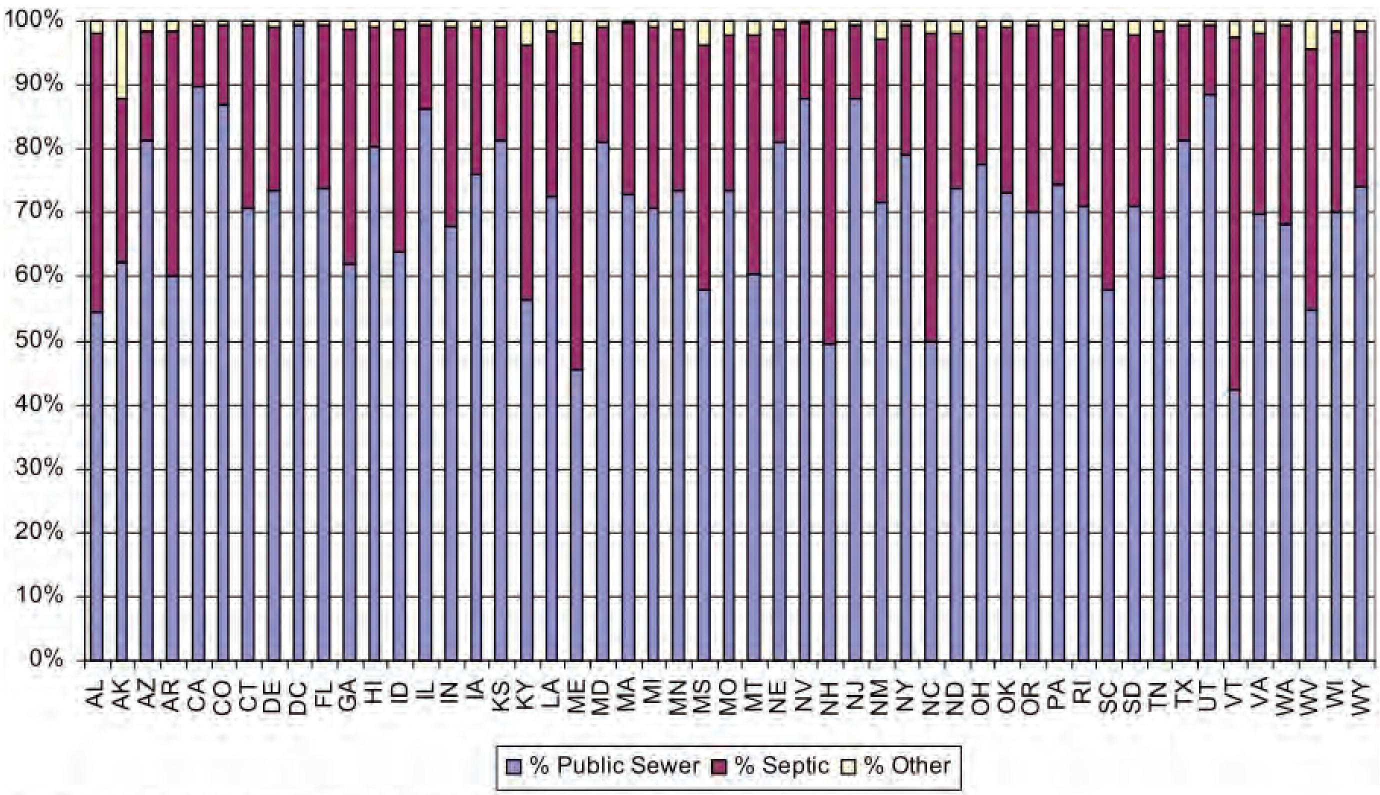
2. Wastewater Treatment

2.1 Wastewater Treatment Standards

The Clean Water Act is the federal legislation that governs the treatment of wastewater. The minimum level of treatment currently required is “secondary treatment,” for which standards are set for biological oxygen demand (BOD) and suspended matter. Each municipality or water utility generally may choose among technologies for achieving a given standard. It is to be noted that WWTP, much like potable water treatment and distribution, is mainly in the hands of local governments. Privately owned wastewater systems account for roughly 20 percent of the wastewater systems but only reach about 3 percent of sewered households in the U.S. (CBO, 2002).

According to the EPA, the number of facilities providing less than secondary treatment declined from 4,800 in 1972 to 868 in 1992, and further declined to just 47 in 2000 (ICF International, 2008). It is to be noted that the remaining facilities providing less than secondary treatment usually have waivers from the requirement. Nearly 5,000 plants perform advanced treatment, exceeding federal requirements to reduce concentrations of nonconventional pollutants, such as nitrogen and phosphorus (responsible for algal blooms and dead zones in the Great Lakes, the Gulf of Mexico and other places).

Figure 20. Share of On-Site Wastewater Treatment for Households by State



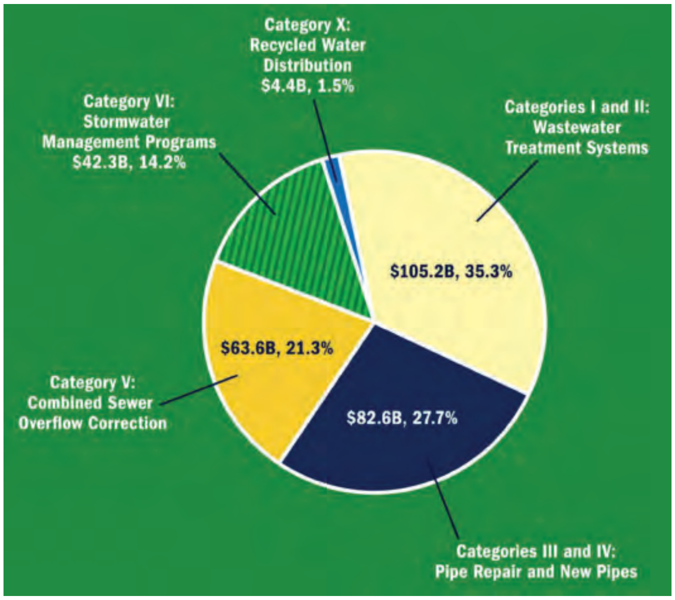
% Sewer = percent of households connected to sewer service.
% Septic = percent of households reporting onsite treatment using septic tank, cesspool, or chemical toilet.
% Other = percent of households reporting other treatment systems.
Source: U.S. Census, 2004a.

Source: Data from U.S. Census in 2004; ICF International, 2008

Federal and state governments play a key role in helping municipalities comply with new federal and state requirements. This support includes state revolving funds (SRFs) for wastewater treatment (with capitalization grants through the EPA), loan and grant programs of the USDA's Rural Utilities Service and the Community Development Block Grants from the Department of Housing and Urban Development (CBO, 2002). However, the large majority of the funding for wastewater services in the U.S. today comes from local ratepayers and local taxpayers. The Congressional Budget Office (2002) notes that the way the wastewater services are controlled and operated raises the risk of undermining the incentives that the industry has to make cost-effective decisions, eventually delaying beneficial change and raising total costs to the nation as a whole.

Although many improvements have been made since the 1970s, considerable investment is needed to replace outdated technology and the aging fleet of WWTPs, most of which were build 40 to 50 years ago (CBO, 2002; ICF International, 2008; EPA, 2010a; Figure 21). In the EPA Clean Watersheds Needs Survey (CWNS) for 2008 (EPA, 2010a), states identified $105.2 billion in needed investment in secondary and advanced wastewater treatment. This figure has nearly doubled since the CWNS for 2000 (EPA, 2003). The CBO estimated in 2002 that for the years 2000 to 2019, annual costs for investment would need to average between $13 billion and $20.9 billion for wastewater systems.

Figure 21. Total Documented Needs for Wastewater Treatment in the U.S.



Source: CWNS, in 2008 dollars; EPA, 2010a

2.2 Wastewater Treatment Plants

i. Publicly Owned Treatment Works (POTW)

Centralized wastewater treatment is provided to more than 220 million Americans by about 16,000 POTWs (EPA, 2010a). To treat wastewater, suspended solids such as sand and grit, pathogens, organic matter and other pollutants are removed from the water to an acceptable level before discharge. Wastewater regulations do not require specific technologies, and thus systems for collecting, treating and disposing of municipal wastewater vary widely in terms of the equipment and processes used (GAO, 2011). There are typically three levels of treatment, the national standard being secondary (biological) treatment (Figure 22). The majority of the population is served by POTW performing tertiary (advanced) treatment (Figure 23). "No discharge" refers to recycled and reclaimed water.

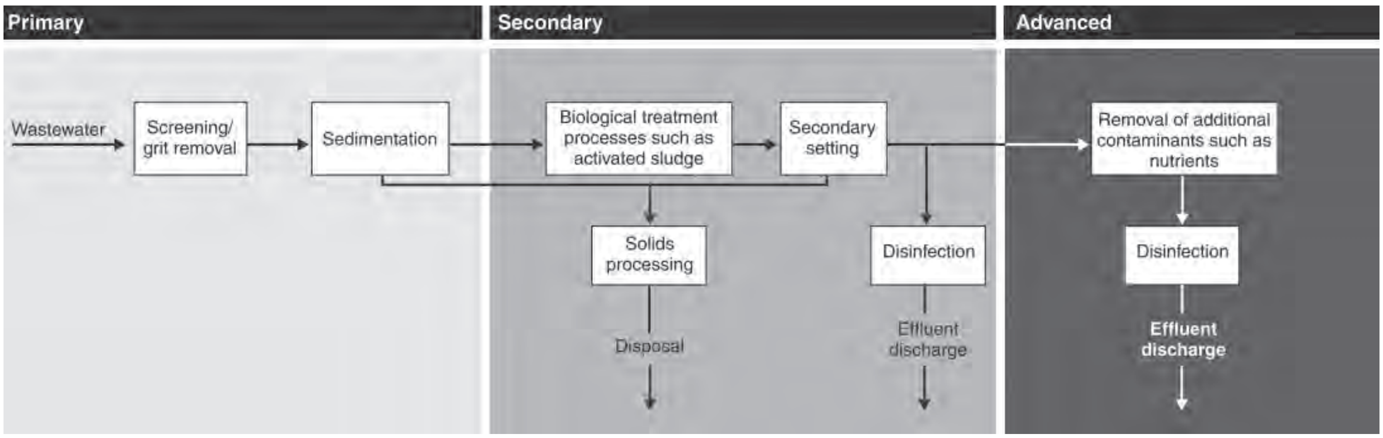
After collection through sewers, wastewater is first screened to remove large debris such as rags, branches and trash. The large debris must be dewatered and processed, and then is burned or sent to a landfill. A grit removal system then separates smaller gravel and sand. Primary treatment consists of solids removal through sedimentation (large settling basins). Some chemicals may be added to assist with solids removal, similarly to potable water treatment. The solids removed during this step are usually treated and reused for fertilizers, incinerated or disposed of in landfills. The more solids there are, the higher the energy requirements are for disposal and incineration (which can require large amounts of natural gas).

These initial physical processes are followed by secondary treatment to remove organic matter and remaining suspended solids through biological treatment. Activated sludge, which relies on aerobic microorganisms to digest and mineralize organic matter, is the most commonly used in WWTP. Wastewater is pumped into an aeration tank; providing oxygen for these organisms is the most energy-intensive step of the process (Figure 24) and is where most energy-efficiency gains are possible. Another aerobic treatment is the trickling filter.

After primary treatment, wastewater is passed over a medium (rocks or plastic). Bacteria attached in biofilms at the surface of the substrate digest the organic material. This method is much less energy intensive but performs more poorly than activated sludge. Finally, wastewater can also be digested anaerobically (in the absence of oxygen) by microorganisms to produce biogas (a mix of about 60 percent methane and about 40 percent carbon dioxide). This method may require electricity or natural gas to maintain an optimal temperature; this can be offset by direct reuse of biogas in combined heating and power (CHP). Produced biosolids are removed in a secondary settling tank (clarifier). Stillwell et al. (2010), Sanders et al. & Webber (2012), Burton (1996) and EPRI (2002) are studies that really break down the energy implications of these steps.

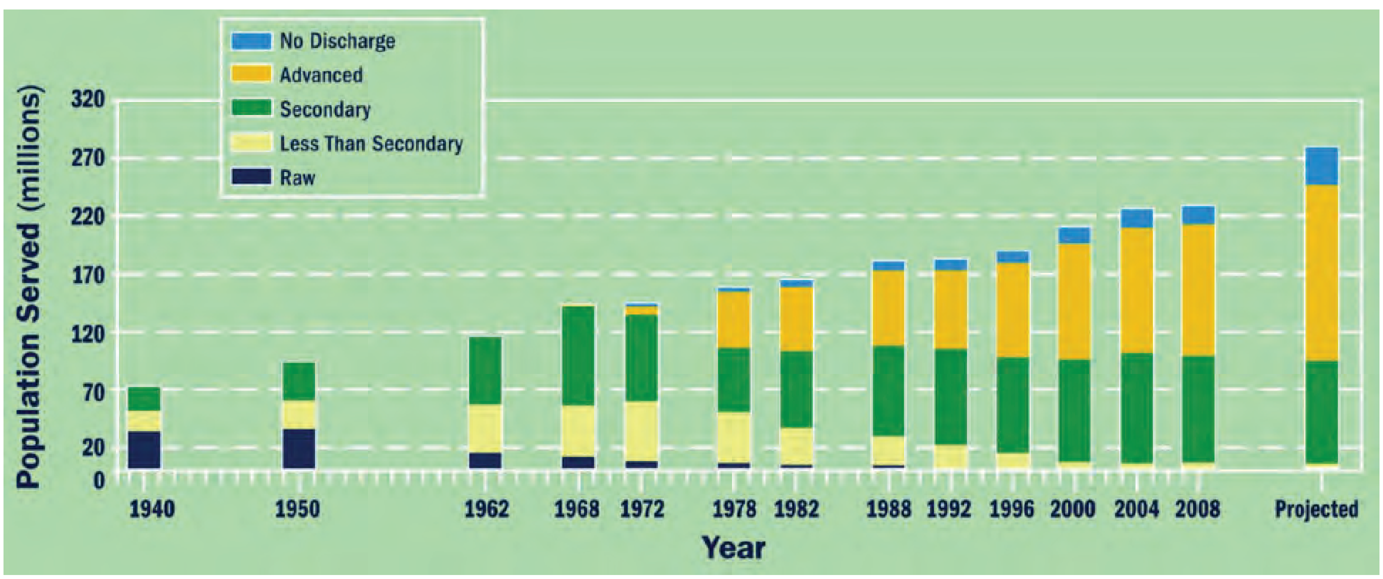
The treated wastewater is then sent to tertiary treatment or disinfected by chlorination, ozone, UV light or a combination of these methods before discharge. Historically, chlorine has been used as a disinfection step; however, WWTPs are gradually moving to the more energy-intensive ultraviolet (UV) or ozone disinfection techniques. This is one of the reasons why the data from Burton (1996) might be particularly outdated. The remaining sludges (biosolids) are thickened (dewatered) and digested anaerobically in a step called biosolids stabilization. Stabilized biosolids can be used as fertilizers, incinerated (for electricity production) or sent to a landfill.

Figure 22. Typical Wastewater Treatment Process



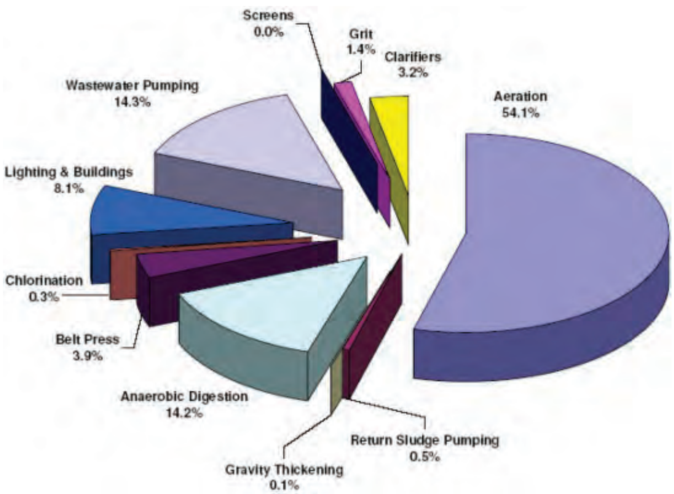
Source: GAO, 2011

Figure 23. Population Served by POTWs Nationwide Between 1940 and 2008 and Projected



Source: EPA, 2010a

Figure 24. Electricity Requirements for Activated Sludge Systems



Source: Science Applications International Corporation, 2006

However, some wastewater must receive additional treatment before discharge in certain receiving waters. Over half of treated effluent is discharged after advanced treatment (Figure 23). This enables the removal of additional contaminants such as nutrients (nitrate and phosphate, through nitrification and denitrification), pesticides and pharmaceuticals (through oxidation and filtration processes) and dissolved solids (through reverse osmosis). Tertiary effluent can be put to beneficial reuse (irrigation in agriculture or for residential and commercial use, groundwater recharge, thermoelectric generation, direct or indirect potable water) or discharged to surface water. These additional steps are often very energy intensive and are responsible for the current trend of increasing energy requirements for wastewater treatment (Table 5).

Table 5 shows the electricity consumption for wastewater treatment by size of plant and technology (EPRI, 2002). This table presents data from Burton (1996), which only includes electricity use and no other energy consumptions, such as natural gas. Moreover, this study does not include any energy credits for biogas production. In contrast with potable water treatment plants, there are important economies of scale with wastewater. Large treatment plants (100 MGD) require half the electricity requirements of smaller facilities (1 MGD).

ii. Privately Operated Wastewater Treatment Works

Privately operated wastewater treatment facilities are designed to deal with specific contaminants generated by a given industrial plant. For example, wastewater treatment plants associated with food processing and pulp/paper facilities will have to treat much higher biological oxygen demand (BOD) concentrations than municipal facilities, which are designed to handle typical domestic waste concentrations and volumes (EPRI, 2002). Since these privately operated treatment plants are smaller and usually have to treat more heavily degraded water, their unit electricity consumption will consequently be higher than for POTWs. EPRI (2002) estimates electricity consumption to be about 2,500 kWh/million gallons. The increasing regulatory requirements for surface water discharges are likely to increase unit electricity consumption by up to 10 percent (EPRI, 2002). Because of increasing costs of both water and electricity, the industry is turning more to effluent recycling.

The USGS estimates that there are approximately 23,000 privately operated treatment facilities in the U.S. associated with industrial plants and commercial operations (EPRI, 2002). The EPRI report, "U.S. Electricity Consumption for Water Supply and Treatment," (2002) is the only review explicitly addressing the water-energy nexus in privately operated treatment facilities and concludes that detailed statistics on the number, type and aggregate flows of these treatment facilities are not available through published sources, which makes them hard to characterize. However, on average, privately owned wastewater treatment facilities will fall into the smallest size range of POTWs.

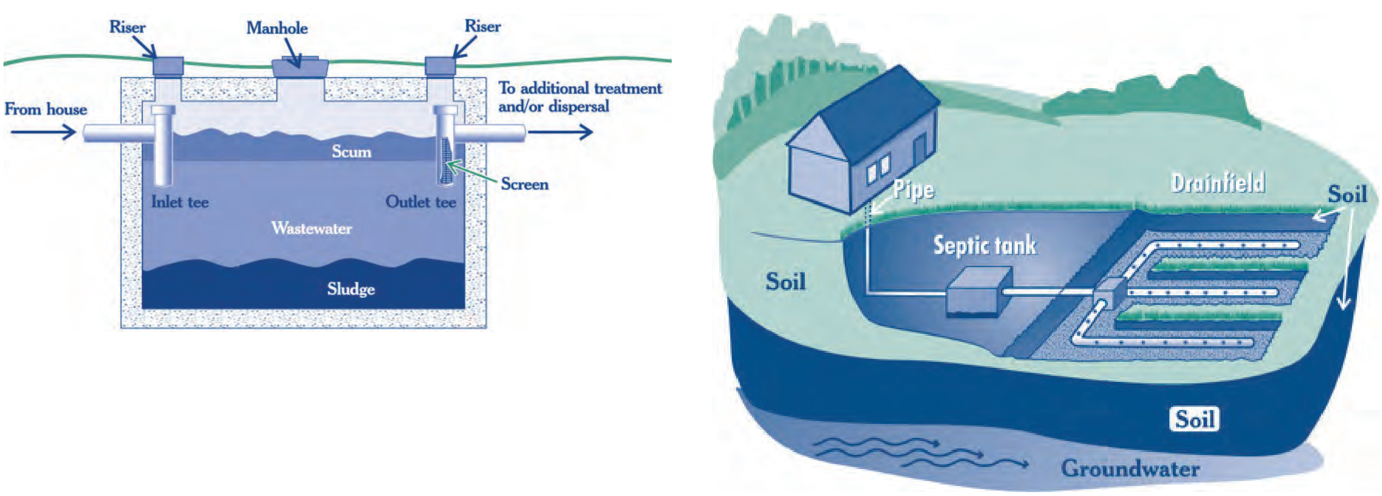
Table 5. Unit Electricity Consumption for Wastewater Treatment by Size of Plant

Treatment Plant Size million gallons/day (cubic meters per day)	Unit Electricity Consumption kWh/million gallons (kWh/cubic meter)			
	Trickling Filter	Activated Sludge	Advanced Wastewater Treatment	Advanced Wastewater Treatment Nitrification
1 MM gal/day ($3,785\ m^3/d$)	1,811 (0.479)	2,236 (0.591)	2,596 (0.686)	2,951 (0.780)
5 MM gal/day ($18,925\ m^3/d$)	978 (0.258)	1,369 (0.362)	1,573 (0.416)	1,926 (0.509)
10 MM gal/day ($37,850\ m^3/d$)	852 (0.225)	1,203 (0.318)	1,408 (0.372)	1,791 (0.473)
20 MM gal/day ($75,700\ m^3/d$)	750 (0.198)	1,114 (0.294)	1,303 (0.344)	1,676 (0.443)
50 MM gal/day ($189,250\ m^3/d$)	687 (0.182)	1,051 (0.278)	1,216 (0.321)	1,588 (0.423)
100 MM gal/day ($378,500\ m^3/d$)	673 (0.177)	1,028 (0.272)	1,188 (0.314)	1,558 (0.412)

Source: EPRI, 2002

2.3 On-Site Sewage Facilities

Figure 25. Septic System



Source: EPA, 2002a

Most on-site sewage facilities (OSSF) are septic systems (Figure 725). As noted previously, a third of Americans (about 100 million) are not connected to municipal sewers, particularly in New England, the Carolinas, West Virginia, Kentucky and Alabama (Figure 20). There is little literature on the energy requirements of these systems. The main energy requirements include initial installation of the tank and lines, operation and maintenance of pumps (if used), and prevention of plant growth on the septic field. Some septic systems require additional pumping for aerobic digestion (similar to a regular

WWTP), needing as much as 1,000 kWh per year, or about 15,000 kWh/MG, 10 times more than at a WWTP (www.biolytix.com, 2012).

OSSFs are often a viable alternative to centralized wastewater treatment if they are planned, designed, installed, operated and maintained properly. No studies have been done to compare on-site wastewater treatment to POTWs for a given municipality. The EPA has identified septic system failures as an important environmental and health problem, affecting groundwater quality or potable water resources, particularly through nitrate and bacteria contamination (ICF International, 2008).

2.4 Process Optimization

Although wastewater treatment is a very energy-intensive process, often taking a heavy toll on the energy spending of municipalities, there appears to be little attention given to energy issues at many plants. In a 2002 survey, the Association of Metropolitan Sewerage Agencies showed that energy management is not a high priority and that few had performance benchmarks including energy cost of wastewater treatment (AMSA, 2002). In spite of this, the EPA and nongovernmental agencies such as the American Water Works Association publish numerous reports and documents on best management practices, energy conservation management and new technologies (Means, 2004; Parsons Corporation, 2006 and 2008; EPA 2010b). The AMSA should reassess the current situation with another survey to see if there has been change. Stillwell et al. (2010) estimate that through optimized aeration and improved pumping alone, WWTPs could save 500 million to 1,000 million kWh annually, which translates to an overall reduction of 3 percent to 6 percent of the energy use in the wastewater sector.

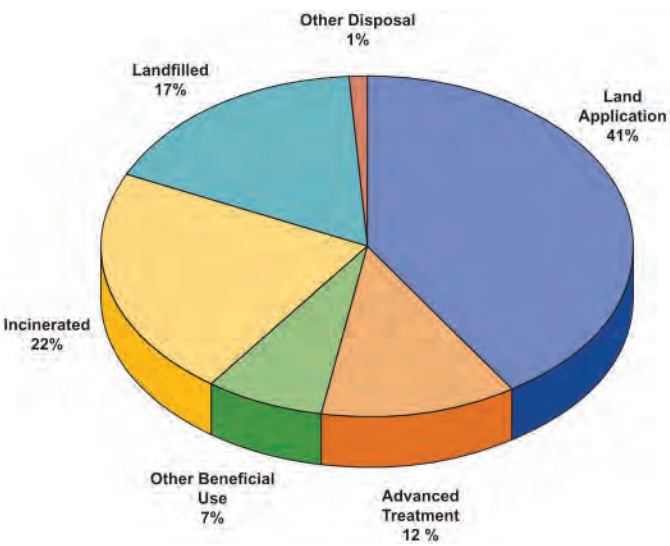
As shown in Figure 24, the main electricity needs for activated sludge are for aeration and pumps. Better management of flows and delayed treatment (at night, for example) can help reduce the electric bill. However, improving existing pumps through maintenance and closer matching of pumps to their duties (such as using variable speed drive [VSD]) can help with gains of up to 30 percent, and new pumps are 5 percent to 10 percent more efficient than previous models (Liu et al., 2012). Improving pumping efficiency requires site-specific data on load factors; this data can be obtained by energy audits. Aging electric motors are responsible for important phase shifts (when current and voltage are not longer in phase), which cause problems on the grid and lead to heavy fines from the public utilities. Well-maintained pumps used at their correct duties can help to easily avoid these fines. Important energy savings can be obtained, leading to well-documented success stories in the industry (CEC, 2005; ICF International, 2008).

Moreover, Liu et al. (2012) report that for activated sludge systems, simple gains of up to 50 percent are possible by aligning control parameters with discharge standards (using dissolved oxygen [DO] probes), translating to a 25 percent reduction in the electric bill of WWTP. This can be done using dissolved oxygen probes, and automated control systems can adjust aeration rates in real time. The oxygen transfer efficiency (OTE) can be improved using better diffusers that create fine bubbles, leading to an enhanced OTE compared to coarse bubble aerators (CEC, 2005; EPA, 2010b). Operators can also take better care of diffusers to prevent fouling.

2.5 Energy Potential of Wastewater Treatment Plants

In addition to energy savings linked to best management practices and system optimization, substantial amounts of energy could be extracted from wastewater. Biogas and biosolids have an enormous potential to offset the energy needs of WWTPs. As shown in Figure 26, biosolids from the aerobic digestion of organic matter can be used beneficially, but a substantial proportion is incinerated (without electricity production) or put in landfills. There are also other potential outlets for WWTPs. Researchers at Stanford University investigated the possibility of turning sewerage into bioplastics or rocket fuel (Rostkowski et al., 2012). Bacteria can produce bioplastics such as polyhydroxyalkanoate acids (PHA) under anaerobic conditions and give a high economic value to municipal wastewater (Pieja et al., 2010; Billington et al., 2011). Nitrous oxide (N2O) can be produced under certain ammonia removal conditions, coined CANDO (Couple Aerobic-anoxic Nitrous Decomposition Operation), which can in turn be used as feedstock for a turbine or co-oxidant for methane combustion (Cantwell et al., 2010).

Figure 26. Summary of Wastewater Solids Management in the U.S.



Source: Parsons Corporation, 2006

Biosolids incineration with electricity generation is a new approach to managing both water and energy in WWTPs. One of its advantages is its high solids reduction along with energy recovery, producing a stable ash waste. However, these facilities require high capital investments, have operational difficulties, and the air emissions can lead to public aversion (Stilwell et al., 2010).

Another option for offsetting energy requirements in WWTPs is to increase beneficial use of digester gas produced by the sewage wastewater, dairy manure and food processing wastes/wastewater (CEC, 2005). Presently, about 50 percent of sewage sludge, 2 percent of dairy manure and less than 1 percent of food processing wastes/wastewater generated in the State of California are utilized to produce biogas (CEC, 2005). On the national level as well, this is a relatively untapped energy source. About 52 percent of wastewater flow uses anaerobic digestion for biosolids but only 30 percent of that gas is used beneficially (Figure 27). Unused biogas is usually flared or vented to the atmosphere, a waste of a renewable resource and a source of air pollution (odor and strong greenhouse gas). Biogas can be used for a combined heat and power (CHP) production.

The Inland Empire Utilities Agency (IEUA) in California is a leader among wastewater treatment agencies for its innovative management of energy. IEUA's wastewater treatment system has several anaerobic digesters and also collects dairy manure from nearby dairies. IEUA's facilities process 65 million gallons of wastewater into high-quality recycled water. At another facility, dairy manure alone is used to produce the methane that is piped to the Chino Basin desalination plant, which treats brackish groundwater (CEC, 2005).

The EPA's Combined Heat and Power Partnership (CHPP) estimates 5 MGD of wastewater is equivalent to about 100 kW of electric power generation capacity. Combining biogas electricity and heat generation with best management practices could provide about half of the electricity requirements of an average facility (Wiser et al., 2010). Some plants in the U.S., such as the WWTPs in San Diego and Carson in California, have been shown to be energy self-sufficient and occasionally produce more power than is needed. Reported biogas energy factors range from 350 to 525 kWh/MG for treated wastewater flows greater than 5 MGD. Based on best management practices and available technology, Stillwell et al. (2010) coarsely estimate that anaerobic digestion could save 600 million kWh to 5,000 million kWh annually in the U.S.

Figure 27. Facilities With Anaerobic Digestion and Digester Gas Utilization in the U.S.

	Average Daily Flow Rate (Millions of Gallons Per Day)						
	< 0.5	0.5-2.5	2.5-7.5	7.5-30	30-75	>75	Total
Number of Plants	11,432	3,013	982	449	101	52	16,029
% of Plants With Anaerobic Digestion Treatment	10%	36%	49%	54%	48%	71%	19%
% of Plants With Digester Gas Utilization	0%	2%	6%	10%	10%	35%	1%
Total Reported Flow (mgd)	1,472	3,363	4,161	6,105	4,692	10,484	30,275
% of Flow With Anaerobic Digestion Treatment	16%	38%	49%	55%	47%	63%	52%
% of Flow With Digester Gas Utilization	1%	3%	6%	12%	10%	29%	15%

Source: ICF International, 2008

In light of these potentially significant energy savings produced by renewable energy, federal, state and local governments could remove potential barriers to the development of these new sources of electricity. For example, current regulations do not allow co-located energy facilities to sell electricity (or energy) at preferential prices, therefore disincentivizing combined heat and power (CHP) or on-site energy generation. Moreover, clear policies for the coupling of energy recovery with wastewater treatment would help grow these technologies with incentives and loans. For instance, in WWTPs, biogas production offsets carbon emissions and could be incentivized with carbon credits. More energy-water partnerships would help broaden and diversify the energy portfolio of the country.

2.6 Constructed Treatment Wetlands

Wetlands are natural water filtration systems. The U.S. has a “no net loss” wetland policy, requiring that every acre of wetland destroyed for development must be rebuilt elsewhere in the same watershed. In addition to constructing wetlands for replacement of environmental values, other constructed wetlands (also called artificial wetlands) have been engineered to be a part of the wastewater treatment process. As the practice of manufacturing artificial wetlands becomes more widespread, it is clear that these artificial wetlands require energy. Building a wetland is a complicated process, often requiring leveling the topography, removing thousands of cubic yards of material, digging miles of streams and planting thousands of trees. No study has been done to compare the energy costs and benefits of wastewater treatment plants and constructed treatment wetlands. While there is a great deal of literature debating the choice of wetland mitigation policies, no articles were found that examine this issue through the lens of potential energy savings.

The size of the wetland is not the only factor that affects water cleanliness. The proximity of a wetland to the end user greatly impacts its ability to replace or reduce the need for a WWTP. Several studies have demonstrated that the mitigation for impacts on urban wetlands happens in more rural areas, where the land is cheaper (Ruhl et al., 2006), but if these constructed wetlands are located too far upstream from the cities, they may not play the same role in water treatment.

Though filtration is wetlands' most direct impact on the amount of energy we spend on water, they can help conserve energy in several other ways. For example, many channelized tributaries in Southern California accumulate sediment and therefore require regular dredging, while a healthy wetlands system could slow the water flow and therefore allow the sediment to settle naturally to the riverbed. Additionally, continuous wetlands can also help protect a watercourse from pollution because it creates an absorbent buffer between the contaminant and the stream (EPA, 2002b; EPA, 2005). Wetlands can also help with flood control, saving the energy that would otherwise be needed to build and maintain levies or dams. Finally, wetlands can help transfer water from the surface to an underground aquifer (albeit with some evapotranspiration), circumventing the need for underground injection.

3. Recycled Water

Wastewater treatment plants discharge about 32 billion gallons per day (BGD) of effluent in the U.S. (NRC, 2012; EPA, 2012). Most of this effluent or treated wastewater is returned to streams, rivers or lakes. However, about 12 BGD, or 38 percent of the total effluent, is discharged to an ocean or estuary. Reusing this treated wastewater, particularly the coastal discharges, would substantially increase available water resources (about 6 percent of total U.S. water use or 27 percent of public supply; NRC, 2012). As population increases, particularly in the water-stressed Southwest, new sources of water are required to meet the needs of urban areas, agriculture and the industry. As shown in Figure 28, water recycling is often one of the cheapest sources of water, after agricultural and urban water use efficiency.

Recycled water presents many benefits to utilities and customers, such as reduced energy consumption associated with production, treatment and distribution of water; a drought-resistant and stable source of local water; and significant environmental benefits, like reduced nutrient loads to receiving water bodies due to reuse of the treated wastewater and thus avoided discharge (NRC, 2012; EPA, 2012). Although the development of recycled water is very promising, high capital investments, public acceptance, the lack of strong federal and state incentives and current state legislation (or lack of it) have substantially slowed it down compared to goals from the 1990s.

Figure 28. Unit Cost Information for Selected Resource Management Strategies

Unit Cost Information for Selected Water Plan Update 2009 Resource Management Strategies	
Resource Management Strategy	Range of Costs (dollars/acre-feet)
Agricultural Water Use Efficiency	$85 – $675
Brackish Groundwater Desalination	$500 – $900
Meadow Restoration	$100 – $250
Ocean Desalination	$1,000 – $2,500
Recycled Municipal Water	$300 – $1,300
Surface Storage	$300 – $1,100
Urban Water Use Efficiency	$223 – $522
Wastewater Desalination	$500 – $2,000

Source: DWR, 2009

3.1 Regulations and Policy

i. Federal Level

There is currently no federal legislation concerning wastewater recycling. The Safe Drinking Water Act does not include specific requirements for treatment or monitoring when municipal wastewater effluent is an important component of source water (NRC, 2012). However, recognizing the growth in the past decade of wastewater reuse and its impact on potable water supplies, it seems clear the federal efforts to address potential exposure to wastewater contaminants will become increasingly important.

The only federal document available is a guideline from the U.S. Environmental Protection Agency for non-potable reuse (EPA, 2012). It is partly based on a review and evaluation of current state regulations, not on rigorous risk assessment methodology (NRC, 2012; EPA, 2012). Scientifically supportable risk-based federal regulations for non-potable water reuse and indirect potable water reuse would provide the nation with minimum acceptable standards and could facilitate water recycling projects, particularly by increasing public acceptance (NRC, 2012). U.S. EPA Region 9 (California, Nevada and Arizona) is the only region to have a website dedicated to water recycling.

ii. State Level

Regulations concerning wastewater reuse vary widely from one state to another. Most states do not have anything more than the guidelines from the EPA. Currently, water rights laws affect the ability of water authorities to promote water-recycling projects. As of 2012, 30 states and one U.S. territory have adopted regulations and 15 states have guidelines or design standards that govern water reuse (EPA, 2012). These water rights laws and regulations concerning wastewater reuse vary by state, and projects can proceed through the acquisition of water rights after water rights have been clarified through legislation or court decisions (NRC, 2012). State water reuse regulations or guidelines for non-potable reuse are not based on rigorous risk assessment methodology that can be used to identify and manage risks. *2012 Guidelines for Water Reuse* by the EPA has an extensive review of state regulations concerning recycled water (EPA, 2012).

Most of the literature on the subject of water reuse is from California's state agencies, institutes and universities. The State of California has long identified the potential of water recycling as a new water supply to meet future demand and mitigate the loss of water rights to the Colorado River and the San Joaquin River Delta. Recycled water is California's fastest-growing new source of water (CEC, 2005). The California Water Code defines recycled water as "water which, as a result of treatment of waste, is suitable for a direct beneficial use or controlled use that would not otherwise occur." The Water Recycling Act of 1991 describes the environmental benefits and public safety of using recycled water; it is considered as a reliable and cost-effective method to help meet California's water supply needs (Department of Water Resources [DWR], 2009). The act set a statewide goal to recycle 700,000 acre-feet per year (AFY) by the year 2000 and 1 million AFY by 2010. Although these goals were not met, they set the foundation for recycled water in California.

According to the California Department of Water Resources, the Department of Public Health (CDPH) adopted water recycling criteria which are based on water source and quality, and specify sufficient treatment based on intended use and human exposure. These criteria are regulated by the Regional Water Quality Control Boards (Regional Water Boards) through permits specifying wastewater treatment methods, approved uses of recycled water and performance standards (DWR, 2009). The objectives of the criteria are to remove pathogens and excess nutrients through enhanced treatment, making the water clean and safe for the intended uses.

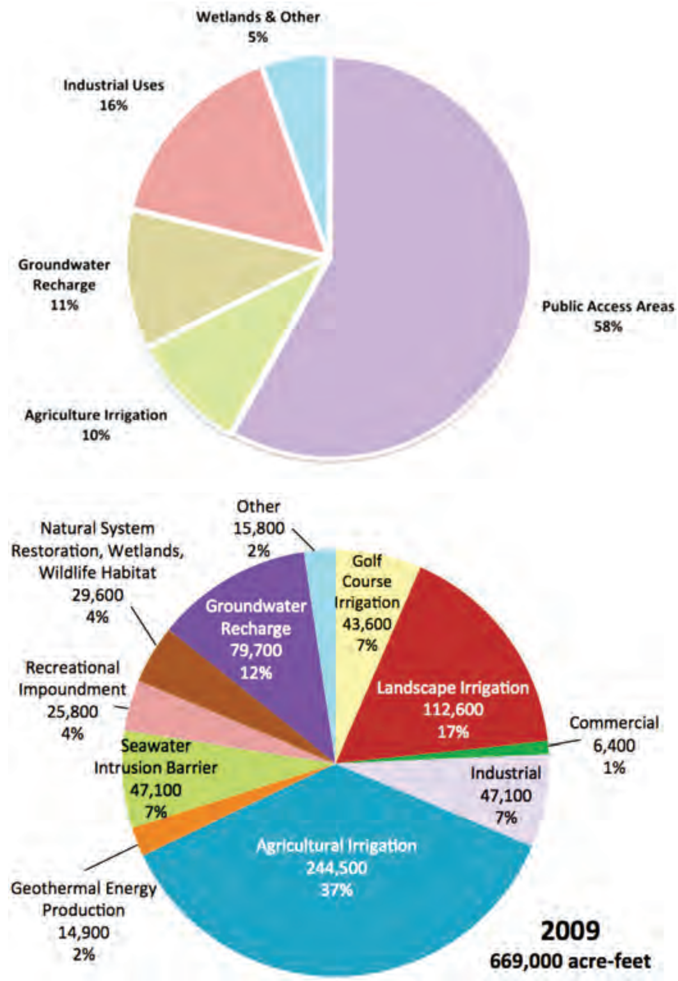
Recycled water in California is most commonly used for groundwater recharge or for landscape or irrigation purposes and industrial processes. It has been identified that by 2020, more than 2.5 BGD will be generated annually by California's urban coastal areas, and much of this could be recycled (Wolff et al., 2004). While the state is only recycling about 500,000 AFY, the Department of Water Resources has set a goal of 1.5 million AFY by 2020 and 2.5 million AFY by 2030 (DWR, 2009). To meet these goals, numerous projects are being funded at the federal (Bureau of Reclamation), state ($1.25 billion through the Safe, Clean and Reliable Drinking Water Act of 2010) and local (Metropolitan Water District and others) levels. The State Water Resources Control Board issued a mandate to increase wastewater reuse levels from 2009 by 200,000 AFY in 2020 and by an additional 300,000 AFY in 2030.

3.2 Water Reuse in the U.S.

The reuse of water is not new. California has had dedicated recycled water systems since the 1920s. In the U.S., as much as 2.5 BGD (2.8 million AFY), or roughly 7 percent to 8 percent of treated municipal effluent is reused beneficially (EPA, 2012); however, the potential is much higher. In California alone, coastal communities release 3.5 million AFY of highly treated water into the Pacific Ocean. Recycled water can serve many purposes: It can be an additional water source (offsetting the need for additional freshwater supplies), a hedge against droughts, an environmentally friendly alternative for treatment and disposal of wastewater, a natural treatment through land application and a reduction in discharge of excess nutrients into surface waters, a source of nutrients for crops or landscape plants, and a means to enhance ecosystems such as wetlands (DWR, 2009). Although the U.S. leads other countries in terms of volume of water recycled, some countries such as Australia have much more aggressive targets (from 8 percent to 30 percent in 2015), and some countries already reuse most of their water, such as Israel, which currently reuses 70 percent of its municipal wastewater effluent (EPA, 2012).

Unfortunately, the end uses and volumes of reclaimed water are not well documented nationally. The last comprehensive survey of water reuse was conducted in 1995 by the U.S. Geological Survey (EPA, 2012). In the 2012 Guidelines for Water Reuse, the EPA characterized water reuse in the U.S. to the extent possible, but the document clearly lacked granular data. California and Florida are among the only states that regularly publish reports on recycled water in their respective states. There is no inventory of water recycling plants and their capacity. The WateReuse Foundation is working on a national database of reuse facilities that could help address this data gap (Bryck et al., 2008; Tchobanoglous et al., 2011; NRC, 2012).

Figure 29. Reclaimed Water Utilization in Florida and California



Source: Florida Water Reuse Program, 2012; California WRFP, 2011

The USGS and the EPA estimate that 90 percent of water reuse comes from only four states: Florida, California, Texas and Arizona (EPA, 2012). Florida publishes a comprehensive annual report of water reuse (Florida Water Reuse Program, 2012). According to the 2011 Reuse Inventory, Florida recycled 722 million gallons per day (MGD) of wastewater effluent, or 0.8 million acre-feet (AF). The majority of this water, about 58 percent, was used for landscaping (Figure 29). In California, the last full review by the State Water Resources Control Board in 2011 showed that recycled water accounted for 669,000 AF (WRFP, 2011). This is about 1 percent of total water needs in

California, but can be as high as 5 percent in Southern California (Bennett et al., 2010). Most of this water is used for agricultural irrigation, followed by landscape and golf course irrigation (WRFP, 2011; Figure 29). Nearly 20 percent of recycled water is used for groundwater recharge and seawater intrusion barriers. Many local agencies are looking to recycled water as a costly but stable alternative to supplies imported from distant locations (Hanak et al., 2011). The Texas Water Development Board estimated that 320 MGD, or 0.36 million AF, were reused in 2010, although no breakdown of use is available (NRC, 2012). In Arizona, over 0.2 million AF are recycled annually (Mayes, 2010), mostly for landscaping and thermoelectric cooling (e.g., Palo Verde Nuclear Power Plant).

i. Non-Potable Reuse

Water reclamation for non-potable applications is well established, particularly in the industrial, agriculture and landscaping sectors. The non-potable recycled water system designs and treatment technologies are generally well accepted by communities, practitioners and regulatory authorities (NRC, 2012). In California and Florida, most of the recycled water is used for non-potable reuse applications (landscaping, agriculture, golf courses, industrial, etc.; Figure 29). In other states, non-potable recycled water usage is concentrated on thermoelectric power plants. In particular, there are many examples of water-energy partnerships such as the Xcel Energy Cherokee Station and the Denver Water Recycling Plant (Colorado), and the Phoenix WWTP and the Palo Verde Nuclear Power Plant (Arizona). Producing approximately 4GW of power, the Palo Verde Nuclear Power Plant is the biggest in the United States.

In industrial applications, recycled water often displaces municipal potable water. In the Pacific Institute's Waste Not, Want Not, the greatest potential in water savings was identified to be in traditional heavy industries (e.g., refineries) by replacing cooling and process water with recycled water (Gleick et al., 2003). Moreover, there is great potential for water recycling in oil and gas industry, where as much as 2 million AF of produced water is recovered from oil and natural gas wells, most of which are in Texas and California (EPA, 2012).

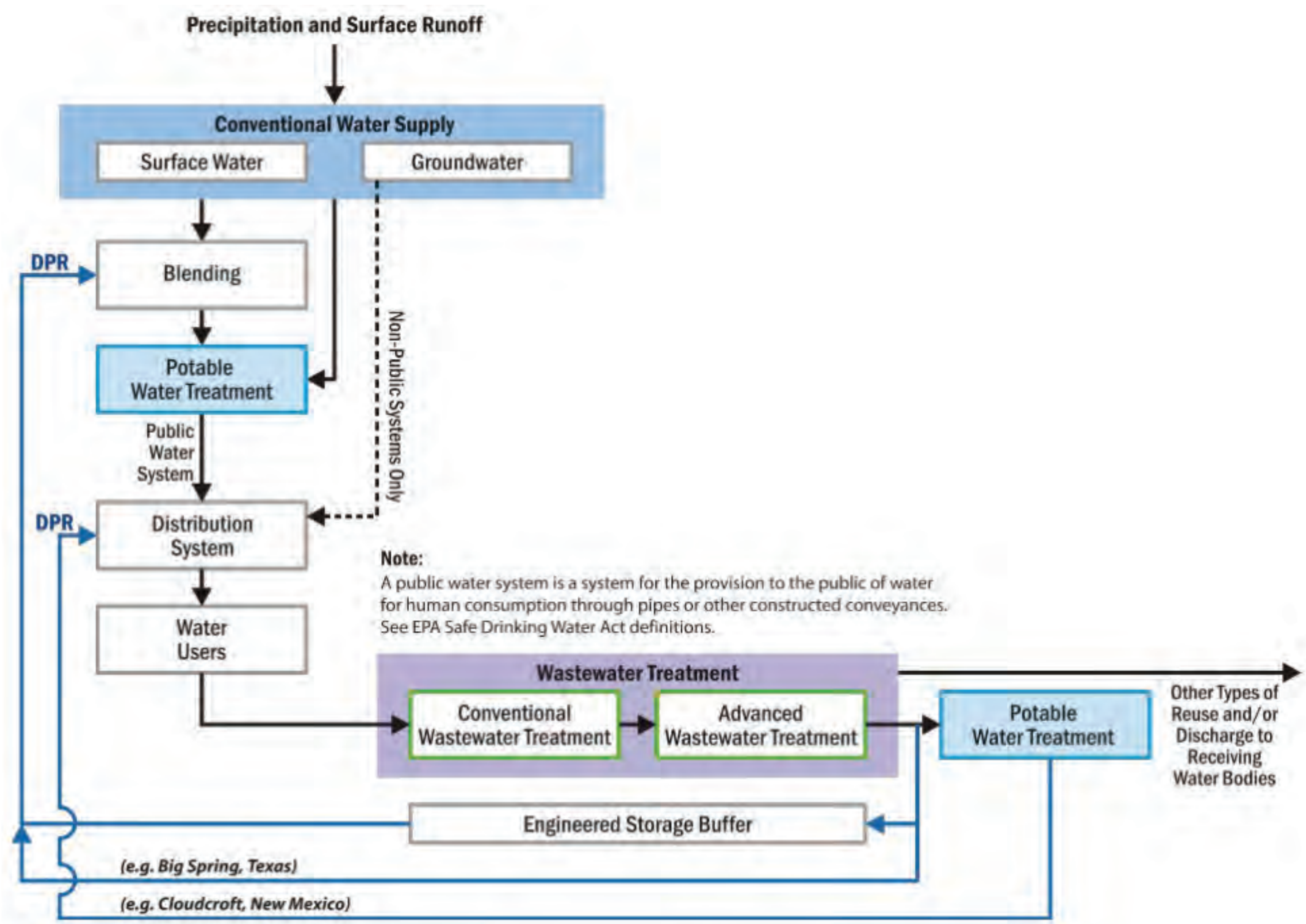
ii. Potable Reuse

Billions of gallons of wastewater effluent are discharged each day into the waterways of the country, thereby augmenting water supplies for drinking water, irrigation or thermoelectric. This is referred to as de facto reuse of treated wastewater. De facto reuse can be an important source of water: Drinking water sources for more than 26 million people in the U.S. contain between 5 percent and 100 percent treated wastewater effluent from upstream discharge during low flow periods (Stillwell et al., 2011). A systematic analysis of the extent of effluent contributions to potable water supplies has not been made in the U.S. for more than 30 years (NRC, 2012). Such an analysis could be extremely useful, particularly as we learn more about the Contaminants of Emerging Concern polluting waterways. Although some countries such as Singapore and Namibia have embraced direct potable reuse (i.e., returning wastewater effluent to the drinking water network after enhanced water treatment), this practice is not yet allowed in the U.S. for fear of public health risks.

The National Research Council, in its comprehensive study of water reuse in the U.S., compared the estimated risks of a conventional drinking water source containing a small percentage of treated wastewater against the estimated risks of different potable reuse scenarios considering some chemical and microbial contaminants (NRC, 2012). The committee found that the two planned potable reuse scenarios do not exceed the contamination risk encountered from existing water supplies and may be much lower (NRC, 2012). Several other publications have investigated the future role of direct potable reuse in the management of water resources (Tchobanoglous et al., 2011; EPA, 2012; Schroeder et al., 2012).

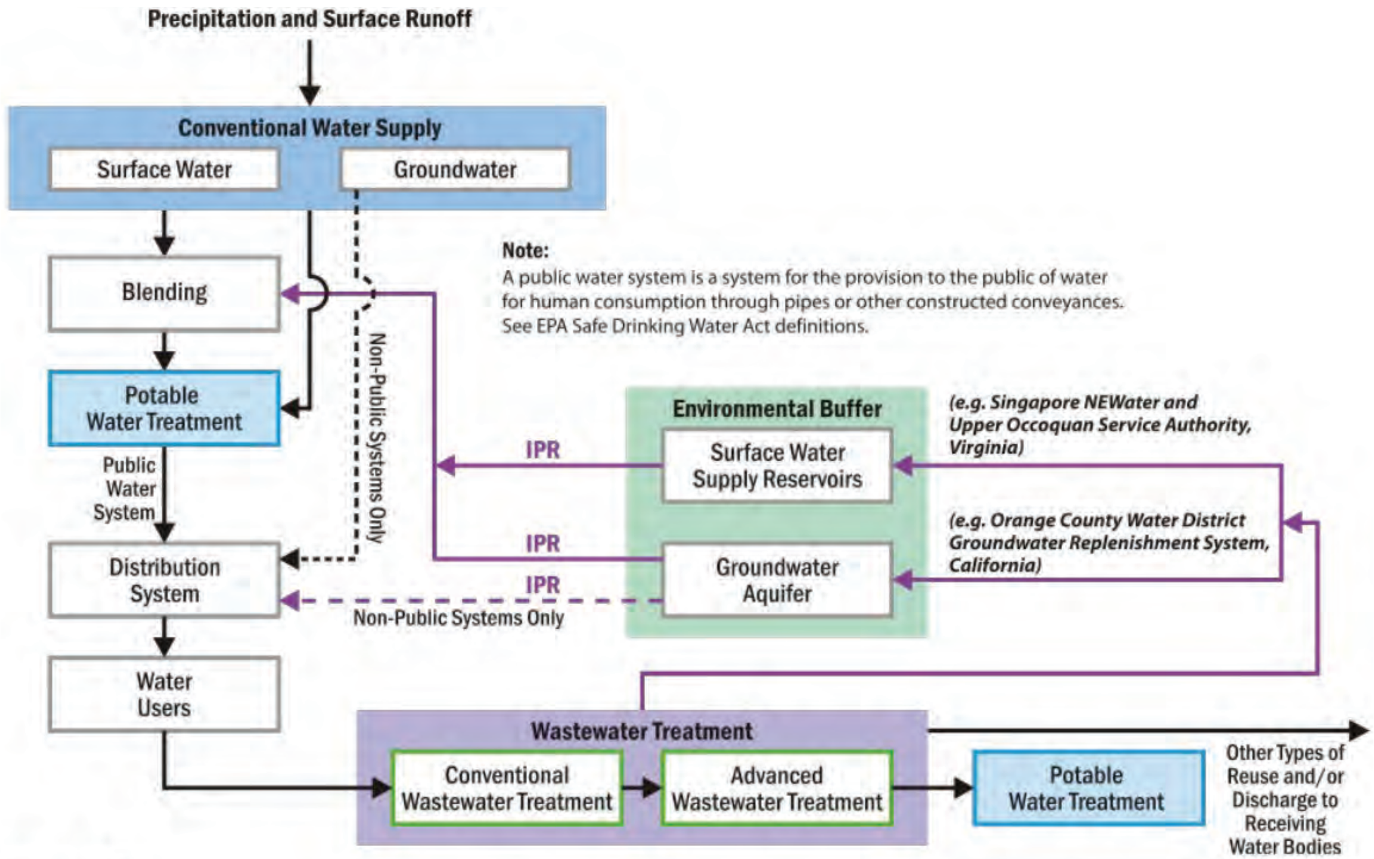
As water demand increases and new water sources are hard to come by, there is a clear trend towards more potable water reuse. There are two types of water reuse: direct potable reuse (Figure 30) or indirect potable reuse (Figure 31). In direct potable reuse, treated wastewater that has been further treated to potable water standards is directly blended with other existing water sources or put into the water distribution system. In indirect potable reuse, treated wastewater is put through an environmental buffer such as surface drinking water reservoirs or groundwater aquifer before being blended with other water sources for drinking water. In Texas, several water reclamation plants return effluent directly into drinking water reservoirs, while in California the recent Groundwater Replenishment System is protecting the county's aquifers through a seawater intrusion barrier and groundwater recharge basins. Over the past 40 years, there is strong evidence that wastewater recycling is much better accepted when it is indirect potable reuse via an environmental buffer such as a groundwater aquifer or surface water supply reservoir (NRC, 2012).

Figure 30. Planned Direct Potable Reuse (DPR) and Examples of Implementation



Source: EPA, 2012

Figure 31. Planned Indirect Potable Reuse (IPR) and Examples of Implementation



Source: EPA, 2012

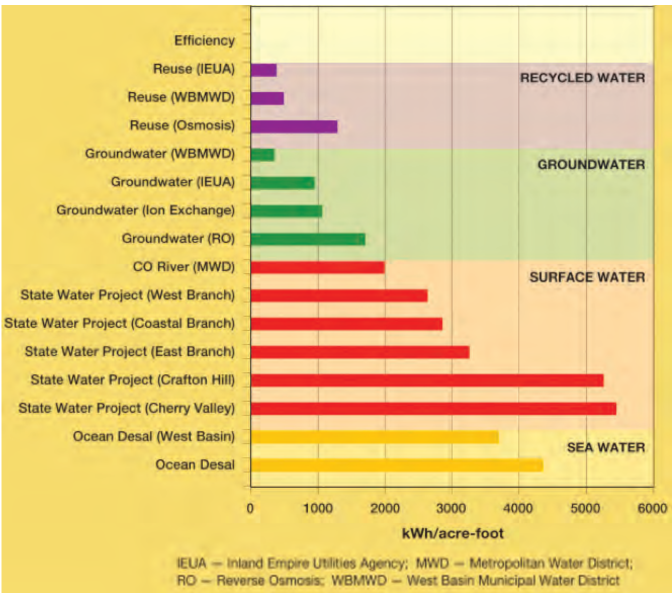
Concerning groundwater recharge (or Aquifer Storage and Recovery [ASR]), surface spreading requires little additional treatment due to soil acting as a filter, but direct injection requires additional treatment to avoid physical, biological or chemical clogging and pathogen introduction in the aquifer (NRC, 2012; EPA, 2012). This tends to require the more energy-intensive membrane processes, but it is also a way to improve groundwater quality by reducing nutrient content and total dissolved solids (TDS), as in Orange County.

3.3 Energy Intensity of Water Recycling

The literature on the energy intensity of water recycling is very sparse and is focused on California. However, in the *2012 Guidelines to Water Reuse*, the U.S. EPA included a section on the water-energy nexus highlighting this topic (EPA, 2012). Several papers have tackled the energy intensity of water recycling, including those by EPRI (2002), California Energy Commission (CEC) (2005), Navigant Consulting (2006, 2008) for the CEC and California Public Utilities Commission (CPUC), GEI Consultants and Navigant Consulting (2010) for the CPUC, Bennett et al. (2010) for the CPUC, and Schroeder et al. (2012). The California Energy Commission, in support of its 2005 Integrated Energy Policy Report, described recycled water as "the least energy-intensive source in the State's water supply." Many utilities have also published gray literature showing the results of their projects (e.g., Inland Empire Utilities Agency, Santa Clara Valley Water District, Orange County Water Department, Metropolitan Water

District of Southern California). Figure 32 shows the different costs of energy for different water supplies in Southern California, highlighting that water recycling is often the least energy-intensive water source after water efficiency.

Figure 32. Energy Intensity of Water Supply Sources in Southern California



Source: Larsen et al., 2007

The energy intensity of recycled water depends primarily on the quality of the inflow (wastewater) and on the end use of this water. Agriculture needs water with low total dissolved solids (TDS) and a high nutrient content. The industry section can use recycled water that is very pure to less pure, depending on the application. Recycled water intended for drinking water needs to be treated to high-quality standards, particularly with regard to pharmaceuticals and chemicals. The more treatment that is needed, the higher the energy bill will be; therefore, energy intensities should be given according to end use. Domestic, commercial and industrial uses of water supplies result in an increase in the mineral content of municipal wastewater. This frequently leads to requiring energy-intensive membrane processes to reduce TDS in the recycled water.

Moreover, the distribution of recycled water generally has a higher energy cost than the distribution of potable water, since wastewater facilities are often sited at lower elevations to take advantage of gravity. The latest study in California found a resultant energy intensity of recycled water on a statewide average basis to be 1,130 kWh/AF or 3,460 kWh/MG (Bennett et al., 2011). This result does not consider the incremental addition of energy to bring the water to reuse quality. In 2006 Navigant Consulting estimated the energy intensity of wastewater recycling and distribution in California to be 1,200 to 3,000 kWh/MG. The literature review conducted by the NRC reported an incremental energy cost of 400 to 1,200 kWh/MG for reclaimed water (NRC, 2012).

The increased use of recycled water displaces or avoids the marginal water supplies, which are the most expensive, often the one with the highest energy intensity. The displaced energy can be very different from the embedded energy, but is very hard to evaluate. Using a total life-cycle analysis, Stokes and Horvath (2009) found a similar result in the U.S., as shown by a myriad of California utilities. For a typical U.S. utility, recycled water is preferable to desalination and comparable to importation in terms of energy. The U.S. EPA estimates that the net energy savings of recycled water are high, at 3,000 to 5,000 kWh/MG (EPA, 2012). And the estimated net energy savings could range from 0.7 to 1 TWh/year, or 3,000 to 5,000 kWh/MG. Stillwell et al. (2011) estimate that the use of reclaimed water saves 1,400 to 1,800 kWh/MG needed for collecting, treating, disinfecting and distributing drinking water for non-potable uses. This implies that California could be saving about 300 GWh of electrical energy annually, with much more savings anticipated as new reclaimed water facilities are built.

i. Water Recycling Facilities

As discussed previously in this Review, wastewater treatment can be a very energy-intensive process. Bringing our sewage to acceptable quality levels for reuse and/or human exposure is costly. The recycled water production cycle needs energy for transport to the reclamation plant, advanced treatment, distribution and perhaps subsurface injection costs. However, most of the energy needed for producing recycled water is already required for wastewater treatment to meet discharge requirements. The focus is therefore on how much extra energy is needed to be able to reuse the wastewater. Table 6 shows the energy intensities of different water treatment levels for different end uses (Cooley & Wilkinson, 2012). This strongly highlights the energy premium of membrane processes. Table 7 shows the U.S. EPA Guidelines for the minimum treatment according to the end use of the recycled water.

Table 6. Energy Intensity of Recycled Water Treatment

Technologies Used	Energy Use (kWh/MG)	End Use
Conventional Tertiary Treatment		
Anthracite coal bed filtration,demineralization, chlorination	982	Irrigation, industrial use
Flocculation, direct filtration, UV/advanced oxidation	1,500	Irrigation, industrial use
Clarification, media filtration, chlorination	1,619	Irrigation, industrial and commercial use
Anthracite coal bed filtration, UV	1,703	Irrigation, industrial use
Rapid mix, flocculation, media filtration, UV	1,800	Irrigation
Membrane Treatment		
Coagulation, flocculation, clarification, UF, RO, UV/advanced oxidation	3,220	Agricultural, industrial use
MF, RO, UV/advanced oxidation	3,680	Groundwater recharge
MF, RO, UV/advanced oxidation	3,926	Seawater intrusion barrier
UF, RO, UV	4,050	Industrial use
MF, RO	4,674	Industrial use
MF, RO	8,300	High-quality industrial use

Source: Cooley & Wilkinson, 2012

Table 7. End Use of Recycled Water and Minimum Treatment

<table>
<tr><th colspan="2">Reuse Category and Description</th><th>Treatment</th><th colspan="2">Reuse Category and Description</th><th>Treatment</th></tr>
<tr><td rowspan="2">Urban Reuse</td><td>Unrestricted</td><td>Secondary, Filtration, Disinfection</td><td rowspan="3">Industrial Reuse</td><td>Once-Through Cooling</td><td>Secondary</td></tr>
<tr><td>Restricted</td><td>Secondary, Disinfection</td><td>Recirculating Cooling Towers</td><td>Secondary, Disinfection (coagulation & filtration could be needed)</td></tr>
<tr><td rowspan="3">Agricultural Reuse</td><td>Food Crops</td><td>Secondary, Filtration, Disinfection</td><td>High-Quality Industrial Use</td><td>Secondary, Filtration, Advanced Wastewater Treatment, Disinfection</td></tr>
<tr><td>Processes Food Crops</td><td>Secondary, Disinfection</td><td rowspan="2">Groundwater Recharge</td><td>Non-Potable Reuse, Spreading</td><td>Primary</td></tr>
<tr><td>Non-food Crops</td><td>Secondary, Disinfection</td><td>Non-Potable Reuse, Injection</td><td>Secondary, Soil Aquifer Treatment</td></tr>
<tr><td rowspan="2">Impound-ments</td><td>Unrestricted</td><td>Secondary, Filtration, Disinfection</td><td rowspan="3">Indirect Potable Reuse</td><td>Groundwater Recharge, Spreading</td><td>Secondary, Filtration, Disinfection</td></tr>
<tr><td>Restricted</td><td>Secondary, Disinfection</td><td>Groundwater Recharge, Injection</td><td>Secondary, Filtration, Advanced Wastewater Treatment, Disinfection</td></tr>
<tr><td>Environmental Reuse</td><td>Create wetlands, enhance natural wetlands, sustain stream flow</td><td>Secondary, Disinfection</td><td>Augmentation of Surface Water Supply Reservoir</td><td>Secondary, Filtration, Advance Wastewater Treatment, Disinfection</td></tr>
</table>

Source: Adapted from EPA, 2012

ii. Engineered Natural Systems

Engineered natural systems offer an interesting alternative to energy-intensive water reclamation plants as they require little to no chemical or energy input. However, there is a lack of standardized guidelines for their design and operation. There is also little scientific data and literature on the subject. Environmental buffers can further remove pathogens and other contaminant levels such as pharmaceuticals and personal care products (contaminants of emerging concern) from the water, provide additional retention time and allow for the recycled water to blend with other raw water sources. However, it cannot be demonstrated that these natural buffers provide public health protection that cannot be offered by engineered processes (NRC, 2012). These systems also require vast spaces, the right topology, the right geography and the right climate. These requirements may be a challenge in dense urban areas like in Southern California.

3.4 Barriers to Water Recycling

Although water recycling seems to be a promising source of water to meet future demand, there are strong barriers to the full development of recycled water. In a study conducted in 2008, Navigant Consulting identified that most water and wastewater agencies cited two primary barriers to increasing use of recycled water: public perception and the high cost of dual plumbing. Moreover, to incentivize the use of recycled water, current rates do not typically return the full cost of treating and delivering reclaimed water to customers (NRC, 2012).

Development and use of recycled water will require significant capital investments, both for water utilities and customers. To offset these capital costs, water and wastewater agencies could be compensated through incentives equivalent to the avoided cost of energy and of water. Customers would also bear the burden of dual plumbing, retrofits being much more expensive than dual plumbing in new buildings. Therefore, it is to be expected that most of the development of recycled water will come from the new construction. For example, on the Stanford University campus, all new buildings are connected to a network of purple recycled water pipes. The Navigant Consulting report identified that in California the high cost of dual plumbing is the major barrier to beneficially use the 90,000 AF of high-quality tertiary treated wastewater effluent currently discharged in the ocean.

The media has played and continues to play a major role in the public perception of water recycling. The "toilet-to-tap" expression, coined by opponents to water reuse, still resonates strongly. However, since the turn of the century, public dialogue about reuse has increased, particularly in areas of water scarcity, and there is greater public knowledge and acceptance about water reuse as an option. In urban areas in Florida, California, Arizona and Texas, where 90 percent of total U.S. reuse occurs, a survey in 2009 by the WateReuse Research Foundation found that two-thirds of respondents knew what recycled water is (EPA, 2012). It has also been found that the language used to describe the process and the purified water plays a major role in public acceptance.

Public involvement with water reuse projects is extremely important for its success, as research has shown that a community has a more favorable attitude toward a project as its level of familiarity with water reuse increases (USBR, 2004). Public outreach, education and involvement programs that put water reuse into perspective and promote shared decision-making help to develop public understanding. Implementation of public information and education programs can be assisted by guidelines posted by the Bureau of Reclamation (USBR, 2004). Outreach channels can include a website, press releases, mail campaigns, tours and briefings (schools and others), cable television ads, telephone surveys, focus groups and legislative lobbying. But intensive campaigns come at a price, and can have a significant impact on the total cost of a project. Singapore has carried out a successful public awareness campaign to build a national commitment to water reuse. There, the NeWater project is now operational, effectively blending ultra-pure treated wastewater into the drinking water supply.

4. Water Discharge

The Clean Water Act governs the discharge of pollutants into the waters in the United States Industrial and municipal WWTP facilities, ensuring that it complies with the National Pollutant Discharge Elimination System (NPDES) that governs the amount of pollutants that facilities are allowed to discharge.

In 2000 Congress amended the Clean Water Act to require permits for discharges from combined sewers (which transport both wastewater and storm water) to WWTPs (GAO, 2011). This was a means to match the EPA's Combined Sewer Overflow Control Policy, which requires facilities to implement certain minimum pollution control practices. Combined sewers are prone to overflow during heavy precipitation, resulting in the uncontrolled discharge of untreated sewage into receiving water bodies. A report by the CBO (2002) identified that $50.6 billion was needed to correct problems with sewer systems that combine storm runoff with wastewater. The EPA (2010a) estimated that $63.6 billion was needed for combined sewer overflow and $42.3 billion was needed for urban storm water management.

The EPA has identified sanitary sewer overflows (SSOs) and combined sewer overflows as a major environmental problem, contaminating waters and causing serious water quality problems, and it is looking for means to reduce them (EPA, 2004; NRC, 2008). The EPA estimates that there are at least 23,000 to 75,000 SSOs per year (not including sewage backups into buildings). These types of discharges have a variety of causes, including blockages, line breaks, sewer defects that allow storm water and groundwater to overload the system, lapses in sewer system operation and maintenance, power failures, inadequate sewer design and vandalism.

5. Conclusion

The two major studies cited regularly in the literature were conducted by EPRI (2002) and Burton (1996). There are concerns that these studies are outdated and do not reflect the stricter treatment processes implemented over the last decade. This suggests that they underestimate the energy needed to treat water (GAO, 2011). Moreover, these studies only investigated the electricity requirements of WWTPs and did not investigate other energy needs such as natural gas, which can be significant (Park & Bower, 2012). Several new energy-intensive advance treatment processes and technologies are being deployed in the water and wastewater utility sector and there are needs to investigate possibilities to reduce their energy footprint.

There is also a need to identify and optimize existing policies, practices and perceptions to lower energy consumption associated with conveyance, treatment, distribution, use and reclamation of water and wastewater. In addition, development of energy optimization policies and practices should be continued. A knowledge gap exists in understanding how to engage operators and managers in the energy savings potential of new energy optimization technologies and practices.

The potential for decentralization of wastewater treatment to generate energy savings or costs is little understood. Investigating the potential benefits and limitations of decentralizing wastewater treatment would benefit the research and discourse in this field.