An Analysis of the Energy Intensity of Water in California: Providing a Basis for Quantification of Energy Savings from Water System Improvements

Robert Wilkinson, Bren School, University of California, Santa Barbara
Gary Wolff, Pacific Institute
William Kost, Bren School, University of California, Santa Barbara
Rachael Shwom, Michigan State University

ABSTRACT

Energy use associated with water use in California is significant, with extraction / conveyance and urban end-uses accounting for major portions. Estimates by the California Energy Commission in 2005, developed as part of the Integrated Energy Policy Report, indicate that 19% of the state's electricity use, and 33% of natural gas use (excluding power plants), is devoted to water use. (CEC 2005) A characterization and initial assessment of statewide energy inputs into all elements of the water system is currently being undertaken by the authors with support from the California Energy Commission's Public Interest Energy Research (PIER) program. The project is seeking to identify energy inputs to water systems in California, from the point where water is extracted from surface or groundwater sources, through conveyance, treatment, distribution, end-uses (thermal, further treatment, pressurization, etc.), wastewater collection, treatment at applicable discharge standards, and disposal. The sum of all of the energy inputs to water that is delivered to, used, and disposed of in a specific location constitutes its energy intensity. This energy intensity factor is in turn the best measure of the potential avoided energy derived from alternative management options, including end-use efficiency measures. Flow diagrams and models have been developed to characterize the energy inputs at each step of the process in order to facilitate consistent analysis of the energy intensity of water.

Introduction

Water and energy systems are interconnected in several important ways. Developed water systems provide energy – through hydropower – and consume energy, primarily through pumping and thermal processes (e.g. water heating). Critical elements of California's water infrastructure are highly energy intensive. Moving large quantities of water long distances and over significant elevation gains in California, treating and distributing it, meeting end-uses for various purposes, and managing the resulting wastewater, accounts for one of the largest uses of electrical energy in the state. (Wilkinson 2000)

Improving the efficiency with which water is used provides an important opportunity to increase related energy efficiency. (*"Efficiency"* as used here describes the useful work or service provided by a given amount of water.) Significant potential economic as well as environmental benefits can be cost-effectively achieved in the energy sector through efficiency improvements in water systems. (Wilkinson 2000; Wolff et al. 2004)

Energy intensity, or *embodied energy*, is the total amount of energy, calculated on a whole-system basis, required for the use of a given amount of water in a specific location. (Wilkinson 2000)

The energy intensity of water varies considerably by geographic location of both end-users and sources. Water use in certain parts of the state is highly energy-intensive due to the combined requirements of conveyance over long distances with significant elevation lifts, local treatment and distribution, and wastewater collection and treatment processes. Significant energy efficiency gains are possible through implementation of cost-effective *water* efficiency improvements. (Owens-Viani et al. 1999) Important work already undertaken by various agencies, departments, associations, private sector users, and non-governmental organizations in the area of combined end-use efficiency strategies has demonstrated this potential. (Vickers 1999; Vickers 2001; Dziegielewski 1999; Gleick et al. 2003)

Large water and energy efficiency improvements have been demonstrated in the municipal and industrial (M&I) and agricultural sectors in California. (Ownes-Viani 1999) In all sectors there is wide variability in both water-use efficiency and energy intensity of the water used depending on water sources, irrigation practices, price, and other factors.

Overview of Energy Inputs to Water Systems

There are four principle energy elements of water systems:

1. primary water extraction, conveyance, and storage
2. treatment and distribution within service areas
3. on-site water pumping, treatment, and thermal inputs (heating and cooling)
4. wastewater collection, treatment and discharge

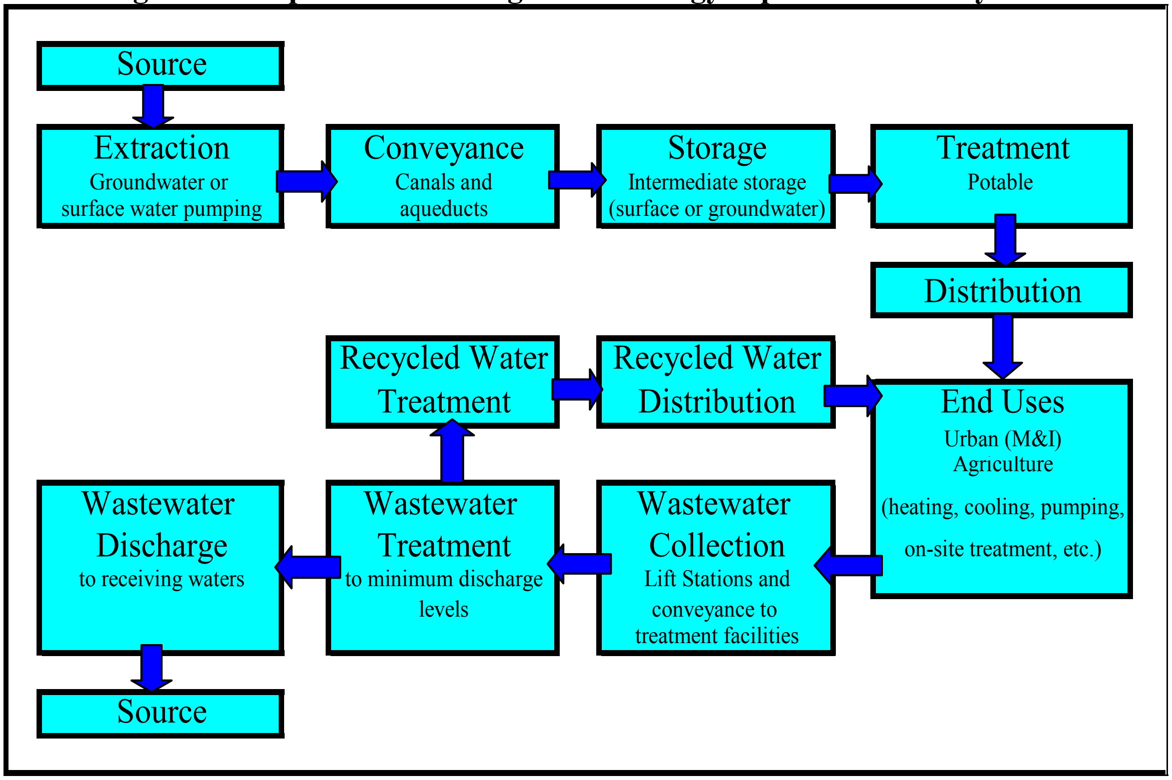
The simplified flow chart below illustrates the steps in the water system process.

Pumping water in each of these stages is energy-intensive. Other important energy inputs include thermal energy (heating and cooling) applications at the point of end-use, and aeration in wastewater treatment processes.

1. **Primary water extraction, conveyance, and storage.** Extracting and lifting water is highly energy intensive. For example, water is pumped from near sea-level in the Sacramento-San Joaquin delta to the San Joaquin-Tulare Lake Basin, and then over mountains to the Central Coast and Southern California, and water is pumped from the Colorado River to metropolitan Southern California. Groundwater pumping also requires significant amounts of energy depending on the depth of the source. Where water is stored in intermediate facilities, such as reservoirs like San Luis or groundwater banks, net energy is required to store and then recover the water.
2. **Treatment and distribution within service areas.** Within local service areas, water is treated, pumped, and pressurized for distribution. Local conditions and sources determine both the treatment requirements and the energy required for pumping and pressurization. Some distribution systems are gravity-driven, while others require pumping.
3. **On-site water pumping, treatment, and thermal inputs.** Individual water users require energy to further treat water supplies (e.g. softeners, filters, etc.), circulate and pressurize water supplies (e.g. building circulation pumps), and heat and cool water for various purposes.

4. **Wastewater collection, treatment, and discharge.** Finally, wastewater is collected and treated by a wastewater system (unless a septic system or other alternative is being used) and discharged. Wastewater is sometimes pumped to treatment facilities where gravity flow is not possible, and the standard treatment processes require energy for pumping, aeration, and other processes.

Figure 1. Simplified Flow Diagram of Energy Inputs to Water Systems



Source: Authors, based on Wilkinson 2000, Wolff 2004, and Klein 2005

Calculating Energy Intensity

Total energy intensity, or the amount of energy required to process the use of a given amount of water in a specific location, may be calculated by accounting for the energy requirements for factors such as:

- imported supplies (surface and groundwater)
- local supplies (surface and groundwater)
- regional conveyance
- treatment
- local distribution
- on-site thermal (heating or cooling)
- on-site pumping
- wastewater collection
- wastewater treatment
- wastewater discharge

Current Research on the Energy Intensity of Water in California

A methodology for analysis and an initial exploratory model was developed by Wilkinson to identify and track energy inputs at each step in the water process. (Wilkinson 2000) Wolff and others at the Pacific Institute followed this work, in collaboration with Cohen and Nelson at the Natural Resources Defense Council (NRDC), to evaluate the energy used in water management based on these methods. (Wolff et al. 2004)

Wolff and others developed detailed spreadsheet-based models, referred to as the "Water-to-Air Models" to automate the calculations performed in the Wolff et al. study and add an air quality impact estimate to the calculations. The models allow users to compare the energy use and related air emissions associated with pairs of water management scenarios that they create. (Wolff 2004) The Water-to-Air models are used in the current analysis.

The objectives of the current research effort are to characterize the energy inputs to water in California, perform a preliminary assessment of statewide water-related energy use, and identify data and informational gaps. Data from the California Department of Water Resources (DWR) are being used for the quantities of water extracted, transported, used, and discharged in California in year 2000, a typical year. Urban and agricultural data have been combined into the urban model rather than modeling these sectors separately to allow statewide outputs from a single model. It also accommodates a data problem that was discovered: no distinction between urban and agricultural water in much of the DWR data set.

Energy Intensity of Water Systems in California

Water systems in California account for significant energy uses in the state.[1] (CEC 2005; Wilkinson 2000) Preliminary results from this analysis suggest that water-related electricity use amounted to about 22% of total electricity use in 2000, a figure slightly higher than the California Energy Commission's (CEC) 19%. (The estimated 61,430 GWh of water-related electricity use for year 2000 is divided by 275,000 GWh of actual statewide electricity use in that year.)

Energy use for conveyance, including interbasin water transfer systems (systems that move water from one watershed to another) in California, was estimated to use about 6.9% of the state's electricity. (Wilkinson 2000) Estimates by CEC's Public Interest Energy Research - Industrial, Agriculture and Water (PIER-IAW) experts indicate that "total energy used to pump and treat this water exceeds 15,000 GWh per year, or at least 6.5 percent of the total electricity used in the State per year." (CEC 2006) They note that the State Water Project (SWP) – the state-owned storage and conveyance system that transfers water from Northern California to various parts of the state including Southern California – is the largest single user of electrical energy in the State, accounting for 2% to 3% of all the electricity consumed in California and using an average of 5,000 GWh per year.

California's water systems are uniquely energy-intensive due in large part to the pumping requirements of major conveyance systems which move large volumes of water long distances and over thousands of feet in elevation lift. Some of the interbasin transfer systems are net energy producers, like the San Francisco and Los Angeles systems that capture water at higher

---

[1] Water conveyance systems alone have been estimated to account for roughly 7% of California's electricity use. (Wilkinson 2000)

elevations and convey it by gravity, while others, such as the SWP and the Colorado River Aqueduct (CRA) require large amounts of electrical energy to convey water.

Water use (based on embodied energy) is the second or third largest consumer of electricity in a typical Southern California home after refrigerators and air conditioners. (Wilkinson 2000; QEI 1992) The electricity required to support water service in the typical home in Southern California is estimated to be between 14% to 19% of total residential energy demand. (QEI 1992) In homes without air conditioning, this figure is even higher. The Metropolitan Water District of Southern California (MWD) reached similar findings. MWD estimated that energy requirements to deliver water to residential customers equals as much as 33% of the total average household electricity use. (Metropolitan Water District of Southern California, 1999) Nearly three quarters of this energy demand is for pumping imported water.

Water system operations pose a number of challenges for energy systems due to factors such as large loads for specific facilities, time and season of use, and geographic distribution of loads. Pumping plants are among the largest electrical loads in the state. For example, the SWP's Edmonston Pumping Plant, situated at the foot of the Tehachapi mountains, pumps water 1,926 feet (the highest single lift of any pumping plant in the world) and is the largest *single user* of electricity in the state. (California Department of Water Resources 1996) In total, the SWP *system* is the largest user of electricity in the state. (Anderson 1999) A study for the Electric Power Research Institute by Franklin Burton found that at a national level, water systems account for an estimated 75 billion kWh per year (3% of total electricity demand). (Burton 1996)

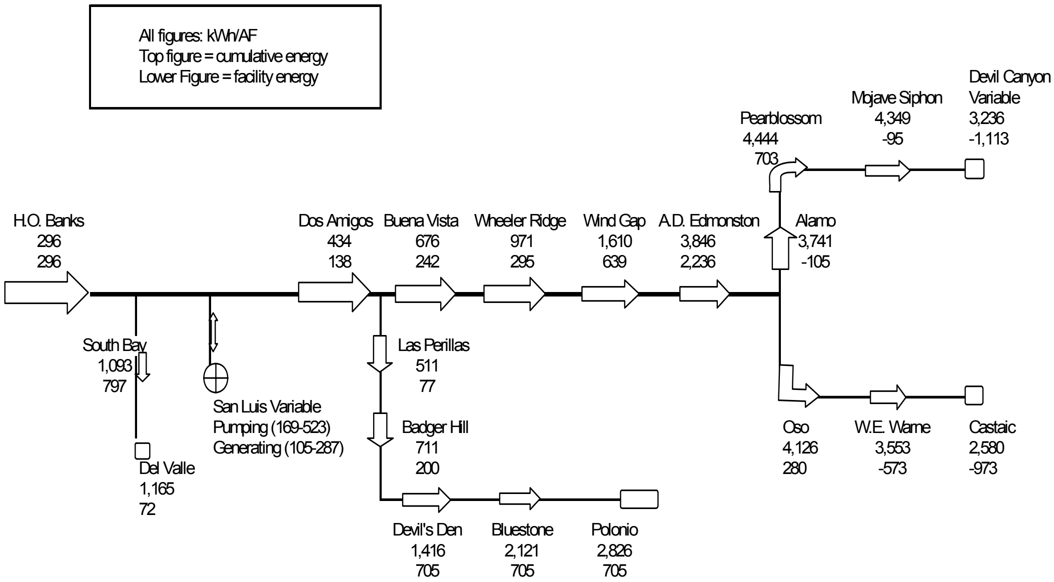
The following schematic shows the cumulative net energy, and the incremental energy inputs or outputs, at each of the pumping and energy recovery facilities of the SWP.[2] (Energy recovery is indicated with negative numbers, which reduce net energy at that point in the system.)

Approximately 3,236 kWh are required to pump one acre-foot of SWP water from the Sacramento-San Joaquin Delta to the end of the East Branch (Devil Canyon), 2,580 kWh/af at Castiac on the West Branch, and 2,826 kWh/af to Polonio on the Coastal Branch. This is raw (untreated) water delivered to those points. From there conveyance continues by gravity or pumping to treatment and distribution within service areas. Approximately 2,000 kWh/af is required to pump Colorado River water to Southern California. (Metropolitan Water District of Southern California 1996)

---

[2] The units used in this report for energy are kilowatt hours (kWh) for electricity and British thermal units (BTUs) for natural gas. For comparison of total energy, BTUs of gas are converted to kWh equivalent. The common unit for water supply is an "acre-foot" (AF). An acre-foot of water is the volume of water that would cover one acre with one foot. An acre-foot equals 325,851 gallons, or 43,560 cubic feet, or 1,233.65 cubic meters. Wastewater is typically measured in "million gallons per day" (MGD). One MGD equals 1,120 AF per year, and one AFY equals 0.000893 MGD. One acre-foot equals 0.325851 MG.

Figure 2. State Water Project Energy Inputs and Recovery
(Kilowatt-Hours per Acre Foot Pumped - Includes Energy Recovery)



Source: Wilkinson, based on data from DWR 1997.

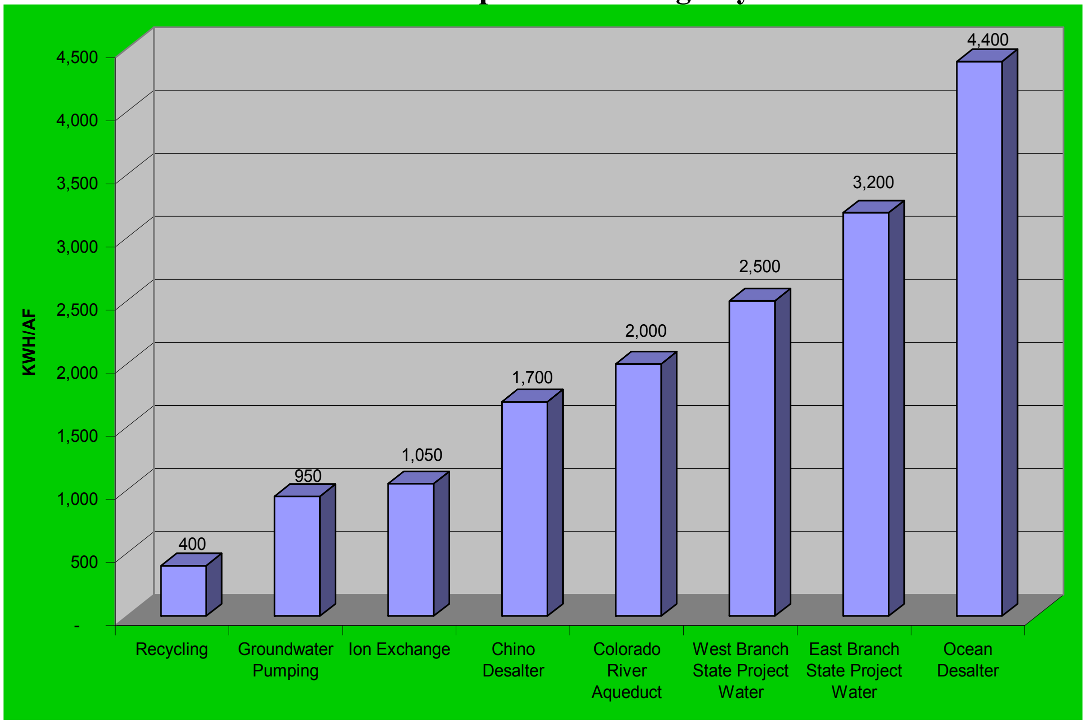
Note that at certain points in the system the energy intensity is as high as 4,444 kWh/af (e.g. Pearblossom) because the service areas are located at higher elevations and do not gain the benefit of energy recovery further along in the system. At 4,444 kWh/af, the *raw* water supplies are roughly equivalent to, or possibly higher than, estimates for desalinated ocean water systems under development.[3]

The following graph shows the energy intensity of several water supply options (including SWP West Branch and ocean desalination for comparison) for the Inland Empire Utilities Agency, a major Southern California water agency.

---

[3] Ocean desalination is estimated at 4,400 kWh/af based on work by Wilkinson for the California Desalination Task Force.

Figure 3. Energy Intensity of Alternative Supply Sources Inland Empire Utilities Agency



Source: Wilkinson based on data from IEUA, DWR, and desalination estimates.

Note that recycled water and local groundwater sources are a relative energy bargain compared to imported supplies. Even the Chino desalter, a reverse osmosis (RO) process for contaminated groundwater that includes groundwater pumping and RO filtration, is far less energy intensive than any of the imported raw water. From an energy standpoint, local sources of reclaimed water and groundwater, including contaminated sources requiring advanced treatment, are a bargain from an energy standpoint.

Similar findings were made for the Central Basin MWD in Southern California. (Wilkinson et al. 2005) Central Basin MWD replenishes groundwater with recycled water treated from two County Sanitation Districts of Los Angeles County operated plants, Los Coyotes Water Reclamation Plant and San Jose Creek Water Reclamation Plant. These plants recycle water for direct discharge, so no additional treatment or energy is required. The total energy requirement for groundwater replenishment with recycled water in Central Basin MWD is 350 kWh/af, which is the energy required to pump the groundwater. West Basin MWD replenishes groundwater by injecting single-pass RO recycled water from the West Basin Water Recycling Plant (WBWRP). The total energy use for this district is 1,565 kWh/af. In order to provide an accounting of the energy requirements for the WBWRP, two water qualities and associated energy inputs are presented. “Title 22” water, gravity filter treatment, requires conveyance pumping energy from Hyperion to WBWRP at 205 kWh/af. The water flows through the filters via gravity, thus no additional energy is required for treatment. The final energy requirement is 285 kWh/af for distribution with a total energy requirement of 490 kWh/af. This is the lowest grade of recycled water that WBWRP produces. Contrasting the “Title 22” water, WBWRP produces single-pass RO water with a total energy requirement of 1,280 kWh/af. This energy demand includes 205 kWh/af for conveyance from Hyperion, 790 kWh/af for treatment with RO, and 285 kWh/af for distribution. Recycled water is also provided for use in refineries at no net energy, since the legal discharge quality is adequate for the industrial purposes, and the water flows by gravity to the refineries.

Groundwater pumping energy requirements vary depending on the lift required. The CEC's PIER IAW (CEC 2006) provides the following assessment of pumping in important parts of the Central Valley: "The amount of energy used in pumping groundwater is unknown due to the lack of complete information on well-depth and groundwater use. DWR has estimated groundwater use and average well depths in three areas responsible for almost two-thirds of the groundwater used in the State: the Tulare Lake basin, the San Joaquin River basin, and the Central Coast region. Based on these estimates, energy used for groundwater pumping in these areas would average 2,250 GWh per year at a 70 percent pumping efficiency (1.46 kWh/acre-foot/foot of lift). In the Tulare Lake area, with an average well depth of 120 feet, pumping would require 175 kWh per acre-foot of water. In the San Joaquin River and Central Coast areas, with average well depths of 200 feet, pumping would require 292 kWh per acre-foot of water."

Data analysis of these different sources provide a reasonably consistent result: Local groundwater and recycled water are far less energy intensive than imported water. Water use efficiency is of course the best investment in most cases.

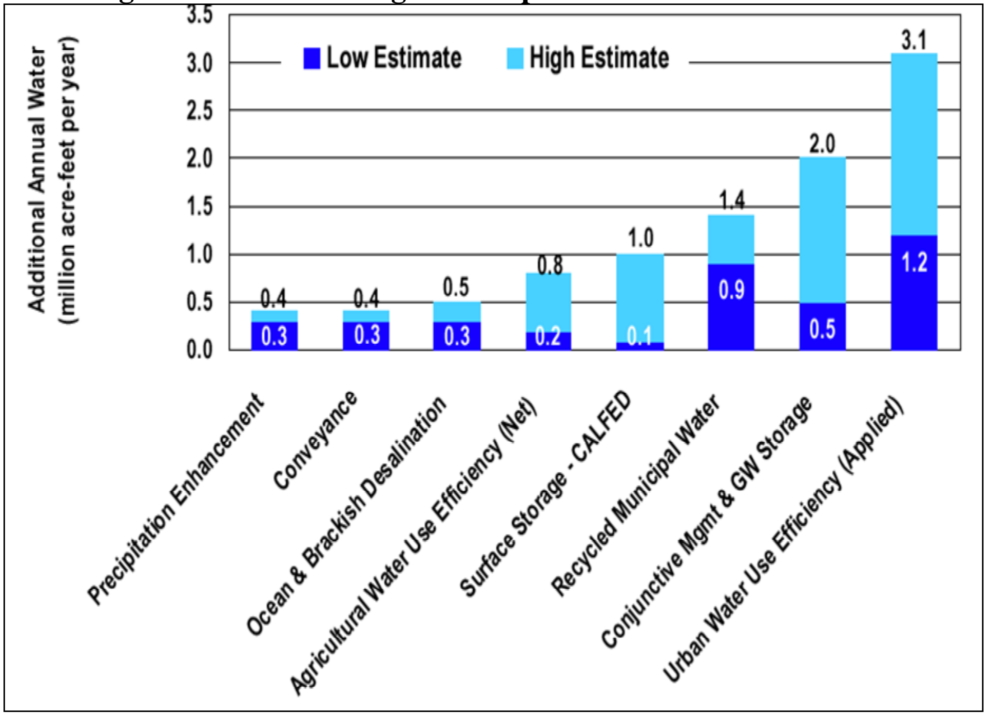
The energy intensity of many water supply sources may increase in the future due to regulatory requirements for water quality. (Burton 1996) It is worth noting that advanced treatment systems such as RO facilities that are being used to treat groundwater, reclaimed supplies, and ocean water have already absorbed most of the energy impacts of the more stringent regulations. By contrast, some of the raw water supplies, such as imported Colorado River and State Water Project supplies from the delta, may require larger incremental energy inputs for treatment. This may further advantage the local sources.

Conclusion: Policy Opportunities in Water/Energy Savings

The CEC reiterated in its 2005 *Integrated Energy Policy Report* (IEPR) that "Reducing the demand for energy is the most effective way to reduce energy costs and bolster California's economy." The CEC notes that: "Energy Commission evaluated the relationship between water and energy systems to better understand this link and determine what, if any, mutually beneficial strategies can be developed to improve both the water and energy sectors. As a result of this initial work, the Energy Commission determined that much can be done to improve both systems." (CEC 2005)

Improvements in efficiency were also identified by the DWR as the largest new water supply for the next quarter century. The CEC staff report notes that: "In many respects, the *2005 Water Plan Update* mirrors the state's adopted loading order for electricity resources described in the Energy Commission's *Integrated Energy Policy Report 2005* and the multi-agency *Energy Action Plan*." (Klein 2005)

Figure 4. Water Management Options for the Next 25 Years



Source: *California Water Plan Update 2005*. DWR 2005.

A study conducted by Wilkinson in 2000 concluded that: "With better information regarding the energy implications of water use, public policy and combined investment and management strategies between energy, water, and wastewater agencies and utilities can be improved. Potential benefits include improved allocation of capital, avoided capital and operating costs, reduced burdens on rate-payers, and environmental benefits. Other societal goals, including restoration and maintenance of environmental quality, can also be addressed more cost-effectively through policy coordination. Full benefits derived through water/energy efficiency strategies have not been adequately quantified or factored into policy, although the California Public Utilities Commission (CPUC) adopted principles supporting such approaches in 1989."[4] (Wilkinson 2000)

It is exciting to note how much progress has been made in five years toward tapping the potential for integrated water/energy efficiency opportunities. The CEC notes in its 2005 *Integrated Energy Policy Report* that: "The Energy Commission, the Department of Water Resources, the CPUC, local water agencies, and other stakeholders should explore and pursue cost-effective water efficiency opportunities that would save energy and decrease the energy intensity in the water sector."[5] (CEC 2005) The CEC staff report is even more direct: "As California continues to struggle with its many critical energy supply and infrastructure challenges, the state must identify and address the points of highest stress. At the top of this list

---

[4] The California Public Utilities Decision cited is CPUC Decision No. 89-12-057, December 20, 1989.

[5] One of top recommendations regarding efficiency in the IEPR is as follows: "The Energy Commission strongly supports the following energy efficiency and demand response recommendations: The CPUC, Department of Water Resources, the Energy Commission, local water agencies and other stakeholders should assess efficiency improvements in hot and cold water use in homes and businesses, and include these improvements in 2006-2008 programs."

is California's water-energy relationship: water-related energy use consumes 19 percent of the state's electricity…" It continues with this interesting finding: "The state can meet energy and demand-reduction goals comparable to those already planned by the state's investor-owned energy utilities for the 2006-2008 program period by simply recognizing the value of the energy saved for each unit of water saved. If allowed to invest in these cold water energy savings, energy utilities could co-invest in water use efficiency programs, which would in turn supplement water utilities' efforts to meet as much load growth as possible through water efficiency. Remarkably, staff's initial assessment indicates that this benefit could be realized at less than half the cost to electric ratepayers of traditional energy efficiency measures." (Klein 2005)

References

Anderson, Carrie, 1999. "Energy Use in the Supply, Use and Disposal of Water in California", Process Energy Group, Energy Efficiency Division, California Energy Commission.

Burton, Franklin L., 1996, *Water and Wastewater Industries: Characteristics and Energy Management Opportunities*. (Burton Engineering) Los Altos, CA, Report CR-106941, Electric Power Research Institute.

[DWR 1996] California Department of Water Resources, 1996. *Management of the California State Water Project*. Bulletin 132-96.

[DWR 1997] California Department of Water Resources, State Water Project Analysis Office, Division of Operations and Maintenance, Bulletin 132-97.

[DWR 2005] California Department of Water Resources, 2005. *California Water Plan Update 2005*. B-160-05, California Department of Water Resources, Sacramento, CA.

[CEC] 2005. California Energy Commission, *Integrated Energy Policy Report*, November 2005, CEC-100-2005-007-CMF.

[CEC] 2006. California Energy Commission, Public Interest Energy Research - Industrial, Agriculture and Water, http://energy.ca.gov/pier/iaw/industry/water.html

Dziegielewski, B. (editor). 1999. Management of water demand: Unresolved issues. Water Resources Update. Issue No. 114, Universities Council on Water Resources. Carbondale, Illinois.

Gleick, Peter H., Dana Haasz, Christine Henges-Jeck, Veena Srinivasan, Gary Wolff, Katherine Kao Cushing, Amardip Mann, 2003. *Waste Not, Want Not: The Potential for Urban Water Conservation in California*, Pacific Institute.

Klein, Gary, 2005. California Energy Commission, California's Water – Energy Relationship. Final Staff Report, Prepared in Support of the 2005 Integrated Energy Policy Report Proceeding, (04-IEPR-01E) November 2005, CEC-700-2005-011-SF.

Metropolitan Water District of Southern California, 1996. *Integrated Resource Plan for Metropolitan's Colorado River Aqueduct Power Operations*.

Metropolitan Water District of Southern California, 1999. Fact Sheet on Electric Industry Restructuring.

Owens-Viani, Lisa, Arlene Wong, and Peter Gleick, Eds., January 1999. *Sustainable Use of Water: California Success Stories*, Pacific Institute.

QEI, Inc., 1992. *Electricity Efficiency Through Water Efficiency*, Report for the Southern California Edison Company.

Vickers, Amy, 1999. The future of water conservation: Challenges ahead. Water Resources Update, Issue No. 114, Universities Council on Water Resources.

Vickers, Amy, 2001. *Water Use and Conservation*, WaterPlow Press, Amherst, MA.

Wilkinson, Robert C., 2000. *Methodology For Analysis of The Energy Intensity of California's Water Systems, and an Assessment of Multiple Potential Benefits Through Integrated Water-Energy Efficiency Measures*, Exploratory Research Project, Ernest Orlando Lawrence Berkeley Laboratory, California Institute for Energy Efficiency. http://www.es.ucsb.edu/faculty/wilkinson.php

Wilkinson, Robert C., Fawzi Karajeh, and Julie Mottin, 2005. Water Sources "Powering" Southern California: Imported Water, Recycled Water, Ground Water, and Desalinated Water: An Analysis of the Energy Intensity of Water Supplies for the West Basin and Central Basin Municipal Water Districts.

Wolff, Gary, Ronnie Cohen, and Barry Nelson. 2004. *Energy Down the Drain: the Hidden Costs of California's Water Supply.* Natural Resources Defense Council

Wolff, Gary. 2004. Quantifying the Potential Air Quality Impacts from Electric Demand Embedded in Water Management Choices. California Energy Commission; and Wolff, Gary, 2004, *User Manual for the Pacific Institute Water to Air Models,* Pacific Institute: Oakland. (The models and user manual are available for free download from www.pacinst.org.)