The Interaction of Water and Energy in California:

Climate Change and Price Impacts

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Abstract

We evaluate the links between water and energy systems in California, and suggests the likely impact of climate change on those systems. Successive sections of this paper organize water system activities according to their responsiveness to water and energy prices, indicate the likely the impact of climate change on water and energy prices, and evaluate these price effects on selected components of the water system.

1. Introduction

Water and energy use are commingled throughout California, from reservoirs generating electricity with water, to residents using that electricity to warm water for tea. Energy drives every link of the water system, from ground storage, to conveyance and distribution, to wastewater treatment. The energy-water link is tight—typically the price of water approximates the cost of electricity used to supply it. The water-energy link is comprehensive—water consumed on the farm is combined with other energy inputs, such as fertilizers and pesticides; water consumed in the home is heated with gas and electricity.

Climate warming, and policies to counteract it, will influence water use via changes in water and energy prices. Climate induced water scarcity will reinforce past trends in water and energy use and accelerate the demand for energy. Groundwater and reservoir storage levels will fall, farmers will grow high value energy intensive crops and urban areas will shift to energy intensive water supplies, including long distance transfers and desalinization. Alternatively, climate induced energy scarcity may counteract this trend, increasing energy intensity of the water sector and effectively decreasing the supply of water. Energy savings may take priority over water savings. Farmers may shift scarce irrigation water toward biofuel crops; supplies of groundwater, recycled water and desalinization water will decrease as energy becomes more costly.

To forecast the impact of climate change on the water system we must first forecast the impact of climate on water and energy prices. This focus on the energy underpinnings of our water supply reveals a need for models of the water system that account for water-energy linkages. Existing models, including irrigation, reservoir management, crop production, and conservation models, usually ignore the influence of energy on water use. Since climate will affect both water and energy, new models of the California water system are needed to evaluate energy's impact on water.

Following this introduction, the Section 2 provides a scheme for organizing water system activities according to how they are likely to react to increases in water and energy prices. Water energy activities are organized into four groups, including activities using energy to supply water, such as water conveyance systems and activities using water to supply energy, such as thermal power plants.

We focus upon a subset of activities covering key stages in the California water system, including storage, groundwater pumping, conveyance, and agricultural and urban end use. Historically, the trend has been for energy use to intensify at each stage of this water system (Navigant 2006). Section 3 provides a rough measure of the current level of energy intensity of water use and compares the price of water with the cost of energy used to provide water to agricultural and urban users.

In Section 4, we summarize the major underlying forces acting upon water and energy markets and their likely impact on future water and energy prices. These forces include climate warming and climate policy. We argue that these forces are likely to increase water and energy scarcity and raise water and energy prices.

These price trends suggest changes in water system activities, and associated changes in water and energy use. Section 5 describes initial research efforts to forecast these changes in water and energy use and suggests additional research needed to improve these forecasts. The increase in water and energy prices will affect all stages of the water system. Existing models used to evaluate and forecast changes in these water system stages are focused on water use, and tend to ignore the influence of changes in energy prices. We argue that energy should be incorporated into these models--both to improve forecasts of changes in energy used by the water system and to allow for more efficient energy use management of the system. Our conclusions are presented in Section 6.

2. Structure for Organizing Water and Energy Activities

In this section, water-energy activities are organized into different groups, including activities using energy to supply water, such as conveyance systems and groundwater pumping and activities using water to supply energy, such as thermal power plants. Additional groupings include reservoirs, which supply water and energy, and home appliances and field crops that use water and energy. Each group of activities is affected by water and energy prices differently such that activities encouraged by rising (relative) water or energy prices are grouped separately from activities encouraged by falling water or energy prices.

2.2 Overview of energy and water topic.

We find four categories where the supply and use of energy and water are interlinked. These categories are illustrated with four quadrants of a diagram (Quadrants I-IV, Figure 1).[1]

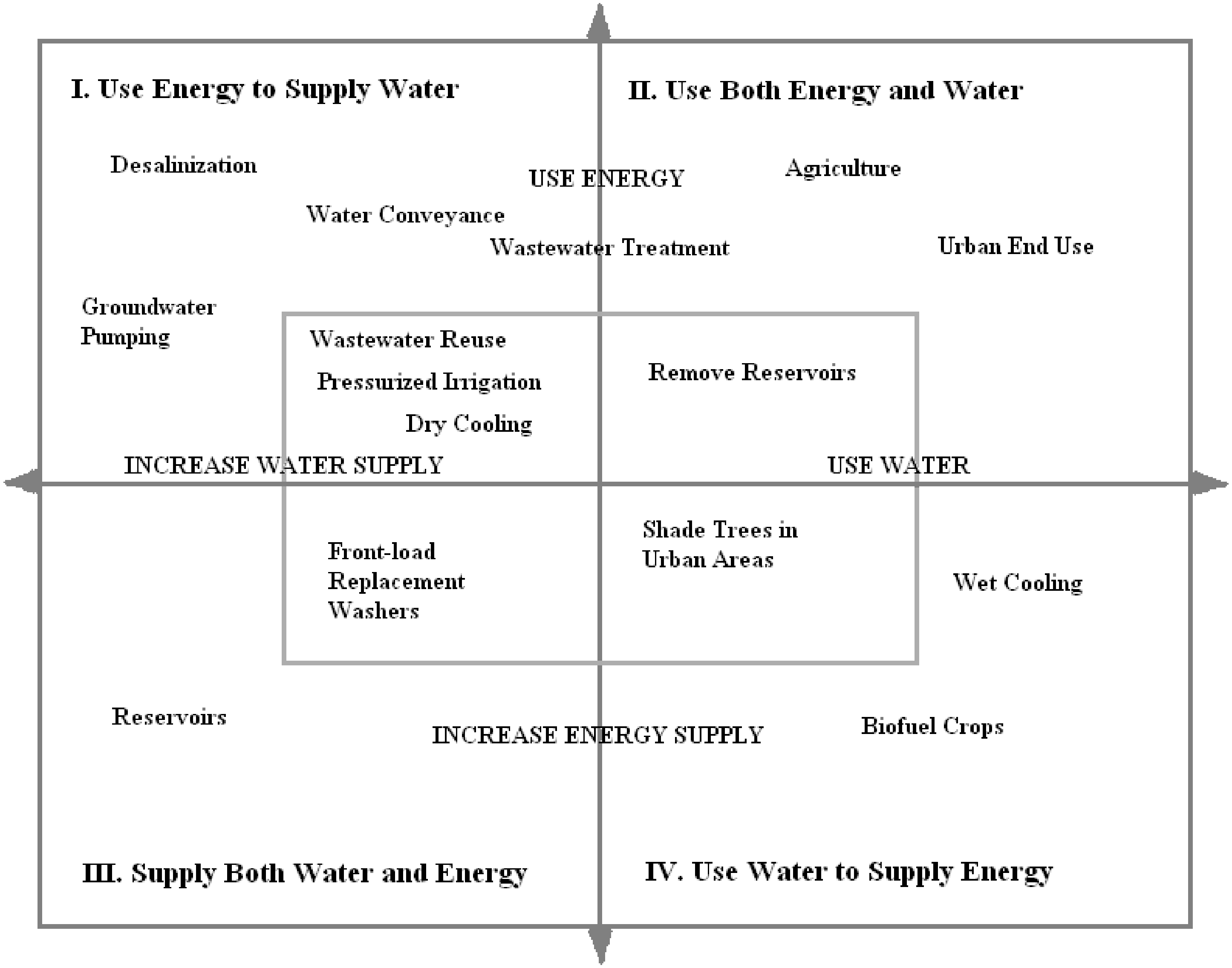


Figure 1. The Uses and Interactions of Water and Energy

The lower left and upper right hand quadrants of the diagram illustrate activities that supply both water and energy and activities that use both water and energy respectively (QII and QIII). Reservoirs are an example of an activity supplying water and energy together (QIII); cloths washing is an example of joint water and energy use (QII).   The upper left hand quadrant covers activities that use energy to supply water, including groundwater pumping and the large pumps along the California Aqueduct (QI). The lower right hand quadrant lists activities that use water to supply energy, such as biofuel crops (Q IV).

2.3 Impacts of Water and Electricity Prices

Each quadrant of Figure 1 is defined according to the impact of changing electricity and water prices. Price impacts occur along the diagonal quadrants. For example, activity levels in the lower left and upper right hand quadrants are positively (QIII) and negatively (QII) correlated with energy and water prices when these prices move together. Thus, a rise in energy and water prices tends to encourage surface storage (QIII) but discourage field crop acreage and long hot showers (QII).

On the other hand, when energy and water prices move in opposite directions, Quadrant I activities are positively correlated and Quadrant IV activities are negatively correlated with prices. For example, a relative rise in water prices supports activities like groundwater pumping that use energy to supply water (QI). This same price effect discourages activities that use water to supply energy such as bio fuels crops and evaporative cooling (QIV).

2.4 Conservation in Response to Price Changes

Conservation is an important response to price changes. Two types of water-energy conservation are distinguished in Figure 1, including activities that decrease the supply or use of both resources (joint conservation), and activities that decrease use of one resource but increase use of the other resource (tradeoff conservation). Examples of both types of conservation are indicated in Figure 1, within the inner dotted box. Residential water conservation illustrates joint conservation (Q III). Examples of tradeoffs include pressurized irrigation and dry cooling thermal power plants. Pressurized irrigation conserves water, but requires energy to pressurize the irrigation system. Technologies for dry cooling of thermal power plants reduce water use, but tend to lower plant efficiency, and decrease the amount of power generated from a given amount of resource fuel.

If relative water prices rise, we expect more water conservation (e.g. pressurized irrigation) and less water-using energy conservation (e.g., dry cooling) (Figure 2). When water and electricity both become more expensive, the trend is towards more joint conservation of water and energy.

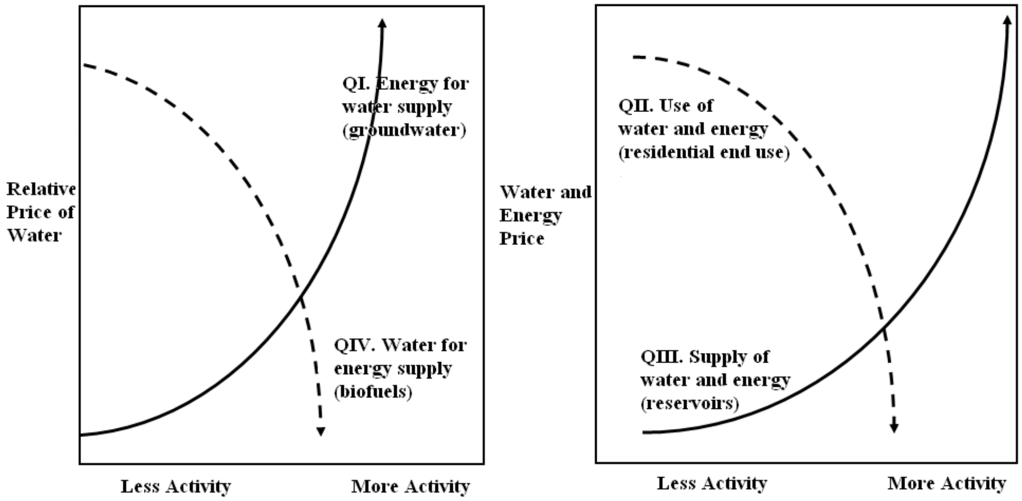


Figure 2. Price Impacts on Water Energy Activities

3. The Water System, the Price of Water and the Cost of Energy

We focus on a subset of water energy activities covering stages in the California water system, including storage, groundwater, conveyance, distribution and agricultural and urban end use. This section provides a rough measure of water and energy use and compares the price of water with the cost of energy used to provide water at each stage. This comparison indicates that the price of water in California corresponds closely to the cost of energy used to supply water.

3.1 Historic Water and Energy Use in California

The expansion of the California water system since 1950 reflects rising demand for water, rising energy inputs to water, and a high water price compared to the cost of electricity. The State and Federal reservoirs were largely constructed over 50 years ago to supply water to agricultural districts in the San Joaquin Valley and growing population centers on the Coast. These reservoirs provided inexpensive water to a wide variety of agricultural users across the Central Valley—their primary function—although today it might be argued that the value of electricity generated by these reservoirs often exceeds the value of the water supplied.

Since that time, the energy cost of expanding water supplies has risen dramatically. These high energy cost water supplies include groundwater pumping and long distance conveyance systems, including the Central Valley and State Water Projects. Groundwater pumping requires moderate to large amounts of electrify, depending upon aquifer depth and the project aqueducts have been especially energy intensive due to the necessity to convey water over significant elevations to supply Southern California (Wilkinson 2000).

Over time, the energy intensity of irrigated agriculture has grown as farmers have switched from furrow to drip and sprinkler irrigation. These new types of irrigation effectively expand the irrigation water supply by making use of electricity to pressurize water distribution systems and increase irrigation water use efficiency. Crop production has grown increasingly energy intensive in other ways as well. Today, planting, harvesting and cultivation are fully mechanized and artificial fertilizers and pesticide use is ubiquitous. Farm equipment, fertilizers and pesticides require large amounts of energy to make and to use.

The energy intensity of urban water use has also grown since 1950. Urban residents now use much more energy than they used to, to heat and to cool water for bathing, cleaning, and drinking, and to irrigate lawns and gardens. Household saturation of appliances such as water furnaces, clothes washers and dishwashers is almost 100 percent. These appliances have tended to grow in size and their associated energy use has increased proportionally. Electricity inputs needed to expand urban water supplies have also increased. Marginal water supplies in some urban areas, including desalting seawater and tertiary treatment and reuse of wastewater, are among the most energy intensive water use practices known. All these agricultural and urban water use practices have increased the quantity of energy needed to supply, convey, and utilize water.

3.2 The Water Supply System

The historical expansion of energy inputs to water supply is illustrated with a stylized diagram of the water system (Figure 3). At the lower left of the diagram, reservoirs supply dry year water to urban and agriculture at negative energy cost (point A, Figure 3). Moving up to the right, additional supply of water is obtained from groundwater pumping, long distance conveyance and pressurized irrigation, all of which require energy inputs (B and D). Crop production involves substantial energy inputs (C), as do available measures to increase urban supplies, including long distance conveyance, recycled wastewater and desalinization (E and F). Finally, urban water end uses absorb even more energy (G).

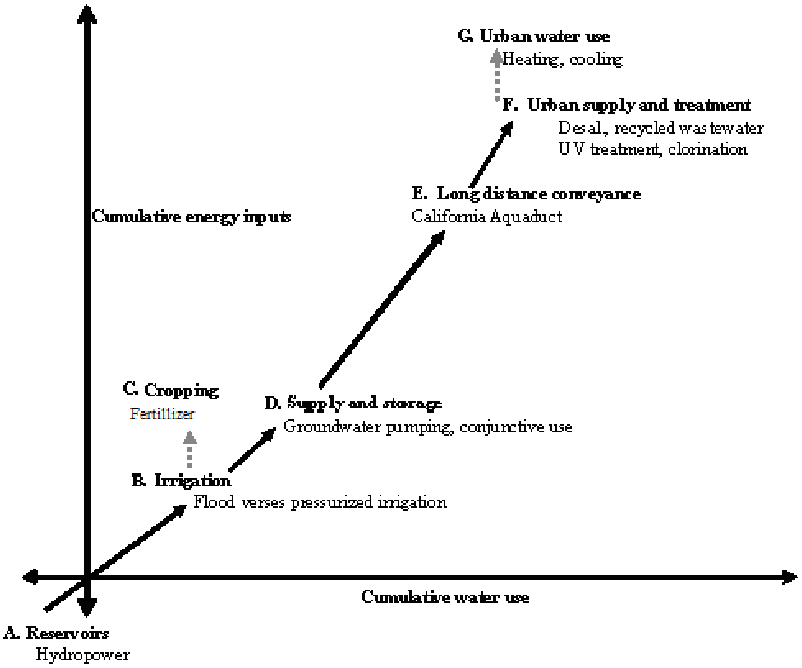
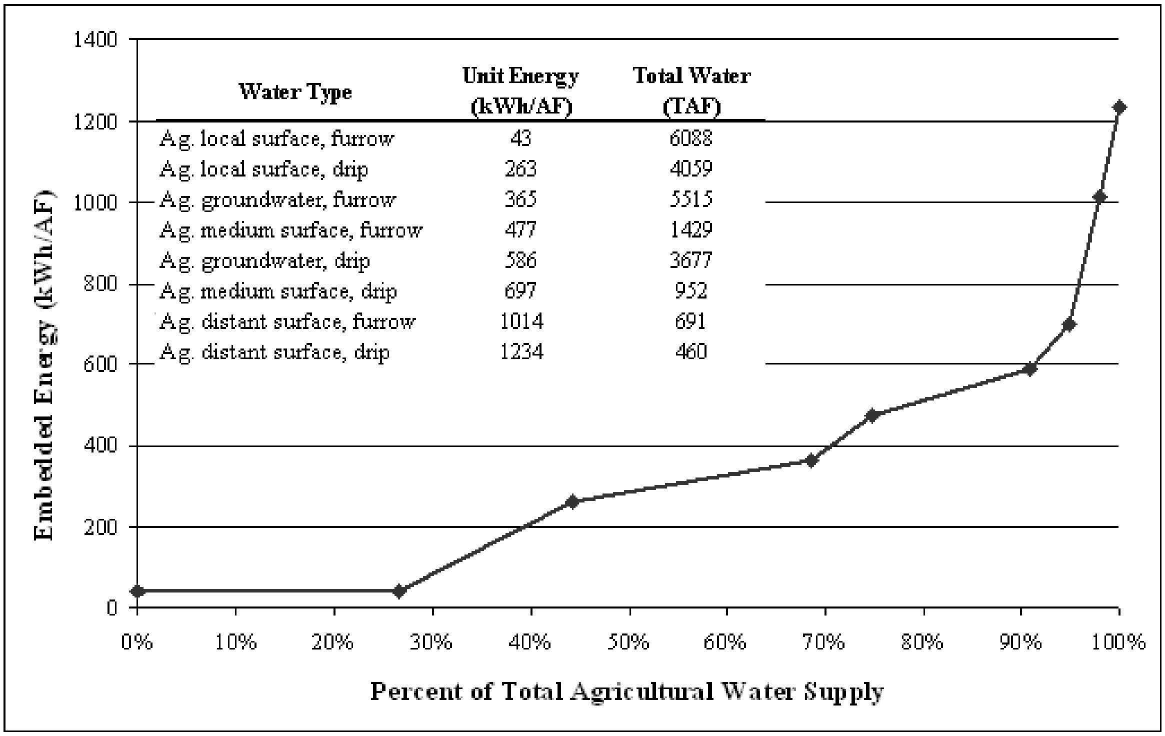


Figure 3. Use of Energy to Increase Urban and Agricultural Water Supplies

3.3 Accounting for Energy in Water Supplies

A rough accounting of energy used to supply water to selected agricultural and urban areas of California suggests that there is a wide spread in energy intensity of water supplies to these user groups (Burt et al 2003). The principle sources of water used to supply agricultural users in the Central Valley include local surface water, project water delivered to the San Joaquin Basin (medium surface), project water delivered to the Tulare basin (distant surface), and groundwater

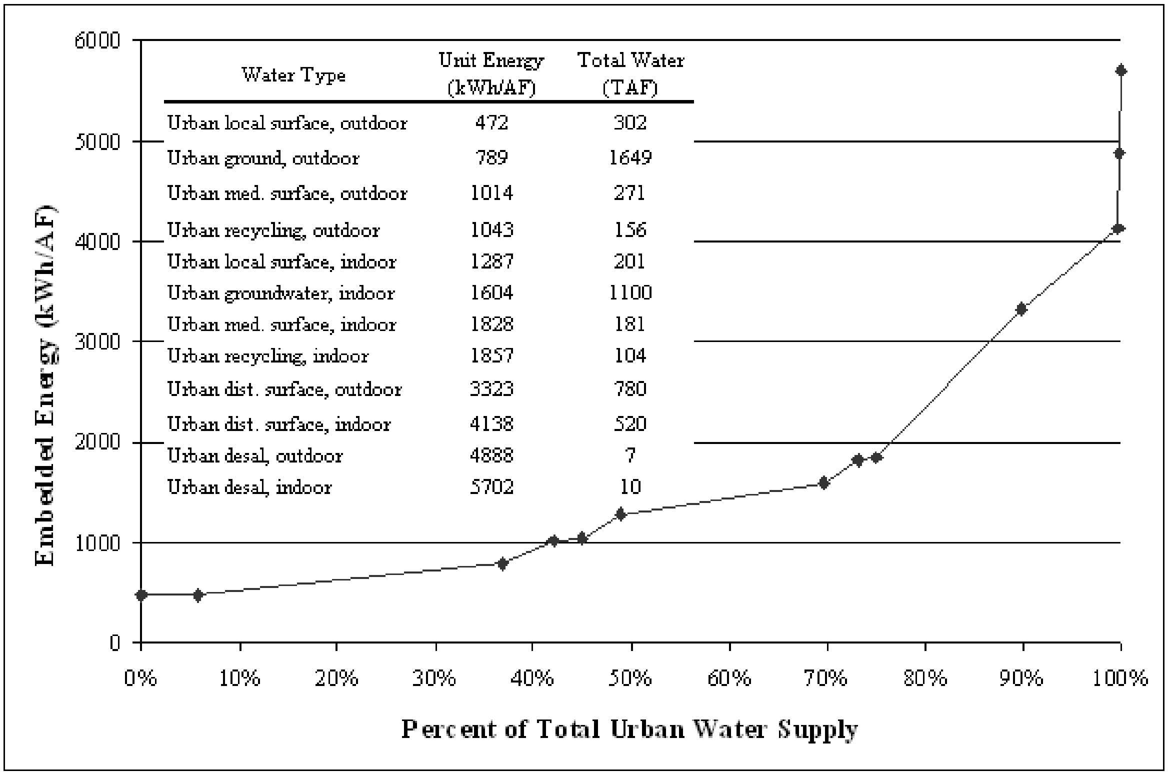
(Figure 4). The energy intensity of these supplies range from a low of 43 kWh per acre foot, for local surface water applied using furrow irrigation to a high of 1,234 kWh per acre foot for Tulare Basin project water applied with pressurized irrigation, averaging 355 kWh per acre foot.



Water Type	Unit Energy (kWh/AF)	Total Water (TAF)
Ag. local surface, furrow	43	6088
Ag. local surface, drip	263	4059
Ag. groundwater, furrow	365	5515
Ag. medium surface, furrow	477	1429
Ag. groundwater, drip	586	3677
Ag. medium surface, drip	697	952
Ag. distant surface, furrow	1014	691
Ag. distant surface, drip	1234	460

Figure 4. Energy Embedded in California Agricultural Water Use (Crop Energy Use Excluded)

Urban areas in San Francisco and South Coast basins are also supplied from groundwater, local surface, medium and long distant surface sources. In addition, these urban areas may be supplied with desalinized ocean and recycled water. The energy intensity of urban water sources is higher and more variable than the energy intensity of agriculture water sources, in part because urban water and wastewater are treated (Navigant 2006) (Figure 5).



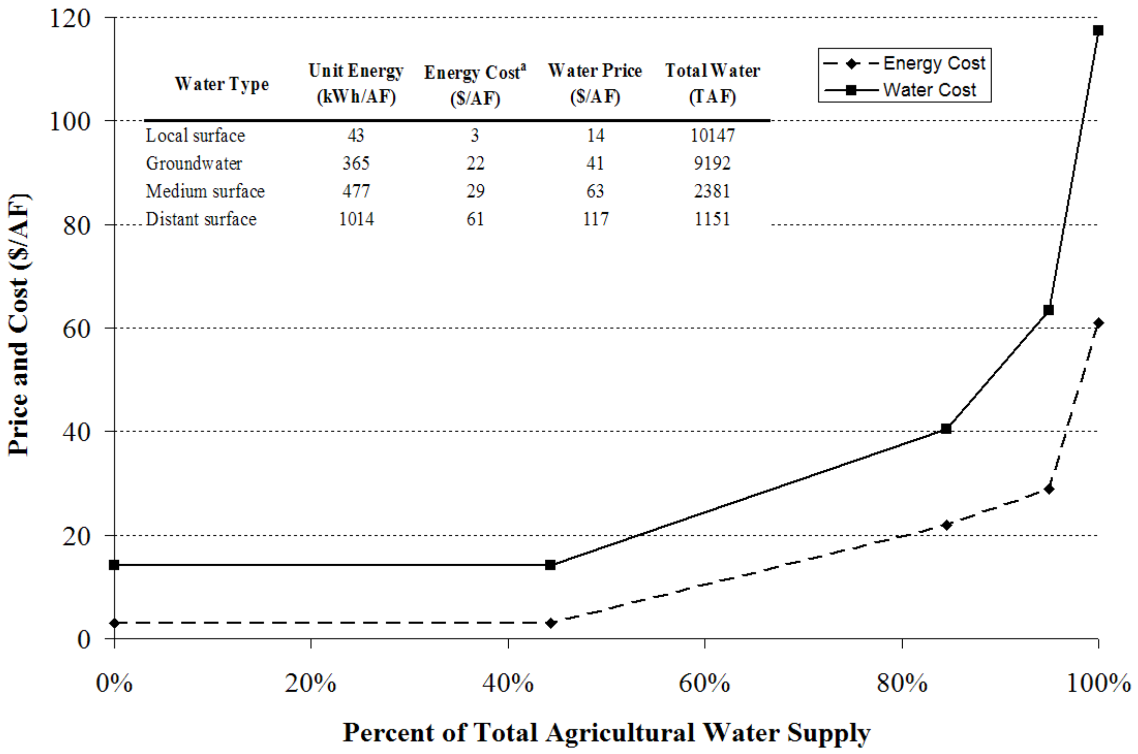
Water Type	Unit Energy (kWh/AF)	Total Water (TAF)
Urban local surface, outdoor	472	302
Urban ground, outdoor	789	1649
Urban med. surface, outdoor	1014	271
Urban recycling, outdoor	1043	156
Urban local surface, indoor	1287	201
Urban groundwater, indoor	1604	1100
Urban med. surface, indoor	1828	181
Urban recycling, indoor	1857	104
Urban dist. surface, outdoor	3323	780
Urban dist. surface, indoor	4138	520
Urban desal, outdoor	4888	7
Urban desal, indoor	5702	10

Figure 5. Energy Embedded in California Urban Water Use (End Use Energy Excluded)

The energy intensity of urban groundwater use ranges from 742 kWh to 1,557 kWh per acre foot, depending upon its use outdoors or indoors (Navigant 2006). Surface water energy use in urban areas ranges from a low of 472 kWh per acre foot for outdoor use in the San Francisco region to a high of 4138 kWh per acre foot for indoor use in the South Coast region. The highest energy intensities are for urban desalinization and recycled water, but only a small amount of water is obtained from these sources.

3.4 Energy Cost and the Price of Water

The cost of energy is a major component of the wholesale water price. Agricultural water prices closely reflect the cost of the embedded energy used to supply that water. The embedded energy costs of water for agriculture range between $3 per acre foot for local surface water and $81 per acre foot for distant surface water, while the prices of agricultural water range between $14 per acre foot for local surface water and $117 for distant surface water (Figure 6).



Water Type	Unit Energy (kWh/AF)	Energy Cost[a] ($/AF)	Water Price ($/AF)	Total Water (TAF)
Local surface	43	3	14	10147
Groundwater	365	22	41	9192
Medium surface	477	29	63	2381
Distant surface	1014	61	117	1151

Figure 6. The Price of Water and Embedded Energy Costs to Agriculture

The relationship between urban retail water prices and embedded energy costs is more difficult to trace but still apparent in the data. Most urban areas rely on a mixture of water sources, making an accurate calculation of embedded energy costs difficult, since urban water districts often sell water at a price based on the average cost of all of water supplies. Among water districts in Orange County for example, embedded energy costs account for about half of the wholesale price and 20% to 80% of the retail price of water (MWDOC 2005). In Figure 7, water and energy data from districts in Orange County are ranked according to embedded energy quantity, with each retail price data point corresponding to the embedded energy data point directly below. The wholesale price of water in Figure 7 is an average across the South Coast region for different sources of water and shows a strong correlation with energy price. The retail price of urban water is not strongly correlated with energy intensity, suggesting that additional factors other than energy costs affect retail prices.

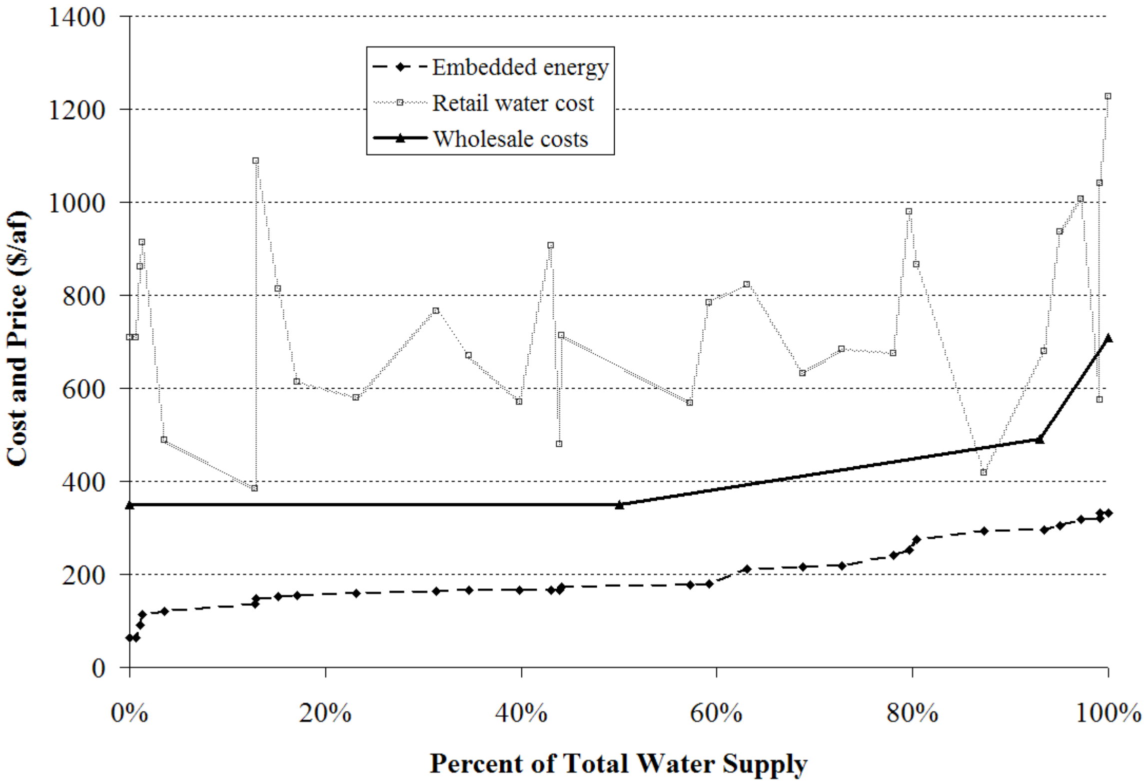


Figure 7. The Price of Water and Embedded Energy Costs to Urban Areas

Note: Average energy cost of water is calculated based on the percent of each water type and the following energy costs for each type of water: MWD ($334/af), groundwater ($74/af), local surface ($47/af), recycled ($104/af). Navigant Consulting: "Refining Estimates of Water Related Energy Use in California."

However, the close relationship between the price of agricultural water and the cost of energy, and the price of urban wholesale water and the cost of energy used to supply water implies that changes to the price of energy in the future will have a strong impact on the price of water.

4. The Impact of Climate Change and Climate Policy on Water and Energy Prices

In this section, we identify some of the impacts of climate change on water and energy markets and impacts on water and energy prices. Of course, climate change is not the only factor affecting prices. Other trends, including population growth, aquatic environment protection, and smog controls, are also important contributing factors to water and energy scarcity or price changes.

Nevertheless, climate warming and climate policy may dramatically impact water and energy prices. These forces are likely to increase water and energy scarcity and thus raise water and energy prices. As suggested in Figure 8, an increase in the relative price of water will decrease activities that use water to produce energy (QIV) and increase activities that use energy to obtain water (QI). A general increase in the prices of water and energy will decrease activities that use both energy and water (QII) and increase activities that supply both energy and water (QIII).

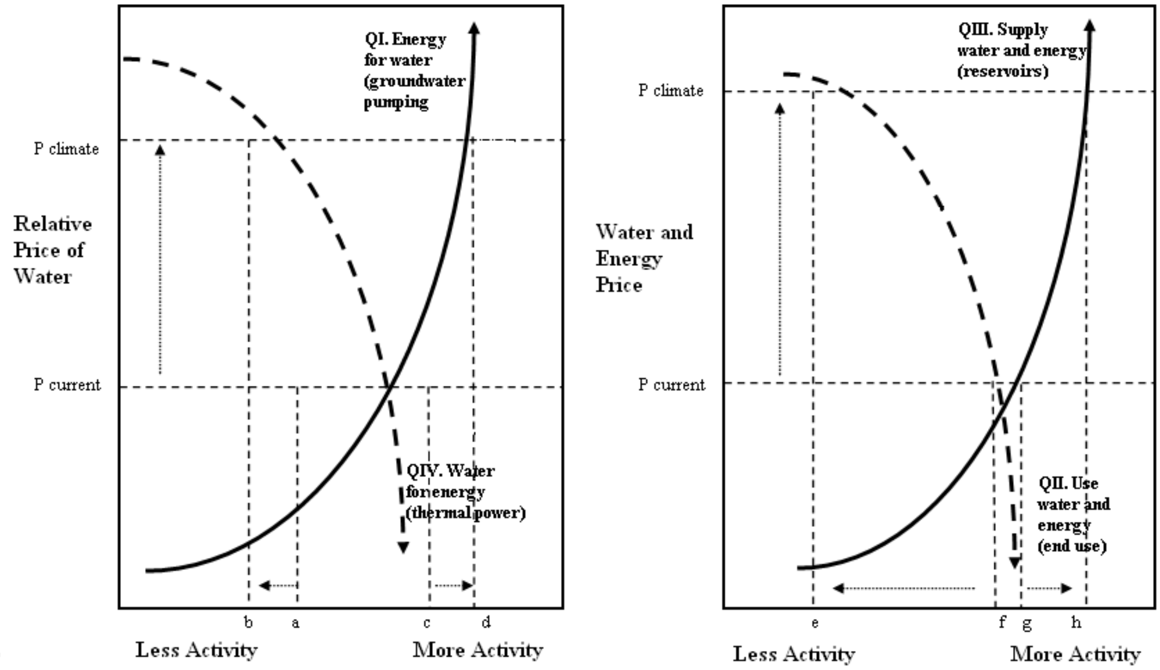


Figure 8. Impacts of Climate Change and Policy on Water and Energy Supplies

4.1 Climate Change Impact on Water Supply

Climate warming will lead to declines in the April 1st Sierra snow pack, a proportional decrease in late summer stream flow, and a drop in project water supplies. The estimated impact of these changes on State and Federal project water deliveries varies by climate model and emissions scenario (Table 1). Averaging across all scenarios, the number of wet years is forecast to drop about 50% and the number of critically dry years is expected to double, from 20% to 40% of all years at the end of the century (Vicuna 2005). Despite forecast variability, we conclude that future water supplies will likely decline substantially below current levels as a result of climate change.

Table 1. Climate Change Impacts on Water Supply

	Wet	Above Normal	Below Normal	Dry	Critical
Historical	34%	14%	12%	22%	18%
PCMB1	40%	11%	19%	14%	16%
PCMA2	33%	11%	16%	18%	22%
PCMA16	8%	8%	16%	11%	56%
GFDLB1	26%	12%	12%	14%	36%
GFDLA2	7%	15%	8%	19%	51%
HadB1	18%	10%	16%	7%	49%
HadA16	14%	12%	12%	12%	49%
Average Model	21%	11%	14%	14%	40%
Average Impact	47%	81%	118%	62%	221%

4.2 Carbon Emission Standards Impact on Energy Price

Policy efforts to limit carbon emissions and avoid the use of inexpensive ‘dirty fuels’ like coal are expected to increase electricity and other energy prices. The likely increase in energy price is difficult to estimate, and estimates range widely. One approach, based on the price of carbon credits and average electricity emissions, suggests that the price of electricity in California will rise two cents for every $20 increase in the value of carbon credits. Carbon credits in Europe are currently around $20 per ton, but they are expected to increase as carbon emission targets become more stringent (Åhman et al 2005). A rough approach for predicting the impact of emission policy on electricity prices is to assume a rise in electricity prices proportional to the average amount of carbon used to generate electricity multiplied by the price of carbon credits in emission markets. This approach suggests that electricity prices will increase 16% assuming a carbon credit price of $20 and 78% assuming a carbon credit price of $100 (Table 2).

Table 2. Impact of Climate Policy on Electricity Prices

	Price Carbon Credits ($/ton CO2)	Electricity Price ($/kWh)
Current Price	**0**	**0.10**
Forecast Prices	**20**	**0.12**
	40	**0.13**
	100	**0.18**

Note: Assumes average of 1.55 pounds of C02 per kWh, as suggested by Energy Star, citing EPA.

4.3 Combined Impacts on Water and Energy Prices

Increasing population, a decline in water supply resulting from climate warming, and measures to cap emissions, will combine to force significant increases in the price of water and energy. Measures to cap emissions increase electricity and other energy prices because such measures limit use of low cost, carbon rich fuels like coal. Rising energy costs, in turn, increase the price of water, which, as shown earlier, is correlated with the cost of the energy used to supply it.

Changing climate is expected to decrease water supplies, particularly supplies that generate electricity or use little energy, such as reservoirs and rivers. To replace this inexpensive water, future users will draw on energy intensive sources, including groundwater, recycled water and desalinization. The price of water will increase both because the price of energy to supply it increases and because the amount of energy used to supply it will rise, due to climate impacts and the changing mixture of supply sources.

We conclude that major forces affecting water and energy use in California will combine to raise water and energy prices, but that water prices will increase more than energy prices. We expect to see an increase in the relative price of water. These energy and water price increases will impact each stage of the water supply system, causing changes in water storage, groundwater use, irrigation method, cropping patterns and urban water use. These changes in water use practices will have dramatic impacts on energy used to supply water.

5. Price Effects on the California Water System

Rising water and energy prices will influence the management of water supply system and the demand for energy in ways difficult but important to forecast. The increase in water and energy prices will affect all stages of the water system. We describe the nature of these activity changes and propose revisions to existing models to better characterize impacts and improve model forecast accuracy.

In the long run, most stages of the water supply system can be managed or designed flexibly, to emphasize the supply of water or of energy depending upon the relative value of the resources. These water system tradeoffs are suggested by a set of linked production possibility curves, illustrating the available water storage, groundwater, irrigation and crop choice, conveyance and urban water use and treatment management options (Figure 9).

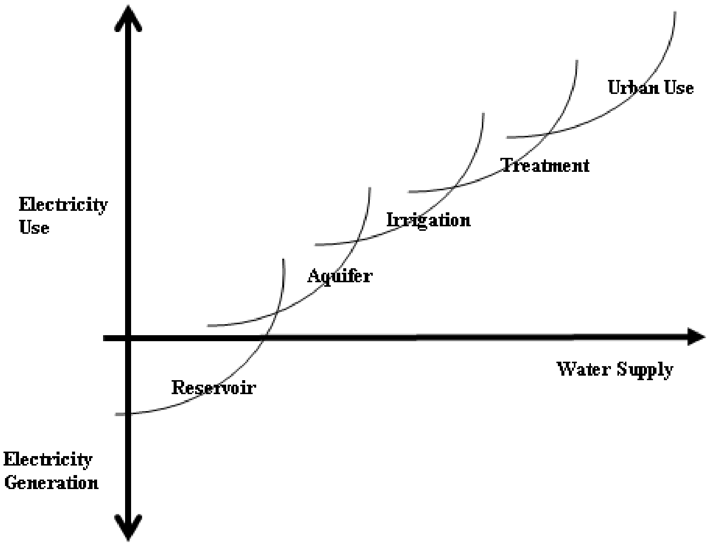


Figure 9. Water Energy Tradeoffs at Different Stages of the Water System

When the relative price of water is high, compared to the price of energy, energy inputs are used to increase water supply —operating at the right hand side of each of the linked production possibility curves. This uses energy to expand cumulative water supply at each stage of the water supply process. When the relative price of water is low, energy is conserved by operating at the left hand side of each production possibility curve.

Climate change will impact water supply management practices according to the impact on relative prices of energy and water. Following an increase in the relative price of water, system managers may take advantage of options to increase water supply at a higher energy cost – despite a rise in energy price.

5.2 Water Storage

These price trends increase the value of surface storage (see Section 1, Figure 2), creating pressure for increased storage as well as more efficient operation of existing storage. Existing reservoir carryover storage rules, designed for one set of prices and concerns, may be changed to reflect increased scarcity and higher relative water prices. Additionally, many components of the water system, a mix of private, State and Federal reservoirs and facilities, are operated independently of one another. Where coordination does take place, it is frequently aimed at increasing only the value of one output, energy or water, but not both.

Perhaps the most dramatic instance of independent operation, and the activity with largest potential gain from coordinated operations, is surface and groundwater storage. The Central Valley is ringed by large surface reservoirs designed to store wet year stream flow for dry year water supply. Beneath the Central Valley floor is a massive system of aquifers that constitutes the largest storage facility available. These two sources of storage are operated independently, with reservoir operators managing surface storage with little regard to the ability of farmers to tap groundwater storage. In addition, reservoir releases generate a quarter of California's electricity supply, and groundwater withdrawals use a large portion of that electricity. Reservoir release schedules often generate electricity during seasons of low energy demand (off peak) while agricultural pumping takes place during seasons of high energy demand (on peak).

Rising water and energy scarcity and increasing relative water prices will create immense pressure for more efficient, coordinated operation of surface and groundwater storage, and of the water system as a whole. Existing models used to plan water system operations do not currently include necessary components to evaluate operating rules for coordinated supply of water and energy.

Recent modeling work of reservoirs and groundwater in east side of the San Joaquin Valley suggests the future direction of reservoir and storage operations (Dale et al 2007). The reservoir-aquifer problem illustrates the impact of changing energy and water prices upon efficient reservoir and groundwater storage. Reservoirs in California tend to be operated according to storage rules that assume historical electricity and water prices. These rules should be changed in accordance with electricity and water price trends. An optimal control model of Merced Irrigation District reservoir and groundwater operations indicates that optimal reservoir and aquifer storage levels will increase when energy prices go up (Dale et al 2007). This finding is explained by economic trade-offs between reservoir storage for agriculture and storage to increase head and generate electricity.

High average reservoir storage levels tend to increase energy generation but decrease agricultural water supply. Assuming current electricity and water prices, current reservoir storage practices are reasonably efficient. However, an increase in reservoir (and aquifer) storage levels would be efficient assuming an increase in relative electricity prices (Figure 10). For example, consider a rise in the price of electricity from $0/MWh to $28/MWh and $56/MWh. In the study region, this price change leads to a rise in end of summer carryover storage from 71% to 88% of reservoir capacity.

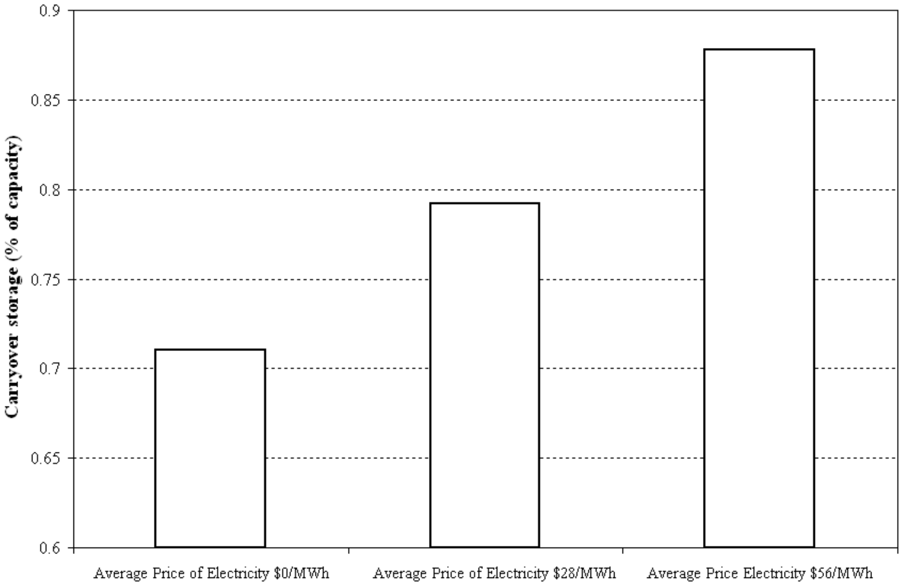


Figure 10. Impact of Climate Change on East Side Reservoir Storage

5.3 Groundwater

Groundwater storage in California, with few exceptions, is an open access resource without controls on its use. This fact, coupled with a projected decrease in surface water supply and rising demand for water, makes a large drawdown in aquifer levels quite likely. Such a drawdown will have a large impact on electricity demand for pumping to groundwater. The groundwater model C2VSIM provides a tool for estimating changing groundwater levels and electricity use resulting from climate change and falling water supplies. Holding cropping patterns constant, we project groundwater levels using C2VSIM assuming a 30%, 50% and 70% declines in surface water supply across the Central Valley, over a 60 year period. Future groundwater levels are projected to decline as illustrated for the southern most portion of the Tulare Basin in the case of a 50% decline in surface supply (Figure 11).

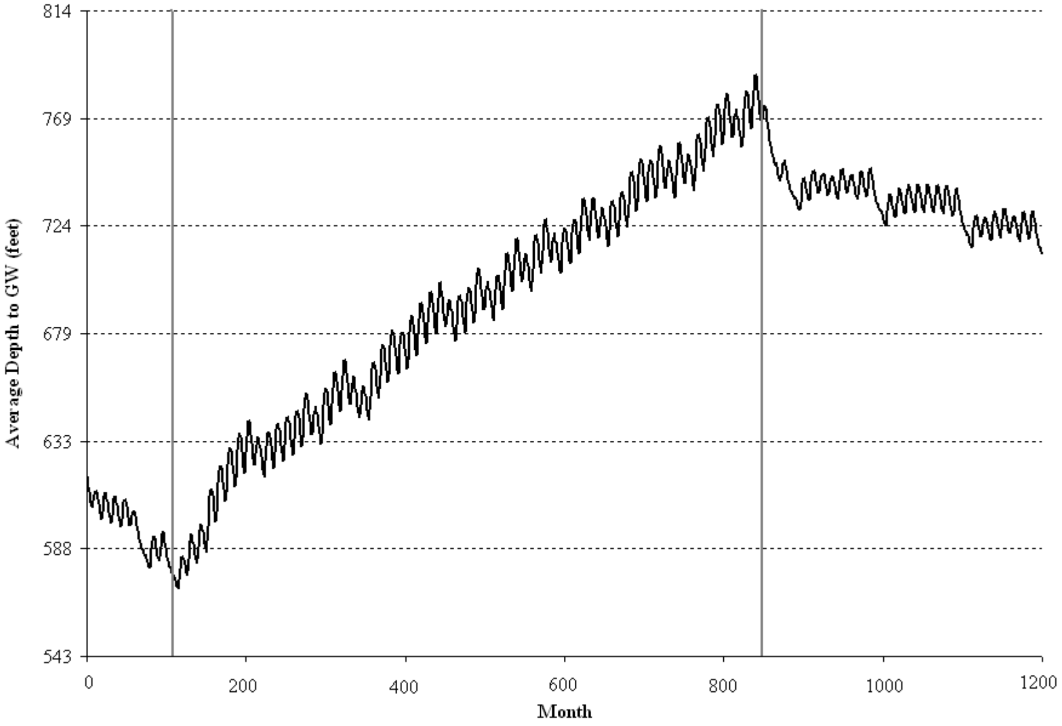


Figure 11. Groundwater Depth During Sixty Year Drought

Note: Gray bars denote the beginning and end of drought. Selected C2VSIM Groundwater Model runs , 70% Decline in Surface Deliveries, Model Region 21 (Kern County)

Averaged across the three Central Valley regions, a 50% decline in surface supply is forecast to lower groundwater levels between 45 and 234 feet. At 1.45 kWh per acre foot per foot of lift, this implies a near doubling of electricity use for groundwater pumping in much of the Central Valley in the next 60 years (Table 3).

Table 3. Climate Induced Decline in Groundwater

Central Valley Region	Groundwater Depth, 2010 (feet)	Groundwater Depth, 2070 (feet)	Decline (feet)	Increased Electricity Use (kWh/AF)
Sacramento Valley	**100**	**145**	**45**	**65**
North Tulare	**127**	**270**	**143**	**207**
Tulare Basin	**312**	**547**	**234**	**340**

The increase in electricity use for groundwater pumping varies according to the severity of the climate impact on surface supply. However, in all regions we expect a substantial increase in electricity use following prolonged shortages with over a 30% decline in surface water availability (Figure 12).

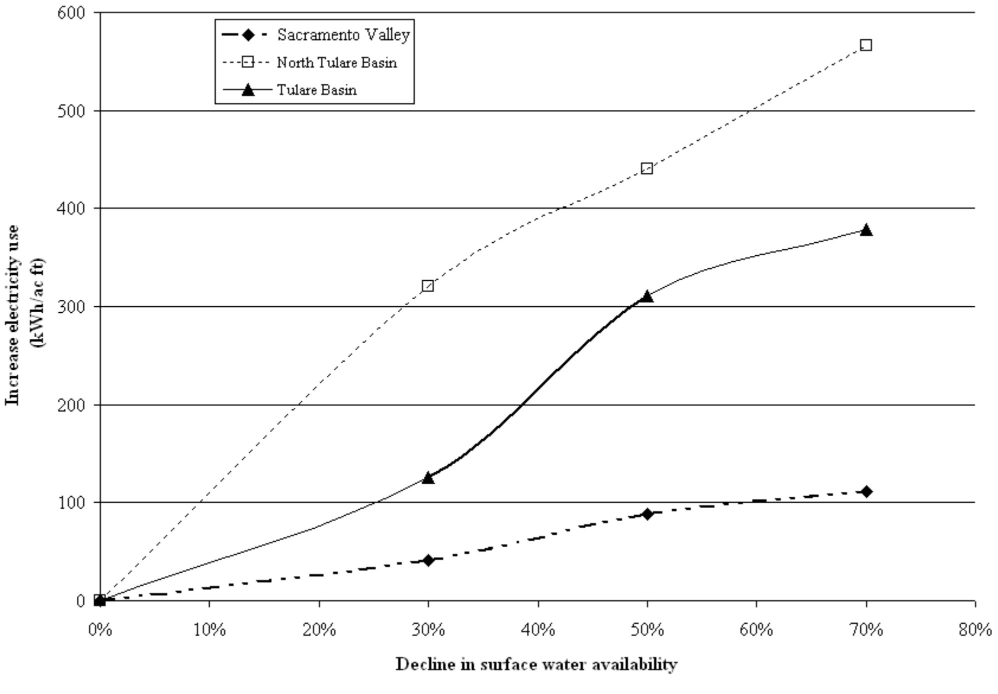


Figure 12. Climate Induced Increase in Groundwater Pump Electricity Use

The potential severity of this problem suggests a need for improved groundwater simulation models. Currently, there are major data and modeling limitations to the accuracy of these types of groundwater forecasts. Data on the quantity of groundwater being pumped in the Central Valley is rare, so calibrating groundwater models is difficult. Similarly, there is little economic information within most groundwater models, including information about electricity prices and crop values, which may influence groundwater pumping as much as a change in surface water supply.

5.4 Irrigation

There is much uncertainty about electricity use in California agriculture due to uncertainty about trends in irrigation practices (CEC 2005). In recent years there has been a large increase in the amount of pressurized irrigation in the California, and a proportional increase in associated electricity use for pressurizing lines and groundwater pumping. Currently, about 40% of crop acres in the Central Valley are irrigated with sprinklers and drip lines and this number is expected to increase (Burt 2005). Pressurized irrigation is energy intensive, requiring by some estimates an average of 220 kWh per acre foot, which is on a par with electricity used to pump groundwater in much of the State (Burt 2005). Indeed, many farmers prefer to use groundwater over surface water with pressurized irrigation systems, increasing the electricity intensity of this practice.

As energy and water prices rise, it becomes increasingly important to understand and forecast trends in irrigation practices. The energy intensity of pressurized irrigation makes it sensitive to changes in electricity prices. A recent study of Klamath Valley irrigation (Boehlert and Jaeger

2006) indicates that rising electricity prices decrease the value of pressurized irrigation. In the study region, doubling the electricity price from $0.03 to $0.07 per kWh decreases the proportion of sprinkler acreage from close to 100% to under 60%.

When electricity and water prices both increase, sprinkler irrigation coverage may go up, despite increasing electricity prices. It is also possible that other types of irrigation practices, including more precise furrow irrigation and laser leveling, will be preferred at higher electricity and water prices. Laser leveling may save as much water as drip irrigation, but uses little or no electricity.

5.5 Cropping

Crop production is an energy intensive practice, rivaling residential water heating in the energy use associated with water consumption. Energy use for planting and harvesting, and pesticide and fertilizer applications is estimated to make up between 10% and 30% of production costs. Crop production costs are themselves quite large, ranging between $300 and $3000 per acre. Across all crops in the Central Valley, these data suggest that energy use to produce crops ranges between 441 kWh and 3097 kWh per acre foot of applied water (EIA 2007), and averages 1299 kWh per acre foot (Table 4), more than doubling the average amount of energy used to irrigate crops (355 kWh per acre foot).

Table 4. Energy Use in Crop Production

Crop	Acreage (1000 acres)	Applied Water (AF)	Crop Production Energy Cost (% of total)	Implicit Crop Production Energy Use (kWh/acre)	(kWh/AF)
Alfalfa	**963**	**4**	**33**	**4,452**	**1,009**
Almonds	**687**	**3**	**9**	**2,264**	**786**
Beans	**1,010**	**2**	**25**	**2,557**	**1,060**
Corn	**555**	**3**	**25**	**2,439**	**871**
Cotton	**778**	**2**	**26**	**2,506**	**1,182**
Grapes	**664**	**3**	**8**	**6,814**	**2,209**
Oranges	**246**	**2**	**13**	**6,960**	**3,097**
Plums	**623**	**3**	**9**	**8,615**	**2,692**
Potatoes	**25**	**4**	**21**	**10,942**	**2,890**
Rice	**617**	**6**	**25**	**2,569**	**441**
Wheat	**577**	**1**	**25**	**1,059**	**913**
All Crop Avg.	**--**	**3**	**20**	**3,826**	**1,299**

The large amount of energy embedded in and linked to crop water use suggests that crop choice and crop production are sensitive to changes in energy and water prices. The sensitivity of crop choice to energy price is suggested by estimating the variation in crop acreage resulting from increased groundwater pumping electricity cost with an agriculture production model. Consecutive runs of the Central Valley Production Model (CVPM), the Department of Water Resources' crop production model, were performed assuming a base groundwater pumping electricity cost, twice the base cost and three times the base cost. These model runs suggest that crop acreage will change substantially after an increase in electricity cost, considering only groundwater pumping. These impacts are not uniform across all crops; doubling the price of electricity lowers crop acreage between 21% for field crops to under 1% for orchard crops and grapes (Table 5).

Table 5. Crop Acreage Changes due to Energy Price Increase

Crop	1000 Acres (1x cost)	1000 Acres (2x cost)	1000 Acres (3x cost)	%Change Energy Use (2x cost)	%Change Energy Use (3x cost)	Implicit Energy Intensity (kWh/Acre)
Alfalfa	**963**	**764**	**645**	**-21**	**-33**	**4,452**
Almonds	**687**	**682**	**679**	**-1**	**-1**	**2,261**
Truck	**1,010**	**958**	**934**	**-5**	**-7**	**2,557**
Corn	**555**	**501**	**456**	**-10**	**-18**	**2,439**
Cotton	**778**	**668**	**602**	**-14**	**-23**	**2,506**
Grapes	**664**	**661**	**658**	**0**	**-1**	**6,814**
Oranges	**246**	**243**	**241**	**-1**	**-2**	**6,960**
Plums	**623**	**620**	**617**	**-1**	**-1**	**8,615**
Potatoes	**25**	**25**	**25**	**-1**	**-2**	**10,942**
Rice	**617**	**549**	**523**	**-11**	**-15**	**2,569**
Wheat	**577**	**570**	**539**	**-1**	**-7**	**1,059**

These estimates suggest the shift in crop acreage due only to one effect of a rise in energy prices—the effect on groundwater pump cost. Including other price effects in the model, such as the cost of irrigation, fertilizer and pesticide inputs, would likely reveal a larger impact of energy prices.

The dramatic growth in biofuel crop acreage highlights another relationship between energy price and crop acreage—on the demand side—missing from current crop production models. Rising energy prices may drive up the price and acreage of bio fuel crops, including corn, sugar beets and sugarcane. The demand for these crops will increase biofuel crop acreage in California, and decrease the acreage of other crops. There will be ripple effects—on crop acreages, prices, water use and energy use—that are now missing from crop production models like CVPM.

5.6 Conveyance and Water Transfers

Historically, California's conveyance systems have linked low cost water supply regions in the North with high value water use regions in the South and along the coast. There is considerable uncertainty about future water supply sources, much of it due to uncertainty about the price of energy. The most populous and fastest growing region in the State, the South Coast, has a variety of new water supply options including water transfers, surface reservoir expansion, and desalinization. The choice of water supply source to the South Coast region will likely determine the pattern of future water infrastructure and conveyance systems.

The unit cost of water from each supply source is largely determined by two factors—the up front capital cost and the operating energy requirement. As a rule, reservoirs are more capital intensive than desalinization plants, but considering hydropower benefits, they use less energy. Similarly, water transfers from the Colorado River and San Joaquin Valley have a higher up front cost than transfers from the Sacramento Valley but use less energy. Up front cost in this case is determined by crop values in the source location, which tend to be highest in the Colorado River and San Joaquin regions, and various transactions costs.

We use this information to estimate of the unit cost of each supply option across a range of energy prices (Figure 13). The cost of each supply option is indicated by a line comparing the unit cost of each option with the price of electricity. At existing energy prices of approximately \$0.10/kWh, Southern California’s lowest cost supply sources are water transfers from the Sacramento Valley. At higher energy prices, water transfers from the San Joaquin and Colorado are the least cost supply sources (Dale et al 2004). At very high energy costs, reservoir expansion becomes cost effective, compared to other options. As shown, desalinization is never cost effective, a conclusion that is obviously contingent on the state of desalinization technology.

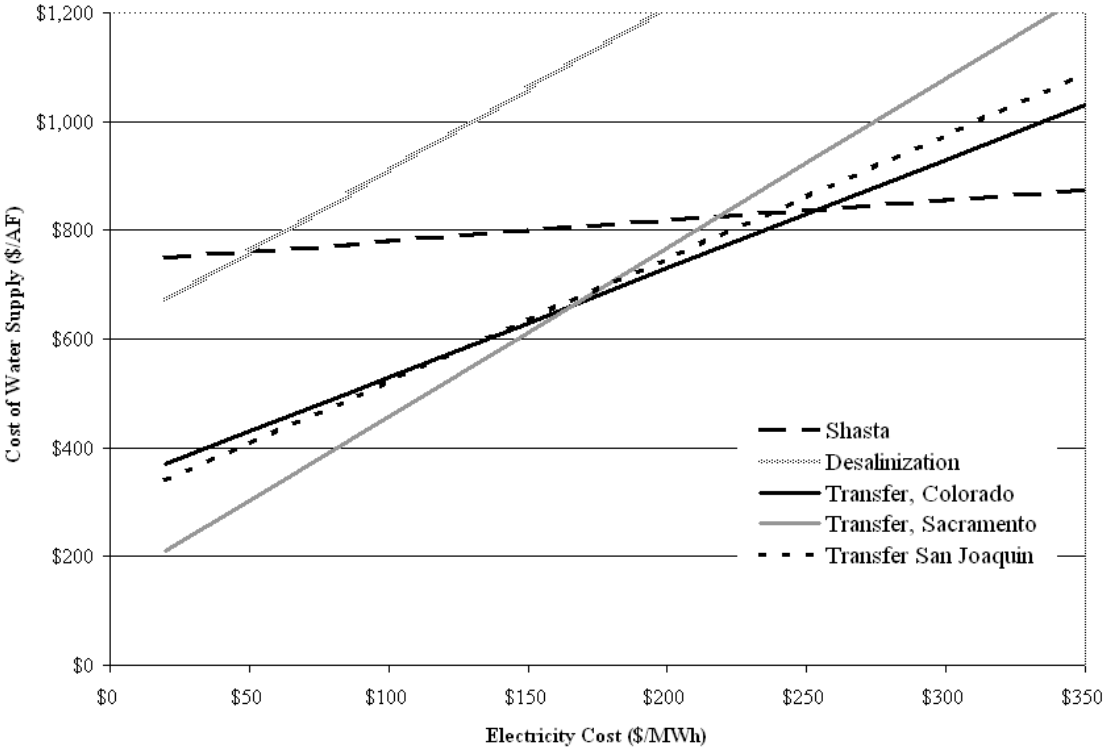


Figure 13. Relative Costs of Water Supplies to Southern California

Water transfers will play an important role in supplying water to Southern California and the source of those transfers will affect the amount of energy used to convey water. To transfer water between Kern County and Metropolitan Water District, water must be lifted over the Tehachapi Mountains, which requires an additional net average of 1297 kWh/AF. Transfers from the Sacramento Valley, which must be pumped through the San Francisco Bay Delta, across the length of the San Joaquin Valley, and over the Tehachapi Mountains, require a net additional 2908 kWh/AF. Transfers from the Colorado River to the South Coast, require an additional 2000 kWh/AF (Wilkinson 2000).

Given past low electricity price levels, it is not surprising that most water transfers to the South Coast have come from the Sacramento Valley. Of the ten such transfers to Metropolitan Water District included in On-Tap and the Water Strategist, the earliest two transfers, in 1997 and 1998, originated in Kern County (Table 6). Since that time, all subsequent transfers originated in the Sacramento Valley.

Table 6. Embedded Energy of Water Transfers

Selling District	County	Water Transfer (AF)	Embedded Energy (kWh/AF)	Total Energy (MWh)
Arvin-Edison WSD	**Kern**	**40,000**	**1,297**	**51,880**
Semitropic WSD	**Kern**	**39,500**	**1,297**	**51,232**
Glenn Colusa ID	**Glenn/Colusa**	**37,972**	**2,908**	**110,423**
Meridian Farms WC	**Sutter**	**3,800**	**2,908**	**11,050**
Natomas Central MWC	**Sacramento**	**6,691**	**2,908**	**19,457**
Pelger MWC	**Sutter**	**2,732**	**2,908**	**7,945**
Pleasant Grove-Verona	**Sutter**	**5,992**	**2,908**	**17,425**
Reclamation Dist. 108	**Colusa/Yolo**	**8,773**	**2,908**	**25,512**
River Garden Farms Co.	**Yolo**	**1,582**	**2,908**	**4,600**
Sutter MWC	**Sutter**	**17,054**	**2,908**	**49,593**

Climate policy and population pressure may increase electricity prices and change the preferred source of water to Southern California. Water transfers will increasingly originate in the Colorado and San Joaquin, rather than Sacramento region. Increased emphasis will be placed on surface reservoir expansion. Given the likely impact of water supply source to conveyance capacity needs and electricity demand, significant changes to the operations of major water projects and reservoirs may be required to optimally facilitate water transfers.

5.7 Urban Water Use

Some of the highest embedded energy use figures occur in the urban water use sector, particularly residential water that is heated and used in dishwashers, cloths washers and showers (Table 7). About 90% of all electricity associated with residential water use goes to these three end uses. Thus, it is not surprising that there has been a lot of attention paid to efforts to conserve urban water. The California Urban Water Conservation Council, an organization set up to promote conservation, enjoys the active participation of over 180 retail water agencies. The CEC Water Energy Relationship report (CEC 2005), and related studies have dealt extensively with this issue (Navigant 2006, Cohen et al 2005) and there are numerous ongoing studies to collect data about water and energy use in the urban sector.

Table 7. Estimated Energy Intensity in Urban Water Use

Residential Water Use	%Residential Water Use	Energy for Heating (kWh/AF)	Energy for Distribution and Treatment (kWh/AF)	Energy in Wastewater Treatment (kWh/AF)	Energy in Conveyance (kWh/AF)	Energy Use Total (kWh/AF)	%Residential Water-Energy Use
Toilet	**24**	**0**	**424**	**815**	**2,000**	**3,239**	**5**
Dishwasher	**2**	**36,867**	**424**	**815**	**2,000**	**40,106**	**4**
ClothsWasher	**14**	**36,867**	**424**	**815**	**2,000**	**40,106**	**34**
Shower	**21**	**36,867**	**424**	**815**	**2,000**	**2,424**	**51**
Landscape	**40**	**0**	**424**	**0**	**2,000**	**--**	**6**
% Annual Residential Water-Energy Use	**100%**	**82%**	**3%**	**3%**	**12%**	**100%**	**100%**

Despite this effort, there seem to be relatively few conservation programs that have substantially impacted urban water and energy use. An explanation for this is that it is difficult to find appropriate incentives to decrease the particular uses of water that consume the most energy, including heating of water for bathing and cleaning.

These water uses are unique in that they respond to changes in both energy and water prices. Indeed, it is hard to say in some cases whether these activities use water to deliver energy, (where energy is defined by its warming and cooling properties) or use energy to deliver water (where water is defined by its evaporative or cleaning properties). The dual nature of these activities implies that traditional incentives for conservation, including changes in only the price of water or only the price of energy, will have a particularly weak impact. A rise in water price may have little impact on shower use if the price of energy remains low. Indeed conservation measures to increase water heater efficiency coupled with a rise in the water price, may have the perverse impact of leaving the incentive to shower unchanged, as no change in the bill will be perceived.

The cost of heated water use includes the cost of heating the water and the cost of the water itself. In California, the cost of electricity used to heat water is much larger than the cost of water itself (EIA 2001). This suggests that heated household water use, about 40% of total residential water use, will be as responsive to changes in electricity price as to changes in water price (Table 8).

Table 8. Household Water and Electricity Use

Water or Energy Use	Value
Annual residential water use (AF)	**0.25**
Annual indoor residential water use (AF)	**0.1**
Annual household electricity use (kWh)	**10,656**
Household water use, with electricity (%)[a]	**36%**
Household electricity for heating water (kWh/year)	**3318**
Average household water heating electricity cost ($/year)[b]	**$116.13**
Average household water bill ($/year)[c]	**$187.18**
Household embedded electricity (% of water bill)	**62%**
Household water (% of electricity bill)	**12%**

a) Includes electricity used for showers and faucets, clothes washers and dishwashers.
b) Assumes $0.14 per kWh cost of electricity. Electric Power Monthly (EIA 2007)
c) Average annual water charges, Orange County urban areas.

This has important implications for evaluating the price elasticity of demand for water. Studies of the impact of water price on residential water use suggest that water use is price inelastic—that a given percent change in water price elicits a relatively small change in water use. One of the reasons for this finding is that much of residential water, particularly residential indoor water (roughly 60%), is heated before use for cleaning and bathing. The elasticity of substitution of water and energy in household water use is difficult to quantify, but a cursory evaluation suggests options to save indoor household water tend to conserve water and energy in equal proportions. In most cases (low flow showerheads, front load cloths washers), water and electricity savings occur jointly—both are saved simultaneously in roughly fixed proportion.

Currently, we have found no studies measuring the elasticity of residential water demand to changes in the price of electricity. Studies of the impact of different joint water and energy incentives on the use of water and energy will become increasingly necessary to promote water and energy conservation, particularly cross price (incentive) impacts, including the impact of different energy rate structures and price changes on urban water use, and different water rate structures and price changes on electricity use.

6. Conclusion and Overview

As energy prices have greatly influenced past water management decisions in California, a change in the energy price brought on by climate warming or climate policy will and should influence future water management. Many features of the existing water system can be explained by relatively low energy prices—including a reliance on groundwater, long distance conveyance, pressurized irrigation, the current choice of crops, heavy fertilizer applications, the inelastic demand for residential water, and household water heating. If the price of energy increases relative to water prices, energy usage will be curtailed—but water usage will also be curtailed. If the price of energy increases less than the price of water, past trends in water and energy use practices may be reinforced; water supplies will grow along with the energy intensity and cost of those supplies.

Table 9. Energy to Supply and Complement Agriculture and Urban Water Use

	Water System Segment	Water Supply Involved (TAF)	Energy Use (GWh)	Energy Intensity (kWh/AF)
A	Reservoirs	--	-24,162	--
	Surface	13,679	588	43
E	Conveyance Distant	1,151	1,118	971
	Conveyance Medium	2,381	1,033	434
B	Groundwater	9,192	3,355	365
C	Pressurization	1,948	2,013	220
D	Crop Use	22,871	29,714	1,299
	AGRICULTURE TOTAL	22,871	37,821	1,654
	Surface	2,255	882	391
E	Conveyance Distant	1,300	3,769	2,900
	Conveyance Medium	452	267	590
	Groundwater	2,749	1,003	365
F	Recycling	264	170	652
	Treatment	5,282	174	33
	Waste Treatment	2,116	1,725	815
G	Residential Heating	2,116	28,246	13,348
	URBAN TOTAL	5,265	36,235	5,894

Note: Crop use energy per acre foot is an average of the total non-water energy inputs used per each acre foot of water a crop requires. This includes the embedded energy in fertilizers and the use of tractors and other equipment.

The stakes are large; a massive amount of electricity is used to supply water to farms and urban areas the agricultural and urban areas of California. Even more energy is used on the farm, and in the household, to complement that water use. A very rough accounting, suggests that total energy use in agricultural and residential areas, used to supply and compliment the use of water, is equivalent to about 70 million MWh (Table 9). More impressive, this total could well increase following a global warming scenario that increases the price of electricity and decreases the supply of water. Such a ‘perfect storm’ scenario could significantly increase energy demands above current levels, and increase energy expenditures much higher, depending upon the new price of electricity.

NOTES

[1] Jay Lund developed a similar chart, presented at the First Western Forum on Energy and Water Sustainability. http://www2.bren.ucsb.edu/~keller/energy-water/first_forum.htm

[2] The embedded cost of energy is defined as the quantity of energy per acre foot times the price of electricity. Electricity prices can be highly subsidized for agricultural water districts, and exact values are difficult to come by. Discussions with industry experts yielded a price range of $0.03-$0.10 per kWh. We have assumed the price of energy for agricultural water districts to be near the middle of this range at $0.06 per kWh.

[3] The water cost is an average based on water prices reported by ACWA for districts in each water source category: Local surface: Yolo County FCWCD, Turlock ID, Modesto ID. Groundwater: East Contra Costa ID, Semitropic WSD, James ID. Medium surface: Panoche WD, Exeter ID, San Luis WD. Distant surface: Wheeler Ridge Maricopa WSD, Belridge WD, Berrenda Mesa WD.

[4] An average urban price of electricity of $0.10/kWh is assumed, suggested by personal communications with El Dorado ID (present costs approximately $0.11/kWh, lower in the past), East Bay MUD, and others.

[5] The population of California is expected to double by the year 2050. Mary Heim. Department of Finance. Demographic Research Unit.

[1] James Bushnell. University of California Energy Institute. Personal Communication. April 2007.

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