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The Water Costs of Electricity in Arizona

Executive Summary

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Water and energy are not only our most important and precious natural resources, they are completely entangled. Providing electricity requires water just as providing water requires electricity. For environmental sustainability and the public good, the relationships between water and energy are among the most vital we must consider. Recognizing this, water and power managers are constantly adjusting, improving, and rebalancing their operations for maximum efficiency in the use of both resources. Nonetheless, conditions are becoming more challenging. On a national basis, the water withdrawn from rivers and other sources for use in electrical generating plants is now at parity with water withdrawn for irrigated agriculture. In Arizona, agriculture still dominates, consuming 75% of the water, but agricultural use is declining with urban growth and water use for electrical generating stations and other industrial purposes is increasing. The research summarized here focuses on conditions in Arizona in four sections: (1) Comparing the water cost of electricity among different fuels, (2) Trading "virtual' water, (3) Water lost from hydroelectric lakes, and (4) Policy considerations.

Comparing the water cost of electricity among different fuels

Despite power exchanges between states, use of treated wastewater, or introduction of new power technologies, water availability in the arid southwest will affect future power plant location, fuel choice, cooling methods, resource competition, innovations, and even the price of electricity. The starting point in considering these choices, changes, and reactions is how much water is used for different fuels. These values (minus hydroelectric) are summarized for Arizona in **Figure 1**. They range from a high of 785 gallons per megawatt-hour (gal/MWhr) for nuclear energy to a low of less than 1gal/MWhr for solar photovoltaic. Like solar photovoltaics, wind also uses virtually no water in the generation phase.[1]

Water use at nuclear and solar plants is of special interest. Nuclear power plants operate in the range of 32-33 percent, compared to around 40 percent for coal and over 50 percent for combined-cycle gas plants. This lower conversion efficiency results in higher consumptive water use. The Palo Verde Nuclear Generating Station, west of Phoenix uses treated wastewater for most of its cooling supply. Using this source of water reduces the potential stress on ground water withdrawal. However, diverting the treated wastewater from the Gila River to Palo Verde precludes recharging the aquifer or supplying other uses.

The other special case is the water used at solar thermal plants. The largest facility of this type operating in Arizona is a one-megawatt installation 30 miles northwest of Tucson, managed by Arizona Public Service (APS). Although APS does not measure the total amount of water they add to compensate for evaporation when electricity is generated at their solar facility, they do measure blowdown (the saline water that is drained off from the cooling towers). Taking into account water lost to blowdown, evaporated from the cooling towers, and washing of the solar panels, the mid-point in the range of water use at the Sahuaro solar facility is 311 gal/MWhr for solar thermal.[2] For several reasons, this value could be exceeded when large-scale facilities begin operating, as seems possible for the 285 MW Solana project near Gila Bend, Arizona.[3] Estimates for solar thermal plants operating in California are in the range of 800 to 1,000 gal/MWhr.

<u>Trading Virtual Water</u>

Because electricity generated by conventional thermal power plants uses cooling water, that water is "embodied" within the electricity in the same sense that water is embodied within agricultural products. Such "virtual water" is thereby traded in and out of Arizona with imports and exports of electricity. Of the almost 105,000,000 MWhr of electricity generated annually on average in Arizona between 2002 and 2006, 31,000,000 MWhr (approximately 30 percent) were exported. On the other hand, 15,000,000 MWhr were imported to the state, largely from New Mexico **(Table 1, Figure 2)**.

Knowing the total electricity generated from each fuel, the amount of electricity exported, and the consumptive use of water per megawatt-hour of power for each fuel, we can calculate the amount of virtual water that crosses state borders. The total exported water is about 52,000 acre-feet **(Table 2)**. Counter-balancing some of this loss, the total imported virtual water is about 22,000 acre-feet each year. The net loss of water to Arizona from thermo-electric plants is about 30,000 AF/yr **(Figure 3)**, enough to supply 150,000 people at current rates of use in Arizona. While it is not possible to identify the exact source of any given electricity exported, the merchant plants are selling their electricity to customers not by long-term contract or partial ownership but to the highest bidder. Given that California's electricity rates are higher than in Arizona, the merchant plants are exporting water as well as electricity from the state.

<u>Water lost from hydroelectric reservoirs</u>

The dams that provide electricity to Arizona impound some of the largest lakes in the country, and all of them are in areas with some of the highest rates of evaporation anywhere. While recognizing that such dams serve multiple functions, they could not generate electricity without the existence of these lakes. Therefore, it is reasonable to attribute some of the water loss to the electricity generated at these dams.[4] The question is how much?[5] We address this question for a sample of regional reservoirs supplying hydropower to Arizona—including Lake Powell behind Glen Canyon Dam and Lake Mead, behind Hoover Dam.

In 2002-2006, Glen Canyon dam generated an annual average of 3,424,537 MWhr, and in 2006 the lake lost 553,000 ac-ft by evaporation and seepage (**Table 3**).[6] Prorating the water loss number by the 17.85 percent of the generated electricity that goes to Arizona gives an apportioned water loss of 98,434 ac-ft, and an equivalent power generation to water lost value of 52,619 gal/MWhr, if the impounded water is considered as having no other use. Downstream, for Hoover Dam and Lake Mead, the comparable amount is 56,419 gal/MWhr, again premised that the sole function of the dam is electricity generation.[7]

While Hoover and Glen Canyon Dams are the largest, there are several others that must be counted as well. Summing the total of the two other significant Colorado River dams—Davis and Parker—the value is 43,518 gal/MWhr. The six dams of the Salt River Project, plus New Waddell Dam, lose to evaporation an additional 52,262 ac-ft per year.[8] In all, 2,288,199 MWhr of hydropower are generated and consumed in Arizona, and about 473,033 ac-ft of water is lost to evaporation from the impoundments.

Taken together, the weighted average of the water lost from all the reservoirs used to generate electricity for Arizona is 55,898 gal/MWhr **(Table 3)**. Again, this initial value assumes that the water has no other use than generating electricity. In other words, this is the raw number.

Estimating how much of this water is attributable to the generation of electricity is controversial and depends upon a number of assumptions. Some water and energy managers would argue that Arizona's larger reservoirs were built for water supply and flood control and therefore the evaporative water losses are not impacted by incidental electricity production. Others might argue that all the evaporation should be considered in determining the water use to produce hydropower. In an effort to advance the discussion of water and energy linkages in Arizona, we propose a methodology in this paper which allocates evaporative water losses to the various uses of the reservoirs based on the economic value of those different uses. Conducting a rigorous economic evaluation was beyond the scope of this project, so our methodology below is illustrative of this approach. However, we believe this work does provide a rough estimate for water consumption attributable to hydropower.

Our approach was to assign a value to each of the four principal uses of the water stored behind Glen Canyon Dam in Lake Powell. We base this value on the wholesale price of the water, whether it is used for recreation, municipalities, irrigation or power generation. For irrigation we used the wholesale value of the crops and livestock in Imperial Valley because the value of the irrigation water delivered to the Imperial Valley is unrealistically low due to subsidies.[9] Applying this method to Glen Canyon Dam and Lake Powell,[10] we calculate four values:

- Electricity – $1 billion [11]
- Recreation – $430 million[12]
- Agriculture – $350 million[13]
- Domestic – $42 million[14]

This means that Lake Powell water has an annual first-sale worth of $1,822,000,000, with 55 percent of this value coming from the sale of electricity. In other words, the virtual water associated with power generation is 55% of 553,000 acre feet of the water lost at Lake Powell, or 304,150 acre feet. For Hoover Dam, 55% of 668,000 yields 367,400 acre feet virtual water. Prorating this number for just the electricity that goes to Arizona from each dam we calculate a yearly loss of 69,622 ac-ft for Lake Mead and 54,290 ac-ft for Lake Powell.[15] Thus, a total of 1,342,385 MWhr of the electricity from these two dams are used in Arizona, and 123,912 ac-ft are consumed in the process. The prorated water lost to generate electricity from Hoover and Glen Canyon is 0.0923073 ac-ft/MWhr, or 30,078 gal/MWhr.

Policy Considerations

Predicted population growth in Arizona will require several thousand megawatts of additional generating capacity. Such added capacity will require water, the amount of which will be influenced by considerations such as the fuel mix, types of technology adopted, as well as the price and use of both electricity and water. It is a complex matter, one that is a part of a larger question of the overall benefits and costs to Arizona of the energy industry in comparison to such other factors as socioeconomics, cultural differences, and quality of life. Moreover, a maze of federal, state and local regulatory constructs have significant impacts on what can be done. Considering here just the matter of water use, four policy themes emerge.

The first theme is cooling technology. All Arizona utilities are considering installing dry-cooling, either as retro-fitted equipment on older plants or initial equipment on future plants. There are presently no such systems in Arizona, although dry-cooling is used at power plants in Nevada, parts of Texas and northern Mexico. One of the drawbacks of such systems, in addition to their extra expense, is that their effectiveness drops off above an ambient temperature of 90 degrees F. Including consideration of humidity, this penalty will range from two to five percent overall (including turbine and steam cycles), compared to a plant equipped with evaporative closed loop cooling (depending on local climate), but up to a 25% loss of efficiency in the hottest weather. The maximum loss of efficiency coincides with the period of greatest power demand, so using averages does not tell the whole story. In addition, the increased capital cost of construction (with dry cooling up to 4 times as expensive as wet cooling for hot dry areas) is such that feasibility of dry cooling in many parts of Arizona is questionable, according to Henry Day of APS. Hybrid systems, which use dry cooling at lower temperatures, are a possible alternative solution; while they increase generation costs, they can provide cooling with 80- 95 percent water savings over wet-cooling systems.[16]

A second them is trading virtual water. Currently Arizona exports a net of about 30,000 acre-feet of water. Some of these exports come from the merchant plants, whose total capacity is about 7,000 MW. Little of the electricity they generate is sold in Arizona. The question is whether such power plants provide enough of a return to the state to compensate for the water they export.

A third theme is the economic value of saved water in supporting the development of renewable energy, particularly solar energy, the most abundant resource in Arizona. If water saved from using solar were assigned a monetary value, that value would help narrow the economic gap between solar and conventional generation. Similar adjustments would also be possible for the value of reduced carbon emissions. Generating electricity from many types of renewable energy requires less water than is used in conventional generation. For example, if we used solar photovoltaics instead of nuclear fuels to generate 1000 MWhr of electricity, we would save 758,000 gallons of water. Such saved water (and carbon dioxide) has a monetary value. In quickly-growing cities in the southwestern U.S., especially those with an abundance of solar energy like Phoenix, this attribute provides increased economic incentives to the support of renewable energy options.

A fourth theme is the water cost of hydroelectric dams, especially where evaporation losses are high. This loss pertains to decisions for future hydroelectric projects in the region, including dedicated pumped-storage facilities.

A fifth theme is whether to place greater emphasis on importing electricity and fuels from areas where water supply is not as critical as it is in Arizona. A key element in the potential for this alternative will be the availability of adequate transmission capacity.

Table 1 – Arizona Electricity Sources MWhr (2002-2006 annual average)				
	In-State Generation	**Imported Generation**	**Exported Generation**	**Net In-State Use**
Coal	38,526,671	13,706,962	9,308,761	42,924,872
Natural Gas	30,135,321	636,079	468,670	30,302,730
Nuclear	27,492,437		14,680,961	12,811,476
Biomass	12,058		12,058	0
Geothermal		65,323		65,323
Hydro	8,760,777	133,529	6,280,250	2,614,056
Solar	16,892			16,892
TOTAL	104,944,156	14,541,893	30,750,700	88,735,349

Note: Net In-State Use is calculated as the sum of in-state generation and imported generation minus exported generation. The use of "import" and "export" is intended to connote to or from the state, recognizing that local dams were built to serve several states, even when they are located in Arizona.

Table 2 – Exported Electricity and Virtual Water (2002-2006 annual average)

	MWhr	MWhr %	Gal/MWhr Average	Ac-ft consumed
Coal	9,308,761	32.60 %	548	15,643
Natural Gas	165,506	0.09%	492	250
Natural Gas (CC)	303,164	1.77%	350	326
Nuclear	14,680,961	51.42 %	785	35,381
Biomass	12,058	0.04%	351	13
Total	**24,470,450**		**687**	**51,613**

Note: One acre foot of water equals 325,851 gallons.

Table 3 - Summary of Power Generation and Evaporation Losses at Dams

<table>
<tr><th>Colorado River Dam</th><th>5yr Ave Generation (MWhr)</th><th>5yr Ave AF consumed</th><th>% of MWh to to AZ</th><th>Total AF Lost for AZ electricity</th><th>Total Gals/MWhr</th></tr>
<tr><td>Glen Canyon</td><td>3,424,537</td><td>553,000</td><td>17.80</td><td>98,434</td><td>52,619</td></tr>
<tr><td>Hoover</td><td>3,858,072</td><td>668,000</td><td>18.95</td><td>126,586</td><td>56,419</td></tr>
<tr><td>Davis</td><td>1,127,715</td><td>113,520</td><td>70</td><td>79,464</td><td rowspan="2">43,518</td></tr>
<tr><td>Parker</td><td>445,098</td><td>85,208</td><td>30</td><td>25,562</td></tr>
<tr><td>SRP Lakes</td><td>229,195</td><td>94,515</td><td>100</td><td>94,515</td><td rowspan="2">68,490</td></tr>
<tr><td>Lake Pleasant</td><td>47,203</td><td>52,262</td><td>100</td><td>52,262</td></tr>
<tr><td>Total</td><td>9,131,820</td><td>1,566,505</td><td></td><td>476,893</td><td></td></tr>
<tr><td>Average of two principal dams</td><td></td><td></td><td></td><td></td><td>55,898</td></tr>
</table>

Note: In the total gallons/MWhr column, Davis and Parker are considered as one entity, as are the SRP Lakes. The SRP lakes and Lake Pleasant are considered together as all are located close to Phoenix. The final total of 55,898 gal/MWhr is the raw value, without pro-rata allocations for different water uses.

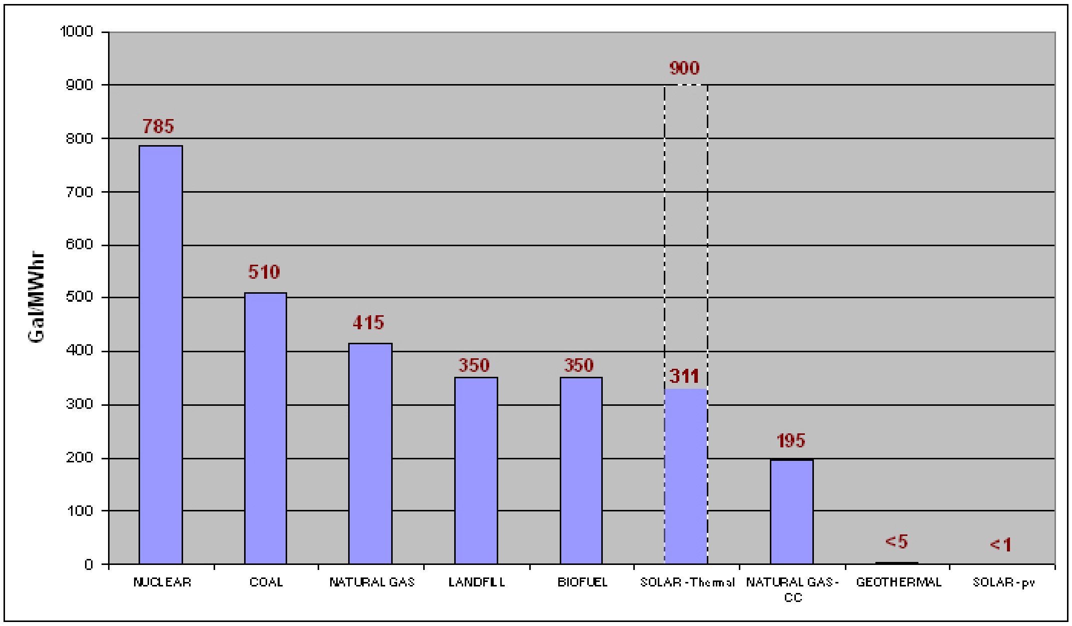

Figure 1 - Average Gallons of water needed to generate one MWhr of electricity from generating facilities supplying Arizona. **Electricity from geothermal power plants is imported from one plant in Imperial Valley. Solar thermal is based on one facility near the Sahuaro fossil plant, northwest of Tucson but should be expected to be higher when more data are available. Larger solar-thermal plants in California use between 800-1000 galls per MWhr.**

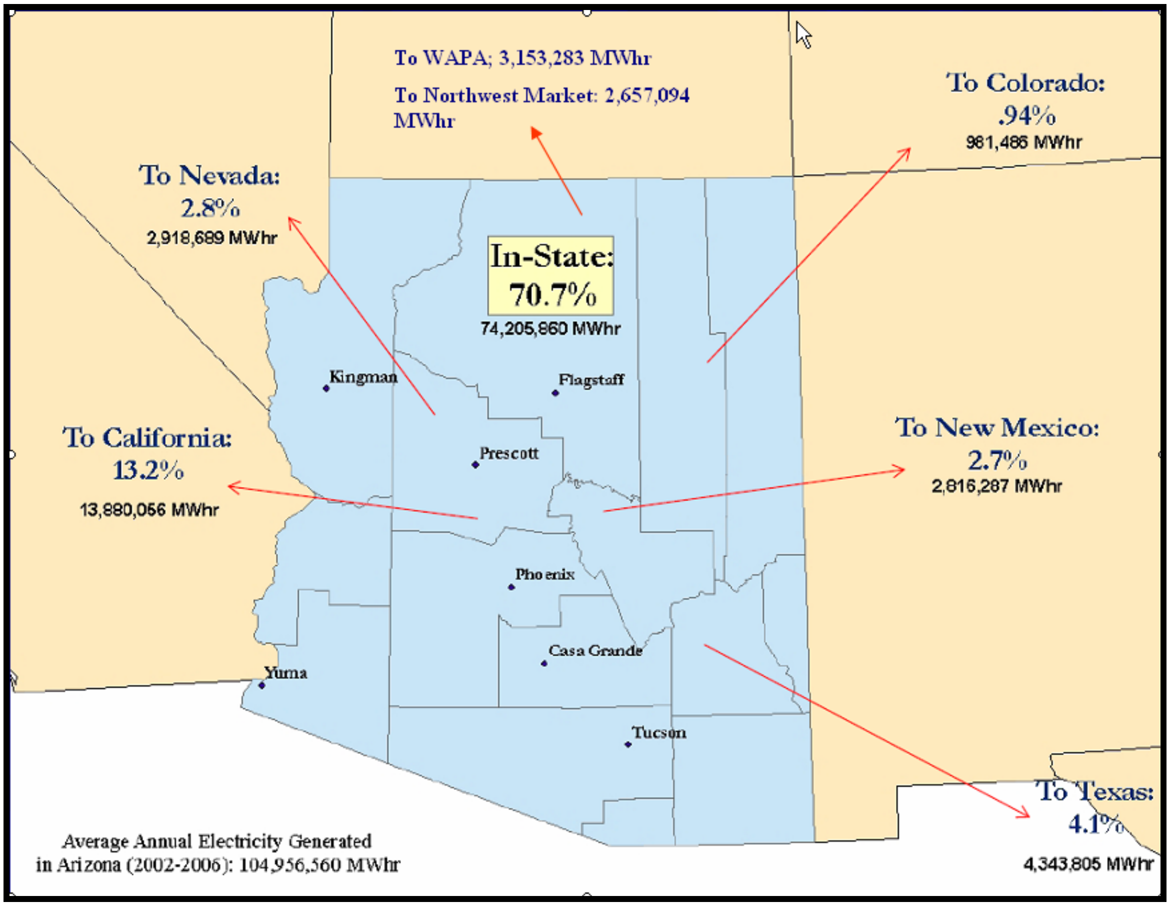

Figure 2- Destination of Exported Electricity. About 71% of the electricity generated in Arizona remains in the state.

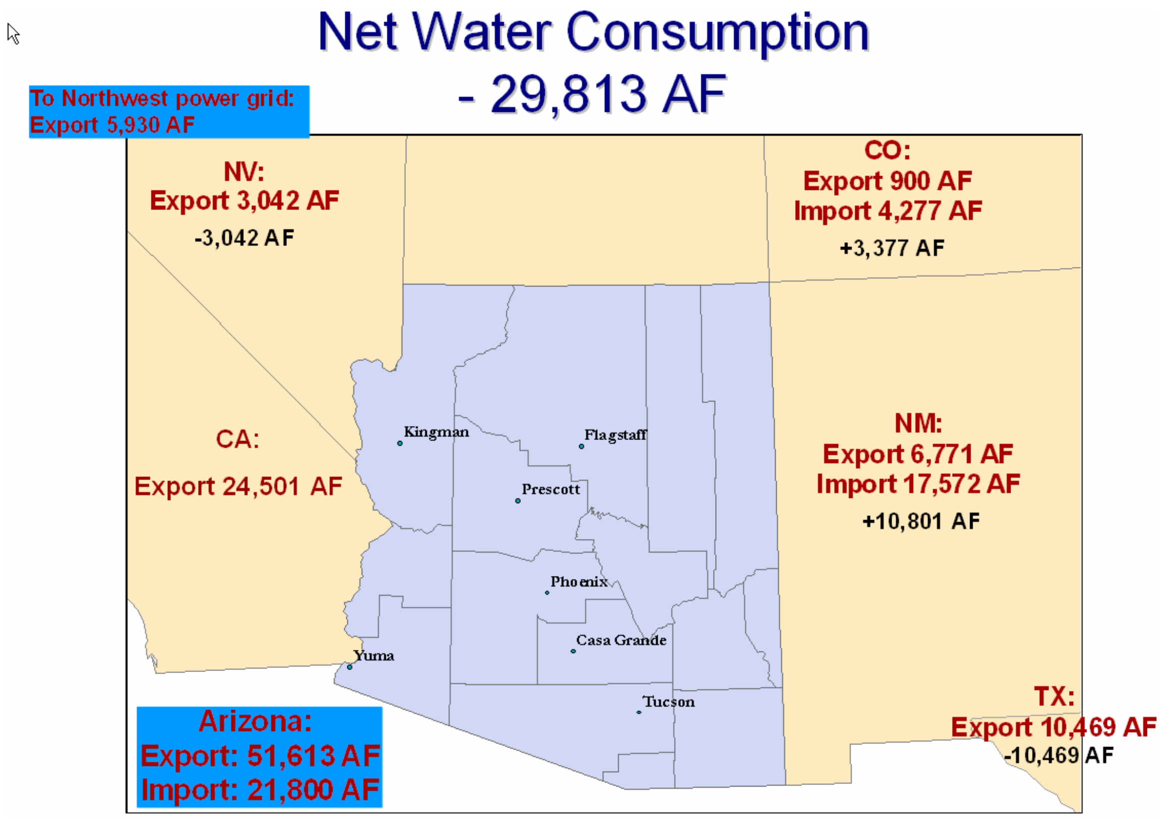

Figure 3 - Net Water Consumption by Arizona for thermo-electrical Generation (imports minus exports)

ENDNOTES

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[1] Wind data were not available for this study.

[2] Blowdown at the Sahuaro solar facility amounts to about 2500 to 3000 gallons per week during the summer and 2500 to 3000 gallons per 10 days during the lower temperature months, according to Ronald Flood of Arizona Public Service. This amounts to 65,000 – 78,000 gallons for the hottest 6 months and 45,000 – 54,000 additional gallons for the coolest six months. This totals 110,000 – 132,000 gallons of water used annually to make up for the discharged and evaporated blowdown. If we assume that such blowdown amounts to about 1/5 of the water that is needed for cooling, then the plant uses 550,000 – 660,000 gallons annually for cooling makeup requirements, Sahuaro uses somewhere between 12,500 gallons to 15,000 gallons per week during the summer and that much over a period of 10 days during the cooler months. Mirror cleaning requires additional, though not large, amounts of water. A recent cleaning used about 800 gallons per row or for the entire solar field, 4,800 gallons. Cleaning is performed about 3 times per year but may vary year to year for dust storms, increasing that number to perhaps 5 times per year. This brings the total to a range of 564,400 – 684,000 gallons annually, or from 281 gals/MWhr to 340 gals/MWhr.

[3] The medium value of 311 gals/MWhr reported here must be considered preliminary until APS installs a direct measurement instrument for the makeup. An operational number for a larger Arizona intallation will become available from the 285 MWe Solana project, proposed for a location near Gila Bend, Arizona. Engineering estimates for that facility are about 928 gals/MWhr of withdrawn water, according to Kate Maracas, local representative of Abengoa Solar, Inc, plant owners. As a comparison, the SEGS (solar electric generating system) plants in the Mojave Desert of California use 800-1000 gallons of water per MWh generated. With wet cooling systems, the cooling tower represents approximately 90% of a Rankine parabolic trough power plant's raw water consumption. The other 10% of water consumption includes the steam cycle makeup cycle (8%) and mirror washing (2%). New technologies being developed for solar thermal power plants could significantly reduce their water consumption. (http://www.nrel.gov/csp/troughnet/power_plant_systems.html#cooling).

[4] US DoE (Department of Energy). 2006. Energy Demands on Water Resources. Report to Congress on the Interdependency of Energy and Water. The report is available at: http://www.sandia.gov/energy-water/docs/121-RptToCongress-EWwEIAcomments-FINAL.pdf.

[5] Peter Gleick suggested an average of 4,500 gal/MWh. Gleick, P.H. 1994. "Water and energy." Annual Review of Energy and Environment Vol. 19, pp. 267-299, Annual Reviews, Inc. Palo Alto, California

[6] Evaporation values for Lake Powell and Lake Mead were provided by Burt Hawkes, CRSP Power Marketing and Contracts Team Leader hawkes@wapa.gov. Evaporation loss would, on average, be greater at full pool. For a sense of the variability, consult U.S. Bureau of Reclamation. Provisional Upper Colorado River Basin Consumptive Uses and Losses Report 2001-2005, June 2007. Glen Canyon Institute suggest that "Lake Powell loses an average of 860,000 acre feet of water to evaporation and bank seepage. This is equivalent to the annual water usage of Los Angeles." http://www.glencanyon.org/aboutgci/faq.php.

[7] The five-year average generation for 2002-2006 on the Arizona side of Hoover Dam is 2,138,513 MWhr, and the evaporation loss for 2006 was 668,000 acre-feet. Of all the electricity generated, 18.95 percent, or 731,105 MWhr, is allocated to customers in Arizona. Applying this percentage of the consumption to the water cost of generating that electricity, delivery to Arizona is responsible for 126,586 ac-ft of lost water.

[8] This figure was interpolated using storage volume of Lake Pleasant, using proportional values to SRP evaporative loses and total storage. Over the 5 years (2002-2006), Davis Dam averaged 1,127,715 MWhr of annual production, and Parker Dam average 445,098 MWhr, for a total from the two dams of 1,572,813 MWhr. Arizona receives half, or 786,406.5 MWhr. Prorating the evaporation loss just for Arizona, the state's water use is 113,520 x 0.7 at Davis + 85,208 x 0.3 at Parker, or a total of 105,026 ac-ft. These figures are the individual evaporation losses for each of those lakes, multiplied by the percentage of electricity from each reservoir going to Arizona (i.e., Arizona's share of the evaporation losses). Treating the dams in tandem for the calculation of gal/MWhr going to Arizona yields 43,518 gal/MWhr for these two dams, compared to 56,419 for Hoover, and 52,619 for Glen Canyon. The Salt River Project estimates that total evaporation loss from its six reservoirs on the Verde and Salt Rivers averaged 94,515 AF per year in the five year period 2002-2006. Their hydroelectric generation comes from the following facilities: Roosevelt, Horse Mesa, Stewart Mountain, and Mormon Flat Dams, plus Crosscut and South Consolidated canal hydro projects. The dams on these reservoirs generated an average of 229,195 MWhr each year during this period. New Waddell Dam, forming Lake Pleasant, also generates electricity. Assuming that the

evaporation rate is similar to the Salt-Verde reservoirs, Lake Pleasant accounts for an additional evaporative loss of 52,262 ac-ft per year. This yields a total of 68,490 gal/MWhr for the Phoenix-area lakes, a number that is calculated from using the 5-year annual electrical generation values for each facility and the annual average evaporation for all of the facilities; i.e., the same methodology as the other reservoirs.

[9] Given the number of assumptions, we offer our water use calculation and our methodology as a starting point for further research and discussion rather than as a definite finding. We acknowledge that water can produce a value-added benefit, but so can electricity. In other words, the end value of both would increase. We also realize that wholesale water prices are often highly subsidized and not necessarily reflective of the economic value of the water supply. The comparisons between different uses of our reservoirs might be better based on retail values of the supply or even the cost of substitute supplies. Making such calculations was far beyond the scope of the present study. We also acknowledge that we have not captured all of the agricultural and domestic/municipal uses of the water provided by the reservoirs, but again believe the methodology used provides an illustration that can be enhanced with subsequent research. While acknowledging these limitations we believe that hydroelectric power is approximately two orders of magnitude more consumptive of water than thermoelectric power.

[10] It is acknowledged that Glen Canyon Dam is but one dam on the Colorado River, and that it is an Upper Basin facility. We did not attempt to factor in these distinctions.

[11] This uses US Bureau of Reclamation figures, assuming a retail value of the electricity generated (see Table 3 for values).

[12] Based on 4.3 million visitor-days at a value of $100 per day.

[13] The gross sales for the crops produced from this assumed amount of water, according to the Imperial Irrigation District, 2005 Annual Water Report. For agricultural use, we have assumed that one million ac-ft, or approximately one-third of the water delivered yearly to the Imperial Valley, is made reliably available because of the existence of Glen Canyon Dam. This assumption is based on the original rational for the construction of the dam, which was in part as a silt trap to lengthen the life of Hoover Dam and also as a storage lake for about two years of average river flow, or 28 million acre-feet. For purposes in this study, it does not consider matters of prior appropriate.

[14] This assumes that one-third of the water delivered to the CAP is available because of the existence of Glen Canyon Dam (a generous estimate). Currently the cost for that water is $82/ac-ft (http://www.cap-az.com/static/index.cfm?contentID=30)

[15] For electricity, it is 611,280 MWhr (17.85% X 3,424,537) for Glen Canyon Dam, plus 731,105 MWhr (18.95% X 3,858,072) from Hoover Dam.

[16] University of Arizona, Water Resources Research Center. 2002. “Dry” Power Plants Produce Energy Using Less Water http://www.ag.arizona.edu/AZWATER/awr/marapr02/feature1.html