Value intensity of water used for electrical energy generation in the Western U.S.; an application of embedded resource accounting

Elizabeth A. Martin and Benjamin L. Ruddell

***Abstract*—This study evaluates the water intensity of thermo-electric power plants in the eleven Western states included within the Western Electricity Coordinating Council region. Water intensities are combined with retail electricity sales using an embedded resource accounting framework to estimate a value intensity of water embedded in electrical energy production and trade in the Western U.S. States with lower water intensities and higher retail electricity prices tend to be net importers of electricity and have the highest value intensities. A 35% increase in the value intensity of water embedded in electricity traded in export was shown to have occurred relative to electricity produced for in-state use. This increase in the value intensity of embedded water suggests that embedded water in the electricity trade has already emerged as a substitute for direct trade in water resources, and that this trade is organized in a manner that appears to benefit both importing and exporting parties.**

***Index Terms*— embedded resource accounting, water-energy nexus, water in energy, embedded water, electrical grid.**

I. Introduction

An analysis of the relationships between climate and economic changes and the energy-water nexus is needed for the purpose of informing National water and energy policy for the 21st century. Climate change is expected to cause increasing temperatures and evaporation, decreased rainfall, and more intense droughts in the Southwestern U.S. As population and industry continue to grow, resource demands increase and become more spatially concentrated around urban areas. This is particularly true of demands for electrical energy. Electrical energy production accounts for the largest percentage of gross water withdrawals in the U.S., placing water resources at the focal point of the energy-water nexus as an important and climate-sensitive constraint on electrical energy production. Reallocation of water supplies in addition to redistribution of the production of electrical energy and other resources will be necessary to adapt reduced supplies to meet increasing and spatially concentrated resource demands.

The *re-location* of existing "old" water resources and *access* to low-quality "new" water resources often involves prohibitive infrastructure costs, energy costs, and legal barriers. However, there is a significant amount of water embedded in electrical energy production. Therefore, the remote production and *virtual* transmission of water in electricity and other resources provides a powerful management solution for an efficient adaptation to water resource challenges. Embedded (or "virtual") water accounting provides a method for the evaluation of proposed electrical energy production adaptations to water limitations. Embedded Resource Accounting (ERA) is a general input/output framework assessing resources embedded in production and trade.

The management of water resources has played a large role in defining the culture of the Western United States. The settlement of the West was made possible through large government subsidized water projects and fixed water rights, rather than through market based economic development of water resources [1]. As a result, the value of water is difficult to directly observe or assess. However, a proxy for the value of a resource such as water, for which there is no functioning market, can be established by observing water embedded in the process of production of marketed goods and services.

We perform an analysis of water resources embedded in the electrical energy trade across the Western U.S. to reveal meaningful trends in the *value intensity* of embedded water in traded electricity. The value intensity for a production process is the quantity of something of value created by the process relative to the quantity of a resource impacted by the process. Value intensity is not an economic measure of price because many objective, subjective, economic, social, and environmental values are outputs of a process, and many inputs are associated with a process. Value intensity is the ratio of the quantity of a single value created or produced to a single resource consumed or impacted.

This study evaluates the water intensity of power generation plants in the eleven Western states included within the Western Electricity Coordinating Council region (Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, and Wyoming), and combines this information with retail electricity sales to estimate the value intensity of water embedded in electrical energy production

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and trade.

II. METHODOLOGY

Consider three resources: *A*, *B*, and *C*. Here, a "resource" is broadly defined and may be a physical resource, a good, a service, or anything that can be valued, produced, consumed, created, or destroyed as a part of a process. Resource *A* is produced through a process using a variety of inputs including resource *B*. We define the quantity *B/A* as the *intensity* of use of resource *B* in the production of resource *A* by such a process. There must exist a market that trades resource *A* for resource *C* at a price expressed as *C/A*.

For this study, *A* = electricity produced by a generation process and traded for currency (MWh), *B* = net raw water consumption, i.e. the "blue" water footprint [2] of an electrical energy generation process (gal), and *C* = currency paid in exchange for electricity by retail consumers ($ USD).

Water, resource *B*, is a non-market resource for which we can establish a non-market value metric relative to a market-traded resource, electricity, resource *A*. This non-market value metric is the value intensity (*VI*) of the embedded water in traded electrical energy that is produced by a specific process. In this case, *VI* is found through computation and analysis of the quantity of water (*B*) embedded in the production and trade of electricity (*A*) in exchange for valued currency (*C*) using the distribution network of electrical energy trade across the Western U.S. and the resource intensities, *B/A* and *C/A*, discussed above.

A. Data

The data used in this study was obtained from Sandia National Laboratory, the U.S. Environmental Protection Agency and U.S. Energy Information Administration online databases.

Data used consists of: Sandia National Laboratory supplied model estimates of megawatt-hours of electricity produced annually (model year 2020) at each power plant within each state for the eleven western U.S. states selected [3-5], Sandia National Laboratory supplied estimated net water consumption data per day for each of the power plants within each state [4-9], EIA reported average utility retail price of electricity for each utility within each state for 2009 [6], and EIA reported total electricity import and export data for each state for 2009 [10].

The resource intensities for the network being examined are presented in Table 1. These intensities are the average water intensity of electricity generation, Φ[s], and the average price of electricity, *f*[s], in State "s". The numbers used in this study were obtained by computing averages for each state based on water consumption of energy generation at each plant and average retail price charged by each utility within each state weighted by total energy produced by each plant and electricity sold by each utility. Note that we aggregate electrical production and distribution together as a single process; this assumption is necessitated by limited data availability.

TABLE 1
WATER INTENSITY OF POWER GENERATION BY STATE, LISTED HIGHEST TO LOWEST, AND PRICE OF ELECTRICITY BY STATE

	Water Intensity (gal/MWh) Φ[s]	**Price ($/MWh) *f*[s]**
New Mexico	437.25	$103.56
Utah	411.77	$81.35
Wyoming	384.17	$85.57
Colorado	352.66	$100.26
Nevada	349.23	$80.10
Montana	297.32	$81.57
Arizona	183.81	$86.23
California	129.69	$125.26
Idaho	83.31	$62.91
Oregon	82.04	$67.65
Washington	52.52	$61.65

California and the Pacific Northwest states (Oregon, Idaho, and Washington) have relatively low water intensities. California's low water intensity may be (as is the case with the Pacific Northwest states) partly due to the use of hydroelectric facilities, but is also likely a result of water conservation measures. Higher water intensities are associated with thermoelectric processes [11].

Electricity prices in each of the eleven western states reveal that California pays the highest prices for electricity in the region, and Pacific Northwest states pay the least (Table 1). States with low average retail electricity prices are mainly the result of the presence of low-cost hydro-electric power from federal dams [12]. High average retail electricity pricing in a state suggests a high energy demand paired with a limited supply and/or high costs of electricity generation.

These intensities combined with data for electrical distribution and trade in the Western United States yield the value intensity of water embedded in that electricity.

B. Estimating the Distribution Network

The electricity generation and distribution network in the Western United States is comprised of power plants, electric utilities, electrical transformers, transmission and distribution infrastructure, etc. For this analysis, we conceptualize the system simply as a transportation network with various resources (electricity, economic currency, and water embedded within electricity) flowing between the nodes (states).

Consumption of electrical energy must equal production for the system as a whole, after accounting for net exports from the network. The EIA production and consumption data for 2009 for the eleven states under analysis results in an excess of electrical energy of less than 1% of the total production [10]. To balance the system for this analysis the exporting states' productions were reduced by this amount (Table 2); the excess electricity is presumed to leave the grid for neighboring grids.

Net trade in electricity, T^{NET}[s], is taken as production minus consumption within each state. States with a positive net trade in electricity will export that amount, and states with a negative net trade will import needed electricity from exporting states via the western power grid network. Unconstrained electrical transmission between all states is assumed.

Nonzero values for Gross Exports, T^{O}[s], and Gross Imports, T^{I}[s], for the 11 states are shown in Table 2. Only nonzero values are shown. By definition, the sum of all T^{O}[s] over all states is equal to the sum of all T^{I}[s] over all states.

TABLE 2

INTERSTATE ELECTRICITY TRADE

	Net Interstate Trade, T^{NET}[s], (MWh)	Gross Export, T^{O}[s], (MWh)	Gross Export Percentage, C^{O}[s], (%)
Arizona	31,685,245.00	31,685,245.00	31.3%
Montana	5,775,543.00	5,775,543.00	5.7%
New Mexico	15,700,958.00	15,700,958.00	15.5%
Nevada	1,655,392.00	1,655,392.00	1.6%
Oregon	5,079,110.00	5,079,110.00	5.0%
Utah	12,389,184.00	12,389,184.00	12.2%
Washington	2,117,039.00	2,117,039.00	2.1%
Wyoming	26,882,529.00	26,882,529.00	26.5%
		Gross Import, T^{I}[s], (MWh)	**Gross Import Percentage, C^{I}[s], (%)**
California	(84,137,000.00)	84,137,000.00	83.1%
Colorado	(4,815,000.00)	4,815,000.00	4.8%
Idaho	(12,333,000.00)	12,333,000.00	12.2%

Nonzero values of Gross Export/Import Percentages, C^{O}[s] and C^{I}[s], are presented as well. Gross import and export percentages give the percentage of the total electrical energy on the power grid that was supplied by each exporting state and the percentage of the total purchased by each importing state. Note that the sum of all C^{O}[s] over all states is equal to 100%, and the same is true for C^{I}[s].

The amount exported from each state to each importing state is estimated as the product of the Gross Export, T^{O}[s], of the exporting state and the Gross Import Percentage, C^{I}[s], of the importing state. i.e., California's C^{I}[s] = 83.1%; therefore 83.1% of the gross export from *each* exporting state is allocated to California. The resulting electricity transfers are shown in Fig. 1. A 2005 study by Marriott and Matthews [13] on electricity generation and consumption mixes in the Western U.S. utilized a similar transportation network approach with a linear programming optimization model to estimate interstate electricity trading for year 2000 which resulted in energy transfers very similar to those found in our study, with California dominating imports and Arizona the largest exporter with corresponding orders of magnitude for all interstate electricity transfers.

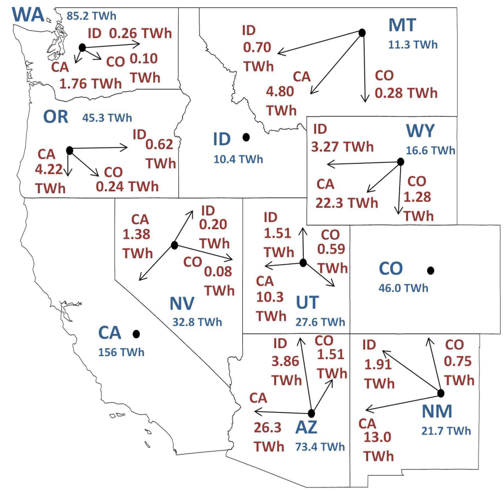

Fig. 1. Electricity trade network for the Western United States (TWh). Electricity transfer quantities are shown for all exporting states to all importing states, indicated by nodes and arrows. Internally produced and consumed electricity for each state is shown in blue. California dominates imports consuming 83.1% of the traded electricity.

C. Estimating Value Intensities

The average retail price (f[s]) paid per megawatt-hour of electricity from Table 1 was applied to the electricity transfers across the Western U.S. shown in Fig. 1 to obtain the average retail price of each transmission. Most states were able to supply their electricity demands with domestically produced electricity; however, in the cases where electricity was exported the price realized by the producer is the average retail price (f[s]) of the receiving (or importing) state.

f_{Market} represents the weighted average market price of available electricity on the grid (of all imports). As shown in (1), f_{Market} is the average f[s] weighted by volume of gross import per state [s] in $USD per megawatt-hour.

$$f_{Market} = \frac{\sum_s f[s] \cdot T^I[s]}{\sum_s T^I[s]} \quad (1)$$

f' represents the average local price of available electricity on the grid (of all exports). As shown in (2), f' is the average f[s] weighted by volume of gross export per state [s] in $USD per megawatt-hour.

$$f' = \frac{\sum_s f[s] \cdot T^O[s]}{\sum_s T^O[s]} \quad (2)$$

The volume of water consumed per megawatt-hour of electricity produced, Φ[s] (Table 1), was applied to the electricity distribution network across the Western U.S. (Fig. 1) in order to determine the amount of embedded water contained within each transfer. Internal water intensities (Φ[s]) were applied for electricity demands met with domestically produced electricity; however, for transfers of electricity from exporting to importing states the Φ[s] applied was that of the supplying (or exporting) state.

Φ_{Market} represents the weighted average embedded water content of the available electricity on the grid (total of all exports). Φ_{Market} is found according to (3) as the average Φ[s]

weighted by volume of gross export per state [s] in gallons per megawatt-hour.

$$\Phi_{Market} = \frac{\sum_s \Phi[s] \cdot T^O[s]}{\sum_s T^O[s]} \quad (3)$$

The *VI* of water embedded in locally produced and consumed electricity for each state (VI^l[s]) was found according to (4), comparing local water intensity to local electricity pricing:

$$VI^l[s] = \frac{f[s]}{\Phi[s]} \quad (4)$$

The *VI* of water embedded in exported electricity (VI^O[s]) was found for each exporting state according to (5), comparing the average market price of electricity available on the grid with the water intensity of each exporting state:

$$VI^O[s] = \frac{f_{Market}}{\Phi[s]} \quad (5)$$

The *VI* of water embedded in imported electricity (VI^I[s]) was found for each importing state according to (6), comparing the price of electricity of each importing state with the average market water intensity of electricity available on the grid:

$$VI^I[s] = \frac{f[s]}{\Phi_{Market}} \quad (6)$$

An average market *VI* for embedded water in electricity purchased from the grid by consumers (imports) was found using (7), comparing the average market price of electricity available on the grid with the average market water intensity of electricity available on the grid:

$$VI_{Market} = \frac{f_{Market}}{\Phi_{Market}} \quad (7)$$

Similarly, an average producer *VI* for embedded water exported was found using (8), comparing the average local price of electricity exported to the grid with the average market water intensity of that electricity:

$$VI' = \frac{f'}{\Phi_{Market}} \quad (8)$$

Comparing *VI*s obtained using (7) and (8), the percent change in *VI* due to trade can be determined. See (9).

$$\Delta = \frac{VI_{Market} - VI'}{VI'} \quad (9)$$

III. Results

Scott and Pasqualetti (2010) reported the results of a thorough multi-year study of the Energy-Water Nexus within Arizona and Sonora. The results of our analysis for exports of water embedded in electricity from Arizona to other states are comparable to those of Scott and Pasqualetti, though our analysis is at a larger scale and lower resolution. Resulting embedded water transfers for the entire network are not presented here, only those for Arizona for comparison purposes. Table 3 compares results from this study with those found previously by others [12].

TABLE 3
NET EXPORT OF EMBEDDED WATER IN ELECTRICITY

Net Export from Arizona to:	Martin and Ruddell (2012)	Scott and Pasqualetti (2010)
California	4,838 Mgal	7,984 Mgal
Northwest (Idaho)	709 Mgal	1,932 Mgal
Colorado	277 Mgal	-1,100 Mgal

The value intensity results are presented in Fig. 2. The results show that higher value intensities are generally associated with states that have lower power generation water intensities and which import electricity (see also Table 1).

The percent increase or decrease in value intensity due to trade is shown for each state. A trend is that exporters generally increase the value intensity of water embedded in exports compared to the value intensity of water embedded in locally consumed electricity, and importers generally decrease in the value intensity of water embedded in imported electricity compared to that of water embedded in domestically produced electricity.

Comparison of the resulting VI_{Market} and *VI'*, which are weighted averages of the previously discussed value intensities, shows that the overall percent change, Δ, is a 35% increase in value intensity of embedded water through trade in electricity on the Western power grid.

IV. Conclusions

Understanding the value intensity of water that is embedded in traded products and services provides useful information and perspective. The Embedded Resource Accounting framework was used to expose the value intensity of water embedded in electricity traded across the Western U.S. This analysis shows the surprising result that an implicit trade in embedded water appears to exist in the Western U.S., and that this trade appears to benefit both importing and exporting states as exporters increase and importers decrease the value intensity of water embedded in electricity trade. In general, States with higher water intensities are net exporters of electricity and embedded water and have lower internal retail prices for electricity. The trade in embedded water, and the value intensity of the water, is dominated in the Western U.S. by the import of these resources by California.

Further work will focus on applying this analysis on a smaller scale (at county, utility, and watershed levels) and performing a similar analysis on the value intensity of water embedded in agricultural products produced and traded in the Western U.S.

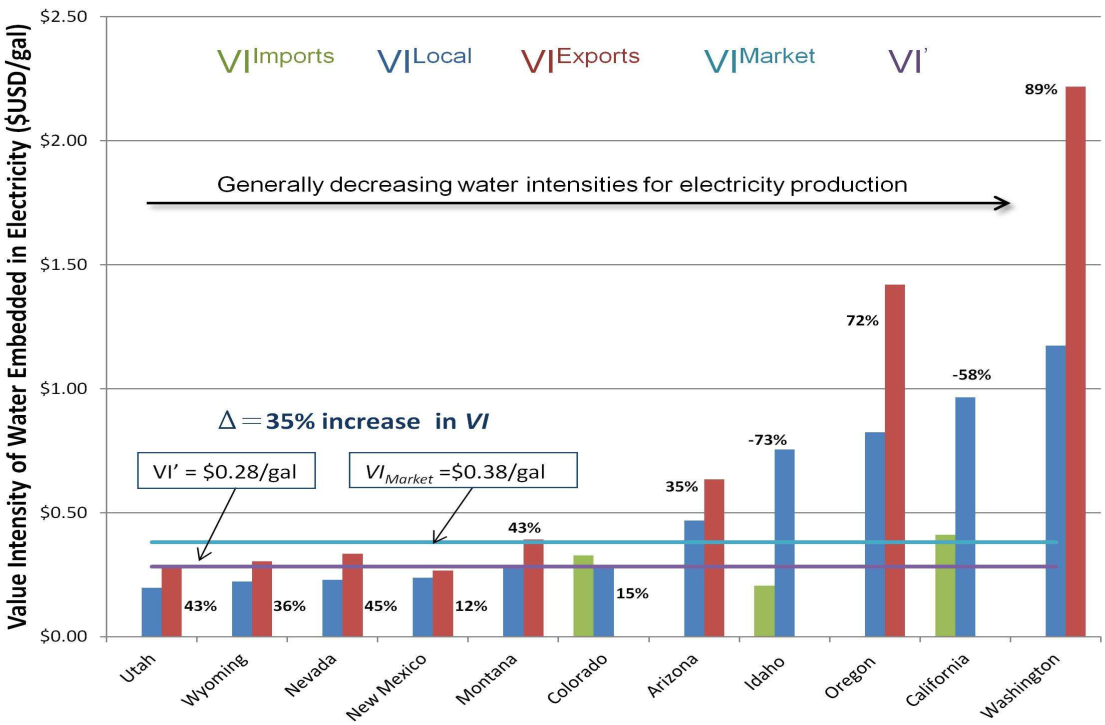

Fig. 2. Value intensities of embedded water within electricity traded throughout the Western United States ($USD/gal). Higher value intensities are generally associated with States that have lower local water intensities per MWh (i.e. less water used per MWh, or more water-efficient generation). Blue bars show local value intensities for water embedded in locally produced and consumed electricity (VI^l). Red bars show value intensities of water embedded in exported electricity (VI^O), and green bars show value intensity of water embedded in imported electricity (VI^I). Exporters generally see an increase in value intensity compared with local value intensity, and importers generally see a decrease in value intensity compared with local value intensity. The percent change in value intensity due to trade for each state is shown. Comparison of resulting VI_{Market} and *VI'* the value intensity of water embedded in electricity production and trade increases an average of 35% overall.

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