Embedded Resource Accounting

With Applications to Water Embedded in Energy Trade in the Western U.S.

by

Elizabeth Anne Adams

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved July 2013 by the
Graduate Supervisor Committee:

Benjamin L. Ruddell, Co-Chair
Braden R. Allenby, Co-Chair
Thomas P. Seager

ARIZONA STATE UNIVERSITY

August 2013

ABSTRACT

Water resource management is becoming increasingly burdened by uncertain and fluctuating conditions resulting from climate change and population growth which place increased demands on already strained resources. Innovative water management schemes are necessary to address the reality of available water supplies. One such approach is the substitution of trade in virtual water for the use of local water supplies.

This study provides a review of existing work in the use of virtual water and water footprint methods. Virtual water trade has been shown to be a successful method for addressing water scarcity and decreasing overall water consumption by shifting high water consumptive processes to wetter regions. These results however assume that all water resource supplies are equivalent regardless of physical location and they do not tie directly to economic markets.

In this study we introduce a new mathematical framework, Embedded Resource Accounting (ERA), which is a synthesis of several different analytical methods presently used to quantify and describe human interactions with the economy and the natural environment. We define the specifics of the ERA framework in a generic context for the analysis of embedded resource trade in a way that links directly with the economics of that trade.

Acknowledging the cyclical nature of water and the abundance of actual water resources on Earth, this study addresses fresh water availability within a given region. That is to say, the quantities of fresh water supplies annually available at acceptable quality for anthropogenic uses. The results of this research provide useful tools for water resource managers and policy makers to inform decision making on, (1) reallocation of

local available fresh water resources, and (2) strategic supplementation of those resources with outside fresh water resources via the import of virtual water.

DEDICATION

To Sonny and Kaia.

ACKNOWLEDGMENTS

Thank you to my committee, Benjamin Ruddell, Braden Allenby, and Thomas Seager at Arizona State University for your guidance, support, and encouragement. Also thank you to Vincent Tidwell of Sandia National Laboratory for your insight and assistance.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

Chapter 1

INTRODUCTION

Problem Statement

An analysis of the causal relationships between climate and economic changes and the water-energy nexus is needed for the purpose of informing National 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 in urban areas continue to grow, resource demands increase and become more spatially concentrated. Energy production accounts for the largest percentage of gross water withdrawals in the U.S. This places water resources at the focal point of these nexus as an important and climate-sensitive constraint on energy production. Reallocation of water supplies in addition to redistribution of the production of these resources will be necessary to adapt reduced supplies to meet increasing and spatially concentrated demands.

The relocation of existing 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 energy and agriculture production. Therefore, the remote production and virtual transmission of these resources provides a powerful management solution for an efficient reallocation of water resources. Trade in virtual water has become a widely utilized mechanism for adaptation to water scarcity, is already part of the solution for water resource management in the Western U.S. This research proposes to develop and demonstrate the application of a methodology for analysis of resources (water in particular) embedded in economically traded commodities in order to answer the following research questions: (1) How is embedded water utilized as a part of the energy and agricultural trade networks in the Western U.S., (2) Does the trade in these resources reduce or increase consumptive water use in the region, (3) What is the economic impact of water as revealed by its embedding in the trade of these resources, and , (4) How can this information be used to formulate adaptive water management policies for the Western United States?

Supporting Evidence

Growing and spatially shifting water resource demands, sometimes exacerbated by decreasing water availability and quality, will increasingly motivate reallocation of water supplies. In a water-scarce context, information is needed to ensure that water is used efficiently to effectively meet the needs of growing populations under scenarios of change (Scott, 2011; Bao and Fang, 2012). Sivakumar (2011) emphasizes urgency in the development of new integrated approaches to water management issues, citing the necessity of including both “hard” and “soft” sciences. Global anthropogenic water uses may already exceed sustainable levels, (Postel, 2000, Alcamo and Henrichs, 2002), and long-term demands sometimes exceed available supplies, as is the case for the Colorado River Basin and in general in the Western United States (Wildman and Forde, 2012). Long term climate change impacts increase the need for new planning strategies (Gober et al., 2010). Climate change and urban population growth are two primary challenges for water resources management [*WWAP*, 2012], and of those, population and economic growth are projected to more significantly impact water stress. For example, Vorosmarty et al. (2000) compared climate and water demand scenarios and concluded that change in water demand was the more important driver of global water scarcity. Adaptive allocation mechanisms are being explored worldwide to meet the growing challenges of increasing uncertainty and risk in water resource availability (WWAP, 2012).

For example, in the Western U.S. climate change is expected to cause increasing temperatures and evaporation, decreased rainfall, and more intense droughts in the Southwestern United States. More importantly, this area was settled through the development of water resources, both physically and politically (Reisner, 1993), and the future of the west is critically linked to the successful management of its available water resource supplies. As population in urban areas grows, resource demands increase and become more concentrated, especially demands for electrical energy. Population grew by 71 percent from 1980 to 2005 in Arizona, Colorado, Nevada, and New Mexico, while electrical power demand increased by 130 percent over the same period (Pitzer, 2009). As the demand for electrical energy in Western U.S. cities rapidly grows, water scarcity has suddenly become a constraint on the expansion of electrical power generation capacity.

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 (Zetland and Gasson, 2012). However, there is a significant amount of water embedded in electrical energy production (Gerbens-Leene et al., 2008). 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.

The term “virtual water” originated in 1993 when used by Allan to describe what he (and others) had previously described as embedded or embodied water (Allan, 1993). In this paper we utilize the terms “embedded” and virtual” interchangeably, with a preference for the prior. Allan’s work showed how the import of virtual water served as an effective approach to meeting water deficits in the Middle East (Allan, 1996). Chapagain and Hoekstra (2008) indicated the importance of including virtual water quantities in water policy studies due to the significant percentage of water that is consumed in the process of creating products for export, as much as 16% of global water use.

Virtual water and Virtual Water Footprints are the subject of significant research in the past ten years. Allan (1996) showed that the Middle East used import of virtual water to effectively balance their water budget and thereby avoid political fallout over available water resources. Chapagain et al. (2006) report a global water savings of 352 x 10^9 m3/year as a result of international agricultural trade from 1997 to 2001. Similarly, Fader et al. (2011) reported global water savings due to trade at 263x10^9 m3. And Konar et al. (2012) reported global water savings due to trade at 224x10^9 m3 in 2008. However, global “savings” of water use through virtual water flow by definition mean that one location is saving water while another location is increasing water use. For example, Porkka et al. (2012) showed that removing virtual water flows from certain regions in China (i.e. halting the export of water-intensive commodities) could create a significant decrease in water scarcity. Guan and Hubacek (2007) illustrated how economic growth in China has resulted in an exacerbation of water scarcity in specific regions through an analysis of virtual water flows in agricultural, industrial and service products. A common theme of the virtual water and Water Footprint literature is that these are the signature of the “outsourcing” of water resource impacts through the global economic network, and as such the embedded resource and footprint metrics are commonly viewed as the fingerprints of unsustainable global environmental outcomes during the global economic era.

Despite the growing interest in virtual water from the global water policy perspective, the concept is not yet being widely utilized as a basis for local water resource management decisions. It is generally understood by local water resource managers that it is not necessary to account for embedded water in order to manage any given physical water resource stock; management of the "physical" water flows is sufficient. It should also be understood that not all global water stocks are interchangeable or equivalent, such that one water resource may sometimes be managed very effectively in isolation from other water resources. Also, different sustainability metrics and objectives are appropriate for differing locations based on the social, environmental, and economic context. For example, in a water-rich region such as the Great Lakes, the appropriate unit of water impact might be water consumption beyond an ecological threshold where fish are impaired (Mubako et al., 2012), instead of simply the net consumptive water use as in the standard Water Footprint and virtual water methods. To be more specific, is evident that the concept of virtual water is not necessary for the management of any particular localized water stock assuming that (a) the local governance of that water resource stock is effective in achieving its own sustainability objectives and (b) that the local operators are neither concerned about any external resource impacts of their activities, nor about (c) the economic consequences of direct economic competition with operations that unsustainably impact those external resources. Because the above is arguably an accurate description of most past and present localized water resources management regimes in the U.S., Europe, and other leading global economies, the virtual water concept has not been widely adopted for local water management.

Chapagain and Hoekstra (2008) indicated the importance of including virtual water quantities in water policy studies due to the significant percentage of water that is consumed in the process of creating products for export, as much as 16% of global water use. Large quantities of virtual water are especially present in commodities produced in the agriculture, energy and manufacturing sectors.

The effectiveness and validity of virtual water trade information for global water policy and decision making has likewise been challenged, especially in critiques by economic theory. Kumar and Singh (2005) concluded that virtual water is not sufficient to stand alone as a deciding factor for water decisions. Their conclusions are based on analysis of empirical virtual water trade data for 131 countries which showed that access to arable land was more indicative of virtual water trade than access to renewable water supplies; this implies that other economic factors besides water availability are more important for agricultural production decisions. *Wichelns* (2010) and *Ansink* (2010) built on this premise using the Heckscher-Ohiln model for economic trade to show that the concept of virtual water trade does not adhere to the constraints of classical economic theory because it efficiently addresses resource scarcity only under certain conditions in which the exporter of virtual water-rich goods also possesses an abundant natural water endowment. In fact, most virtual water export is from locations with substantial water scarcity. For example, the water-scarce region of Northern China is a large net exporter of water embedded in manufactured goods, and the water-scarce Southwestern United States is a large net exporter of water embedded in agricultural goods (*Mubako*, 2011, *Hoekstra and Hung*, 2002). This is strong evidence that virtual water impacts and water use efficiency has not been a primary consideration in global economic development decisions, and that this is not a problem from a theoretical perspective.

Water is just one resource among many, and is not exempt from the basic principles of economics, although it is an unusually difficult resource to understand economically. As *Hanemann* (2006) points out, water can be classified as a public good, a private good, or a common pool resource, depending on its particular use in particular situations. Water is mobile and cyclical and is constantly being used and re-used in the coupled natural and human system. Water is unevenly and unpredictably distributed in time and space. Water supply systems carry immense capital costs, and prices paid for water often do not reflect scarcity of the resource. Water is used in huge volumes so marginal value is very low, but it is essential for life so absolute value is high. Governance of water often assumes abundance of the underlying stock and tends to be more politically sensitive than for most resources. These difficulties make the virtual water framework more relevant, perhaps, than other embedded resource concepts (e.g. embedded labor, embedded copper, etc.) because virtual water provides pseudo-economic information that can be used along with other information to more fully understand the complex issues involved in managing water resources.

The use of network based and embedded resource accounting methodologies is becoming increasingly common in water resources management. Input-output analysis has shown to be an insightful tool when applied to water policy. Chanan et al. (2008) compiled a review of such analyses and suggest that Australian decision makers incorporate this methodology into their repertoire. Some of the earliest published work in this area was done by Finster (1971), who combined trade in embodied water with economic input-output analysis to a case study of Arizona's economy to successfully illustrate the effectiveness of demand-oriented water policy in establishing sustainable water supplies in a water stressed region. More recently the use of combining direct and indirect water consumption data with economic trade has been used to establish water economic productivities for agriculture (Velázquez, 2006), and to examine intersectoral water consumption patterns in Spain (Aldaya et al., 2010). In Arizona, the City of Peoria (2007) has recently begun using water value metric comparisons for land use decision-making, making land allocation decisions based on water embedded in land uses.

Chapter 2

EMBEDDED RESOURCE ACCOUTING FOR WATER RESOURCE APPLICATIONS; PART 1, WATER EMBEDDED IN THE WESTERN U.S. ELECTRICAL ENERGY TRADE

Abstract

Water resource management faces the dual challenge of climate change and growing demand for water by the human economy. A fundamental adaptive resource-economic tool is the outsourcing of water use through trade in embedded or "virtual" water as an alternative to direct water use. Research has documented the global trade in embedded water, particularly at the national level and with respect to agricultural and industrial products. This paper focuses on the less-studied regional scale, and on the trade in water embedded in Electricity within a power grid.

Studies of indirect water use and water footprints have assumed that all water resource stocks are equivalent without regard to location. Additionally, existing studies have not integrated indirect resource usage with the price structures that underlie the economic drivers of outsourced or "virtual" resource use. In this study we develop and apply Embedded Resource Accounting (ERA), a generalized mathematical framework for resource footprinting and indirect resource use accounting which addresses these two limitations. ERA may be used to quantify and describe interactions between the human economy and multiple natural resources in a coupled natural human system.

In this first of two papers we demonstrate that States outsource substantial water use via electricity production. This trade increases total water used for electricity production in the Western U.S. and shifts water use to more water-limited States. Nevertheless, the

results indicate that water scarcity is not a major factor affecting production patterns of electricity in the Western US.

Introduction

Multiple challenges to sustainable water resources management currently exist. Anthropogenic water uses may already exceed sustainable levels at a global scale, [*Postel,* 2000], and long-term demands in many regions exceed available supplies, as is the case for the Colorado River Basin and the Western United States in general [*Wildman and Forde,* 2012; *Tidwell et al.*, 2012]. Anticipated long-term climate change impacts increase the need for adaptive strategies [*Gober et al.,* 2010]. One adaptive option for water scarcity in a specific location on Earth is to utilize trade in “virtual” water, which is essentially the outsourcing of water resource impacts to a supplier via trade or indirect exploitation. This outsourcing substitutes an indirect and usually distant impact for a direct resource impact.

The term “virtual water” originated in 1993 when used by *Allan* [1993] to describe what he (and others) had previously described as embedded or embodied water and is generally defined as the quantity of water consumed in the production of a product or service. In this paper we utilize the terms “embedded” and “virtual” interchangeably, with a preference for the former.

Allan’s work showed how the import of virtual water served as an effective approach to closing water deficits in the Middle East through the importation of grain products [*Allan,* 1996]. *Chapagain and Hoekstra* [2008] have indicated the importance of including virtual water quantities in water policy studies due to the significant percentage of water that is consumed in the process of creating products for export, as much as 16% of global water use. Large quantities of virtual water are especially present in the primary economy in agriculture, energy, and manufacturing sectors, but embedded resources are associated with all economic or environmental goods and services, even in the information and government sectors. However, the trade in virtual water is not currently managed directly, and is rather simply a reflection of the economic, cultural, political, physical and other forces that determine the flow of materials and the trade in goods and services within a coupled natural-human system.

Kumar and Singh [2005] concluded that virtual water trade is not sufficient to stand alone as a deciding factor for water resource management decisions. Their conclusions are based on analysis of empirical virtual water trade data for 131 countries which showed that access to arable land was more indicative of virtual water trade patterns than access to renewable water supplies; this implies that other economic factors besides water availability are more important for agricultural production decisions. *Wichelns* [2010] and *Ansink* [2010] built on this premise using the Heckscher-Ohlin general equilibrium model for international economic trade to show that the concept of virtual water trade does not adhere to the constraints of classical economic theory because it efficiently addresses resource scarcity only under certain conditions in which the exporter of virtual water-rich goods also possesses an abundant natural water endowment; this assumption is frequently violated. In fact, most virtual water export is from locations with substantially limited water availability. For example, the water-scarce region of Northern China is a large net exporter of water embedded in manufactured goods, and the water-scarce Southwestern United States is a large net exporter of water embedded in agricultural goods [*Hoekstra and Mekonnen*, 2012; *Mubako*, 2011].

It has nevertheless been argued that a global approach to water resource management, including virtual water concepts, can create efficiencies, save water, and leverage comparative advantage (Hoekstra, 2011 and Hoekstra, 2006). *Chapagain et al.* [2006] report global water savings of 352 km^3/year as a result of international agricultural trade from 1997 to 2001. Similarly, *Fader et al.* [2011] reported global water savings due to trade at 263 km^3/year, and *Konar et al.* [2012] reported global water savings due to trade at 224 km^3/year in 2008. However, global "savings" of water use through virtual water flow implies that one location is saving water while another location is increasing water use. For example, *Porkka et al.* [2012] showed that removing virtual water flows from certain regions in China (i.e. halting the export of water-intensive commodities) could create a significant decrease in local water scarcity. It is therefore important to understand that water use in one location is not necessarily a simple substitute for water use in another location, because water may differ in value, and because different water managers may have different and conflicting goals and decision-making horizons (Rushforth et al., 2013).

Despite the growing interest in virtual water from the global water policy perspective, the concept is not yet being widely utilized as a basis for local water resource management decisions. This is because economic development is largely a local level decision (e.g., siting a new power plant, developing a parcel of land, or decision concerning what crops to grow), and economic decisions drive embedded water trade. Institutions do not exist to strategically manage embedded water trade. Indeed, it is not necessary for local water resource managers to account for embedded water in order to manage any given physical water resource stock; sustainable management of the "physical" water flows and direct impacts is by definition sufficient to sustainably manage the resource stock, if not to optimize global sustainability objectives (Rushforth et al, 2013).

Also, consumptive water use is not the only water resource management issue; specifically, different sustainability metrics and objectives are appropriate for differing locations based on the social, environmental, and economic context. For example, in a water-rich region such as the Great Lakes, the appropriate unit of water resource impact might be water consumption beyond an ecological water scarcity or ecosystem flow threshold where fish are harmed [*Mubako et al.*, 2013], instead of the simple net consumptive water use as in the standard Water Footprint and virtual water methods. Often a quality criterion will drive discussions.

What then is the utility of virtual water and the broader embedded resource concepts for integrated water resource management, especially at the local resource scale? If unsustainable water resource impacts are a result of outsourcing across political, economic, and regulatory boundaries, how can these principles be used to improve sustainability both locally and globally? We argue that embedded resource footprint information can be utilized to drive sustainable outcomes by applying indirect pressure upstream through the global supply chain (Rushforth et al, 2013). The mechanism for this pressure might include consumer education, regulatory caps or taxes, or voluntary industry self-regulation. Local resource managers can use this information to quantify the dependency of local systems on external resources, for the purpose of managing sustainability, vulnerability, and resilience of these systems vs. local and global disruptions. And finally, this information can be used to incorporate both direct and indirect resource impact information into an "apples to apples" comparison between alternative uses of a resource in terms of the benefits derived from that resource use in situations where decisions between alternative uses might be necessary but where markets and pricing (an ideal mechanism) [*Zetland,* 2011] are either inappropriate, unavailable, or unreliable for water decision making under scarce conditions.

The use of network based methods (e.g. input-output analysis) shows promise as a platform for embedded water trade analysis. *Chanan et al.* [2008] compiled a review of such analyses and suggest that Australian decision makers incorporate this methodology into their repertoire. Some of the earliest published work in this area was done by *Finster* [1971], who combined trade in embodied water with economic input-output analysis to a case study of Arizona's economy to successfully illustrate the effectiveness of demand-oriented water policy in establishing sustainable water supplies in a water stressed region. More recently the use of combining direct and indirect water consumption data with economic trade has been used to establish water economic productivities for agriculture [*Velázquez,* 2006], and to examine intersectoral water consumption patterns in Spain [*Aldaya et al.,* 2010b]. In Arizona, the *City of Peoria* [2007] has recently begun using water value metric comparisons for land use decision-making, making land allocation decisions based on water embedded in land uses.

With this study we introduce a general-purpose mathematical framework, which we call *Embedded Resource Accounting* (ERA). ERA is a synthesis and generalization of footprint, "virtual" flow, life cycle, material flow, and input-output methods that are presently used to quantify and describe anthropogenic interactions with the economy and the natural environment. As a general method, ERA allows for analysis of multiple resource stocks, of multiple types of resources and provides a means for explicit commensuration of different stocks using equivalency factors. ERA is similar to a number of existing life-cycle and footprint family methods, but requires independent definition because it generalizes and formalizes assumptions and mathematics that have previously been implicit or application-specific. Some of these methods, including the standard Water Footprint, are special cases of the more general ERA framework presented here (Rushforth et al., 2013). The concept of embedded resources is a venerable and intuitive one, with roots in the ideas of resource flows sustaining an urban metabolism (Wolman, 1965) and embedded energy within human energy systems and ecosystems (Odum and Odum, 1976).

This paper first derives the ERA framework in a generic context for the analysis of embedded resource trade and resource stock footprints in a way that links directly with the economics of the directly traded good or service. We then demonstrate this method through application to quantify a special case, namely the water footprint of electricity production and consumption in Western U.S. States, and the water embedded in traded electricity, on the Western U.S. power grid. The results of this analysis are presented in two parts. The current paper, Part 1, presents the mathematical framework and then a specific application to delineate the water footprint components and embedded water trade in a power grid. Part 2 (Adams et al. 2013, in submission to WRR) analyzes the relationship between electricity prices and the attendant embedded water trade, providing an explanation for the observed trade patterns.

This paper addresses the following specific research questions; (1) How can a generalized method be derived to account for a network of trade in a diversity of indirect impacts and applied to address specific water footprint and embedded water problems, (2) What portion of the water footprint of electrical energy production and consumption by Western US States is associated with traded electricity and embedded water, (3) Does the trade in embedded water increase or decrease total water consumption in this system, and (4) How does water availability affect the observed trade under current conditions?

Introduction to Embedded Resource Accounting (ERA) Methods

Embedded Resource Accounting (ERA) is a generalized network based footprint method that can be applied to understand the trade of any combination of resource stocks and processes in a coupled human-natural system. ERA is not a fundamentally new concept, but is rather a a synthesis of well-established life cycle and material flow analyses, virtual water, various resource footprint approaches, and input-output concepts (Rushforth et al., 2013). ERA works by constructing a "multinet" [*Bilmes,* 2000; *Taylor*, 2005] of multiple types of trades and quantifying the direct and indirect impacts of a process on each stock. ERA links natural and human systems, including physical, informational, social, and financial components among others. ERA obeys principles of conservation and uses a mass balance approach to track exchanges and interactions amongst processes, as in material flow analysis [*Fischer-Kowalsi and Huttler,* 1999]. Total use of a resource by a process is taken as the sum of both the direct and indirect use of the resource, as in most footprint methods (Rushforth et al., 2013), but with an explicit and partial commensuration of different resource stocks. The ERA framework asserts that,

(1) all net impacts caused by a process, both indirect and direct, constitute the "footprint" of that process, and that processes therefore have as many kinds of footprints as they have direct and indirect inputs,

(2) resources can be arbitrarily defined and are not necessarily tangible resources like water; resources might be information, happiness, pollution, or services, or anything that is quantifiably affected, positively or negatively, by a process.

(3) different resource stocks, even of the same type, are not necessarily equivalent to each other, so the commensuration of different stocks must be done carefully and explicitly,

(4) the production of positively or negatively *valued* goods and services by a supplied process (e.g. jobs, revenue, happiness, pollution) can be indirectly ascribed to its suppliers as an embedded "value footprint" in exactly the same manner as the resource impacts of a supplying process (e.g. water use) are included indirectly in the resource footprint of the supplied process, and,

(5) direct and indirect impacts can be separated in time as well as in space, especially in the sense that processes create indirect impacts in the past and future and that these impacts are not necessarily fully equivalent to direct or indirect impacts occurring in the present.

ERA defines a system using processes, resource stocks, and equivalencies between resource stocks. Each process can control multiple resource stocks of multiple types. Processes may or may not be associated with points, areas, or volumes in space.

Each resource stock is controlled by (or "belongs to") a single process, however, processes may directly impact their own resource stocks as well as the stocks of other processes. The resource stock type is broadly defined and may be a type of physical resource, a good, a service, or anything that can be valued, which is produced, consumed, created, or destroyed, either passively or actively, due to a process. Equivalencies are defined between every pair of resource stocks, and are functionally analogous to exchange rates.

Equivalencies are particularly important when dealing with water resource stocks because, as *Hanemann* [2006] points out, "…one liter of water is not necessarily the same as another liter of water if it is available at a different location, at a different point in time, with a different quality, or with a different probability of occurrence." The most common special cases of equivalency are "externality" where two resource stocks are completely nonequivalent and nonexchangeable in the classical economic sense of an externality [*Buchanan and Stubblebine*, 1962; *Collin*, 2006], and its opposite, "locality" where two resource stocks are completely commensurate, equivalent, and exactly exchangeable. Equivalence is usually a function of physical, temporal, quality, social, environmental, and economic distance and connectivity between two processes.

ERA Governing Equations. The basic ERA equation (1) solves for E, the total impact (or footprint) of a process on a resource stock, as the sum of the net direct U and indirect V impacts of a process i on a resource stock of type r_j (controlled by all processes *j*) via all partial indirect impacts through intermediary resource stocks of type r_k controlled by all processes *k*. Equivalency Q is from the point of view of process *i* and is indexed as between process *i*'s resource stock of type r_i and process *j*'s resource stock of type r_j at point in time *t*. If a distance or lag in time is involved such that *i* creates a future impact on r_j, the time lag, *l*, is included as an index in the *Q* term.

$$E(i,j,r_j,r_k,l)[t] = \left[U(i,j,r_j)[t] + V(i,j,r_j,r_k)[t]\right] * Q(i,r_i,j,r_j,l)[t] \qquad (1)$$

The indices used in equation (1), and throughout this paper, are described in Figure 1 (also see Figure 2 and contextual examples in section 2.3 for further clarification). Some users may wish to substitute the notation of *F* = *D* + *I*, or *Footprint* equals net *Direct impacts* plus net *Indirect impacts*; the suggested notation in Equation 1 intones that *Embedded impacts* equal consumptive *Use (direct)* plus net imported *Virtual (indirect) trade*.

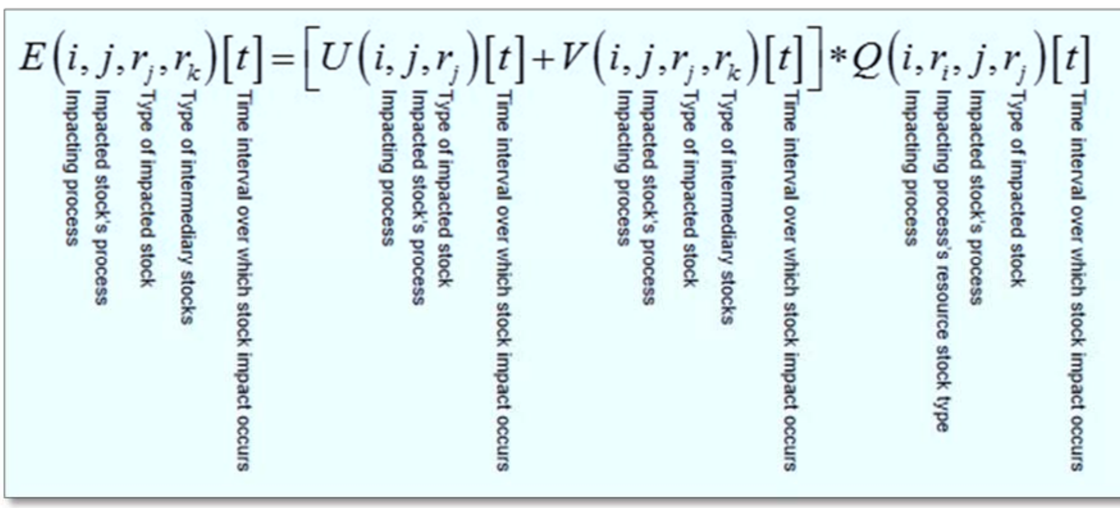

Figure 1. ERA index assignment explanation.

By definition, the sum of *E* across all processes i is equal to the net direct impact U^{net} on the resource r_j by all processes because each embedded impact V is offset by an equal and opposite *V* for the system as a whole. This closure ensures conservation of flows of resource mass and direct and indirect impacts in the system except as a stock's mass is specifically created or destroyed by a process, or in the case where *E* is computed from the perspective of a specific observer that does not fully commensurate different resource stocks (Rushforth et al., 2013). In plain language, ERA conserves total impacts on any given resource stock by shifting the accounting of impacts from exporters' direct impacts to importers' indirect impacts. As a result, the following equality holds under these conditions,

$$\sum_i E\left(i,j,r_j,r_k\right)=\sum_i U\left(i,j,r_j\right)=U^{net}\left(j,r_j\right) \quad (2)$$

Processes can produce and thereby increase a resource stock. Production *P* of resource stock of type r_j by process *j* is given as,

$$P\left(j,r_j\right)[t]=\sum_{i=j} U\left(i,j,r_j\right) \quad (3)$$

Therefore, from the principle of continuity, the change, *ΔS*, in discrete time in the stored mass, S, of process j's resource stock of type r_j at a point in time *t* is equal to the difference between its production *P* by process *j* and the net direct impact U^{net} on r_j by all other processes (equations 4 and 5).

$$\Delta S\left(j,r_j\right)[t]=P\left(j,r_j\right)[t]-U\left(j,r_j\right)[t] \quad (4)$$

$$S\left(j,r_j\right)[t]=S\left(j,r_j\right)[t-1]+\Delta S\left(j,r_j\right)[t] \quad (5)$$

Note that for some resource stocks storage is impossible so *S* and *ΔS* would be zero in this special case regardless of whether production and consumption balance (Rushforth et al., 2013).

Although the general ERA equations above are written explicitly for time and intertemporal equivalencies, for the sake of clarity and simplicity we will drop the time indices in subsequent equations and proceed with a derivation for the special case that assumes a single fixed interval in time, as will usually be the case, including for our chosen case study.

We will also assume that no partial equivalencies exist in which case either $Q = 1$ (stocks are "local") or $Q = 0$ (stocks are "external"). Local and external components will be separated and denoted with "l" and "x" superscripts, respectively, so that they may be studied separately. To accomplish this separation we use a locality and an externality matrix in place of the equivalency matrix. The locality matrix, L, is a binary $i \times j \times r$ -dimension matrix giving a value of 1 for pairs of resource stocks that are local (fully equivalent), and a value of 0 otherwise. The locality matrix identifies which processes and resource stocks are local to one another, and which are external. Note that it is possible for a process to create both direct and indirect impacts against an external or partially equivalent resource stock controlled by a different process. The externality matrix is related to the locality matrix by,

$$X(i,j,r) = -\left[L(i,j,r) - 1\right]. \tag{6}$$

The only data inputs required for this application of ERA are an $i \times j \times r$ dimension input-output table IO and the equivalency matrix Q, or for this case the L and X matrices in place of Q. As in a material flow or input-output analysis, the input-output network table gives the flow of a resource stock (of type r_j) from process j to process i, but unlike the usual input-output tables, this one also includes conceptual resource flows such as information, currency, etc. U is the net direct impact by process i on process j 's resource stock of type r_j, calculated as the net difference on the gross input-output network table, or in the consumptive use special case as the difference between the withdrawal W and return R (equation 7). By rule, U cannot be negative, so any negative component is set to zero; negative direct impacts are instead correctly represented as positive impacts of transposed matrix indexing. U is separated into local and external components through multiplication of the *IO* matrix by the Locality and Externality matrices as follows.

$$U(i,j,r_j) = IO(j,i,r) - IO(i,j,r) = W(i,r_j) - R(i,r_j) \quad (7)$$

$$U^l(i,j,r_j) = U(i,j,r_j) * L(i,r_i,j,r_j) \quad (8)$$

$$U^x(i,j,r_j) = U(i,j,r_j) * X(i,r_i,j,r_j) \quad (9)$$

$$U(i,j,r_j) = U^l(i,j,r_j) + U^x(i,j,r_j) \quad (10)$$

The foundation of the indirect component of ERA is the *partial embedded indirect resource impact,* V_p, given in equation (11) (also see the diagram in Figure 2). The net indirect impact on process j's resource stock of type r_j by process i is evaluated with respect to process i's impact on process k's resource stock of type r_k, which was produced by k in association with a direct impact by k on r_j. V_p quantifies the indirect impact of process i on resource r_j via *i's* direct impact on r_k, such that a proportionate fraction ($U / \Sigma_n U$) of k's direct impact on r_j is embedded within i's direct impact on r_k. Note that if i is the only process impacting r_k then the coefficient $U / \Sigma_n U = 1$.

$$V_p(i,j,r_j,k,r_k) = \frac{U(i,k,r_k)}{\sum_n U(n,k,r_k)} * U(k,j,r_j) \quad (11)$$

To avoid double counting of resource footprints, we enforce the rule that a process may not indirectly impact its own stocks (i.e. enforce $i \neq j$ in V_p summations). This avoids multiplication of resource footprints in the common scenario where two-way trade exists between a pair of processes, for example when money is traded for electricity or another good or service in the economy. The only common one-way trades exist between anthropogenic and natural processes, such as when resources are extracted from or pollution is discharged to a natural stock by an economic process.

The sum across all processes k with stocks of type r_k directly impacted by i gives process i 's indirect impact on r_j, see equations (12) and (14) for V_{IN}. The sum across all indirectly impacting processes i gives intermediary process k 's indirect impact on r_j, see equations (13) and (15) for V_{OUT}. V_{IN} and V_{OUT} are separated into local and external components through multiplication by the Locality and Externality matrices as shown in equations (12-15); the equivalency matrix Q would be used instead of L, and the V^x term ignored, in the general case.

$$V_{IN}^{l}\left(i,j,r_j,r_k\right)=\sum_{k}V_p\left(i,j,r_j,k,r_k\right)*L\left(i,j,r_j\right) \quad (12)$$

$$V_{OUT}^{l}\left(j,r_j,i,r_i\right)=\sum_{m}V_p\left(m,j,r_j,i,r_i\right)*L\left(i,j,r_j\right) \quad (13)$$

$$V_{IN}^{x}\left(i,j,r_j,r_k\right)=\sum_{k}V_p\left(i,j,r_j,k,r_k\right)*X\left(i,j,r_j\right) \quad (14)$$

$$V_{OUT}^{x}\left(j,r_j,i,r_i\right)=\sum_{m}V_p\left(m,j,r_j,i,r_i\right)*X\left(i,j,r_j\right) \quad (15)$$

The net embedded indirect impacts shown in equation (1) are the differences between the indirect impacts V_{IN} accruing to process *i* and the pass-through indirect impacts V_{OUT} for which *i* is an intermediary, given as,

$$V^{l}\left(i,j,r_j,r_k\right)=V_{IN}^{l}\left(i,j,r_j,r_k\right)-V_{OUT}^{l}\left(j,r_j,i,r_i\right) \quad (16)$$

$$V^{x}\left(i,j,r_j,r_k\right)=V_{IN}^{x}\left(i,j,r_j,r_k\right)-V_{OUT}^{x}\left(j,r_j,i,r_i\right) \quad (17)$$

$$V\left(i,j,r_j,r_k\right)=V^{l}\left(i,j,r_j,r_k\right)+V^{x}\left(i,j,r_j,r_k\right) \quad (18)$$

Finally, we may restate the ERA equation (1) as,

$$E=U^{l}+U^{x}+V_{IN}^{l}-V_{OUT}^{l}+V_{IN}^{x}-V_{OUT}^{x} \quad (19)$$

The following section provides conceptual examples to help clarify use of the ERA framework and the reasoning behind its generalized formulation.

Conceptual Illustrations and Clarifications. ERA methods obey the physical principles of continuity and conservation while including indirect impacts by directly exchanging the direct impacts caused by “intermediary” direct users for indirect or embedded impacts caused by end-users. For example, if a company directly utilizes a local potable water resource for the production of a service, the consumer of that service would indirectly account for the water resource impact, rather than the intermediary company that directly impacted the water resource. If the resource stock is surface water and groundwater supplies in a geographical location, the ERA method accounts for the creation and distribution of a Water Footprint Network (WFN) standard “blue water footprint” by a process and its trades; if the resource stock is the atmosphere’s carbon concentration, ERA gives a "carbon footprint", and if the resource stock is ecosystem productivity, ERA gives an "ecological footprint" (Rushforth et al., 2013).

If there are multiple outputs from a process, the equations derived above make it clear that the full total of that process's direct impacts is embedded indirectly in each of the process's outputs. For example, if a farm process directly consumes one gallon of water, and produces an apple, an orange, and a banana (i.e. r_k = [a o b]), then one gallon of direct water impact is indirectly embedded in the apple, and the orange, and the banana, for a total of three gallons of embedded water from the process (i.e. $\Sigma_{rk} V_{OUT}(farm,wts,w,r_k)$ = 3 gallons). Likewise, if the process impacted many other resource stocks such as land, air, fertilizer, labor, etc., each of these impacts would be fully embedded in each of the outputs. ERA therefore does not attempt to ascribe a portion of the process's footprint to a specific output. Hence it is necessary to consider one intermediary stock type r_k at a time, in order to maintain conservation of mass for indirect stock impacts. However, if desired, it is possible to adjust footprints to fit a multiple input or multiple output process, as explained in Part 2 (Adams et al. 2013, Submitted to WRR).

For example, consider electricity generation in the Southwestern United States, and see Figure 2 for notation. If we, (1) let *j* represent a water supply process in Arizona with a water-type stock, r_j; (2) let *k* represent an electricity generation process in Arizona with an electricity-type stock, r_k; and (3), let *i* and *m* represent electricity consumption processes in Arizona and California, respectively, with currency-type stocks r_i and r_m, we define a system such that *i* is local to *j* and *k*. Therefore, the electricity consumption by *i* is local to the water supply process *j*, and consumption by *m* is external to *j*. $U^I(k,j,r_j)$

represents direct use of r_j, Arizona's water stock, by k, Arizona electricity generation. $U^l(i,k,r_k)$ and $U^x(m,k,r_k)$ represent direct use of r_k, Arizona's electricity stock by i, Arizona electricity consumers, and m, California electricity consumers. This direct flow of electricity is accompanied by an indirect flow of embedded water, given by the partial indirect embedded resource impact V_p. $V_p{}^l(i,j,r_j,k,r_k)$ gives the indirect impact by i, Arizona electricity users on Arizona's water stock, r_j, through the direct use of Arizona electricity stock, r_k. Similarly, $V_p{}^x(m,j,r_j,k,r_k)$ gives the indirect impact by m, California electricity users on Arizona's water stock, r_j, through the direct use of Arizona electricity stock, r_k. $U^l(i,j,r_j)$ and $U^x(m,j,r_j)$ give direct impact on the Arizona water stock by Arizona and California electricity consumers, which in this example are both zero.

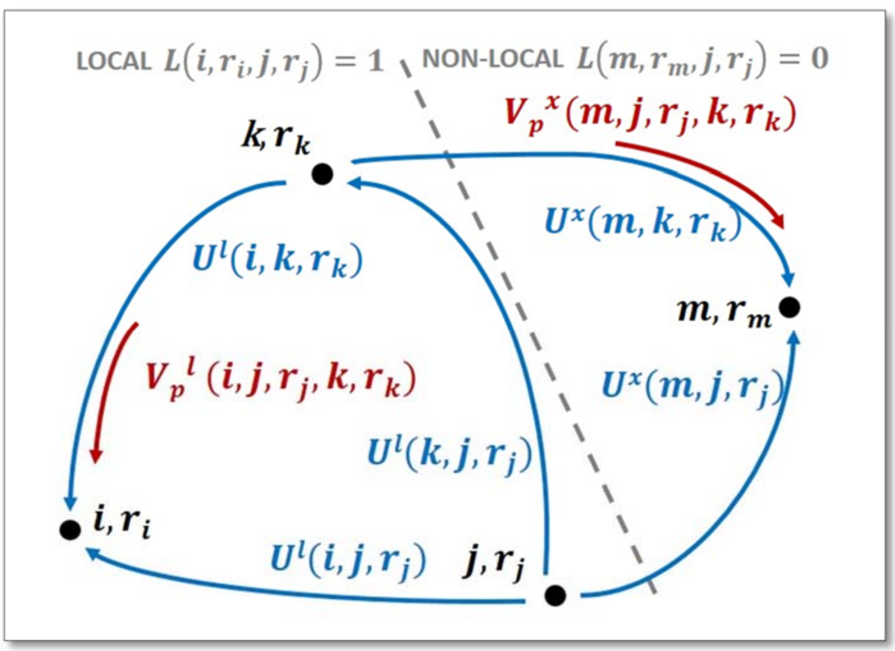

Figure 2. Sample ERA network illustrating direct and indirect resource flows between processes, delineated by Locality.

The typical embedded resource trade involves an exchange of currency for an outsourced good or service in which a resource stock impact is embedded. This makes the *currency intensity* a particularly important special case (see Part 2, Adams et al. 2013, Submitted to WRR). In the example above water resources are moving directly from process *j* to process *k;* electricity resources are moving directly; and water resources indirectly (embedded in the electricity), from *k* to *i* and from *k* to *m* in exchange for currency. Currency moves directly from *i* to *k* and from *m* to *k* in exchange for r_k. Comparison of this "exchange rate" between currency and embedded water allows for a unique type of economically meaningful analysis.

The natural system coupled with the human economy is a crucial part of the global embedded resource trade, and the water cycle is a particularly active part of the system. Because economically "consumed" water usually involves a direct impact of a production process on a water stock via evaporation, there is an attendant indirect impact of the Atmospheric process on the same water stock. If this evaporated moisture is directly returned to the impacted water resource stock during the current time period via precipitation, or if upstream rainfall causes a river to return this water, the net impacts of the production process may be reduced. Rivers, the Atmosphere, Aquifers, the Ocean, Soil Moisture, Snowpack, and other components of the hydrosphere are Hydrology and Water Resource (HWR) processes with their own behavior and which control water stocks. Using these and other geophysical processes, the natural component of the system may be coupled with the human component and assessed seamlessly using the ERA framework.

Resource Intensities. Whenever a process has both inputs and outputs (whether direct or indirect), we can calculate the *intensity* of the relationship between these inputs and outputs. The Average Resource Intensity, *I*, is the ratio of the total impact on one resource stock of type r_j to the total impact on another resource stock of type r_i, in units of r_j / r_i, as revealed by a process or a group of processes i and accounting for indirect impacts via *i*'s impact on intermediary stocks of type r_k. I is calculated as the net direct and indirect impacts of process *i* on all other process' (*j*) resource stocks of type r_j, divided by the net direct and indirect impact by all processes (*i*) on process *j*'s resource stock of type r_j, with all indirect impacts calculated via intermediary resource stock of type r_k. The numerator is the direct and indirect "consumption" or stock-reducing impact of process *i* on all resource stocks of type r_j. The denominator is the direct and indirect "production" or stock-increasing impact of process *i* on its own resource stock of type r_i, which is coincident with the net direct and indirect impacts of all processes *m* (including the controlling process *i*) on r_i.

$$I\left(i,r_j,r_i,r_k\right)=\frac{\sum_j E\left(i,j,r_j,r_k\right)}{\sum_m E\left(m,j,r_j,r_k\right)} \qquad (20)$$

Resource intensities can be found using total impacts, local impacts, or external impacts, and can represent either direct, indirect, or combined impacts, depending on the *E* values used in the calculation. In many but not all cases, *I* is simply a ratio of inputs to outputs.

Resource intensities are a fundamental means of comparison of different processes and resources that has been frequently but informally employed in many studies. For example, *Davis and Caldeira*, [2010] utilized a variety of resource intensities [energy intensity of GDP (energy per unit GDP), carbon intensity of energy consumption (emissions per unit energy), and the carbon intensity of GDP or more generally, of trade, (kg of CO_2 per $USD)] to calculate global carbon emissions. Similarly, *Wackernagel et* *al.* [1999] used energy intensities for individual countries (in units of GJ/ ha per year) to develop the energy components of the overall ecological footprint for the area. The unit Virtual Water Content (VWC) of agricultural crops used by *Konar et al.,* [2012] is a unit water resource intensity expressed as kg of water consumed per kg of raw crop produced. The methods used for determining the VWC itself originated with *Hoekstra and Hung* [2002]. In the ERA mathematics we contribute a formalism to intensity calculations as well as the explicit inclusion of both direct and indirect impacts on all kinds of stocks, explicit equivalency between stocks, and the ability to calculate both indirect intensities of a supplier's impact on the stocks of value created by a supplied process, and the indirect intensities of the impact of a supplied process.on a resource stock.

In the literature, Intensities are often communicated in inverted form such that production is in the numerator and consumption in the denominator (e.g, MWh/gal), but this does not change the fundamental meaning of the metric; we use inverse quantities interchangeably in our results without distinction. Note that it is possible that $i = j$, that I is negative, and also that both numerator and denominator reflect stock-increasing or stock-reducing values.

It is possible in principle to ascribe and thus embed a portion of the process's total footprint to one of several outputs; this could be accomplished by the introduction to the mathematics of an appropriate marginal footprint factor. Water is only one input of many, and in human production processes its marginal value often accounts for less than 1% of the total value resulting from a process. These considerations are discussed in the second part of this work (Adams et al. 2013, in submission to WRR).

Net Resource Savings. It is possible to compute the net reduction in system-wide impact on a specific type of resource stock due to trade in that embedded resource, by posing a hypothetical comparison between an observed embedded trade network and how much of a resource stock would have been consumed (or produced) if every process substituted direct impacts at local resource intensities for its indirect impacts. An existing example in, *Konar et al.* [2012] builds on the work of *Aldaya et al.* [2010a] using the VWC to find Global Water Savings (GWS) values as a result of international crop trade. $GWS_{e,i,x,s} = T_{e,i,x} * \left(VWC_{i,x,s} - VWC_{e,x,s}\right)$ from *Konar et al.,* [2012], where e, i, x and s identify exporting country, importing country, commodity being traded, and water source. T is the total volume of x traded from e to i, and $VWC_{i,x,s} - VWC_{e,x,s}$ is the difference in water use efficiency between i and e. This equation implicitly assumes full equivalency between the water stocks consumed by importers and exporters. In general, using ERA notation, the analogous systemic net Resource Savings, *RS,* are given as the net reduction in systemic impact on resource stock of the type of r_j due to the outsourcing of impacts from process *i* to process *j*,

$$RS(i, j, r_j) = U(j, i, r_j) \cdot \left[I^I(i, r_j, r_i, r_k) - I^Q(i, r_j, r_i, r_k)\right]. \qquad (21)$$

The generalized ERA form as implemented for freshwater resources differs from GWS in that it allows in *I* for partial or total non-equivalency between the importer's and exporter's stocks, such that *RS* might for example be 100% from the perspective of the importer if the exporter only utilizes water stocks that are completely external and non-equivalent ($Q = 0$) to the importer's water stocks. Of course, *RS* can be calculated for any resource stock type, including notably currency.

Application of ERA to Water and the Electrical Energy Trade in the Western US

This study utilizes 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), combined with retail electricity sales, to compile the network input-output tables required as input variables for ERA analysis.

We define three types of resource stocks in this analysis: electricity, water, and currency. Electricity (MWh) is produced by an electrical energy generation process and traded for currency ($ USD), and net raw water (gal) is consumed (i.e. the "blue" water footprint, *Hoekstra et al.,* 2011), by an electrical energy generation process (gal).

We aggregate all like processes within a U.S. State into a single process for purposes of analysis. Each of the eleven states in the study has three types of processes, a Hydrology and Water Resources (HWR) surface and aquifer water supply process, an electrical energy generation process, and an electrical energy consumption process. Water supply processes, representing a state's total water supply, provide water to electrical energy production processes, which produce and then trade electrical energy for the consumption process's currency. The final process in this study is the HWR atmosphere process, which receives water resources output from electrical energy production processes. In sum, there are three processes (water supply, electricity production, and electricity consumption) within each of the eleven states, plus one atmosphere process acting as a sink for exported water from electrical cooling and evaporation for a total of thirty-four processes, and three resource types per.

The State scale is the appropriate scale of aggregation for this study because water rights and retail electricity prices are governed at the State level, and because we are interested primarily in inter-Basin and inter-regional electrical trade rather than local utility scale distribution patterns. Data limitations at finer scales associated with electrical utilities and distributors also make the State scale the smallest feasible scale for the study. Furthermore, cities are the major users of electrical power, and it is a fortunate coincidence in the WesternUS that no major metropolitan regions are located at State boundaries (and recall that international trade is neglected). Therefore, State boundaries neatly contain major metropolitan regions and utilities, except in the case of California where at least three major and distinct regions exist. The locality or externality of resource stock impacts across State boundaries is defined using locality and externality matrices. A binary locality matrix was developed to establish locality of the resource stocks. Processes occurring in the same state were identified as local (value = 1), all others external (value = 0). The binary externality matrix was determined from the locality matrix per equation (6).

Martin and Ruddell [2012], utilized the same dataset as this study but applied a simplified and context-specific analytical method to obtain results. Readers may wish to examine this work's approximations which provide a shortcut to certain results, albeit without the ability to manipulate the fundamental assumptions.

Data. The data used in this study was obtained largely from U.S. Energy Information Administration (EIA) online databases including average utility retail pricing of electricity for each utility within each state for 2009 for the eleven western U.S. states selected [*USEIA,* 2011a], and total electricity import and export data for each state for 2009 [*USEIA,* 2011b]. Other data utilized in this study includes megawatt-hours of electricity produced annually (year 2009) at each power plant within each state and estimated average daily water consumption for each of the power plants within each state [*USEPA,* 2010; *USEIA* 2005; *Tidwell et al.*, 2012].

The resulting average resource intensities for the network being examined are presented in Table 1. These intensities are the average water intensity of electricity generation, and the average price of electricity, within each state. The numbers used in this study were obtained by computing weighted 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. We aggregate electrical energy production, transmission, and distribution together as a single process and do not account for profit or value added between steps in the electrical supply chain.

Table 1. State resource intensities[a,b]

	Water Intensity (gal/MWh)	Price ($/MWh)
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

[a]Average water intensity of power generation by state,
listed highest to lowest, and average retail price of electricity by state
[b]from *Martin and Ruddell* [2012]

California and the Pacific Northwest states (Oregon, Idaho, and Washington) have relatively low water intensities for generation, in part due to extensive hydroelectric generation. California's low water intensity is also related to greater use of natural gas and renewable energy sources [*Macknick et al.,* 2011] and to laws regulating once-through use of cooling water. Higher water intensities are generally associated with thermoelectric processes, especially nuclear and coal, as compared with other sources [*USEIA,* 2011c], although controversy exists regarding methods of calculating the water intensity of hydroelectric power [*Mekonnen and Hoekstra,* 2012, *Scott and Pasqualetti*, 2010]. Average water intensities used in this study generally agree by order of magnitude with global average water footprints for energy production published by *WFN* [2013].

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 dams [*USEIA,* 2011c], but also generally reflect some combination of permissive regulatory environments and low-cost locally available fuel sources.

Electricity Trade Network Estimation. The power grid in the Western United States is a complex system of electricity generation, distribution and consumption. The network used in this analysis is a simplified version. We define the network conceptually as a basic transportation network in which resources (electricity, water and economic currency) flow between State aggregated processes.

The system is taken as closed and conservative such that electricity production is equal to electricity consumption within the network. The data shows electricity production in excess of demand as approximately 1% [*USEIA*, 2011b]. This excess electricity is presumed to have been exported outside of the Western U.S. (i.e. Mexico, Canada, Texas, etc.), and was subtracted proportionately from each of the exporting states' generation totals in order to balance the system.

These methods have chosen both to aggregate groups of processes and to exclude from analysis other processes that are connected through trade across an arbitrary boundary. The following assumptions are implied in order to neglect the error in water footprint and resource intensity calculations that is introduced by these simplifications. First, in order to *exclude* processes outside a boundary (e.g. in this case Mexico, Canada, and the Eastern US), one or the other of two assumptions must be made: either (1) excluded processes have similar resource intensities to included processes, or (2) trade with excluded processes is sufficiently small relative to intra-system trade such as to render differences in resource intensities negligible as a weighted component of the total system's trade. Second, in order to *aggregate* processes together (e.g. all consumers or exporters of electricity in a State), the aggregated processes must both (1) have similar resource intensities to each other, and (2) share with each other the same net import or export relationships with all of the included processes. In the current analysis, the assumptions for exclusion of Mexico, Canada, and non-Western States are clearly justified, but the assumptions for aggregation of consumption and production processes in States are questionable and might therefore reduce the representativeness of the results for specific producers and consumers in each State.

Estimation of the electricity trade across the network is summarized in Table 2 and the resulting interstate transfers are shown in Figure 3.

Table 2. Interstate electricity trade[a]

	Net Interstate Trade (MWh)	Gross Export (MWh)	Gross Export Percentage (%)
Arizona	31,685,245	31,685,245	31.30%
Montana	5,775,543	5,775,543	5.70%
New Mexico	15,700,958	15,700,958	15.50%
Nevada	1,655,392	1,655,392	1.60%
Oregon	5,079,110	5,079,110	5.00%
Utah	12,389,184	12,389,184	12.20%
Washington	2,117,039	2,117,039	2.10%
Wyoming	26,882,529	26,882,529	26.50%
		Gross Import (MWh)	**Gross Import Percentage (%)**
California	-84,137,000	84,137,000	83.10%
Colorado	-4,815,000	4,815,000	4.80%
Idaho	-12,333,000	12,333,000	12.20%

[a]adapted from *Martin and Ruddell* [2012]

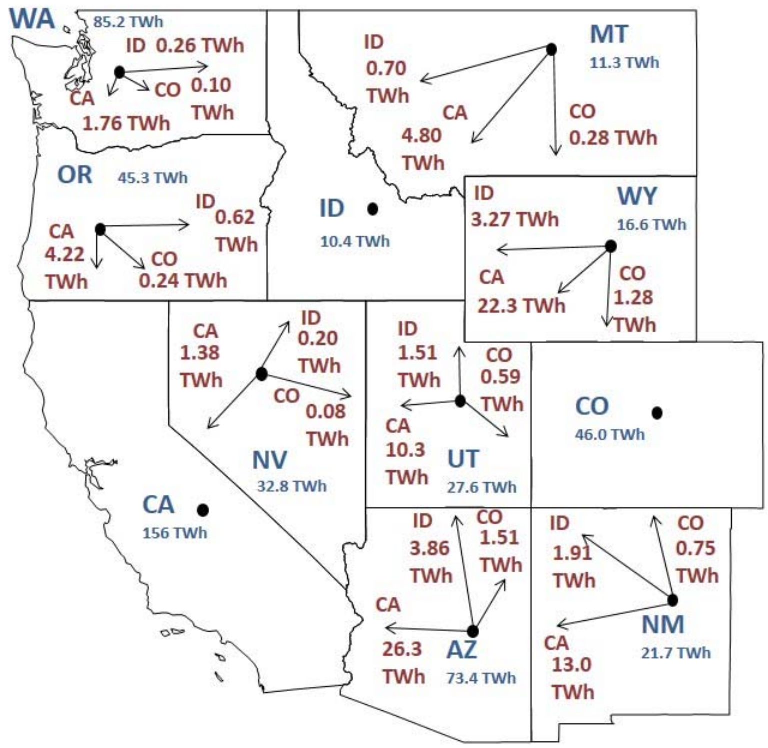

Figure 3. Estimated interstate electricity trade (TWh). Electricity transfer quantities are shown for all exporting states to all importing states as well as internally produced and consumed electricity for each state. California dominates imports consuming 83.1% of the traded electricity.

A study by *Marriott and Matthews* [2005] on electricity generation and consumption mixes in the Western U.S. utilized a similar transportation network approach with a linear optimization model to estimate interstate electricity trading for year 2000. This study found energy transfers similar to those found in our study, with California dominating imports and Arizona the largest exporter. *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 qualitatively comparable to those of Scott and

Pasqualetti, though our analysis is for a larger spatial and temporal scale and uses less detailed data. Table 3 compares results from this study with those found previously by *Scott and Pasqualetti* [2010].

By combining this estimated information for electrical energy production and trade with the corresponding currency payments and with the consumption of water by generators through the movement of water from State water supply stocks to the atmosphere, we construct an input-output table for directional pairwise impacts on the resource stocks of thirty-four processes.

Table 3. Net export of embedded water in electricity[a]

Net Export from Arizona to:	***This Publication, [2013]***	***Scott and Pasqualetti, [2010]***
California	4,838 Mgal	7,984 Mgal
Northwest (Idaho)	709 Mgal	1,932 Mgal
Colorado	277 Mgal	-1,100 Mgal

[a]adapted from *Martin and Ruddell* [2012]

Results

Figure 4 illustrates the direct U and indirect V components of the water footprint E for each State on the Western U.S. power grid. The generator's embedded water flows to both internal (instate) and external (interstate) consumers. In Figure 4, the sum total of instate generators' (*gen*) embedded outflows of the State's water supply process's (*wts*) water stock (*w*) to instate consumers (*con*) within electricity trades is shown as $\omega_{LOCAL} = \Sigma_{wts} V^1_{OUT}(wts,w,gen,e) = \Sigma_{wts} V^1_{IN}(con,wts,w,e)$. The sum total of instate consumers' embedded water inflows within electricity trades from interstate generators is $\omega_{IMPORT} = \Sigma_{wts} V^x_{IN}(con,wts,w,e)$. The sum total of electricity generators' embedded water outflows to interstate consumers is $\omega_{EXPORT} = \Sigma_{wts} V^x_{OUT}(wts,w,gen,e)$. These are Embedded Water Footprints of both producing and consuming processes, broken into imported, exported, and locally derived components; we will proceed to estimate these Water Footprints aggregated at the State level.

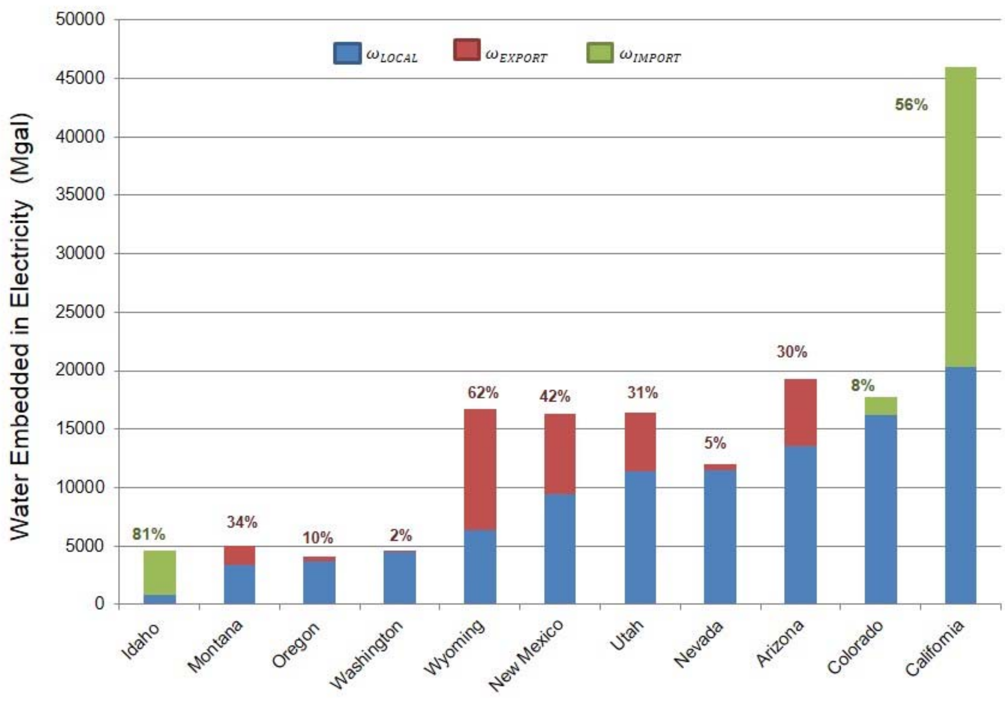

Figure 4:Water footprint, *E,* for the electrical energy consumers of the Western U.S., by state. ω_{LOCAL} is the water embedded in electricty produced instate and traded to instate customers. ω_{EXPORT} is the water embedded in electricty that is exported from the state. ω_{IMPORT} is the water embedded in electricity that is imported to the state. Percentages indicate percent of the footprint that is involved in interstate trade, either imported or exported. ($\sum \omega_{IMPORT} = \sum \omega_{EXPORT}$).

Because ERA methods ascribe resource impacts to their ultimate cause (the consumer), rather than the proximate cause (the generator), it is immediately apparent that the net water footprint *E* of electrical energy generators is zero if all of the electrical energy generated is traded away to other processes which consume the electrical energy. The footprint instead accrues to the consumers of the electrical energy. Because the direct impact *U* of generators on instate water supplies is exactly offset by local and external embedded outflows *V*, $U\left(i, j, r_j\right) = \omega_{LOCAL} + \omega_{EXPORT}$. Therefore, following the form of equation (19), the water footprint *E* of the generator process is zero, as,

$E = \omega_{LOCAL} + \omega_{EXPORT} + 0 - \omega_{LOCAL} + 0 - \omega_{EXPORT} = 0$.

For consumers, the direct impact *U* is zero in this simplified case. Similarly, there are no outputs of virtual water supplies ($V_{OUT}^{l} = V_{OUT}^{x} = 0$), but consumers of electricity have both local and non-local inputs of embedded water. Therefore, following the form of equation (19), the water footprint *E* of the consumer process is the sum of the local and external water footprints, as, $E = 0 + \omega_{LOCAL} - 0 + \omega_{IMPORT} - 0 = \omega_{LOCAL} + \omega_{IMPORT}$.

The determination of equivalency of instate vs. external water resource stocks is critical for the calculation of the footprint from the perspective of a specific observer. Usually the observational point of view on the system coincides either with that of the controlling process of a specific resource stock, or the indirect consumer of a stock, or of an observer of the total system including all stocks of a type. If these stocks are fully equivalent (i.e. "local") to the consumer's own water stock then the summation above holds, but if they are fully external then the above summation reduces to $E = \omega_{LOCAL}$ from the perspective of that consumer process, reflecting in the footprint a perspective that ignores external impacts. In our present study we take the perspective of a hypothetical manager of the total system of water resources of the Western U.S., and as such we include both local and external impacts in our water footprint calculation; this point of view mimics that advocated by global water management proponets (e.g. Hoekstra, 2006). A state water resource manager, however, might only include local water impacts in the calculation (Rushforth et al., 2013). Note that from a systemic perpective including all processes in Figure 4, $\sum \omega_{IMPORT} = \sum \omega_{EXPORT}$, so water impacts are conserved.

Several patterns emerge from the results in Figure 4, which is organized by ascending ω_{LOCAL}. When analyzing these water consumption patterns it is useful also to keep in mind available water resource supplies within the region. *Tidwell et al.* [2012] provide a metric of physical water availability by watershed for the U.S. in which water availability is calculated as the ratio of current water demands to water-supply. They developed separate measures for surface and groundwater supplies which are mapped to show regions of limited water availability (see *Tidwell et al.* [2012] Figure 3). Their results show that the majority of the Western United States has little to no surface water resources available for new development, particularly in Wyoming and the desert southwest.

Figure 4 shows that the State with the highest embedded water footprint of electricity consumption *E* is California, and the lowest is Montana. This pattern fits the general trend of the states' population which is closely correlated with electrical consumption. The states that import a large fraction of *E* as indirect or embedded water impacts are Idaho (81% imported) and California (56% imported), and the states that export a large fraction ω_{EXPORT} of directly used water as embedded in electrical energy are Wyoming (61% exported), New Mexico (42% exported), Montana (34% exported), Utah (31% exported), and Arizona (30% exported). California is by far the largest importer of water embedded in electricity and dominates the import of embedded water (roughly 26 Billion gallons), and Wyoming is the largest exporter of water embedded in electricity (roughly 10 Billion gallons). Notably, the water-rich and hydropower-rich states of Oregon and Washington export little, and the relatively water limited [*Tidwell et al.*, 2012] states of Wyoming, New Mexico, Utah, and Arizona export the vast majority of water embedded in electricity traded in this system.

The embedded water export pattern in Figure 4 appears to be qualitatively consistent with the availability of abundant and inexpensive fuel sources (e.g. Wyoming coal), relatively low population and energy demand (e.g. Wyoming), and a regulatory environment that is relatively tolerant of fossil fuel emissions and the construction of transmission lines (e.g. states of the Mountain West in general). On the demand side, this trade appears to be consistent with the purpose of supplying electrical energy and embedded water to reconcile California's demand in excess of its local supply, and to sell electricity to California's large and high-priced market.

The pattern in Figure 4 is inconsistent with an economic and regulatory regime that drives the production and export of electricity primarily toward states with abundant water resources; otherwise, Oregon and Washington would be significant exporters of embedded water. However, on the demand side, it is possible that water scarcity is a significant determining factor in California's implicit policy of embedded water import. Figure 4 therefore illustrates a general result of this study, that electrical energy supply and embedded water export in the Western U.S. is not organized primarily around the availability of abundant water supplies, but rather by other factors yet to be exactly quantified. Figure 4 also illustrates the result that California dominates demand for embedded water in electrical energy on the Western U.S. power grid, and that California avoids a sizeable impact on its local water resources through the substitution of external embedded water supplies.

Finally, by combining the electricity production and consumption processes as illustrated in Section 4.1, we are able to calculate a Resource Savings, *RS*, for consumed water in the system as a result of electricity trade. These results are presented in Table 4 and show that the overall water consumption in the Western U.S. is increased as a result of this trade system. California realizes an increase of 47% in total water consumption by electricity generation to satisfy its demand, or nearly 15 Billion gallons, as a result of the indirect water impacts of its electricity import. Idaho effects an increase in water consumption of electricity generation of 145%, or nearly 3 Billion gallons, as a result of the indirect water impacts of its import of electricity, compared with water that would have been used locally and directly to satisfy the same demand through in-State generation. Colorado is the only importing state to show water resource *savings* as a result of this trade, however at 1% of Colorado's water consumption due to electricity generation (227 Million gallons) this savings is inconsequential for the system as a whole.

Table 4. Water Savings through trade in electricity on the Western U.S. power grid[a]

	U (Mgal)	***V*** (Mgal)	***E*** (Mgal)	***U'*** (Mgal)	***RS*** (Mgal)	***RS*** (%)
	Actual	**Actual**	***U + V***	**If-local**	***U' - E***	***RS/U'***
Arizona	19322	-5824	13498	13498	0	0
California	20289	25703	45992	31200	-14792	-47%
Colorado	16230	1471	17701	17928	227	1%
Idaho	868	3768	4636	1896	-2740	-145%
Montana	5070	-1717	3353	3353	0	0
New Mexico	16330	-6865	9465	9465	0	0
Nevada	12023	-578	11445	11445	0	0
Oregon	4129	-417	3713	3713	0	0
Utah	16461	-5102	11359	11359	0	0
Washington	4587	-111	4476	4476	0	0
Wyoming	16690	-10328	6363	6363	0	0
System Totals:	*132000*	*0*	*132000*	*114695*	*-17304*	*-15%*

[a]Savings shown are based on Equation 21, comparing water intensities of imported electricity to water intensities of the importing states themselves. The result is a roughly 17 Billion gallon (or 15%) ***increase*** in water consumption for the system as a whole.

Conclusions

The Embedded Resource Accounting framework was formally introduced in this study. ERA is a generalized process-oriented, input-output, and network-based framework for complex system analysis that is agnostic to the definition of resource stocks or the equivalence of resource stocks from the perspective of a specific observer. This method is applied in this paper by quantifying the indirect and the direct components of the water footprint of electrical energy consumption in the Western U.S., along with the pattern of trade of embedded water.

Embedded water plays a large role in the electrical energy trade network in the Western United States with more than 30 Billion gallons embedded in interstate traded electricity (132 Billion gallons over the entire system). For net-importing states, a significant fraction of the embedded water footprint of electricity consumers is externally and indirectly sourced.

The water-limited Southwestern U.S. states (Arizona, New Mexico, and Nevada) [*Tidwell et al.*, 2012] are major exporters of water embedded in electricity. The most water-intensive electricity producers, New Mexico and Utah, are among the driest in the Western U.S. [*Tidwell et al.*, 2012], and a number of water limited states, including New Mexico, Utah, and Arizona, are exporting over a third of their water embedded in electricity to other states (see Figure 4). It is possible that these exports may exacerbate current or future water scarcity in these states. Both in Idaho and California, electricity consumers have a much larger water footprint for their electrical energy consumption if the indirect component of the water footprint is considered in addition to the direct component of water consumed by in-State generators. The electricity generators in electricity exporting states have a lower net water footprint than is immediately apparent from the direct use of in-State water supplies.

Water savings calculations across the Western U.S. show that overall water consumption is increased due to the electricity trade, as compared with a hypothetical system where all electricity is consumed in the state where it was produced. California realizes an increase in the net water footprint of its electricity consumers of 47%, and Idaho effects an increase of 145%. Water use for electricity production is, in a net sense, being shifted to States with less available water. This overall increase in water consumption and its shift to drier States is anti-efficient with respect to water consumption and may exacerbate overall water scarcity in the Western U.S., especially in the Southwest and in the Lower Colorado River Basin.

However, water use efficiency is clearly not currently a major organizing principle of this hydro-economic system. Other forces appear to be determining this pattern of water footprints and trade in embedded water. Future work will take a closer look at the economics of this trade, using ERA to tie embedded water to the currency traded for electricity. These results will be published in Part 2 of this study.

Important applications of these findings are easy to imagine. For example, a water shortage looms on the Lower Colorado River system, with reductions in water allocations from this system possible in the near future. States with junior water rights, such as Arizona, are also major suppliers of embedded water to States with senior water rights, such as California. In such a scenario, ERA reveals the vulnerability of California to the reduction in water supplies in other States that may be more directly impacted by water shortages occurring in a river basin that both agents share. California will likely experience higher prices, or reduced supplies, of electrical power and embedded water in such an eventuality. A reduction in direct water use by Arizona's power sector will result in a proportionate reduction in California's embedded water supply. This information is useful because it can motivate cooperation between California and its embedded water suppliers to mitigate the effects of a water shortage- cooperation that might not happen if California did not appreciate this significant linkage.

It might also be useful to study variations of the Western US power grid in which water use was shifted to more water-available and water-efficient locations and power production technologies, or in which spatially diverse sourcing of embedded water were utilized as a hedge against the effects of local and regional drought on electrical power supplies.

Interested readers are invited to contact the authors for access to the *ERA* 1.0 Matlab code that calculates ERA results, and to cite this publication in reference to that software.

References

Aldaya, M. M., J. A. Allan, and A. Y. Hoekstra (2010a), Strategic importance of green water in international crop trade. *Ecol. Econ., 69*, 887-894.

Aldaya, M. M., P. Martinez-Santos, and M. R. Llamas (2010b), Incorporating the water footprint and virtual water into policy: Reflections from the Mancha occidental region, Spain. *Water Resour. Man., 24*, 941-958.

Allan, T. (1993), Fortunately there are substitutes for water: Otherwise our hydropolitical futures would be impossible, paper presented at Conference on Priorities for Water Resources Allocation and Management, Overseas Dev. Admin., London.

Allan, J. A. (1996), Policy responses to the closure of water resources. In *Water Resource Policy: Allocation and Management in Practice*, ed. P. Howsam and R. carter. London: Chapman and Hall.

Ansink, E. (2010), Refuting two claims about virtual water trade, *Ecol. Econ., 69*, 2027-2032.

Bilmes, J. (2000), Dynamic Bayesian Multinets, Proceedings of the 16th Conference on Uncertainty in Artificial Intelligence, pp. 38-45.

Buchanan, J. M. and W. C. Stubblebine (1962), Externality, *Economica*, *29(116),* 371-384.

Chanan, A., J. Kandasamy, and D. Sharma (2008), A Role for input-output analysis in urban water policy decisions in Australia, paper presented at 2008 International Input-Output Meeting, Seville, Spain.

Chapagain, A. K., A. Hoekstra, and H. Savenije (2006), Water saving through international trade of agricultural products, *Hydrol. Earth Syst. Sci., 10*, 455–468.

Chapagain, A. K., and A. Y. Hoekstra (2008), The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water International, 33*(1), 19-32. doi: 10.1080/02508060801927812.

City of Peoria, Arizona (2007), Principles of sound water management. November 20, 2007. Available from: http://www.peoriaaz.gov/uploadedFiles/PrinciplesofSoundWaterManagement11_20_07f.pdf.

Collin, P. H. (2006), *Dictionary of Economics*, A & C Black, Great Britain, eISBN-13: 978-1-4081-0221-3.

Davis, S. J. and K. Caldeira (2010), Consumption-based accounting of CO_2 emissions, *PNAS, 107(12),* 5687-5692, Available www.pnas.org/cgi/doi/10.1073/pnas.0906974107.

Finster, R. D. (1971), Improving water resource allocation through demand-oriented water policy. *Water Resour. Bull., 7(1)*, 1-25.

Fischer-Kowalsi M., and W. Huttler (1999), Society's metabolism: the intellectual history of material flow analysis, Part II, 1970 - 1998. *J. Indust. Ecol., 2(4),* 107-137.

Gober, P., Kirkwood, C. W., Balling Jr., R. C., Ellis, A. W., & Deitrick, S. (2010). Water planning under climatic uncertainty in Phoenix: Why we need a new paradigm. *Annals of the Assoc. of American Geographers, 100(2)*, 356-372.

Hanemann, W. M. (2006). Chapter 4: The economic conception of water. In P. P. Rogers, M. R. Llamas & L. Martinez-Cortina (Eds.), *Water crisis: Myth or reality?* (pp. 61-91)

Fader, M., D. Gerten, M. Thammer, J. Heinke, H. Lotze-Campen, W. Lucht, and W. Cramer (2011), Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade, *Hydrol. Earth Syst. Sci., 15*, 1641–1660.

Hoekstra, A.Y. (2011), The Global Dimension of Water Governance: Why the River Basin Approach is No Longer Sufficient and Why Cooperative Action at Global Level Is Needed, Water, 3, 21-46, doi:10.3390/w3010021.

Hoekstra, A.Y. (2006), The Global Dimension of Water Governance: Nine Reasons for Global Arrangements in Order to Cope with Local Water Problems, UNESCO-IHE Value of Water Research Report Series, No.20.

Hoekstra, A. Y., A. K. Chapagain, M. M. Aldaya, and M. M. Mekonnen (2011), *The Water Footprint Assessment Manual: Setting the Global Standard.* Earthscan Publishing. Water Footprint Network. Available from: http://www.waterfootprint.org/downloads/TheWaterFootprintAssessmentManual.pdf.

Hoekstra, A.Y. and M.M. Mekonnen. (2012), The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America, 109*(9), 3232-3237, doi: 10.1073/pnas.1109936109.

Hoekstra, A.Y. and P. Q. Hung. (2002), Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade. *Value of WaterResearch Report Series No. 11*. UNESCO-IHE, Delft, The Netherlands. Available from: www.waterfootprint.org/Reports/Report11.pdf.

Konar, M, C. Dalin, N. Hanasaki, A. Rinaldo, and I. Rodriguez-Iturbe (2012), Temporal dynamics of blue and green virtual water trade networks. *Water Resour. Res., 48*,W07509, doi:10.1029/2012WR011959.

Kumar, M. D. and O. P. Singh (2005), Virtual water in global food and water policy: Is there a need for rethinking? *Water Resourc. Manag., 19*, 759-789, doi:10.1007//s11269-005-3278-0.

Macknick, J., R. Newmark, G. Heath, and K. C. Hallett (2011), A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies, NREL/TP-6A20-50900, National Renewable Energy Laboratory, Golden, CO, pp. 29.

Marriott, J. and S. Matthews (2005), Environmental effects of interstate power trading on electricity consumption mixes. *Environ. Sci. and Tech., 39,* 8584-8590.

Martin, E.A. and B.L. Ruddell (2012), Value intensity of water used for electrical energy generation in the Western U.S.; An application of embedded resource accounting. *IEEE International Symposium of Systems and Technology, Conference paper.* Boston, Mass.

Mekonnen, M.M. and A.Y. Hoekstra (2012), The blue water footprint of electricity from hydropower. *Hydrol. Earth Syst. Sci., 16*, 179-187, doi: 10.5194/hess-16-179-2012.

Mubako, S.T. (2011), Frameworks for estimating virtual water flows among U.S. states, *Dissertations*, Paper 341, http://opensiuc.lib.siu.edu/dissertations/341.

Mubako S.T., Ruddell B.L., and A. Mayer (2013), The relationship between water withdrawals and freshwater ecosystem water scarcity quantified at multiple spatio-temporal locations and scales for a Great Lakes watershed. *J of Water Resources and Management.*

Odum, H.T. and E.C. Odum. 1976. Energy Basis for Man and Nature. McGraw-Hill, NY.

Porkka, M., M. Kummu, S. Siebert, and M. Floerke (2012), The role of virtual water flows in physical water scarcity: The case of central Asia. *Int. J. Water Resour. Dev., 28*(3), 453-474. doi: 10.1080/07900627.2012.684310.

Postel,S. L. (2000), Entering an Era of Water Scarcity: The Challenges Ahead, *Ecol. Appl., 10(4)*, 941-948.

Rushforth, R.R., E.A. Adams, and B.L. Ruddell (2013), Generalizing Ecological, Water and Carbon Footprint Methods and their Worldview Assumptions using Embedded Resource Accounting, Water Resources and Industry, in press.

Scott, C., and M. Pasqualetti (2010), Energy and water resources scarcity: Critical infrastructure for growth and economic development in Arizona and Sonora. *Nat. Resour. J., 50*, 645-682.

Taylor, P.J. (2005), Leading World Cities: Empirical Evaluations of Urban Nodes in Multiple Networks, *Urban Studies, 42*, 1593-1608.

Tidwell, V.C., P.H. Kobos, L.A. Malczynski, G. Klise, and C.R. Castillo (2012), Exploring the water-thermoelectric power nexus, *Journal of Water Planning and Management*, *138*(5), 491-501.

USEPA (U.S. Environmental Protection Agency) (2010), Emissions and Generation Resource Integrated Database (eGRID), version 1.0.

USEIA (U.S. Energy Information Administration) (2005), *Steam-Electric Plant Operation and Design Data,* EIA-767, (available at http://www.eia.gov/cneaf/electricity/page/eia767/).

USEIA (U.S. Energy Information Administration) (2011a), Online. Sales data tables. *Electricity*. Accessed October 2011. http://www.eia.gov/electricity/data.cfm#sales.

USEIA (U.S. Energy Information Administration) (2011b), Online. Supply and Disposition of Electricity. State electricity profiles. *Electricity*. Accessed October 2011. http://www.eia.gov/electricity/state/.

USEIA (U.S. Energy Information Administration) (2011c), Online. Factors affecting electricity prices. *Energy Explained*. Accessed December 2011. http://www.eia.gov/energyexplained/index.cfm?page=electricity_factors_affecting_prices.

Wackernagel, M., L. Onisto, P. Bello, A. C. Linares, I. S. L. Falfan, J. M. Garcia, A. I. S. Guerro, M. G. S. Guerro (1999), National natural capital accounting with eth ecological footprint concept, *Ecol. Econ., 29,* 375-390.

WFN (Water Footprint Network) (2013), Online. Product Water Footprints. Energy. Accessed February 2013. http://www.waterfootprint.org/?page=files/Water-energy.

Wichelns, D. (2010), Virtual water: a helpful perspective, but not a sufficient policy criterion, *Water Resour. Manag., 24*, 2203-2219.

Wildman, R. A., Jr., and N. A. Forde (2012), Management of water shortage in the Colorado river basin: Evaluating current policy and the viability of interstate water trading. *J. American Water Resour. Assoc., 48*(3), 411-422. doi: 10.1111/j.1752-1688.2012.00665.x.

Wolman, A. (1965). The metabolism of cities. Scientific American, 213(3),179-190.

Zetland, D. (2011). *The End of Abundance: economic solutions to water scarcity*. Aguanomics Press. ISBN: 978-0615469737.

Chapter 3

EMBEDDED RESOURCE ACCOUTING FOR WATER RESOURCE APPLICATIONS; PART 2, THE DOLLAR INTENSITY OF WATER EMBEDDED IN ELECTRICITY

Abstract

Many areas in the Western U.S. are at or near 100% utilization of available high-quality water resources, making sustainable management of these resources increasingly challenging. Demands are also increasing for goods and services that require significant amounts of water to produce, including electrical power. Although markets for water resources are poorly developed, markets are well developed for water-intensive goods and services. As a result, the “virtual” outsourcing of water impacts embedded within the trade in water-intensive goods and services has become a widely utilized, albeit usually unintentional, substitutionary adaptive mechanism for water scarcity. Embedded Resource Accounting (ERA) methods can observe a type of shadow price, the Dollar Intensity, by observing how the implicit trade of embedded resources is associated with the explicit trade in marketed goods and services. This paper uses ERA to analyze water embedded in the electricity trade in the Western U.S. and explain the relationship between water availability, electrical energy generation, embedded water, and the balance of economic trade in electricity. An implicit and rational market for trade in indirect water use embedded within electricity appears to exist on the Western U.S. power grid as indicated by Dollar Intensities of water embedded in traded electricity. However, water availability is not currently a significant factor organizing the trade. These methods are generally applicable to resource economics and management, especially where

environmental and social impacts are implicitly outsourced or traded via explicit market mechanisms.

Introduction

Climate change is expected to cause increasing temperatures and evaporation, decreased rainfall, and more intense droughts in the Southwestern United States. Settlement of this area was made possible through the subsidized development of infrastructure and rights-based allocation of water resources [*Reisner,* 1993], and the future of the west is critically linked to the successful management of its available high-quality and low-cost water resources. Anthropogenic water uses may already exceed sustainable levels, [*Postel,* 2000], and there is evidence of long-term demands exceeding available supplies, as is the case for the Colorado River Basin and the Western United States in general [*Wildman and Forde,* 2012]. As population in urban areas grows, resource demands increase and become more spatially concentrated, especially the demands for electrical energy in the Urban Metabolism (Wolman, 1965). Population grew by 71 percent from 1980 to 2005 in Arizona, Colorado, Nevada, and New Mexico, and electrical power demand increased by 130 percent over the same period [*Pitzer,* 2009]. Water availability has become a constraint on the expansion of electrical power generation capacity in the rapidly growing Western U.S. [*Tidwell et al.*, 2012].

New planning strategies are needed to ensure water needs are met, especially in the face of potential long-term climate change impacts [*Gober et al.,* 2010]. Adaptive allocation and management mechanisms are being explored worldwide to meet the growing challenges of increasing uncertainty and risk in water resource availability [*WWAP*, 2012; *NRCNA*, 2004], while new and innovative sources of information are sought to ensure that water is used efficiently and effectively to meet the needs of growing populations.

Trade in "virtual" or embedded water, which is a way to describe the outsourcing of water impacts as a substitute for direct use of water, is one option for human adaptation to water scarcity. The term "virtual water" originated in 1993 when used by Allan to describe what he (and others) had previously described as embedded or embodied water [*Allan,* 1993]. In this paper we utilize the terms "embedded" and "virtual" interchangeably, with a preference for the former. Water is embedded as an indirect impact implicitly associated with a traded social, environmental, or economic good or service. Allan's work showed how the import of virtual water served as an effective approach to meeting water deficits in the Middle East [*Allan,* 1996]. *Chapagain and Hoekstra* [2008] confirmed the importance of considering virtual water in water policy studies due to the significant percentage of direct human water consumption by countries that is associated with the production of international export of goods and services (as much as 16% of global water consumption). However, this trade in virtual water is rarely managed and is primarily a reflection of economic, cultural, political, climate, and other forces.

This paper presents Part 2 of a study developing the Embedded Resource Accounting (ERA) framework for water footprint, virtual water, and water economic applications. The ERA framework and an application to determine water footprints and embedded water trade associated with the Western U.S. electrical power grid are presented in Part 1 of this study (Adams et al., 2013, Submitted to WRR). Embedded water was shown to be a major component of the overall water footprint of electrical energy consumption in the Western U.S. and to spatially shift and increase the total water consumption in the system, but water availability did not appear to be a significant factor affecting the balance of trade in embedded water.

By combining water footprint and embedded water calculations with electrical trade data and the price structure of the exchange of currency for electricity, the relationship between economic trade and embedded resource impacts is revealed. We observe embedded resource Dollar Intensities of embedded water ($ per gallon) and how these resource intensities are associated with patterns of imported and exported embedded water. Part 2 of this study builds on the results presented in Part 1 to address the following research questions: (1) How do Dollar Intensities of water embedded in electricity relate to water price and value? (2) How do trends in Dollar Intensities of embedded water relate to water availability?, and finally, (3) What factors explain state-level decisions to import or export embedded water in electricity in the Western US?

Methods

This study uses the ERA framework presented in Part 1 (Adams et al. 2013, in submission to WRR). The interested reader should refer to Part 1 for a complete description of the ERA framework's mathematics and assumptions.

The basic ERA equation is,

$$E\left(i, j, r_j, r_k\right) = \left[U\left(i, j, r_j\right)[t] + V\left(i, j, r_j, r_k\right)[t]\right] * Q\left(i, r_i, j, r_j\right)[t] \qquad (1)$$

where E is the net direct U and indirect V impacts of a process (i) on a resource stock (r_j), after adjustment to account for the equivalency Q between the resource stocks in question. In the current application, no partial equivalencies were considered, i.e.

resource stocks are either fully equivalent and *local*, *Q=1*, or non-equivalent and *external*, *Q=0*. Local and external components are denoted by "*l*" and "*x*". By computing ratios of resource impacts by processes we are able to find the average Resource Intensity, *I*, where,

$$I\left(i,r_j,r_i,r_k\right)=\frac{\sum_j E\left(i,j,r_j,r_k\right)}{\sum_m E\left(m,j,r_j,r_k\right)} \tag{2}$$

I, is the ratio of the total impact on one resource stock of r_j (e.g. consumption) to the total impact of another resource stock of type r_i (e.g. production), in units of r_j/r_i, as revealed by a process or group of processes *i* and accounting for indirect impacts via *i*'s impact on intermediary stocks of type r_k. Average Resource Intensities can be found using total impacts, local impacts, or external impacts depending on the *E* values used in the calculation. In many special cases *I* is simply a process's ratio of inputs to outputs.

In this paper we introduce a new metric derived from the average Resource Intensity equation 2. In the case where the produced resource is valued through trade in a currency medium of exchange, the equation becomes a value equation and the result is a *Dollar Intensity, DI*. This is a special case of *Value Intensity* [*Martin and Ruddell*,2012]. Note that *DI* is not a strict measure of value or price in the classical economic sense. However, *DI* is a type of shadow price that can be related to a standard shadow price, as demonstrated below. Furthermore, *DI* integrates economic trade to meet market demand with physical production and cost concepts, as is true of any price.

A simple unit analysis illustrates the meaning of the *DI*. Electricity is the common stock-in-trade for which consumers trade currency and for which producers impact local water resources as an input to their processes. Thus, to obtain a Dollar Intensity for the embedded water in *$USD/gal* we combine electricity retail prices (*$USD/MWh*), and the water intensity for electricity generation (*MWh/gal*).

$$\left(\frac{USD\$_{consumer}}{MWh_{consumer}}\right) \times \left(\frac{MWh_{producer}}{gal_{producer}}\right) = \left(\frac{USD\$_{consumer}}{gal_{producer}}\right) \tag{3}$$

The first term in equation (3), the electricity consumer price, is governed (or set) by the economic *market* for the stock in trade, which implicitly includes issues of demand and supply and market regulation; the second term, the electricity producer water efficiency of generation, is governed (or set) by the *technology* of the production process, which implicitly considers issues of production cost and production regulations.

The consumer and the producer have two opposing and normative objectives. The consumer seeks to minimize its price paid ($USD/MWh) for the stock in trade, while the producer seeks to maximize the same. The producer also seeks to maximize its technological efficiency (Mgal/$USD). The resulting *DI,* ($USD\$_{consumer}/gal_{producer}$ describes the system's equilibrium including all factors affecting the market and the production process, in terms of the relationship between the market value of the electricity and the net impacts on the water resource stock. The economic definition of value is expressed in terms of economic behavior in the context of supply and demand. Value may be defined as the willingness to pay for something, in this case indirect water impacts [WTP, *Brouwer et al.*, 2009]. This *DI* represents the electricity consumer's WTP to outsource one additional (or marginal) unit of water resource impact.

However, recall that *DI* is computed with reference to only one input and one output, and without considering value added in the process. Most processes add value and use many inputs, e.g. capital, labor, and materials. Some processes also produce multiple valued outputs. *DI* may be adjusted to reflect these attributes and estimate a standard shadow price. The standard Shadow Price P_s is related to *DI* through the application of an adjustment factor *A*, as shown in equation (4):

$$P_s\left(r_j\right) = DI\left(i, r_i, r_j, r_k\right) \times A\left(k\right). \tag{4}$$

In this case we approximate *A* as,

$$A\left(k\right) = \left[\frac{f^I\left(k, r_j\right) f^O\left(k, r_k\right)}{1 + m\left(k\right)}\right], \tag{5}$$

where $f^I(k,r_j)$ is the fraction of dollar cost of r_j of the total dollar cost of all inputs to process *k*, and $f^O(k,r_k)$ is the fraction of the dollar price of r_k of the total dollar price of all outputs of process *k*. *m*(*k*) represents the percentage value added, or markup, for process output r_k. If Dollars are not the medium of exchange, then fractions are denominated in the correct medium of exchange. Recall that in this analysis the entire supply chain including production, transmission, and distribution are aggregated as one production process, so fractions and percentages should reflect the total along the supply chain.

For example, to find *A* for water embedded in electricity we can make the following assumptions; markup will be close to zero for a public utility electricity provider, the fraction of electricity among the process's valued outputs is close to 100%, and the percent of cost related to water as an input will be very low, approximated as 1% of total costs. To put this in perspective, water supplies account for between approximately 0.1% [Los Angeles electric power sector using disruption method, Rose et al. 2012] and 8% [irrigated agriculture process, FAO 1993] of input costs (or alternatively end values) of processes. For m=0, $f^I(k,r_j)$ = 0.01, and $f^O(k,r_k)$=1.0, *A*(*k*)=

0.01. Therefore the standard shadow prices (P_s) of the embedded water impacts will be approximately one-hundredth of the corresponding *DI*'s in this example.

It is difficult to separate within a process the marginal contributions of a specific input to a specific output, and this proprietary data is rarely available for public or scientific purposes. We do not use P_s for our analysis, but rather *DI*, because *A* is unknown. However, "apples to apples" comparisons between processes are valid in relative terms as long as *A* is similar for all production processes *k* under consideration. We assume this similarity in the current analysis, which allows the qualitative interpretation of *DI* patterns as price patterns, as long as the specific enumeration of the prices is not important. This assumption should be reconsidered in future work.

Data utilized for this study includes the water intensity of power generation plants for the eleven Western states within the Western Electricity Coordinating Council region (Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, and Wyoming), and retail electricity sales for these states, allowing for development of the network input-output tables required as input variables for ERA analysis (Adams et al. 2013, in submission to WRR). The input data used is a compilation of approximations based on a combination of reported and estimated numbers obtained largely from U.S. Energy Information Administration (EIA, 2013) online as well as data sets from the study by *Tidwell et al.* [2012].

The State scale is the appropriate scale of aggregation for this study because water rights and water management are governed at the State level, and because we are interested primarily in inter-Basin and inter-regional electrical trade rather than local distribution patterns. Also, electrical power prices are regulated at the State scale. Data limitations at finer scales associated with electrical utilities and distributors also make the State scale the smallest feasible scale for the study.

There are three types of resource stocks being considered: electricity (MWh), curreny ($ USD), and water (gal). Electricity is produced by a generation process and traded for currency, net raw water is consumed (i.e. the "blue" water footprint [*Hoekstra et al.,* 2011]) by electrical energy generation processes, and currency is paid in exchange for electricity by retail consumers. The electricity acts as a common stock-in-trade between producers and consumers.

The power grid in the Western United States is a complex system of electricity generation, distribution and consumption. The network used in this analysis is a simplified version. We define the network conceptually as a basic transportation network of unlimited capacity in which resource stocks flow between controlling and consuming processes.

Estimation of the electricity trade across the Western US power grid network is presented in detail in Part 1 of this study, with results illustrated for clarity in Figure 1

(Adams et al. 2013, in submission to WRR).

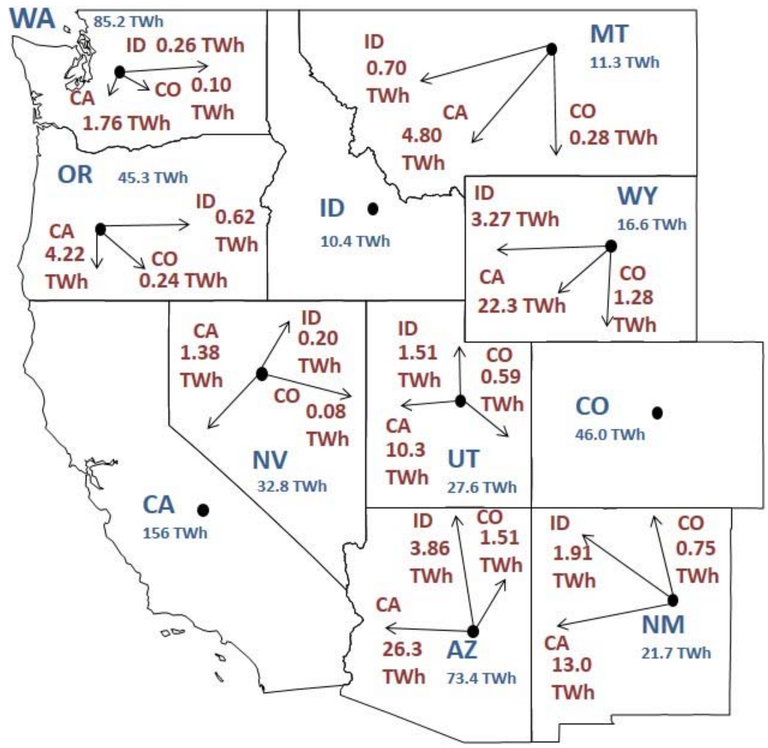

Figure 1. Estimated interstate electricity trade (TWh). Electricity transfer quantities are shown for all exporting states to all importing states (red) in addition to internally produced and consumed electricity for each state (blue). California dominates imports consuming 83.1% of the traded electricity. From (Adams et al. 2013, in submission to WRR).

Results

In this result we reveal the Dollar Intensity (*DI*) of water embedded in electricity traded on the Western U.S. power grid. The *DI* results are illustrated in Figure 2.

By utilizing the local and external components *E* of the ERA equation, we separately examine and compare the *DI*'s associated with embedded water that is consumed within the State where it originated against those of embedded water consumed external to the state in which it originated.

The *Local DI* (DI_{LOCAL}, $USD/gal) is the Dollar Intensity of the embedded water in electricity consumed by a process (utility customer) *Local* to the water supply stock used to generate the electricity. Local Dollar Intensity is found using equation (2) with the local footprint E^l which neglects external components of E. Therefore, using i = electricity consumption processes (*con*), $r_j =$ water supply stocks (*w*), $r_i =$ money stocks (*$*), and $r_k =$ electricity stocks (*e*), and water stocks (*w*), equation (2) gives gallons of local water embedded in locally produced and traded electricity per US$ exchanged for that electricity. The inverse of this result is the local Dollar Intensity of the embedded water,

$$DI_{LOCAL}\left(cons,\$,w,e\right)=\frac{\sum_m E^l\left(m,cons,\$,e\right)}{\sum_j E^l\left(cons,j,w,e\right)} \qquad (6)$$

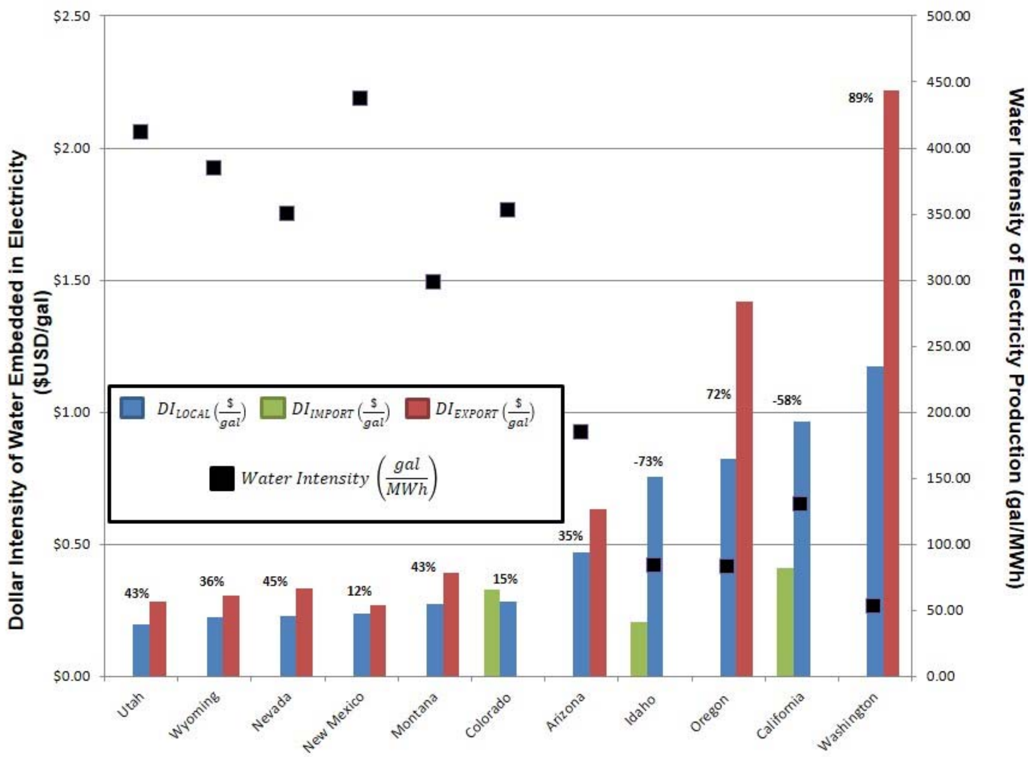

Figure 2. Dollar Intensities (*DI,* $USD/gal) of water embedded in electricity traded on the Western U.S. power grid. DI_{LOCAL} is for the water embedded in electricity produced and traded to instate consumers. DI_{EXPORT} is for the water embedded in electricity exported from the state. DI_{IMPORT} is the water embedded in electricity imported from another state. Percentages shown indicate the difference of traded vs. local *DI*'s for each State. The States are arranged in order of ascending local dollar intensity. Water intensity of electricity generation in each state is shown with black marks, and trends as opposite of dollar intensity.

In a similar fashion, by only considering external footprint components E^x, we obtain the *Import Dollar Intensity* (DI_{IMPORT}, $USD/gal), which is the Dollar Intensity of the embedded water in electricity consumed by a process (utility customer) *External* to the water supply stock used to generate the electricity. Using the notation above,

$$DI_{IMPORT}\left(cons,\$,w,e\right)=\frac{\sum_{m}E^{x}\left(m,cons,\$,e\right)}{\sum_{j}E^{x}\left(cons,j,w,e\right)} \tag{7}$$

Referring again to equation (3), for DI_{IMPORT}, the economic term (retail price) is unchanging; however the technology is that of the exporting states. So differences between a State's DI_{LOCAL} and DI_{IMPORT} reflect different producer water intensities relative to instate intensities.

Similarly, the *Export Dollar Intensity* (DI_{EXPORT}, \$USD/gal) is the Dollar Intensity of the embedded water in electricity consumed by a process (utility customer) *External* to the water supply stock used to generate the electricity, from the perspective of the producing process and relative to its local water intensity of electricity production, as,

$$DI_{EXPORT}\left(gen,\$,w,e\right)=\frac{\sum_{j}E^{x}\left(gen,j,\$,\$\right)}{\sum_{m}E^{x}\left(m,w,w,e\right)} \tag{8}$$

Referring again to equation (3), for DI_{EXPORT}, the technology term (water efficiency of electricity production) is unchanging; however the retail price paid is that of the importing States. Therefore, differences between a State's DI_{LOCAL} and DI_{EXPORT} reflect changes differences in the consumer's retail price paid for the electricity relative to instate prices.

In Figure 2, higher Local *DI*'s of embedded water are generally associated with States that have lower local water intensities for electrical generation (i.e. more water-efficient electricity generation technology) and lower local retail electricity prices. The highest Local *DI*'s are seen by Arizona, Idaho, Oregon, California, and Washington (highest), with significantly lower Local *DI*'s for the other States (Utah is lowest).

The lowest Local *DI* was found in Utah (roughly \$0.20/gal) and is less than one-fifth of the highest found in Washington (roughly \$1.20/gal), indicating that significantly more total economic value is associated with water embedded in electricity traded within some states, and that some States provide water to electrical generators under different terms. If, for example, the Adjustment Factor *A* is set at 0.01, this reveals standard shadow prices for water supplies used in electricity production ranging from one-fifth of a cent to 1.2 cents per gallon in Western US States.

Each state is either a net importer or exporter of electricity and therefore also water embedded in electricity. Generators in every net exporting state realize higher *DI*'s for exported embedded water than for internally consumed embedded water.

The percentage difference between local and external Dollar Intensities as a result of trade for each State is shown in Figure 2. Comparing the weighted average of all Local and External *DI*'s for net exporting states yields an overall 35% increase in the *DI* of embedded water in electricity realized as a result of trade, from 0.28 to 0.38 $/gal. Similarly, a 58% decrease in the *DI* of embedded water in electricity is achieved through import from the power grid as compared with electricity locally generated within net-importing states, from 0.91 to 0.38 $/gal.

Conclusions

Tidwell et al., [2012] shows that the Western US has limited water availability for new development of electrical power capacity. Fortunately, our results show that interstate embedded water trade plays a large role in the electrical energy supply network of this area. This finding means that a thriving trade in embedded water already exists via the Western US power grid, creating the potential for indirect water use to be substituted for direct water use in the event that power generation capacity needs to be expanded in water-limited locations or where capacity is decreased due to localized drought. This network of trade in embedded water is detailed in Part 1 of this study (Adams et al. 2013, in submission to WRR).

A new method is derived using the Embedded Resource Accounting methods to observe a type of shadow price for water based on the willingness to pay to substitute indirect embedded water use for direct water use in a trade network. This method yields a 'Dollar Intensity' or *DI* which is an indirect resource intensity that can be related to a standard shadow price for water. Using this method it is demonstrated that embedded water flows primarily from states with lower Dollar Intensities of embedded water toward states with higher Dollar Intensities of embedded water. This pattern illustrates the equilibrium that has been reached in the Western US power grid through market tension wherein power consumers seek to minimize the Dollar Intensity (related to price) of indirect water use, and power producers seek to maximize the same. The resulting pattern in Dollar Intensities gives the appearance of a rational market for embedded water implied within the power grid, in which embedded water moves from lower to higher values despite the lack of an explicit market for the water.

The water-limited Southwestern US States (Arizona, New Mexico, and Nevada) [*Tidwell et al.*, 2012] are major exporters of water embedded in electricity. States that are net exporters of water embedded in electricity are in this case also net exporters of electricity, with relatively low electrical power prices, and correspondingly low Dollar Intensities for water embedded in electricity. These States generally share in a combination of abundant local energy resources, low populations and electrical demands, and/or a relatively favorable regulatory environment for power producers; these factors, rather than an abundance of unallocated water resources, approximately explain the pattern of embedded water export in the system. The pattern of trade and the total economic value associated with embedded water trade in this system is dominated by the import of these resources by California.

Referring to Figure 2, net exporters have lower Dollar Intensities for embedded water than do net importers, which is a correlation that one would expect in a rational market for water resources. However, the states with the most abundant water, Washington, Oregon, and Idaho, are also those with the highest Dollar Intensities for both locally consumed and externally exported embedded water, which is the opposite of the expectation if water resource abundance is an important determining factor for electrical energy production and trade. However, if the *DI* is understood as a type of shadow price, this result appears to be a benefit to both importers and exporters as one expects from a rational market.

If water resources were scarce or highly valued, one would expect to see higher *DI*'s in such States. We do see higher *DI*'s in some States, but they are not the States with low water availability due to arid climate. They are rather the States with high electricity prices and tight power markets, high populations, large economies, restrictive regulations for water development, and many competing uses for water resources. Water is more dear for reason of its uses in the marketplace in these States, rather than because of an underlying climate-related supply shortage.

This result parallels earlier findings that arable land availability, not water availability, appears to determine production patterns for water embedded in the international agricultural trade [*Kumar and Singh,* 2005], and that virtual water flows are not necessarily consistent with water scarcity [*Nova et al.,* 2009]. In a pattern that is contrary to the principles of comparative advantage relative to a scarce and costly process input, electricity production is being outsourced to states with less water efficient power generation technologies. This finding is consistent with the absence of economically defined scarcity for water resources used in electricity production for export. However, the import by California of large amounts of water embedded in electricity may plausibly reflect strategic but economically invisible water scarcity in that state, paralleling for example the original Virtual Water argument by *Allan* [2002] that the nation of Jordan imports agricultural goods largely to circumvent a local water shortage.

Given the rapidly increasing scarcity of readily available freshwater resources in the Western U.S., this negative result for the role of water scarcity in determining embedded water sourcing begs a question as to whether future electrical energy development and embedded water trade will begin to be driven more substantially by water availability and cost considerations. *Zetland* [2011] stresses that institutions supplying water to users need to connect prices to scarcity, so that when scarcity increases users are faced with a price increase, signaling a change in availability of the resource. In the future it is likely to become more important for planners of development in all economic sectors, including electrical energy production, to consider the cost and availability of water as a part of economic development decisions, as scarcer water is utilized for higher-value uses. This paper depicts a current reality that is in stark contrast to one where revealed water prices reflect scarcity, at least in the sense that scarcity may come to affect some power producers in the near future as rising demand conflicts with low availability of unallocated supplies. Under current conditions producers appear to be largely insulated from any real or perceived water scarcity problem.

An increasing economic scarcity of water could be reflected in the embedded water trade by a growth of electrical energy production outside of the water-scarce Southwestern US, especially within the water-rich Pacific Northwestern US. In that circumstance it would be necessary to expand long-distance electrical energy transmission capacity to support transmission of energy from Oregon and Washington to California. This development would release Southwestern water supplies to support these States' own rapidly growing electrical consumption demands. Alternatively, Southwestern states could continue to develop new electric generation capacity but with low water use technologies (e.g. wind, PV, or dry cooling).

Future work should take advantage of the multi-resource capabilities of Embedded Resource Accounting to compare the Dollar Intensities of embedded water of the major water-using sectors of the global economy. For example, a comparison could be made between the electrical energy production sector and the agricultural and industrial uses of water in a given location, and the relative dollar intensities of imported and exported goods and services could be compared to evaluate reallocation or marketing policies for water. Other strategic resources besides water (e.g. land and skilled labor) should likewise be included as resources so that the relative importance of water intensity, land intensity, labor intensity, and dollar intensity of embedded water can be analyzed to understand what uses have higher and lower value intensities. The indirect costs created by regulation or other indirect effects can be observed, for example by using resource intensities to infer and reveal equivalencies between different stocks.

This information can be utilized by policymakers to understand how local and external strategic resources are being impacted by various natural and economic processes and to quantify what value is being produced (and for whom) through these processes. The direct and indirect resource dependencies and connections between localities, such as States, municipalities, countries, river basins, etc., can be delineated. It is possible in principle using these methods to determine when direct or indirect trading in water or other resources is more cost effective. Finally, information about embedded resources can help to reveal the vulnerability and resilience of a locality's natural and human economies to the depletion or disruption of external resource stocks, and can help to inform policies of sustainability and resilience by which a locality can manage its indirect connections to external resources' stocks in order to achieve various policy objectives.

Refernces

Allan, T. (1993), Fortunately there are substitutes for water: Otherwise our hydropolitical futures would be impossible, paper presented at Conference on Priorities for Water Resources Allocation and Management, Overseas Dev. Admin., London.

Allan, J. A. (1996), Policy responses to the closure of water resources. In *Water Resource Policy: Allocation and Management in Practice*, ed. P. Howsam and R. carter. London: Chapman and Hall.

Allan, J.A. (2002), Hydro-peace in the Middle East: Why No Water Wars? A Case Study of the Jordan River Basin. *SAIS Review XXII(2),* 255–272.

Brouwer, R., D. Barton, I. Bateman, L. Brander, S. Georgiou, J. Martin-Ortega, S. Navrud, M. Pulido-Velasquez, M. Schaafsma, and A. Wagtendonk (2009)*, Economic valuation of environmental and resource costs and benefits in the water framework directive: Technical guidelines for practitioners.* Institute for Environmental Studies, VU University of Amsterdam, the Netherlands.

Chapagain, A. K., and A. Y. Hoekstra (2008), The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water International, 33*(1), 19-32. doi: 10.1080/02508060801927812.

EIA (2013), Annual Energy Outlook 2013, U.S. Energy Information Administration, April 2013.FAO (Food and Agriculture Organization of the United Nations) (1993), *The state of food and agriculture*. FAO Agriculture Series, no. 26. ISBN 92-5-103360-9. Rome, Italy.

Hoekstra, A. Y., A. K. Chapagain, M. M. Aldaya, and M. M. Mekonnen (2011), *The Water Footprint Assessment Manual: Setting the Global Standard.* Earthscan Publishing. Water Footprint Network. Available from: http://www.waterfootprint.org/downloads/TheWaterFootprintAssessmentManual.pdf.

Kumar, M. D. and O. P. Singh (2005), Virtual water in global food and water policy: Is there a need for rethinking? *Water Resourc. Manag., 19*, 759-789, doi:10.1007//s11269-005-3278-0.

Martin, E.A. and B.L. Ruddell (2012), Value intensity of water used for electrical energy generation in the Western U.S.; An application of embedded resource accounting. *IEEE International Symposium of Systems and Technology, Conference paper.* Boston, Mass.

Nova, P., A. Garrido and C. Varela-Ortega (2009), Are virtual water "flows" in Spanish grain trade consistent with relative water scarcity? *Ecol. Econ. 68*, 1454-1464. doi: 10.1016/j.ecolecon.2008.10.013.

NRCNA (National Research Council of the National Academies) (2004). *Management for Water Resources Project Planning*. Washington, DC: The National Academies Press.

Pitzer, G. (2009), *The Water-Energy Nexus in the Colorado River Basin*, Colorado River Project, Water Education Foundation, River Report 7, Available from: http://www.watereducation.org/userfiles/RiverReport_Summer09_WEB.pdf.

Postel,S. L. (2000), Entering an Era of Water Scarcity: The Challenges Ahead, *Ecol. Appl., 10(4)*, 941-948.

Reisner M. (1993), *Cadillac Desert: The American west and its disappearing water*. New York: Penguin Books.

Rose, A., I.S. Wing, D. Wei, and M. Avetisyan (2012), *Total regional economic losses from water supply disruptions to the Los Angeles County economy*. Los Angeles County Development Corporation Report. University of Southern California.

Tidwell, V.C., P.H. Kobos, L.A. Malczynski, G. Klise, and C.R. Castillo (2012), Exploring the water-thermoelectric power nexus, *Journal of Water Planning and Management*, *138*(5), 491-501. Wildman, R. A., Jr., and N. A. Forde (2012), Management of water shortage in the Colorado river basin: Evaluating current policy and the viability of interstate water trading. *J. American Water Resour. Assoc., 48*(3), 411-422. doi: 10.1111/j.1752-1688.2012.00665.x.

Wolman, A. (1965). The metabolism of cities. Scientific American, 213(3),179-190.

WWAP (World Water Assessment Programme). (2012), *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk.* Paris, UNESCO.

Zetland, D. (2011). *The End of Abundance: economic solutions to water scarcity*. Aguanomics Press. ISBN: 978-0615469737.

Chapter 4

EMBEDDED RESOURCE ACCOUTING FOR WATER RESOURCE APPLICATIONS; IMPACTS OF FUELS EXTRACTION AND TRADE IN THE WESTERN U.S.

Abstract

Population and resource demands continue to grow in the Western U.S. Climate change places added stress on management and predictability of existing resources making sustainable resource management an ever more important topic – particularly for water resources.

The relocation of existing water resources and the development of 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 energy and agriculture production. Therefore, the remote production and virtual transmission of these resources provides a powerful management solution for adaptation to changing conditions of available water resources. Trade in virtual water has become a widely utilized mechanism for adaptation to water scarcity, is already part of the solution for water resource management in the Western U.S.

Embedded Resource Accounting ERA is a new methodology that allows us to quantify and illustrate resource consumption offsets that result from outsourcing of resource intensive processes, utilize the economics of trade to infer an environmental resource value metric (dollar intensity) of embedded resources, and examine the relationships created by the direct and indirect connections within resource trade networks.

This paper uses ERA to analyze primary energy fuel resource extraction (coal, natural gas, petroleum) in the Western U.S. and reveal relationships between water availability, embedded water, energy fuel source extraction and the balance of economic trade in these fuels.

An implicit and rational market for trade in indirect water use embedded within energy fuels appears to exist in the Western U.S. as indicated by Dollar Intensities of water embedded in traded fuels. However, water availability is not currently a significant factor organizing the trade. These methods provide beneficial tools to inform sustainable resource management decision making by highlighting opportunities to build resilience into the systems.

Introduction

Multiple challenges to sustainability in water resources management currently exist. Water is different from other resources. Water flows within streams, rivers and underground aquifers; water seeps into the ground, evaporates, re-condenses, and falls from the sky as precipitation. Water is mobile and cyclical and is constantly being used and re-used. Further, the natural hydrologic cycle of water is heavily intertwined with anthropogenic water uses, creating a coupled human and natural system in which water continually goes through many changes in state, quality, and location. As a result, available high quality fresh water resources are unevenly and unpredictably distributed in time and space. Climate change is expected to increase uncertainty in annual renewable water resources due to fluctuations in precipitation and an increase extreme weather events such as flooding and prolonged droughts.

Anthropogenic water uses of fresh water resources may already exceed sustainable levels at a global scale, [*Postel,* 2000], and long-term demands in many regions exceed available supplies, as is the case for the Colorado River Basin and the Western United States in general [*Wildman and Forde,* 2012; *Tidwell et al.*, 2012]. Anticipated long-term climate change impacts increase the need for adaptive strategies [*Gober et al.,* 2010]. One adaptive option for water scarcity in a specific location is to utilize trade in "virtual" water, which is essentially the outsourcing of water resource impacts to a supplier via trade or indirect exploitation. This outsourcing substitutes an indirect (and usually distant) impact for a direct resource impact.

New planning strategies are needed to ensure water needs are met, especially in the face of potential long-term climate change impacts [*Gober et al.,* 2010]. Adaptive allocation and management mechanisms are being explored worldwide to meet the growing challenges of increasing uncertainty and risk in water resource availability [*WWAP*, 2012; *NRCNA*, 2004], while new and innovative sources of information are sought to ensure that water is used efficiently and effectively to meet the needs of growing populations.

Trade in "virtual" or embedded water, which is a way to describe the outsourcing of water impacts as a substitute for direct use of water, is one option for human adaptation to water scarcity. The term "virtual water" originated in 1993 when used by Allan to describe what he (and others) had previously described as embedded or embodied water [*Allan,* 1993]. In this paper we utilize the terms "embedded" and "virtual" interchangeably, with a preference for the former. Water is embedded as an indirect impact implicitly associated with a traded social, environmental, or economic good or service. Allan's work showed how the import of virtual water served as an effective approach to meeting water deficits in the Middle East [*Allan,* 1996]. *Chapagain and Hoekstra* [2008] confirmed the importance of considering virtual water in water policy studies due to the significant percentage of direct human water consumption by countries that is associated with the production of international export of goods and services (as much as 16% of global water consumption). However, this trade in virtual water is rarely managed and is primarily a reflection of economic, cultural, political, climate, and other forces

By combining embedded water calculations with fuel resource trade data and the price structure of the exchange of currency for fuels, a relationship between economic trade and embedded resource impacts is revealed. We observe embedded resource Dollar Intensities of embedded water ($ per gallon) and how these resource intensities are associated with patterns of imported and exported embedded water.

This study addresses the following research questions: (1) What portion of the water footprint of fuel resource extraction and consumption by Western US States is associated with traded energy fuels and embedded water, (2) How does water availability affect the observed trade under current conditions? (3) How do Dollar Intensities of water embedded in energy fuels relate to water price and value? (4) How do trends in Dollar Intensities of embedded water relate to water availability?, and finally, (5) What factors explain state-level decisions to import or export embedded water in energy fuels in the Western US?

Methods

This study uses the ERA framework presented by *Adams et al.* [2013a, in submission to WRR]. The interested reader should is referred here for a complete description of the ERA framework's mathematics and assumptions.

The basic ERA equation is,

$$E\left(i,j,r_j,r_k\right)=\left[U\left(i,j,r_j\right)[t]+V\left(i,j,r_j,r_k\right)[t]\right]*Q\left(i,r_i,j,r_j\right)[t] \qquad (1)$$

where E is the net direct U and indirect V impacts of a process (i) on a resource stock (r_j), after adjustment to account for the equivalency Q between the resource stocks in question. In the current application, no partial equivalencies were considered, i.e. resource stocks are either fully equivalent and *local*, $Q=1$, or non-equivalent and *external*, $Q=0$.

By computing ratios of resource impacts by processes we are able to find the average Resource Intensity, I, where,

$$I\left(i,r_j,r_i,r_k\right)=\frac{\sum_j E\left(i,j,r_j,r_k\right)}{\sum_m E\left(m,j,r_j,r_k\right)} \qquad (2)$$

I, is the ratio of the total impact on one resource stock of r_j (e.g. consumption) to the total impact of another resource stock of type r_i (e.g. production), in units of r_j/r_i, as revealed by a process or group of processes i and accounting for indirect impacts via i's impact on intermediary stocks of type r_k.

In addition we utilize a new metric derived from the average Resource Intensity equation 2, presented in *Adams et al.* [2013a, in submission to WRR].. In the case where the produced resource is valued through trade in a currency medium of exchange, the equation becomes a value equation and the result is a *Dollar Intensity, DI*. Note that *DI* is not a strict measure of value or price in the classical economic sense. However, *DI* is a type of shadow price that can be related to a standard shadow price, as demonstrated below. Furthermore, *DI* integrates economic trade to meet market demand with physical production and cost concepts, as is true of any price.

A simple unit analysis illustrates the meaning of the *DI*. The energy resource is the common stock-in-trade for which consumers trade currency and for which producers impact local water resources to extract. Thus, to obtain a Dollar Intensity for the embedded water in *$USD/gal* we combine retail fuel prices (*$USD/unit of energy resource*), and the water intensity for fuel extraction (*unit of energy resource/gal*).

$$\left(\frac{USD\$_{consumer}}{Fuel_{consumer}}\right) \times \left(\frac{Fuel_{producer}}{gal_{producer}}\right) = \left(\frac{USD\$_{consumer}}{gal_{producer}}\right) \tag{3}$$

The first term in equation (3), the fuel consumer price, is governed (or set) by the economic *market* for the stock in trade, which implicitly includes issues of demand and supply and market regulation; the second term, the energy resource producer water efficiency of extraction, is governed (or set) by the *technology* of the extraction process, which implicitly considers issues of production cost and production regulations.

The consumer and the producer have two opposing and normative objectives. The consumer seeks to minimize its price paid ($USD/unit of fuel) for the stock in trade, while the producer seeks to maximize the same. The producer also seeks to maximize its technological efficiency (unit of fuel/gal). The resulting *DI,* ($USD\$_{consumer}/gal_{producer}$) describes the system's equilibrium including all factors affecting the market and the production process, in terms of the relationship between the market value of the fuel resource and the net impacts on the water resource stock. The economic definition of value is expressed in terms of economic behavior in the context of supply and demand.

Value may be defined as the willingness to pay (WTP) for something, in this case indirect water impacts [*Brouwer et al.*, 2009]. This *DI* represents the energy consumer's WTP to outsource one additional (or marginal) unit of water resource impact.

An increase in the *DI* indicates either an increase in price paid by the consumer, or an increase in water efficiency in production technology, or both. To evaluate changes in *DI* as a result of trade, we calculate three separate *DI* values. We begin with a "baseline" in-state or Local *DI* which includes in-state price paid and in-state water intensity. The Import and Export *DI* values help illustrate the effects of trade.

The Import *DI* is calculated for states that import energy resources from other states, so their price paid is held constant and the water efficiency is a weighted average of production states from which the resources are being imported. So a comparison between Local *DI* and Import *DI* for importing tells us whether imports are coming from more or less efficient technologies than what exist currently in-state. From a water conservation standpoint, we would desire an increase in *DI* from Local to Import indicating that imported resources were produced using more efficient technology than exists locally.

The Export *DI* is calculated for states that export energy resources to other states, so the water efficiency is held constant and the price paid is a weighted average of import states to which the resources are being exported. Therefore, a comparison between Local *DI* and Export *DI* for exporting entities is an indicator of increased profitability of exports versus in-state sales of the resources. From a market standpoint for a producing state, an increase would indicate an increase in profitability per gallon of water invested in energy production.

Data

The data used in this analysis was obtained largely from U.S. Energy Information Administration (EIA) online databases including: average pricing of delivered coal for the electricity sector within each state for 2011 for the eleven western U.S. states selected [*USEIA,* 2012e], coal import and export data for electricity sector (which accounts for 93% of U.S. domestic distribution) for each state for 2011 [*USEIA,* 2012a], weighted average prices of natural gas for states paid by end use consumer [*USEIA*, 2013d,e], natural gas export prices for 2011 for Mexico and Canada [*USEIA*, 2013g], natural gas production and trade quantities for each state [*USEIA*, 2013b,c], average retail gasoline prices (all grades) by state, 2011 [*USEIA*, 2013h], petroleum production and consumption by state, 2011 [*USEIA*, 2012c, 2013f], and foreign imports of crude oil and petroleum products by country of origin, 2011 [*USEIA*, 2012d].

Other data utilized in this study includes estimated average water consumption intensities of coal extraction and oil production each states for each state [*Elcock,* 2010], and estimated water intensities of natural gas extraction for each state [*Elcock*, 2008]. The input data for this study must be understood to be an approximation based on a combination of reported and estimated numbers.

The resulting average resource intensities for the network being examined are presented in Table 1. These intensities are the average water intensity of coal production (surface or underground mining), average water intensity of natural gas processing (plus hydrostatic testing and pipeline transport), average water intensity of oil production (weighted average between conventional production and thermal steam of crude oil exploration and production), the average prices of coal imports for the electricity sector, natural gas imports, and retail gasoline within each state for 2011. We aggregate fuel extraction, transmission, and distribution together as a single process. This assumption is necessitated by limited data availability and is discussed further in the next section.

Table 1 presents the resource intensities utilized in this analysis for the three primary fuel resources investigated. Entities are listed in order of highest water intensity for coal extraction, showing that the most water intensive coal extraction is done in Utah, and the most water efficient in Arizona and Wyoming. Average prices per short ton of coal range from $22 in Montana to $74 in California, most likely a reflection of environmental regulations as California actually uses very little coal for electricity generation. Water intensities for natural gas do not fluctuate much across the region, with most states having the same average water intensity. Extrapolation of this water intensity for natural gas extraction beyond the Western U.S. to include Canada is assumed reasonable since the water intensities are so near uniform across the region and no additional data is available to contradict, however this assumption may introduce error into resultant quantities of imported embedded water in natural gas. Similar to natural gas, water intensities for oil extraction and production do not fluctuate across the region, with all producing states having the same average water intensity. Extrapolation of this water intensity for beyond the Western U.S. to include all other producers is assumed reasonable since the water intensities are so near uniform across the region and no additional data is available to contradict, however this assumption may introduce error into resultant quantities of imported embedded water in oil.

Table 1. State resource intensities for fuel production and consumption[a,b]

	Coal		Natural Gas		Oil	
	Water Intensity (gal/ton)	**Price ($/ton)**	**Water Intensity (gal/million cubic feet)**	**Price ($/thousand cubic feet)**	**Water Intensity (gal/barrel)**	**Price ($/barrel)[b]**
Utah	106.0	$ 39.04	2550	$ 6.83	28.06	$ 72.05
Colorado	86.9	$ 33.37	2550	$ 6.99	28.06	$ 73.40
New Mexico	34.1	$ 38.02	2550	$ 6.37	28.06	$ 65.47
Montana	21.3	$ 22.37	2730	$ 8.29	-	$ 65.84
Wyoming	12.8	$ 25.64	2550	$ 6.44	28.06	$ 65.84
Arizona	12.0	$ 38.33	2550	$ 7.17	28.06	$ 72.05
California	-	$ 74.28	2550	$ 7.21	28.06	$ 65.04
Idaho	-	-	-	$ 7.42	-	$ 69.52
Nevada	-	$ 53.91	2550	$ 6.49	28.06	$ 65.84
Oregon	-	$ 30.00	2550	$ 7.84	-	$ 71.59
Washington	-	$ 36.91	-	$ 9.91	28.06	$ 65.84
US Ave	-	$ 46.29	-	$ 6.82	28.06	$ 67.94
Mexico	-	-	-	$ 4.18	28.06	-
Canada	-	-	2550	$ 4.45	28.06	-
Global Ave					28.06	

[a]Average water intensity of fuel resource production by state, organized from highest to lowest intensity of coal production

[b]Estimated 19 gallons of gasoline per barrel [*USEIA*, 2013a]

Estimation of Trade Networks

Energy trade in the Western United States is a complex system of, extraction, distribution, and consumption. The networks used in this analysis are simplified versions. We define the networks conceptually as a basic transportation networks in which resources (energy fuels, water, and economic currency) flow between controlling and consuming processes. The systems are taken as closed and conservative such that fuel production is equal to consumption within each network.

For each fuel source the network under analysis consists of eleven western continental U.S. states: Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, and Wyoming. The State scale is the appropriate scale of aggregation for this study because water rights and water management are governed at the State level, and because we are interested primarily in inter-Basin and inter-regional electrical trade rather than local distribution patterns. Some variation exists between total networks utilized for the different fuels as a result of data availability and the extent of trade occurrence beyond the boundaries of the western United States. The specifics of each network are described in the following passages.

These methods have chosen both to aggregate groups of processes and to exclude from analysis other processes that are connected through trade across an arbitrary boundary. The following assumptions are implied in order to neglect the error in water footprint and resource intensity calculations that is introduced by these simplifications. First, in order to *exclude* processes outside a boundary, one or the other of two assumptions must be made: either (1) excluded processes have similar resource intensities to included processes, or (2) trade with excluded processes is sufficiently small relative to intra-system trade such as to render differences in resource intensities negligible as a weighted component of the total system's trade. Second, in order to *aggregate* processes together (e.g. all consumers or exporters of a fuel resource in a State), the aggregated processes must both (1) have similar resource intensities to each other, and (2) share with each other the same net import or export relationships with all of the included processes. In the current analysis, assumptions for exclusion of entities beyond the Western U.S. are justified according as referenced above (and is described in the following sections in additional detail), but the assumptions for aggregation of consumption and production processes within States are questionable and might therefore reduce the representativeness of the results for specific producers and consumers in each State.

Coal. The coal trade network is explicitly defined within USEIA data. To match trade quantities with available price data coal used within the electrical energy sector was identified and used for this analysis. Coal trade information was obtained directly from *USEIA* [2012a] data tables. All coal imports to the western states of concern are from within the system. Exports to states outside of the network are lumped together as "Other U.S. States." Combining all other states importing coal from the Western US will not significantly impact results. The weighted average in network price per ton of coal is $34.27 (prices range from $22 to $74 per ton) and the average US price for coal in the electrical energy sector is $46.29 (see Table 1). Coal trade for the electricity sector across the network is summarized in Table 2 and the resulting interstate transfers are shown in Table A1 in Appendix A.

Table 2. Interstate trade of coal in the electricity sector

	Production for instate consumption (thousand tons)	Imports (thousand tons)	Exports (thousand tons)
Wyoming	24902	0	400652
Montana	23895	555	14730
Colorado	20920	10004	11170
New Mexico	24530	0	8211
Utah	15424	1977	2874
Arizona	7872	14976	0
California	0	838	0
Idaho	0	0	0
Nevada	0	3105	0
Oregon	0	2352	0
Washington	0	3523	0
Other US States	NA	400309	NA

Natural Gas. The data available for natural gas trade is less consistent and complete than that available for coal. The system required adjustment to balance as error quantities were found between calculated consumption (production + imports - exports) and reported consumption. These errors were applied to consumption quantities by state; the production and trade quantities were used as reported. Production and trade values are essential to the calculation of resource intensities in this analysis, therefore maintenance of accuracy in those numbers was priority. The error is due to a combination of storage changes, losses and data errors. The effects are reflected in water footprint of natural gas consumption values only, not values related to resource trade. Also, Mexico and Canada are significant trade partners of natural gas and are included as additional entities in the network. . A large percentage (29%) of network imports to the western states of concern are from Canada. Exports to Mexico are accounted for separately as well. U.S. states outside of the network are lumped together as “Other U.S. States” to which over 40% of the system’s natural gas is exported. As with coal trade, combining all other states importing natural from the Western US will not significantly impact our results. The weighted average in network price per thousand cubic feet of natural gas is $7.22 (prices range from $6.37 to $9.91 per thousand cubic feet) and the average US price for coal in the electrical energy sector is $6.82 per thousand cubic feet (see Table 1).

The network was defined assuming total connectivity between all entities with exports divided proportionally among importing entities according to the percent of total import by each importing entity. Estimation of natural gas trade across the network is summarized in Table 3 (nonzero values only) and the resulting interstate transfers are shown in Table A2 in Appendix A.

Table 3. Natural Gas Estimated Trade Network

	Net Interstate Trade (million cubic feet)	**Gross Import (million cubic feet)**	**Gross Import Percentage (%)**
Arizona	-306794	1167295	5.58%
California	-1863660	1863660	33.90%
Idaho	-83216	83216	1.51%
Nevada	-245304	245304	4.46%
Oregon	-172851	172851	3.14%
Washington	-317343	317343	5.77%
Other US States	-2375539	2375539	43.21%
Mexico	-133313	133313	2.42%
		Gross Export (million cubic feet)	**Gross Export Percentage (%)**
Colorado	1005837	1005837	18.29%
Montana	19625	19625	0.36%
New Mexico	875172	875172	15.92%
Utah	169548	169548	3.08%
Wyoming	1844573	1844573	33.55%
Canada	1583265	1583265	28.80%

Petroleum. Oil trade in the United States is primarily defined by foreign imports. The U.S. consumed 6,916,553 thousand barrels of crude oil in 2011, and produced 2,065,172 thousand barrels. Requiring foreign imports of 70% of the crude oil consumed. Western states in my analysis produced just 18% of consumption demand for the region in 2011 [*USEIA*, 2012c, 2013e]. The network for this analysis was defined by identifying crude oil production and consumption (transportation sector) quantities in each of the 11 western states in the system and for the U.S. as a whole.

Trade within each state taken as production minus consumption. Only Wyoming, Montana, and New Mexico produced oil in excess of in-state consumption for 2011. The rest of the U.S. was lumped together as a single entity in the system, and one of a large importer of petroleum. To meet the trade deficit in the region and in the U.S. foreign imports were identified [*USEIA*, 2012d]. Total foreign imports balanced with calculated domestic consumption resulted in an excess of 15%. This amount was reduced from the total foreign import quantities for system balance. This imbalance is a result of a combination of issues. Production data from EIA include estimations and adjustments in total crude oil quantities, estimates of domestic crude oil field production, independent rounding of individual components. The resultant import value utilized here provides sufficient information for the development of resource intensities and water footprints for comparison across regions of interest.

The network was defined assuming total connectivity between all entities with exports divided proportionally among importing entities according to the percent of total import by each importing entity. The estimation of oil trade across the network is summarized in Table 4 (nonzero values only) and the resulting transfers are shown in Table A3 in Appendix A.

Table 4. Petroleum Estimated Trade Network

	Net Trade (thousand barrels)	**Gross Import (thousand barrels)**	**Gross Import Percentage (%)**
Arizona	-84530	84530	2.95%
California	-348957	348957	12.18%
Colorado	-35351	35351	1.23%
Idaho	-23319	23319	0.81%
Nevada	-35301	35301	1.23%
Oregon	-55937	55937	1.95%
Utah	-17546	17546	0.61%
Washington	-107808	107808	3.76%
Other US States	-2155681	2155681	75.26%
		Gross Export (thousand barrels)	**Gross Export Percentage (%)**
Montana	3709	3709	0.13%
New Mexico	35464	35464	1.24%
Wyoming	37592	37592	1.31%
Canada	811964	811964	28.35%
Mexico	402052	402052	14.04%
Other Foreign Countries	1573649	1573649	54.94%

The variability in networks of analysis from the completely regionally constrained network of the WECC [*Adams et al.*, 2013] to the global network of the petroleum market, allows us to examine a spectrum of

By combining this estimated information for energy fuel production and trade with the corresponding currency payments and with the consumption of water for fuel extraction through the movement of water from State water supply stocks to the atmosphere, we construct input-output tables for directional pairwise impacts on the resource stocks of thirty-four processes for each fuel type, see *Adams et al.* [2013a, in submission to WRR] for detailed description of methods.

Results

Water Footprint of Coal. Figure 1 illustrates the direct *U* and indirect *V* components of the water footprint *E* for each State for coal production and consumption. Embedded water in extracted coal flows from producing states to both internal (instate) and external (interstate) consumers.

Calculation of *E* from equation (1) is performed from the position of both the producer process and the consumer process. On the production side, the direct impact *U* of production on instate water supplies is exactly offset by local and external embedded outflows. Therefore, following the form of equation (1), the water footprint *E* of the generator process is zero.

For consumers, the direct impact *U* is zero in this simplified case. Similarly, there are no outputs of virtual water supplies, but there are both local and non-local inputs of embedded water. Therefore the water footprint *E* of the consumer process is the sum of the local and external water footprints.

The determination of equivalency of instate vs. external water resource stocks is therefore critical for the calculation of the water footprint. In our present study we take the perspective of a hypothetical manager of the total water resources of the Western U.S., and as such we include both local and external impacts in our water footprint calculation. A state water resource manager might only include local water impacts in the calculation.

Note that for the total system in Figure 1, $\sum \omega_{IMPORT} = \sum \omega_{EXPORT}$, so water is conserved.

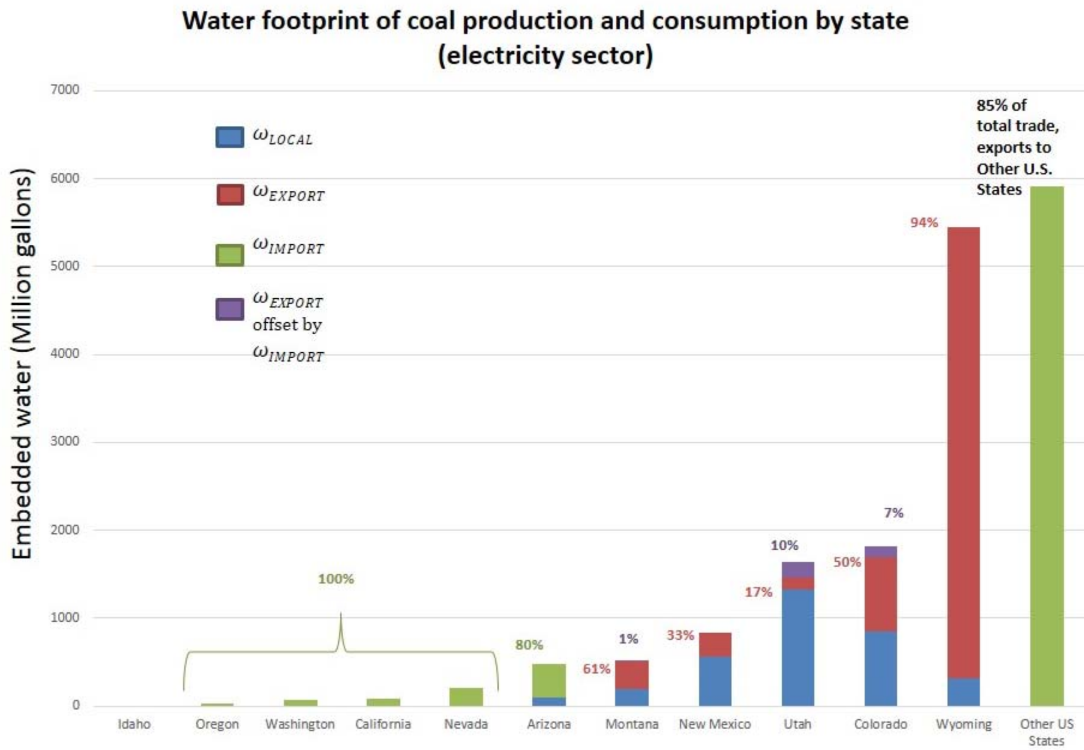

Figure 1. Water footprint, *E,* for coal extraction and consumption the Western U.S., by state. ω_{LOCAL} is the water embedded in coal extracted instate and traded to instate customers. ω_{EXPORT} is the water embedded in coal that is exported from the state. ω_{IMPORT} is the water embedded in coal imported to the state. Percentages indicate percent of individual state's footprint that is involved in interstate trade, either imported or exported. For states that have both imports and exports of embedded water in coal the offset is show as well. Percentages shown for trade with entities outside of the western states system being analyzed (other U.S. states) is a percentage of total trade.

Figure 1 shows clearly that Wyoming is the predominant water user for coal production (on the order of 5.5 billion gallons) in the Western U.S. Additionally, more than 90% of the embedded water is exported out of state – and of those exports the great majority are also being exported out of the region to other US States. Utah shows up as the largest in-state consumer of embedded water in coal, followed by Colorado, New Mexico and Arizona. Arizona is the only state showing a substantive consumptive use of embedded water in coal that is not also a net exporter of coal.

Dollar Intensities of Coal. In this result we reveal the Dollar Intensity of water embedded in coal trade in the Western U.S. Recall from Table 1 that the water intensity of coal extraction processes (i.e. water use efficiency in gal/ton) and the currency intensity of coal consumption processes (i.e. retail price in $/ton) are known for each State and this data was utilized to estimate the *IO* tables underlying these ERA calculations. Coal consumers trade in both embedded water and money, allowing for use of equation (2) to find a dollar intensity of the water embedded in the extracted coal.

By utilizing local and external components of the ERA equation, it is possible to separately examine and compare the partial indirect prices associated with embedded water that is consumed within, versus that consumed external to, the State where it originated. Refer to *Adams et al.* [2013b] for additional information on the derivation of *DI* calculations.

Figure 2 shows three dollar intensity values, the local dollar intensity, DI_{LOCAL} represents the dollar intensity of water embedded in locally produced coal that is then sold and consumed instate, export dollar intensity, DI_{EXPORT} is the water embedded in coal that is exported from the state, import dollar intensity, DI_{IMPORT} is the water embedded in coal that is imported to the state. Comparing weighted averages of local DI_{LOCAL} for exporting states and DI_{IMPORT} for importing entities (including Other U.S. states) a 75% increase in *DI* of the embedded water is realized as a result of trade.

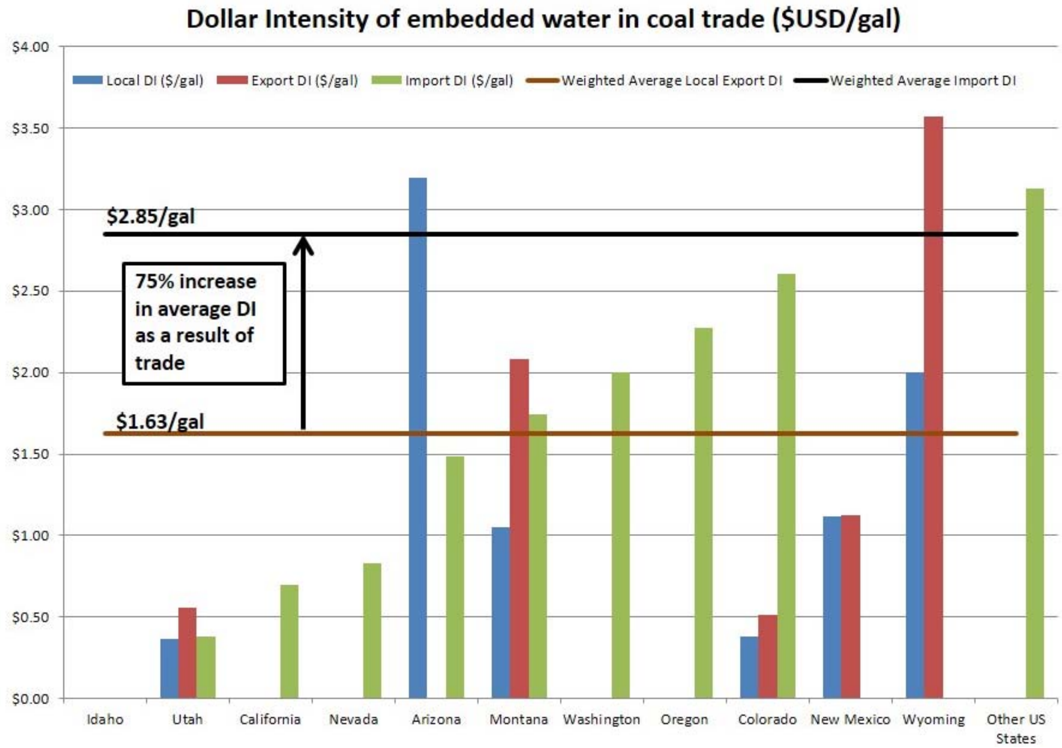

Figure 2. Dollar Intensities (*DI,* $USD/gal) of water embedded in coal traded for electrical power production in the Western U.S. DI_{LOCAL} is the water embedded in coal produced instate and traded to instate consumers . DI_{EXPORT} is the water embedded in coal that is exported from the state. DI_{IMPORT} is the water embedded in coal that is imported to the state. Comparing weighted averages of local DI_{LOCAL} for exporting states and DI_{IMPORT} for importing entities (including Other U.S. states) a 75% increase in DI of the embedded water is realized as a result of trade.

Dollar intensities before and after trade are the lowest in Utah. Utah also has the highest water intensity of coal extraction, i.e. the least water efficient coal extraction technologies in the Western U.S. (Table 1).

In the case of Arizona, there is a large drop in *DI* between Local and Import dollar intensities. This appears as a desirable outcome for a rational economic market. However, in the case of *DI* a decrease is either due to a reduction in price (good from a consumer standpoint) or a reduction in water efficiency (not good.). See equation (3). Arizona is a net importer of coal, so the difference due to trade in not in the price, therefore the reduction is a result of outsourcing of this process to less areas with less water efficient processes for the extraction of coal. For every other state with multiple DIs we see an increase from the Local DI to the import or Export DI as a result of trade –signaling either an increase in price (good from a producer standpoint) or an increase in water efficiency (a good thing from a water management standpoint).

States who are the biggest consumers of coal and associated embedded water are states who produce coal and pay relatively lower retail prices. Recall that 85% of the embedded water in coal is exported out of the network to other U.S. States – this significantly influences the after trade *DI* (weighted average of the import *DI*), from which we see a 75% increase occurring due to trade.

Water Footprint of Natural Gas. Figure 3 illustrates the direct *U* and indirect *V* components of the water footprint *E* for each State for natural gas production and consumption. The calculations were performed in the same manner as that described in the previous passages on the Water Footprint of Coal.

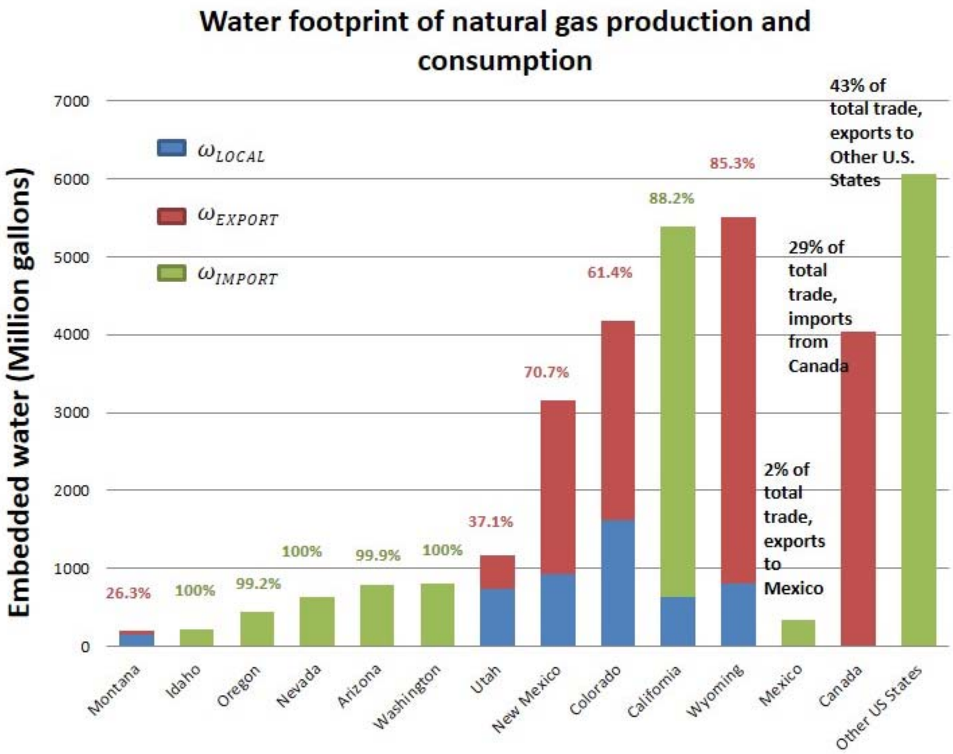

Figure 3. Water footprint, *E,* for natural gas extraction and consumption the Western U.S., by state. ω_{LOCAL} is the water embedded in natural gas extracted instate and traded to instate customers. ω_{EXPORT} is the water embedded in natural gas that is exported from the state. ω_{IMPORT} is the water embedded in natural imported to the state. Percentages indicate percent of individual state's footprint that is involved in interstate trade, either imported or exported. Percentages shown for trade with entities outside of the western states system being analyzed (Mexico, Canada, and other U.S. states) are percentages of total trade.

California is the major end-user of water embedded in natural gas. Other major users of embedded water in natural gas are exporting states (WY, CO, and NM) and each exports the majority of water used.

This result highlights a significant embedded water link between California and Western states, Wyoming, Colorado and New Mexico. This link represents an embedded water dependence as well as an energy dependence.

Dollar Intensities of Natural Gas. Here we reveal the Dollar Intensity of water embedded in the natural gas trade in the Western U.S. using the same methods described for determination of the Dollar Intensities of Coal.

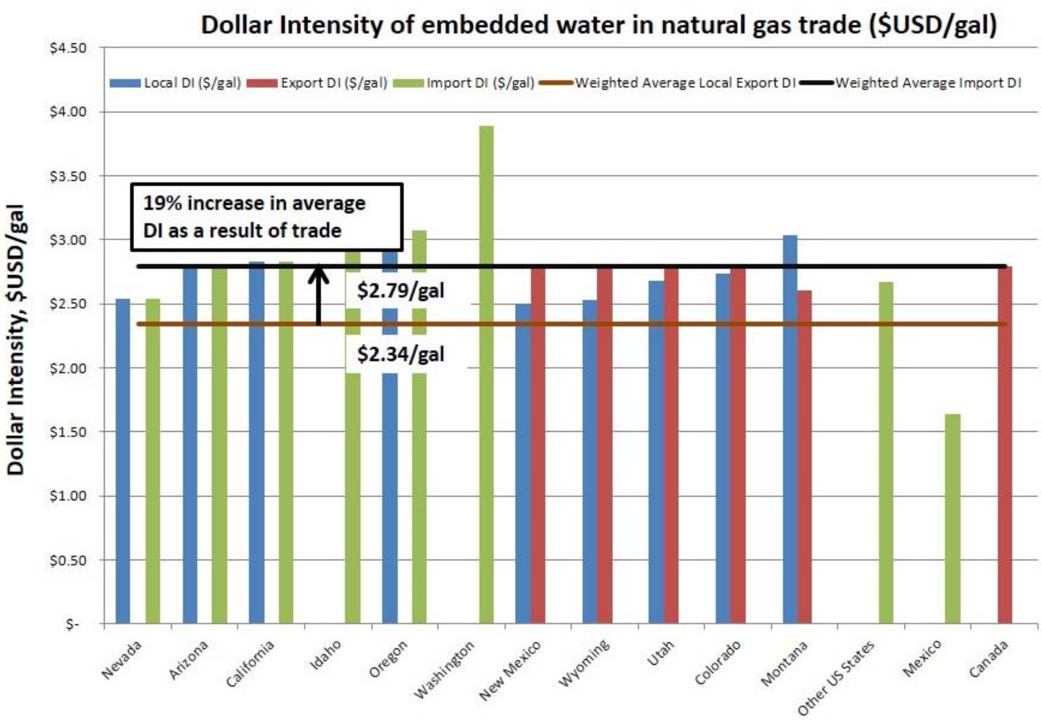

Figure 4. Dollar Intensities (*DI,* $USD/gal) of water embedded in natural gas traded in the Western U.S. DI_{LOCAL} is the water embedded in natural gas produced instate and traded to instate consumers . DI_{EXPORT} is the water embedded in natural gas that is exported from the state. DI_{IMPORT} is the water embedded in natural gas that is imported to the state. Comparing weighted averages of local DI_{LOCAL} for exporting states and DI_{IMPORT} for importing entities (including Mexico an Other U.S. states) a 19% increase in DI of the embedded water is realized as a result of trade.

Dollar intensities of water in natural gas are relatively uniform across the region. Washington, an importer of natural gas exhibits the highest dollar value of embedded water in this resource fuel. Table 1 shows that Washington state pays the highest retail prices in the region for natural gas.

Overall, trade in natural gas increases the dollar value of the embedded water by 19%.

Water Footprint of Petroleum. Figures 5 and 6 illustrate the direct *U* and indirect *V* components of the water footprint *E* for each State for oil production and consumption. Here again, the calculations were performed in the same manner as that described in the above passages on the Water Footprint of Coal. The obvious difference is that of the scale of this trade network. The Western United States, and the United States itself, is a net importer of crude oil and petroleum products [*USEIA*, 2012d]. Figure 5 shows the footprints of the entire network included in the analysis. Figure 6 provides additional detail for the Western U.S.

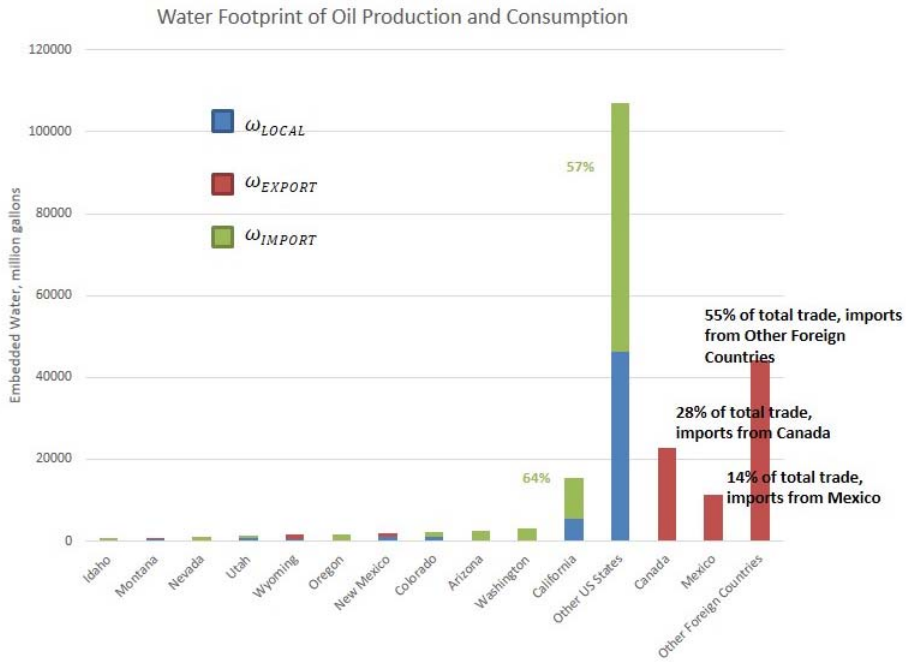

Figure 5. Water footprint, *E,* for oil extraction and consumption the Western U.S., by state. ω_{LOCAL} is the water embedded in oil extracted instate and traded to instate customers. ω_{EXPORT} is the water embedded in oil that is exported from the state. ω_{IMPORT} is the water embedded in oil imported to the state. Percentages indicate percent of individual state's footprint that is involved in interstate trade, either imported or exported. Percentages shown for trade with foreign entities (Mexico, Canada, and Other Foreign Countries) are percentages of total trade.

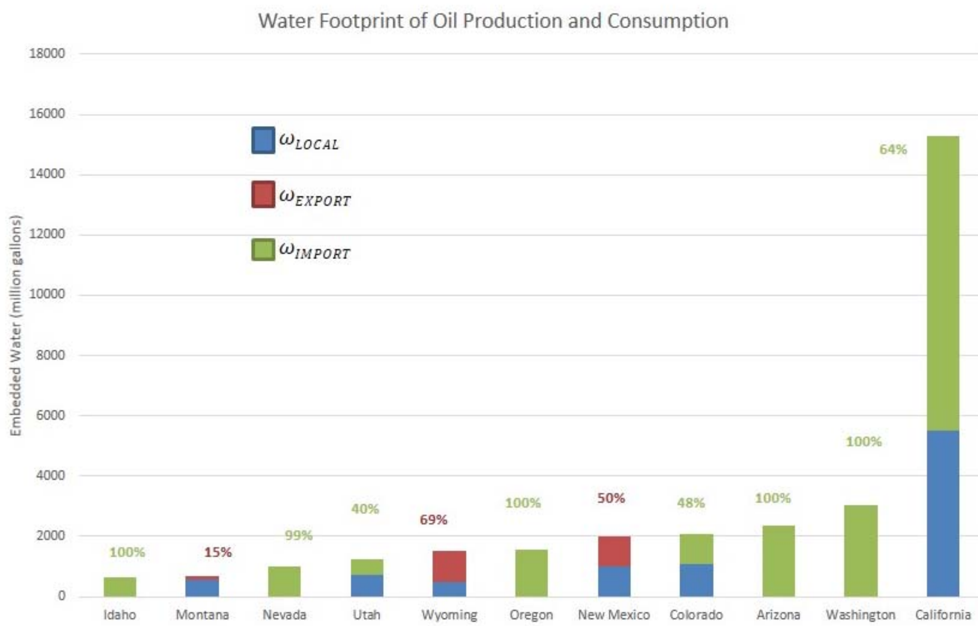

Figure 6. A closer look at the Western U.S. water footprint due to petroleum production and consumption. Water footprint, *E,* for oil extraction and consumption the Western U.S., by state. ω_{LOCAL} is the water embedded in oil extracted instate and traded to instate customers. ω_{EXPORT} is the water embedded in oil that is exported from the state. ω_{IMPORT} is the water embedded in oil imported to the state. Percentages indicate percent of individual state's footprint that is involved in interstate trade, either imported or exported.

The United States is a major world importer of petroleum resources, and associated embedded water. California has the largest impact on petroleum and embedded water consumption within the Western US region under analysis (similar to electricity and natural gas), two-thirds of which is obtained via imports, again highlighting its reliance on outside resources – energy and embedded water resources.

Nearly all imports to the system (97%) are from foreign countries – illustrating a reliance on foreign water supplies embedded in petroleum.

Dollar Intensities of Petroleum. Here we reveal the Dollar Intensity of water embedded in the oil trade in the Western U.S. using the same methods described for determination of the Dollar Intensities of Coal. Figure 7 shows Dollar Intensities before and after trade. Since there are no net exporting states, there are no Export DI values.

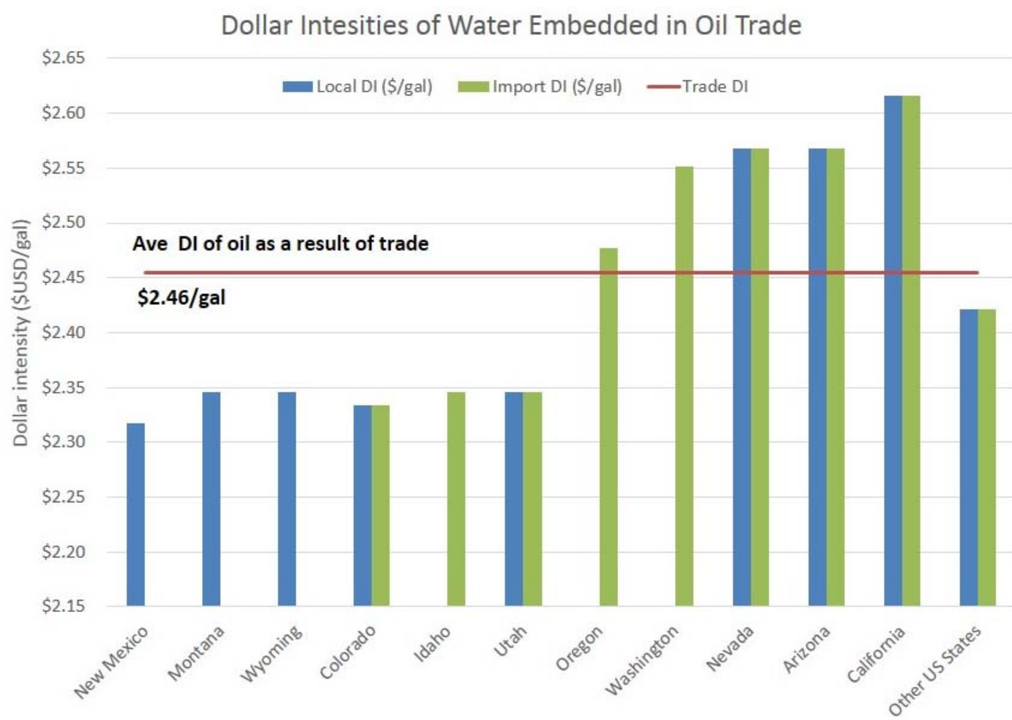

Figure 7. Dollar Intensities (*DI,* $USD/gal) of water embedded in petroleum trade in the Western U.S. DI_{LOCAL} is the water embedded in coal produced instate and traded to instate consumers . DI_{IMPORT} is the water embedded in coal that is imported to the state. Comparing weighted averages of local DI_{LOCAL} for exporting states and DI_{IMPORT} for importing entities, including Other U.S. states, only a slight (0.13%) increase in DI of the embedded water is realized as a result of this trade.

There is not a dramatic change in dollar intensities in any location because the estimated water intensities for oil production are the same in all areas (see Table 1) – all changes are related to fuel prices.

No Western States are net exporters – nor is the United States in general. Embedded water in petroleum is apparently the most valuable where gas prices are the highest, which explains why we see the highest DI values are for California. This is likely a result of high demand. And interesting point reveals itself in Dollar Intensities of other four states with the values above the system average -two dry, and water limited states (AZ and NV) and two relatively wet, water abundant states (OR and WA). These states house large urban population centers, allowing for this to be explained as in relation high resource demand, but highlights a common theme throughout these analyses – the market does not appear related to water availability.

Conclusions

Acknowledging the cyclical nature of water and the relative abundance of actual water resources on Earth, this study is concerned with fresh water availability within a given region – the Western United States. We are focusing on quantities of fresh water supplies annually available at acceptable quality for anthropogenic uses, specifically here as related to use in the energy sector. The results of this research provide useful tools for water resource managers and policy makers to inform decision making on, (1) reallocation of local available fresh water resources, and (2) strategic supplementation of those resources with outside fresh water resources via the import of virtual water.

Figure 1, 3, 5, and 6 illustrate that a significant portion of the water embedded in fuel resource extraction and consumption by Western US States is associated with traded energy fuels and embedded water. This trade is occurring among Western States, however, the boundaries for each fuel type differ significantly. A comparison of these results along network boundaries will be performed and conclusions drawn about where "optimal" boundaries lie – given specific objectives – in the following chapter. Objectives are focused on both conservation and optimal use of available freshwater resources within the energy sector by the Western U.S.

The trends revealed in these analyses indicate that abundance or scarcity of available fresh water supplies has no effect on trade. This may simply be an illustration of the fact that the West is not currently experiencing a scarcity in water resource supplies. However, it also does not reveal a picture of conservation of available water resources, or of a necessary sustainable management of water resources.

Generally speaking, and referring to equation (3) in the case where water is an important and valued (i.e. scarce) input to the process we can expect the dollar intensity to go up, because both the price and the efficiency would be expected to increase if water becomes a scarce resource. So this *could* be an indicator of scarcity. The results here, again, do not show a picture of scarcity. State-level decisions to import and export embedded water in energy fuels in the Western US appear to be influenced not by availability of fresh water supplies, rather by energy demands and prevalence of fuel resource stocks within the states.

The following and final chapter of this paper will combine results of the water embedded in energy fuel resources analyzed here as well as the water embedded in electricity analysis. The objective of this final chapter is to illustrate how these ERA analyses of embedded resources (water in particular) can serve as innovative and beneficial tools to inform regional resource management and policy setting for sustainable resource management.

References

Adams, E.A., R.R. Rushforth, B.L. Ruddell, V.C. Tidwell (2013a), Embedded resource accouting for water resource applications; Part 1, Water embedded in the western U.S. electrical energy trade. In review. Submitted to WRR.

Adams, E.A., R.R. Rushforth, B.L. Ruddell, V.C. Tidwell (2013b), Embedded resource accouting for water resource applications; Part 2, The dollar intensity of water embedded in electricity. In review. Submitted to WRR.

Allan, T. (1993), Fortunately there are substitutes for water: Otherwise our hydropolitical futures would be impossible, paper presented at Conference on Priorities for Water Resources Allocation and Management, Overseas Dev. Admin., London.

Allan, J. A. (1996), Policy responses to the closure of water resources. In *Water Resource Policy: Allocation and Management in Practice*, ed. P. Howsam and R. carter. London: Chapman and HallBrown, T. C. (2006), Trends in water market activity and price in the western United States, *Water Resources Research*, 42, W09402, doi:10.1029/2005WR004180.

Chapagain, A. K., and A. Y. Hoekstra (2008), The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water International, 33*(1), 19-32. doi: 10.1080/02508060801927812.

Elcock, D. (2008). Baseline and projected water demand data for energy and competing water use sectors, ANL/EVS/TM/08-8. Argonne National Laboratory, Environmental Science Division.

Elcock, D. (2010), Future U.S. water consumption: The role of energy production. *JAWRA* 46(3):447-460. Doi: 10.1111/j.1752-1688.2009.00413.x.

Gober, P., Kirkwood, C. W., Balling Jr., R. C., Ellis, A. W., & Deitrick, S. (2010). Water planning under climatic uncertainty in Phoenix: Why we need a new paradigm. *Annals of the Assoc. of American Geographers, 100(2)*, 356-372.

Mielke, E., L. Diaz Anadon, and V. Narayanamurti (2010). Water consumption of energy resource extraction, processing and conversion, a review of the literature for estimates of water intensity of energy-resource extraction, processing to fuels, and conversion to electricity. Energy Technology Innovation and Policy Discussion Paper No. 2010-15. Harvard Kennedy School, Harvard University.

Ostrom, E., J. Burger, C.B. Field, R.B. Norgaard, and D. Policansky (1999), Revisiting the Commons: Local lessons, global challenges. Science. 284(5412), 278-282. http://www.jstor.org/stable/2898207.

Postel,S. L. (2000), Entering an Era of Water Scarcity: The Challenges Ahead, *Ecol. Appl., 10(4)*, 941-948.

Tidwell, V.C., P.H. Kobos, L.A. Malczynski, G. Klise, and C.R. Castillo (2012), Exploring the water-thermoelectric power nexus, *Journal of Water Planning and Management*, *138*(5), 491-501.

USEIA (U.S. Energy Information Administration) (2012a), Online. Annual Coal Distribution Report http://www.eia.gov/coal/distribution/annual/ Accessed June 20, 2013.

USEIA (U.S. Energy Information Administration) (2012b), Online. Annual Energy Review. http://www.eia.gov/totalenergy/data/annual/index.cfm. Accessed July 10, 2013.

USEIA (U.S. Energy Information Administration) (2013a), Online. How many gallons of gasoline does one barrel of gasoline make? Tools. FAQS. http://www.eia.gov/tools/faqs/faq.cfm?id=24&t=7. Accessed July 3, 2013.

USEIA (U.S. Energy Information Administration) (2013b), Online. *Table 2. Natural gas production, transmission, and consumption by state, 2011*, Natural Gas Annual. http://www.eia.gov/naturalgas/annual/ Accessed June 12, 2013.

USEIA (U.S. Energy Information Administration) (2013c), Online. *Table 12. Interstate movements and movements across U.S. borders of natural gas by state, 2011*, Natural Gas Annual. http://www.eia.gov/naturalgas/annual/ Accessed June 12, 2013.

USEIA (U.S. Energy Information Administration) (2012c), Online. *Table 14. Production of crude oil by PAD district and state, 2011*, Petroleum Supply Annual, Volume 1. http://www.eia.gov/petroleum/supply/annual/volume1/. Accessed July 6, 2013.

USEIA (U.S. Energy Information Administration) (2013d), Online. *Table 16. Natural Gas delivered to consumers by sector, and by state and sector, 2011*, Natural Gas Annual. http://www.eia.gov/naturalgas/annual/ Accessed June 12, 2013.

USEIA (U.S. Energy Information Administration) (2013e), Online. *Table 24. Average price of natural gas delivered to consumers by state and sector, 2011*, Natural Gas Annual. http://www.eia.gov/naturalgas/annual/ Accessed June 12, 2013.

USEIA (U.S. Energy Information Administration) (2012d), Online. *Table 26. Imports of crude oil and petroleum products into the United States by country of origin, 2011*, Petroleum Supply Annual, Volume 1. http://www.eia.gov/petroleum/supply/annual/volume1/. Accessed July 6, 2013.

USEIA (U.S. Energy Information Administration) (2012e), Online. *Table 34. Average Price of Coal Delivered to End Use Sector by Census Division and State*, Annual Coal Report. http://www.eia.gov/coal/annual/ Accessed June 23, 2013.

USEIA (U.S. Energy Information Administration) (2013f), Online. *Table F15: Total petroleum consumption estimates, 2011*. http://www.eia.gov/state/seds/sep_fuel/html/pdf/fuel_use_pa.pdf. State energy data system. Accessed July 6, 2013.

USEIA (U.S. Energy Information Administration) (2013g), Online. *U.S. Natural Gas Exports By Country, 2011*, Annual Data. Natural Gas. http://www.eia.gov/dnav/ng/ng_move_expc_s1_a.htm Accessed June 12, 2013.

USEIA (U.S. Energy Information Administration) (2013h), Online. *Weekly retail gasoline and diesel prices, 2011.* Petroleum and Other Liquid. Data. http://www.eia.gov/dnav/pet/pet_pri_gnd_a_epm0_pte_dpgal_a.htm. Accessed July 8, 2013.

Wildman, R. A., Jr., and N. A. Forde (2012), Management of water shortage in the Colorado river basin: Evaluating current policy and the viability of interstate water trading. *J. American Water Resour. Assoc., 48*(3), 411-422. doi: 10.1111/j.1752-1688.2012.00665.x.

WWAP (World Water Assessment Programme). (2012), *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk.* Paris, UNESCO.

Chapter 5

POLICY IMPLICATIONS

Abstract

An analysis of the causal relationships between climate and economic changes and the water-energy nexus is needed for the purpose of informing National policy for the 21st century. There is an apparent need for energy policy that ties to the water resources needed for its production. The amount of water required for energy resource generation is not insignificant, and these virtual water quantities (the amount of water required to produce a commodity) ought to be included in the development of policy for resource management. The connection between available water resources and energy supplies is not clearly identified in current policy and is needed for the sustainable resource management in these sectors [*USDOE*, 2013; *Mead*, 2013; *Wilson*, 2012].

Nobel Prize winner, *Elinor Ostrom*, [1999], argues that local resources are most effectively managed at local scales by local institutions. Her theory is supported by empirical evidence and specific examples of the successful long term management of common pool resources. Others have reviewed arguments for and against a global water governance and concluded that given the propensity of corruption and exploitation in world politics and "since the scope of [water's] benefits and externalities is still mostly local or regional" administration of governance at a global scale is inappropriate [*Gawel and Bernsen*, 2011].

It is with this in mind that these tools are presented. We are not specifying policy from an outside perspective; our goal is to arm resource managers and policy makers with additional tools for assessing data within their regions. This paper supports the notion that

local resource management can be the most effective, and with that goal, presents innovative tools to help inform resource management, specifically water resource management by illustrating opportunities to build resilience into the resource systems. We show how ERA tools can assist decision makers by assessing available data (resource intensities of production and consumption combined with economics of resource trade) to illuminate options for reallocation of limited resources in times of shortages or scarcity.

Introduction

Water resources differ from other natural resources, and the sustainable management of water resources therefore brings with it unique challenges. Water flows within streams, rivers and underground aquifers; water seeps into the ground, evaporates, re-condenses, and falls from the sky as precipitation. Water is mobile and cyclical and is constantly being used and re-used. The natural hydrologic cycle is heavily intertwined with anthropogenic water uses, creating a coupled human and natural system in which water continually changes state, quality, and location. As a result, available high quality fresh water resources are unevenly and unpredictably distributed in time and space. Unsustainable management of water resources has led to the loss of significant fresh water supplies in many places around the world. Climate change is expected to increase uncertainty in annual renewable water resources due reduced precipitation and an increase extreme weather events such as flooding and prolonged droughts.

A significant amount of available water supplies are required to produce energy resources, and anticipated climate change impacts in the Southwestern U.S. place increasing risk on energy resources [*USDOE*, 2013]. And population and industry in urban areas continue to grow, increasing resource demands. Population in Arizona, Colorado, Nevada and New Mexico grew by 71 percent from 1980 to 2005, and power demand increased by 130 percent in the same time period [*Pitzer*, 2009].

An analysis of the causal relationships between climate and economic changes and the water-energy nexus is needed for the purpose of informing National policy for the 21st century. There is an apparent need for energy policy that ties to the water resources needed for its production. The amount of water required for energy resource generation is not insignificant, and these virtual water quantities (the amount of water required to produce a commodity) ought to be included in the development of policy for resource management. The connection between available water resources and energy supplies is not clearly identified in current policy and is needed for the sustainable resource management in these sectors [*USDOE*, 2013; *Mead*, 2013; *Wilson*, 2012].

The Western Governors' Association's (WGA) 2011 Water policy resolution acknowledges that the water-energy nexus is an important issue in the region and acknowledges that, "energy development and electricity generation may be a significant driver of future water demands." Followed by a recommendation for "increased coordination across the energy and water management communities," citing concerns of fully allocated water basins across the west, growing demands, and increased variability in future water supplies as motivation for the coordination [*WGA*, 2013]. However, the WGA's 10-Year Energy Vision, released this summer (2013) does not include any provisions on water-energy collaboration. The two continue to be managed, legislated, and analyzed separately. An explicit connection between extended drought in the West and energy generation adaptation is not apparent in current policies. [*WGA,* 2011, 2013].

Wyoming, a top energy producer in the U.S., and a leading energy producer in the world, has not developed a plan explicitly for the management of water resources related to energy production either... yet. This state has however taken the largest steps in this direction with the release of the state's own energy strategy, *Wyoming Leading the Charge***.** Governor Matthew Mead cited the absence of sound energy policy at the federal level as the state's primary motivation in developing this document [*Mead*, 2013a]. The strategy contains 47 initiatives against which successes are to be measured. The goals span four general themes and address water resource management under the umbrella of Natural Resource Conservation. Water and the development of a statewide water strategy and management plan are referenced throughout the different themes and across initiatives as critical components to the success of the overall energy strategy [*Mead*, 2013b]. Wyoming is the largest producer and net exporter of energy resources, and embedded water, in the region. Wyoming exported an estimated 10.4 quadrillion Btu of energy resources in 2011 [*USEIA*, 2013b].

On the consumption side of the spectrum, the state of California is a leader in resource management and a significant driver of resource trade in the west. California has a population of roughly 38 million people and is the 9th largest economy in the world. California does have water-energy nexus and climate policy, and teams that address these challenges through research and policy recommendations, such as California's Energy Commission and the Water-Energy Climate Action Team within the California EPA. However, the water energy focus of these groups appears to be on energy-in-water (energy required to pump water, treat water, etc.), not on water-in-energy. California is the major net importer and consumer of energy resources and embedded water in the region. California consumed an estimated 7.8 quadrillion Btu of energy (across all sectors) in 2011 [*USEIA*, 2013a]. There is a significant amount of water embedded in this energy that California is reliant upon neighboring states and other regions for. This aspect of the water-energy nexus appears to be overlooked by current policy.

Both Wyoming and California rely on water resource supplies from within the Colorado River Basin (CRB). The CRB is one of the most tightly managed and regulated river basins in the world. The Colorado and its tributaries support 30 million people and 400 acres of farmland across seven states [*USBR*, 2013]. The Colorado River dams and major tributaries are managed by USBR under a set of policies collectively known as the Law of the River. The Law of the River is the outcome of decades of disagreements resulting in multiple compact agreements, treaties, congressional acts, and a Supreme Court decision. The details of which are clearly summarized by *MacDonnell* [2006] for the interested reader. California receives water supplies from the Lower CRB, and generally uses more than its legal allocation to meet demands. This has been made possible by the Upper CRB not using its full allocations. Unfortunately, despite the multiple layers of regulation associated with the CRB, there is only one existing enforceable policy document for periods of water shortage within the CRB: the *2007 Colorado River Basin Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* [*USBR*, 2007]. These guidelines do not acknowledge a connection between energy production and a water supply shortage. The results of this analysis show that there is a clear and significant connection between the two justifying the consideration of such information when developing policy.

Nobel Prize winner, *Elinor Ostrom*, [1999], argues that local resources are most effectively managed at local scales by local institutions. Her theory is supported by empirical evidence and specific examples of the successful long term management of common pool resources. Others have reviewed arguments for and against a global water governance and concluded that given the propensity of corruption and exploitation in world politics and "since the scope of [water's] benefits and externalities is still mostly local or regional" administration of governance at a global scale is inappropriate [*Gawel and Bernsen*, 2011].

It is with this in mind that these tools are presented. We are not specifying policy from an outside perspective; our goal is to arm resource managers and policy makers with additional tools for assessing data within their regions. This paper supports the notion that local resource management can be the most effective, and with that goal, presents innovative tools to help inform resource management, specifically water resource management by illustrating opportunities to build resilience into the resource systems.

Methods

This study uses the ERA framework presented by *Adams et al.* [2013a, in submission to WRR]. The interested reader should is referred here for a complete description of the ERA framework's mathematics and assumptions.

The basic ERA equation is,

$$E\left(i,j,r_j,r_k\right)=\left[U\left(i,j,r_j\right)[t]+V\left(i,j,r_j,r_k\right)[t]\right]*Q\left(i,r_i,j,r_j\right)[t] \qquad (1)$$

where E is the net direct U and indirect V impacts of a process (i) on a resource stock (r_j), after adjustment to account for the equivalency Q between the resource stocks in question. In the current application, no partial equivalencies were considered, i.e. resource stocks are either fully equivalent and *local*, *Q=1*, or non-equivalent and *external*, *Q=0*.

By computing ratios of resource impacts by processes we are able to find the average Resource Intensity, *I*, where,

$$I\left(i,r_j,r_i,r_k\right)=\frac{\sum_j E\left(i,j,r_j,r_k\right)}{\sum_m E\left(m,j,r_j,r_k\right)} \tag{2}$$

I, is the ratio of the total impact on one resource stock of r_j (e.g. consumption) to the total impact of another resource stock of type r_i (e.g. production), in units of r_j/r_i, as revealed by a process or group of processes *i* and accounting for indirect impacts via *i*'s impact on intermediary stocks of type r_k.

In addition we utilize a new metric derived from the average Resource Intensity equation 2, presented in *Adams et al.* [2013a, in submission to WRR]. In the case where the produced resource is valued through trade in a currency medium of exchange, the equation becomes a value equation and the result is a *Dollar Intensity, DI*. Note that *DI* is not a strict measure of value or price in the classical economic sense.

A simple unit analysis illustrates the meaning of the *DI*. The energy resource is the common stock-in-trade for which consumers trade currency and for which producers impact local water resources to extract. Thus, to obtain a Dollar Intensity for the embedded water in *$USD/gal* we combine retail fuel prices (*$USD/unit of energy resource*), and the water intensity for fuel extraction (*unit of energy resource/gal*).

$$\left(\frac{USD\$_{consumer}}{Fuel_{consumer}}\right)\times\left(\frac{Fuel_{producer}}{gal_{producer}}\right)=\left(\frac{USD\$_{consumer}}{gal_{producer}}\right) \tag{3}$$

The first term in equation (3), the fuel consumer price, is governed (or set) by the economic *market* for the stock in trade, which implicitly includes issues of demand and supply and market regulation; the second term, the energy resource producer water efficiency of extraction, is governed (or set) by the *technology* of the extraction process, which implicitly considers issues of production cost and production regulations.

The consumer and the producer have two opposing and normative objectives. The consumer seeks to minimize its price paid ($USD/unit of fuel) for the stock in trade, while the producer seeks to maximize the same. The producer also seeks to maximize its technological efficiency (unit of fuel/gal). The resulting *DI,* ($USD\$_{consumer}/gal_{producer}$) describes the system's equilibrium including all factors affecting the market and the production process, in terms of the relationship between the market value of the fuel resource and the net impacts on the water resource stock. The economic definition of value is expressed in terms of economic behavior in the context of supply and demand. Value may be defined as the willingness to pay (WTP) for something, in this case indirect water impacts [*Brouwer et al.*, 2009]. This *DI* represents the energy consumer's WTP to outsource one additional (or marginal) unit of water resource impact.

An increase in the *DI* indicates either an increase in price paid by the consumer, or an increase in water efficiency in production technology, or both. To evaluate changes in *DI* as a result of trade, we calculate three separate *DI* values. We begin with a "baseline" in-state or Local *DI* which includes in-state price paid and in-state water intensity. The Import and Export *DI* values help illustrate the effects of trade.

The Import *DI* is calculated for states that import energy resources from other states, so their price paid is held constant and the water efficiency is a weighted average of production states from which the resources are being imported. So a comparison between Local *DI* and Import *DI* for importing tells us whether imports are coming from more or less efficient technologies than what exist currently in-state. From a water conservation standpoint, we would desire an increase in *DI* from Local to Import indicating that imported resources were produced using more efficient technology than exists locally.

The Export *DI* is calculated for states that export energy resources to other states, so the water efficiency is held constant and the price paid is a weighted average of import states to which the resources are being exported. Therefore, a comparison between Local *DI* and Export *DI* for exporting entities is an indicator of increased profitability of exports versus in-state sales of the resources. From a market standpoint for a producing state, an increase would indicate an increase in profitability per gallon of water invested in energy production.

This analysis utilizes results previously developed using the ERA methodologies descried here to study water embedded in energy in the Western United States. A water in electricity generation and consumption study was performed and the results presented by *Adams et al.* [2013a, b], and a water in energy fuel extraction and consumption study was performed and is presented in Chapter 4 of this paper.

Results

Here we combine the results of the previous analyses to compare water resource impacts and dollar intensities among different energy resources. Utilization of these previous studies allows us to introduce three significant and beneficial uses of ERA methodologies for sustainable resource management planning.

Firstly, we compare water efficiencies of different energy resources. An opportunity for decisions to include consideration of energy returns on quantities of water invested in their production is enabled by normalizing the resources to energy units of Btus. This normalization to energy units allows for meaningful comparisons to be observed and considered, however is should be noted that this does not provide a precise "apples to apples" comparison because there are differences water requirements of refining and end use processes that are not specifically identified.

Secondly, with use of the Dollar Intensity Utilizing resultant Dollar Intensities of the water embedded in traded energy resources allows for comparison of these intensities by type of energy resource, as well as how they are impacted by trade. Again looking at a return on water investment, here looking at that return in the familiar units of currency as a result of trade. This is not an ROI in the economic sense, but rather from an environmental perspective, with the primary concern being water productivity. Making these comparisons highest water value uses can be discerned, providing management institutions an additional metric by which water uses can be prioritized.

And finally, we look at variations in our metrics (water resource impacts of energy and dollar intensities of water embedded in traded energy) as a function of changing ERA equivalencies, Q, from equation (1). As the range of resource equivalencies is reduced or expanded the apparent water footprints and dollar intensities of the embedded water also shift. Patterns in these changes illustrate regions of maximum/minimum water resources exposure and embedded water dollar intensities.

Water Efficiency of Fuel Resource Extraction and Production. The results utilized from the previous studies are inclusive of two types of energy sources, primary and secondary. The top three primary energy resources consumed in the United States in 2011 (petroleum, natural gas and coal) were analyzed in the previous analysis. Primary energy resources require conversion to secondary energy resources to be usable in society as energy. Electricity is the most familiar secondary energy source, also known as an energy carrier. As the initial study of this paper showed, a tremendous amount of water is involved in the generation of electricity, especially through thermoelectric power plant processes. Therefore, for this first result in comparisons of water efficiencies of the various energy resources, the only the primary resources are compared against each other.

Figure 1 shows the water efficiencies in units of thousand Btu per gallon of water for the studied energy resources. The energy resources are normalized to Btu's for comparison. This result illustrates an energy return on water investment for each fuel type.

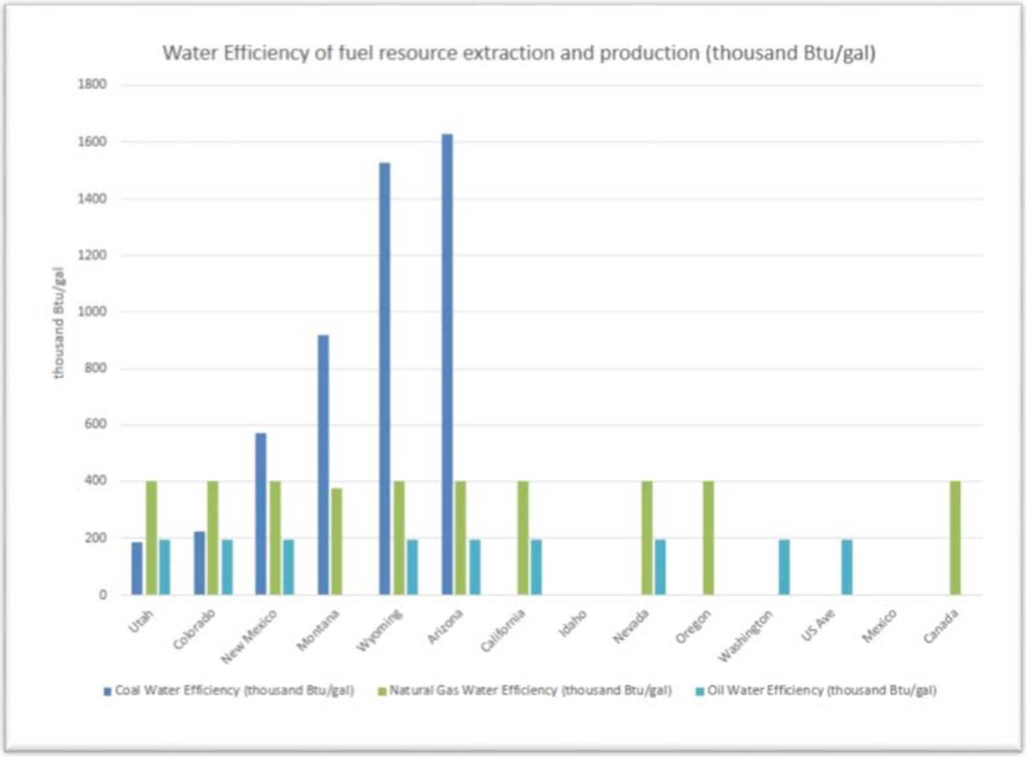

Figure 1. Comparison of the water efficiencies of the studied energy sources, normalized to Btu's.

This result shows that the most water efficient energy resource produced in the Western U.S. is coal, followed by natural gas and then oil.

Water conservation and water efficiency is a basic sustainable water resource management strategy. In times of water shortage, and as an adaptive measure to long-term or permanently reduced water availability it is useful to measure similar processes to determine which are more or less water efficient. Less water efficient resource production will require prioritized adaptive measures. For example, states with the highest water efficiencies for coal production (Arizona, Wyoming and Montana) may be incentivized to prioritize this type of resource production over less water efficient resources. Alternatively, low water efficient coal producers (Utah and Colorado) may be incentivized regionally to improve water efficiencies or even abandon coal production in favor of more water efficient energy resource production. Again, this is viewing the scenario purely from a view of concern over available water resources, not accounting for other system variables that are involved. This should be regarded as an additional tool to help illustrate one piece of the puzzle, through which managers may decipher ways to build additional resilience into their resource systems (such as reallocating water from less to more water efficient processes during times of low water availability).

Figure 2 shows the inverse of Figure 1, a comparison of the water intensities of the production of energy sources in units of gallons per million Btu. Here again the energy sources have been normalized to Btus for comparison.

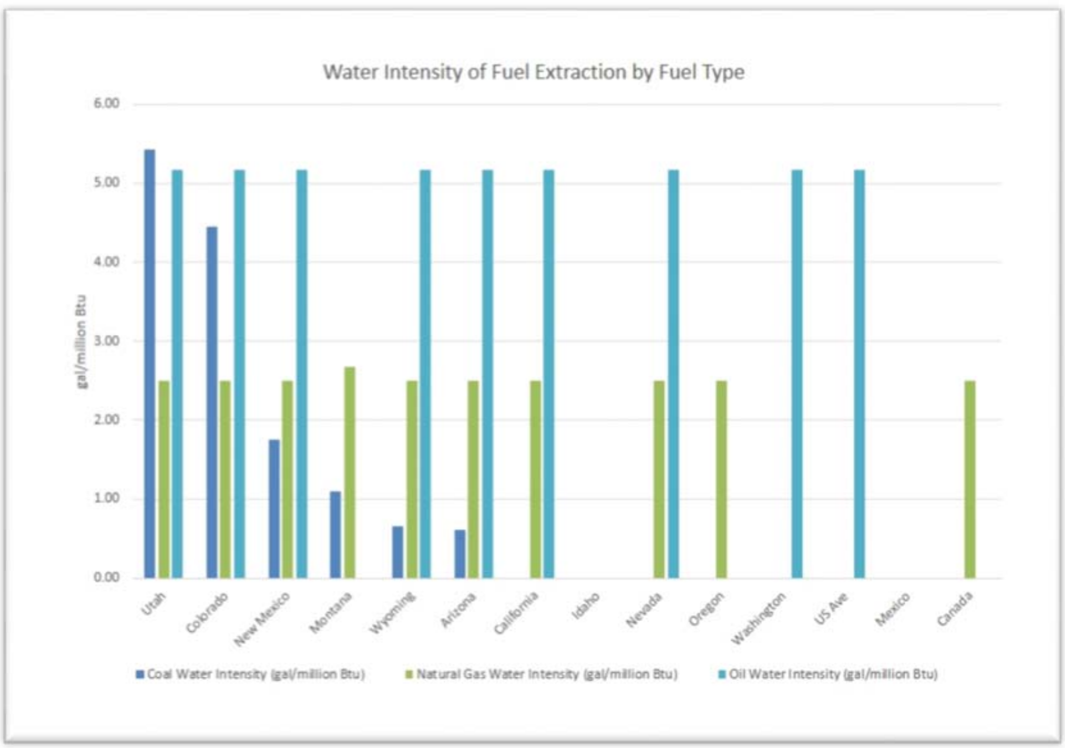

Figure 2. Comparison of the water intensities of the production of energy sources, again normalized to Btu's.

This result compares water intensities of energy resource extraction/generation to see which are the most (and least) water efficient. It is giving an alternate view of the same information presented in Figure 1, and as such we can draw like conclusions. Here, coal production in Utah and Colorado stand out as water inefficient extraction processes, at a similar efficiency as that of oil production in the region. And natural gas appears as a moderate water user throughout the region.

Assessing Highest Water Value Uses. In a 2006 report to Congress, the DOE stated that the nation "should carefully consider energy and water development and management so that each resource is used according to its full value." And that, "Given current constraints, many areas of the country will have to meet their energy and water needs by properly valuing each resource, rather than following the current U.S. path of largely managing water and energy separately" [*USDOE*, 2006].

The valuation of resources is a complex task. Here we approach it from the perspective of a Dollar Intensity of one embedded resource (water), that is revealed through the economic trade in another resource (energy resources) in which the first is embedded. The resultant Dollar Intensity of embedded water in units of dollars per gallon, does not give a price for water but can serve as an environmental value indicator.

Utilizing Dollar Intensities of the water embedded in traded energy resources allows for comparison of these intensities by type of energy resource, as well as how they are impacted by trade.

Figure 3 illustrates in-state dollar intensities of embedded water in energy resources. This is the dollar intensity of water embedded in energy resources produced instate using water resources originating in-state, and that energy then consumed in-state. These are dollar intensities of embedded water not influenced by inter-state trade.

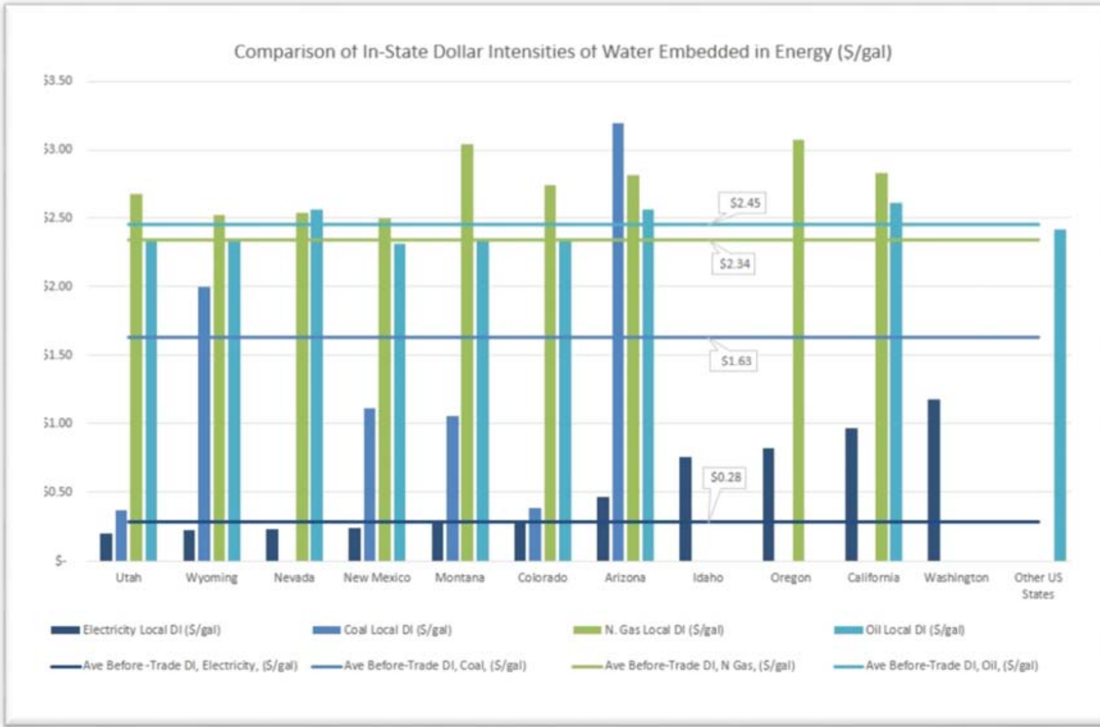

Figure 3. Comparison of In-State Dollar Intensities (*DI*, $USD/gal) of water embedded in energy in the Western U.S. The In-State DI for each fuel type is shown for each state; average In-State (Before-Trade) DI values are shown for the system.

This result illustrates the difference in relative value of water embedded in different energy types. The highest *DI* is associated with oil, and the lowest with electricity. Given this one might ask: Why is water being used for less valuable processes? Why, for example, are Utah and Colorado using water resources to produce coal and electricity when they see much higher *DI* values associated with Natural Gas and Oil production? The answer is that the dollar intensities do not reflect water pricing but can serve as an environmental value indicator. Economically viable energy and fuel markets are operating within Utah and Colorado. These markets are likely driven by energy prices, energy resource availability, and market regulations – NOT water availability. And this is logical as water prices remain negligible and water scarcity only a looming possibility.

It is also necessary to look at dollar intensities of embedded water as they are impacted by resource trade. The consumer of energy and the producer of energy have two opposing and normative objectives from the perspective of our analyses. The consumer seeks to minimize its price paid ($USD/Btu) for the stock in trade (energy resources), while the producer seeks to maximize the same. The producer also seeks to maximize its technological efficiency, energy produced per gallon of water consumed (Btu/gal).

Figure 4 illustrates export dollar intensities of embedded water in energy resources. This is the dollar intensity of water embedded in energy that was produced in-state, using water resources originating in-state, and that energy was then exported and consumed out-of-state. These are dollar intensities of embedded water after trade.

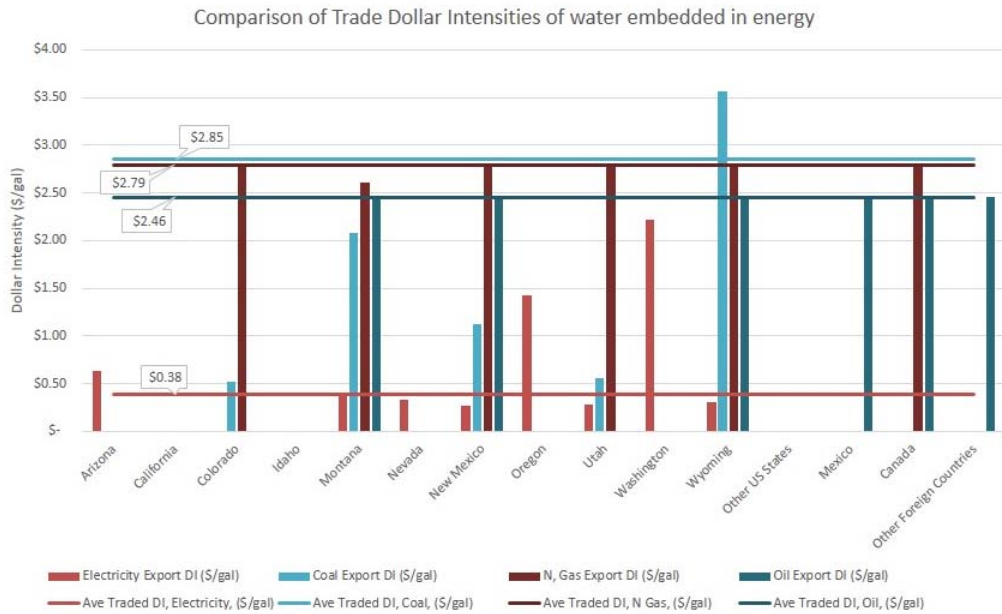

Figure 4. Comparison of Export Dollar Intensities (*DI,* $USD/gal) of water embedded in energy in the Western U.S. The Export DI for each fuel type is shown for each state; average Export (Trade) DI values are shown for the system.

This result illustrates the difference in relative value of water embedded in different energy types. The highest *DI* is associated with coal, and the lowest again is with electricity.

This result also illustrates the importance of considering the effects of trade on the dollar intensities of embedded water. Comparison of this figure with the previous figure shows the general increase seen in *DI*'s through trade in fuels. Dollar intensities for embedded water in both natural gas and coal increase to levels above those for oil after trade is accounted for. Looking at Wyoming in particular as an example of a net exporting state of energy resources, Figure 3 shows the highest *DI* for Wyoming is in its production and in-state consumption of natural gas. However, in Figure 4 we see that after trade water embedded in coal has the highest dollar intensity. This result shows that if managing for the highest value water uses, trade should be taken into account as without it a different decision would be made.

Generally speaking, in the case where water is an important and highly valued (i.e. scarce) input to the process we can expect the dollar intensity to go up, because both the price and the efficiency would be expected to increase. So this *could* be an indicator of scarcity. The results from these analyses do not show a picture of scarcity. If water resources were scarce or highly valued, one would expect to see higher *DI*'s in states with less abundant water resource supplies. However, what is actually happening and is apparent in these results is that water is that the importance of water is not connected to its sustainability as a resource, or its abundance or scarcity within a state; the importance f water is tied to its uses within the marketplace as a result of energy prices, high populations, large economies, restrictive regulations, and competing uses.

Figure 5 presents a comparison of the average dollar intensities of embedded water in each energy type and the total impact as a result of trade in energies.

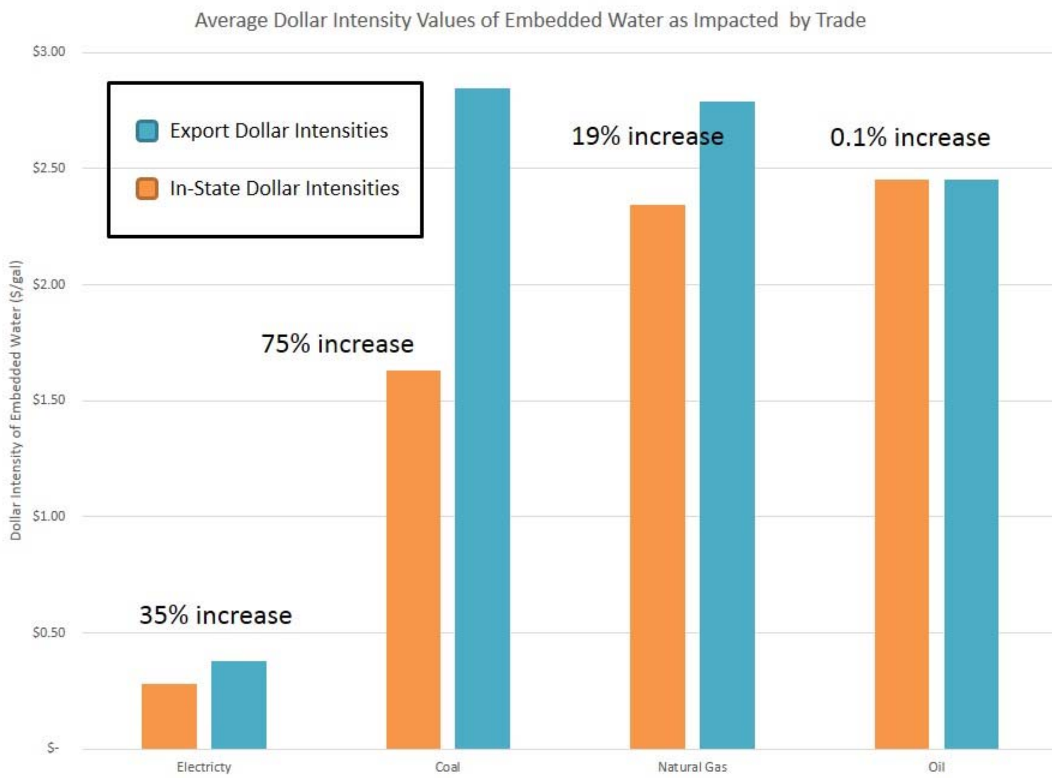

Figure 5. Summary of change in Dollar Intensity ($/gal) of water embedded energy resources as a result of trade.

This result illustrates the difference in Dollar Intensity of water embedded in different energy types as well as the effects of trade on the Dollar Intensity of embedded water within each fuel type.

The most significant increase is that of the *DI* of water embedded in coal. Electricity, though it has the lowest dollar intensities of embedded water by an order of magnitude than those associated with primary energy resources, does see a significant increase in dollar intensity as a result of trade as well. In a generic context we can postulate that this is a "good" thing. That either the prices are increased on exported electricity and coal indicating a healthy economic marketplace for the commodities, or the water efficiencies of production in the exporting states are higher than the system wide average water efficiencies of electricity and coal production, or both.

Future work should investigate these changes using time series analyses to see how dollar intensities are impacted by trade during a span of a decade, decades, and even seasonally during a single year.

Changing network boundaries through equivalency adjustments. These results illustrate a distinct advantage to using the ERA methods. We illustrate the effects of changing resource equivalency from the perspective of a consumption process and from the perspective of a production process. We approach this analysis from the perspective of resource managers of the largest energy trade partners in the Western U.S., California and Wyoming.

We first present California's apparent water footprint of energy consumption along a spectrum of changing boundaries. The ERA energy analyses previously completed facilitate the inclusion of this spectrum. Firstly we analyzed the water footprint due to electricity consumption – a regionally contained market confined to the WECC. The network boundaries grew with each successive analysis. Coal and natural gas trade networks extend to the rest of the United States and to include other countries within North America (Canada and Mexico). And finally, the petroleum trade network is a global trade network with the majority of supplies being imported from foreign countries.

Figure 6 illustrates how California's apparent water footprint changes as the boundaries of water resource equivalency are adjusted.

The left hand side of the x-axis shows the water footprint of energy use considering water resource originating in California only (CA). Moving right the next value is California's water footprint including water originating in all of the states of the Lower Colorado River Basin States (CA, AZ, and NV). Next is the water footprint of energy consumption including water resources originating in all of the seven Colorado River Basin States (CA, AZ, NV, CO, UT, WY, and NM), and then to include all Western States (CA, AZ, NV, CO, UT, WY, NM, OR, WA, ID and MT), and so on until reaching the global scale at the far right hand side of the x-axis.

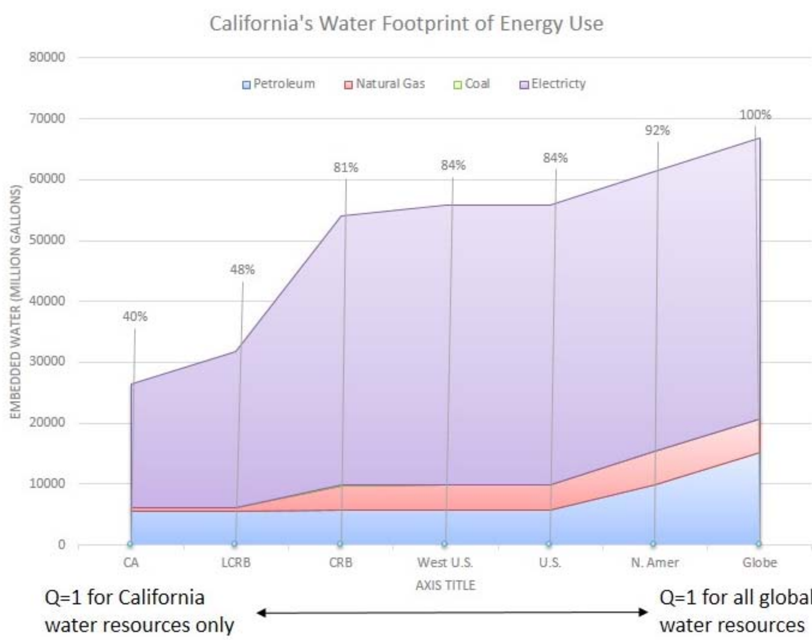

Figure 6. Cumulative water footprint of California energy consumption. The total water footprint of consumption increases as the boundary of equivalent water resources changes. The left hand side of the plot shows the water footprint of only those water resources that originated within the state of California. As the plot moves to the right, the boundary of equivalency in increased to include water resources originating in areas outside of the state, including next the states of the Lower Colorado River Basin, then all of the Colorado River Basin states, and following this pattern until all global water resources are included.

This result illustrates California's water reliance as a function of geography, and how vulnerability and control are two sides of the same coin. Over 84% of the water embedded in California's energy usage originates in states of the CRB. By relying on water sources from regions that share the same sources as California the risks of a prolonged drought in the CRB are multiplied – not only would deliveries of direct water supplies to California be affected, also energy resources imported from other CRB states could be impacted. On the other side of the coin, California has much greater influence on water policy and water use within the CRB than it does on more distant resources.

The Lower Colorado River Basin (LCRB) includes Nevada, Arizona and California. Annual allocations on the LCRB are 4.4 million acre-feet (MAF) to California, 2.8 MAF to Arizona, and 0.3 MAF to Nevada. There is one major caveat to the allocations however. In order to get the Central Arizona Project canal constructed Arizona agreed to take junior water rights on its apportionment of Colorado River Water to those of California, such that in the event of a shortage on the Lower Colorado California is guaranteed to receive its full allotment before Arizona is provided any of theirs [*Rinne*, 2000; *MacDonnell*, 2006]

The results of our analysis illustrate how reduced available water supplies across the region could impact electricity and other energy resources imported by California, first from Nevada and Arizona who would suffer water shortages earlier and more severely than California, but also potentially from other exporting states in the CRB – such as Wyoming.

This result shows where resilience exists or should be built into the energy portfolio - to include geographical diversity of virtual water imports - to ensure that an importer does not place all its “eggs in one basket,” or one river basin as the case may be.

From the producer perspective Figure 7 illustrates how Wyoming’s apparent water footprint changes as the boundaries of water resource equivalency are adjusted.

Here the left hand side of the x-axis shows the water footprint of energy use considering water resources originating in Wyoming (WY) without consideration of any indirect or virtual outflows of the embedded water. Here 100% of the water used to produce energy in the State of Wyoming is allocated to Wyoming. Moving right the next value shows Wyoming’s water footprint less the amount of virtual water exported to Upper Colorado River Basin States embedded in energy exports (UT, CO, and NM). Next is Wyoming’s water footprint less the amount of virtual water exported to All Colorado River Basin States (CA, AZ, NV, CO, UT, and NM) embedded in energy exports, then to include reduction for exports to all Western States (CA, AZ, NV, CO, UT, WY, NM, OR, WA, ID and MT), and so on until reaching the global scale at the far right hand side of the x-axis.

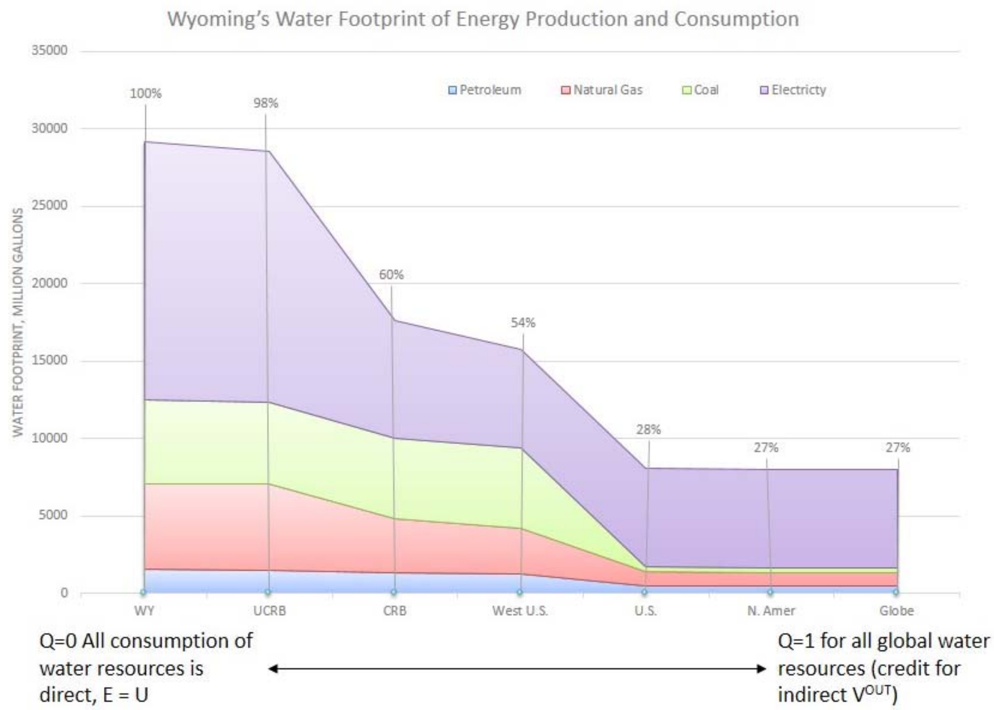

Figure 7. Cumulative water footprint of Wyoming energy production. The total water footprint of production decreases as the boundary of equivalent water resources changes. The left hand side of the plot shows the total water footprint for energy produced within Wyoming, regardless of where that energy (and embedded water) was eventually consumed. As the plot moves to the right, the boundary of equivalency is increased and takes into account Wyoming's indirect (or embedded) exports of water resources.

This result illustrates Wyoming's sphere of embedded water exports. Most of the embedded water is exported from the state (73%). Nearly half to other Western US states – with the largest percentage, roughly 40% going to LCRB states (AZ, CA, and NV).

If water were to become scarce in Wyoming, this result illustrates that electricity production for export would be the first to be impacted as such a significant water user in the state for exports. This would affect neighboring states who import electricity supplies from Wyoming, especially the arid Southwest States of the LCRB. Unfortunately, water and electricity managers do not actively/widely consider the impact to power availability of a water shortage in neighboring regions [*Harto and Yan*, 2011].

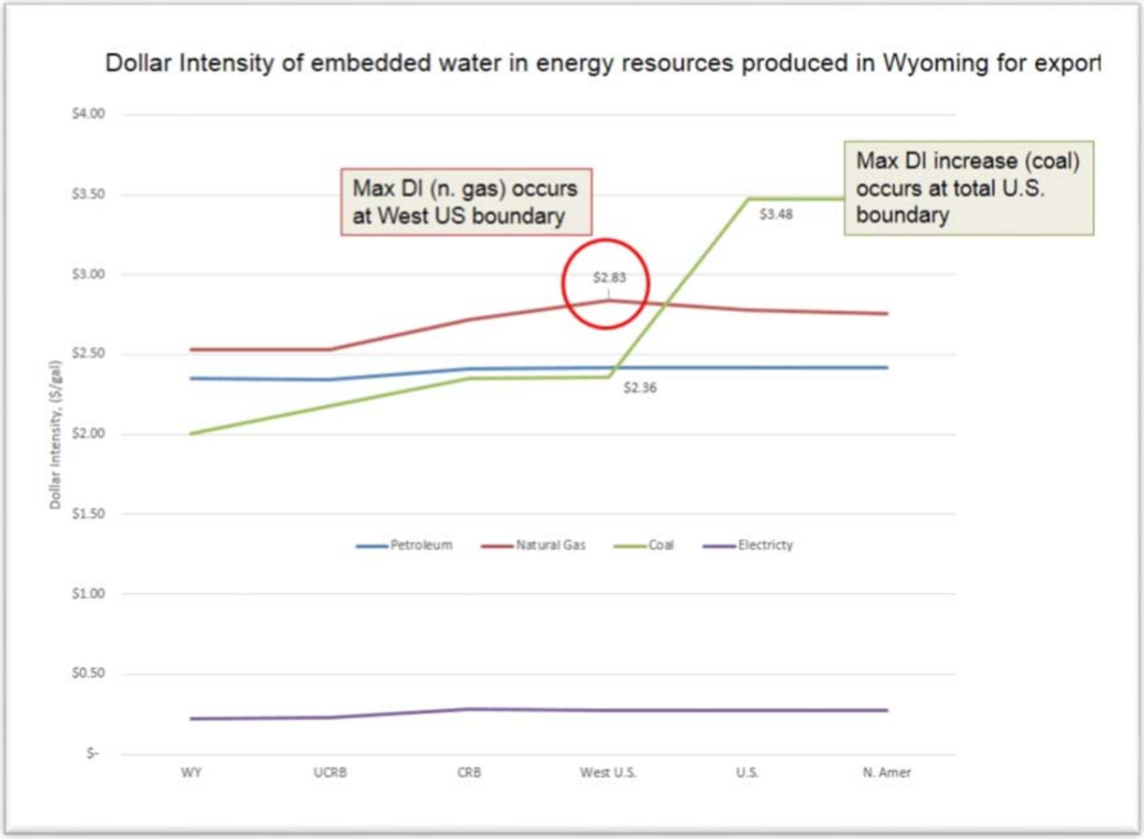

Figure 8. Dollar intensities of water embedded in energy resources exported by Wyoming as the boundary of equivalency (*Q*) of water resources is adjusted.

This result illustrates the dollar intensity of embedded water within energy resources produced in Wyoming for export out of the state. The domain is the same as presented for Wyoming's apparent water footprint in Figure 7, beginning within the state of Wyoming and expanding as the graph moves left to include additional U.S. states, and finally to include trade within North America (including Canada and Mexico). In general the dollar intensities increase as the network boundary is increased. The optimality, in terms of dollar intensity of embedded water, for the trade networks is informed by this analysis. The natural gas trade network, for example, achieves its maximum dollar intensity at the level of trade with Western U.S. states, and begins to decrease after that point. Suggesting that in terms of highest water value uses, the optimal trade network in natural gas resources is confined to within the Western U.S. The coal network however, sees the largest increase in dollar intensity of embedded water as the network grows from the Western U.S. to include the entire U.S., suggesting a larger network is optimum in this case.

Conclusions

Virtual water trade is an increasingly common approach to addressing decreased fresh water availability. ERA provides useful tools for understanding the impacts of virtual water trade from perspectives of both net importers and net exporters of virtual water supplies. These tools can help illuminate potential conflict within a system, highlight vulnerabilities, and reveal options for building resilience into coupled human natural systems. This paper illustrates the utility of ERA analyses to inform policy strategy by comparing results of resource impact (water footprint) and dollar intensities of water embedded in energy produced and traded in the Western United States.

Less water efficient resource production will require prioritized adaptive measures in times of water shortages. States with the highest water efficiencies for coal production (Arizona, Wyoming and Montana) may be incentivized to prioritize this type of resource production over less water efficient resources. Alternatively, low water efficient coal producers (Utah and Colorado) may be incentivized regionally to improve water efficiencies or even abandon coal production in favor of more water efficient energy resource production.

Comparison of dollar intensities of water embedded in the different energy resources reveals the variation among an implicit value of embedded water within the different energy types. The dollar intensities do not reflect water pricing but can serve as an environmental value indicator. The results of this analysis show that energy and fuel markets are not driven by availability of water resources but by more significant market forces such as energy prices, energy resource availability, and market regulations.

Generally speaking, dollar intensities of embedded water are metrics indicative of water scarcity. In the case where water is an important and valued (i.e. scarce) input to the process we can expect the dollar intensity to go up, because both the price and the efficiency would be expected to increase if water becomes a scarce resource. The results here do not show a picture of scarcity.

ERA methods allow for examination of trade networks under a range of boundary conditions by adjusting resource equivalency factors. Using this analysis we illustrate an indirect water dependence by California on other states within the LCRB. This exemplifies the need to include virtual water trade in policy. In this case of California, the state has historically relied on more than its allotted share of CRB water to meet local demands, and therefor any reduction in available water supplies to the state will create management challenges. And, as illustrated in this series of analyses California is *indirectly* dependent on water from both Arizona and Nevada, so a water shortage in the LCRB is likely to have consequences for all users, not only those holding junior water rights [*Harto and Yan*, 2011]. These consequences (higher prices, reduced resource availability) are like to be seen in electricity first. Electricity generation is most vulnerable to water scarcity as it requires large quantities of water for production at all times. This information could incentivize California to collaborate and compromise on LCRB water shortage options, and removes a level of desperation from Arizona and Nevada's positions.

Trade in energy resources appears to positively impact dollar intensities of embedded water for all of the energy resources in the analysis. These results indicate that, from the perspective of an energy resource producer concerned with utilizing water for highest value uses, trade increases the implicit value of the embedded water. The most significant increases in dollar intensities of embedded water as a result of trade were seen in the electricity and coal trade networks. Future work should investigate these changes using time series analyses to see how dollar intensities are impacted by trade during a span of a decade, decades, and even seasonally during a single year.

This paper supports the notion that the sustainable management of local resources is most effectively accomplished by local institutions with the best working knowledge of the resources. We show how ERA tools can assist decision makers by assessing available data (combines resource intensities of production and consumption with economics of resource trade) to illuminate options for reallocation of limited resources in times of shortages or scarcity.

References

Blaney, J. (2008), American Water Policy, Temple Journal of *Sci. Tech. & Envtl. Law*, 26(1), pp 75-112.

Brown, T. C. (2006), Trends in water market activity and price in the western United States, *Water Resources Research*, 42, W09402, doi:10.1029/2005WR004180.

Colorado River Compact (1922), http://www.usbr.gov/lc/region/pao/pdfiles/crcompct.pdf. Accessed June 27, 2013.

Dawadi, S. and S. Ahmad (2012), Changing climatic conditions in the Colorado River Basin: Implications for water resource management. *Journal of Hydrology*, 430-431, 127-141.

D'Odorico, P., F. Laio, and L. Ridolfi (2010), Does globalization of water reduce societal resilience to drought?, *Geophys. Res. Lett*., 37, L13403, doi:10.1029/2010GL043167.

Rinne, W. (2000), How the Colorado River Operates. United States Bureau of Reclamation, Lower Colorado Region. White Paper.

Harto, C. B., & Yan, Y. E. (2011). *Analysis of drought impacts on electricity production in the western and Texas interconnections of the United States.* Argonne National Laboratory, Environmental Science Division. Oak Ridge, TN: U.S. Department of Energy.

Li, Y. and B. J. Lence (2007), Estimating resilience for water resources systems, Water Resour. Res., 43, W07422, doi:10.1029/2006WR005636

MacDonnell, L.J. (2009), Colorado River Basin. *Water and Water Rights*. Vol 4, 5-54.

McCormick, Z.L. (1994), Interstate water allocation compacts in the Western United-States – Some suggestions. *Water Resources Bulletin. 30(3)*, 385-395.

Mead, Matthew (2013). Wyoming Energy Strategy 2013 Release. Press conference. Video Streamed live on May 13, 2013. Available http://youtu.be/DBAsswd00k0. Accessed July 16, 2013.

National Academies (U.S.)., National Research Council (U.S.)., National Research Council (U.S.)., & National Research Council (U.S.). (2010). *Hidden costs of energy: Unpriced consequences of energy production and use*. Washington, D.C: National Academies Press.

NOAA. 2013. *Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 9. Climate of the Contiguous United States.* Kunkel, K.E, L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Wuebbles, and J.G. Dobson. NOAA

Technical Report. National Environmental Satellite, Data, and Information Service (NESDIS) 142-9, 78 pp. http://scenarios.globalchange.gov/sites/default/files/NOAA_NESDIS_Tech_Report_142-9-Climate_of_the_Contiguous_United_States_3.pdf.

Ostrom, E., J. Burger, C.B. Field, R.B. Norgaard, and D. Policansky (1999), Revisiting the Commons: Local lessons, global challenges. *Science. 284(5412)*, 278-282. http://www.jstor.org/stable/2898207.

USBR (United States Bueau of Reclamation) (2007), Colorado River Basin Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead. http://www.usbr.gov/lc/region/programs/strategies.html. Accessed June 27, 2013.

USBR (United States Bueau of Reclamation) (2013), Colorado River Basin Water Supply and Demand Study, Final Report. http://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Study%20Report/StudyReport_FINAL_Dec2012.pdf. Accessed June 27, 2013.

USDOE (United States Department of Energy) (2013), U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather. DOE/PI-0013. Available http://energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather. Accessed July 16, 2013.

USDOE (United States Department of Energy) (2006), Energy Demands on Water Resources. A Report to Congress on the Interdependency of Energy and Water. Available: http://www.sandia.gov/energy-water/congress_report.htm. Accessed July 16, 2013.

USEIA (United States Energy Information Administration), (2013a). Online. California: State Profile and Energy Estimate, 2011. http://www.eia.gov/state/data.cfm?sid=CA#Consumption. Accessed July 16, 2013.

USEIA (United States Energy Information Administration), (2013b). Online. Wyoming: State Profile and Energy Estimate, 2011. http://www.eia.gov/state/rankings/?sid=WY#series/101. Accessed July 16, 2013.

WGA (Western Governor's Association), (2013). Online. 10-year energy vision, goals and objectives. http://www.westgov.org/reports/cat_view/95-reports/280-2013. Accessed July 16, 2013.

WGA (Western Governor's Association), (2011). Online. Water resource management in the west. Policy resolution 11-7. http://www.westgov.org/policies/cat_view/42-resolutions/158-water/248-2011. Accessed July 16, 2013.

Wildman, R.A. and N.A. Forde (2012), Management of water shortage in the Colorado River Basin: Evaluating current policy and the viability of interstate water trading, *J. American Water Resources Assoc.*, doi: 10.1111/j.1752-1699.2012.00665.x.

Wilson, W., T. Leipzig and B Griffiths-Sattenspiel (2012), *Burning our rivers. The water footprint of electricity.* A River Network Report. http://www.rivernetwork.org/sites/default/files/BurningOurRivers_0.pdf. Accessed July 16, 2013.

REFERENCES

Adams, E.A., R.R. Rushforth, B.L. Ruddell, V.C. Tidwell (2013a), Embedded resource accouting for water resource applications; Part 1, Water embedded in the western U.S. electrical energy trade. In review. Submitted to WRR.

Adams, E.A., R.R. Rushforth, B.L. Ruddell, V.C. Tidwell (2013b), Embedded resource accouting for water resource applications; Part 2, The dollar intensity of water embedded in electricity. In review. Submitted to WRR.

Aldaya, M. M., J. A. Allan, and A. Y. Hoekstra (2010), Strategic importance of green water in international crop trade. *Ecol. Econ., 69*, 887-894.

Aldaya, M. M., P. Martinez-Santos, and M. R. Llamas (2010), Incorporating the water footprint and virtual water into policy: Reflections from the Mancha occidental region, Spain. *Water Resour. Man., 24*, 941-958.

Allan, J. A. (1996), Policy responses to the closure of water resources. In *Water Resource Policy: Allocation and Management in Practice*, ed. P. Howsam and R. carter. London: Chapman and HallBrown, T. C. (2006), Trends in water market activity and price in the western United States, *Water Resources Research*, 42, W09402, doi:10.1029/2005WR004180.

Allan, J. A. (1996), Policy responses to the closure of water resources. In *Water Resource Policy: Allocation and Management in Practice*, ed. P. Howsam and R. carter. London: Chapman and Hall.

Allan, J.A. (2002), Hydro-peace in the Middle East: Why No Water Wars? A Case Study of the Jordan River Basin. *SAIS Review XXII(2),* 255–272.

Allan, T. (1993), Fortunately there are substitutes for water: Otherwise our hydropolitical futures would be impossible, paper presented at Conference on Priorities for Water Resources Allocation and Management, Overseas Dev. Admin., London.

Allan, T. (1993), Fortunately there are substitutes for water: Otherwise our hydropolitical futures would be impossible, paper presented at Conference on Priorities for Water Resources Allocation and Management, Overseas Dev. Admin., London.

Ansink, E. (2010), Refuting two claims about virtual water trade, *Ecol. Econ., 69*, 2027-2032.

Bilmes, J. (2000), Dynamic Bayesian Multinets, Proceedings of the 16th Conference on Uncertainty in Artificial Intelligence, pp. 38-45.

Blaney, J. (2008), American Water Policy, Temple Journal of *Sci. Tech. & Envtl. Law*, 26(1), pp 75-112.

Brown, M. T., and S. Ulgiati (2002), Emergy evaluations and environmental loading of electricity production systems, *Journal of Cleaner Production*, 10(4), 321-334.

Brown, M. T., and S. Ulgiati (2004), Energy quality, emergy, and transformity: HT Odum's contributions to quantifying and understanding systems, *Ecological Modelling*, 178(1), 201-213.

Brown, T. C. (2006), Trends in water market activity and price in the western United States, *Water Resources Research*, 42, W09402, doi:10.1029/2005WR004180.

Buchanan, J. M. and W. C. Stubblebine (1962), Externality, *Economica*, *29(116),* 371-384.

Chanan, A., J. Kandasamy, and D. Sharma (2008), A Role for input-output analysis in urban water policy decisions in Australia, paper presented at 2008 International Input-Output Meeting, Seville, Spain.

Chapagain, A. K., A. Hoekstra, and H. Savenije (2006), Water saving through international trade of agricultural products, *Hydrol. Earth Syst. Sci., 10*, 455–468.

Chapagain, A. K., and A. Y. Hoekstra (2008), The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water International, 33*(1), 19-32. doi: 10.1080/02508060801927812.

City of Peoria, Arizona (2007), Principles of sound water management. November 20, 2007. Available from: http://www.peoriaaz.gov/uploadedFiles/PrinciplesofSoundWaterManagement11_20_07f.pdf.

Collin, P. H. (2006), *Dictionary of Economics*, A & C Black, Great Britain, eISBN-13: 978-1-4081-0221-3.

Colorado River Compact (1922), http://www.usbr.gov/lc/region/pao/pdfiles/crcompct.pdf. Accessed June 27, 2013.

D'Odorico, P., F. Laio, and L. Ridolfi (2010), Does globalization of water reduce societal resilience to drought?, *Geophys. Res. Lett*., 37, L13403, doi:10.1029/2010GL043167.

Davis, S. J. and K. Caldeira (2010), Consumption-based accounting of CO_2 emissions, *PNAS, 107(12),* 5687-5692, Available www.pnas.org/cgi/doi/10.1073/pnas.0906974107.

Dawadi, S. and S. Ahmad (2012), Changing climatic conditions in the Colorado River Basin: Implications for water resource management. *Journal of Hydrology*, 430-431, 127-141.

Elcock, D. (2008). Baseline and projected water demand data for energy and competing water use sectors, ANL/EVS/TM/08-8. Argonne National Laboratory, Environmental Science Division.

Elcock, D. (2010), Future U.S. water consumption: The role of energy production. *JAWRA* 46(3):447-460. Doi: 10.1111/j.1752-1688.2009.00413.x.

Fader, M., D. Gerten, M. Thammer, J. Heinke, H. Lotze-Campen, W. Lucht, and W. Cramer (2011), Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade, *Hydrol. Earth Syst. Sci., 15*, 1641–1660.

Finster, R. D. (1971), Improving water resource allocation through demand-oriented water policy. *Water Resour. Bull., 7(1)*, 1-25.

Fischer-Kowalsi M., and W. Huttler (1999), Society's metabolism: the intellectual history of material flow analysis, Part II, 1970 - 1998. *J. Indust. Ecol., 2(4),* 107-137.

Gober, P., Kirkwood, C. W., Balling Jr., R. C., Ellis, A. W., & Deitrick, S. (2010). Water planning under climatic uncertainty in phoenix: Why we need a new paradigm. *Annals of the Assoc. of American Geographers, 100(2)*, 356-372.

Hanemann, W. M. (2006). Chapter 4: The economic conception of water. In P. P. Rogers, M. R. Llamas & L. Martinez-Cortina (Eds.), *Water crisis: Myth or reality?* (pp. 61-91)

Harto, C. B., & Yan, Y. E. (2011). *Analysis of drought impacts on electricity production in the western and Texas interconnections of the United States.* Argonne National Laboratory, Environmental Science Division. Oak Ridge, TN: U.S. Department of Energy.

Hoekstra, A. Y., A. K. Chapagain, M. M. Aldaya, and M. M. Mekonnen (2011), *The Water Footprint Assessment Manual: Setting the Global Standard.* Earthscan Publishing. Water Footprint Network. Available from: http://www.waterfootprint.org/downloads/TheWaterFootprintAssessmentManual.pdf.

Hoekstra, A.Y. and M.M. Mekonnen. (2012), The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America, 109*(9), 3232-3237, doi: 10.1073/pnas.1109936109.

Hoekstra, A.Y. and P. Q. Hung. (2002), Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade. *Value of WaterResearch Report Series No. 11*. UNESCO-IHE, Delft, The Netherlands. Available from: www.waterfootprint.org/Reports/Report11.pdf.

Kenny, J., N. Barber, S. Hutson, K. Linsey, J. Lovelace, and M. Maupin (2009), Estimated use of water in the United States in 2005. *U.S. Geological Survey Circular 1344*.

Konar, M, C. Dalin, N. Hanasaki, A. Rinaldo, and I. Rodriguez-Iturbe (2012), Temporal dynamics of blue and green virtual water trade networks. *Water Resour. Res., 48*,W07509, doi:10.1029/2012WR011959.

Kumar, M. D. and O. P. Singh (2005), Virtual water in global food and water policy: Is there a need for rethinking? *Water Resourc. Manag., 19*, 759-789, doi:10.1007//s11269-005-3278-0.

Li, Y. and B. J. Lence (2007), Estimating resilience for water resources systems, Water Resour. Res., 43, W07422, doi:10.1029/2006WR005636

MacDonnell, L.J. (2009), Colorado River Basin. *Water and Water Rights*. Vol 4, 5-54.

Macknick, J., R. Newmark, G. Heath, and K. C. Hallett (2011), A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies, NREL/TP-6A20-50900, National Renewable Energy Laboratory, Golden, CO, pp. 29.

Marriott, J. and S. Matthews (2005), Environmental effects of interstate power trading on electricity consumption mixes. *Environ. Sci. and Tech., 39,* 8584-8590.

Martin, E.A. and B.L. Ruddell (2012), Value intensity of water used for electrical energy generation in the Western U.S.; An application of embedded resource accounting. *IEEE International Symposium of Systems and Technology, Conference paper.* Boston, Mass.

McCormick, Z.L. (1994), Interstate water allocation compacts in the Western United-States – Some suggestions. *Water Resources Bulletin. 30(3)*, 385-395.

Mead, Matthew (2013). Wyoming Energy Strategy 2013 Release. Press conference. Video Streamed live on May 13, 2013. Available http://youtu.be/DBAsswd00k0. Accessed July 16, 2013.

Mekonnen, M.M. and A.Y. Hoekstra (2012), The blue water footprint of electricity from hydropower. *Hydrol. Earth Syst. Sci., 16*, 179-187, doi: 10.5194/hess-16-179-2012.

Mielke, E., L. Diaz Anadon, and V. Narayanamurti (2010). Water consumption of energy resource extraction, processing and conversion, a review of the literature for estimates of water intensity of energy-resource extraction, processing to fuels, and conversion to electricity. Energy Technology Innovation and Policy Discussion Paper No. 2010-15. Harvard Kennedy School, Harvard University.

Mubako S.T., Ruddell B.L., and A. Mayer (2012), The relationship between water withdrawals and freshwater ecosystem water scarcity quantified at multiple spatio-temporal locations and scales for a Great Lakes watershed, *in press.*

Mubako, S.T. (2011), Frameworks for estimating virtual water flows among U.S. states, *Dissertations*, Paper 341, http://opensiuc.lib.siu.edu/dissertations/341.

National Academies (U.S.)., National Research Council (U.S.)., National Research Council (U.S.)., & National Research Council (U.S.). (2010). *Hidden costs of energy: Unpriced consequences of energy production and use*. Washington, D.C: National Academies Press.

NOAA. (2013). *Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 9. Climate of the Contiguous United States.* Kunkel, K.E, L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Wuebbles, and J.G. Dobson. NOAA Technical Report. National Environmental Satellite, Data, and Information Service (NESDIS) 142-9, 78 pp. http://scenarios.globalchange.gov/sites/default/files/NOAA_NESDIS_Tech_Report_142-9-Climate_of_the_Contiguous_United_States_3.pdf.

Ostrom, E., J. Burger, C.B. Field, R.B. Norgaard, and D. Policansky (1999), Revisiting the Commons: Local lessons, global challenges. Science. 284(5412), 278-282. http://www.jstor.org/stable/2898207.

Pitzer, G. (2009), *The Water-Energy Nexus in the Colorado River Basin*, Colorado River Project, Water Education Foundation, River Report 7, Available from: http://www.watereducation.org/userfiles/RiverReport_Summer09_WEB.pdf.

Porkka, M., M. Kummu, S. Siebert, and M. Floerke (2012), The role of virtual water flows in physical water scarcity: The case of central Asia. *Int. J. Water Resour. Dev., 28*(3), 453-474. doi: 10.1080/07900627.2012.684310.

Postel,S. L. (2000), Entering an Era of Water Scarcity: The Challenges Ahead, *Ecol. Appl., 10(4)*, 941-948.

Reisner M. (1993), *Cadillac Desert: The American west and its disappearing water*. New York: Penguin Books.

Rinne, W. (2000), How the Colorado River Operates. United States Bureau of Reclamation, Lower Colorado Region. White Paper.

Rushforth R.R., E.A. Adams, and B.L. Ruddell (2012), Embedded Resource Accounting: Generalizing Ecological, Water and Carbon Footprint Methodologies. *In review, Water Resources and Industry*.

Scott, C., and M. Pasqualetti (2010), Energy and water resources scarcity: Critical infrastructure for growth and economic development in Arizona and Sonora. *Nat. Resour. J., 50*, 645-682.

Solley, W., R. Pierce, and H. Perlman (1995), Estimated Use of Water in the United States in 1995, *U.S. Geological Survey Circular 1200*.

Taylor, P.J. (2005), Leading World Cities: Empirical Evaluations of Urban Nodes in Multiple Networks, *Urban Studies, 42*, 1593-1608.

Tidwell, V.C., P.H. Kobos, L.A. Malczynski, G. Klise, and C.R. Castillo (2012), Exploring the water-thermoelectric power nexus, *Journal of Water Planning and Management*, *138*(5), 491-501.

Tidwell, V.C., P.H. Kobos, L.A. Malczynski, G. Klise, and C.R. Castillo (2012), Exploring the water-thermoelectric power nexus, *Journal of Water Planning and Management*, *138*(5), 491-501.

Tol, R. S. J. (2012), On the Uncertainty About the Total Economic Impact of Climate Change, *Env. Resource Econ., 53(1)*. doi: 10.1007/s10640-012-9549-3.

USBR (United States Bueau of Reclamation) (2007), Colorado River Basin Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead. http://www.usbr.gov/lc/region/programs/strategies.html. Accessed June 27, 2013.

USBR (United States Bueau of Reclamation) (2013), Colorado River Basin Water Supply and Demand Study, Final Report. http://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Study%20Report/StudyReport_FINAL_Dec2012.pdf. http://www.usbr.gov/lc/region/programs/crbstudy/finalreport/index.html. Accessed June 27, 2013.

USDOE (United States Department of Energy) (2006), Energy Demands on Water Resources. A Report to Congress on the Interdependency of Energy and Water. Available: http://www.sandia.gov/energy-water/congress_report.htm. Accessed July 16, 2013.

USDOE (United States Department of Energy) (2013), U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather. DOE/PI-0013. Available http://energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather. Accessed July 16, 2013.

USEIA (U.S. Energy Information Administration) (2005), *Steam-Electric Plant Operation and Design Data,* EIA-767, (available at http://www.eia.gov/cneaf/electricity/page/eia767/).

USEIA (U.S. Energy Information Administration) (2010), Net generation by state by type of producer by energy source. Rep. EIA-906, Washington, DC.

USEIA (U.S. Energy Information Administration) (2011a), Online. Sales data tables. *Electricity*. Accessed October 2011. http://www.eia.gov/electricity/data.cfm#sales.

USEIA (U.S. Energy Information Administration) (2011b), Online. Supply and Disposition of Electricity. State electricity profiles. *Electricity*. Accessed October 2011. http://www.eia.gov/electricity/state/.

USEIA (U.S. Energy Information Administration) (2011c), Online. Factors affecting electricity prices. *Energy Explained*. Accessed December 2011. http://www.eia.gov/energyexplained/index.cfm?page=electricity_factors_affecting_prices.

USEIA (U.S. Energy Information Administration) (2012a), Online. Annual Coal Distribution Report http://www.eia.gov/coal/distribution/annual/ Accessed June 20, 2013.

USEIA (U.S. Energy Information Administration) (2012b), Online. Annual Energy Review. http://www.eia.gov/totalenergy/data/annual/index.cfm. Accessed July 10, 2013.

USEIA (U.S. Energy Information Administration) (2012c), Online. *Table 14. Production of crude oil by PAD district and state, 2011*, Petroleum Supply Annual, Volume 1. http://www.eia.gov/petroleum/supply/annual/volume1/. Accessed July 6, 2013.

USEIA (U.S. Energy Information Administration) (2012d), Online. *Table 26. Imports of crude oil and petroleum products into the United States by country of origin, 2011*, Petroleum Supply Annual, Volume 1. http://www.eia.gov/petroleum/supply/annual/volume1/. Accessed July 6, 2013.

USEIA (U.S. Energy Information Administration) (2012e), Online. *Table 34. Average Price of Coal Delivered to End Use Sector by Census Division and State*, Annual Coal Report. http://www.eia.gov/coal/annual/ Accessed June 23, 2013.

USEIA (U.S. Energy Information Administration) (2013a), Online. How many gallons of gasoline does one barrel of gasoline make? Tools. FAQS. http://www.eia.gov/tools/faqs/faq.cfm?id=24&t=7. Accessed July 3, 2013.

USEIA (U.S. Energy Information Administration) (2013b), Online. *Table 2. Natural gas production, transmission, and consumption by state, 2011*, Natural Gas Annual. http://www.eia.gov/naturalgas/annual/ Accessed June 12, 2013.

USEIA (U.S. Energy Information Administration) (2013c), Online. *Table 12. Interstate movements and movements across U.S. borders of natural gas by state, 2011*, Natural Gas Annual. http://www.eia.gov/naturalgas/annual/ Accessed June 12, 2013.

USEIA (U.S. Energy Information Administration) (2013d), Online. *Table 16. Natural Gas delivered to consumers by sector, and by state and sector, 2011*, Natural Gas Annual. http://www.eia.gov/naturalgas/annual/ Accessed June 12, 2013.

USEIA (U.S. Energy Information Administration) (2013e), Online. *Table 24. Average price of natural gas delivered to consumers by state and sector, 2011*, Natural Gas Annual. http://www.eia.gov/naturalgas/annual/ Accessed June 12, 2013.

USEIA (U.S. Energy Information Administration) (2013f), Online. *Table F15: Total petroleum consumption estimates, 2011*. http://www.eia.gov/state/seds/sep_fuel/html/pdf/fuel_use_pa.pdf. State energy data system. Accessed July 6, 2013.

USEIA (U.S. Energy Information Administration) (2013g), Online. *U.S. Natural Gas Exports By Country, 2011*, Annual Data. Natural Gas. http://www.eia.gov/dnav/ng/ng_move_expc_s1_a.htm Accessed June 12, 2013.

USEIA (U.S. Energy Information Administration) (2013h), Online. *Weekly retail gasoline and diesel prices, 2011.* Petroleum and Other Liquid. Data. http://www.eia.gov/dnav/pet/pet_pri_gnd_a_epm0_pte_dpgal_a.htm. Accessed July 8, 2013.

USEIA (United States Energy Information Administration), (2013a). Online. California: State Profile and Energy Estimate, 2011. http://www.eia.gov/state/data.cfm?sid=CA#Consumption. Accessed July 16, 2013.

USEIA (United States Energy Information Administration), (2013b). Online. Wyoming: State Profile and Energy Estimate, 2011. http://www.eia.gov/state/rankings/?sid=WY#series/101. Accessed July 16, 2013.

USEPA (U.S. Environmental Protection Agency) (2010), Emissions and Generation Resource Integrated Database (eGRID), version 1.0.

Velazquez, E. (2006), An input-output model of water consumption: Analysing intersectoral water relationships. *Ecol. Econ., 56*, 226-240.

Wackernagel, M., L. Onisto, P. Bello, A. C. Linares, I. S. L. Falfan, J. M. Garcia, A. I. S. Guerro, M. G. S. Guerro (1999), National natural capital accounting with eth ecological footprint concept, *Ecol. Econ., 29,* 375-390.

WFN (Water Footprint Network) (2013), Online. Product Water Footprints. Energy. Accessed February 2013. http://www.waterfootprint.org/?page=files/Water-energy.

Wichelns, D. (2010), Virtual water: a helpful perspective, but not a sufficient policy criterion, *Water Resour. Manag.*, *24*, 2203-2219.

Wildman, R. A., Jr., and N. A. Forde (2012), Management of water shortage in the Colorado river basin: Evaluating current policy and the viability of interstate water trading. *J. American Water Resour. Assoc.*, *48*(3), 411-422. doi: 10.1111/j.1752-1688.2012.00665.x.

Wildman, R. A., Jr., and N. A. Forde (2012), Management of water shortage in the Colorado river basin: Evaluating current policy and the viability of interstate water trading. *J. American Water Resour. Assoc.*, *48*(3), 411-422. doi: 10.1111/j.1752-1688.2012.00665.x.

Wildman, R.A. and N.A. Forde (2012), Management of water shortage in the Colorado River Basin: Evaluating current policy and the viability of interstate water trading, *J. American Water Resources Assoc.*, doi: 10.1111/j.1752-1699.2012.00665.x.

Wilson, W., T. Leipzig and B Griffiths-Sattenspiel (2012), *Burning our rivers. The water footprint of electricity.* A River Network Report. http://www.rivernetwork.org/sites/default/files/BurningOurRivers_0.pdf. Accessed July 16, 2013.

WWAP (World Water Assessment Programme). (2012), *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk.* Paris, UNESCO.

WWAP (World Water Assessment Programme). (2012), *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk.* Paris, UNESCO.

Yang, H., L. Wang, K. Abbaspour, and A. Zehnder (2006), Virtual water trade: An assessment of water use efficiency in the international food trade, *Hydrol. Earth Syst. Sci.*, *10*, 443–454.

Zetland, D. (2011). *The End of Abundance: economic solutions to water scarcity*. Aguanomics Press. ISBN: 978-0615469737.

APPENDIX A

TRADE NETWORK ESTIMATION TABLES

Table A1. Input-Output table of Interstate coal transfers for the electric sector, 2011 (short tons)

	Arizona	California	Colorado	Idaho	Montana	Nevada	New Mexico	Oregon
Arizona	7872483							
California								
Colorado	184277		9749723					
Idaho								
Montana	761439				9165075			108462
Nevada								
New Mexico	8211291						16318377	
Oregon								
Utah		837636				1742647		
Washington								
Wyoming	5818897		10004169		554530	1361874		2243208

Table A1. Input-Output table of Interstate coal transfers for the electric sector, 2011 (short tons) continued

	Utah	Washington	Wyoming	To other US States
Arizona				
California				
Colorado	1976723			9009210
Idaho				
Montana		2342712		11517260
Nevada				
New Mexico				
Oregon				
Utah	12550528			293652
Washington				
Wyoming		1180782	24901919	379488564

Table A2. Input-Output Table of Natural Gas Estimated Trade, 2011 (million cubic feet)

	Arizona	California	Colorado	Idaho	Montana	Nevada	New Mexico
Arizona	168						
California		250177					
Colorado	56127	340948	631739	15224		44877	
Idaho				0			
Montana	1095	6652		297	54999	876	
Nevada						3	
New Mexico	48835	296656		13246		39047	362131
Oregon							
Utah	9461	57472		2566		7565	
Washington							
Wyoming	102929	625254		27919		82299	
Other US States							
Mexico							
Canada	88347	536678		23964		70640	

Table A2. Input-Output Table of Natural Gas Estimated Trade, 2011 (million cubic feet) continued

	Oregon	Utah	Washington	Wyoming	Other US States	Mexico
Arizona						
California						
Colorado	31622		58056		434594	24389
Idaho						
Montana	617		1133		8479	476
Nevada						
New Mexico	27514		50514		378137	21221
Oregon	1344					
Utah	5330	287977	9786		73257	4111
Washington			0			
Wyoming	57991		106468	317343	796988	44726
Other US States						
Mexico						
Canada	49776		91385		684084	38390

Table A3. Input-output Table Oil Estimated Trade Network, 2011 (thousand barrels)

	Arizona	California	Colorado	Idaho	Montana	Nevada	New Mexico
Arizona	37						
California		196189					
Colorado			39056				
Idaho				0			
Montana	109	452	46	30	20441	46	
Nevada						408	
New Mexico	1047	4320	438	289		437	35962
Oregon							
Utah							
Washington							
Wyoming	1109	4580	464	306		463	
Other US States							
Canada	23961	98917	10021	6610		10007	
Mexico	11865	48980	4962	3273		4955	
Other Foreign Countries	46439	191709	19421	12811		19394	

Table A3. Input-output Table Oil Estimated Trade Network, 2011 (thousand barrels) continued

	Oregon	Utah	Washington	Wyoming	Other US States
Arizona					
California					
Colorado					
Idaho					
Montana	72	23	140		2791
Nevada					
New Mexico	693	217	1335		26689
Oregon	0				
Utah		26286			
Washington			0		
Wyoming	734	230	1415	17163	28291
Other US States					1652865
Canada	15856	4974	30560		611059
Mexico	7851	2463	15132		302572
Other Foreign Countries	30730	9639	59227		1184279