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Policy and institutional dimensions of the water–energy nexus

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ABSTRACT

Energy and water are interlinked. The development, use, and waste generated by demand for both resources drive global change. Managing them in tandem offers potential for global-change adaptation but presents institutional challenges. This paper advances understanding of the water–energy nexus by demonstrating how these resources are coupled at multiple scales, and by uncovering institutional opportunities and impediments to joint decision-making. Three water–energy nexus cases in the United States are examined: (1) water and energy development in the water-scarce Southwest; (2) conflicts between coal development, environmental quality, and social impacts in the East; and (3) tensions between environmental quality and economic development of shale natural gas in the Northeast and Central U.S. These cases are related to Eastern, Central, and Western regional stakeholder priorities collected in a national effort to assess energy–water scenarios. We find that localized challenges are diminished when considered from broader perspectives, while regionally important challenges are not prioritized locally. The transportability of electricity, and to some extent raw coal and gas, makes energy more suitable than water to regionalized global-change adaptation, because many of the impacts to water availability and quality remain localized. We conclude by highlighting the need for improved coordination between water and energy policy.

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1. Introduction: beyond the resource use nexus between water and energy

The *water–energy nexus*, as conventionally conceived, treats energy and water as being interlinked primarily in terms of resource use. In this view, energy is required to secure, deliver, treat, and distribute water (Siddiqi and Anadon, 2011). Conversely, water is used, consumed, and often degraded to develop, process, and deliver energy for consumption (Rio Carrillo and Frei, 2009). Concern over production and consumption of coupled energy and water use stems principally from the operational focus of water and power utility companies. Infrastructure and technology are at the core of this conceptualization of water–energy coupling, which we characterize as the 'pumps and turbines' approach. Because of this emphasis on resource consumption, the nexus is often characterized in resource use efficiency terms, e.g., cubic meters of water needed to generate a kilowatt hour of electrical power or, conversely, kilowatt hours of electricity consumed per cubic meter of water supplied. The input–output understanding of energy and water interlinkages is mirrored by footprint calculators—now firmly established as metrics of the carbon, energy, or water consumption of human activities (Gerbens-Leenes et al., 2009; Griffiths-Sattenspiel and Wilson, 2009). Yet, despite such operational interdependencies between water and energy, there are few examples of tandem management of both resources (Sovacool and Sovacool, 2009a; Electric Power Research Institute (EPRI), 2002).

Resources are managed at multiple scales. Here, we refer to local as the domain of utilities and city governments. We consider regional to encompass multiple local domains, but in which management remains focused on identifiable locations and specific resources, e.g., the state (or province) regulating a particular water utility to pump a prescribed volume from a reservoir. However, regions can also cross state boundaries, for instance, the Western region of the United States or resource units like large river basins. This can lead to territorial mismatch; however, for management purposes, administrative boundaries are more relevant than the physical boundaries of a resource. At the

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national level, decision-making over resources extends beyond management to policy setting, in which national sovereignty concerns prevail. And global decision-making, e.g., through United Nations bodies, tends to be normative but non-binding in that it requires the conviction of national governments.

Researchers relying on the operational understanding of the water–energy nexus frequently address national and global demand for resources by pointing to the need for increased local production and consumption of energy and water (Sovacool, 2009; Sovacool and Sovacool, 2009b). Such proposals rarely pay adequate attention to local-scale consequences and impacts. This is because proposed solutions are oriented towards outcomes (resource use and adequacy of supply) without fully exploring processes (institutions and policy frameworks that influence decision-making). For example, development of coal or natural gas can have serious impacts on environmental quality and human health. Although such concerns are well recognized, they are invariably treated as externalities and generally not included in the conventional approach to coupled energy and water use. Where these impacts are addressed, they may be seen merely as factors requiring engineered mitigation strategies. As we will demonstrate below, local decision-makers may have limited capacity or authority to address such impacts when energy development is pursued by powerful national or global commercial interests. Nevertheless, local capacity challenges can be compensated for through "regulatory cooperation" at higher institutional scales (Holzinger and Knill, 2004). This points out that the water–energy nexus is also fundamentally about decision-making.

Increasingly, there are national calls for joint water and energy resource management. In the U.S., the Energy and Water Research Integration Act was formulated "to ensure consideration of water intensity in the Department of Energy's energy research, development, and demonstration programs to help guarantee efficient, reliable, and sustainable delivery of energy and water resources" (Govtrack, 2011). Although this was not enacted into law before the 2010 closing of the 111th Congress it did draw policy attention to the nexus. It also represents an important national step towards energy–water policy coupling. Contemporary water policy does consider the energy implications of water use, although often in basic terms of increased financial costs for the energy required to pump, treat, and reclaim water. Alternatively, nationally important energy policy initiatives are emerging that actively consider water resource implications (Carter, 2010; Sovacool and Sovacool, 2009a). Institutional inertia in both the energy and water sectors can effectively lock out competing and more efficient options (Unruh, 2000). For example, transition to less water intensive energy technologies is limited by existing infrastructure and institutional arrangements created to support current electricity generating technology. However, incremental alterations to existing infrastructure and environmental policy could overcome these challenges (Unruh, 2002). Despite recent policy initiatives such as the Energy and Water Research Integration Act, the coupled consideration of energy and water is nascent. Local-state-federal institutional mechanisms seeking to link energy and water resource management effectively remain decoupled.

This paper evaluates how energy and water, when considered together rather than as individual resources, reveal a broader set of institutional relationships and highlight decision-making challenges faced by society. To move beyond the nexus in input–output terms, we develop and apply two central concepts, namely the *resource coupling* of energy and water, and *multi-tiered institutional arrangements* for resource management decision-making. By resource coupling, we mean the interdependence of energy and water not simply at the operational point of use in the 'pumps and turbines' view we characterized above, but foremost at regional levels of natural resource stocks, e.g., surface water, groundwater, and non-conventional water such as effluent, in relation to changing human demands for energy and the water that will be required to generate it. Resource coupling occurs at multiple spatial scales but is qualitatively different from the multi-tiered nature of institutions, as alluded to in our definitions of scale, above. For instance, the process of energy-development permitting that is overseen by federal or state agencies means that local resources may not be managed by local authorities. Thus, energy–water resource linkages do not necessarily match the scale of institutions, often for justifiable reasons including the need to retain regulatory oversight, institutional accountability (of agencies to elected leadership), and calls for public safety and risk mitigation.

In the cases below we will explore the water and environmental impacts of energy development—an important dimension of resource coupling that is rarely considered in the input–output understanding of the nexus. The scale of impacts is a critical consideration. When focusing only on the point of water or energy use, waste and pollution generated in resource development are seen as 'environmental externalities,' a term we challenge by exposing decision priorities imposed from the global and national to regional and local scales.

As a complement to resource coupling, multi-tiered institutional arrangements – specifically laws, policies, and organizations that operate across jurisdictional levels for the management of resources – offer a wider set of alternatives for decision-making (Scott and Pasqualetti, 2010). Regulations for water or energy service provision and their compliance, in the U.S. for example, tend to operate in the domain of state and occasionally federal governments with separation of regulatory agencies from politically elected leadership. Regulatory commissions approve operating plans and rate structures—in part to protect the public from 'natural monopolies' that utilities can represent. At the same time, multi-tiered institutional arrangements increasingly safeguard against the effects that global or national-level resource demand can have on regional or local environmental impacts or quality of life.

In expanding water and energy linkages beyond point-of-use to resource coupling and multi-tiered institutions, our primary objective is to move the water–energy nexus construct beyond an input–output relationship into the realm of resource governance, policy, and global-change adaptation. This centrally involves better understanding of local environmental and social impacts of the increasing global demands for energy and water. Thus, selection of case examples is informed theoretically to elucidate this primary objective.

This paper is organized as follows. The introduction expands the conventional understanding, which characterizes the water–energy nexus as simply a question of linked resource use. Instead, we advance the notion that water and energy are coupled at multiple scales, not merely at the point of end use as resources. Following this reasoning, global demands for energy have local impacts on water resources that are intrinsic to the nexus relationship. Crucially, we also consider decision-making for the development, use, and associated impacts of both resources in a way that acknowledges their interlinkages and shows their interdependent nature. At the same time, local and regional decision-making for water and energy resources raise opportunities for adaptation to global change processes. But this is only possible by moving beyond input–output relationships and requires investigating institutional and policy dimensions of water and energy coupling. This expanded understanding is illustrated by multiple cases from the U.S., each illustrating an important dimension of the broader water–energy nexus. We then

integrate conceptual propositions we have raised in the highlighted cases by developing water–energy portfolios for the Western, Central, and Eastern regions of the U.S. based on reports from a regional stakeholder engagement process (Sandia National Laboratories (SNL), 2005). The regional cases and portfolio options are discussed in light of the broader definition of the nexus and uncover new understandings of water and energy coupling. Finally, in the conclusion we synthesize insights derived in the preceding sections while at the same time identifying new questions for analysis and opportunities the water–energy nexus holds for adaptation to global change.

2. Overcoming the governance mismatch between global drivers and local resources

Globally, population and economic growth drive demand for resources. Numerous other factors intensify demands for freshwater and reliable energy, for example, climate change and variability (Intergovernmental Panel on Climate Change (IPCC), 2007), rapid urbanization (United Nations (UN) Population Division, 2008), and globalized energy markets (Smil, 2005). As pressures on resources increase, conflict may ensue as nations vie for resources and communities seek to reconcile differing priorities and values in the face of complex tradeoffs brought on by resource scarcity. Locally, adaptation to rising temperatures in expanding cities increases water and energy demand (Guhathakurta and Gober, 2007). Yet, at a regional scale in the U.S., for example, the demographic drift of urban populations from the densely populated Northeast towards the Southwest reduces national energy use for heating and cooling (Sivak, 2009). Adaptive strategies to reduce vulnerability to global change drivers can themselves increase resource use and environmental degradation. In the Southwest, adaptation to rising temperatures and variable water availability tends to increase per capita energy and water consumption for cooling, irrigation, and other uses. Such place-based responses to climate variability may effectively raise carbon emissions from conventional power generation, and thus over the longer term, act against regional or national climate mitigation efforts that seek to reduce emissions.

The demand and use of energy and water in myriad local contexts must be managed considering the regional, national, and global scales of the development and supply of resources together with associated human and environmental impacts. These interdependencies among source regions and demand sites for energy are very different than source and demand links for water. Energy is a transformable and more transportable resource than water. Regional and transboundary initiatives have undeniably proven useful in resolving water challenges (Norman and Bakker, 2009; Jerrett et al., 2003) and in conferring adaptive capacity (Wilder et al., 2010). Nevertheless, the transmutability and versatility of energy, particularly of electricity, across a range of human activities enhance its role in adaptation strategies.

The interdependencies between energy and water are rooted in specific characteristics of these resources, particularly individual consumer practices that influence demand. For example, residential hot water heaters account for considerable energy demand, or the water demand tradeoffs between air-conditioning that requires evaporative cooling at the power plant and in-home evaporative coolers in arid regions that consume water onsite. At the same time, however, the institutions created to manage and regulate energy and water have the effect of interlinking both resources. This situation leads to policy choices such as private vs. public utilities to supply energy and water, centralized vs. decentralized infrastructure, pricing mechanisms, facility siting, etc. Local, regional, state, national, and global decision processes, laws, and agreements all influence water and energy supply and demand.

In the next sections, we present three cases selected from among numerous possible alternatives based on our conceptual focus on local impacts resulting from national or global demand for resources. As a result, the cases address the theoretical water–energy nexus problem highlighted above. Each case represents an important and visible instance of water–energy coupling. The cases illustrate how local-to-global energy–water coupling interacts with tiered institutions. Additionally, the policy responses to impacts demonstrate the multi-tiered institutions aspect of our argument. Fig. 1 shows a broad regionalization (Western, Central, and Eastern) of the continental U.S., which we refer to for the stakeholder dialog process described. The specific local cases that we document are illustrative of regional resource coupling. The Southwestern, Northeastern and Central, and Eastern cases highlight resource issues and institutional concerns at the energy–water interface. Collectively these cases raise generalizable inferences for energy–water coupling and tiered decision-making, and they pose questions for further enquiry.

2.1. Southwestern case: the electricity—water (scarcity) nexus

The current and anticipated water and energy infrastructure in the state of Arizona embodies the coupled nature of water and energy and is particularly representative of the southwestern U.S. Large-scale infrastructure also suffer from the institutional disconnect between local and regional management. Currently, large-scale systems are relied on to provide electricity and water in the arid Southwest. This dependence requires high inputs of both resources just to ensure resource availability and delivery. Emphasis on regional power grids and inter-basin water transfers undermines the potential contributions of local renewable energy sources and water and energy conservation opportunities. Centralized energy production and large-scale water conveyance projects have long been predicated on an assumption of resource inexhaustibility. Thus, the Southwest – particularly Arizona – is emblematic of the reliance on scarce water and the use of non-renewable energy. In 2007, coal, natural gas, and nuclear power plants generated virtually all of the electricity used in Arizona, with less than half a percent coming from non-hydro renewable energies such as solar photovoltaic, wind, and geothermal. Concern for the water demands of electric generation – conventional processes consume 415–785 gal (1.57–2.97 m^3) of water per megawatt hour (Pasqualetti and Kelley, 2007) – has prompted the Arizona Corporation Commission to deny permits for several conventional and solar power plants (Arizona Corporation Commission (ACC), 2002) or to require the use of modified technology (Willcox RangeNews, 2007).

Conversely, water resource development in Arizona has relied on energy-intensive groundwater pumping and large-scale water projects (Scott et al., 2007). The Central Arizona Project (CAP) is a 336-mile (540 km) aqueduct that annually meets the demand for 1.5 million acre feet (1.85 km^3) of Colorado River water (Eden et al., in press). Institutionally, the CAP as a water management agency makes decisions that significantly affect both water and power in the state. Pumping water via the CAP to Phoenix requires 1525 kilowatt hours per acre foot (kWh/AF) and a total of 3140 kWh/AF to Tucson, equivalent to 1.24 kWh/m^3 and 2.55 kWh/m^3, respectively. These pumping costs are three to ten times greater than the energy requirements for pumping from local water sources (Hoover, 2009); however prevailing water scarcity means local water sources are inadequate to meet demand.

As the state's largest consumer of electricity, the CAP relies on the Navajo Generating Station, which burns six thousand tons of

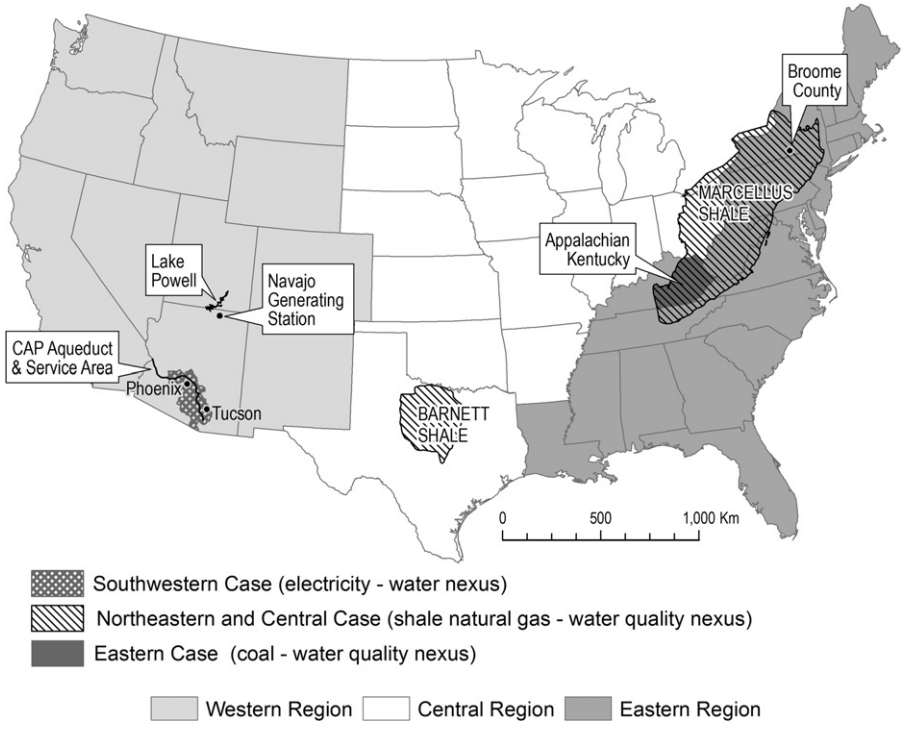


Fig. 1. Major U.S. regions and case locations.

coal per day and takes cooling water from Lake Powell, a reservoir formed behind Glen Canyon Dam in arid northern Arizona (see Fig. 1). The disparate geographic locations of the water and energy resources needed to maintain the current and expected demands illustrate the extensive coupling of these resources. However, resource withdrawal from one location and consumption in a different location highlights local-regional tradeoffs in which concentrated water demand is displaced not only from its sources, and the energy consumed to deliver the water, but also from the local water-quantity and air-quality impacts that result from the power generation. This is a generic challenge in water-scarce contexts (Siddiqi and Anadon, 2011).

Adaptive resource management in the context of growth with variable and scarce water and energy must be addressed institutionally, based on coherently articulated local and state-level planning for growth and resource use. Because of its role as the state's water 'wholesaler', CAP currently manages infrastructure that extensively couples energy and water resources across multiple scales in Arizona, serving as an important link among disparate water utilities (its retail customers) and electrical utilities (its commercial partners in power generation). Under current institutional arrangements, then, CAP adeptly complies with water, energy, and environmental quality regulation. However, as urban growth and water variability drive diversification, including off-network and reclaimed water sourcing as well as off-grid renewable energy development, the current sole-source dependence and extensive spatial patterns of resource coupling in Arizona will inexorably devolve. However, as shown in the next case, continued reliance on coal to meet energy demands has numerous impacts at multiple scales of resource coupling.

2.2. *Eastern case: the coal—water quality nexus*

Coal makes up nearly half of the U.S.'s electrical generation and 90% of its fossil fuel energy reserves (Energy Information Administration (EIA), 2010). The concept of 'clean coal' figures prominently in regional and national discussions of energy policy (Department of Energy (DOE), 2007). From this perspective, the challenges center largely on making power plants more efficient and sequestering or offsetting carbon emissions. Yet in Appalachian Kentucky, where much of coal is extracted, the focus of 'clean coal' is not on energy but on water—a discussion virtually absent from the national-level conversation.

Early 20th century mining towns, built quickly for large, relatively transient populations, left a legacy of inadequate – or absent – sewage systems, which today is manifest in streams with high bacterial loads (Banks et al., 2005). Acid mine drainage is the hydro-signature of large-scale deep mines active from the 1950s to the 1980s. As early as the 1950s, local opposition to mining was centered on water-related impacts to landowners and communities: downstream flooding and landslides, and contamination of wells and other drinking water supplies (Eller, 2009). Through the 1960s and 1970s opposition swelled regionally. The focus was on contracts granting companies carte blanche to mine without liability for injury or damage to either water or land (Baber, 1988). Many of these contracts had been executed generations earlier by farmers whose livelihoods were made from the land's surface, when mining was a pickax-and-pony affair. In some cases, institutional arrangements for localized mining ventures that began before industrialization would lead to modern strip mining, financed by national and increasingly global commercial mining interests, but with significant place-based environmental quality impacts.

While the 1977 Surface Mining Control and Reclamation Act alleviated many of the slope stabilization problems, it did not affect the blast fracturing that contaminated wells and drinking water, nor did it effectively control runoff quantity and quality. Current large-scale surface and mountaintop removal techniques can result in the wholesale burial of headwater streams and the decline of both surface water and groundwater quality, which is well documented to affect both human and ecological communities (Palmer et al., 2010), problems that are ubiquitous in mountain headwater communities across Appalachia. Diagnostic sampling of more than 900 first-order streams across six Kentucky

counties found at least one extreme water impairment – and often multiple impairments – in more than 70% of the samples (Jones et al., 2007).

Illustrative of our concern with multi-tiered institutions, this case demonstrates that mediation (for example, through impact fees, environmental regulation, or monitoring) is difficult to sustain under the power asymmetries between local jurisdictions and mining companies. On the other hand, employment and economic prosperity could be considered the compensation for this widespread human and ecological impact. Coal clearly dominates the local economies in Appalachia, accounting for upwards of 40% of the labor force in some counties and generating millions in severance taxes for state coffers; but this strong economic presence has not necessarily translated into healthy local economies. Appalachian Kentucky's coal-producing counties are perpetually among the poorest in the nation, a status they have held continually through many rises and falls in coal productivity.

This coupling of energy development and environmental quality in Appalachia demonstrates how national energy demands are met through coal extraction with acute alteration of local watershed processes. The impacts occur directly as water quality threats to human and ecosystem health and indirectly as consequences of inadequate infrastructure to reduce environmental health risks. As discussed in the section on stakeholder priorities, these impacts are viewed as remediable or are overlooked entirely in regional and national policy discussions.

2.3. Northeastern and central case: the shale natural gas–water quality nexus

Natural gas raises opportunity for economic development, especially in the Northeastern and Central U.S. that have some of the largest fields. For example, the Marcellus shale formation (see Fig. 1) covers about 95,000 square miles (246,000 km^3) and contains up to 500 trillion cubic feet of natural gas (1.4×10^{12} m^3), equivalent to approximately 20 years of national consumption in 2008. Several factors combine to make the Marcellus economically viable for gas production, including technological advancements in horizontal drilling and hydraulic fracturing ('fracking'), increases in natural gas prices, and proximity to demand. The potential economic benefits of gas development are enormous and the Marcellus has attracted national and global energy interests. Economic analyses of similar projects in Arkansas and Texas, such as the Barnett Shale, valued total production at $2.6 billion and $10.1 billion, respectively, and the Marcellus is a much larger deposit. This is particularly enticing given that many of the counties in the region, particularly those in New York and Pennsylvania, have median household incomes below the respective states' median incomes and below those of the country as a whole. National gas companies have been entering into lease agreements with landowners anxious to reap the benefits of lease and royalty payments. Local and state governments anticipate increased tax revenue. At the same time, other landowners and community members stridently oppose gas development due to concerns for quality of life, property values, and environmental impacts (Montz et al., 2010). Nevertheless, some 700 leases were recorded in Broome County, New York, alone between 2006 and 2008.

Water is a critical component in fracking. Each well requires 2–9 million gallons (7600 to 34,100 m^3) of water, with about half recovered and released on the land surface and into streams (Brownell, 2008). Large volumes of water need to be transported by trucks to individual well sites, requiring new roads and leading, among other things, to increased nonpoint source pollution. More critical are the potential water quality impacts of fracking (the fluid contains friction reducers, acids, and microbicides) on groundwater and the discharge of wastewater (with brine, hydrocarbons, metals, and radioactive elements, depending on local geology) in receiving streams, rivers, and lakes. In Pennsylvania where drilling is occurring, residents with wells have reported decreased water levels, increased sediment clogging filters, and gas in domestic well water. Institutional responses to the relatively recently introduced practice of fracking often lack peer-reviewed information as a basis for decision-making because documentation is limited.

In early 2009, the New York Governor placed drilling on hold in that state pending review by the Department of Environmental Conservation. In September 2009, a Draft Supplemental Generic Environmental Impact Statement (SGEIS) addressing required permit conditions for gas drilling was issued for public comment. After receiving more than 13,000 public comments on that draft, a Preliminary Revised Draft SGEIS was released in July 2011 for further comment. Through this entire process, supporters and opponents of gas development have continued to build their constituencies as science struggles to catch up to practice. Individual landowners with leases, those without leases, local, regional, and state agencies and organizations, and individuals who do not own land all represent stakeholders with differing opinions about what is best for the future of the region. While some of the controversy is related to the anticipated distribution of benefits and costs, much can be attributed to conflicting views on energy and water. Nationally, gas is portrayed as critical to energy independence and as a resource that creates fewer local impacts than coal development. Locally, controversies over developing the Marcellus are characterized by multi-tiered decision-making and competing goals (individual economic gain versus local and regional water quality), little scientific agreement (over uncertainties about the amount, composition, fate, and impacts of fracking fluids), limited time and resources (particularly of individual landowners and local interest groups compared to gas industry representatives), and inequalities in access to power and information (LaChappelle et al., 2003). Taken separately, these controversies can be difficult to resolve; when combined at different spatial and temporal scales, and presented to different stakeholders, they can become intractable. The tradeoffs associated with multiple potential outcomes of this evolving case are under scrutiny in New York as an issue of environmental impact, landowner rights, and institutional capacity to comprehensively address the economic and environmental costs and benefits.

3. Stakeholders' tradeoff priorities and modeled energy–water portfolios

Integrated assessment and planning for energy and water can identify key tradeoffs that cross sectors, resources, and institutional boundaries (Hightower and Pierce, 2008). The case studies above represent challenges that are brought to the fore as society accommodates energy resource demands and seeks to assess the concomitant tradeoffs and impacts. The problem of water and energy interdependencies may be viewed as messy or "wicked" problems (Rittel and Webber, 1973). This problem type is difficult to evaluate and there is no clear optimal solution; instead alternatives and scenarios are best used to inform policy dialog and incorporate pluralistic viewpoints. Melding water and energy considerations heightens complexity and exacerbates the need to address issues of trust and confidence as alternative scenarios and institutional arrangements are considered (Bellaby, 2010). As a result, emphasis on the process of stakeholder interaction is a recognized feature of the discipline of integrated assessment (Jakeman and Letcher, 2003) and increasingly a necessary

condition for dealing with messy problems, e.g., in water resources management (Jakeman et al., 2008). The use of multiple interpretative frameworks, iterative stakeholder assessment, and modeled systems analysis is becoming more common in the emerging approach known as adaptive water management (AWM). Rather than considering a model as a product to be analyzed, AWM integrates modeling as part of a socially constructed process that represents the joint understanding of a problem, or collective judgment of scientists, decision-makers, and other stakeholders as expressed in the model framework.

For the present analysis, a simple integrated assessment model was developed using systems dynamics techniques as an alternative method to assess multiple dimensions of the water–energy nexus and to complement the cases as described above. The model was conceptualized using reported outcomes from a series of five structured "Energy and Water Nexus" (EWN) workshops convened by The Department of Energy through open invitation to all sectors with interests in energy or water planning (Sandia National Laboratories (SNL), 2005). Over 500 representatives of energy companies, electric and water utilities, regulators, environmental groups, and Indigenous nations attended the workshops (Sandia National Laboratories (SNL) (2010, 2005)). Stakeholder interactions in the workshops identified key concerns, priorities, and perceived needs for energy and water with results aggregated into Western, Central, and Eastern U.S. regions (Sandia National Laboratories (SNL), 2005), as shown in Fig. 1. An analysis of the stakeholder workshop results, specifically related to resource coupling and tiered institutions, was completed for the present paper.

Outcomes of the workshops informed the systems dynamics model development. Core data for inclusion in the scenario analysis were drawn from publicly available datasets (e.g. Hutson et al., 2004; Energy Information Administration (EIA), 2008) and peer-reviewed studies to consider multiple scenarios that would meet projected national energy demand in 2030 (see Table 1).

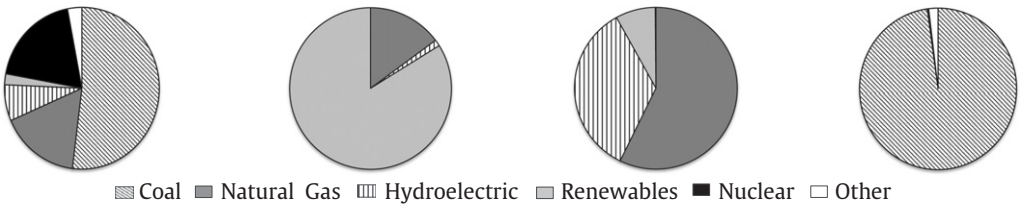
The *Business as Usual* scenario was based on the current mix of energy sources as reported in the Annual Energy Outlook (Energy Information Administration (EIA), 2008). Three additional scenarios were generated using a non-classical genetic optimization algorithm to identify successive scenarios with multi-objective formulations and constraints that incorporated limits to hydroelectric generation and water consumption, and maximized power generation costs.

The *Renewables & Natural Gas* scenario addresses tradeoffs inherent in the Southwestern case, which exemplifies how an energy portfolio must be optimized for a region's resource limitations (Department of Energy (DOE), 2006; SNL, 2010). In general, the EWN workshops report indicates that Western region stakeholders identified strategies to increase hydropower, but solar and wind alternatives were not indicated as key concerns by this group (SNL, 2005). The modeled scenario minimizes water consumption and use (including return flows). Moderate natural gas generation accompanies solar and wind. To increase solar and wind options, the optimization had to be constrained to limit hydroelectric production and ignore (or unbound) electric generation costs. As indicated in the final row of Table 1, however, institutional constraints limit the feasibility of achieving this scenario. In particular, institutional inertia of commercial developers "locked-in" to carbon-based energy sources as well as inadequate investment in research, development, and incentives for adoption of renewables are two of the principal limitations to the *Renewables & Natural Gas* scenario.

Arid regions may find that using less water for energy in the future overrides concerns about carbon emissions from conventional generation. At the same time, shifts in climate patterns for these regions closely tied to hydroelectric resources could force citizens to tolerate a higher cost for a lower-impact energy generation portfolio. Given this combination of concerns, integrated resource planning could derive counter-balancing portfolios in more water abundant regions, such as the Eastern U.S.

National and Eastern region stakeholders from the EWN workshops indicated concerns about water quantity and quality degradation related to fossil fuel extraction and regional-scale pollution (SNL, 2005), similar to the Eastern and Northeastern & Central cases we presented above. These EWN workshops stakeholders recognized possible benefits from using polluted waters, such as from coal bed methane or mine waters. In the case of non-conventional (specifically shale) natural gas development, the institutional disconnect occurs as disagreement between decision-makers at the same scale (landowners), some of whom value the short- to medium-term economic benefits over others'

Table 1
National electricity demand scenarios for 2030 considering coupled water resources and institutional arrangements.

Scenario, 2030	Business as usual	Renewables and Natural Gas	Natural Gas, Hydroelectric and Renewables	Coal
Energy source (5500 BkWh total national)				
Water-energy resource coupling	Medium-high water impact, particularly from coal and nuclear	Low water impact, especially with solar photovoltaic and wind; higher for solar thermal	Medium water impact; water quality impairment from fracking; ecosystem impacts of dam construction	High water quality impact and carbon emissions
Multi-tiered institutional considerations	Current utility configuration and regulatory systems; continued U.S. emissions mitigation challenges	Overcoming carbon lock-in; facility siting concerns (local generation, regional distribution); technology, infrastructure deployment challenges	Reservoir siting challenges ('not in my backyard'); local water quality to be mitigated by national, global energy developers; regulated by state, national agencies	Energy demand centers (urban, coastal) compensate coal source regions (rural, interior); local water quality to be mitigated by national, global energy developers; regulated by state, national agencies

concerns for the short- to long-term environmental and amenity costs. For these conditions, the *Natural Gas, Hydroelectric & Renewables* scenario identified a portfolio with natural gas in combination with hydroelectric generation to offset water use.

The Eastern region EWN workshops stakeholders are reported to have focused on direct generation related concerns, but neglected to incorporate concerns about the impacts driven by exogenous energy demand. This global level demand drives the development of transportable resources such as coal, at the expense of local communities and with high regional environmental impacts in areas such as Appalachia in the Eastern case above. Interestingly, national level stakeholders from the EWN workshops viewed impacts from coal bed methane or mine waters as a near-term problem that presents a long-term opportunity for energy development (SNL, 2005), a clear discrepancy from the urgency described at the local level for mountaintop mining communities of Appalachia that endure environmental and health impacts.

Coal remains a key component of the national energy portfolio. Using the objective of minimizing electricity cost, the model unequivocally generated coal-dominated options such as the *Coal* scenario. Only after assigning penalty functions and additional limiting factors were non-coal options generated as candidate solutions by the model. These limits were based on two sets of concerns, increasingly expressed through institutional means. First, local impacts on water and environmental quality resulting from coal development as illustrated in the Eastern case (Appalachia) pose a serious challenge. Consumers nationally who benefit from reduced commercial costs of energy will contribute financially to offset impacts in coal-producing regions. This is a process of 'internalizing externalities'. As noted in Table 1, such a process itself would have to overcome spatial disconnects, given that energy demand centers are often far from energy producing regions. Second, and perhaps more critically from the global change perspective, the carbon emissions implications of the *Coal* scenario are untenable; thus, this scenario is not given further consideration.

The modeled results presented here are indicative of how quantitative and qualitative approaches can be combined to generate scenarios and evaluations. Integrated and systems dynamics models have the potential to inform substantive dialog on water–energy challenges. The use of modeled results in stakeholder settings (such as the EWN workshops) holds significant potential to guide dialog especially on the discrepancies between regional and national perspectives as identified through modeled results. Thus, integrated assessment provides an interpretative framework for evaluating the water–energy nexus and highlighting insights and discrepancies in relation to resource coupling and multi-tiered institutional arrangements as discussed in the next section.

4. Discussion: resource coupling and multi-tiered institutional arrangements

The three cases and the regional scenarios presented highlight the dissonance between scales of water–energy coupling and levels of institutional decision-making, as synthesized in Table 2. We present and discuss three principal resource concerns and two institutional concerns, indicated by the row breaks with these titles in the table. First, it is evident that spatial dislocation of energy and water sources and demands results in coupling that is manifest beyond the point of use of either resource. For example, power generation in the Southwestern case is far removed from the water off-take point for the CAP aqueduct, which in turn is distant from water demand sites. This creates a resource management challenge that involves multiple jurisdictions, especially local and state governments, which often do not collaborate on resource policy. Further, regional and global demands for energy generate a series of local environmental concerns, which constitute the second principal resource coupling issue that emerges from the consideration of the cases.

This second resource-coupling dimension of the water–energy nexus is the externalization of impacts. For example, urban energy consumers using coal-generated electricity do not perceive or prioritize environmental and water impacts of generation or energy development. This also highlights social equity and environmental justice dimensions of the water–energy nexus.

Table 2
Energy–water resource coupling and multi-tiered institutional considerations.

	Southwestern – electricity – water nexus	Eastern – coal – water quality nexus	Northeastern and Central – shale natural gas – water quality nexus	National – energy – water tradeoff scenarios
Energy–water resource coupling				
Energy and water sources and demands	Local sources, regional demands	Local sources, national demands	Local sources, regional and national demands	Domestic and global sources, national demand
Local environmental and social impacts	Water scarcity, emissions, air quality, continued growth	Land and water quality, social and economic marginalization	Water quality, local interest group rivalry	Localized impacts diminished in national perspective
Global change implications	Electricity central to climate adaptation, current generation hinders climate change mitigation	Continued coal dependence has emissions and local impacts	Natural gas preferred energy source that has local impacts comparatively lower than for coal	Energy portfolio diversification, water resource implications offset by regional generation, electricity transmission
Multi-tiered institutions				
Institutional coordination	Sole water source reliance leading toward localized innovation	Asymmetry between local jurisdictions and national commercial interests	Interest group politics leading to provisional state regulation	Stakeholder consultation and scenario modeling, nascent federal energy-water policy
Policy to reconcile local impacts with national demand, adapting to global change	Enhanced solar (photovoltaic) to minimize water demand; long-term mitigation through energy diversification and renewable water	Regulation of local impacts; increased total (not just commercial) cost of coal; waste product water for beneficial energy generation	Social conflict mediation; embed cost of waste remediation in price of delivered gas	Portfolio scenarios to enhance low local-impact renewable energy and water sources; manage tradeoffs across scales

That is, consumers may benefit from low commercial cost energy while corporations make profits; however, the impacts are often borne by low-income residents of energy-rich regions such as Appalachia. In order for social and environmental impacts to be addressed by regulation, effective institutions must be built and enforcement must consistently be strengthened through legal means and with adequate financial and human resources.

The third instance of resource coupling refers to the global change implications of energy and water development, use, and waste generation. It is evident that energy use will increase as societies respond to climate change, e.g., for cooling and air-conditioning, transportation of food, etc. However, energy development itself, in particular electricity generation, is a primary contributor to carbon emissions. In order to enhance energy–water coupling in a manner that provides global-change adaptation potential that does not at the same time exacerbate medium- and long-term mitigation opportunities, demand management is essential, especially through pricing of water and energy service delivery, efficient technologies (although this alone will not suffice), and recognition of the imperative of mutually beneficial water–energy conservation.

Because electricity is more readily transported between regions and because of its versatility (not least, for water conveyance, treatment, supply, and reclamation), it is the resource that will prove most robust for adaptation strategies. However, greater transportability of energy resources is a primary cause of local impacts, especially on water resources, resulting from global energy management decisions. These multiple tradeoffs are complex and must be addressed across scales in a rational, equitable, and informed manner—a point illustrated in comparing results from the integrated assessment model versus the regional scenarios and EWN workshops dialog process with stakeholders described above. For example, integrated assessment of this type has potential to provide more informed decision-making, if it is backed institutionally and politically with programs and financial resources to implement alternatives identified in the process.

The next general class of water–energy nexus implications is institutional in nature. Following down the synthesis presented in Table 2, we are concerned with two dimensions of multi-tiered institutions. The first refers to institutional coordination required to bring water and energy management into line. This is not a small challenge. As we have demonstrated in the Northeastern and Central case, there are opposing tendencies in shale natural gas development and compensation of locally impacted stakeholders. How this ultimately is resolved will depend on the willingness of multiple parties to negotiate solutions and to modify their expectation of short-term benefits and strategies in a manner that generates broader societal and environmental gains. Global and national negotiations leading to the Montreal Protocol that effectively reduced the use of chlorofluorocarbon and abated atmospheric ozone depletion offer a relevant example.

The second institutional aspect, and final one considered in Table 2, is the policy imperative to reconcile spatial scales of resource coupling (local impacts of national and global energy demand) as well as the broader adaptation challenge referred to above. We are not advocating a unified, cross-jurisdictional, scale-neutral water–energy policy; this is too simplistic. Instead, we are concerned with identifying multi-level policy opportunities to bring water management and policy closer in line with energy policy. This will partly be achieved through technology choices, e.g., photovoltaics, but will also centrally involve regulations, conflict mediation, and greater consideration of the resource coupling challenge posed by our expanding understanding of the water–energy nexus. In part, this challenge can be met through integrated assessments that provide an underlying scientific basis to foster trust and confidence that may be strengthened through stakeholder engagement.

5. Conclusion: water–energy nexus institutions and policy

This paper demonstrates the need to include institutions and decision-making in the water–energy nexus. This is a change from the present, where the water–energy nexus is conventionally viewed solely as a resource management approach. Our point is to highlight the policy and institutional dimensions of one of the most pressing coupled-resource and environmental challenges of our time. Mutual energy and water interactions present local to global resource tradeoffs at a range of scales and with critical, multi-tiered institutional and decision-making complexities. Our analytical approach focused on case studies and assessment of U.S. regional scenarios. These are framed by growing human demand for resources and by climate change and variability—global change drivers that necessitate societal adaptive strategies. We have attempted to shed light on how these processes play out across scales with multiple stakeholders having differential access to information.

The analysis in the paper leads to four central assertions regarding institutions and policy dimensions of the water energy nexus. These include, first, the need to explicitly consider institutions and decision-making, not just input–output relationships between water and energy. Second, due to energy resource transmutability and due to the implications of climate change for energy policy (via the emissions reduction imperative), energy policy offers more scope for global-change adaptation than water policy. Water will remain primarily a local or regional resource, despite globalized approaches to understanding its linkages and societal and environmental impacts. Third, the cases and regional scenarios considered in this paper shows how externalizing water, environmental, and social impacts of energy development can be a result of disarticulated policy options, and that instead, seeking mechanisms to internalize impacts can bring water and energy policy into closer alignment. Finally, some degree of tradeoff between water and energy resource use is inevitable; however, such tensions can be mitigated to an extent by cross-scale resource substitution (e.g., additional energy for water reclamation where primary water sources are scarce) and multi-tiered institutional solutions (e.g., 'regulatory cooperation').

Our assessment of the policy and institutional dimensions of the water–energy nexus would not be complete without consideration of further questions in need of creative scholarship. Several questions for future enquiry are posed by a resource-policy approach to the fundamental human-environment challenges of energy and water coupling. How do local physical and social dynamics of energy and water development influence broader demands for resources? In turn, how does the water–energy nexus feed back to global change processes, including population and economic growth (particularly in expanding cities), climate change and variability (through resource use that influences emissions), and interlinked markets (particularly for energy and increasingly water)? These are fundamental policy challenges that stem from the inextricable linking of our two most precious resources.

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