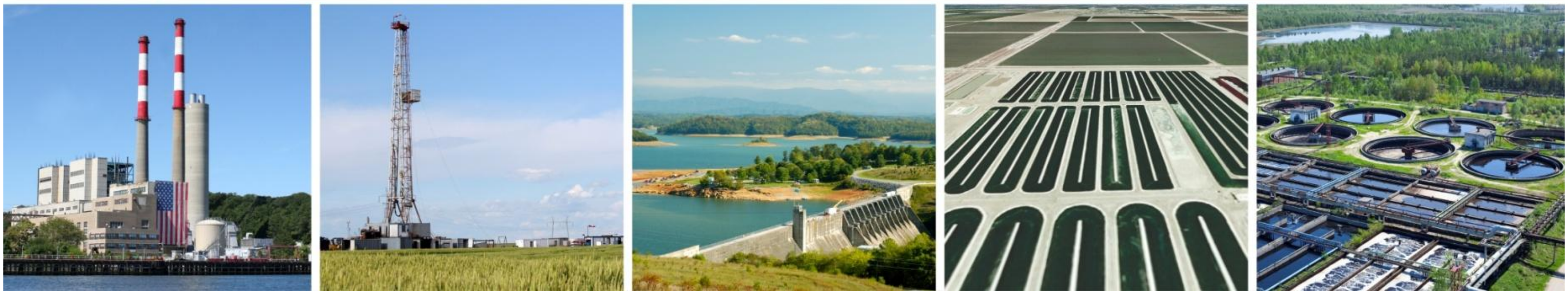
2014

U.S. DEPARTMENT OF
ENERGY

The Water-Energy Nexus: Challenges and Opportunities

Overview and Summary



Present day water and energy systems are interdependent. Water is used in all phases of energy production and electricity generation. Energy is required to extract, convey, and deliver water of appropriate quality for diverse human uses, and then again to treat wastewaters prior to their return to the environment. Historically, interactions between energy and water have been considered on a regional or technology-by-technology basis. At the national and international levels, energy and water systems have been developed, managed, and regulated independently.

Recent developments have focused national attention on the connections between water and energy infrastructure. When severe drought affected more than a third of the United States in 2012, limited water availability constrained the operation of some power plants and other energy production activities. Hurricane Sandy demonstrated the compounding ramifications of vital water infrastructure losing power. The recent boom in domestic unconventional oil and gas development brought on by hydraulic fracturing and horizontal drilling has added complexity to the national dialogue about the relationship between energy and water resources.

Several current trends are further increasing the urgency to address the water-energy nexus in an integrated and proactive way. First, climate change has already begun to affect precipitation and temperature patterns across the United States. Second, U.S. population growth and regional migration trends indicate that the population in arid areas such as the Southwest is likely to continue to increase, further impacting the management of both energy and water systems. Third, introduction of new technologies in the energy and water domains could shift water and energy demands. Moreover, policy developments addressing water impacts of energy production are introducing additional complexities for decision making.

These trends present challenges as well as opportunities for the U.S. Department of Energy (DOE). An integrated, strategic approach can guide technology research, development, demonstration, and deployment (RDD&D) to address regional water-energy issues and also have national and global impacts. Enhancing and integrating data and models will better inform researchers, decision makers, and the public.

Key Messages:

- Energy and water systems are interdependent.
- We cannot assume the future is like the past in terms of climate, technology, and the evolving decision landscape.
- Water scarcity, variability, and uncertainty are becoming more prominent, potentially leading to vulnerabilities of the U.S. energy system.
- It is time for a more integrated approach to address the challenges and opportunities of the water-energy nexus.
- DOE has strong expertise in technology, modeling, analysis, and data that can contribute to understanding the issues and solutions across the entire nexus.
- Collaboration with DOE's many current and potential partners is crucial.

Role of the U.S. Department of Energy

The water-energy nexus is integral to two DOE policy priorities: climate change and energy security. DOE's program offices have addressed the water-energy nexus for many years; however, this work has historically been organized on a program-by-program basis, where water has been considered among a number of other factors.

In the fall of 2012, DOE initiated a department-wide Water-Energy Tech Team (WETT) to increase cohesion among DOE programs and strengthen outreach to other agencies and key external stakeholders in the water and energy sectors. WETT developed *The Water-Energy Nexus: Challenges and Opportunities* to provide an analytical basis from which to address these objectives and to provide direction for next steps.

The report frames the integrated challenge and opportunity space around the water-energy nexus for DOE and its partners. It further explains and strengthens the logical structure underpinning DOE's long-standing technology and modeling research and development (R&D) efforts, and lays the foundation for future efforts. The report identifies six strategic pillars that will serve as the foundation for coordinating R&D.

The report is intended as an invitation for collaboration to DOE's many current and potential partners in the water-energy arena. Many other federal agencies also have important activities at the water-energy nexus, as do regional, state, tribal, and local authorities.

Six Strategic Pillars to Address the Water-Energy Nexus

1. Optimize the freshwater efficiency of energy production, electricity generation, and end use systems
2. Optimize the energy efficiency of water management, treatment, distribution, and end use systems
3. Enhance the reliability and resilience of energy and water systems
4. Increase safe and productive use of nontraditional water sources
5. Promote responsible energy operations with respect to water quality, ecosystem, and seismic impacts
6. Exploit productive synergies among water and energy systems

Other important organizations include private companies, national non-governmental organizations (NGOs), international governments, universities, and municipal facilities.

Activities discussed in the report are subject to future evaluation to determine the priority, appropriate agency (private, state, local, or federal), and appropriate share of any cost or responsibilities. Many federal agencies have missions related to topics and activities discussed in this report and, if adopted in future budgets, such activities could reside at federal agencies other than DOE.

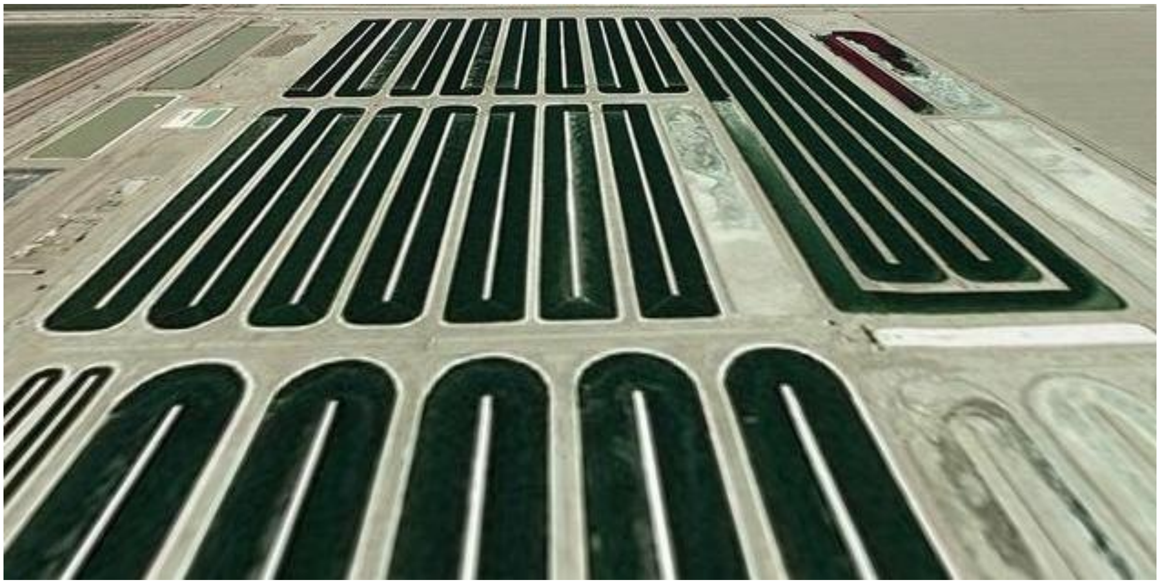


Figure 1. Algae biofuel production (source: PNNL)

The Water-Energy Nexus

U.S. flows of energy and water are intrinsically interconnected, in large part due to the characteristics and properties of water that make it so useful for producing energy and the energy requirements to treat and distribute water for human use. This interconnectivity is illustrated by Figure 6, a hybrid Sankey diagram that shows the magnitude of energy and water flows on a national scale. The diagram illustrates that thermoelectric power generation both withdraws large quantities of water for cooling and dissipates tremendous quantities of primary energy due to inefficiencies in converting thermal energy to electricity ("withdrawn" water is diverted from a surface water or groundwater source). The intensity of water use and energy dissipated varies with generation and cooling technology.

As the largest single consumer of water, agriculture competes directly with the energy sector for water resources ("consumed" water is withdrawn and not returned to its source because it has evaporated, been transpired by plants, incorporated into products etc.). However, agriculture also contributes indirectly to the energy sector via production of biofuels. Both connections could be strained by increasing concerns over water availability and quality. In addition, water treatment and distribution for both public drinking water supply and municipal wastewater require energy.

Significant aspects of water and energy flows do not appear in the diagram. Flows will change over time, and anticipated changes in flows are important to consider when prioritizing investment in technology and other solutions (see Figure 2). Future increased deployment of some energy technologies, such as carbon capture and sequestration, could lead to increases in the energy system's water intensity, whereas deployment of other technologies, such as wind and solar photovoltaics, could lower it.

In addition, there is significant regional variability in the water and energy systems, their interactions, and resulting vulnerabilities. For example, producing oil and natural gas through horizontal drilling and hydraulic fracturing has the potential to impact local water quantity and quality, which can be mitigated through fluid lifecycle management (see Figure 3). Large volumes of water produced from oil and gas operations present both localized management challenges and potential opportunities for beneficial reuse.

The energy requirements for water systems also have regional variability, based on the quality of water sources and pumping needs.

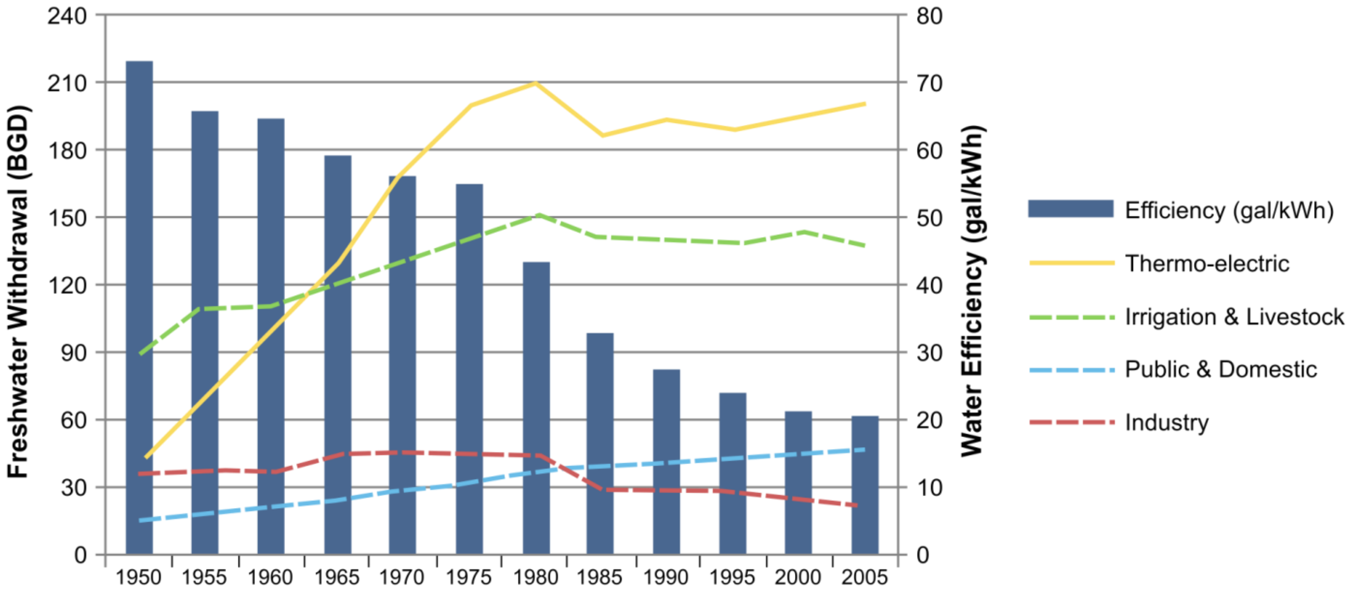


Figure 2. Water use for thermoelectric generation and other sectors.

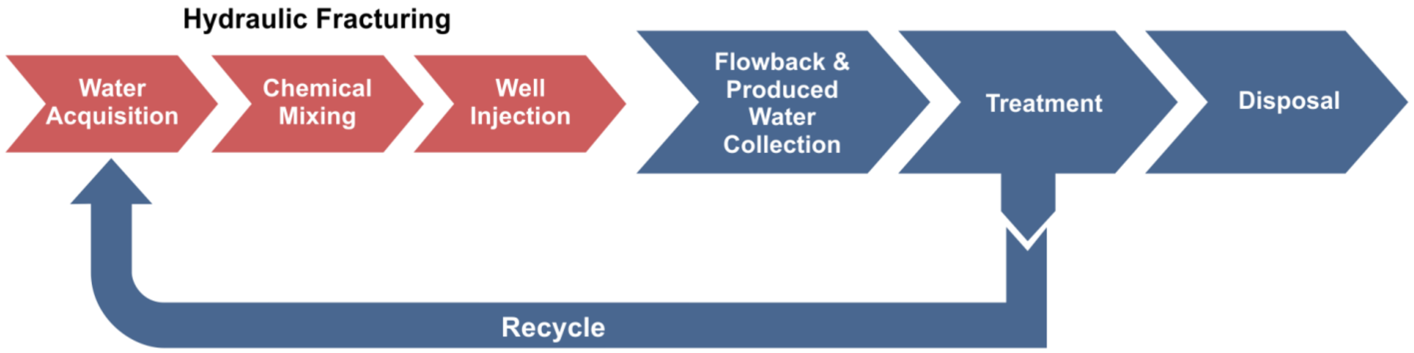


Figure 3. Fuels production water life cycle.

Trends

Water availability will affect the future of the water-energy nexus. While there is significant uncertainty regarding the magnitude of effects, water availability and predictability will be altered by changing temperatures, shifting precipitation patterns, increasing variability, and more extreme weather.

Changes in precipitation and temperature patterns—including earlier snowmelt—will likely lead to more regional variation in water availability for hydropower, bioenergy feedstock production, and other energy needs. Rising temperatures have the potential to both increase the demand for electricity for cooling and decrease the efficiency and capacity of thermoelectric generation. These changes and variations pose challenges for energy infrastructure resilience.

Water and energy needs will also be shaped by population growth and migration patterns, as well as changes in fuels used and energy technologies deployed. According to Energy Information Administration (EIA) data, planned retirements and additions of electricity generation units and cooling systems will decrease water withdrawals, will likely increase water consumption, and will increase the diversity of water sources used (see Figure 4).

Many of the forces affecting the water-energy nexus are out of DOE's control. However, the future of the nexus hinges on a number of factors that are within the DOE's scope of influence, including technology options, location of energy activities, and energy mix.

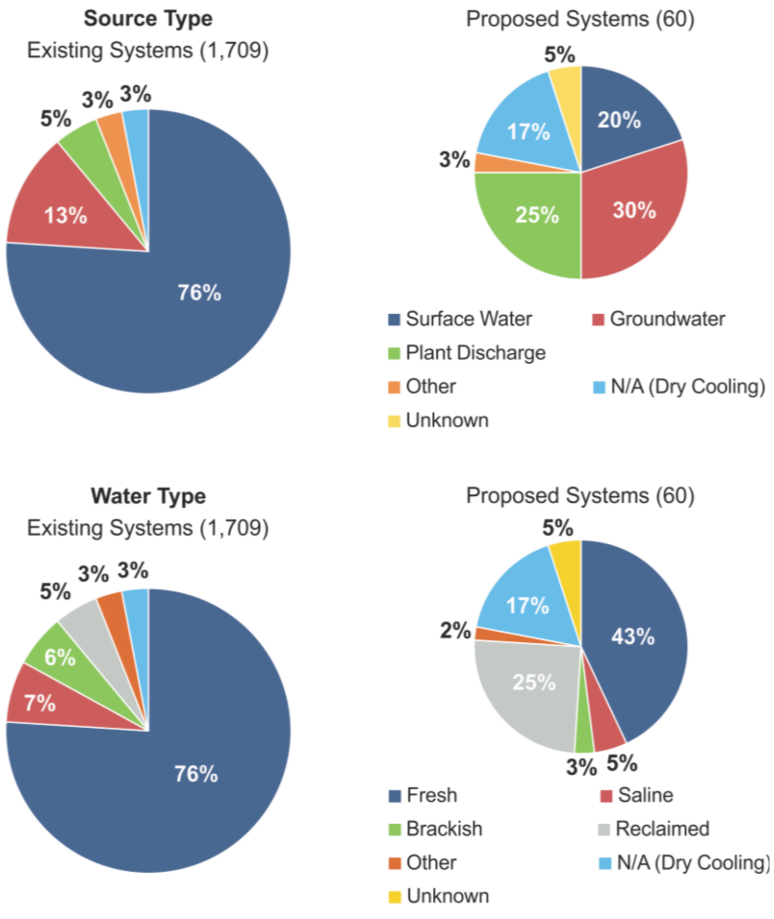


Figure 4. Existing and proposed cooling systems by source type and water type.

Proposed systems are scheduled to come online between 2013 and 2022.

Decision-making Landscape

The decision-making landscape for the water-energy nexus is shaped by political, regulatory, economic, environmental, and social factors, as well as available technologies. The landscape is fragmented, complex, and evolving; incentive structures are overlapping and not necessarily consistent.

Water is inherently a multi-jurisdictional management issue. States and localities vary in philosophies regarding water rights; the divide is particularly pronounced between western and eastern states (see Figure 5).

There is also variation across states in relevant energy policies, including renewable portfolio standards, regulation of oil and gas development activities, and regulation of thermoelectric water intake and discharge. Regulations for both oil and gas development and thermoelectric water use are currently undergoing substantial change.

Energy for water is also the subject of policy activity at multiple scales, from appliances to municipal water treatment. A more integrated approach to the interconnected energy and water challenges could stimulate the development and deployment of solutions that address objectives in both domains.

The water-energy nexus policy challenges are not unique to the United States; many other nations are addressing the nexus based on their own circumstances. For example, China is coal-rich but water-poor and is adopting direct and indirect measures to reduce water intensity in coal-fired power generation.

Qatar is hydrocarbon-rich but water–poor, and increasingly relies on desalinated water for drinking. Qatar is moving to power this desalination with renewable power and waste heat.

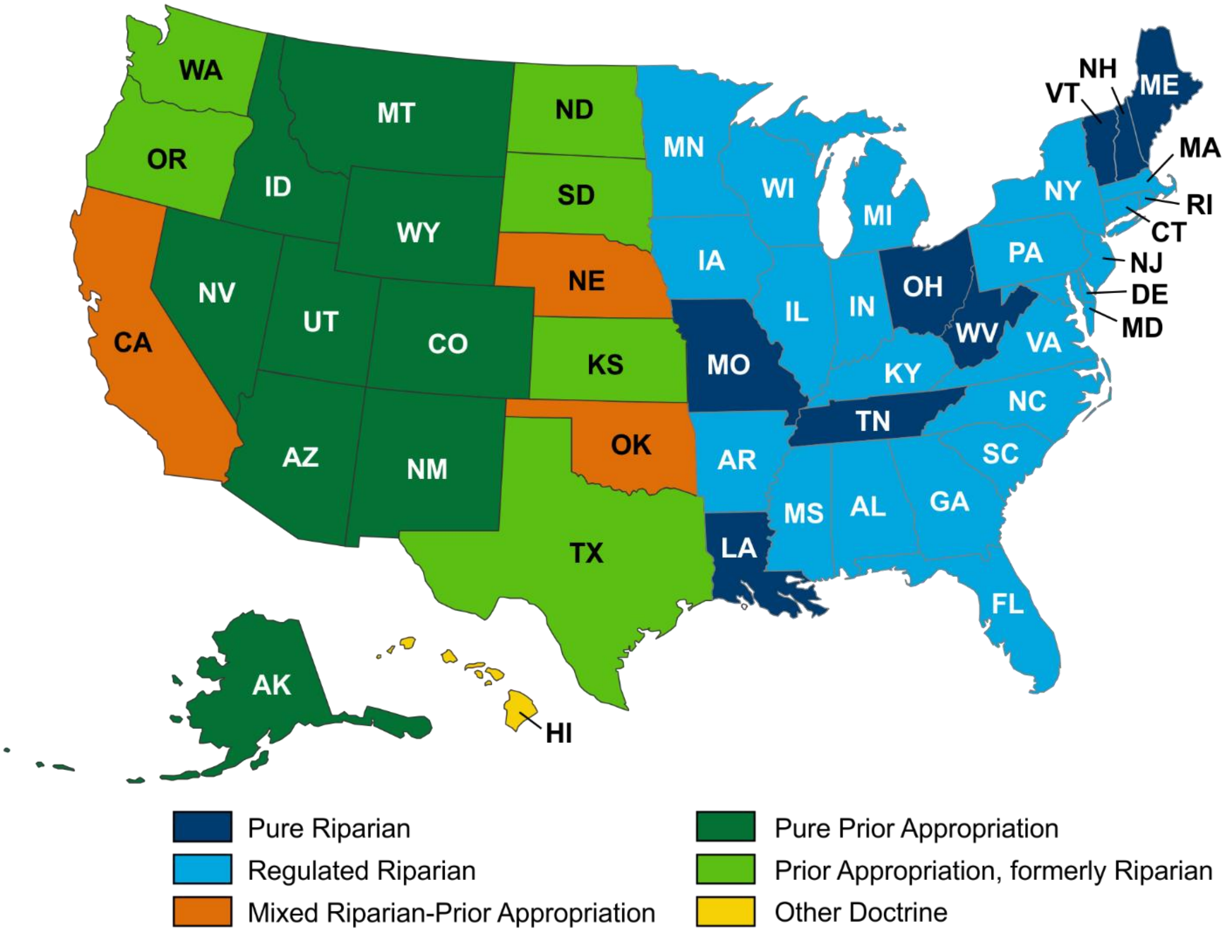
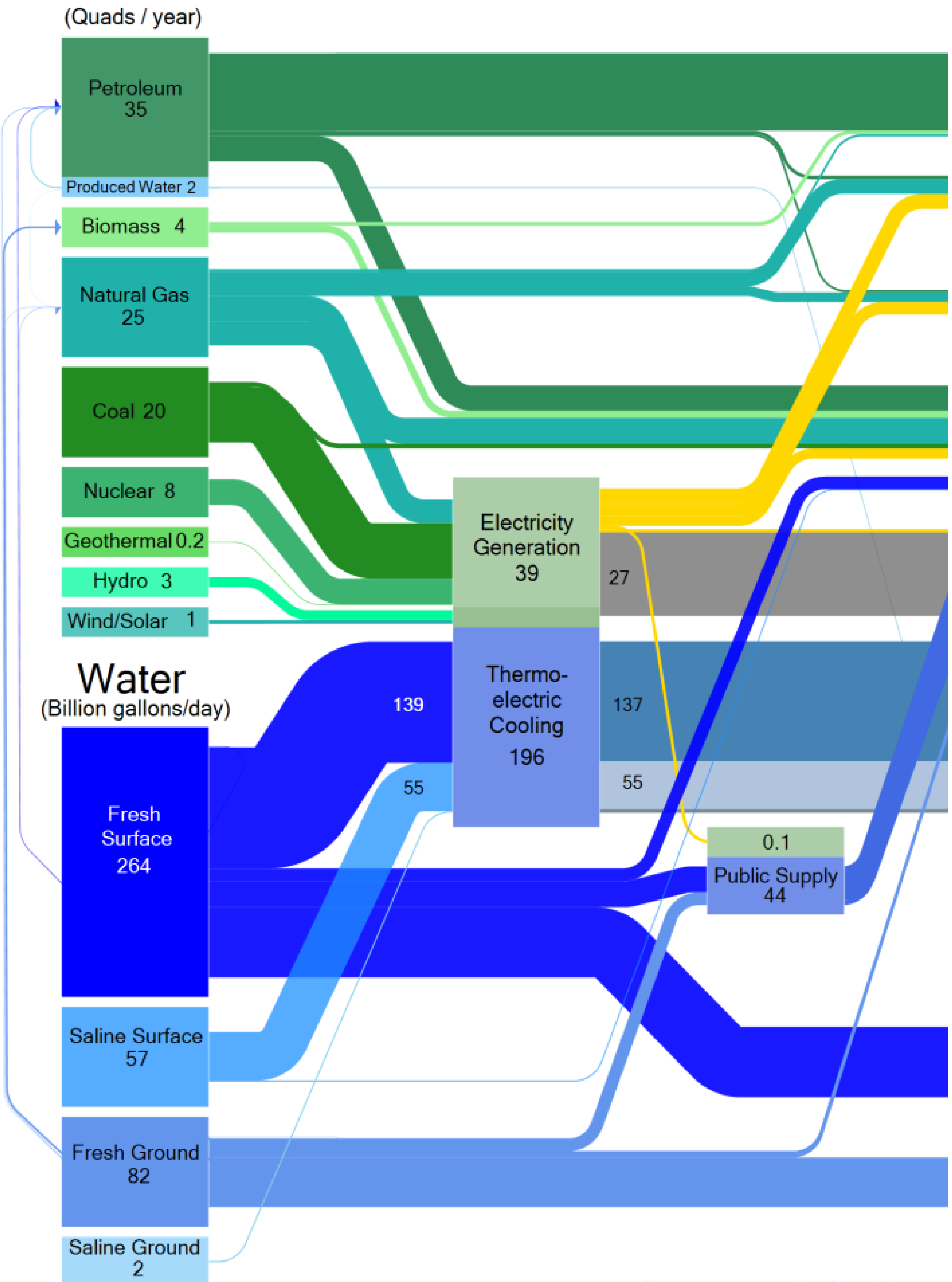
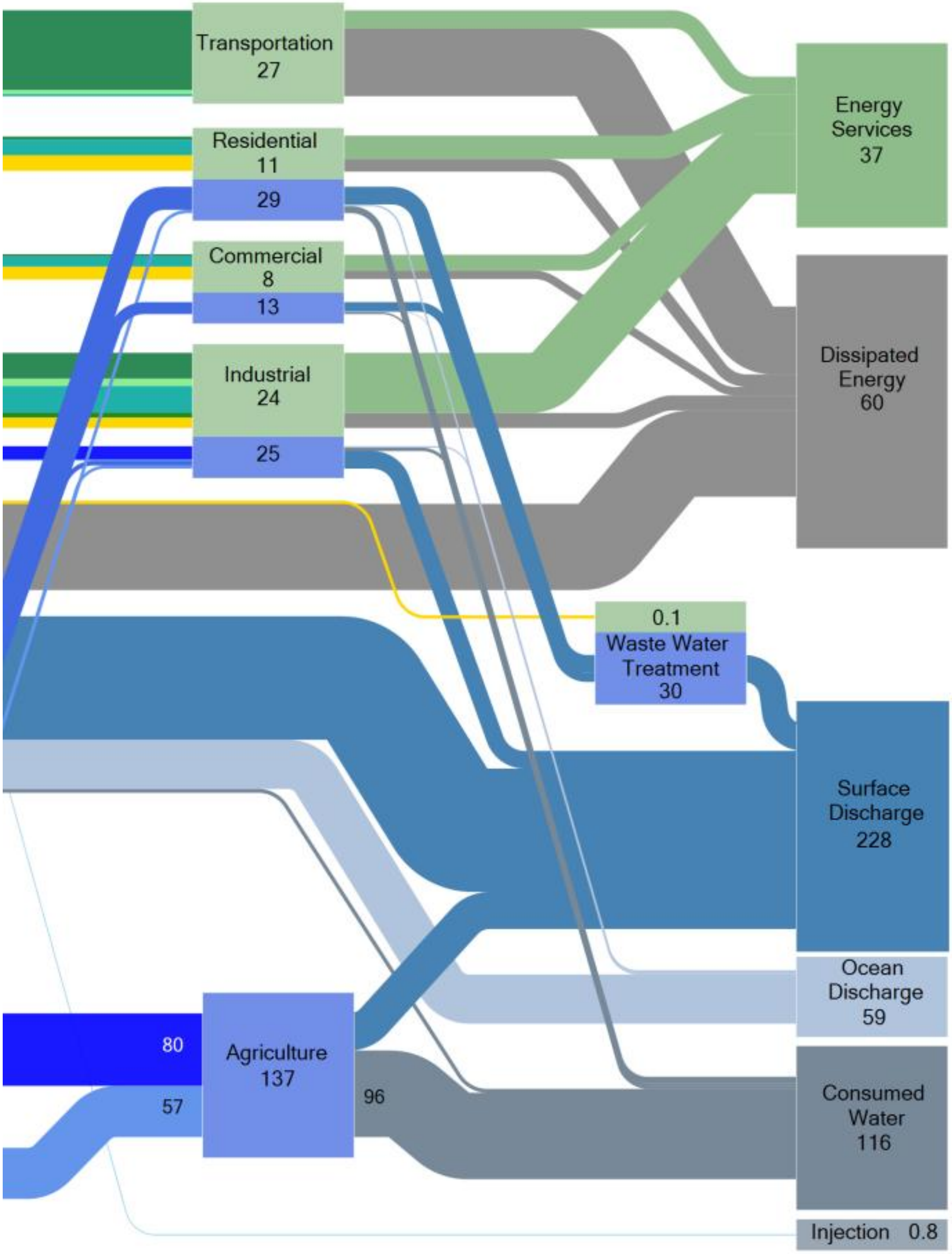


Figure 5. Water governance policies in the United States, by state.



Energy reported in Quads/year.

Figure 6. Energy and water flows in the



Water reported in Billion Gallons/Day.

United States, by magnitude

Technology RDD&D

There are a number of technologies that support water-efficient energy systems or energy-efficient water systems. These technologies are at various stages of research, development, demonstration, and deployment.

A range of technologies can optimize freshwater use for energy through waste heat recovery, dry cooling, alternate fluids, and process water efficiency (Figure 7). Cooling for thermoelectric generation is an important target for water efficiency because it withdraws large quantities of water and dissipates tremendous quantities of primary energy.

One approach to reduce thermoelectric and other cooling requirements, along with associated water use, is to reduce the generation of waste heat through more efficient power cycles (e.g., the recompression closed loop Brayton cycle). Another option is to increase the productive use of waste heat, such as through thermoelectric materials, enhancements in heat exchanger technologies, or low temperature co-produced geothermal power.

The water efficiency of cooling systems can also be improved through advancements in technologies such as air flow designs, water recovery systems, hybrid or dry cooling, or treatment of water from blowdown.

Technology RDD&D Opportunities

Opportunities exist throughout the stages of technology research, development, demonstration, and deployment:

- Recovery of dissipated energy
- Advances in cooling systems
- Alternatives to freshwater in unconventional oil and gas
- Desalination and nontraditional waters
- Net-zero wastewater treatment
- Efficient equipment and appliances

Improvements in sensors, data collection, analysis, and reporting will yield benefits to multiple decision-makers.

Addressing energy and water systems as an integrated whole can stimulate additional innovations.

In addition, there are opportunities to optimize water use in other parts of the overall energy system. Alternative fluids can replace freshwater in hydraulic fracturing, geothermal operations, and power cycles. Process freshwater efficiency in carbon capture, bioenergy feedstock production, and industrial processes can be improved.

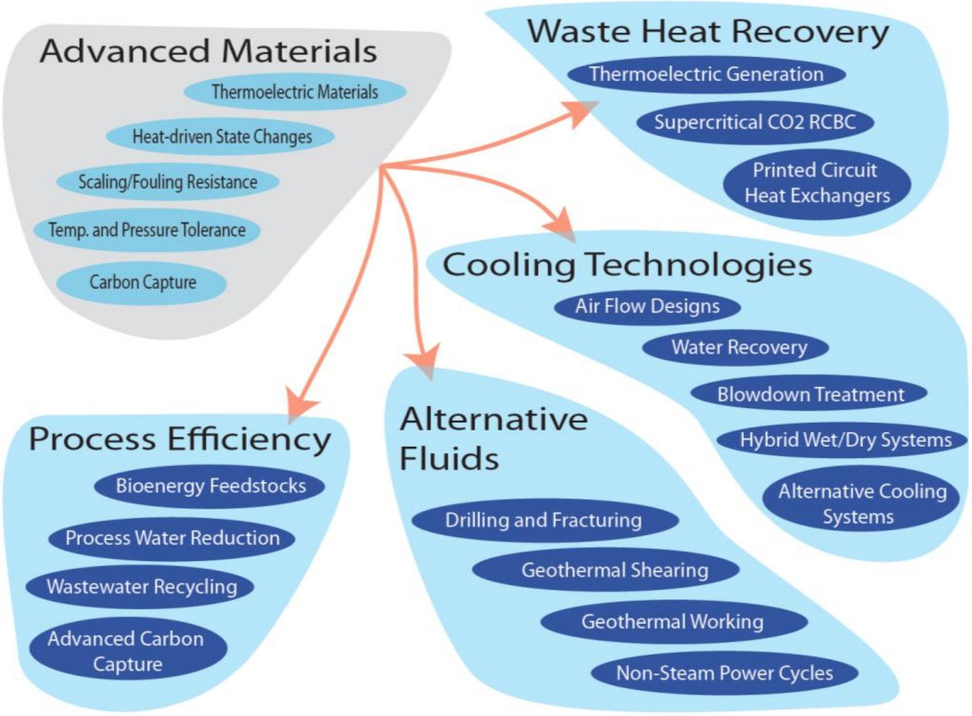


Figure 7. Representative problem/opportunity spaces in water for energy.

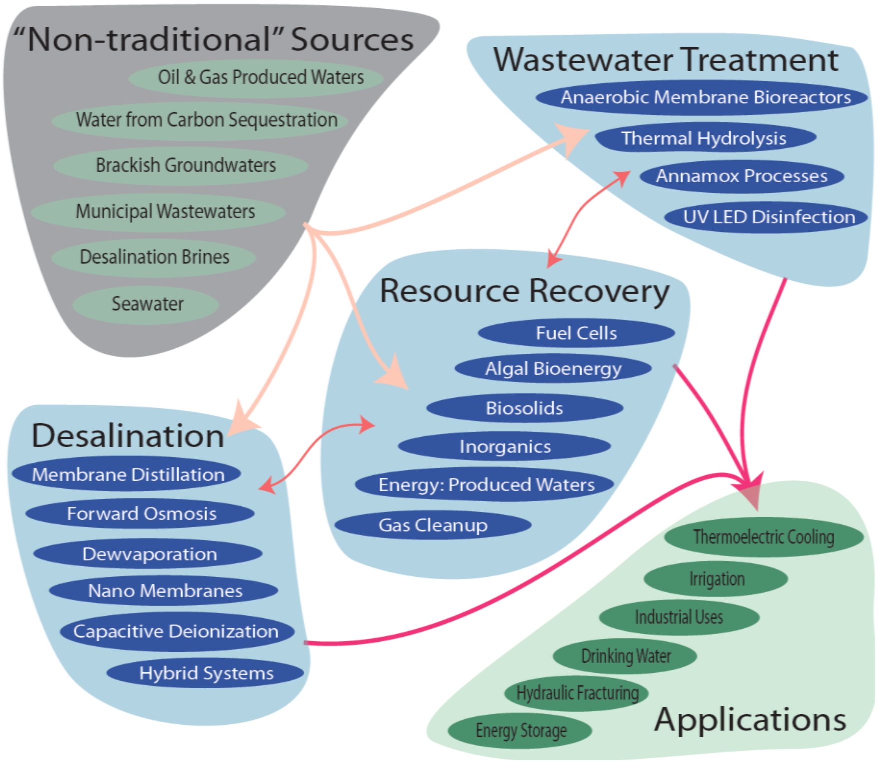


Figure 8. Representative problem/opportunity spaces in energy for and from water.

Many of the technologies that improve water efficiency are enhanced by advances in materials, including thermoelectric properties, heat-driven state changes, scaling and fouling resistance, and enhanced temperature and pressure tolerance.

Water treatment technologies can enhance energy efficiency of water systems and enable the productive and safe use of non-traditional water resources for energy and non-energy applications (see Figure 8). Such improvements in water treatment and management have particular use for treating oil- and gas-produced waters, as well as saline aquifers, brackish groundwater, brines, seawater, and municipal wastewater. For saline sources, promising water treatment technologies include membrane distillation, forward osmosis, dewvaporation, nanomembranes, and capacitive deionization. For municipal wastewater, treatment technologies include anammox systems, anaerobic pretreatments, and anaerobic membrane bioreactors. In addition, the biosolids contained in wastewater can be a source of methane energy.

Opportunities to pursue synergies between water and energy systems include use of waste heat for desalination and combined heat and power. Water systems can also be used for energy storage or electricity demand management. The design of these integrated systems often requires analysis to characterize the specific economically and environmentally optimized configurations.

Technology deployment is another important consideration. A number of public policy tools can inform and stimulate the adoption of technologies and practices in the range of markets that have a role in the water-energy nexus. Energy and water utilities, for example, are characterized by long investment cycles, are subject to a panoply of regulations, and operate under stringent performance expectations. This combination often constrains operator willingness to undertake the risks of investing in new technologies. In some cases, loan guarantees and/or public/private demonstration projects may make such investments more attractive.

Consumer markets are driven more by price and intangibles, and product lifecycles tend to be shorter; appliance standards may inform product selection in these instances. Business applications such as combined heat and power fall somewhere in between; they might be well served by opportunities to share best practices and lessons learned.

Data, Modeling, and Analysis

Integrated analysis and modeling of the water-energy nexus requires the simulation of many human and natural systems and their complex interactions and dynamics. The connection of water and energy to land is particularly important (see Figure 9), as are the connections to global and regional climate, technology options and strategies, and broader aspects of socioeconomic development. The latter includes population, migration, regional economics, and competing demands for energy, water, and land resources, to name a few. These simulations necessarily span many temporal and spatial scales; improving the telescopic capabilities of these interacting systems is a considerable but addressable scientific challenge.

While DOE has a substantial body of modeling expertise, there is a need to target the development of more integrated modeling, data, and information platforms around use-inspired questions and user driven needs (see Figure 10). Ultimately, such work must lead to projections and scenarios at decision-relevant scales. Enhanced characterization and communication of uncertainties is also important.

Data, Modeling, and Analysis Context and Needs

- The water-energy nexus is affected by many moving parts including supplies, demands, land use and land cover, population/migration, technologies, policies, regional economics, weather extremes, and climate.
- Improved integration of models spanning these domains can better reflect the dynamics of interactions and interdependencies among complex systems.
- Available data and information needs span a wide range of spatial and temporal scales, necessitating improved capacity for “telescopic resolution.”
- Layered data-knowledge built around DOE data and other observation, model-generated, and reported data sets can lead to emergent insights and broadly accessible toolkits supporting energy and coupled energy-water system resilience.
- Stakeholder decision-making needs extend beyond these more integrative modeling frameworks and data-knowledge systems and must target:
  - Qualitative and quantitative scenarios
  - Probabilistic approaches
  - Insights into system shocks and extremes
  - Improved characterization of uncertainties

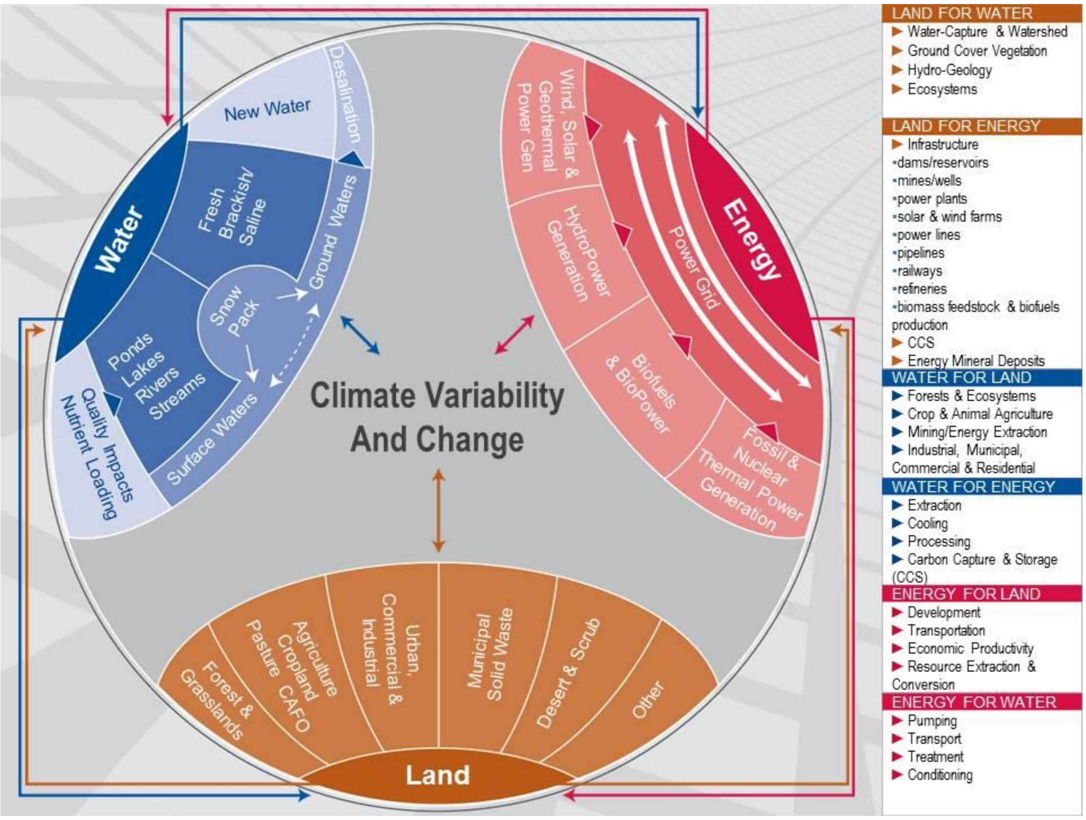


Figure 9. Illustration of the significance of l three-way dynamics of E-W-L systems as represented through integrated assessment research.

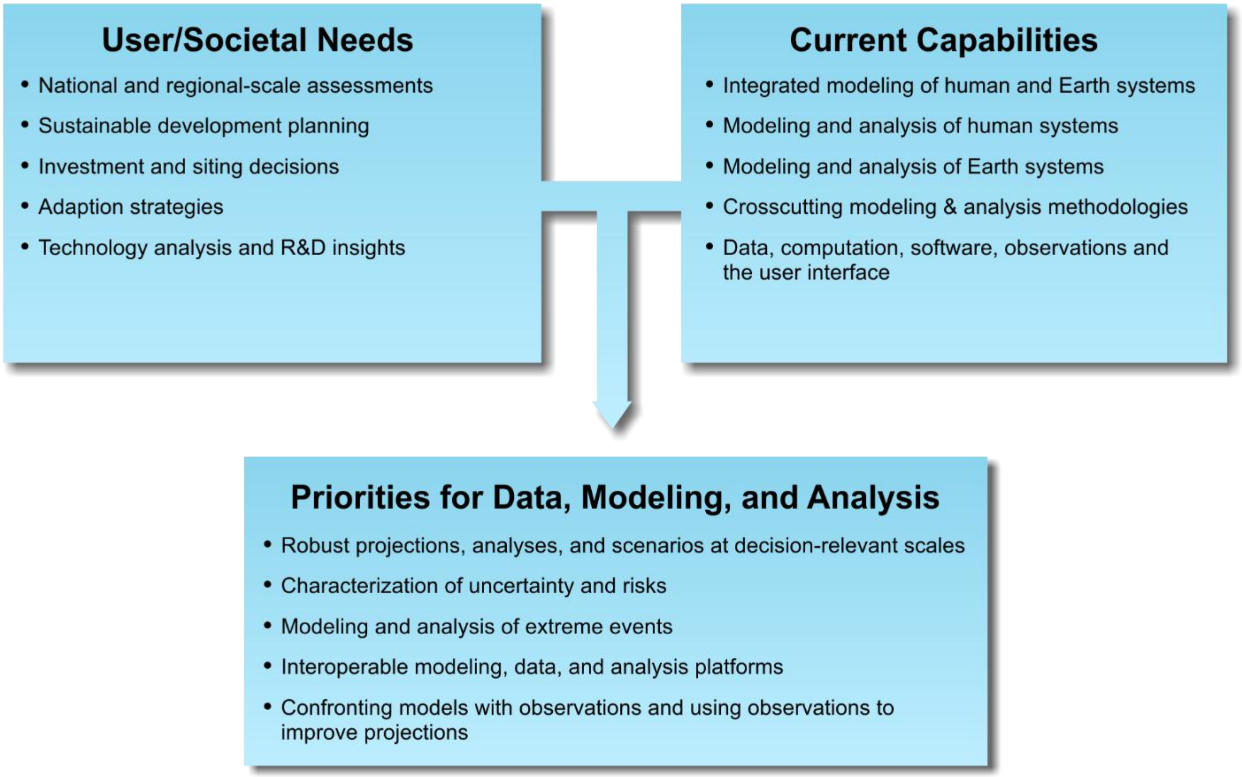


Figure 10. Needs, capabilities, and priorities for data, modeling and analysis.

In addition, improving forecasting capacities of extreme events and possible tipping points is needed to inform investment and siting decisions as well as other potential adaptation options. For DOE, these insights can inform technology RDD&D priorities and market evaluation studies. Advances will require integration of multiple models originally designed for disparate purposes, including the integration of technology-specific models with larger-scale efforts.

Finally, models require extensive validation with observations and empirical data. The iterative process of calibration can provide valuable direction to future cycles of model development, data collection, and, in the end, provision of information in forms that are both accessible and meaningful to a broad range of users.

Next Steps

The water-energy nexus presents an array of technical and operational challenges at local, regional, and national scales. There is a key national need for data-driven and empirical solutions to address these challenges. The next step is to substantially increase the impact of ongoing activities by strategically integrating and building on existing technology, modeling, and data work. Understanding the challenges and developing the solutions will necessitate early engagement with a diverse set of stakeholders.

Investment in technology advances throughout the technology continuum from research to development, demonstration, and deployment can address key challenges. Potential applications of interest for technology solutions cover several broad areas, including water efficiency in energy systems, energy efficiency in water systems, and productive use of nontraditional waters.

The next step is to develop a technology research portfolio analysis addressing risks, performance targets, impacts, RDD&D pathways, and learning curves.

Strong analysis will highlight potential synergies for technologies that span multiple programs.

Models and analysis are important to inform understanding and decision-making across complex coupled energy and water systems. DOE can place additional focus on technology models and their integration into broader multi-scale models addressing energy, water, and land under climate variability and change. This set of models can form an integrated analytical platform that supports understanding of the current and potential future interactions among the energy and water systems. The models can be used to develop scenarios incorporating factors such as energy technology deployment and climate variability.

The models and scenarios can then inform technology portfolio analysis, as well as relevant operations, planning, and other decisions made by stakeholders at scales ranging from facility to nation and seconds to decades. Characterizing uncertainty and examining extreme events are also priorities.

There is also an opportunity for DOE and its partners to assemble and improve water-energy data. For some aspects of the water-energy nexus, there is a considerable amount of data and information that exists but is inaccessible. Decision-making will be improved by integrating these data into an accessible system designed around the needs of both researchers and users.

Some aspects of the water-energy nexus, such as water quality characteristics of produced waters, suffer from a lack of consistent and coherent data collection at appropriate levels of granularity. To address these gaps, DOE can work with federal agencies and other partners on sensing, surveying, compilation, analysis, modeling, presentation, and interactive updating of data sets to improve data quality and usability. This enhanced data system can be used to calibrate the integrated models described above and the models can also be used to inform data collection.

With the importance of water in energy production and the increasing uncertainty of water supply, there is a growing need for a more coherent approach to inform relevant policies. The current water-energy decision-making landscape is complex and fragmented. The nation’s water and energy policies have been developed independently from one another, and in many cases there are strong regional differences in policy frameworks and objectives.

DOE can build on its modeling and analysis to help illuminate the key relevant issues brought by the strong interconnections between water and energy systems. In many cases, these interconnections relate directly to energy system reliability and resilience under changes in water resources. Reliability and resilience, in turn, align with broad Administration energy policy initiatives such as the Quadrennial Energy Review and Climate Action Plan. Important work is wide-ranging, including topics such as the development of metrics describing energy system resilience under water constraints, analysis of the connections between energy and water efficiency at multiple scales, and an examination of the impact of infrastructure investment programs.

Finally, DOE can strengthen its interactions and collaborations with diverse stakeholders. Important partners span all sectors, including federal agencies, state and local governments, foreign governments, private industry, academic institutions, non-governmental organizations, and citizens. Integration and collaboration will enable more effective research, development, demonstration, and deployment of key technologies; harmonization of policies where warranted; shared robust datasets; informed decision-making; and public dialogue.

For more information about work undertaken by the U.S. Department of Energy, Energy Policy and Systems Analysis (EPSA), visit the DOE website:

www.energy.gov

For more information about the Water-Energy Tech Team, please submit inquiries by email:

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