Capturing Synergies Between Water Conservation and Carbon Dioxide Emissions in the Power Sector

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Abstract

In order to gain a more thorough understanding of potential conflicts and synergies between power generation and water use, we developed a mixed-integer linear programming model of the power sector that captures the key relationships with water. We used the model to develop a series of scenarios for each of four case studies—the North Grid of China, India, France, and the state of Texas in the United States. We found that cost-effective options exist that can cut water use, reduce risks to the power sector, and also reduce emissions of conventional pollutants and greenhouse gases from electricity generation. This report focuses on strategies we recommend to capture those synergies.

Executive Summary

Electricity generation from thermoelectric power plants is inextricably linked to water resources at nearly all stages in the power production cycle, yet this critical constraint has been largely overlooked in policy and planning. While this assumption suggests that water is inexpensive and abundant, global water resources are increasingly strained by economic development, population growth, and climate change. As demand increases, competition for limited water resources among the agricultural, industrial, municipal, and electric power sectors threatens to become acute in several global regions.

Modeling the Electricity-Water Nexus

In order to gain a more thorough understanding of potential conflicts and synergies between power generation and water use, we developed a mixed-integer linear programming model of the power sector that captures the key relationships with water. We used the model to develop a series of scenarios for each of four case studies—the North Grid of China, India, France, and the state of Texas in the United States. We chose these cases because water is posing challenges to power generation in each of them.

We developed a baseline projection for each case study, and then modeled a number of scenarios, including limits on water availability, reduced power demand from end-use energy efficiency, expansion of renewable energy, and carbon caps, among others.

Findings and Strategies to Address Water Challenges and Mitigate CO_2 Emissions

We found that cost-effective options exist that can cut water used in electricity generation and also reduce emissions of conventional pollutants and carbon dioxide.

From the case study analysis, we developed a set of recommended strategies, presented in detail in this report:

- Promote energy efficiency and demand-side management.
- Deploy renewable energy technologies that do not require cooling.
- Avoid building new freshwater-cooled thermoelectric power plants in water-stressed regions.
- Improve monitoring, data collection, and analysis for policy, planning, and permitting.
- Increase research and development support for advanced power sector technologies that reduce water use and provide other co-benefits.

A companion report, *A Clash of Competing Necessities: Water Adequacy and Electric Reliability in China, India, France, and Texas,*[1] describes the four case studies and the analysis that supports the recommendations above. Documentation of the model is provided in its appendix.

Next Steps

The intent of the research was to better appreciate the issues at play and put forward a set of strategies to reduce the dependence on water of the power sector, thereby enhancing its reliability as well as the water- and pollutant-related co-benefits that could be derived.

It is critically important that policymakers, government officials, and other decision makers and reform advocates are aware of the significant reliability risks increasingly posed by water resource constraints. A key takeaway from the work reported here is that tools that enable the full consideration of water-related conflicts and synergies need to be developed and applied in order to avoid those future risks.

[1] Faeth, Benjamin K. Sovacool, Zoë Thorkildsen, Ajith Rao, David Purcell, Jay Eidsness, Katie Johnson, Brian Thompson, Sara Imperiale, and Alex Gilbert. *A Clash of Competing Necessities: Water Adequacy and Electric Reliability in China, India, France, and Texas.* July 2014. CNA Corporation. IRM-2014-U-007191. http://www.cna.org/sites/default/files/research/EWCEWNCaseStudiesJuly2014FINAL.pdf

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Glossary

bcm	billion cubic meters
BP	British Petroleum
CBM	coal-bed methane
CCGT	combined-cycle gas turbine
CCS	carbon capture and storage/sequestration
CERC	Central Electricity Regulatory Commission (India)
CREZ	Competitive Renewable Energy Zone (Texas)
CWC	Central Water Commission (India)
DG ENER	Directorate-General for Energy (European Commission)
EDF	Électricité de France
FERC	Federal Energy Regulatory Commission (U.S.)
EIS	Environmental Impact Statement
EA	Environmental Assessment
EE	energy efficiency
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
EWN	Energy-Water Nexus
GHG	greenhouse gases
GW/GWh	gigawatt/gigawatt hours
IEA	International Energy Agency
IGCC	Integrated Gas Combined Cycle
kW/kWh	kilowatt/kilowatt hour
LBNL	Lawrence Berkeley National Laboratory
MMBtu	million BTUs (British Thermal Unit)
MW/MWh	megawatt/megawatt hours
NEPA	National Environmental Policy Act (U.S.)
NOx	nitrogen oxides
NRDC	Natural Resources Defense Council
O&M	operations and maintenance
OECD	Organization for Economic Cooperation and Development

PARIS21	Partnership in Statistics for Development in the 21st Century
PM	particulate matter
PUC	Public Utility Commission
PV	Photovoltaic
R&D	research and development
RAP	Regulatory Assistance Project
RE	renewable energy
RPS	Renewable Portfolio Standard
SGCC	State Grid Corporation of China
tcf	trillion cubic feet
TW/TWh	terawatt/terawatt hours
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
USGS	U.S. Geological Survey

Introduction to the Electricity-Water Nexus

At the height of the 2011 drought, the worst one-year drought in Texas history, the president of the Electric Reliability Council of Texas (ERCOT) wrote to the head of the Texas Public Utility Commission warning of unusual stresses on the power grid, "even for a Texas summer."[2]

Most of the state was designated as being under "exceptional" drought conditions Figure 1. Demand for electricity was at an all-time high because of the heat, and the water needed to cool the state's coal, nuclear, and gas power plants was in short supply. In some places, water levels had dropped below intake pipes; in others, the available water was too hot to provide effective cooling. Texans were warned that rolling blackouts were possible, as power plants that could not be properly cooled would have to shut down.

In the end, ERCOT met demand without blackouts, though it came close. A key factor in keeping the power flowing during the drought was that Texas had been aggressively developing wind power. Currently, Texas generates more power from the wind than any other state.[3] During that summer of 2011, about 10 percent of the electricity Texans needed came from wind, as much as 18 percent on some days.[4] Wind is a power source that requires no water, unlike a thirsty source such as coal. In addition, state and federal energy efficiency programs lowered demand from what it otherwise would have been, and Texas had much more natural gas-fired generation than the national average – gas requires just half the cooling water of coal. If those adaptations had not been made, blackouts would have been much more likely.

[2] Doggett, Trip. Letter to Donna L. Nelson, Chairman, Public Utility Commission of Texas, August 18th, 2011. http://www.ercot.com/content/news/presentations/2011/CEO%20letter%20to%20PUC%20Chairman%20Nelson%20081611.pdf

[3] American Wind Energy Association (AWEA). "State Wind Energy Statistics: Texas." April 10, 2014. http://www.awea.org/Resources/state.aspx?ItemNumber=5183

[4] ERCOT. Wind Integration September 2011 Archive. http://www.ercot.com/content/gridinfo/generation/windintegration/2011/09/ERCOT%20Wind%20Integration%20Report%2009-25-11.pdf

Shutdowns due to water shortages are not uncommon in the power sector, and as water becomes scarcer under a variety of pressures, they may become regular occurrences.

Worldwide, a threefold increase in population during the past century has coincided with a six-fold increase in water use.[5] A sample of studies illustrates the point.

- A study by the 2030 Water Resources Group analyzed the future of water resource availability and concluded that under an average economic growth scenario, human global water requirements would grow from 4,500 billion cubic meters per year (bcm) in 2009 to 6,900 bcm by 2030.[6] This 50 percent increase in the demand for water, driven largely by agriculture, electric power generation, industry, and municipalities, has the potential to leave a 40 percent gap between water supply and demand in 2030.

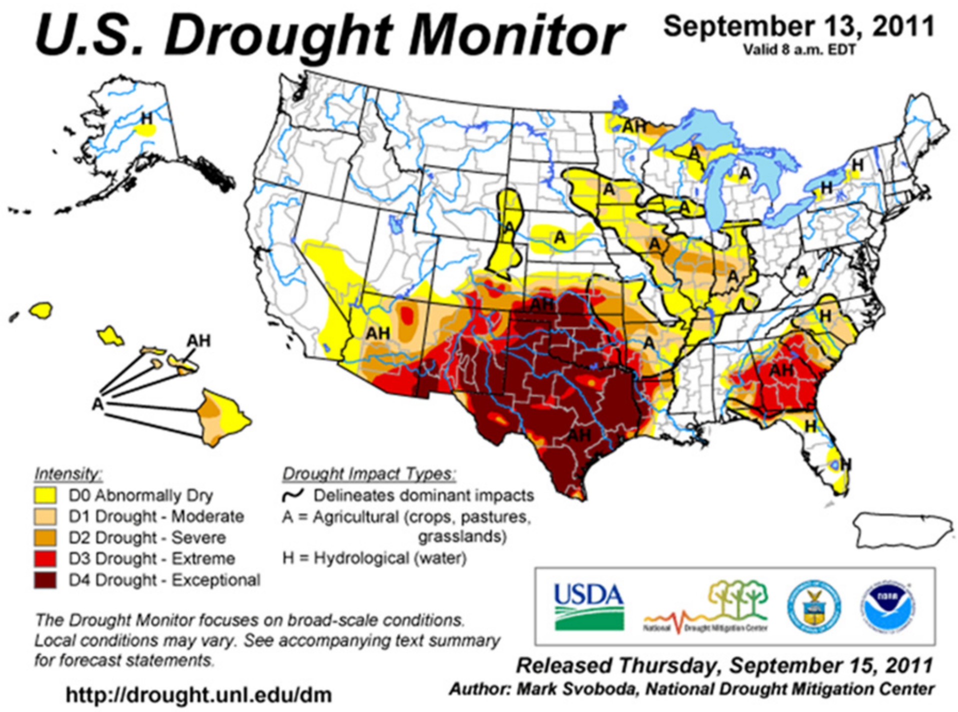
- Modeling by the United Nations Environment Programme (UNEP) identified a set of hotspot areas under growing water stress, including most of India and much of Northern China.[7]

[5] Bogardi et al., "Water Security for a Planet Under Pressure."

[6] 2030 Water Resources Group, *Charting Our Water Future: Economic Frameworks to Inform Decision Making* (Washington, DC: Water Resources Group, 2009).

[7] J. Alcamo and T. Henrichs, "Critical Regions: A Model-Based Estimation of World Water Resources Sensitive to Global Changes," *Aquatic Sciences* 64 (2002): 352–362

Figure 1. Almost all of Texas was covered by "exceptional" drought in 2011



- A study jointly conducted by the World Resources Institute and HSBC Bank projected that India, Malaysia, the Philippines, Thailand, and Vietnam all will soon be confronting localized shortages and climatic patterns with longer dry seasons and more frequent droughts. The report considered plans to add thermal power plants in each of these four countries as highly risky, since those additions would occur mostly in water-stressed and water-scarce regions. As the report aptly noted, "new thermal and hydro power development places long-term bets on water availability—yet future water supplies are often uncertain and potentially oversubscribed in the most electric power hungry and water scarce regions."[8]

[8] Amanda Sauer, Piet Klop, and Sumeet Agrawal, *Over Heating: Financial Risks from Water Constraints on Power Generation in Asia* (Washington, DC: World Resources Institute, 2010), p. 3.

- In 2012, the International Energy Agency (IEA) for the first time noted in its *World Energy Outlook* that power generation technology choices increasingly would be driven by water constraints,[9] including in China, India, and parts of the United States.

- In the United States, water managers surveyed in 36 states said they anticipate freshwater shortages under normal conditions in the near future.[10] Another survey of more than 700 utility leaders found "water management was rated as the business issue that could have the greatest impact on the utility industry."[11]

- In 2013, *Bloomberg New Energy Finance* reported that 85 percent of China's electricity generation capacity is located in water-scarce areas and will require $20 billion in retrofits to improve resilience. Some 60 percent of China's capacity lies in the north, which has just 20 percent of its freshwater supply. While electric power production currently accounts for 15 percent of China's freshwater withdrawals, by 2030 it could be 25 percent.[12]

These studies all point to the increasing scarcity of water resources around the globe and the threat that scarcity poses to the reliability of the electric power sector. There is the question of sustainable freshwater resource availability on one side, but on the other is the growth in power generation around the world and its potential to dramatically increase water demand. Between 2010 and 2040, power demand could more than double in northern China, more than triple in India, and increase by almost three-quarters in Texas.[13] If power demand is largely met with more and more coal, water use could grow along with it. The "nexus" image captures that tension: the question of sustainable freshwater resource availability on the one side, and on the other the growing demand for power around the world and its potential to dramatically increase water demand.

[9] International Energy Agency, *World Energy Outlook 2012,* p. 516.

[10] U.S. General Accounting Office, Freshwater Supply: States' Views of How Federal Agencies Could Help Them Meet the Challenges of Expected Shortages. GAO-03-514 (Washington, DC: U.S. General Accounting Office, July 2003).

[11] Ron Binz, Richard Sedano, Denise Furey, and Dan Mullen, *Practicing Risk-Aware Electricity Regulation: What Every State Regulator Needs to Know.* A Ceres Report (Boston, MA: Ceres, April 2012).

[12] Bloomberg New Energy Finance. China's Power Utilities Exposed to Water Disruption. March 25th, 2013. http://about.bnef.com/press-releases/chinas-power-utilities-exposed-to-water-disruption/

[13] Faeth et al., *A Clash of Competing Necessities: Water Adequacy and Electric Reliability in China, India, France, and Texas.* July 2014. http://www.cna.org/sites/default/files/research/EWCEWNCaseStudiesJuly2014FINAL.pdf

Water use in the power sector

Most electricity is produced by turbines, turned by steam from thermal generators that heat water to steam by burning coal or natural gas or by nuclear fission. Inherent inefficiency in the system results in waste heat, which must be removed by cooling in a very water-intensive process. That cooling, which is essential to safe operation of the power plant, is the primary focus of this report.

There are two ways that power plant cooling systems use water and affect water resources: withdrawal and consumption:

Withdrawal is "water removed from the ground or diverted from a surface-water source for use."[14] For thermal generation cooling purposes, withdrawn water is used to absorb waste heat and is then discharged back into the environment. In 2005, 41 percent of all freshwater withdrawals in the United States were for thermoelectric cooling, more than for any other sector including agriculture.[15]

Consumption is "the [portion] of water withdrawn that is evaporated … or otherwise removed from the immediate water environment."[16]

Thermal power plants employ one of the following three types of cooling systems, with very different implications for water withdrawal and consumption:[17]

Once-through, or open-loop systems withdraw water from a surface source, often a river; circulate it to absorb heat; and then return it to the water source.[18] These systems withdraw significantly more water than do the recirculating systems described below—between 10 and 100 times as much per unit of generation—but they consume significantly less water. During the cooling process, a fraction of water withdrawals are consumed and lost to evaporation.[19] (Figure 2)

[14] J.F. Kenny, N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin, *Estimated Use of Water in the United States in 2005.* Circular 1344 (Reston, VA: U.S. Geological Survey, 2009), p. 38.

[15] Ibid., p. 1.

[16] Ibid., p. 47.

[17] See Electric Power Research Institute, *Water & Sustainability,* vol.1, *Research Plan* (Palo Alto, CA: Electric Power Research Institute, 2002), Section 2-12.

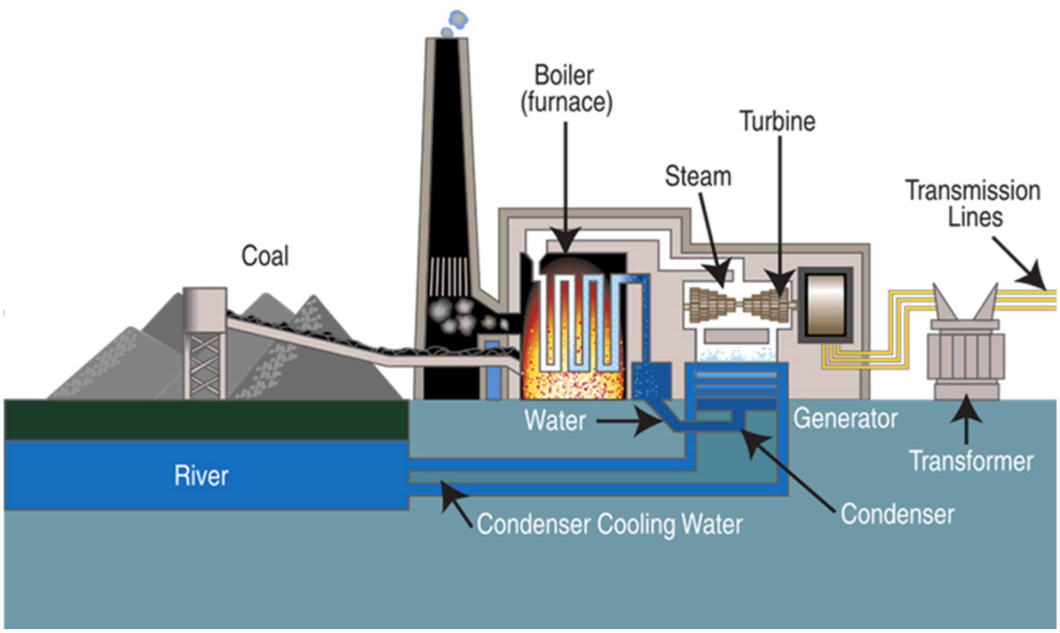
[18] Ibid.

[19] J. Macknick, R. Newmark, G. Heath, and K.C. Hallett, *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies.* Technical Report NREL/TP-6A20-50900 (Golden, CO: National Renewable Energy Laboratory, March 2011), pp. 3, 5.

Recirculating, closed-loop, or tower systems withdraw water and then recycle it within the power system rather than discharging it.[20] These systems withdraw less water but consume at least twice as much as open-loop systems.[21]

Dry cooling systems use air flows to remove heat. Dry cooling systems are less efficient than other cooling methods because they use enormous cooling fans to move large volumes of air. They also are more expensive than the other systems.[22]

Figure 2. A typical once-through coal-fired power plant. After the steam drives the turbine, waste heat is transferred to the cooling water at the condenser then discharged back into the water source, in this example, a river. Some waste heat is also lost through the smokestack.



Source: Tennessee Valley Authority, http://www.tva.com/news/downloads.htm tva.com

[20] Ibid.

[21] See Macknick et al., A Review of Operational Water Consumption and Withdrawal Factors, p. 5.

[22] Ibid., p. 508; Erik Mielke, Laura Diaz Anandon, and Venkatesh Narayanamurti, *Water Consumption of Energy Resource Extraction, Processing, and Conversion.* Energy Technology Innovation Policy Discussion Paper Series #2010-15 (Cambridge, MA: Belfer Center for Science and International Affairs, 2010), p. 32.

Dependable access to water resources for cooling purposes is of paramount importance to ensure power is generated reliably and safely. Reliability can be affected by water resource constraints in two primary ways: First, water resources (such as from the river shown above) may not be available in adequate quantities at low enough temperatures for cooling. Second, the hot water that results from the cooling process may be restricted from discharge back into the environment when the temperature of the receiving water surpasses an established threshold. Under either of these conditions, power plants may be forced to limit operations or shut down altogether.

Focusing on water demand, Table 1 compares withdrawal and consumption numbers by fuel type and cooling technology. For any fuel, once-through cooling systems withdraw much more water than recirculating systems do, making once-through systems more vulnerable to drought. (For all fuels, dry cooling requires no water, and so is not shown in the table.) For any water cooling system, nuclear uses the most water, coal the next highest amount, and natural gas the least. This is due to the relative efficiencies of the plant type to convert fuel to steam. Gas plants have the highest efficiency, so they have much less waste heat to remove, thus require less water. Wind and solar photovoltaic (PV) do not require cooling, though PV does use some water for washing.

Table 1. Median withdrawal and consumption values by fuel type and cooling technology

Fuel Type	Cooling Technology	Median Water Use (m^3/MWh)[a]	
		Withdrawal	Consumption
Nuclear	Once-through	168	1.0
	Tower	4.2	2.5
Natural Gas[b]	Once-through	43	0.4
	Tower	1.0	0.7
Coal w/CCS[c]	Tower	4.3	3.2
Coal[d]	Once-through	86	0.4
	Tower	2.3	1.9
Solar Photovoltaic	n/a	0.1	0.1
Wind	n/a	0	0

Source:

a. One cubic meter (m^3) is equal to 264 gallons of water. MWh means megawatt-hour.
b. Natural gas combined cycle (NGCC).
c. CCS is carbon capture and sequestration.
d. Supercritical/advanced coal.

Water conservation, air pollution and carbon dioxide emissions

Synergies exist for some options in the power sector to meet growing electricity demand in cost-effective ways that conserve water, as well as offer the benefits of reducing conventional air pollutants and cutting greenhouse gas emissions (GHGs). Table 2 shows cost and environmental performance data for a selection of options to provide supply or cut demand.

The least expensive option of all is to slow demand growth through end-use energy efficiency improvements. Not only is efficiency the cheapest approach because it avoids the need for new capacity altogether, but it also eliminates cooling water needs and emissions.

The least expensive option for new generation capacity is natural gas, which has significant environmental benefits over coal, which is the dominant fuel for power production globally. For natural gas, water withdrawals and consumption are less than half that of coal for the same cooling technology. In addition, there are no emissions of particulate matter (PM) or sulfur dioxide (SO_2), 90 percent lower nitrous oxide emissions (NO_x), and less than 50 percent the carbon dioxide emissions than for coal.

Unsubsidized wind power costs are currently lower than coal or nuclear, and they are continuing to drop as the technology continues to improve.[23] Wind does not require any cooling water and does not release any emissions. Solar PV also has very positive environmental performance, though the costs are currently high. PV costs are coming down, however, with a 60 percent average price drop between 2011 and the end of 2013.[24]

For two key technologies to reduce GHGs—nuclear and coal with carbon capture and sequestration (CCS)—there are water penalties as opposed to savings. Because nuclear is less efficient and doesn't lose heat through smokestacks, and coal with CCS has high parasitic loads, both technologies have considerably higher cooling water requirements. Dry cooling is not currently used for nuclear for safety reasons, and it has not been demonstrated for coal with CCS.

[23] Department of Energy. "2012 Wind Technologies Report." August 2013. http://www1.eere.energy.gov/wind/pdfs/2012_wind_technologies_market_report.pdf

[24] Solar Energy Industries Association. "Solar Energy Facts: 2013 Year In Review." http://www.seia.org/sites/default/files/YIR%202013%20SMI%20Fact%20Sheet.pdf.

Table 2. Synergies exist between water conservation, cost, and environmental performance

	Median Water Use (m^3/MWh)[a]		Cost[b] (per MWh)	Air Pollutants (kg/MWh)			
Fuel Type	Withdrawal	Consumption		PM	SO_2	NO_x	CO_2
Natural Gas[c]	1.0	0.7	$66	–	–	0.03	359
Wind	–	–	$80[e]	–	–	–	–
Nuclear	4.2	2.5	$96	–	–	–	–
Coal	2.3	1.9	$96	0.06	0.32	0.26	761
Coal w/CCS[d]	4.3	3.2	$122[f]	0.05	–	0.33	92
Solar Photovoltaic	0.1	0.1	$130	–	–	–	–
Energy efficiency	–	–	$0–50	–	–	–	–

a. Assumes tower/recirculating cooling.

b. Total system levelized cost of energy.

c. Natural gas combined cycle (NGCC).

d. Wind and PV costs are unsubsidized.

e. Derived from EIA (2014) based on difference between IGCC and IGCC with carbon capture and sequestration (CCS).

Sources: Macknick et al., 2011; EIA, "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2014," April 2014; NETL, Bituminous Performance Tool, http://www.alrc.doe.gov/energy-analyses/pubs/Bituminous_Performance_Tool_Rev6.swf.

Electricity-water modeling

From the numbers presented in Table 2, we can see that greater implementation of end-use energy efficiency, natural gas, and wind power—particularly as substitutes for coal—could cost-effectively conserve water, improve air quality, and cut carbon dioxide emissions from the power sector. If falling PV cost trends continue, that technology could also provide competitive water, air, and GHG benefits in the future.

In order to better understand the energy-water challenges in the power sector and identify opportunities to mitigate them, CNA developed a new power sector model that accounts for water use and water constraints. We call it the CNA Electricity-Water Nexus model.

CNA applied the model to four case studies—, with analytical, background, and data collection support from RAP and the Vermont Law School. Our case studies include the North Grid in China, India, France, and the state of Texas in the United States. For each case, we first developed a baseline, and then ran the model under various test scenarios. The Baseline scenario for all our cases assumes there are no limits on water use, an assumption typical of power sector models. The scenarios common to each case included greater end-use efficiency, water limitations, greater use of renewable energy, and some form of a carbon cap.[25]

Our purpose in building and applying a new model was to get a better understanding of water use and of technology and policy options. The model and results are scoping tools. We intend the results to be broad indicators; further, in our discussions, we are concerned with significant changes in direction and scale, rather than granular differences. In the remaining sections of this report, we present five strategies to mitigate water challenges in the power sector, and use selected modeling results to illustrate them. These strategies are based on the case study analysis. In a separate report,[26] we provide full descriptions of the case studies and results from the scenarios we tested, as well as additional information about the model itself.

The Electricity-Water Nexus model is a mixed-integer linear programming model that seeks to find the optimal solution to meet electric power demand at least cost. Mixed-integer linear programming means that part of the model solution can only be in whole numbers—in this case, the number of power plants. The model simulates new construction, retirement due to aging, and early retirements due to cost-ineffectiveness.

We constructed the model to meet power demand for each year of the simulation by choosing from a set of representative power plants:

- Six options for fuel—three thermal (coal, natural gas, and nuclear) and three renewable (hydro, wind, and PV)
- Four combustion options for coal —conventional or subcritical and advanced or supercritical, each without and with CCS
- Four combustion options for gas—conventional and combined cycle, each without and with CCS

[25] Development of the model was supported by the Regulatory Assistance Project (RAP); analytical, background, and data collection support was provided by RAP and the Vermont Law School.

[26] Faeth et al., *A Clash of Competing Necessities: Water Adequacy and Electric Reliability in China, India, France, and Texas.* July 2014, IRM-2014-U-007191. http://www.cna.org/sites/default/files/research/EWCEWNCaseStudiesJuly2014FINAL.pdf

- Three cooling options for the thermal plants—once-through, recirculating, and dry

For each representative power plant, we defined a set of characteristics:

- Cost—fixed (amortized capital costs, fixed operating costs); variable (variable operation and maintenance costs including fuel, transmission costs)

- Generation—capacity; capacity factor (the percent of time the plant can run)

- Environmental performance—water withdrawal and consumption; emissions of nitrogen oxides (NO_x), mercury, sulfur dioxide (SO_2), particulate matter (PM), and carbon dioxide (CO_2).

Demand projections come from official published sources, case-by-case; we did not make independent assessments of demand. Cost data come from studies done for the U.S. Department of Energy's (DOE) Energy Information Administration (EIA); water withdrawal and consumption data come from the National Renewable Energy Laboratory (NREL); and environmental data come from the National Energy Technology Laboratory (NETL). Assumptions about the future costs and performance of renewable power options come from a variety of sources, including NREL.

Strategies to Address Water Challenges and Mitigate CO_2 Emissions

Based upon our case study analysis,[27] we developed a set of strategies to reduce the dependence of the power sector on water, thereby enhancing its reliability as well as the co-benefits that could be derived. The strategies we recommend are:

a. Promote energy efficiency and demand-side management.

b. Deploy renewable energy technologies that do not require cooling.

c. Avoid building new freshwater-cooled thermoelectric power plants in water-stressed regions.

d. Improve monitoring, data collection, and analysis for policy, planning, and permitting.

e. Increase research and development support for advanced power sector technologies that reduce water use and provide other co-benefits.

In the following sections, we examine each strategy, providing examples from our modeling work that illustrate the point and the benefits of the particular strategy.

Promote energy efficiency and demand-side management

We tested an end-use efficiency scenario for each of our case studies and found that it was universally the lowest-cost resource for achieving important reductions across all key areas: water use, emissions, and cost. Remaining potential exists in all regions

[27] Faeth et al., *A Clash of Competing Necessities: Water Adequacy and Electric Reliability in China, India, France, and Texas.* July 2014, IRM-2014-U-007191. http://www.cna.org/sites/default/files/research/EWCEWNCaseStudiesJuly2014FINAL.pdf

covered in our analysis, although China and India have the most significant potential in this area. Energy efficiency is often viewed as a capacity resource and is increasingly able to compete as such in forward capacity auctions, further supporting its economics. Increasing energy efficiency, one study concluded, "is generally the largest, least expensive, most benign, most quickly deployable, least visible, least understood, and most neglected way to provide energy services."[28]

To illustrate the potentially large gains that can be achieved by implementing end-use energy efficiency, we show the results of the Baseline and the High Energy Efficiency (Hi EE) scenarios from our French case study. Under the Baseline, which we took from the 2009 report of the European Commission's Directorate-General for Energy (DG ENER),[29] demand grows over time, though relatively slowly compared with our other case studies. French electricity generation currently is dominated by nuclear power, at 82 percent of the fuel mix. Other sources include hydroelectric (10 percent), natural gas (5 percent), and wind and PV (total 3 percent). By 2040, with 28 percent demand growth, the mix is projected to be 70 percent nuclear, 8 percent hydro, 3 percent natural gas, and 18 percent wind and PV.

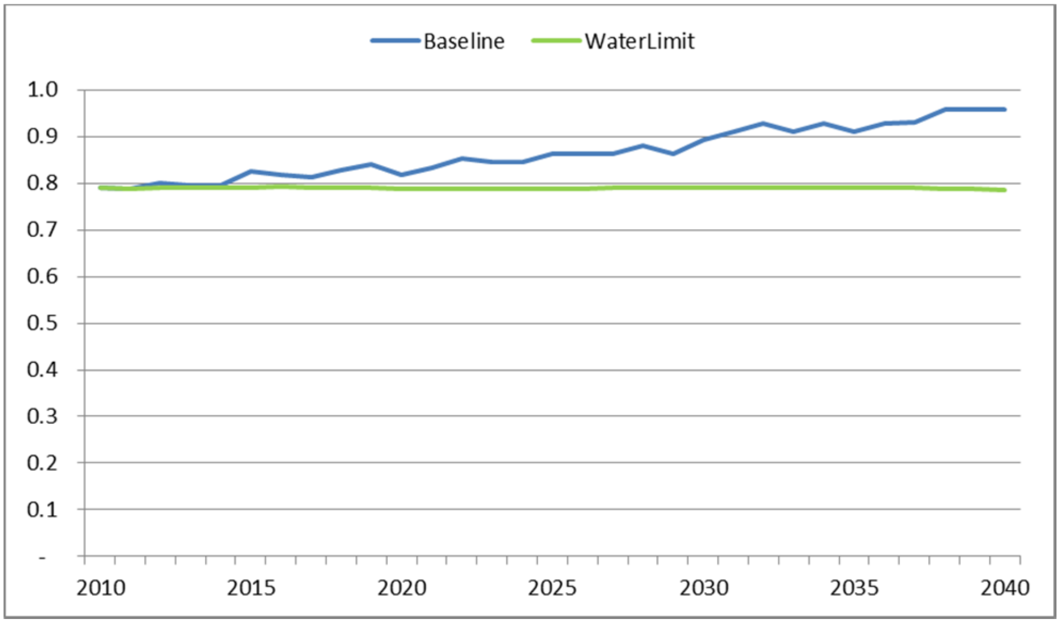
Under the Hi EE scenario, demand grows very little (just 3 percent) by 2040 and the fuel mix is different, with more nuclear (77 percent) and less wind and PV (13 percent). This is because the adoption of renewables is limited to replacing turnover of the existing capacity, rather than to meeting growing demand.

Figure 3 presents the model's results for water consumption. In the Baseline, water consumption grows 21 percent, a growth rate slower than power demand because of the increasing proportion of wind and PV, which have no water requirements. In contrast, the Hi EE scenario shows no net growth in water consumption.

[28] Lovins B. Amory, "Energy End-Use Efficiency" (paper prepared for the Rocky Mountain Institute, Snowmass, CO, September 19, 2005), http://www.institutebe.com/InstituteBE/media/Library/Resources/Existing%20Building%20Retrofits/Energy-End-Use-Efficiency.pdf.

[29] European Commission, Directorate-General for Energy, *EU Energy Trends to 2030 (Update 2009)* (Luxembourg: Publications Office of the European Union, 2010), http://ec.europa.eu/energy/observatory/trends_2030/doc/trends_to_2030_update_2009.pdf.

Figure 3. Water consumption by scenario for France

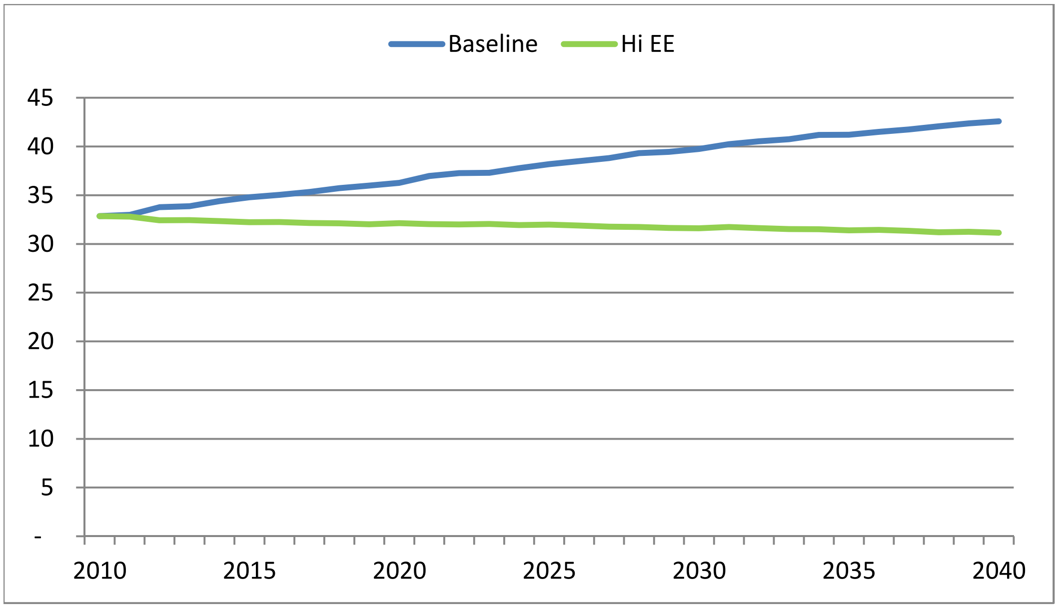


Units = bcm/year

Figure 4 shows the cost benefits of the Hi EE scenario. In contrast to a 30 percent increase in system costs over the 30-year simulation for the Baseline, the Hi EE scenario produces a 5 percent decline. We assumed a $35/MWh cost for each unit of demand cut each year. This is considerably cheaper than the other available options for France, which include nuclear, on- and off-shore wind, and PV. Gas and coal were excluded from the generation options due to carbon policies and resource limitations.

With cost and environmental advantages, end-use efficiency is clearly the first-best approach

Figure 4. Total system costs for France



Units = billion euros/year

Deploy renewable energy technologies that do not require cooling

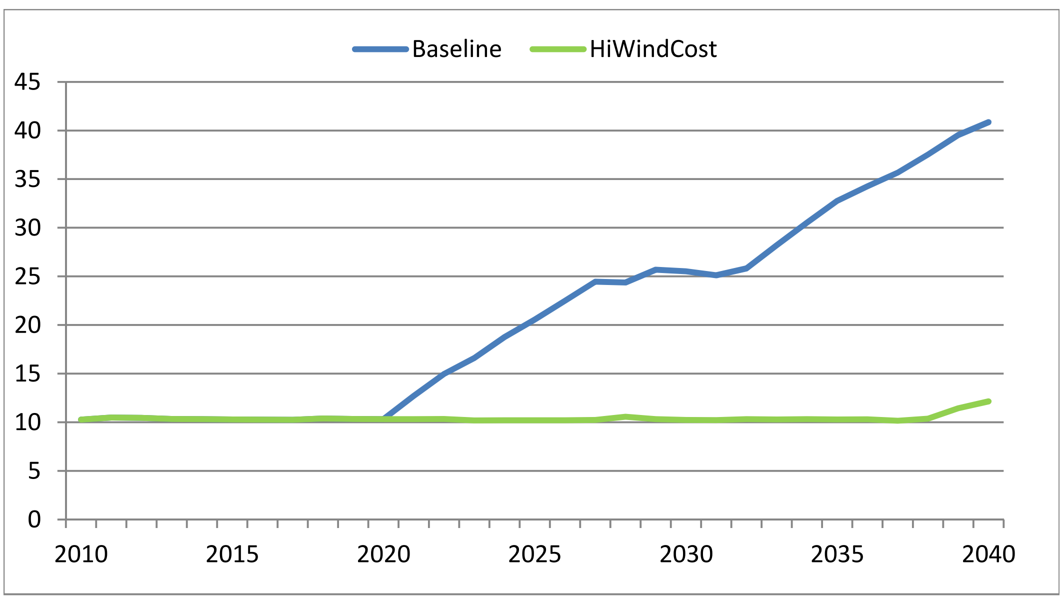
While demand-side measures that reduce the magnitude of future capacity additions are critical to mitigating future exposure to water supply problems, our modeling results and analysis of growth projections indicate that additional supply-side resources will be required in regions experiencing high growth. End-use energy efficiency cannot make up the entire gap in these cases.

With water resource adequacy issues already affecting currently installed capacity in the cases covered in this report, even current thermal resources are threatened by water constraints. New supply-side resources are required in order to meet demand reliably at least cost, and in such a way that reduces the power sector's exposure to reliability issues created by water limits and water competition. This is a critical role that, with few exceptions, only renewable energy—in particular wind, and in the future PV—will be capable of filling.

Wind and PV have clear advantages in terms of environmental performance compared with other power generation options, with practically no water use, no conventional air emissions, and no carbon dioxide emissions. Dry cooled coal power has a water advantage, though no air quality or GHG gains; and it is relatively expensive (costing perhaps 10 percent or more than water-cooled coal). Nuclear has air quality and GHG advantages, though it is not cost-competitive. Natural gas is much better than coal along these lines, but still uses some water and emits CO_2. It may be possible, however, to develop air-cooled gas generation that applies CCS, though the research focus has been on coal. Gas also has issues tied to leaks of methane, a potent greenhouse gas, from fracking. It appears those problems are fixable, however.

We tested a scenario for our Texas case study that assumed renewable energy prices would remain at their current levels (HiWindCost). In the Baseline for Texas, we assumed that wind prices would drop by 25 percent over the 30-year simulation and that subsidies were not available. Figure 5 provides the results. In the Baseline, unsubsidized wind becomes competitive with natural gas by 2020. Once competitive, we show wind growing rapidly to a bit more than 40 percent of the annual power generation.

Figure 5. Share of wind in the power generation mix for Texas



Units = percent

With subsidies, wind currently is competitive and the sector is booming in Texas. Wind integration for March 25, 2014, hit a record high of 37 percent.[30] ERCOT has been able to achieve increasingly higher wind integration because of a new transmission line, more frequent load balancing, and advanced weather forecasting.

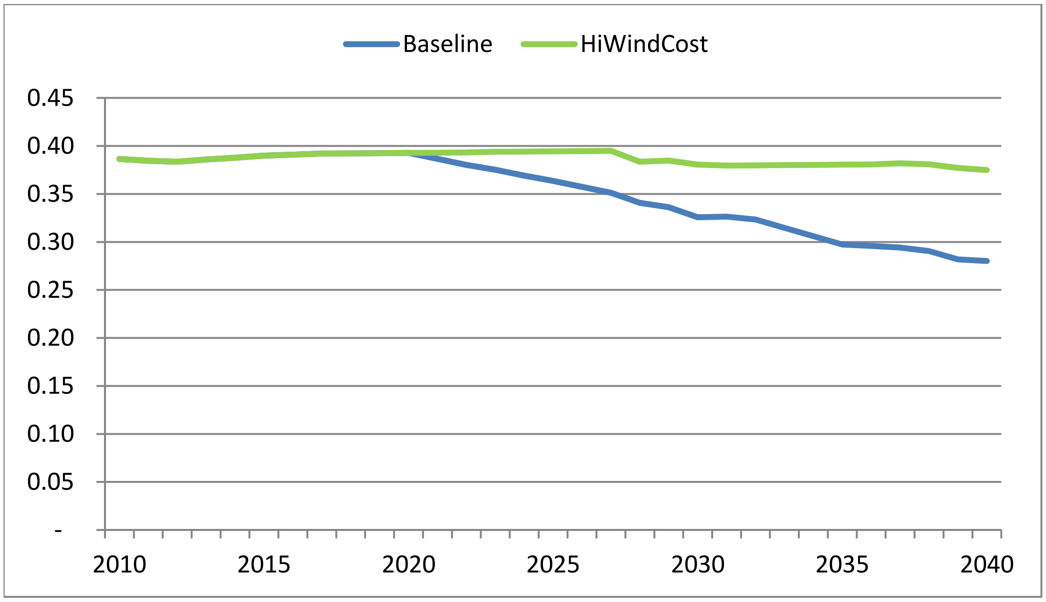
In the HiWindCost scenario, wind is kept out of the generation mix except for an assumed 10 percent renewable portfolio standard. The impact on water consumption is shown in Figure 6. In the Baseline, coal is uncompetitive and is gradually retired. We found that the U.S. Environmental Protection Agency's proposed Rule 111(d) under the Clean Air Act to limit generation options that emit more than 1,000 pounds of CO_2/MWh was irrelevant because low gas prices already kept coal out of the mix.

To replace coal and meet demand, gas and wind capacity both grow in the Baseline. The substitution of coal by less water-demanding gas and water-free wind results in a drop in water consumption of about one-third by 2040. In contrast, if all the substitution and growth were met only by gas, as in the HiWindCost scenario, increases could be avoided, but consumption would drop only marginally. In addition, without wind, CO_2 emissions would grow by about 10 percent, rather than dropping by 20 percent as in the Baseline—although all conventional air pollutants would drop by about 80 percent in either scenario.

In all of our case studies, the only way to generate power in a way that simultaneously produces improvements in water consumption, air quality, and GHG emissions is through wind and PV.

[30] ERCOT, *ERCOT Grid Operations: Wind Integration Report: 3/25/2014.* http://www.ercot.com/content/gridinfo/generation/windintegration/2014/03/ERCOT%20Wind%20Integration%20Report%2003-27-14.pdf.

Figure 6. Water consumption by scenario for Texas



Units = bcm/year

Avoid building new freshwater-cooled thermoelectric power plants in water-stressed regions

Perhaps the simplest hedge electric utilities and governments can use against increasing water risk is to simply stop building (or build fewer) new thermoelectric generation plants in areas of water stress or scarcity, or to equip new plants with dry cooling.

The addition of new conventional power plants has two inherent water-related risks that threaten reliability and suggest electric utilities should no longer construct them in water-stressed regions: In times of scarcity, they may not be able to withdraw water needed for normal operation. During low flows or high ambient temperatures, they may be prohibited from discharging water, in order to prevent ecosystem damage.

To encourage flexibility in meeting demand, and in recognition of large supply needs in India and similar cases, exceptions should be permitted in water-stressed areas—if new plants use dry or hybrid cooling, use unconventional sources of water such as brackish water or seawater, obtain water use rights from other users, or undertake water conservation strategies upstream.

Of our four case studies, the most extreme is India, which faces two highly challenging circumstances: a very significant existing gap between electricity demand and supply, and considerably stressed water resources under mounting pressures from a growing economy and population. Meeting high electricity demand in India with thermal generation would be a challenge even if water resources were unlimited. As it is, the nation must somehow supply this growth without additional water resources, or face the prospect of taking them from the agricultural sector. Some 52 percent of India's population currently lives in water-scarce regions, and 73 percent of the electricity capacity owned by the country's three largest utilities is located in water-scarce or stressed regions.[31]

For this case, we drew from a study done for the Planning Commission of India by Lawrence Berkeley National Laboratory (LBNL).[32] Its authors looked at "moderate" and "aggressive" application of renewables and efficiency for reducing power shortages as well as potentially large coal imports that will be necessary if India remains dependent on coal. The study highlights the growing global demand for coal and increasing volatility in coal prices. In contrast, estimates are that India's renewable resources are growing, and their costs are coming down.

The Baseline scenario for India shows electricity demand growing by 479 percent by 2040.[33] The LBNL study's "Modestly Secure and Clean Scenario (Moderate)" assumes that wind, PV, and energy efficiency make up 40 percent of the mix by 2030; the "Aggressive" scenario has these making up 60 percent of the total by 2030. The LBNL report concludes that wind and PV resources will not be constraining factors to renewable power generation, as these are as much as six times the power demand expected in 2030.

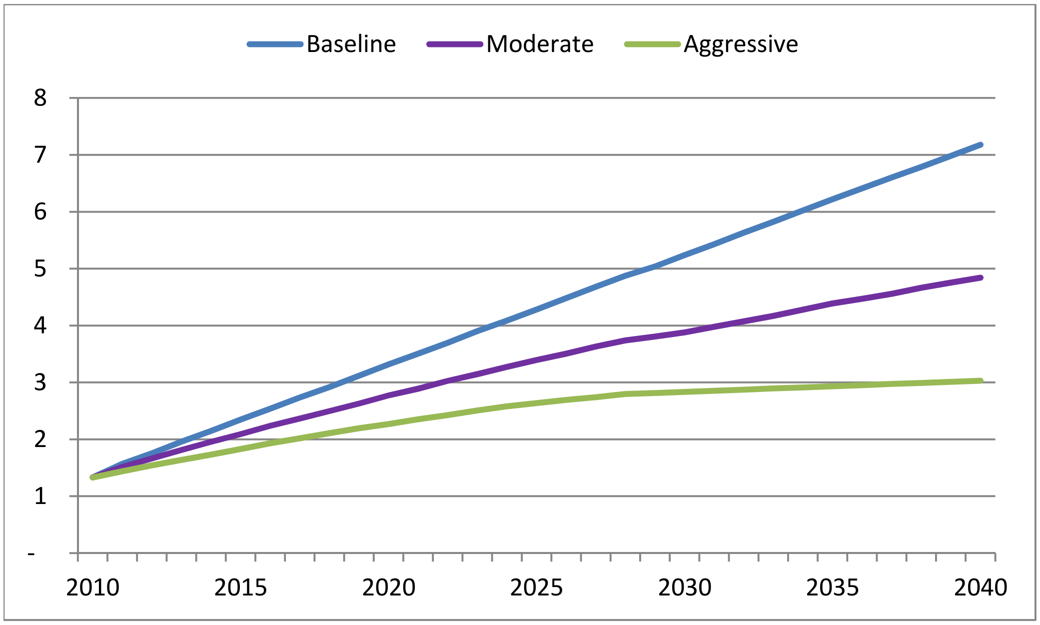
[31] FICCI-HSBC Knowledge Initiative, *Water Use and Efficiency in Thermal Power Plants* (New Delhi: Federation of Indian Chambers of Commerce and Industry, 2011). Water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use. Water scarcity is defined as the point at which the aggregate impact of all uses impinges on the supply or quality of water to the extent that the demand by all sectors cannot be satisfied fully.

[32] Nikit Abhyankar, Amol Phadke, Jayant Sathaye, Ranjit Bharvirkar, Alissa Johnson, Ranjit Deshmukh, Cathie Murray, Bob Lieberman, and Ajith Rao, *Modeling Clean and Secure Energy Scenarios for the Indian Power Sector in 2030.* LBNL Report (Berkeley, CA: Lawrence Berkeley National Laboratory, May 2013), http://eetd.lbl.gov/sites/all/files/lbnl-6296e_pdf.

[33] Because the LBNL study goes only to 2030, we extended its three scenarios by straight-line method to 2040.

Our results for water consumption for the three scenarios are presented in Figure 7. In the Baseline, water consumption increases by 457 percent by 2040, about the same amount as the growth in demand. Coal starts and ends at about 70 percent of the mix. At this level of water demand, reliability problems caused by water resources could be severe.

Figure 7. Water consumption by scenario for India



Units = bcm/year

In contrast, water consumption increases by just 264 percent by 2040 for the Moderate scenario, and just 128 percent for the Aggressive scenario. In spite of lower demand and considerably less coal in the mix (an 83 percent drop), in these alternative scenarios we still see water consumption growing considerably, very likely bumping into hard freshwater limits. However, Water consumption levels in the power sector could be manageable in India, however, if the remainder of the water requirements could be avoided with dry cooling, or met through water re-use or use of brackish water for cooling.

By moving away from coal and applying end-use energy efficiency and renewables, as this case does, it is possible to avoid large-scale freshwater-cooled thermal generation in water-stressed regions. Though not shown here, our results also indicated not only reductions in water consumption, but also improvements in air quality and GHG emissions at a marginally higher cost.

Improve monitoring, data collection, and analysis for policy, planning, and permitting

Although water availability is clearly a critical issue for the power sector, neither the U.S. Environmental Protection Agency nor the U.S. Department of Energy has policy models that include water. This means that even though the EPA regulates the power sector, which withdraws more water than any other, the agency is unable to consider the water use impact of its regulations, which include rules on cooling methods. At least in part, this is because the EPA has no authority to regulate water quantity, only quality. DOE's Energy Information Administration, which produces the government's official long-term energy forecasts, also leaves water out of its policy modeling.

What we found from our modeling, however, was that considering water availability can produce very different projections for how the power sector would develop in the future. It can also alter the feasibility of technology options. Omitting water use in policymaking is not unique to U.S. agencies, but is typical around the world, as evidenced by the absence of power sector models that include water in the research literature.

We provide an example from our China North Grid case study to illustrate the point. Among other scenarios, we modeled a Baseline, a water limit (WaterLimit), and a carbon dioxide cap (CO2CAP). The Baseline is heavily dependent on coal, starting out at 98 percent of the power generation and ending up at 77 percent, with the remainder mostly wind, but also some natural gas. As we said, the Baseline scenario always assumes no limits on water use.

For comparison, we modeled a scenario that assumes that water is limited (WaterLimit), which is a more realistic assumption for the North Grid.[34] We calculate the amount of water consumed in 2010, the initial year of the simulation, and then constrain the model so that water consumption in the power sector cannot exceed that limit for the remainder of the run. As mentioned in the introduction to this report, 60 percent of China's generating capacity lies in the north, which has just 20 percent of its freshwater supply. It would seem foolish to ignore a major constraint to power generation in an area where demand is growing rapidly.

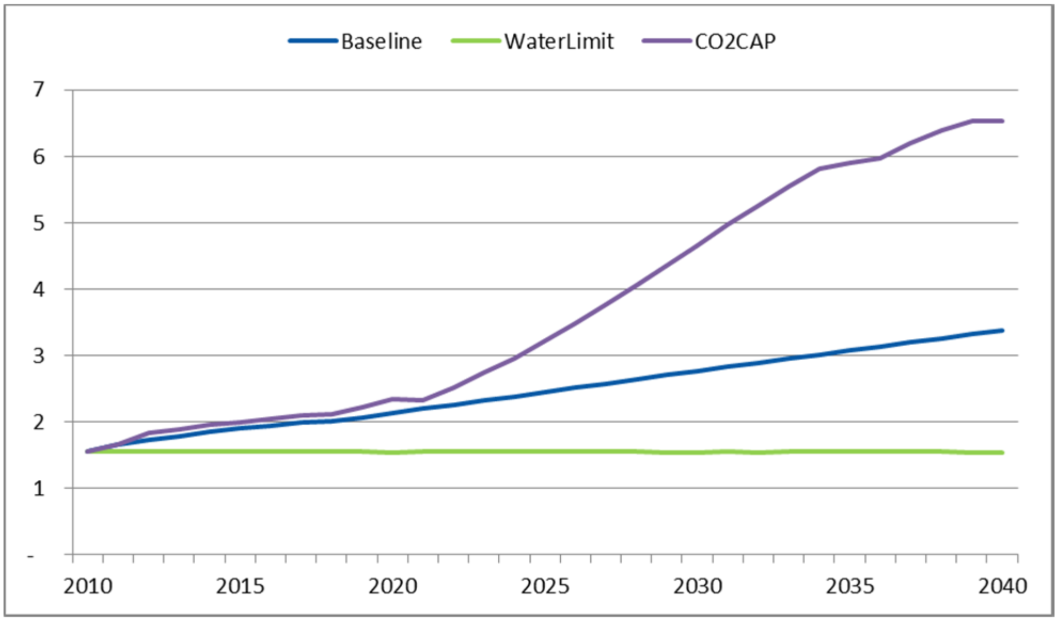
The fuel mix for the WaterLimit scenario is quite different from the Baseline's. There are two principal changes: Coal plants shift to a much higher degree of dry cooling, and less coal is used for generation by the end; 62 percent of generation instead of 77. In addition, considerable wind resources are brought in, 30 percent of generation, double the 15 percent of the Baseline. We allowed large amounts of wind to come

[34] Bloomberg New Energy Finance, 2013.
http://about.bnef.com/white-papers/the-future-of-chinas-power-sector/

into the solution because the area around the North Grid has exceptional wind resources.[35]

Our results for water consumption show it going up by 118 percent in the Baseline (Figure 8) whereas it is static for the WaterLimit scenario.

Figure 8. Water consumption by scenario for the North Grid of China



Units = bcm/year

This blind spot extends to policy and technology analysis for the sector. One area where this really matters is climate mitigation policy, because of the water use impacts of carbon capture and sequestration, which uses much more cooling water than does coal technology without CCS (see Table 1).

We tested the use of CCS for China to consider its likely impact on water use. The carbon cap scenario (CO2CAP) presented here mimics a scenario run by the IEA for its 2012 *World Energy Outlook*.[36] In this scenario, carbon dioxide emission are represented by a three-quarters sine wave—they go up by 20 percent during 2010–2010, back down to the starting point during 2020–2030, and drop 20 percent below

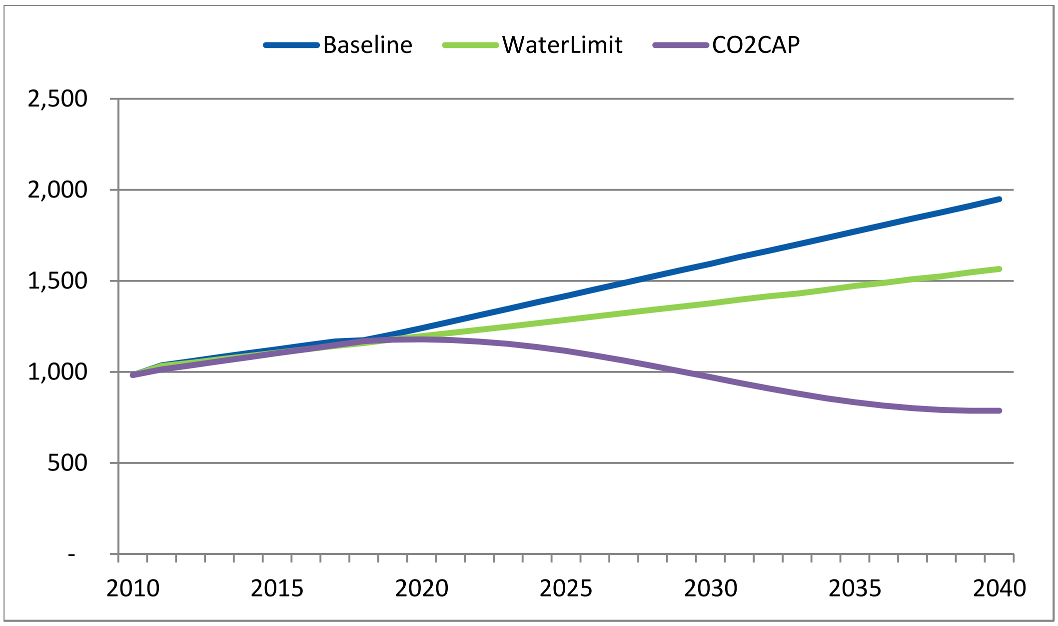
[35] International Energy Agency and Energy Research Institute, *Technology Roadmap: China Wind Energy Development Roadmap 2050* (Paris: OECD/International Energy Agency), p. 14, https://www.iea.org/publications/freepublications/publication/china_wind.pdf.

[36] IEA, 2012.

the 2010 value by 2040, as shown in Figure 9. In contrast, carbon dioxide emissions for the Baseline double between 2010 and 2040, and the WaterLimit scenario has CO_2 emissions growing by just 60 percent.

We tested several ways to meet the carbon cap; here we show the use of CCS as the primary mechanism. While the cap is met, the impact on water consumption is substantial: 322 percent larger than the WaterLimit consumption value by 2040, and 171 percent larger than even the Baseline (Figure 8).

Figure 9. Carbon dioxide emissions for the North Grid of China



Units = million tons/year

It's very likely that CCS would not be a viable option in the North Grid of China due to water resource constraints, but the extent of the problem would be unknown if water were not included in our model. Other options, including greater end-use energy efficiency, wind, and some substitution of natural gas for coal (assuming China can access its shale gas), could also meet the cap with substantially less water consumption.

These two figures show how different water consumption can be under various policy and technology scenarios. They also show how different results can be when water is or is not included as a constraint. This is why we recommend analysis that includes water for policy, planning, and permitting, but also better monitoring and data collection to understand potential water limits.

Increase research and development support for advanced power sector technologies that reduce water use and provide other co-benefits

During our background analysis, data collection, and modeling, we had occasion to consider a variety of technologies applied in different contexts. Through the work, we developed an appreciation of the technical and cost characteristics of these technologies and of their potential to reduce water use in the power sector, as well as to provide other co-benefits.

Based on these considerations, we developed a short list of specific investments that because they would provide financial and social benefits, merit public investment.

End-use energy efficiency. The cost of energy efficiency is already relatively low; nevertheless, many opportunities exist to develop additional technologies and undertake research to understand the best policies to get these technologies implemented.

Renewable energy sources that do not require cooling. Not all renewable energy sources avoid using water for cooling; biomass, for example, can require as much cooling water as coal, and some geothermal systems need considerably more.[37] Further research to improve capacity factors for wind and PV, for example, would speed their implementation.

Alternative water sources. Saltwater at coastal locations has longed been used for cooling. Adapting cooling systems to use local sources of nonpotable water could also reduce freshwater use. Researchers have investigated treating and reusing nonpotable, brackish, or other wastewaters to cool power plants. The most common applications, though not widespread, include using secondary treated municipal wastewater, passively treated coal mine drainage, and ash pond effluent. While these water sources reduce freshwater withdrawals, they increase costs, can adversely affect cooling equipment, and pose regulatory compliance issues. Research to overcome these challenges could prove worthwhile.

Systems to manage the variability of renewable power. A key factor limiting the integration of wind and PV into the grid is their variability. Advances in forecasting and grid management would reduce the impact of variability and allow greater

[37] Macknick et al., 2011.

integration, trimming water use as generating capacity and integration increase. In Texas, wind integration has gone up steadily over the last few years, currently to as much as 37 percent on some days. ERCOT has managed to produce such high numbers relatively quickly by cutting the time between load balancing from 15 to 5 minutes, and by adopting weather prediction tools that are much more accurate.[38] Further research into systems to manage variability would likely have very positive benefits, as would technologies such as batteries.

Energy conversion efficiencies. The need for cooling is directly dependent on the efficiency of energy conversion from fuel to power. Supercritical coal plants, for instance, consume less than subcritical coal plants due to the former's higher heat rate and higher steam pressures.[39] Similarly, higher efficiency nuclear plants also require less water. A nuclear plant running at 33 percent thermal efficiency will need to get rid of about 14 percent more heat than one at 36 percent efficiency.[40]

Small modular reactors. Conventional nuclear plants cannot be dry cooled for safety reasons, but new models of small modular reactors (SMR) can be.[41] Research to reduce cost and improve efficiency of these SMRs could reduce the water disadvantages of nuclear power while retaining its air quality and climate benefits. New designs of this category of reactor are simpler, and have economies of scale by reproducing the same reactor built in factories, and also have advantages in siting.[42] SMRs also can produce high energy conversion rates, providing "the potential for dramatically reduced impact on local water supplies, thus making nuclear power viable to customers in arid regions."[43]

Dry cooled carbon capture and sequestration. Baseline power sector projections for many countries, particularly China and India, expect that coal-fired power generation will grow for at least several more decades. While the research presented here

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[38] Lasher, Warren, Director, System Planning, ERCOT. Personal communication. February 13, 2014.

[39] U.S. Department of Energy/National Energy Technology Laboratory, *Power Plant Water Usage and Loss Study* (Washington, DC: DOE-NETL, May 2007 revision), pp. 71, 81.

[40] World Nuclear Association. "Cooling power plants." Updated September 2013. http://www.world-nuclear.org/info/Current-and-Future-Generation/Cooling-Power-Plants/

[41] Ibid.

[42] World Nuclear Association. "Small Nuclear Power Reactors." Updated April 2014. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Small-Nuclear-Power-Reactors/

[43] King, Marcus, LaVar Huntzinger and Thoi Nguyen. *Feasibility of Nuclear Power on U.S. Military Installations.* CNA Corp. March 2011. http://www.cna.org/sites/default/files/research/Nuclear%20Power%20on%20Military%20Installations%20D0023932%20A5.pdf.

demonstrates that cost-effective alternatives to coal exist, it would nevertheless be worthwhile to develop CCS systems that can be dry cooled, eliminating their water consumption constraint.

Conclusion

Electricity generation from thermoelectric power plants is inextricably linked to water resources at nearly all stages in the power production cycle, yet this critical constraint has been largely overlooked in policy and planning.

While this omission suggests that water is inexpensive and abundant, global water resources are increasingly strained by economic development, population growth, and climate change.[44] As demand increases, competition for limited water resources among the agricultural, industrial, municipal, and electric power sectors threatens to become acute in several global regions. It is critically important that policymakers, government officials, and other decisionmakers and reform advocates are aware of the significant reliability risks increasingly posed by water resource constraints.

We find though, that these risks can be managed in ways that are cost-effective and provide additional co-benefits, including improvements in air quality and reductions in greenhouse gases. Key approaches to do this include end-use energy efficiency; renewable energy that does not require cooling water, particularly wind; and a move away from coal to natural gas. Not all power production options provide these synergies. Nuclear power has air quality and climate mitigation benefits, but is very thirsty. Coal with carbon capture and sequestration requires considerably more water than does conventional coal.

The intent of the exercise we reported here was to better understand the issues at play and develop strategies that could alleviate the challenges the power sector is likely to face as water resource availability becomes increasingly constrained.

A key takeaway from this work is that tools that enable the full consideration of water-related conflicts and synergies—such as the CNA Electricity-Water Nexus model—need to be developed and applied in order to avoid future risks.

[44] International Energy Agency, *World Energy Outlook 2012* (Paris: IEA, November 2012), p. 502.

The CNA Corporation

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