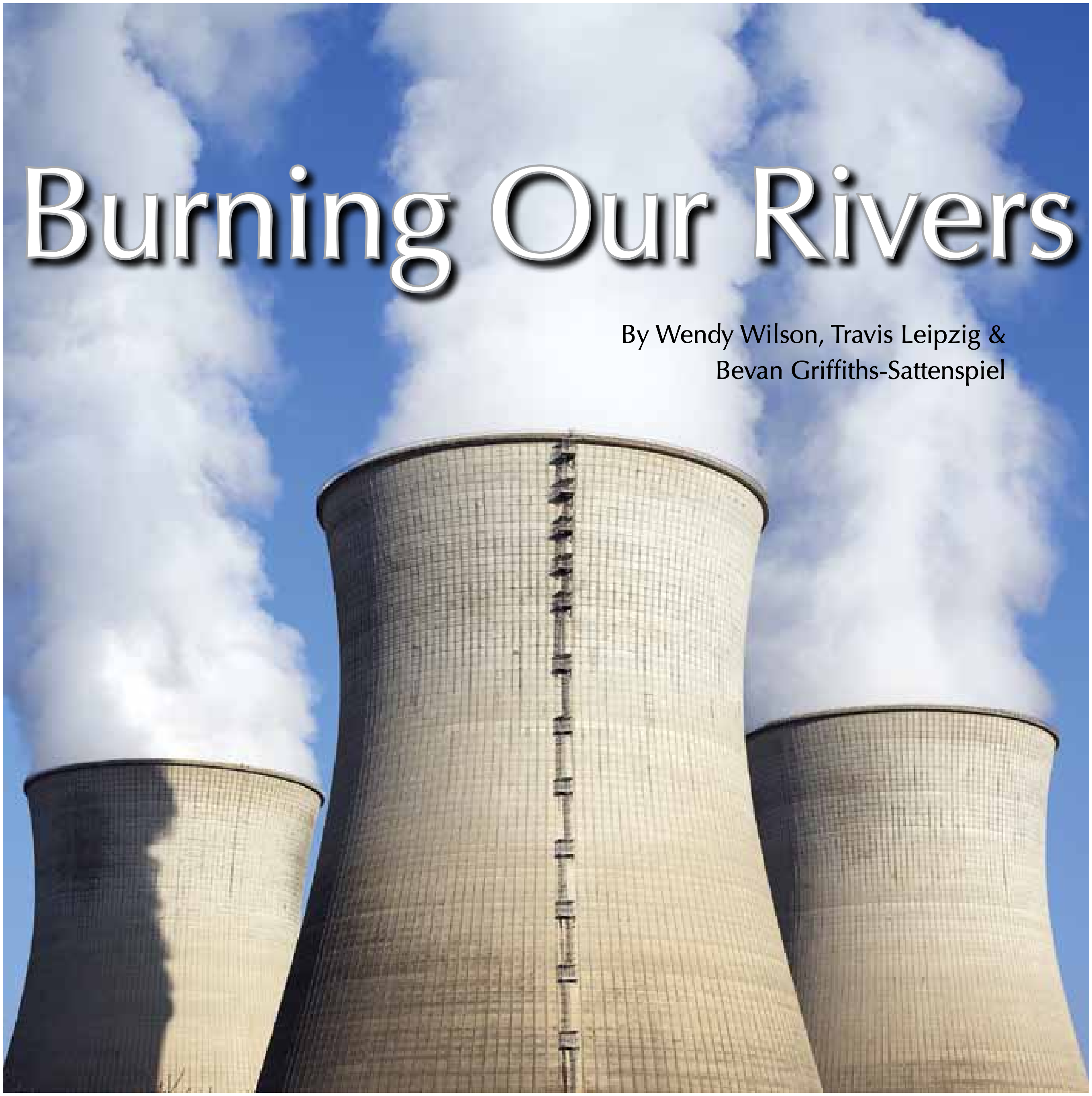

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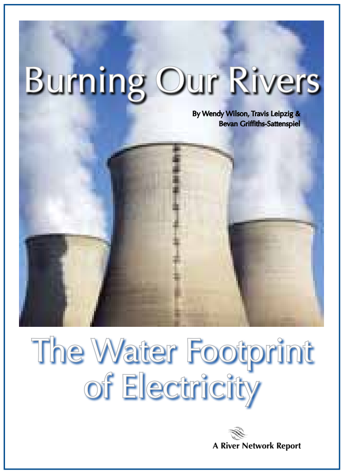
The Water Footprint of Electricity

A River Network Report



Burning Our Rivers:
The Water Footprint of Electricity

By Wendy Wilson, Travis Leipzig & Bevan Griffiths-Sattenspiel

Written in part with financial support of the Kresge Foundation.

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A River Network Report
Rivers, Energy & Climate Program

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SECTION 1

INTRODUCTION

It takes *water to produce electricity.* As many Americans retreat to air-conditioned environments to get out of the heat, the flame increases under our limited freshwater resources. The electrical energy used to create our comfort zones requires massive withdrawals of water from our rivers, lakes and aquifers to cool down nuclear, coal and natural gas power plants. Some of this water is evaporated while the majority of this water is warmed up—causing thermal pollution—killing aquatic life, increasing toxic algae blooms and decreasing the sustainability of our water supplies.

Thermoelectric energy (including coal, nuclear and natural gas) is the fastest growing use of freshwater resources in the country. The U.S. Geological Survey (USGS) reports that 53% of all of the fresh, surface water withdrawn from the environment for human use in 2005 went to operating our thirsty electrical grid.[1] Water behind dams is not included in USGS numbers. So, while all other sectors of society are reducing per capita water use and overall water diversion rates, the electrical industry is just getting started.

This report is a snapshot of the current water impacts of electrical production and an introduction to the choices we face as a nation trying to sustain water and energy in a warming world. Many watersheds in the United States (U.S.) are already running out of water to burn—especially in the Southeast, the Great Lakes and in many parts of the West. Over the last several years, Georgia has experienced water stress because Georgia Power's two nuclear plants require more water than all of the water consumed by residents of downtown Atlanta, Augusta and Savannah combined.[2] In 2011, the Union of Concerned Scientists (UCS) reported that, in at least 120 vulnerable watersheds across the U.S., power plants are a factor contributing to water stress.[3]

As a nation, we have "water-friendly" energy options. Energy efficiency and water conservation programs are crucial strategies that can help protect our waterways from the impacts of electricity production. Expanding the deployment of wind energy and photovoltaic (PV) solar power could vastly reduce water-use conflicts in some regions. And we must change the technologies we use in existing power plants. Energy companies could conserve more water by modernizing "once-through" cooling systems than could be saved by all of our nation's residential water conservation programs combined.[4]

But instead of moving towards greater water efficiency and use of renewables, we are trending towards an electrical grid that uses more water and is less reliable. Without stronger federal water use standards, thermoelectric plants may continue using water-intensive cooling technologies. At the same time, water

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[1] USGS, Estimated Use of Water in the United States in 2005 (p. 38).

[2] Sovacool "Running on Empty" (p.25).

[3] Averyt, K., J. Fisher, A. Huber-Lee, A. Lewis, J. Macknick, N. Madden, J. Rogers, and S. Tellinghuisen. 2011. *Freshwater use by U.S. power plants: Electricity's thirst for a precious resource.* A report of the Energy and Water in a Warming World Initiative. Cambridge, MA: Union of Concerned Scientists (p. 25).

[4] Public water use of 44.2 Bgal/day—if reduced 50% could save 22 Bgal/day; Electrical use of 201Bgal/day—if reduced 20% would save 40Bgal/day withdrawn water.

uncertainty is causing cities to explore new water sources such as desalinization, deeper wells and longer pipelines—all of which would increase electrical use. Across the country "non-conventional" drilling for natural gas has raised concerns about water quality. In Colorado, natural gas "fracking" operations have actually begun to compete with farmers for water.[5] The water footprint of coal-fired power plants will only increase with new carbon capture and sequestration (CCS) technologies.[6]

Based on the available published water-use information, we calculate that in 2009 the water footprint of U.S. electricity was approximately 42 gallons per kilowatt hour (kWh) produced. An average U.S. household's monthly energy use (weighted by cooling technology and fuel mix) requires 39,829 gallons of water, or five times more than the direct residential water use of that same household. This estimate does not include major portions of the lifecycle of electrical production for which we could not find documentation. As the world's largest electrical consumer, the U.S. needs to consider the sustainability of this course before investing in more water-intensive electrical infrastructures.

Today, our thirsty electric grid carries pollutants into our rivers and causes algae-blooms and fish kills. But, there are other paths. According to our calculations, eliminating 'once-through' cooling—by itself—could reduce the water footprint of thermoelectricity by more than 2/3rd. Increasing wind and PV solar energy to 40% of the grid would have a similar effect and reduce consumptive water use by 11%. Taken together, these two actions could reduce the water footprint of thermoelectricity by 82% and consumptive water use by 27%. While there are site-specific limitations and trade-offs to consider, our society stands to benefit from a wider discussion of how water saved in the energy sector might be used to meet future needs, grow food or restore fisheries and water quality.

PURPOSES OF REPORT & LIMITATIONS

> *"A product's "water footprint" is divided into three categories: green, blue and gray water. The green water consumption describes the evapotranspiration of rainwater during plant growth, which is especially relevant for agricultural products. Blue water consumption is the volume of ground and surface water that evaporates during production. Thus, it comprises the amount of water that is not returned into the environmental compartment from which it has been withdrawn initially. As the water that is returned to the environment (e.g., effluent of wastewater treatment plants) can be of lower quality, the gray water describes the total amount of water that is polluted by that effluent. Hence, gray water equals the volume of water required to dilute the used water until it reaches commonly agreed quality standards."*[7]

This report focuses on the *blue water footprint* of electrical production (water transformed from liquid to vapor) and the *gray water footprint*—which includes both water withdrawn from rivers, lakes and aquifers for thermal electric cooling or otherwise used "in-stream" for hydropower production. A *green water footprint* can also be applied to biomass and liquid biofuels used to generate electricity—a small but growing part of our electrical grid. Someday, perhaps algae-based fuels and more advanced biogas technologies will be brought into wider commercial production at which point their substantial *green water footprint* should also be researched.

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[5] http://www.denverpost.com/environment/ci_20299962/colorado-farms-planning-dry-spell-losing-auction-bids?source

[6] Mielke, E. et al. "Water Consumption of Energy Resource Extraction, Processing and Conversion," 2010.

[7] Markus Berger * and Matthias Finkbeiner, Water Footprinting: How to Address Water Use in Life Cycle Assessment? *Journal of Sustainability*, April 2010.

In 2009, River Network published a report called *The Carbon Footprint of Water,* which explored the energy and greenhouse gas emissions embedded in the nation's water supplies. We estimated that the equivalent of at least 520 million Megawatt hours (MWh) of electricity per year is required to move, treat and heat water each year in the United States—comparable to 13% of total U.S. electricity consumption. At a minimum, this water-related energy use generates over 290 million metric tons of CO_2 emissions per year and accounted for 5% of total U.S. CO_2 emissions in 2005.[8]

In *Burning Our Rivers: The Water Footprint of Electricity*, we explore the other side of the water-energy nexus. We provide a comparative analysis of the lifecycle water impacts—called the water footprint—of varying energy technologies. We compare both the water used or withdrawn and the water "consumed" or evaporated by electrical production.

Energy policy is primarily regulated by the U.S. Department of Energy (DOE), the Federal Energy Regulatory Commission (FERC) and state Public Utility Commissions (PUCs), while water policies are overseen by fifty state agencies and multiple branches of the federal government—including the U.S. Department of Interior's Geological Survey (USGS), the Army Corps of Engineers (ACE) and the U.S. Environmental Protection Agency (EPA). This makes it difficult to compare data for water use and energy generation, but all the more important that we try.

Methodologies for directly measuring water use and requirements for reporting vary widely across the country. The EPA estimated that the 633 presently operating power plants in this country have the combined capacity to withdraw more than 135 trillion gallons per year for cooling.[9] This report relies on primary research conducted by the USGS, DOE's National Renewable Energy Laboratory (NREL), the National Energy Technology Laboratory (NETL), the Energy Information Agency (EIA) and many other sources. When possible, we used water withdrawal and consumption factors from "Lifecycle Uses of Water in U.S. Electricity Generation," from the Journal of Renewable and Sustainable Energy Reviews.[10] We also reviewed important sources of new information from the Pacific Institute, the Union of Concerned Scientists (UCS), the World Policy Institute (WPI) and the Natural Resources Defense Council (NRDC). When multiple references were available for a given energy technology, we averaged those findings in most cases.

This analysis provides an average water use footprint for the primary electrical technologies and sources of electricity both "upstream" in mining and fuel production and "on-site" of the energy conversion process. We highlight full lifecycle water impacts whenever possible, but found that research to be substantially incomplete. The gaps in information for "upstream" water use are evident in both Table 1 and Table 2 (see pages 10-11). We did not find research on the full "cradle to grave" water impacts of constructing and decommissioning dams, nuclear power stations or hydraulic fracturing for natural gas drilling.

Our review of the water footprint of biomass sources was limited because of the large variety of feedstock types.

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[8] River Network, "The Carbon Footprint of Water," 2009. http://www.rivernetwork.org/sites/default/files/The%20Carbon%20Footprint%20of%20Water-River%20Network-2009.pdf

[9] NRDC, 2011, Comments to U.S. EPA on Proposed 316(b) Rulemaking (p. 2).

[10] Vasilis Fthenakis and Hyung Chul Kim.V, September 2010 (Volume 14, Issue 7). Fthenakis also serves in the Department of Energy Sciences and Technology at Brookhaven National Laboratory, a research laboratory funded by the U.S. Department of Energy.

SUMMARY OF RECOMMENDATIONS

Our heavy reliance on "burning" our freshwater resources creates a host of pollution and water scarcity problems across our country. Understanding the local impacts of our energy use is a critical step towards reducing water pollution (especially thermal pollution) and restoring our rivers, streams, lakes and aquifers. We have many policy options including closing old thermo-electric plants, integrating water and energy planning for greater efficiency and developing greater access to the electric grid for low-water renewables such as wind and PV solar.

In general, moving away from fossil fuels towards renewable energy sources will help stretch our limited freshwater resources. But not all renewable energy development has low water impacts and disturbing natural land, for any type of energy development alters a site's hydrology and potentially threatens rare ecosystems. Non-water related concerns with renewable energy projects, particularly centralized solar plants (either PV or concentrating solar thermal) and wind, include the loss of natural habitat from the large areas of land required for solar panels or wind turbines and direct wildlife conflicts (i.e., sage grouse habitat, migratory bird and bat casualties). These are real tradeoffs that must be considered on a site-specific basis. Using rooftops, disturbed land and parking lots for solar arrays may help minimize some of these concerns.

There are other important technological changes that can reduce water pollution and overuse. For example, in Ohio, four inefficient and outdated coal-fired plants will soon be closed. The cooling water for those antique "once-through" coal-fire facilities was coming directly from Lake Erie for over 50 years, being returned to the Lake much warmer, contributing to algae blooms. According to a study by USGS, 70% of all water taken from Lake Erie for human use is for thermoelectric plants. A substantial *co-benefit* to closing these plants will be reduced fish kills, algae blooms and an aquatic dead zone in America's heartland.

We can also take a closer look at decommissioning older dams in places where there are more water-efficient ways of meeting electrical demand or adding turbines to existing dams not currently being used to produce power. Many hydropower dams are owned by the federal government, authorized directly by Congress and rarely subjected to a rigorous cost-benefit analysis before being built.

Local watershed organizations and freshwater protection groups need to get more involved in energy conservation programs. Groups can get involved in water quality permitting and help increase community awareness of the associated problems. Municipal water suppliers and farmers need to be engaged in energy planning. Given the need for better energy planning and the potential for water-use conflicts, all stakeholders need to make their voices heard.

If we change our electrical infrastructure across the country with water in mind, we can expect a more reliable energy grid, better fishing and recreation, more secure public water supplies and lower greenhouse gas emissions. Presented with this list of potential benefits, leaders in many communities might ask, "Why did we wait so long?"

SECTION 2

RESULTS

In the Western U.S., all water flows towards irrigators and cities, turning hydropower turbines along the way. The reservoirs associated with hydropower dams lose water through evaporation, fragment rivers and reduce water quality. In many places in the Eastern U.S., the biological health of rivers and lakes is heavily compromised by thermal pollution associated with thermoelectric cooling.

Electricity—*as we generate it today*—depends heavily on access to free water. The impact to our freshwater resources is an external cost of electrical production. What the market considers "least cost" electricity is often the most water intensive. There are clearly some low water technologies and some water hogs. For example, wind and PV solar technologies have by far the lowest water-use factors (from zero to 231 gallons used per MWh produced) and hydropower, coal and nuclear have the largest water use factors (ranging from 14,811 to 440,000 gallons per MWh).[11]

The actual water footprint of electricity varies tremendously by fuel, generating efficiency, cooling technology, climate, geography, the body of water used for cooling and the physical layout of the power plant site. Our summary comparisons of water-use factors by fuel type are found in Table 1 (see p. 10). These are based on estimates of the prevalence of various cooling technologies in the U.S. electrical grid. We weighted these factors based on 2009 data from NETL.

Finally, Table 2 (see p. 11) is weighted on the prevalence of each fuel in the U.S. electrical grid. **As a result, we calculate that an average kWh of electricity in the U.S. used or consumed 41.6 gallons of water in 2009.** In reality, the amount of water used or consumed to produce a kWh varies widely, highest in places where evaporative losses are greatest and least where power is supplied by PV solar and wind.

An average household uses just under 1,000 kWh of electricity each month based on the 2010 U.S. Census data (958 kWh for a 2.4 person household). Table 3 (see p. 12) shows that, based on the mix of fuels and cooling technologies, the average U.S. household indirectly uses 39,829 gallons of water per month through the associated water footprint of electricity.

For comparison, that same household would use 7,336 gallons directly each month for residential purposes.[12] Therefore, we can say that we use five times more water *indirectly* through electrical production than through all of our household sinks, toilets, dishwashers, washing machines, faucets and hoses combined.

This report doesn't attempt to quantify the enormous environmental consequences of electricity production and its associated water use. Arguably, every body of surface water in the country has been

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[11] Because of the weighted averages by prevalence cooling type our water-use factors are slightly different than those calculated by NREL (see Appendix A).

[12] U.S.G.S., 2005 average per person use of 99 gallons/day.

impacted by mercury contamination from coal-fired plants. Fish and aquatic species are the "canary" in the coal mine—but the coal mine is our drinking supply. We believe a stronger recognition of all of the associated impacts of electrical production will help us focus on possible ways of protecting our water supplies.

Table 1. Water Use Factors for U.S. Electric Generation
(Weighted by 2009 Cooling Technologies)

	Upstream Water Use *(Gal/MWh)*		**Power Generation Water Use** *(Gal/MWh)*		**Total Water Use** *(Gal/MWh)*	
Electric Fuel	**Withdrawal**	**Consumption**	**Withdrawal**	**Consumption**	**Withdrawal**	**Consumption**
Coal	538	186	15,514	506	16,052	692
Hydroelectric	N/A	N/A	440,000	9,000	440,000	9,000
Natural Gas	323	23	6,161	149	6,484	172
Nuclear	79	40	14,732	532	14,811	572
Solar Thermal	N/A	N/A	800	800	800	800
Geothermal	N/A	N/A	700	700	700	700
Photovoltaic Solar	229	N/A	2	2	231	2
Wind	60	N/A	<1	<1	<61	<1
Biomass	N/A	N/A	N/A	N/A	N/A	N/A

Chart 1. Lifecycle Water Use of Electricity *(Gallons/MWh)*

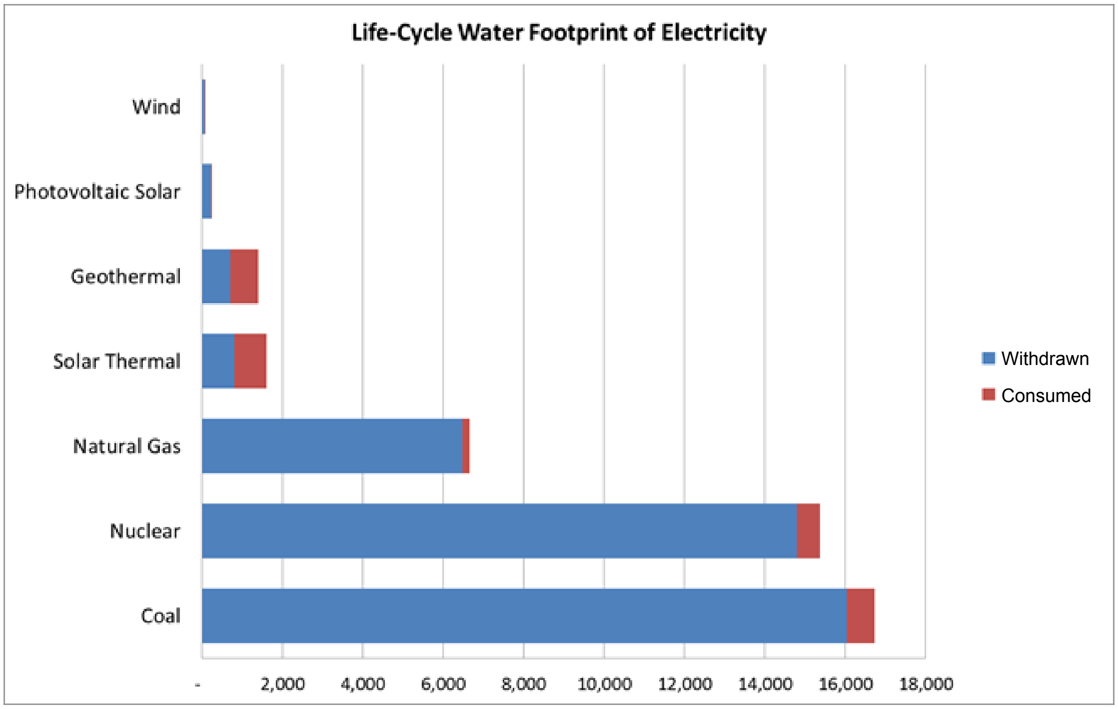


Chart 2. Water Consumption by Fuel Source *(including Hydropower)*

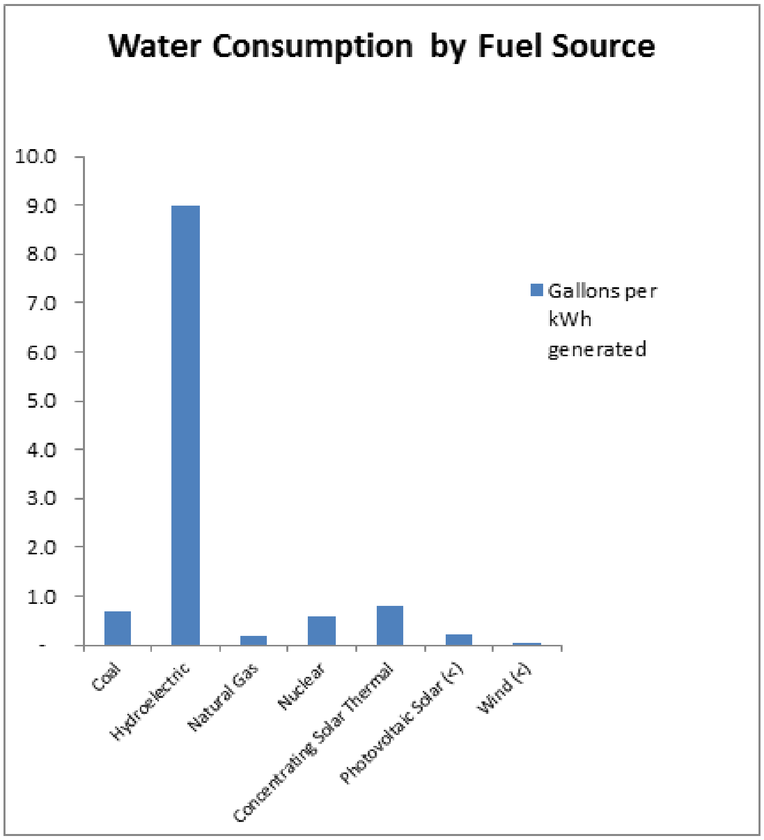


Table 2. Water Footprint of a Megawatt-hour *(Gals/MWh weighted national average)(Weighted by Production)*				
Fuel	**Percent of electricity in U.S. 2009**	**"Blue Water" Consumption**	**"Gray Water"** *(Additional Non-consumptive)*	**Total Water Footprint**
Coal	44.5	308	6,835	7,143
Hydroelectric	6.8	612	29,308	29,920
Natural Gas	23.3	40	1,472	1,512
Nuclear	20.2	116	2,880	2,995
Geothermal	0.3	2	-	2
PV Solar	0.7	0.01	2	2
Wind	1.9	.02	2	1
Other	2.3	-	-	-
Total U.S. Gal/MWh	100%	1,078	40,498	41,575

Table 3. Total Water Footprint of a Kilowatt-hour

(Gallons per kWh)
2009 U.S. Electric Grid
(National weighted average)

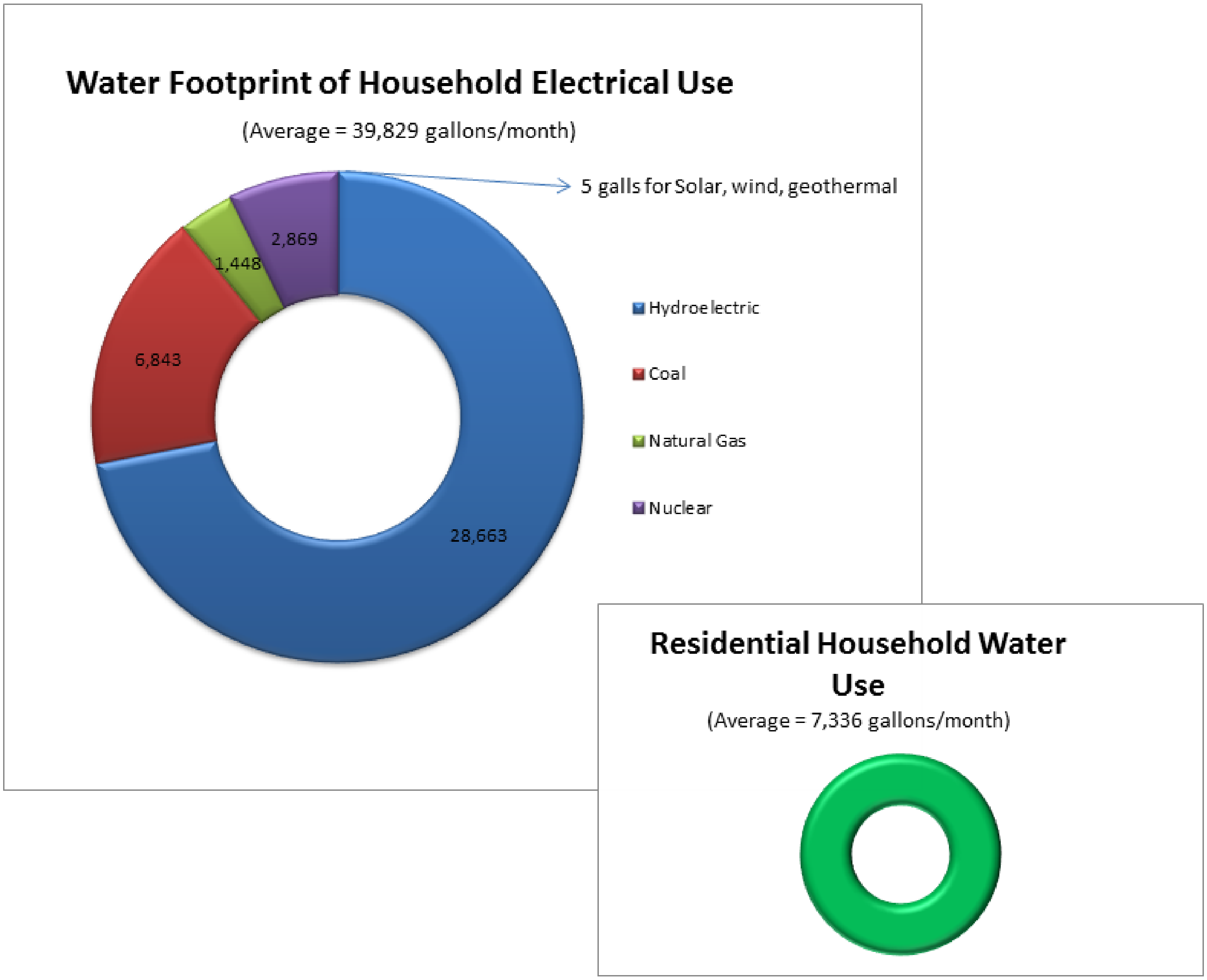
Hydroelectric	29.920
Coal	7.143
Natural Gas	1.512
Nuclear	2.995
Geothermal	0.002
Solar	0.002
Wind	0.001
Total	41.575

Table 4. Average Monthly U.S. Household Water Footprint of Electricity

(Based on national weighted average)
(Gallons used to produce 958 kWh)

Hydroelectric	28,663
Coal	6,843
Natural Gas	1,448
Nuclear	2,869
Geothermal	2
Solar	2
Wind	1
Total	39,829

Chart 3. Water Footprint of Household Electrical Use versus Direct Household Water Use



SECTION 3

THE WATER FOOTPRINT OF ELECTRICITY

COAL

Coal is the most commonly used fuel source for electricity generation in the United States, accounting for just over 44.5% of the country's total power production in 2009. More than twice as much electricity is produced from coal-fired power plants than from any other energy source in the U.S.[13]

Coal has been declared "America's dirtiest energy source" by the Natural Resources Defense Council due to the extensive environmental damage caused by the coal industry.[14] Immense amounts of water are used or polluted to mine, wash and transport coal before it even reaches the power plant, while even more water is used or consumed at the power plant. Mining for coal drastically alters landscapes, frequently disrupting and polluting freshwater resources. Washing coal leaves behind millions of gallons of heavily contaminated "sludge" that can pollute freshwater supplies if not stored properly. Coal-fired power plants are America's largest source of greenhouse gas emissions (emitting approximately 2.125 billion metric tons of carbon in 2008[15]) and are a leading contributor to mercury pollution, acid rain and toxic waste.

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"Not only is coal-fired power one of the dirtiest sources of electricity, emitting approximately 2.125 billion metric tons of carbon for every MWh of electricity produced, it is also one of the thirstiest sources. Coal plants withdraw approximately 16,052 gallons and consume approximately 692 gallons for every MWh produced. The massive freshwater withdrawals that are not consumed by cooling towers are returned to the source contaminated and at higher temperatures, threatening fish and other aquatic wildlife, creating toxic algae blooms and adding to the energy required to treat that water downstream before it is pumped into our communities."

At a leveled cost between $100.40 per megawatt hour for conventional coal power and $129.30 per megawatt hour for "advanced coal" with carbon capture and sequestration,[16] coal remains one of the cheapest and most abundant sources of energy in the United States. However, these expenses do not reflect the added externalized, real costs of coal power, including health hazards from air emissions, mercury pollution, loss of ecosystem services and damage from climate change. A study from the National Research Council found that the health costs alone from emissions at coal-fired power plants amount to at least $62 billion per year—not including loss of ecosystem services, costs of global warming and mercury pollution. Despite coal's heavy toll on human health and the environment, still more than

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[13] EIA Electric Power Annual: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html

[14] http://www.nrdc.org/energy/coalnotclean.asp

[15] http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html

[16] http://www.eia.doe.gov/oiaf/aeo/electricity_generation.html

50 new traditional coal-fired power plants have been commissioned or are in developmental stages as of January, 2012.[17]

A MWh of electricity generated by coal withdraws approximately 16,052 gallons and consumes approximately 692 gallons of water (see Table 1, p. 10).

The water footprint of coal electricity includes the following:

Table 5.1. Water Footprint of Coal - Upstream*
(Excludes Water Used at the Power Plant)

Lifecycle Stage	Withdrawal *(Gal/MWh)*	Consumption *(Gal/MWh)*
Mining/Processing	58	16
Transport *(slurry pipeline)*	473	170
Plant Construction	7	N/A
Total	538	186

* See Appendix A for methodology.

Table 5.2. Water Footprint of Coal: Electric Power Generation*

Cooling Technology	Withdrawal *(Gal/MWh)*	Consumption *(Gal/MWh)*
Once-through	35,135	301
Recirculating wet	749	700
Cooling Pond	11,157	416
Weighted Average	15,514	506

* See Appendix A for a detailed methodology.

Table 5.3. Water Footprint of Coal: Electric Power Generation with Carbon Capture

Cooling Technology	Withdrawal *(Gal/MWh)*	Consumption *(Gal/MWh)*
Recirculating Wet	5240	4690
Recirculating Wet *(retrofitted plant)*	36,000	1300

Coal Mining & Processing

Water is used for a myriad of coal mining processes, including equipment cooling and lubrication, dust suppression, fuel washing and processing, and post-mining re-vegetation.[18]

Coal Production by Coal-Producing Region, 2010

U.S. Total: 1,085.3 Million Short Tons

Note: Totals do not include refuse recovery.
Source: U.S. Energy Information Administration, *Quarterly Coal Report*, October-December 2010 (April 2010).

There are two common types of coal mining: surface and underground. Surface mining takes place where coal seams are relatively shallow, including such practices as strip mining, mountaintop removal and open-pit mining. Underground mining is used to access deeper beds of coal by digging under sedimentary rock using such practices as long-wall and room-and-pillar mining.

Mining for coal, in particular surface mining, typically results in the alteration or outright destruction of large areas of land. These land use changes can result in numerous negative consequences for nearby waterbodies, including altered flow patterns and water pollution from heavy metals and minerals leaching into surface and groundwater supplies.

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[17] http://www.netl.doe.gov/coal/refshelf/ncp.pdf

[18] U.S. DOE, Energy Demands on Water Resources (p. 20).

Mountaintop removal mining in the Southeastern U.S. provides a good illustration of the impacts coal mining can have on our rivers, lakes, streams and groundwater resources. Based on a review of over 30 studies on the effects of mountaintop removal mining in the Appalachian Region encompassing sections of Kentucky, West Virginia, Virginia and Tennessee, the U.S. EPA has found:[19]

In Appalachia, the quest for coal destroyed an estimated 724 miles of streams between 1985-2001 when debris from mountaintop removal mining was dumped into nearby valleys.

- Streams in proximity to mountaintop removal sites show increased mineral concentrations in the water—zinc, sodium, selenium and sulfate—as well as, less diverse and more pollutant-tolerant macroinvertebrates and fish species.
- Forests become fragmented and the regrowth of trees and natural vegetation on reclaimed land is hindered due to soil compacting. Loss of forested lands—currently affecting more than 400,000 acres of watershed in the Appalachian Region—appears to increase soil erosion, decrease stormwater infiltration and increase the probability of flooding.
- Approximately 1,200 miles of headwater streams were directly impacted by mountaintop removal between 1992 and 2002 in the study area. An estimated 724 stream miles were destroyed by valley fills from 1985 to 2001. The elimination or degradation of headwater streams has far reaching impacts due to the role headwaters play in supporting fragile ecosystems and regulating nutrients, water quality and flow quantity downstream.[20]

Acid mine drainage is a common form of water pollution that can result from both surface and underground coal mining. When rain or groundwater comes into contact with sulfur compounds found in the waste rock pulled out of coal mines, sulfuric acid and dissolved iron can form and carry heavy metals and minerals into nearby water supplies. Common impacts from acid mine drainage include iron precipitate forming red, orange or yellow sediments in the bottom of streams, increased levels of sulfate, total dissolved solids, calcium, selenium, magnesium and manganese, as well as, greater electrical conductivity, acidity, sodium and nitrate in nearby waters.[21] The degraded, highly acidic water disrupts ecosystems, can damage structures such as bridges and culverts and make water less habitable, potentially non-potable and unfit for recreational purposes. It has been estimated that between 9,000 and 22,000 miles of streams in the U.S. have been damaged by acid mine drainage as a result of coal mining.[22]

Before coal is transported from the mine to a power plant, it must be processed and washed to remove dirt and impurities. Water requirements for coal preparation vary depending on the condition of the coal coming out of the mine, as well as, the power plant's specific washing requirements. According to the DOE, between 20 and 40 gallons of water are used to wash one ton of coal, or approximately 3.4 to 6.8 gallons of water per MWh of electricity produced.[23] Washing coal creates water contaminated with heavy metals and other pollutants, and if improperly managed, this 'produced water' can end up seeping into groundwater or draining into rivers and lakes where it can devastate wildlife, pose health risks for neighboring communities and degrade recreational areas.

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[19] http://www.epa.gov/region03/mtntop/pdf/mtm-vf_fpeis_summary.pdf (p. 3)

[20] NRDC, Coal in A Changing Climate (p. 8). http://www.nrdc.org/globalwarming/coal/coalclimate.pdf

[21] U.S. EPA: http://ga.water.usgs.gov/edu/wumi.html

[22] NRDC, Coal in A Changing Climate (p. 8). http://www.nrdc.org/globalwarming/coal/coalclimate.pdf

[23] DOE, Energy Demands on Water Resources (p. 55) the calculations use conversions:1 mmbtu = 293.1 kwh; 1 mmbtu = .292997 mwh; 1 gal of water per .292997 mwh = 3.4 gal per mwh; 2 gal of water per .292997 mwh = 6.8 gal per mwh.

On average, water withdrawals for coal mining, washing and processing amount to approximately 58 Gal/MWh of electricity produced.[24] At this rate, approximately 313 million gallons of water are used each day to mine and process coal—enough water to meet the needs of over 1.8 million Americans.[25]

Coal Transportation & Storage

Coal is transported from the mine to the power plant either by freight, which significantly contributes to the carbon intensity of the coal power lifecycle or through coal slurry pipelines, which has the most direct and negative impacts on water resources in the transportation piece of the coal power lifecycle. Slurry pipelines use enormous amount of water, generally requiring a volume of water equivalent to the volume of coal being transported. The largest coal slurry pipeline in the world was the Black Mesa project, which during it's time of operation, transferred 5 million tons of coal per year over a distance of 270 miles between coal mines in Arizona and the Mohave Power Plant in Southern Nevada. Although the pipeline was closed in 2005, when the Black Mesa was in operation, more than 1 billion gallons of water were withdrawn each day from groundwater aquifers in the southwestern desert to transport coal to its destination.[26]

If improperly managed, slurry-storage can pose numerous severe risks to water quality, riparian habitats and the health of neighboring communities.[27] One of the most catastrophic coal-ash slurry spills in the U.S. occurred on December 22, 2008, at the Tennessee Valley Authority's Kingston Fossil Plant.

As a result of improperly stored burn-off ash at the Tennessee plant, a containment dyke burst spilling 5.4 million cubic yards of liquid coal ash—enough to flood more than 3,000 acres up to one foot deep—into the nearby Tennessee River. The spill flowed several miles downstream from the site, destroying houses and rail lines, covering roads and nearby ponds and adding toxins and heavy metals to nearby drinking water supplies.[28]

Electric Power Generation

The process of power generation accounts for more water withdrawal and consumption than any other stage in the coal power lifecycle. Like all thermoelectric power plants, water is used to cool and condense steam. The magnitude of what is withdrawn and consumed is dependent on the type of cooling technology employed at a given power plant. On average (a weighted average taking into account the current mix of cooling technologies being used at coal plants in the U.S.), coal-fired electricity requires the withdrawal of approximately 15,514 gallons and the consumption of 506 gallons of water per MWh for cooling purposes.

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[24] Fthenakis and Kim, 2010. Lifecycle uses of water in U.S. electricity generation

[25] http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html (based on 1,985,801 MMWh of electricity generated by coal in 2008) Assuming 171.8 gallons per capita per day from http://www.aquacraft.com/Publications/resident.htm

[26] Gleick, 1994

[27] DOE, Water Demands on Energy (p. 23).

[28] http://www.tva.gov/emergency/archive/ash_release_1-15-09.pdf

The burning of coal at power plants produces copious amounts of carbon and other emissions which adversely affect the quality of air, water and human health. Coal is a leading contributor to climate change and the most carbon-intensive fossil fuel. With average annual carbon emissions in the U.S. at approximately 2.125 billion metric tons, or about 2,250 pounds of CO_2 emitted for each MWh of electricity produced,[29] coal-fired power plants accounted for approximately 81% of CO_2 emissions attributable to the U.S. electric power sector in 2008.[30]

Table 5.4. Primary Emissions Associated with Coal-Fired Electricity*

Substance	Volume *(lbs/MWh)*	Known Effects
Sulfur Dioxide (SO_2)	13	Linked to acid rain and increased incidence of respiratory illnesses *(Learn more about acid rain, see sidebar below.)*
Nitrogen Oxide (NO_x)	6	Linked to the formation of acid rain and photochemical smog
Carbon Dioxide (CO_2)	2,250	Primary contributor to greenhouse gas emissions and global warming
Mercury (Hg)	.00063	Linked with neurological and developmental damage in humans and other animals.

* http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html

Efforts to reduce carbon and other hazardous greenhouse gas emissions from coal plants through carbon capture and sequestration (CCS) technologies drastically increases the water footprint of coal-fired electricity. Some CCS technologies require the use of significant amounts of additional water to cool and 'scrub' the flue gas as it comes out of cooling towers, while other technologies use water to capture and pump carbon into non-atmospheric reservoirs, such as depleted oil and gas reservoirs and un-mineable coal seams.[31] In addition to significantly increasing water use at the power plant, CCS technologies also lower the power plant's energy output, again increasing the overall water footprint of the electricity produced. When applied to recirculating wet cooling technologies at advanced coal plants, CCS increases the water withdrawal and consumption requirements by nearly seven times, while applying the same technologies to older conventional coal plants can increase withdrawal requirements by nearly fifty times.[32]

ACID RAIN

According to the U.S. EPA, "Acid rain" is a broad term referring to deposited materials from the atmosphere containing higher than normal amounts of nitric and sulfuric acids. Man-made sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_X) resulting from fossil fuel combustion, are a leading cause of acid rain. While natural sources such as volcanoes and decaying vegetation contribute to acid rain, in the United States, roughly 2/3 of all SO_2 and 1/4 of all NO_X come from electric power generation that relies on burning fossil fuels, like coal.*

The ecological effects of acid rain are most clearly seen in aquatic environments, such as streams, lakes and marshes. Approximately 580 streams in the Mid-Atlantic Coastal Plain are acidic primarily due to human-causes. In the New Jersey Pine Barrens, for example, over 90 percent of the streams are acidic, which is the highest rate of acidic streams in the nation. Over 1,350 of the streams in the Mid-Atlantic Highlands (mid-Appalachia) are acidic, primarily due to acidic deposition.

The U.S. EPA has found acid rain causes a cascade of effects that harm or kill individual fish, reduce fish population numbers, completely eliminate fish species from a waterbody and decrease biodiversity. As acid rain flows through soils in a watershed, aluminum is released from soils into the lakes and streams located in that watershed. So, as pH in a lake or stream decreases, aluminum levels increase. Both low pH and increased aluminum levels are directly toxic to fish. In addition, low pH and increased aluminum levels cause chronic stress that may not kill individual fish, but leads to lower body weight and smaller size and makes fish less able to compete for food and habitat.**

* http://www.epa.gov/acidrain/what/index.html
** http://www.epa.gov/acidrain/effects/surface_water.html

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[29] http://www.eia.doe.gov/electricity/page/co2_report/co2emiss.pdf (p. 4)

[30] http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html (Table 11)

[31] http://sequestration.mit.edu/

[32] V. Fthenakis, H.C. Kim. Life-Cucle uses of Water in U.S. electricity Generation (p. 2044).

NATURAL GAS

Natural gas is the second leading fuel source for current electricity production in the United States. According to the EIA, in 2009 roughly 921 million megawatt hours of electricity were generated by natural gas power plants, accounting for approximately 23.3 percent of national energy demand.[33,34] Natural gas is the least carbon intensive fossil fuel.[35] Electricity produced by natural gas emits roughly 40% fewer greenhouse gasses than coal fired power.

Because of a relative abundance of domestic natural gas reserves and an over-capacity of power plants built in the 1990's, natural gas has the potential to rapidly replace coal-generating units.[36] This means that the current fleet of combined-cycle natural gas plants could be more fully deployed without significant additional capital investment. The opening of unused plants to offset coal-fired power production could reduce nationwide CO_2 emissions by over 10%.[37] However, despite potential emissions savings from replacing coal plants with natural gas, the process of extracting natural gas poses numerous risks to fresh groundwater supplies, which should be more fully explored.

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Despite having lower carbon and water intensities than other sources of thermoelectricity, recent trends in shale gas development by means of hydraulic fracturing or "fracking," are posing severe water quality concerns, as known poisonous chemicals are pumped into the ground to release shale gasses.

The upstream natural gas withdrawal and consumption figures reported here exclude hydraulic fracturing, as there is not sufficient data available. Additionally, the electric power generation withdrawal and consumption figures reported in Table 1 (p. 10) assume that approximately 1/3 of the natural gas plants are using single cycle technologies and 2/3 are using combined cycle technologies.[38]

On average, a MWh of electricity generated by natural gas withdraws approximately 6,484 gallons and consumes approximately 172 gallons of water per MWh of electricity produced (see Table 1, p. 10).[39]

The water footprint of natural gas electricity includes the following (see following tables, p. 19):

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[33] http://www.eia.doe.gov/cneaf/electricity/epa/figes1.html

[34] http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html

[35] http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11

[36] A recent study by researchers at MIT found that natural gas-fired power plants only operate "The current fleet of natural gas combined cycle (NGCC) units has an average capacity factor of 41 percent, relative to a design capacity factor of up to 85 percent. However, with no carbon constraints, coal generation is generally dispatched to meet demand before NGCC generation because of its lower fuel price." http://web.mit.edu/mitei/research/studies/release-natural-gas.pdf

[37] http://web.mit.edu/mitei/research/studies/release-natural-gas.pdf

[38] NETL, 2011.

[39] http://www.eia.gov/electricity/annual/archive/03482009.pdf

Table 6.1. Water Footprint of Natural Gas: Upstream*

(Excluding Water Used at the Plant)

Lifecycle Stage	Withdrawal *(Gal/MWh)*	Consumption *(Gal/MWh)*
Extraction/Purification	44	15
Transportation/Storage	14	8
Environmental Control	235	N/A
Total	323	23

* See Appendix A for detailed methodology.

Table 6.2. Water Footprint of Natural Gas: Electric Power Generation*

(Single Cycle Technologies)

Technology	Withdrawal *(Gal/MWh)*	Consumption *(Gal/MWh)*
Once-through	22,692	211
Recirculating Wet	251	424**
Cooling Pond	7,899	111
Weighted Average	14,844	244

* See Appendix A for detailed methodology.
** Realistically, gallons withdrawn should be higher than gallons consumed, however, this shows there is a lack of comparable research data.

Table 6.3. Water Footprint of Natural Gas: Electric Power Generation

(Combined Cycle Technologies)

Technology	Withdrawal *(Gal/MWh)*	Consumption *(Gal/MWh)*
Once-through	11,373	60
Recirculating Wet	288	270
Cooling Pond	59,445	240
Weighted Average	1,170	95

Extraction/Purification

Historically, natural gas was an unwanted byproduct of coal or oil extraction, and today natural gas is typically found in and around other fossil fuel deposits. Extracting natural gas from existing wells, often referred to as enhanced oil and gas recovery, involves pumping air or water into cracks in coal beds to pressurize caverns, bringing the oil or gas to the surface for transport. On average, the conventional mining and processing of natural gas requires approximately 44 gallons of water per MWh of electricity produced.

Non-conventional natural gas extraction called hydraulic fracturing (or fracking), involves the pumping of a mixture of water, sand and chemical additives into the ground which break apart and expand cracks in the ground forcing the gases to rise to the surface.

Approximately 20-40% of fluids injected into the ground during the process of fracking remain in the ground,[40] posing serious threats to current and future drinking water supplies. Many communities who have had gas companies move in and begin fracking operations have complained of contaminated groundwater supply. Some communities even claim that fracking has caused their well-fed tap water to become flammable.

A U.S. EPA draft report investigated groundwater contamination near Pavilion, Wyoming, (a community with over 30 fracking sites in the area). The report findings show that "groundwater samples from deep

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[40] http://www.earthworksaction.org/FracingDetails.cfm

wells contained traces of methane, dissolved hydrocarbons, diesel range organics, glycols, alcohols and low molecular weight acids. Additionally, high concentrations of benzene, xylenes, gasoline range organics, diesel range organics and total purgeable hydrocarbons were detected in groundwater from shallow well monitoring, and the report states that "surface pits (used for storage of storage/disposal of fracking waste fluid) are a source of shallow groundwater contamination in the area of investigation."[41]

Electric Power Generation

As with other thermoelectric fuel sources, the majority of the water used in the natural gas electricity lifecycle is at the power plant for cooling steam produced by burning gas. Depending on the technologies employed within a natural gas fired power plant, water withdrawal and consumption rates can vary largely. On average, natural gas facilities employing single cycle technologies use approximately 14,844 gallons per MWh, while facilities using combined cycle technologies use approximately 1,170 gallons per MWh. Based on the current prevalence of single cycle and combined cycle technology in the U.S., we estimate that an average megawatt hour of electricity generated by natural gas requires water withdrawals of 1,616 gallons and consumes 149 gallons of water.

NUCLEAR

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Nuclear power may be a relatively carbon neutral source of electricity, but it consumes more water than coal fired power and poses substantial risks to water quality.

Nearly 25% of the world's nuclear reactors are located in the U.S., making it the world's leading producer of nuclear power with a net generation of approximately 799 million MWh in 2009.[42] Nuclear power supplies roughly 20% of U.S. electricity demand, accounting for the third largest share of power generation in the nation behind coal and natural gas.[43]

Nuclear power generation emits essentially zero carbon or other greenhouse gasses, making this source a much cleaner option than fossil fuels from a climate change perspective.[44] However, there is likely other hidden greenhouse gas intensive processes in the nuclear power lifecycle (before the power plant operations) in which information and reporting is not readily available. Despite the low emissions benefits, nuclear power has its own downfalls. Nuclear power uses highly radioactive and dangerous fuel to generate electricity, creating the problem of proper radioactive waste storage. Another downfall to nuclear power is that it is one of the largest single users of water in the energy industry.

Similar to coal-fired power plants, nuclear power plants traditionally operate with single-cycle cooling technologies, which are systematically more water intensive than all other thermodynamic cooling technologies. Additionally, because nuclear fission is less thermodynamically efficient than the combustion of coal, the water required to generate nuclear power is slightly greater than that of coal-fired power.

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[41] EPA draft report *Investigation of Ground Water Contamination Near Pavilion, Wyoming* (p. xi).

[42] http://www.eia.doe.gov/cneaf/nuclear/page/nuc_generation/gensum2.html

[43] http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html, http://www.eia.doe.gov/cneaf/electricity/epa/figes1.html, http://www.eia.doe.gov/cneaf/nuclear/page/operation/statoperation.html

[44] http://www.eia.doe.gov/cneaf/nuclear/page/analysis/ghg.pdf (p. 4)

On average (weighted average by mix of technologies employed), over the full lifecycle, nuclear power withdraws approximately 14,881 gallons and consumes 572 gallons of water per MWh (see Table 1, p. 10).[45]

The water footprint of nuclear powered electricity includes the following:

Table 7.1. Water Footprint of Nuclear: Upstream*
(Excluding Water Used at Plant)

Lifecycle Stage	Withdrawal *(Gal/MWh)*	Consumption *(Gal/MWh)*
Mining/Processing	66	19
Plant Construction	8	3
Spent Fuel Disposal	5	N/A
Total	79	40

* See Appendix A for a detailed methodology.

Table 7.2. Water footprint of Nuclear Electric Power Generation*

Cooling Technology	Withdrawal *(Gal/MWh)*	Consumption *(Gal/MWh)*
Once-through	37182	268
Cooling Pond	806	674
Wet Tower *(recirculating wet)*	1030	762
Total *(weighted average by cooling type)*	14,732	532

* See Appendix A for a detailed methodology.

Extraction/Processing

Uranium, the chemical element used as a fuel source in nuclear power plants, is extracted at 20 locations in the U.S., primarily in and around the states of Wyoming, Colorado, Utah, Arizona, New Mexico and Texas.[46] On average, uranium mining and processing requires the withdrawal of approximately 66 gallons and the consumption of 19 gallons of water for each kilowatt hour of electricity produced (see Table 7.1).

Uranium mining results in large amounts of slurry or produced water. With interest in nuclear power growing in recent years, older uranium mines in New Mexico and Utah are considering reopening. If reopened, these mines could generate between 3 and 5 million gallons of contaminated ‘slurry’ water each day that must be properly handled and disposed of.[47] Although, upon extraction uranium ore is not highly radioactive, the disposal of uranium slurry must be meticulously regulated, as any amount of radioactive material requires a very long time (several thousands of years in some cases) to decay. Improper disposal of radioactive materials can lead to seepage into waterways and pose serious threat or death to plant,

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[45] http://www.eia.gov/electricity/annual/archive/03482009.pdf
[46] http://www.eia.gov/cneaf/nuclear/page/reserves/ures.html
[47] DOE, Energy Demands on Water Resources (p. 56).

animal and human life. Historically, the disposal of mining slurry (coal, uranium, oil, gas) has typically been into nearby bodies of water, or buried in the ground.[48]

Electric Power Generation

Much like electricity generated from fossil fuels, nuclear power is produced through a similar thermodynamic process of heating water to create steam which spins a turbine attached to a generator. In place of using fossil fuels, nuclear power plants use refined uranium as a fuel source, essentially harnessing the power of controlled nuclear explosions through a process called 'nuclear fission' to generate electricity. As uranium undergoes nuclear fission within a reactor, uranium atoms split, giving off heat and creating new, highly-radioactive isotopes and elements.[49]

The fission of uranium for nuclear power generation is not greenhouse gas intensive, with essentially zero CO_2 emissions at the nuclear reactor. However, there are carbon and other emissions in other stages of the nuclear power lifecycle (uranium mining, processing, transportation and environmental control), although such information is not readily available. Despite apparent greenhouse gas emissions benefits, nuclear power comes at a greater cost to our nations water resources. More water is typically needed for cooling nuclear power plants than other fossil fuels, requiring an average water withdrawal of 14,731gallons of water for each MWh of electricity produced and consumes 532 gallons.

To maintain optimum efficiency levels in the nuclear reactor, spent uranium must be replaced regularly, creating the problem of vast quantities of radioactive waste that must be disposed of. As the U.S. EPA states, "the safe disposal of this waste is one of the most controversial environmental subjects facing the federal government and affected states."[50] Spent fuel is both thermally hot and highly radioactive with a decay period between 30 and 250,000 years, so the waste must be handled with extreme care. Spent radioactive waste is typically stored onsite at the plant, putting adjacent communities and waterways at risk of radioactive contamination.

Radioactive Waste Storage

After a few years of being in the nuclear reactor, the uranium is moved into cooling ponds (adding another water intensive process to the nuclear power lifecycle) before it is moved to dry storage casks. Spent fuel is stored under water not only to remove heat from the radioactive materials, but it must be buried under enough water to shield plant operators from contact with radiation.[51] According to the Union of Concerned Scientists, over 400 accidental leaks have occurred at nuclear plants in the United States, some spills involving millions of gallons of radioactively contaminated water, and some remaining undetected for years. Accidental leaks have occurred at nearly every nuclear plant in the country.[52]


© AFP/Getty Images

The recent meltdown at the Fukushima nuclear plant in Japan and the desperate effort to prevent it by using water cannons provided a compelling reminder of how vital water is to cooling power plants.

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[48] Uranium Mining & Milling: the Need, the Processes, the Impacts, the Choices: Administrator's Guide (p. 3:59).

[49] http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/radwaste.pdf (p. 1)

[50] http://www.epa.gov/rpdweb00/docs/radwaste/402-k-94-001-snf_hlw.html

[51] http://www.epa.gov/rpdweb00/docs/radwaste/402-k-94-001-snf_hlw.html

[52] http://www.ucsusa.org/assets/documents/nuclear_power/nuclear-power-radioactive-releases.pdf (p. 2)

As some elements in spent nuclear fuel remain dangerously radioactive for several thousands of years, permanent storage facilities must be established to isolate the waste and protect public health and safety and the environment for at least one million years.[53] Until an agreement is made on the approval of an appropriate, safe and permanent radioactive nuclear waste storage facility, spent radioactive waste remains on site of many nuclear plants, posing potential threats to local waterways and communities. Despite the energy industry's attempts to play down the health effects attributable to nuclear spills, even low radioactive exposure can prove highly detrimental, especially to children and elderly.

Both nuclear power generating facilities and radioactive waste storage units are highly vulnerable to extreme weather events and natural disasters, and the risks are exacerbated by being next to large bodies of water. The world saw just how devastating the vulnerabilities of nuclear facilities can be on March 11, 2011, when a 9.0 magnitude earthquake and a 45-foot high tsunami moving over 500 mph ripped through Japan, crippling the Fukushima Dai-Ichi nuclear plant. These events left the plant's cooling towers without power, causing hydrogen explosions within the facilities, ultimately requiring immense amounts of water to be manually sprayed into the facilities in order to prevent an all-out power plant meltdown.[54] While nearly 200,000 Japanese residents were relocated to avoid potentially fatal radioactive exposure, highly potent radioactive contaminants quickly made their way into ground and ocean waters and soil as far as 25 miles away from the site—pollution that will undoubtedly affect the livelihood of the region for years to come.[55]

HYDROPOWER

In 2009, conventional hydropower generated approximately 273.5 million MWh of electricity per year, comprising nearly 7% of overall production.[56] More than half of the nation's hydroelectric capacity is located in Oregon, Washington and California.[57]As shown in Chart 2 (p. 11), the water footprint of hydropower is an order of magnitude greater than coal or nuclear electricity.

The National Renewable Energy Laboratory estimates that hydroelectric facilities used 3.16 trillion gallons of water per day in 1995—20 times the volume of water that passes through thermoelectric power plants and 2.6 times the average annual runoff in the lower 48 states.[58] This "in-stream use" involves storing water behind a dam and diverting it through a penstock and turbine to produce hydroelectricity. On average, approximately 5.1 million gallons of water goes through a hydro

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Every day, approximately 9 billion gallons of water—enough to meet the daily demands of more than 50 million Americans—evaporates from reservoirs behind hydroelectric dams such as those on the Colorado, Columbia and Snake Rivers.

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[53] http://www.epa.gov/ocir/hearings/testimony/110_2007_2008/2008_0715_rjm.pdf

[54] http://www.nytimes.com/2011/03/30/world/asia/30japan.html?_r=4&pagewanted=2

[55] http://www.businessweek.com/ap/financialnews/D9M59PR00.htm

[56] http://www.eia.gov/electricity/annual/archive/03482009.pdf

[57] http://www.eia.doe.gov/electricity/page/co2_report/co2report.html

[58] With regards to how hydropower use can exceed average annual runoff, USGS notes: "It is possible for the hydroelectric power water use to exceed average annual runoff because some water is used several times as it passes through several hydroelectric dams on a river." http://water.usgs.gov/watuse/pdf1995/pdf/circular1200.pdf (p. 54)

plant for every MWh of electricity produced. Much like water used for thermoelectric cooling, water behind dams is affected by thermal gain, reduced water quality, and loss of aquatic biodiversity. In total, approximately 9 billion gallons of water evaporates behind hydroelectric facilities per day, enough water to meet the daily demands of over 50 million Americans.[59,60] While most of the water used to power turbines in hydro facilities remains in the river system, about 18,000 gallons evaporate from the surface of reservoirs per MWh. This report discounts the water consumed for hydroelectricity in the most recent study (NREL, 2006) by 50% because the reservoirs studied serve multiple purposes such as irrigation, water supply, flood management and recreation.[61]

The overall water footprint of hydroelectricity includes the following:

Table 8.1. Water Footprint of Hydropower*

Water Use *(Gal/MWh)***	Consumption *(Gal/MWh)*
440,000	9,000

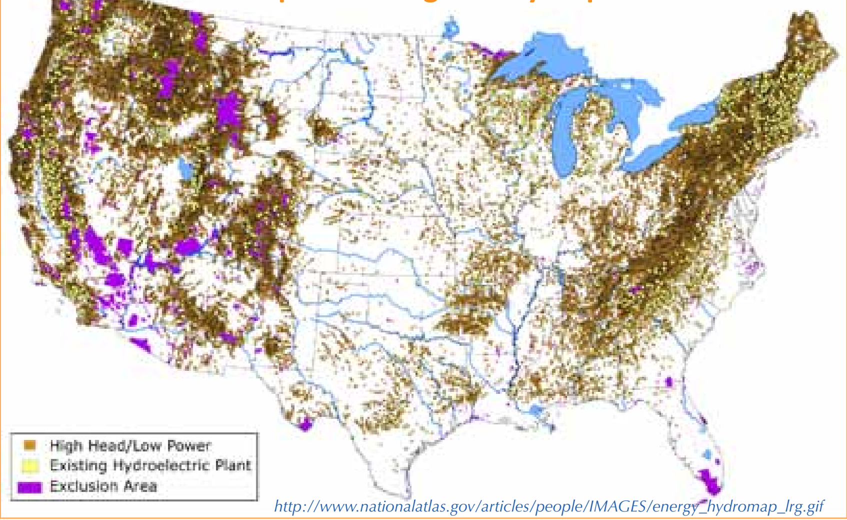
* See Appendix A for a detailed methodology.
** Assumes 3.16 trillion gallons of water withdrawn per day for hydropower production (http://water.usgs.gov/watuse/pdf1995/pdf/circular1200.pdf (pg. 54) and approximately 700,000 MWh of electricity generation per day in 2008 (http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html).

Table 8.2. Water Consumption in Hydropower Reservoirs by Region*

Region	Gallons per MWh
Western	12,400
Eastern	55,100

* http://www.nrel.gov/docs/fy04osti/33905.pdf (p. 4)

Map of Existing U.S. Hydropower Plants



http://www.nationalatlas.gov/articles/people/IMAGES/energy_hydromap_lrg.gif

Dam Construction & Electric Power Generation

Conventional hydroelectricity requires building dams or large structures to divert river flow through turbines. The generation capacity of a hydroelectric facility and its overall impacts on the surrounding environment varies geographically with temperature and typography. In general, the Western United

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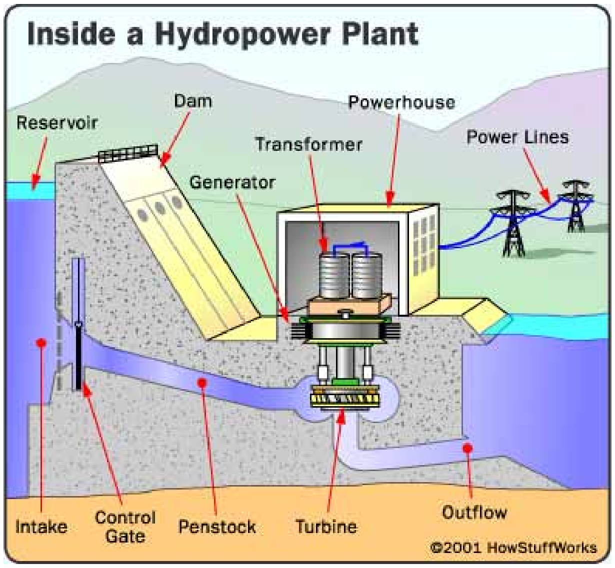
[59] An evaporative consumption of 9 billion gal/day assuming corroborates with an estimation by the Army Corps of Engineers at approximately 9.1 billion gal/day; http://www.nrel.gov/docs/fy04osti/33905.pdf (p. 3)

[60] Assuming a personal water consumption of 171.8 gallons per person per day as taken from http://www.aquacraft.com/Publications/resident.htm,; 9,000,000,000 (gallons/day) / 171.8 (gallons/person/day) = 52,386,500 people.

[61] "There is no easy way to disaggregate on a national level the end uses for hydroelectric dam water into irrigation, flood control, municipal water, and thermoelectric power plant cooling." NREL, 2003. http://www.nrel.gov/docs/fy04osti/33905.pdf (p. 2)

States has deeper reservoirs while the Central and Eastern United has shallower reservoirs. As shown in Table 8.2, there is evidence that hydropower facilities in the Western U.S. consume approximately 77% less water per MWh generated than those in Eastern states.



While hydropower facilities are widely assumed to produce carbon-free electricity, the reservoirs created behind dams can be a source of greenhouse gas emissions.[62] Flooding a region to create a reservoir causes the decomposition of vegetation and soils beneath the reservoir, as well as, debris and other plant-life which flow into the reservoir. Studies have shown that in tropical regions—where water temperatures are much warmer allowing for faster decomposition—the carbon and methane emissions associated with decomposition in the reservoir can be between 3 and 54 times the amount of emissions associated with a typical thermoelectric plant generating the same amount of electricity.[63] With a carbon footprint of this magnitude, it has been estimated that hydropower reservoirs could be responsible for approximately 4% of human-caused global warming.[64]

In addition to being a potential source of greenhouse gas emissions, hydropower facilities create an array of other environmental problems. Building hydroelectric facilities drastically alters the ecology of our nation's rivers. Fish and other aquatic wildlife can become trapped or blocked by dams and have their natural migration habits and breeding patterns disrupted—as in the case of species that migrate between oceans and freshwater, such as eels and salmon.[65] Flat-water reservoirs have significantly higher temperatures than free-flowing rivers, and much higher rates of evaporation, or consumption, than naturally flowing rivers. Attributing just half of this evaporation to hydroelectric use makes hydropower the most water consumptive of all major electricity sources (see Table 1, p. 10).

There are a number of strategies that can be employed to limit environmental harm from hydropower facilities. Older, outdated dams—which often generate electricity inefficiently or do not generate any at all—can be deconstructed, allowing for the restoration of the river's natural habitat. Outdated hydropower plants can often be upgraded to improve electric generation efficiency. For example, the Cheoah Dam in Robbinsville, North Carolina recently upgraded its equipment by replacing the oldest units with new high-efficiency turbines, generators and transformers that will allow the facility to produce over 28% more power than before, without increasing water impacts.[66] There are also opportunities to add turbines to dams built for flood control, recreation or other purposes.

There are also low impact, run of the river and micro-hydroelectric technologies that can minimize impacts on aquatic ecosystems. For more information on advance hydropower technologies visit the DOE's Hydropower Research and Development program: http://www1.eere.energy.gov/windandhydro/hydro_rd.html.

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[62] http://www.internationalrivers.org/en/node/383
[63] http://www.internationalrivers.org/en/node/383
[64] http://www.internationalrivers.org/node/1398
[65] http://www.sandia.gov/energy-water/docs/121-RptToCongress-EWwEIAcomments-FINAL.pdf (p. 23)
[66] http://apps1.eere.energy.gov/news/progress_alerts.cfm/pa_id=392

Hydropower is popularly misunderstood as both a renewable energy source and low-carbon. While water is a renewable natural resource, healthy aquatic ecosystems are not. And while hydropower dams do not burn fossil fuels, their total lifecycle carbon emissions are greater than other renewables. Recent research of Canadian dams indicate that "in addition to any indirect emissions from facility construction, newly flooded boreal reservoirs may emit CO_2 at a rate close to 32 to 63% that of the least emitting natural gas plant.[67] Even higher carbon emissions are expected for dams in tropical forests.

GEOTHERMAL

If you have ever had the pleasure of taking a dip in a natural hot spring, then you've experienced first-hand the powers of geothermal energy. As the Earth's core holds a constant, staggeringly hot temperature, heat may be extracted from deep underground and converted into electricity using steam turbines.

© Brian Suda, Flickr Creative Commons

Most geothermal technologies do not require extensive use of freshwater resources. However, the impacts of such development should be reviewed on a site-specific basis.

With a current capacity of approximately 3,100 Megawatts, the United States is the leading producer of geothermal power, accounting for about 30% of installed geothermal power worldwide.[68] Currently identified, but untapped, geothermal resources could provide nearly 23,000 MW of power for 30 years in the United States, while undiscovered resources could provide as much as five times that amount according to the National Renewable Energy Laboratory.[69]

As fuel combustion is not required to produce geothermal electricity the way it is for thermoelectricity, greenhouse gas emissions at geothermal power plants are negligible—comparable to wind and PV solar power.[70] The water use associated with any geothermal electric plant is specific to the technology used by the plant. Of the primary technologies, geopressured power plants and geothermal flash power plants consume the least water and Enhanced Geothermal Systems (EGS) have the highest potential for freshwater use.[71]

On average (weighted average by mix of technologies employed), geothermal electricity withdraws and consumes approximately 700 gallons of water for every MWh of electricity produced.

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[67] William Steinhurst, et al; Hydropower Greenhouse Gas Emissions State of the Research, 2012.

[68] http://www.geo-energy.org/pdf/reports/GEA_International_Market_Report_Final_May_2010.pdf

[69] http://www.nrel.gov/docs/fy00osti/28204.pdf (p. 2)

[70] http://www.epa.gov/cleanenergy/energy-and-you/affect/non-hydro.html#footnotes

[71] Corrie Clark, et al., Life Cycle Environmental Impacts of Geothermal Systems, Argonne National Laboratory, 2012.

The water footprint of geothermal electricity includes the following:

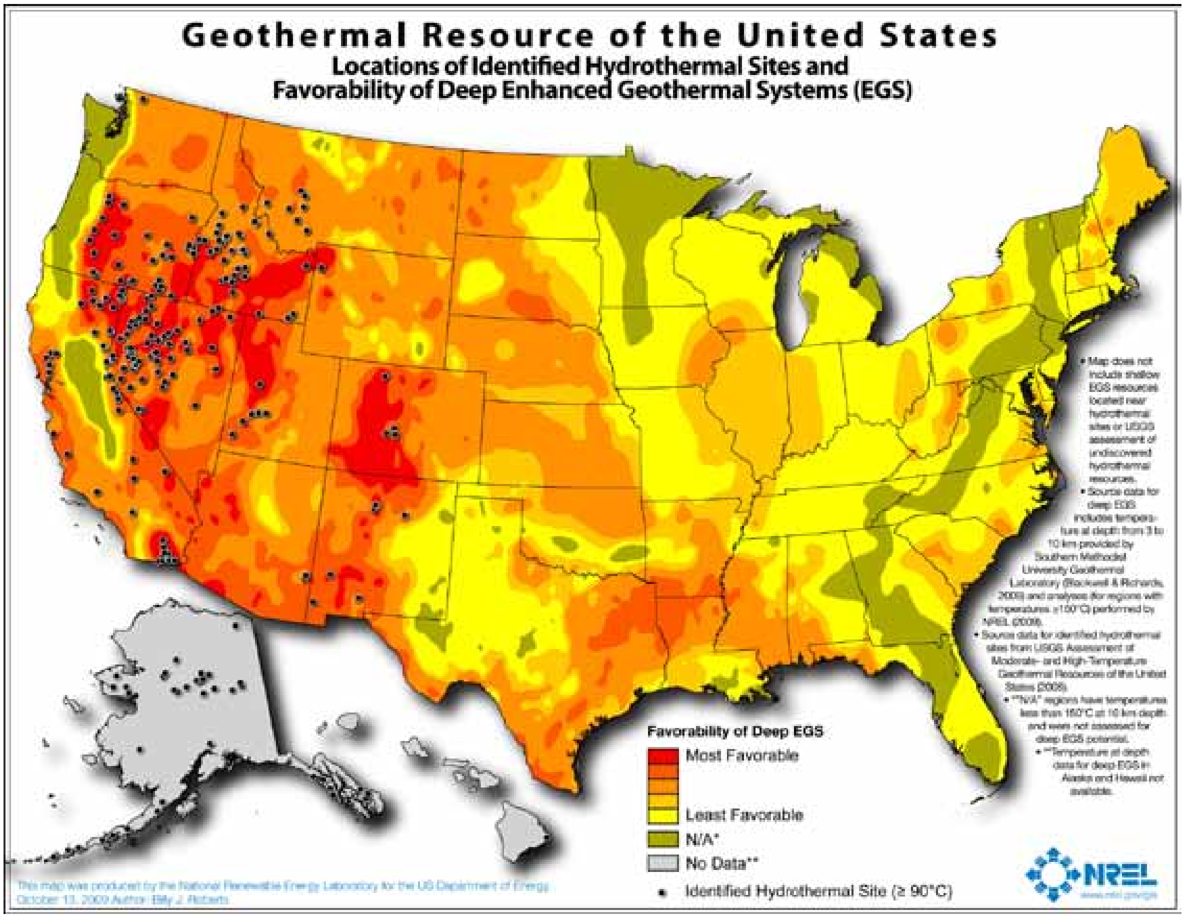
Table 9.1. Water Footprint of Geothermal-Electricity Generation*

Technology	Withdrawal *(Gal/MWh)*	Consumption *(Gal/MWh)*
Tower	2,555	2,555
Dry	492	492
Hybrid	814	814
Weighted Average**	700	700

* See Appendix A for methodology.
** Weighted average based on Harvard 2010 figures.

Extraction

The availability for the extraction of geothermal resources varies by geologic location. Historically, this underground heat source was mostly only accessible where cracks in the earth had already been established such as at tectonic plate fault lines. New technologies have significantly expanded the geographic accessibility of geothermal heat, allowing for the use of direct use heat wells and residential heat pumps across most of the western United States.[72]



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[72] http://www1.eere.energy.gov/library/pdfs/geothermal_energy_power_from_the_depths.pdf (p. 6)

Extraction of geothermal heat from the earth, involves pumping water or air deep into wells or cracks in the earth causing the heated water or steam rises to the surface where it can be converted into electricity. As liquid and gases are removed from underground, replacement fluids must be pumped back into the ground through a separate injection well to help replenish the reservoirs and maintain pressure underground to prevent a sinking of the land at the surface.

Electricity Generation

The most common geothermal electricity generation technology used is a flash steam power plant. With this technology, as hot water and steam are pumped out of the ground, it is sent through a flash tank where pressure is significantly lowered, turning the water content to steam which propels a turbine attached to a generator. Geothermal power plants can operate 24 hours a day, allowing them to serve as a great base-load electricity source. Additionally, as geothermal plants are active approximately 95-99% of the time, they are also much more efficient than coal and nuclear power plants which are in operation approximately 60-70% of the time.[73]

Other applications for geothermal power include direct use and residential heat pumps. Direct use typically involves using a well to extract heated water between approximately 68-302 degrees Fahrenheit which can go directly into piping for use. The hot water can also be pumped through a heat exchanger to deliver heat to a desired space, such as greenhouses, fish hatcheries, resorts and spas, district heating projects and even some industrial projects.[74] Conversely, these heat pumps can be used for space cooling during summer months, pulling the heat out of a desired space and converting it to heated water that can be stored in underground wells. Geothermal heat pumps used for space heating and cooling, use approximately 30-60% of the electricity requirements in comparison to traditional heating and cooling systems.[75]

PHOTOVOLTAIC (PV) SOLAR

Photovoltaic (PV) solar power converts sunlight directly into electricity using semiconductors, typically made from purified crystallized silicon or other "thin-film materials." PV solar systems require approximately less than three tenths of one percent of the water consumption requirements to produce one Megawatt hour of electricity than coal fired power, and result in significantly fewer greenhouse gas emissions over the entire electricity generation lifecycle. According to the U.S. Department of Energy, "*Producing electricity with photovoltaics emits no pollution, produces no greenhouse gases and uses no finite fossil-fuel resources. The environmental benefits of PV are great.*"[76]


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PV Solar is both one of the cleanest and least water intensive sources of electricity available.

From a water and greenhouse gas emissions perspective, PV solar power is one of the best technologies available. Virtually

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[73] http://www.nrel.gov/docs/fy00osti/28204.pdf (p. 3)

[74] http://www1.eere.energy.gov/library/pdfs/geothermal_energy_power_from_the_depths.pdf (p. 6)

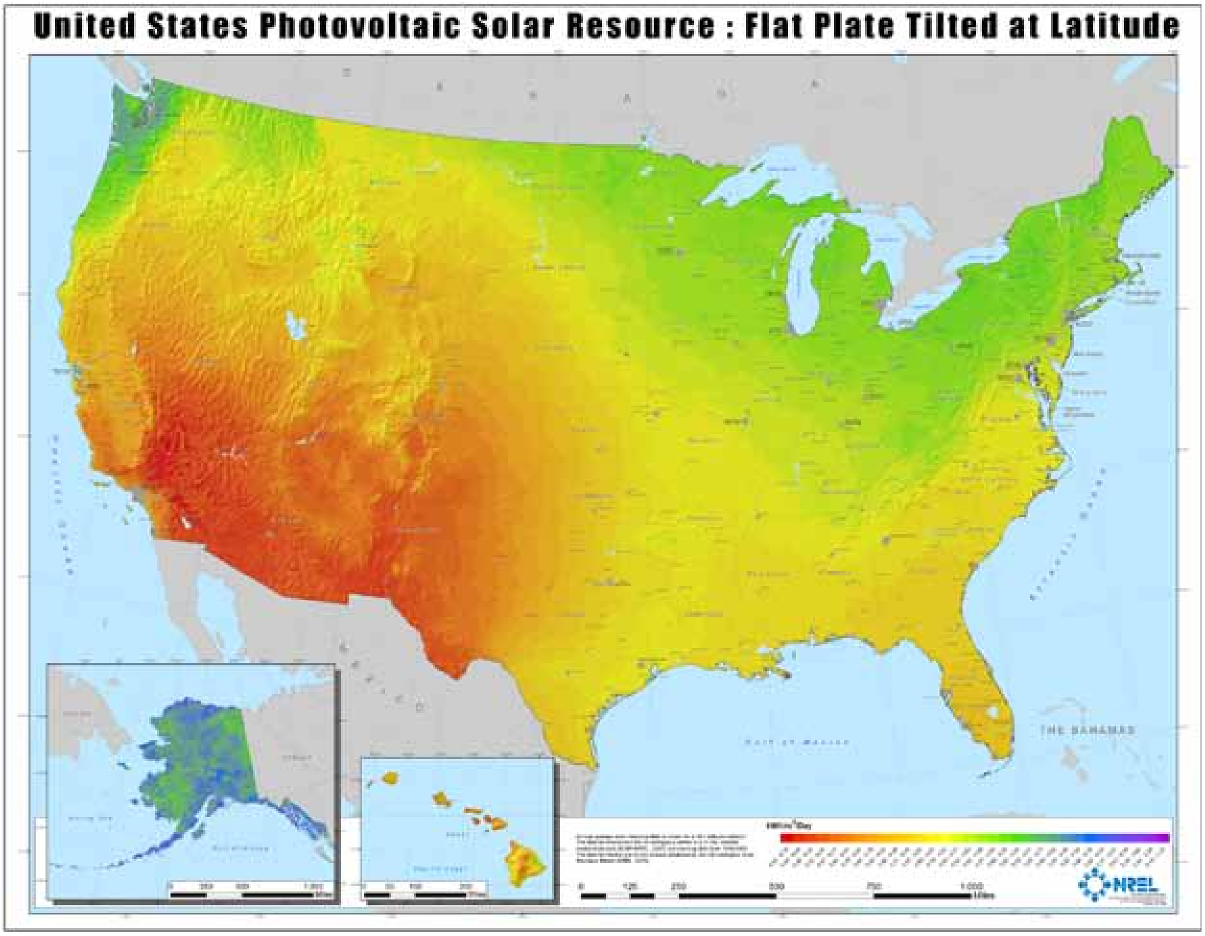
[75] http://www1.eere.energy.gov/library/pdfs/geothermal_energy_power_from_the_depths.pdf (p. 7)

[76] http://www.nrel.gov/docs/fy04osti/35489.pdf

the only use of water during the lifecycle of PV solar is the panel manufacturing process. Upon installation, the generation of Photovoltaic solar electricity operates essentially without any resource requirements other than a negligible amount of water used to occasionally wash dust and debris off panels. On average, approximately 2 gallons of water is consumed for each Megawatt hour of electricity produced.

The energy payback period for PV solar systems—which refers to the time it takes for a solar panel to produce an amount of energy equivalent to the energy it took to construct the panel—is between one and four years. Over the approximately 30 year lifespan of a typical PV solar system, the system will generate roughly 9 to 17 times the amount of energy used to produce it. As research and development continues in this emerging industry, the payback period of PV technologies will likely become even more rapid in the future.[77]

Photovoltaic solar power is currently the fastest growing source of clean and renewable electricity, growing globally at an average rate of 60% *per year* between 2004 and 2009—increasing 100-fold since 2000.[78] As shown in the image below, the United States has ample solar resources, especially in the Southwest where water supply issues are of particular concern. Because generating electricity from solar panels uses far less water than conventional technologies, large-scale deployment of PV solar could massively reduce strain on water supplies.



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[77] http://www.ecotopia.com/Apollo2/knapp/PVEPBTPaper.pdf (p. 1)
[78] http://www.ren21.net/globalstatusreport/REN21_GSR_2010_full.pdf (p. 19)

Although solar power is currently among the most expensive energy technologies available at a levelized cost of $396.10 per megawatt hour, advancements in research and development, economies of scale and a price on carbon emissions will very likely bring down costs of PV solar systems, making them more cost-competitive with traditional electricity sources.[79]

PV solar systems also offer a large degree of flexibility. They can be used for utility-scale centralized power plants, as well as, smaller-scale distributed applications, such as residential or commercial rooftop arrays, remote street signs, lighting or monitoring equipment, and as a portable power supply for transportation or mobile devices.

On average, over the full lifecycle, PV solar power withdraws approximately 231 gallons and consumes approximately 2 gallons of water for every MWh of electricity produced.

The water footprint of PV solar power includes the following:

Table 10.1. Water Footprint of PV Solar*

Lifecycle Stage	Withdrawal *(Gal/MWh)*	Consumption *(Gal/MWh)*
Manufacture	229	N/A
Electric Power Generation	2	2

* See Appendix A for methodology.

Manufacturing and Installation

The manufacture and assembly stage of PV solar systems is the most resource intensive phase of the lifecycle, withdrawing approximately 230 gallons of water for each Megawatt hour of electricity produced. Water consumption factors for this stage are currently indeterminate as rates of water recycle and reuse within manufacturing facilities is not available. As the production and installation processes of solar panels are typically powered by grid electricity, these stages result in essentially the only greenhouse gas emissions and water use throughout the entire lifecycle of PV solar electricity production.

Electric Power Generation

Once a solar panel is manufactured and installed, virtually zero greenhouse gases are emitted and only a very small volume of water is consumed for washing panels throughout the estimated 30 year panel lifespan. A recent peer-reviewed study found that at least 89% of the greenhouse gas and other air emissions associated with electricity production could be prevented by displacing electricity from the grid with PV solar power. To put it another way, a rooftop solar system that can meet half of a household's electricity use would avoid conventional power plant emissions of more than half a ton of sulfur dioxide, one-third a ton of nitrogen oxides and 100 tons of carbon dioxide emissions.

According to Dr. Vasilis Fthenakis of the Department of Energy Sciences and Technology at Brookhaven National Laboratory and the Center for Lifecycle Analysis at Columbia University, the water consumption rate for cleaning solar panels is approximately 2 gallons of water for each MWh of electricity produced. However, the actual volume of water required for washing PV solar arrays depends largely on the location of where the system is installed, taking into consideration the amount of dust or

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[79] http://www.eia.doe.gov/oiaf/aeo/electricity_generation.html

debris that may be blown onto the panels and the frequency of rainfall (as rainfall can clean the panels).

Just like grime on a residential window can limit the amount of light that enters a house, dust on solar panels can reduce the amount of light reaching the semiconductor to produce energy. As reported by Dr. Malay K. Mazumder from the University of Arkansas at Little Rock, a dust layer one-seventh of an ounce per square yard decreases the amount of electricity produced by certain types of solar panels by 40%. Most manufacturers assume solar panels will only have to be washed a couple times per year. However, in some dryer, dustier locations such as the arid southwest, panels may have to be washed more frequently to maintain optimal solar conversion rates.

CLEANING PANELS WITHOUT WATER:

A technology called an electro-dynamic dust shield can remove dust without any water by sending a small electronic pulse through a transparent layer on the surface of the panel. The technology was first developed by NASA and was recently used to clean dust from the Mars Rover.

Although the water required for solar panel cleaning is drastically less than the water required to cool thermal power plants, many locations that are prime for PV solar development are also facing water scarcity, implying that even small water demands from PV solar plants could have a significant impact on water availability. New technologies or practices will likely obviate the need to use water for cleaning solar panels in the future. Despite the minimal water currently needed to wash panels, water requirements for PV solar are *significantly* less than traditional sources of electricity such as coal, nuclear and natural gas. Therefore, a massive deployment of PV solar power stations throughout the U.S. to offset power produced by other, more water intensive power sources can *drastically* reduce pressure on the nation's water supplies.

CONCENTRATING SOLAR THERMAL (CST)

Unlike traditional thermoelectric power plants that burn fuel to generate electricity, concentrating solar thermal (CST) technologies harness the energy of the sun using large arrays of reflective materials to heat a fluid to create steam which spins a turbine—making CST power generation essentially carbon free.[80] There are four primary CST technologies—parabolic trough, linear Fresnel, power tower and dish/engine—each system with different water requirements for cooling and cleaning needs (see Table 11.1).


Courtesy of Sandia National Laboratories

In terms of water footprints, not all solar power is created equal. Photovoltaic (PV) solar uses hardly any water, but concentrating solar arrays, like the power tower arrays pictured above, consumes as much—or even more—water for cooling than some coal and nuclear plants.

The U.S. has had nine CST plants in operation in the Mojave Desert over the last 20 years—all parabolic trough designs—with a combined generating capacity of 354 megawatts.[81] In 2010, the Department of Interior approved permits for the construction of five new CST plants on public lands, four in California and one in Nevada, one of which—the Blythe Solar Project—will be the largest CST station in the world with a generational

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[80] http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html

[81] DOE, Water Demands of Energy (p. 67)

capacity of approximately 1,000 megawatts.[82,83] If CST power capacity is to be significantly expanded in the future as a means of clean, renewable and water efficient power, future utility scale systems should be designed to include dish/engine cycles or dry cooling technologies as a means to significantly reduce the water footprint of electricity produced.

On average (weighted average by mix of technologies employed), concentrating solar power withdraws and consumes approximately 800 gallons of water for every MWh of electricity produced.

The water footprint of concentrating solar power includes the following:[84]

Table 11.1. Water Footprint for Different CST Technologies* *(Recirculating Wet Cooling)*

Technology	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*
Parabolic Trough	800	800
Linear Fresnel	1000	1000
Power Tower	625	625
Dish/Engine	20	20

* http://www1.eere.energy.gov/solar/pdfs/csp_water_study.pdf (p. 17)

Electric Power Generation

There are currently four primary plant designs for concentrating solar thermal power: parabolic trough which consumes approximately 800 gallons of water per MWh of electricity produced; linear Fresnel, consuming approximately 1000 gallons per MWh; power tower, consuming an average of 625 gallons of water per MWh; and dish/engine, consuming only 20 gallons per MWh. Currently in the U.S, only parabolic trough solar thermal systems operate at the utility scale, producing approximately 400 MW of electricity generating capacity.

Despite a relatively high water demand in comparison to other renewable energy sources, concentrating solar thermal power has the potential to cost effectively supply large amounts of clean and renewable energy. Many of the water concerns associated with solar thermal are already being addressed through the use of reclaimed or integrated water, or by adopting dry or hybrid cooling technologies. For instance, regulators in California recently approved several of the first large scale solar thermal plants in two decades after power plant developers agreed to use dry cooling technologies for one of the projects, and use recycled water from a wastewater treatment plant that will be piped over from neighboring communities for another project, rather than relying on the already severely limited water supply of the Mojave Desert.

On page 33 are descriptions of the different concentrating solar technologies as described by the Department of Energy in a report to congress, ‘Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation.’

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[82] http://www.doi.gov/news/pressreleases/Salazar-Approves-Fifth-Solar-Project-on-Public-Lands.cfm
[83] http://www.blm.gov/wo/st/en/info/newsroom/2010/october/NR_10_25_2010.html
[84] Upstream water use data is not available for concentrating solar power technologies.

PARABOLIC TROUGH

Parabolic trough systems concentrate sunlight onto a receiver tube located near the center of a parabolic curved, trough-like reflector. A receiver tube contains a heat transfer fluid which collects heat from the sun to generate steam to spin a turbine like a traditional thermoelectric power plant. Parabolic trough systems can also be equipped to burn natural gas when the sun isn't shining, or use thermal storage, so that power is available to meet utility peak load requirements. As with any thermoelectric plants, the exhaust steam has to be cooled, consuming about 800 gallons of water per MWh for cooling with a dry system. The condensers can be either water-cooled or air-cooled, or a hybrid combination.

LINEAR FRESNEL

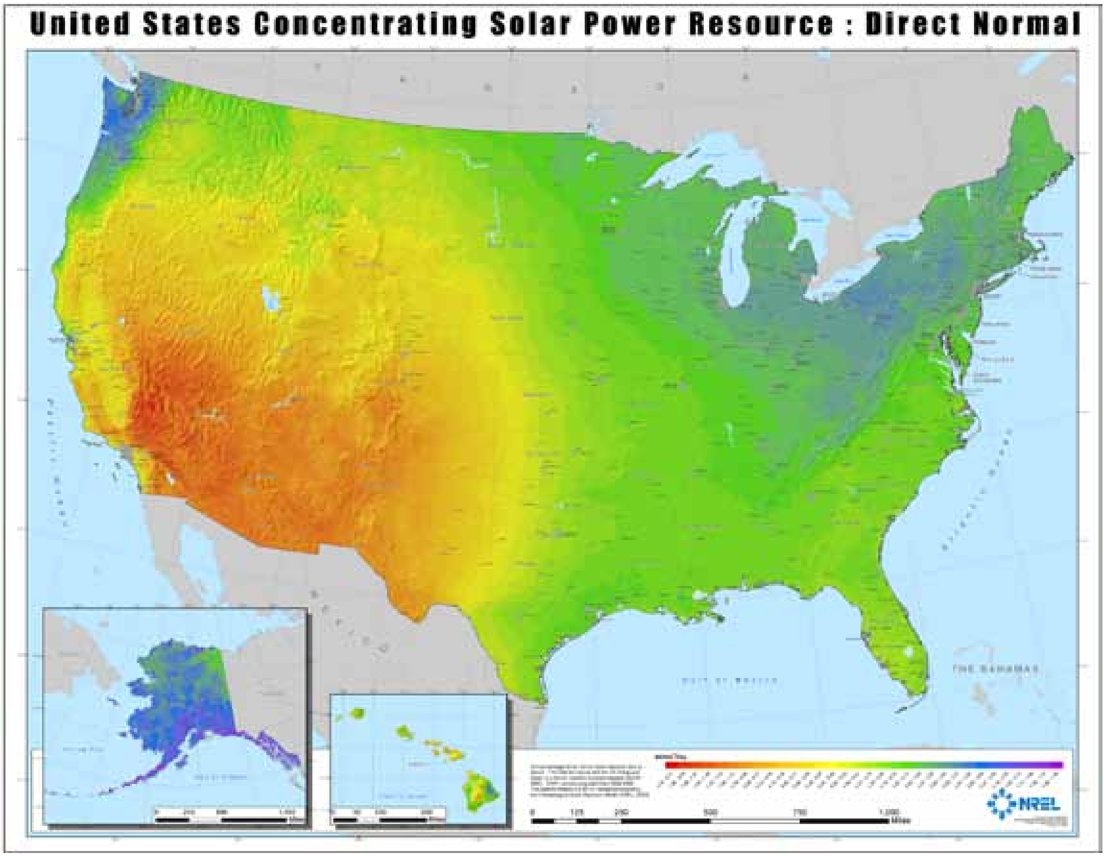
Linear Fresnel CST employs a line-focus technology similar to parabolic troughs in that it consists of reflectors that track the sun in one axis and focus the beam radiation onto fluid-carrying receiver tubes. The difference is that it uses a series of ground-mounted mirrors, and the receiver tube is elevated above the mirrors and fixed. The optical efficiency of linear Fresnel CST is lower than that of parabolic troughs, but comes with a cost savings and reduced land-use tradeoff.

POWER TOWERS

Power towers utilize a field of tracking mirrors, called heliostats, which reflect the sun's rays to a receiver located on top of a tall, centrally located tower. The solar energy is absorbed by pressurized water or molten salt working fluid flowing through the receiver. The operating temperature of power towers is higher than that of line-focus collectors (parabolic troughs and linear Fresnel), but lower than dish/sterling systems. Power towers can be coupled with a molten salt energy storage system, allowing energy to be stored at 1050 degrees Fahrenheit. When needed, hot salt can be removed from storage tanks and used to generate steam to drive a conventional steam-turbine engine.

DISH/ENGINE SYSTEMS

Dish/engine systems use a field of individual parabolic-shaped dish reflectors that each focus sunlight onto an engine/generator that uses the Stirling thermodynamic cycle to directly produce electricity without producing steam. Because it tracks the sun in two axes, it captures the maximum amount of direct (or beam) solar radiation throughout the day. Because of its high concentration ratio, dish/engine systems can achieve very high temperatures (about 1452 degrees Fahrenheit) and high efficiencies, converting over 30% of the sunlight to electrical energy. Individual dish/engine units currently range from 1 to 25 kW in size. Power plants of any size can be built by installing fields of these systems, and they can be installed on uneven levels, unlike other CST technologies.



BIOMASS


© NREL, Tribal Energy and Environmental Information Clearinghouse

"While biomass serves as a relatively carbon neutral source of electricity, its water footprint can actually be significantly greater than that of traditional thermoelectric sources, varying largely by the biomass fuel source."

Biomass fuel sources are quite varied and can be used to produce heat, liquid fuels and electricity. Some bio-crops, wood, wood wastes and forest debris are converted to heat and produce commercial-scale electricity; while other bio-crops, agricultural residues and food wastes are used to produce ethanol and bio-diesel. Industrial and residential wastes or co-products can be used to produce heat (or co-generate electricity) to help meet the energy needs of waste treatment and other industrial facilities. As a source of electricity, biomass can have a uniquely large water footprint because of the evapotranspiration associated with irrigated bio-crops.

Biomass is largely considered a carbon-neutral source of electricity. Although carbon is produced when biomass is combusted, it is not fossil carbon. As crops grow they absorb carbon dioxide from the air and when they are burned, the CO2 is returned to the air, causing a zero net increase of atmospheric carbon.[85] However, the water intensity of biomass-fueled electricity varies widely based on the irrigation needs of the various bio-crops.

Biomass Production

Crop irrigation (or "blue water footprint") is the most significant use of water needed for biomass electricity, although the water requirements differ by crop species and the geographic location of crop production. Globally, the sugar beet is the most water efficient biomass crop, requiring on average, nearly 44,000 gallons of water to yield enough plant matter to produce one MWh of electricity. Jatropha (not grown in North America) is the least water efficient biomass crop, requiring on average over 375,000 gallons of water to produce one MWh. Crops grown in the Southwest U.S. require more water than crops in the Midwest, due to temperature and drier conditions. The "green" water footprint of each crop refers to evapotranspiration of rainwater.

The global average water footprints of biomass crops are:

Table 12.1. Water Footprint (WF) of Biomass Crops *(Gal/MWh)*

Crop	Total WF *(Gal/MWh)*	Blue WF *(Gal/MWh)*	Green WF *(Gal/MWh)*
Sugar Beet	43,908	25,839	18,069
Maize	47,550	19,020	28,530
Sugar Cane	47,550	25,677	21,873
Barley	66,570	37,089	29,481
Rye	74,178	34,236	39,942
Paddy Rice	80,835	29,481	51,354
Wheat	88,443	51,354	37,089
Potato	99,855	44,697	55,158
Cassava	140,748	19,971	120,777
Soybean	164,523	90,345	74,178
Sorghum	171,180	74,178	97,002
Rapeseed	364,233	217,779	146,454
Jatropha	376,596	219,681	156,915

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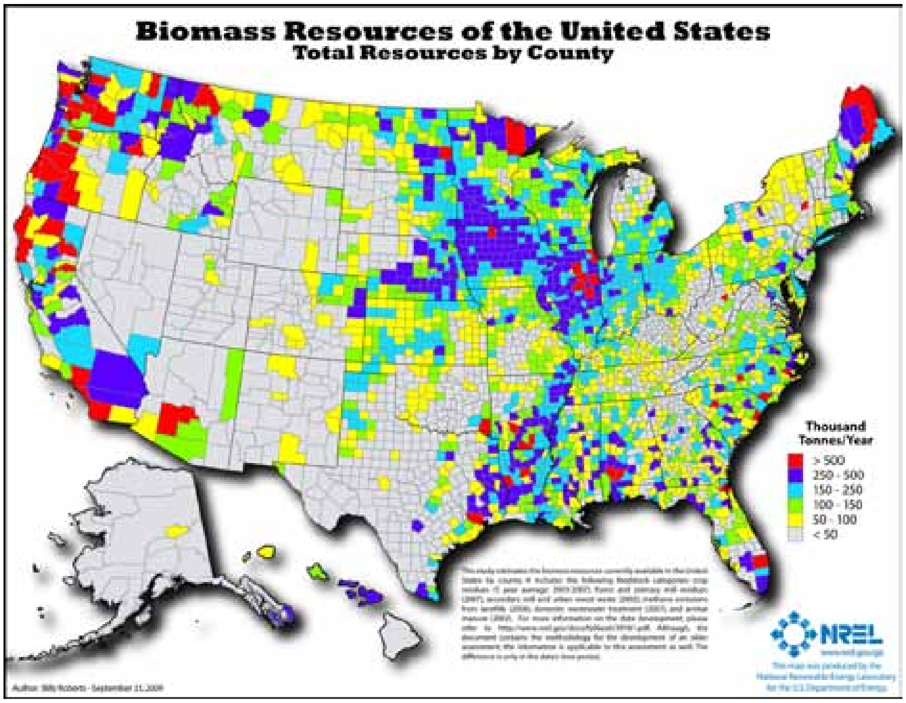
[85] http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html



Because forests are irrigated with natural rainfall, the production of wood and forest debris for electric conversion does not have an associated "blue" water footprint, making it a lower-water alternative than bio-crops. Wood and forest debris (including tree limbs, tops, needles, leaves and bark) can be gathered as part of forest thinning activities or after commercial logging. Removing excess woody debris from managed forests for use as fuel or other wood products can also help reduce fire risks.

Electricity Generation

As with all thermoelectric fuel sources, the energy output of biomass is directly affected by power plant efficiencies. Burning energy crops to drive a steam turbine has an efficiency of approximately 20% to 25%, while gasification for driving a gas turbine allows higher conversion efficiencies (approximately 40-45%).[86] Additionally, like all thermoelectric conversion processes, water is needed for cooling in the power plant. We did not find research on the specific water-use factors of those few facilities which are using biomass as a thermoelectric fuel.

However, in recent years however, the number of plants using woody biomass has started to increase with the support of federal financial incentives, affordable supplies of woody materials, and associated environmental benefits.[87] The state of Oregon is home to one of the nation's first commercial-scale wood biomass conversion facilities, Biomass One. It began operations in the 1980's, and produces approximately 25 MW of electricity—enough to power over 20,000 homes—and recovers 355,000 tons of wood waste from area landfills each year.[88]

An important and growing part of the biomass industry is bio-waste or biogas energy. Many municipal wastewater treatment facilities have bio-waste energy recovery systems. These plants typically store

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[86] Fthenakis and Kim, 2010 (p. 2042).

[87] http://www.gao.gov/new.items/d06336.pdf

[88] http://www.biomassone.com/electricity.php

solid waste in an anaerobic digester to create methane gas which is used as heat energy, or to cogenerate electricity. There is tremendous potential to increase the use of biogas, as only 6% of the bio-solids are currently being used for energy.

According to the Water Environment Research Foundation (WERF), biogas energy has the potential in the U.S. to generate 10 times the energy needed by wastewater treatment facilities and enough power to meet the needs of New York City, Houston, Dallas and Chicago.89 For example, Iona Sewage Treatment Plant in Vancouver, B.C., uses bio-waste to supply 70% of the district's heating needs and reduces carbon emissions associated with heating buildings in the district by 50%. In Portland, Oregon, the Columbia Boulevard Wastewater Treatment Plant can generate 1.7 megawatts (over 12 million kilowatt hours per year or 40% of the facility's daily power demand) and saves $60,000 in annual energy bills.

WIND

Humans have been harnessing the power of wind for centuries, although it has only been in the last several years that wind power has become a widespread, utility scale source of electricity. Recent advancements in wind technologies have improved its efficiency and brought down costs by nearly 90% in the last 20 years, making wind power a reliable, cost-effective source clean energy.[89] Producing approximately 35,160 MWh of wind powered electricity annually, the United States is currently the world leader in wind power production, contributing approximately 22.1 % to total worldwide wind power capacity.[90] There are zero carbon emissions, and virtually no water use associated with the actual process of wind power generation, however there are some negligible emissions and water use embedded in the turbine manufacturing process.


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Each megawatt-hour of electricity generated by wind could save as much as 600 gallons of water which would have been used for steam cooling at a thermoelectric power plant.

According to the American Wind Energy Association, current operational levels of wind power—offsetting traditional thermoelectric sources of electricity—prevent approximately 62 million tons of carbon emissions and save 20 billion gallons of water annually.[91] Each megawatt-hour of electricity generated by wind could save as much as 600 gallons of water which would have been used for steam cooling at a thermoelectric power plant. With estimates of increasing total wind power capacity in the United States to 20% of total power generation by the year 2030, the Department of Energy calculates an approximate savings of 4 trillion gallons of water.[92] As reported in *20% Wind Energy by 2030*, "Of the 4 trillion gallons of water saved nationally, 29% will be in the West, 41% will be in the Midwest/Great Plains, 14% will be in the Northeast and 16% will be in the Southeast."

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[89] http://www.awea.org/pubs/factsheets/EconomicsOfWind-Feb2005.pdf

[90] http://www.wwindea.org/home/images/stories/worldwindenergyreport2009_s.pdf (p. 14)

[91] http://www.circleofblue.org/waternews/2010/world/in-solar-power-lies-path-to-reducing-water-use-for-energy/

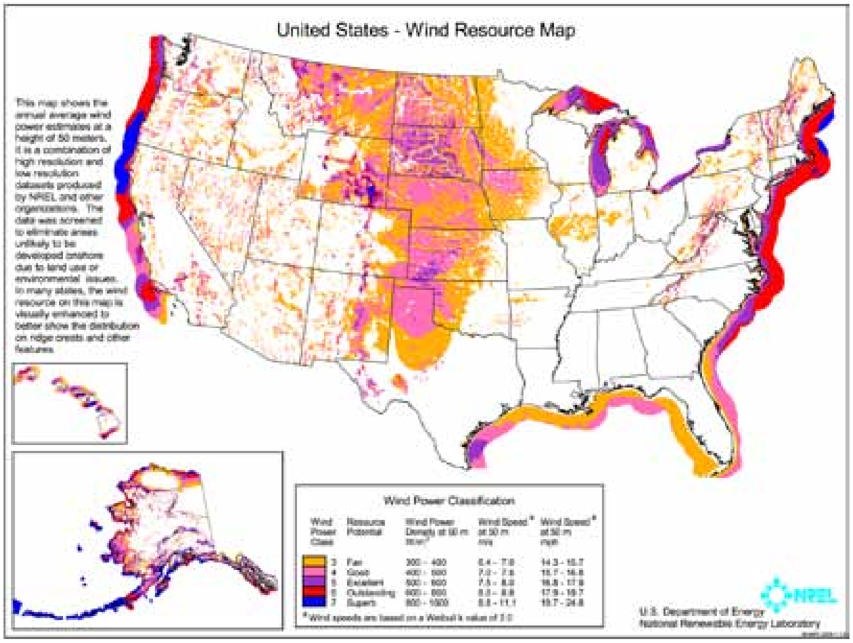
[92] http://www.20percentwind.org/20percent_wind_energy_report_revOct08.pdf (p. 166)

The water footprint of wind power includes the following:

Table 13.1. Water Footprint of Wind*		
Lifecycle stage	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*
Construction	60	N/A
Maintenance/Operation	>1	>1
* See Appendix A for methodology.		

Manufacture, Transport & Assembly

The only notable water use and greenhouse gas emissions associated with wind powered electricity takes place in the manufacture, transport and assembly of wind turbines. Turbine manufacturing plants and assembly processes operate on traditional energy sources that are intrinsically water and carbon intensive. Further, the transport of materials to manufacturing plants and the transport of turbine pieces to wind fields for assembly typically require the consumption of transportation fuels. According to Dr. Vasilis Fthenakis of the Department of Energy Sciences and Technology and the Center for Lifecycle Analysis, water consumption embedded in the manufacture, transport and assembly stages of wind power amounts to approximately 60 gallons of water for every Megawatt hour of electricity produced.



This map shows the annual average wind power estimates at a height of 50 meters. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental issues. In many states, the wind resource on this map is visually enhanced to better show the distribution on ridge crests and other features.

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed* at 50 m m/s	Wind Speed* at 50 m mph
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

*Wind speeds are based on a Weibull k value of 2.0

U.S. Department of Energy
National Renewable Energy Laboratory

Electric Power Generation

After manufacture, transport and assembly of wind turbines, the only costs, water use and carbon emissions associated with generating wind electricity are a result of turbine washing and maintenance—and are relatively negligible. Approximately half of one gallon of water is consumed for turbine cleaning purposes for every Megawatt hour of electricity produced.

The most pivotal factor in the generation of wind powered electricity is the availability of wind. Wind potential varies geographically, with the most wind available in flatter regions void of obstructions to wind gusts. Despite being the world leader in total wind power capacity—producing just over 35,000

MWh annually—the United States has yet to tap into the greatest source of national wind "potential energy" that lies off its coasts. The second greatest potential wind energy lies in the Great Plains and Midwest regions. By tapping into this massive offshore wind potential, the U.S. has the opportunity to hugely expand current wind power operations, significantly offsetting greenhouse gas emissions and water consumption and pollution that would be attributed to typical thermoelectric power sources.

Unfortunately, as wind is never a consistent force, wind powered electricity cannot be generated at a constant rate. Inconsistent wind patterns cause wind turbines to generate electricity at an approximate 30% efficiency rate—higher on days of heavy wind and lower on days with little or no wind. This somewhat low efficiency of wind power generation requires the need for electricity storage capacity to account for days of little to no wind and peak electricity demand. One technique that can be employed to account for days of low wind is the integration of wind and hydropower. By placing wind turbines next to dams, hydro reservoirs can be used to store energy in the form of water, releasing water when needed to generate extra electricity.[94]

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[94] http://www.nrel.gov/docs/fy06osti/37790.pdf

SECTION 4

RECOMMENDATIONS

River Network is a leading voice for freshwater protection and conservation in America today. Our network includes thousands of local watershed protection groups who understand that rivers, lakes and aquifers are not inexhaustible. We recognize that electrical production has major water-related impacts, which are already far too high to be sustained. The time to change this is now, given that climate change is increasing hydrologic variability and putting more communities at risk.

The three primary recommendations of this report are:

1. As a nation, we should focus on renewable energy sources and low water technologies.
2. We need to plan to sustain our resources, including better measurements of water use and stronger regulation of the water impacts of energy development.
3. As a society, we can save both water and energy by building more robust watershed-level conservation programs and community-based collaboration.

Today, on average in the U.S., approximately 42 gallons of freshwater is withdrawn or used to produce a kilowatt hour of electricity. Every gallon withdrawn or used is impacted in some way, whether by passing through a turbine (straining out and damaging aquatic life), being lost through evaporation in cooling towers, warmed in a reservoir (impacting aquatic life and water quality) or chemically polluted. In many places, the freshwater used to generate electricity might be more valuable for other uses, such as drinking water for cities, irrigation water for farms or environmental flows for fisheries and habitat restoration.

In the long run, all Americans and economic sectors must recognize the consequences and risks associated with wasting water. Already in many states, elevated water temperatures impact electrical production. A more volatile and less predictable hydrologic regime will make these "thirsty" technologies even less reliable. We can find more sustainable options by using the water-energy nexus as a crucial lens for analysis, management and planning.

RECOMMENDATION 1

Change what we burn and how we burn it at existing power plants.

1.1 Speed the retirement of out-of-date electric facilities and cooling technologies, and incentivize "water-friendly" renewable energy sources such as PV solar, and wind.

Wind and PVsolar require virtually no water to generate electricity, and their lifecycle water footprints are far smaller than hydro, nuclear or fossil fuels. The technology exists for wind to provide 20% of our electricity by 2024.[1] Since the majority of the water used by wind and PV solar is "upstream" (to acquire and process materials for fabrication), manufacturing can be focused in water rich regions without increasing water impacts in dry regions.

A renewal of the federal Production Tax Credit would cut wind developmental costs by 25%.[2] Establishing a price on greenhouse gas emissions with a carbon tax or a cap and trade system would also increase the cost competitiveness of the wind industry. Federal, states and local governments can give incentives for renewable energy development with feed-in tariff programs. States can also consider the water impacts of least-cost rate proceedings and stronger Renewable Energy Standards.

1.2 Deploy the best available cooling technologies and pollution controls at existing power plants across the country.

Nuclear and fossil fuel electric facilities, as currently deployed in the U.S., have a much larger water footprint than is generally understood. Coal supplies half of our electricity and therefore has the largest total water footprint in the sector. Nuclear technology generally has the highest on-site consumption of water, but the full life-cycle water needs of uranium production and disposal are not well known. In general, combined-cycle power plants improve the thermal conversion efficiency of power plants and make dry or hybrid cooling more economically feasible by enabling the installation of smaller units.

Although there are tradeoffs between water efficiency and power production, the electric industry should be encouraged to move away from once-through systems in favor of recirculating, hybrid cooling technologies and dry cooling systems in areas of limited water. EPRI and NETL are actively researching other advanced cooling technologies which may improve options.[3] Stronger, standardized federal requirements for power plant cooling technologies under the Clean Water Act 316(b) amendments could help speed this process and encourage companies towards greater water efficiency.

Power plant operators should be encouraged to increase water recycling and reuse within plants by capturing vapor in wet cooling towers and stacks.[4] The greater use of degraded or reclaimed water for power plants is also an option in many places. EPRI is inventorying degraded water sources, which could be matched with cost-effective pretreatment technologies and used in power plants.[5]

1.3 Carefully assess carbon capture and sequestration technologies that depend on increased water use.

Globally, coal-fired plants will continue to be used for decades. The success of climate mitigation efforts would be greatly enhanced by rapid development and deployment of CCS. However, there

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[1] National Renewable Energy Lab, also see: http://climateprogress.org/2010/01/20/nrel-study-shows-20-percent-wind-is-possible-by-2024/

[2] http://www.awea.org/pubs/factsheets/EconomicsofWind-Feb2005.pdf (p. 4)

[3] For more information on research into reducing water use at power plants, see EPRI's Water and Advanced Cooling program: www.epri.com/advancedcooling or NETL's Innovations for Existing Plants Water-Energy Interface program: http://www.netl.doe.gov/technologies/coalpower/ewr/water/index.html

[4] http://mydocs.epri.com/docs/public/000000000001015444.pdf

[5] http://mydocs.epri.com/docs/public/000000000001015444.pdf

will be increased water impacts brought about by CCS. Coal plants using CCS will probably consume more water and possibly have greater water pollution impacts. Combined cycle plants (rather than pulverized coal) appear to be the most promising—but not the only potential technology—for developing effective CCS. According to a recent MIT report, “The U.S. government should provide assistance only to coal projects with CO_2 capture in order to demonstrate technical, economic and environmental performance.”[6] States should also require complete, site-specific assessment of the water needs, impacts and vulnerabilities of proposed CCS projects.

1.4 Help dam-affected rivers respond to change.

Climate change creates new challenges for dam managers across the country. The White House Council on Environmental Quality (CEQ) issued a task force report outlining the water-related impacts of climate change and the potential responses of federal agencies.[7] The Water Protection Network promotes improved operations of federal dams through reforming national Principals and Guidelines for water development projects.

Consideration should be given to developing new public review processes to better account for how federal dams and their associated floodplains are managed, help meet the challenges of climate change and maximize community benefits and environmental outcomes. For example, the federal hydropower system (built by the Army Corps of Engineers) on the Lower Snake River threatens the continued existence of four stocks of wild salmon and steelhead. Despite years of successful litigation by environmental groups, serious consideration of dam removal has been blocked by political stalemate. A full public review of the current costs and benefits of the Lower Snake River dams could help build plans to replace the energy generated by the dams through conservation and efficiency programs.[8]

In contrast, action by environmental groups in the National Hydropower Reform Coalition and local watershed leaders has successfully improved relicensing requirements for many privately owned dams. The relicensing process (along with collaboration and federal funding) has made dam removal possible and successful in Wisconsin, Maine, Oregon and Washington.

RECOMMENDATION 2

Plan to sustain both water and energy by measuring energy-related water use and strengthening regulation of water impacts in the electric industry.

2.1 Strengthen water impacts analysis and agency coordination during siting and permitting of new and/or renewed energy generating facilities.

Bureaucratic inertia and regulatory siloes are perhaps the biggest impediments to reducing the water impacts of electricity. Most agencies just don’t understand the goals of their sister agencies. The Environmental Defense Fund recommends that states take the lead to assure that all new

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[6] The Future of Coal, MIT, 2007 (p. 7). http://web.mit.edu/coal/The_Future_of_Coal.pdf

[7] CEQ, Climate Change Adaptation Task Force, Priorities for Managing Freshwater Resources in a Changing Climate, 2011.

[8] Northwest Energy Coalition, Bright Future Report, 2009. http://www.lightintheriver.org/reports.html

power plant applications receive a thorough analysis of cooling options, water availability and less water-intensive options.[9] State Public Utility Commissions should evaluate how the externalized cost of "burning water" might be considered in consumer protection and least-cost planning processes. States have the right to apply operating conditions to FERC licenses through their respective fish and wildlife agencies. Under the Clean Water Act and the Safe Drinking Water Act, the U.S. EPA has the authority to regulate water intake and pollution from power plants, but generally the states are responsible for implementing these regulations.[10]

2.2 Improve data collection and monitoring on water use and pollution at existing electrical generation facilities.

While efforts to better coordinate between agencies continue, the public and decision-makers may not have enough information to avert conflicts between energy and other water users. In 2009, the U.S. Congressional Budget Office reported that the Energy Information Administration (EIA) did not have complete data in many areas and does not systematically collect needed information on advanced cooling technologies or alternative water sources.

The USGS discontinued distributing data on water consumption by power plants and now only provides information on water withdrawals.[11] The data collected also varies widely from state to state. California and Arizona have taken formal steps to monitor and minimize water use at power plants, while in at least some states, some generating facilities are not even required to obtain water use permits.[12]

2.3 Develop and adopt standardized "Energy-Return-on-Water-Invested" (EROWI) decision support tools for energy companies and public utility commissions.

This has the potential to improve the data collected and could better inform private investment decisions. Many studies (DOE 2006, EPRI 2002, Mulder 2010, Fthenakis 2010) have attempted to determine EROWI for various energy technologies, but have invariably been limited by the quality and consistency of data. The lack of an effective water-use accounting methodology is particularly problematic to evaluating the impacts of biofuels. In 2007, federal legislation mandated that the U.S. produce 36 billion gallons of biofuels by 2022, yet few studies considered increased changes to irrigation demand needed to implement this strategy.[13]

2.4 Close loopholes and exemptions to federal and state environmental laws currently enjoyed by the oil and gas industry regarding exploration, drilling and hydraulic fracturing.

The expanded use of freshwater and chemicals in underground injection wells and surface retention ponds pose significant human health risks and raise questions about the integrity of our

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[9] Stillwell, A.S; King, C.W;Webber, M.E; Duncan, I.J; Harberger, A., Energy-Water Nexus in Texas, Ecology and Society, 2011.

[10] Sections include *CWA* §303; *CWA §316(a*), and *CWA §316(b)*, which requires "the best technology available" for cooling water intake structures. For more information: http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/IEP_Power_Plant_Water_R&D_Final_1.pdf

[11] U.S. GAO, "Energy-Water Nexus: Improvements to Federal Water Use Data Would Increase Understanding of Trends in Power Plant Water Use." 2009

[12] http://www.gao.gov/new.items/d1023.pdf

[13] http://www.springerlink.com/content/kv23735373476t71/

nation's environmental safety net. Current industry exemptions to the Safe Drinking Water Act, the Resource Conservation and Recovery Act, the Emergency Planning and Community Right to Know Act, the stormwater provisions of the Clean Water Act and the National Environmental Policy Act, all put an undue legal burden on communities concerned about protection of their freshwater resources.

2.5 Encourage businesses and industries to switch to on-site renewables and energy providers that use PV solar and wind to reduce their water footprint.

Socially-concerned financial investors should make sure that the carbon footprint AND the water footprint of companies is properly evaluated—especially in regions of the country highly reliant on hydropower, nuclear and coal-fired electricity. Unfortunately, some techniques for corporate water footprinting consider energy use only as a generalized supply-chain "overhead factor" (calculated on a value-added basis), which vastly undervalues this important resource.[14] The Water Footprinting Network[15] and the International Organization for Standardization are part of an invaluable effort to improve techniques. As these tools are refined, greater consideration should be given to the upstream use of electricity, co-generation and negotiating with suppliers to purchase "water-friendly" electricity.

2.6 Include water in state Climate Action Planning (CAP).

Most CAPs underestimate the amount of energy that could be saved through water conservation efforts and do not consider how climate change might reduce water availability. These plans should be better informed and more fully supported by the National Oceanic & Atmospheric Administration's (NOAA) programs, such as the Regional Integrated Science Assessments (RISA) and the U.S. Geological Survey (USGS). NRDC has recently produced a helpful comparison between states of the "water-readiness" of their climate planning activities.[16]

RECOMMENDATION 3

Strengthen watershed level and community-based programs to reduce water and electricity use.

3.1 Promote efficiency.

It is hard to overstate the role energy efficiency could play in efforts to improve the sustainability of water resources. For example, in 2009, the Austin Energy General Manager in Austin, Texas explained that if the city could cut the amount of power it received from a local coal-fired power plant by just one-third, it would free up a billion gallons of water for other uses.[17] The Center for American Progress reports that energy retrofitting of 40% of U.S. buildings would generate

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[14] Mekonnen, M.M. and Hoekstra, A.Y. (2011) National water footprint accounts: the green, blue and grey water footprint of production and consumption, Value of Water Research Report Series No.50, UNESCO-IHE. Accessed 3/23/2012. http://www.waterfootprint.org/Reports/Report50-NationalWaterFootprints-Vol1.pdf

[15] Arjen Y. Hoekstra, Ashok K. Chapagain, Maite M. Aldaya and Mesfin M. Mekonnen. The Water Footprint Assessment Manuals*:* Setting the Global Standard*.* http://www.waterfootprint.org/downloads/TheWaterFootprintAssessmentManual.pdf

[16] http://www.nrdc.org/water/readiness/

[17] http://www.statesman.com/blogs/content/shared-gen/blogs/austin/cityhall/entries/2009/08/19/even_when_its_not_about_water.html

625,000 jobs and cut U.S. energy bills by $64 billion a year.[18] Federal standards and state-level plans can set the stage for increased efficiency and conservation, but often the most crucial ingredient is leadership from local government, community groups, water districts and energy utilities.

3.2 *Collaborate for success.*

In 2011, the Alliance for Water Efficiency (AWE) and the American Council for an Energy-Efficient Economy (ACEEE) published an important report called *Addressing the Energy-Water Nexus: A Blueprint for Action and Policy Agenda*. The Blueprint offers national priorities and themes for cross-sector collaboration to reduce water and energy use.[19] Both groups continue to move forward with these reforms, while providing essential services to utilities and local units of government. River Network is also a resource for local watershed groups and collaborative stakeholder organizations leading community education and engagement programs.

3.3 *Encourage wider adoption of Integrated Resource Recovery (IRR) approaches to meet community needs.*

IRR considers wastewater management, energy, stormwater, drinking water and solid waste in one framework under several key principles.[20] These include designing with nature and directing stormwater to permeable surfaces or bioswales, which require less energy to manage and help recharge groundwater levels.

3.4 *Assure stronger public involvement in water conservation planning, instream flow and surface water protection across the country.*

Federal energy licensing and state water allocation processes are notoriously opaque to public input and operate largely below media's radar. Local groups and citizen watchdogs can seek intervener status in federal permits, participate in state water rights proceedings, water quality permitting, and engage in state comprehensive water planning processes where they exist.[21]

Even in water-rich states, such as those in the Great Lakes region, water conservation is crucial to effectively managing water for environmental and economic gains. The eight U.S. states covered by the Great Lakes-St. Lawrence River Basin Water Resources Compact have agreed to strong water conservation and efficiency goals and objectives covering all water users, including thermoelectric power plants. The Compact obligates each state to develop and implement several new policies including: 1) water efficiency goals and objectives and 2) a water conservation and efficiency program. Unfortunately, the NRDC reports that implementation has been slow and uneven across the region.[22] However, these public processes provide unprecedented opportunities for citizen involvement in water resource protection.

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[18] Center for American Progress. Efficiency Works: Creating Good Jobs and New Markets Through Energy Efficiency, 2010. http://www.americanprogress.org/issues/2010/08/pdf/good_jobs_new_markets.pdf

[19] Blueprint for Water and Energy, 2011. http://www.aceee.org/white-paper/addressing-the-energy-water-nexus

[20] http://www.cd.gov.bc.ca/lgd/infra/library/Resources_From_Waste_IRR_Guide.pdf

[21] The Electrical Consumer Protection Act of 1986 requires FERC to consider state Comprehensive Water Plans and can help states protect rivers from proposed federal hydropower projects.

[22] NRDC, Great Lakes Compact's water conservation implementation efforts, 2011. http://www.nrdc.org/water/greatlakescompact.asp

3.5 Promote green infrastructure, watershed restoration and community-based sustainability programs.

River Network and many allied groups across the country participate in projects to improve hydrologic functions and increase the quality of life of urban citizens. A recent report by American Rivers and others demonstrates how investing in green infrastructure is saving money, water and energy.[23] Many important projects have been initiated under the U.S. EPA's "Green Reserve"[24] program and funded with State Revolving Funds. Financial support for these programs is crucial. There are many examples of successful municipal water conservation, efficiency and reuse programs. Citizen support for these programs and effective cost-recovery are critical elements of success.

As a nation, we have the power to reduce the water footprint of the electricity we use by an order of magnitude. But there are tremendous economic barriers to change, such as inadequate water-use reporting, widespread unvaluing of freshwater and developing better ways of attributing the cost of water pollution. Overcoming these obstacles will help us meet the demands of a growing population and our need for a sustainable environment.

In this report we set out to identify water-intensity factors that would help local communities assess energy alternatives and fuels. We found that the water-intensity of a thermoelectric plant is more closely tied to cooling technology and combustion efficiency than to the type of fuel it uses. Direct comparisons of water-use factors are best done on a site-specific and plant-specific basis.

We found agreement between researchers that hydropower has the highest water use factors (although methodologies and co-benefits vary) of any source of electricity. We found that PV solar and wind are considered the most "water-friendly" sources of electricity and have the lowest water use factors. The water-use factors for thermoelectric fuels are in the middle, and the water impacts of these fuels are subject to debate. In the case of natural gas, coal and nuclear energy, the majority of the potential gray water footprint may not be reflected in current research.

Comparing coal and nuclear electricity is complicated as well. While nuclear technology has the highest water consumption factors, coal plants may have higher water withdrawals. For this report, we averaged current research by fuel and technology and then weighted it by the proportion of cooling technology used in 2009. Although our final numbers may differ, we do not intend to contradict other observers who interpret these technologies' water footprints in a different order.[25]

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[23] American Rivers, et al. Banking on Green, April 2012. http://www.americanrivers.org/assets/pdfs/reports-and-publications/banking-on-green-report.pdf

[24] This is a budget set-aside within both of the U.S. EPA's CWA and SDWA state revolving funds.

[25] The Union of Concerned Scientists' EW3 Initiative is a good example of site-specific analysis.

SUGGESTED RESEARCH

This report attempted to define a full lifecycle water footprint of electricity for the U.S., but clearly underestimates it in many ways. A more accurate lifecycle assessment (LCA) would be much higher if it could count the impacts of solar thermal development on desert environments, the water needed for nuclear waste disposal, dam construction and decommissioning, mountaintop coal mining, coal ash spills, chemical pollution from hydraulic fracking and mercury pollution of our waterways.

The research literature on LCA of electrical fuels appears uneven. Future researchers should try to be clear as to what boundaries are placed on the system they are examining, whether indirect water costs are considered or how the values of co-products are assigned.

Research on the water impacts of energy, especially hydropower, need to be as site-specific as possible. For example, Lake Mead in the desert Southwest has a water-intensity factor of 89 gallons per kilowatt hour, while a global study of dams comprising 8% of the world's hydropower capacity placed water-intensity at 6.4 gallons/kwh. Existing hydro studies are difficult to compare, as some results are modeled and others directly measured.

We would also encourage future research around the impacts of water pollution and the "gray water footprint," as well as, the "green water footprint" of emerging biomass and biofuel technologies. This will require additional research and much more standardization of water-footprinting protocols within the scientific and technical communities.[26]

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[120] The International Organization for Standardization leads an ongoing effort in this area.

APPENDIX A

METHODOLOGY

A.1 Overview

In calculating "upstream" water withdrawals and consumption for each electricity source, we averaged water use figures for mining, processing, transportation, plant construction, etc. by source as presented in Fthenakis and Kim's *Life-cycle uses of water in U.S. electricity generation* article from the Renewable and Sustainable Energy Reviews journal. We then calculated "on-site" water withdrawal and consumption figures for each electricity source by averaging water use figures (also presented in *Life-cycle uses of water in U.S. electricity generation*), and then weighed figures for each thermoelectric fuel source by the mix of technologies employed in 2009 as presented in NETL and DOE's *Estimating Freshwater to Meet Future Thermoelectric Generation Requirements* report. We determined full lifecycle water withdrawal and consumption figures presented in Table 1 (see p. 10) by adding "upstream" and "on-site" figures presented in each electricity source section.

Tables 1.A and 1.B (the next 4 pages) show our calculations for "on-site" water use at coal, nuclear and natural gas power plants, by averaging figures by cooling technology, weighing them by prevalence and converting figures from liter/megawatt hour to gallon/megawatt hour.

Appendix Table 1.A: Average Water Use Factors for Thermoelectric Plants by Cooling Technology

Fuel Type	**Cooling type**	**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*		**Average for Technology**		**Weighting Factors**		
Coal					**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*			
	Once-through	76,000	1,140	Average Once-through	133,000	1,140			
	Once through	190,000	1,140		**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*			
	Once-through, Subcritical*	103,000	530	*Omitted from average. No data on prevalance. Consistent w/ NREL factors.	35,135	301			
	Once-through, Supercritical*	85,600	450						
	Once-through*	N/A	1,210						
	*Once-through (Fluidized-bed)**	N/A	950						
	Cooling Pond, Subcritical	67,800	3,030	Average Cooling Pond	**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*			
	Cooling Pond, Supercritical	57,200	242		42,233	1,574			
	Cooling Pond (1100-2300)	1,700	1,450		**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*			
	Wet Tower, Subcritical	2,010	1,740		11,157	416			
	Wet Tower, Subcritical	2,590	2,560						
	Wet Tower, Subcritical	4,430	4,430						
	Wet Tower, Supercritical	2,500	1,970	Average *Wet Tower (Recirculating)*	**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*			
	Wet Tower, Supercritical	3,940	3,940		2,834	2,648			
	Wet Tower, Supercritical	2,270	2,240		**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*			
	Wet Tower *(1900-2300)*	2,100	1,800		749	700	**Coal - Percent of Cooling Technology Used**		
	Wet Tower	N/A	3,100				Wet Recirculating	Once-through	Cooling Pond
	Wet Tower, Eastern	N/A	2,800	**Average Coal** *(Weighted)*	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*	0.48	0.391	0.127
	Wet Tower, Western	N/A	1,900		**15,514**	**506**	National Energy Technology Laboratory (NETL), 2009		

Table 1.A. continued on page 49

Appendix Table 1.A. continued from page 48

Fuel Type	**Cooling type**	**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*		**Average for Technology**		**Weighting Factors**		
Nucle-ar					**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*			
	Once-through	119,000	530	Average Nuclear Once-through	140,750	1,015			
					Withdrawal *(Gal/MWh)*	**Consumption** *(Gal/MWh)*			
	Once-through *(95000-230000)*	162,500	1,500		37,182	268			
	Cooling Pond *(1900-4200)*	3,050	2,550	Nuclear Cooling Pond *(only on value)*	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*			
					806	674			
	Wet Tower	4,200	2,300	Average Nuclear Wet Tower *(recirculating)*	**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*			
	Wet Tower *(3000-4200)*	3,600	3,100		3,900	2,883			
	Wet Tower *(LWR)*	N/A	3,200		**Withdrawal** *(Gal/MWh)*	**Consumption** *(g/MWh)*	**Nuclear - Percent of Cooling Technology Used**		
	Wet Tower (HTGR)	N/A	2,200		1,030	762	Wet Recirculating	Once-through	Cooling Pond
	Wet Tower (PWR)	N/A	3,100	**Average Nuclear** *(weighted by cooling)*	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*	0.436	0.381	0.145
	Wet Tower (BWR)	N/A	3,400		**14,732**	**532**			NETL,2009
Oil/ Gas-steam	Once-through	85,900	341	Average Oil/Gas-steam Once-through	**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*			
	Once-through	N/A	1,100		85,900	797			
	Once-through	N/A	950		**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*			
					22,692	211			
	Cooling Pond	29,900	420	Oil/Gas-steam Cooling Pond *(one value)*	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*			
					7,899	111			
	Wet Tower	950	610	Average Oil/Gas-steam Wet Tower	**Withdrawal** *(L/MWh)*	**Consumption** *(Gal/MWh)*			
	Wet Tower	N/A	3,100		950	1,603			
	Wet Tower *(oil)*	N/A	1,100		**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*	**Oil/Gas-steam - Percent of Cooling Technology Used**		
					251	424	Wet Recirculating	Once-through	Cooling Pond
				Average Oil/Gas-steam *(weighted by cooling use)*	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*	0.238	0.592	0.171
					14,844	**244**			NETL,2009

Table 1.A. continued on page 50

Appendix Table 1.A. continued from page 49

Fuel Type	**Cooling type**	**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*		**Average for Technology**		**Weighting Factors**			
NGCC	Once-through	34,100	76	Average NGCC Once-through	**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*				
	Once-through *(28,000-76,000)*	52,000	380		43,050	228				
					Withdrawal *(Gal/MWh)*	**Consumption** *(Gal/MWh)*				
					11,373	60				
	Cooling Pond	22,500	910	NGCC Cooling Pond *(one value)*	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*				
					5,944	240				
	Wet Tower	568	490	NGCC Average Wet Tower *(recirculating wet)*	**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*				
	Wet Tower	1,030	1,020		1,092	1,023				
	Wet Tower	1,900	1,900		**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*				
	Wet Tower	870	680		288	270				
	Dry Cooling	15	15	NGCC Dry Cooling *(one value)*	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*				
					4	4	**Combined Cycle (NGCC and IGCC) % Cooling Technology Used**			
				Average NGCC *(weighted by cooling tech)*	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*	Wet Recirculating	Once-through	Dry	Cooling Pond
					1,170.28	**95**	0.308	0.086	0.59	0.017
				Natural Gas Weighted Average	6,161	149				
IGCC	Wet Tower	855	655	IGCC* *(average)*	**Withdrawal** *(L/MWh)*	**Consumption** *(L/MWh)*	NETL,2009			
	Wet Tower *(1420-1760)*	1,590	1,390		1,561	1,395				
	Wet Tower *(2600-3100)*	2,850	2,855	*Omitted from average. No data on prevalance. Consistent w/ NREL factors.	**Withdrawal** *(Gal/MWh)*	**Consumption** *(Gal/MWh)*				
	Wet Tower	950	680		412	369				

NGCC = natural gas combined cycle
IGCC = integrated gasification combined cycle
LWR = light water reactor
HTGR = high temperature gas-cooled reactor
PWR = pressurized water reactor
BWR = boiling water reactor
NREL = National Renewable Energy Laboratory

Appendix Table 1.B: Median Water Use Factors for Electric Power Generation in the U.S. by Fuel & Technology *(Gal/MWh)*

Electricity Source			Upstream		Power Generaton (on-site)		Total	
			Withdrawal	Consumption	Withdrawal	Consumption	Withdrawal	Consumption
Coal		Wet Tower *(recirculating)*	528	186	749	700	1,287	886
		Once-through			35,135	301	35,673	487
		Cooling Pond			11,157	416	11,695	602
Hydroelectric			0	0	440,000	9,000	440,000	9,000
Natural Gas (NGCC, Oil/Gas-steam)	Combined Cycle	Once-through	323	23	11,373	60	11,696	83
		Recirculating			288	270	611	293
		Dry			4	4	327	27
		Cooling Pond			5,944	240	6,267	263
		Once-through Oil/Gas-steam			22,692	60	23,015	83
		Cooling Pond - Oil/Gas-steam			7,899	111	8,222	134
		Wet Tower Oil/Gas-steam			251	424	574	447
Nuclear		Wet Tower *(recirculating)*	79	40	1,030	762	1,109	802
		Once-through			37,182	268	37,261	308
		Cooling Pond			806	674	885	714
Concentrating Solar Thermal		Wet Cooling	N/A	N/A	856	856	856	856
		Dry Cooling	N/A	N/A	79	79	79	79
		Dish Stirling	N/A	N/A	4	4	4	4
Geothermal			N/A	N/A	700	700	700	700
Photovoltaic (PV) Solar			229	N/A	2	2	231	2
Biomass			N/A	N/A	N/A	N/A	N/A	N/A
Wind			60	N/A	<1	<1	61	1

A.2 Methodology by Electricity Source

COAL

Lifecycle

- *Mining/processing* values represent an average (the mean) of all mining, washing and beneficiation figures in Table 1 (for withdrawals) and Table 2 (for consumption) in Fthenakis, 2010.

- *Transport* values represent an average of train and slurry pipeline figures from Fthenakis' Tables 1 (for withdrawals) and 2 (for consumption).

- *Plant Construction* values represent an average (the mean) of the range of figures for upstream withdrawal for construction of coal power plants in Table 1 in Fthenakis, 2010.

Electric generation

- *Once-through* values represent an average (the mean) of all once-through withdrawal and consumption figures, including subcritical, supercritical and fluidized bed from Fthenakis' Table 6.

- *Recirculating wet* values represent an average of all cooling pond and wet tower figures, including subcritical, supercritical, eastern and western, from Fthenakis' Table 6.

- *Weighted Average* values assume 60.7% of coal plants employ recirculating wet cooling technologies, 39.1% of plants employ once-through cooling technologies and 0.2% of plants employ dry cooling technology. Fthenakis did not report any information on dry cooling for coal; therefore, we conservatively assumed when calculating the weighted averages that water consumption for coal-fired dry cooling is zero.

Carbon Capture/Sequestration

- These figures represent an average (the mean) of sub/supercritical wet tower figures for coal from Fthenakis' Table 7.

NUCLEAR

Lifecycle

- *Mining/Processing* values represent an average (the mean) of uranium mining, milling, conversion, diffusion/centrifuge enrichment and fuel fabrication figures from Fthenakis' Tables 1 (for withdrawal) and 2 (for consumption).

Electricity Generation

- *Recirculating wet cooling* values represent an average (the mean) of cooling pond and wet tower figures from Fthenakis' Table 6.

- *Weighted Average* values assume 38.1% of nuclear plants employ once-through cooling technologies and 61.9% of plants employ recirculating wet cooling technologies.

NATURAL GAS

Lifecycle

- *Extraction/purification* values represent an average (the mean) of on/off shore extraction and purification figures from Fthenakis' Tables 1 (for withdrawals) and 2 (for consumption).

- *Transportation/storage* values represent an average of transportation and storage figures from Fthenakis' Tables 1 (for withdrawals) and 2 (for consumption).

Electric Power Generation *(Single Cycle)*

- *Once-through* values represent an average (the mean) of Fthenakis' 'Oil/Gas-steam' - once-through figures in Table 6.

- *Recirculating wet* values represent an average of 'Oil/Gas-steam'- cooling pond and wet tower figures in Fthenakis' Table 6.

- *Weighted Averages* assume 59.2% of nuclear plants employ once-through cooling technologies, 61.9% employ recirculating wet cooling technologies, and zero plants employ dry cooling technologies.

Electric Power Generation *(Combined Cycle)*

- *Once-through* values represent an average (the mean) of Fthenakis' 'NGCC' - once-through figures in Table 6.

- *Recirculating wet* values represent an average of Fthenakis' 'NGCC' - cooling pond and wet tower figures in Table 6.

- *Weighted Averages* assume 8.6%% of plants employ once-through cooling technologies, 32.5% employ recirculating wet cooling technologies, and 89.0%% employ dry cooling technologies. It should be noted that the data for combined cycle plants represents about 7% of the total combined cycle plants currently in operation. This is because not all plants provided cooling data, so the table was created using information available at the time. If all plants reported cooling data, it is most likely that dry cooling would represent a much smaller percentage of the total combined cycle cooling.

GEOTHERMAL

Dry System

- Values represent averages (the mean) of Fthenakis' Geothermal Dry system figures in Table 8.

Hot Water System

- Values represent averages (the mean) of Fthenakis' Geothermal Hot water system figures in Table 8.

WIND

Lifecycle

- *Construction* values represent an average (the mean) of off shore, on land and on shore figures in Fthenakis' Table 4.

- *Maintenance/Operation* values represent an average of wind figures in Fthenakis' Table 8.

CONCENTRATING SOLAR THERMAL

Average Water Footprint

- *Wet cooling* values represent an average (the mean) of all Tower, parabolic trough (wet) and trough figures in Fthenakis' Table 8.

- *Dry cooling* values represent Fthenakis' 'parabolic trough, dry cooling' figure in Table 8.

Different Technologies

- *Power Tower* values represent an average (the mean) of the range reported for power tower: recirculating cooling in Table 2 of DOE's report to congress.

PHOTOVOLTAIC SOLAR

Lifecycle

- *Manufacture* values represent an average (the mean) of the sum of on-site and upstream water use figures for each PV technology in Fthenakis' Table 4.

- *Electricity Generation* values represent an average of Fthenakis' PV figures in Table 8.

HYDROPOWER

Withdrawal

- Value assumes 3.16 trillion gallons of water are used per day for hydropower production (http://water.usgs.gov/watuse/pdf1995/pdf/circular1200.pdf p. 54) approximately 440 gallons per kWh (Pacific Institute, 2011, Water for Energy: Future Needs for Electricity in the Intermountain West, p. 22). It should be noted that hydropower reservoirs serve multiple purposes, including irrigation, water supply, flood management and recreation. Therefore, not all of the water behind dams is directly attributable to electricity generation. However, we consider all of this water "used" because it is reduced in quality (impacted by solar gain and de-oxygenated to some extent) in reservoirs.

Consumption

- Gleick, 1994 calculated 4,490 gallons per MWh as a national average. NREL (Torcellini, et al, 2003) estimated that dams with hydroelectric facilities in the U.S. consume 18,000 gallons for each MWh delivered (p. 12). This is a huge difference between studies. Averaging these two numbers, as has been done in other parts of this report, would result in a consumptive value of 11,245 gallons per MWh.

- We’ve chosen a lower estimate for this report, responding to NREL methodology, which did not attribute loses to multiple uses in hydropower reservoirs. By attributing 50% of the NREL modeled losses to hydropower, we suggest that at least 9,000 gallons per MWh should be considered a conservative estimate.

A.3 Source Tables

For ease of comparison, all report figures and the above tables are presented in Gals/MWh. Tables 3.A. through 3.H. are reproductions of the original sources we worked from in calculating our figures. Full citations are listed in Appendix B.

Table 3.A: Water Withdrawals, Expressed as Liters per MWh Electricity *(L/MWh)* during Fuel Acquisition and Preparation for Thermoelectric Fuel Cycles in the United States

Fuel Cycle	Stage	Withdrawal - On-site *(L/MWh)*	Withdrawal - Upstream *(L/MWh)*
Coal	Eastern Underground Mining *a	190	507
	Eastern Surface Mining *b	38*c	148
	Western Surface Mining *d	N/A	11
	U.S. Coal Mining	106	N/A
	Beneficiation *(material fractionation)*	>45	53
	Transportation - Train	N/A	26-38
	Transportation - Slurry Pipeline	450	3100
	Construction - Coal-power Plant	N/A	11-45
Nuclear	Uranium Mining	38	15
	Milling	19	68
	Conversion	15	8
	Enrichment - Diffusion	79	1150
	Enrichment - Centrifuge	8	102
	Fuel Fabrication	3	0.4
	Power Plant Construction - PWR	N/A	19
	Power Plant Construction - BWR	N/A	38
	Spent Fuel Disposal	N/A	19
Natural gas	Extraction - On shore	130	300
	Extraction - Off shore	0.8	0.4
	Purification	64	N/A
	Pipeline Transportation	1.5	38
	Storage - Underground	N/A	15
	Power Plant Environmental Control	N/A	890

*a: including coal washing; *b: seam thickness = 0.9 m; *c: washing only; *d: seam thickness = 7 m

Table 3.B: Water Consumptions during Fuel Acquisition and Preparation of Thermoelectric Fuel Cycles in the United States

(L/MWh)

Fuel Cycle	Stage	Consumption *(L/MWh)*
Coal	Surface Mining	11-53
	Underground Mining	30-200
	Washing	30-64
	Befeficiation	42045
	Transportation – Slurry Pipeline	420-870
Nuclear	Surface Uranium Mining	200
	Underground Uranium Mining	4
	Milling	83-100
	Conversion	42
	Enrichment – Diffusion	45-130
	Enrichment – Centrifuge	4-19
	Fabrication	11
Natural gas	Extraction – On shore	NG*
	Extraction – Off shore	NG
	Purification	57
	Pipeline Transportation	30

* NG: Negligible

Table 3.C: Water Withdrawal Factors of PV Technologies, in Liters per MWh Electricity, for Manufacturing the Devices and Building the Power Plants

(insolation = 1800 kWh/m2/year; lifetime = 30 years; performance ration = 0.8)

Type	On-site *(L/MWh)*	Upstream *(L/MWh)*
Multi-si	200	1470
Mono-si	190	1530
Frame	N/A	64
CdTe	0.8	575
BOS	1.5	210

Table 3.D: Water Withdrawal Factors of the Wind-fuel Cycle during Manufacturing the Devices and Building the Plant

Type	Upstream (L/MWh)	Capacity factor
Off shore, Denmark	230	0.29
On land, Denmark	170	0.25
Off shore, Denmark	170	0.46
On shore, Denmark	320	0.32
On land, Italy	250	0.19
On shore, Spain	210	0.23

Table 3.E: Water Demand, Expressed in Liters per Gigajoules *(L/GJ)* of Biomass/Bioenergy Production

Energy type	Biomass	On-site *(L/GJ)*	Water use type	Upstream *(L/GJ)*
Electricity	Hybrid Poplar, U.S.	0	W/C	52
	Herbaceous Perennials, Southwestern U.S., Irrigation	121,000	W	310
	Maize, Global average	20,000	C	N/A
	Sugar Beet, Global average	27,000	C	N/A
	Soybean, Global average	95,000	C	N/A
	Jatropha, Global average	321,000	C	N/A
Ethanol	Corn, U.S.	350-12,100	W	N/A
	Corn, U.S.	270-8,600	C	N/A
	Switchgrass, U.S.	50-260	W/C	N/A
	Corn, Illinois	505	W	N/A
	Corn, Iowa	170	W	N/A
	Corn, Nebraska	18,700	W	N/A
	Corn, U.S.	130-56,800	C	N/A
	Sugar beet, Global average	35,000	C	N/A
Biodiesel	Soybean, Global average	217,000	C	N/A
	Rapeseed, Global average	245,000	C	N/A

W = withdrawal; **C** = consumption; **W/C** = consumption is equal to withdrawal.
GJ instead of MWh were used to represent both electrical and thermal end use energy.

Table 3.F: Water Use Factors for Thermoelectric Power Plants

Power Plant	Cooling Type	Withdrawal *(L/MWh)*	Consumption *(L/MWh)*
Coal	Once-through, Subcritical	103,000	530
	Once-through, Supercritical	85,600	450
	Once-through	76,000-190,000	1140
	Once-through	N/A	1210
	Once-through *(fluidized-bed)*	N/A	950
	Cooling Pond, Subcritical	67800	3030
	Cooling Pond, Supercritical	57200	242
	Cooling Pond	1100-2300	1000-1900
	Wet Tower, Subcritical	2010	1740
	Wet Tower, Subcritical	2590	2560
	Wet Tower, Subcritical	4430	4430
	Wet Tower, Supercritical	2500	1970
	Wet Tower, Supercritical	3940	3940
	Wet Tower, Supercritical	2270	2240
	Wet Tower	1900-2300	1700-1900
	Wet Tower	N/A	3100
	Wet Tower, Eastern	N/A	2800
	Wet Tower, Western	N/A	1900
Nuclear	Once-through	119000	530
	Once-through	95000-230000	1500
	Cooling Pond	1900-4200	1700-3400
	Wet Tower	4200	2300
	Wet Tower	3000-4200	2800-3400
	Wet Tower (LWR)	N/A	3200
	Wet Tower (HTGR)	N/A	2200
	Wet Tower (PWR)	N/A	3100
	Wet Tower (BWR)	N/A	3400
Oil/Gas-steam	Once-through	85900	341
	Once-through	N/A	1100
	Once-through	N/A	950
	Cooling Pond	29900	420
	Wet Tower	950	610
	Wet Tower	N/A	3100
	Wet Tower *(oil)*	N/A	1100
NGCC	Once-through	34100	76
	Once-through	28000-76000	380
	Cooling Pond	22500	910
	Wet Tower	568	490
	Wet Tower	1030	1020
	Wet Tower	1900	1900
	Wet Tower	870	680
	Dry Cooling	15	15
IGCC	Wet Tower	855	655
	Wet Tower	1420-1760	1360-1420
	Wet Tower	2600-3100	2570-3140
	Wet Tower	950	680

NGCC = natural gas combined cycle; **IGCC** = integrated gasification combined cycle; **LWR** = light water reactor; **HTGR** = high temperature gas-cooled reactor; **PWR** = pressurized water reactor; **BWR** = boiling water reactor.

Table 3.G: Water Use Factors for Fossil Power Plants with Carbon Capture with 90% Capture Efficiency

(the numbers in parentheses denote the values without carbon capture)

Power Plant	Cooling Type	Withdrawal *(L/MWh)*	Consumption *(L/MWh)*
Coal	Wet tower, Subcritical	5600 (2610)	5030 (2570)
	Wet tower, Supercritical	4880 (2270)	4350 (2230)
	Wet tower, Retrofitted Plant	36000	1300
IGCC	Wet Tower	2200-2500 (1400-1800)	1800-2000 (1360-1440)
NGCC	Wet Tower	2100 (1000)	1900 (1000)

Table 3.H: Water Use for Renewable Power Plants.

Power Plant	Type	Withdrawal *(L/MWh)*	Consumption *(L/MWh)*
Geothermal	Dry System	7570	5300
	Dry System	6800	6800
	Hot Water System	15000	15000
	Hot Water System	44700	2300-6800
CSP	Tower	2900	2900
	Tower	3200	3200
	Tower, Wet Cooling	3100	3100
	Parabolic Trough, Wet Cooling	3700	3700
	Parabolic Trough, Dry Cooling	300	300
	Parabolic Trough, Wet Cooling	3100	3100
	Parabolic Trough, Wet Cooling Trough	3100-3800	3100-3800
	Trough	2100	2100
	Dish Stirling	15	15
PV Solar		0	0
		15	15
CPV Solar		0	0
		15	15
Wind		0	0
		4	4
Hydro		0	17,000
		0	38-210000
		0	5300
Biomass	Steam Plant	1800	1800
	Biogas-steam, Wet Cooling	2100	1700
	Biogas-steam, Dry Cooling	150	0

CSP = concentrating solar power; **PV** = Photovoltaic; **CPV** = concentrated photovoltaic;
SEGS = Solar electric generation station; **DNI**: direct normal irradiation.

APPENDIX B

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