

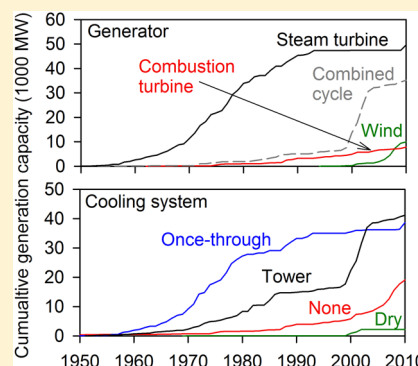
Controls on Water Use for Thermoelectric Generation: Case Study Texas, U.S.

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Supporting Information

ABSTRACT: Large-scale U.S. dependence on thermoelectric (steam electric) generation requiring water for cooling underscores the need to understand controls on this water use. The study objective was to quantify water consumption and withdrawal for thermoelectric generation, identifying controls, using Texas as a case study. Water consumption for thermoelectricity in Texas in 2010 totaled ~0.43 million acre feet (maf; 0.53 km³), accounting for ~4% of total state water consumption. High water withdrawals (26.2 maf, 32.3 km³) mostly reflect circulation between ponds and power plants, with only two-thirds of this water required for cooling. Controls on water consumption include (1) generator technology/thermal efficiency and (2) cooling system, resulting in statewide consumption intensity for natural gas combined cycle generators with mostly cooling towers (0.19 gal/kWh) being 63% lower than that of traditional coal, nuclear, or natural gas steam turbine generators with mostly cooling ponds (0.52 gal/kWh). The primary control on water withdrawals is cooling system, with ~2 orders of magnitude lower withdrawals for cooling towers relative to once-through ponds statewide. Increases in natural gas combined cycle plants with cooling towers in response to high production of low-cost natural gas has greatly reduced water demand for thermoelectric cooling since 2000.



INTRODUCTION

With ~90% of electricity generation in the U.S. in 2010 (www.eia.org) requiring water for cooling in thermoelectric (steam electric) power plants, it is important to understand how much water is used for thermoelectric generation to assess vulnerability of power generation to water shortages and determine potential impacts of generation on water resources. Many recent reports highlight the role of water in electricity generation.^{1–4} Life cycle analysis indicates that most water in thermoelectric power plants is used for cooling steam rather than in fuel extraction, atmospheric emissions controls, or other purposes.^{5,6} Large-scale expansion of natural gas production using hydraulic fracturing and increased use of natural gas in thermoelectric generation may have important implications for water resources.^{7,8} Because of the long lifespan of power plants (30–50 years), the current fleet represents a legacy of past fuel choices, generator technologies, and cooling systems.

There seems to be a lack of generic understanding on water use for thermoelectric generation. Water use is a general term that can refer to water withdrawals, defined by the U.S. Geological Survey (USGS) as water removed from a water source, most of which is returned to the source, or water consumption, defined as the portion of water removed that is lost to the system by evaporation and unavailable to other users.⁹ Many studies emphasize the large water withdrawals associated with thermoelectric generation (41% of U.S. water withdrawals in 2005); however, 98% of this water is returned to the source.⁹ Equating water withdrawals for thermoelectric

generation to the number of cities that could be supplied with water (67–70 New York cities¹) seems to ignore the fact that ~98% of the water is available to other users downstream of the return, although the water is not available to others between points of withdrawal and return.¹⁰ Some studies suggest that thermoelectric generation is also a major consumer of freshwater resources;^{11,7} however, U.S.-based estimates indicate that consumption for thermoelectric generation was ~3% of total freshwater consumption in the U.S.¹² While much emphasis has been placed upon reducing water withdrawals by converting cooling systems from once-through cooling to wet cooling towers, a recent report highlights the increased water consumption rates of cooling towers.¹³

There are many concerns about data availability and quality for quantifying cooling water requirements for thermoelectric generation. The Government Accountability Office (GAO) recommended that the Department of Energy-Energy Information Administration (DOE-EIA) and USGS collaborate to improve water use estimates.¹⁴ The EIA relies on self-reporting from power plant operators on electricity generation and water use and has revised its forms twice since 2009 to improve the data. The USGS is using various approaches to estimate consumption and withdrawals, including analysis of EIA data and a new linked water and heat balance.^{15,16}

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However, USGS suggests that accurate measurement and reporting of water use is required to develop reliable estimates of water use at local scales.¹⁵

What Are the Basic Components of Thermoelectric Power Plants and How Do They Use Water? If we want to reduce water use for thermoelectric generation, we need to understand the primary drivers or controls on water consumption and withdrawal.¹⁷ Because of long lifespans of power plants, current power plant choices may impact water resources for decades into the future. Many studies show that different aspects of power plants, such as energy source, generator technology, or cooling system have varying water requirements. For example, switching fuel sources from coal to natural gas saves water⁷ and switching from once-through cooling to cooling towers increases water consumption.¹⁸ Therefore, it is important to understand the basic components of thermoelectric power plants and how they relate to water consumption and withdrawal.

Major components of thermoelectric power plants include the (a) energy source, (b) generator technology or prime mover to generate electricity, and (c) cooling system¹⁷ (Figure 1). Thermoelectric power plants primarily generate electricity by either burning fossil fuels (coal or natural gas) or using nuclear fission to boil pure water, creating steam that drives turbines that generate electricity (Figure 2). Thermoelectric

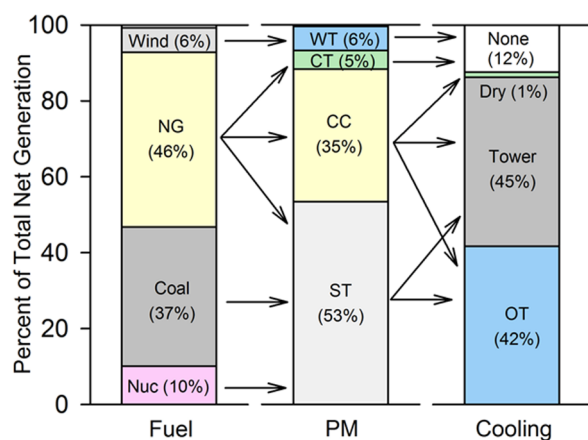


Figure 1. Basic components of power plant systems based on net electricity generation for Texas in 2010 (411 million MWh or TWh), including thermoelectric energy sources: nuclear (10%) and fossil fuels [coal (37%), natural gas (46%)], and nonthermoelectric energy sources, mostly wind (6%), and other minor fuel sources (total ~1%, not shown), including hydroelectric, petroleum, and biomass; generator technologies or prime movers (PM) (steam turbines, ST, 53%), combined cycle (CC, 35%), gas, or combustion turbines (CT, 5%), wind turbines (WT, 6%), and other minor generator types (total ~1%, not shown), including hydroelectric turbines and internal combustion engines; and cooling systems, once-through (OT, 42%), wet cooling towers (45%), dry cooling towers (1%), and no cooling (12%). Steam turbines use Rankine cycle to generate electricity and are not fuel specific: they are used with nuclear, coal, and natural gas energy sources. All nuclear and coal plants in Texas use steam turbines. Combined cycle plants use combustion turbines (CT) and steam turbines (ST) and are fuel specific, used with natural gas. Integrated gasification combined cycle (IGCC) can be used with coal, but these plants are very rare in the U.S. and globally. Combustion turbines are also referred to as gas turbines and are similar to jet engines. They use natural gas as a fuel source and the Brayton cycle to generate electricity.

plants generated 86% of net electricity in Texas and 89% in the U.S. in 2010 (www.eia.org).

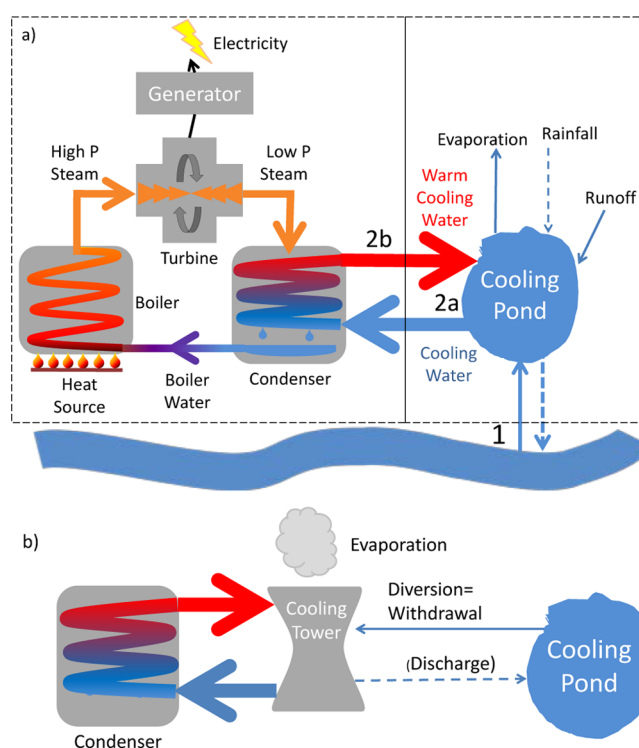


Figure 2. Schematic diagrams of power plant steam turbine generation and cooling systems: (a) steam turbine (coal, nuclear, or natural gas) with once-through recirculating pond cooling system. The internal closed-loop steam cycle is shown, including boiler, turbine, and condenser, and the external cooling cycle is also shown from pond to condenser, returning to pond. The footprint could be defined for the power plant with water circulation/withdrawal for cooling based on the cycle labeled 2; alternatively, a larger footprint could be defined including the pond with water withdrawal from the river to the pond (labeled 1) and representing the amount of water required to replenish the pond water (termed *makeup water*). (b) Wet cooling tower with dominant circulation between the power plant and the tower and low withdrawal from the pond or other water source to the tower. Water can be returned to the pond (discharge) or the system may have zero discharge. For classification of cooling systems by EIA, see Supporting Information, Figure S1).

Primary Energy Sources. Primary energy sources in thermoelectric power plants in Texas include nuclear, coal, and natural gas sources (www.eia.org) (Figure 1).

Generator Technologies. Generator technologies, or prime movers, for thermoelectric power plants for Texas include steam turbines (ST), combustion turbines (CT), sometimes referred to as gas turbines, and combined cycle (CC).

Traditional CTs have no cooling water requirements; however, newer models use a relatively minor amount of water to prechill inlet air. A combined cycle plant combines CTs with STs in sequence, generally in a ratio of 2 CTs to 1 ST. Because cooling water is not required for traditional CTs, the rule-of-thumb is that CC plants require about a third of the water that ST plants require because of the general ratio of 2 CTs/1 ST.

Cooling Systems. Cooling systems in thermoelectric power plants are required to condense steam. These cooling systems can be based on water, air, or both (hybrid system). Cooling

water forms a separate system from the closed-loop steam cycle. Water-based cooling systems are broadly classified as (1) once-through or open-loop systems (e.g., rivers, lakes, reservoirs, ponds) (Figure 2a); and (2) recirculating or closed-loop systems (wet cooling towers) (Figure 2b).

The term *once-through* technically refers to water moving once through the condenser. Once-through systems in the eastern U.S. generally consist of power plants that withdraw water directly from a river and then discharge that water back to the river farther downstream at a higher temperature. Dissipation of waste heat from the power plant in water bodies (rivers or ponds) occurs by evaporation, long wave radiation, conduction (as sensible heat), and convection.¹⁹ The evaporative component of that dissipation represents the consumptive water use. It is difficult to apply the once-through concept to ponds where water is continuously recirculated between the pond and the power plant (labeled 2a in Figure 2a). In many analyses, the term *withdrawal* is applied to this circulation. However, if the plant boundary is redrawn to include the pond, withdrawals might instead refer to water transfers from another river/lake/reservoir to the cooling pond (typically termed *diversion*, labeled 1 in Figure 2a) to replace evaporative losses in the cooling pond, in which case circulation between the pond and the plant would not be accounted for separately. Classifications of cooling systems according to EIA are shown in Supporting Information, SI, Figure S1. In wet cooling towers, water moves through the condenser and then to the tower, where it evaporates (Figure 2b). Evaporation is the only significant heat-dissipation process in wet cooling towers; therefore, consumption is up to 50% greater for cooling towers relative to once-through systems that can also dissipate heat using radiation, conduction, and convection.¹⁹

What is the Status of Knowledge of Water Use for Thermoelectric Generation? Several recent studies provide reviews or meta-analysis of water use estimates from the literature.^{2,3,20,4} However, many estimates in the literature are based on dated information of uncertain quality.^{21,22} Multiple regression was used to identify important determinants of water use for power generation based on 1996–2000 EIA data.²¹ However, reliable estimates of water consumption were particularly difficult to obtain from earlier data.²¹ Many of the values provide representative water use estimates for common thermal power plants and cooling system types rather than an assessment of original data from EIA or other sources. Some recent studies are based on analysis of original data from EIA, for example, 2006 EIA data for Texas²³ and 2008 EIA data for the U.S.²⁴ Many of the studies focus on future projections of water use for various environmental regulations, climate change scenarios, and carbon-based policies.^{25,26}

Study Objective. The primary objectives of this study were to quantify water consumption and withdrawal for thermoelectric generation and to better understand controls on water use. Texas provides an excellent case study because of data availability on water use from multiple sources (EIA, Texas Commission on Environmental Quality, TCEQ, and Texas Water Development Board, TWDB). The detailed analysis and cross-checking and verification of water-use data from multiple sources conducted in this study and meetings with power plant operators to assess data quality represent one of the most intensive examinations of raw data to date. Additionally, Texas' climatic conditions range from humid in the east to arid in the west, providing an analog for U.S. electricity generation. Heavy reliance on surface water for cooling in Texas is also typical of

that in the U.S. The range of fuel sources (coal, natural gas, and nuclear) and variety of generator technologies and cooling systems are typical of those in the U.S. The understanding of controls on water use developed in this study should be applicable to all thermoelectric power generation. Recent trends in water use related to expansion of natural gas (NG) plants in Texas is much more advanced than what is occurring in the U.S. but may provide some ideas of what is projected to occur throughout the U.S. in the near future, with large-scale expansion of NG production through hydraulic fracturing. Data from 2010 were used because this year represents near normal climatic conditions (precipitation 35.4 in. [899 mm], 26% higher than long-term mean of 28.1 in. [714 mm], 1896–2010). This work builds on a previous study quantifying water consumption for thermoelectricity in Texas in 2006²³ by taking advantage of improvements in EIA data since 2006 and focusing on controls rather than on future projections. Quantitative information on water use and understanding of controls provided by this study should be very valuable for future management of water and energy to ensure reliable electric generation.

■ DATA SOURCES AND ANALYSES

Water use for thermoelectric cooling was obtained from the EIA, TCEQ, and TWDB databases. Power generation is organized by generator technology and water use is associated with cooling systems in EIA Form 860, but direct links between generators and cooling systems are not provided. Generators are associated with boilers and boilers are, in turn, associated with cooling systems. Each connection may represent a one-to-one, one-to-many, or many-to-one association. Information on generators and cooling systems were aligned. Operational information, including monthly power generation and water use, are reported in EIA Form 923. Water use is categorized as rates of diversion (labeled 1 in Figure 2a), withdrawal (2a), discharge (2b), and consumption (SI, Figure S1).

The TCEQ water rights database includes reported monthly total diversion (assumed to represent EIA withdrawal), return, and consumption volumes from surface water. The TWDB database includes reported annual total power plant water intakes (purchased or self-produced) by source (surface water, groundwater, salt water, or reuse) and reported as water withdrawal and water use. For comparison with EIA data, TWDB water use was assumed to represent consumption; however, it may reflect diversion. Data from TCEQ and TWDB, unlike that from EIA, represent total plant values for all uses and may not be cooling system specific because information on cooling systems is not included in these databases. Water consumption or withdrawal intensities or rates (gal/kWh or L/kWh) were calculated by dividing water consumption or withdrawal by net generation.

Power plant capacity factors were calculated by dividing actual power plant output (net generation) by theoretical output if operated at full nameplate capacity. Thermal efficiencies were calculated according to fuel source and generator technology by dividing electricity output (net generation MWh) by heat input of fuel source (gigajoule, GJ), using the conversion factor (1 MWh = 3.6 GJ).

■ RESULTS AND DISCUSSION

Evaluation of Reliability of Water Use Data. Cooling water was required for 264 generators at 143 operational power

plants in Texas in 2010, representing 354 TWh of cooled net generation, and accounting for 86% of total net generation (411 TWh). Data on water consumption was reported by EIA for 71 plants (65% of net generation), by TCEQ for 43 plants (56% of net generation), and by TWDB for 62 plants (58% of net generation) (SI Table S1). Data on water withdrawal was reported by EIA for 82 plants (73% of net generation), TCEQ for 45 plants (55% of net generation), and TWDB for 64 plants (61% of net generation). There was no water consumption or withdrawal data for 39 plants (10% of net generation). EIA did not include any information on nuclear plants for 2010.

EIA data on water consumption/withdrawal were used as the default data and represent the only data source for most regions in the U.S. Comparison of water use from EIA and TCEQ, where both are available, indicates that water use values agree to within 20% for 80% of overlapping consumption rates and 57% of overlapping withdrawal rates for once-through systems (Figure 3). Many of the consumption and withdrawal rates for

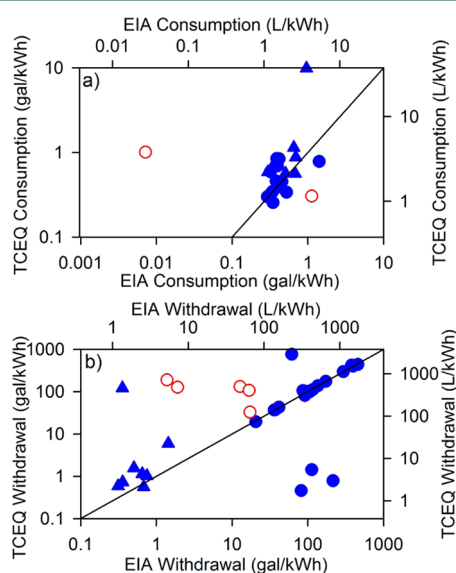


Figure 3. Comparison of (a) water consumption and (b) water withdrawal intensities for power plants reported by EIA and by TCEQ. Circles: Once-through cooling ponds, Triangles: wet cooling towers. Solid symbols represent EIA data that were selected, while open symbols indicate TCEQ data that were selected. Diagonal lines represent 1:1 relationship. For additional comparisons among data sources, see Supporting Information, section 2.

power plants with cooling towers reported to TCEQ, though reasonable, tend to be somewhat greater than those reported to EIA, possibly reflecting additional consumption for purposes other than cooling. Some of the outliers are up to an order of magnitude different, suggesting reporting of consumption for withdrawal or vice versa. Although TCEQ reports diversion, the values are often close to withdrawals reported by EIA but sometimes may reflect true diversion. For example, the South Texas Project nuclear plant reports diversion, which is close to consumption for that plant, whereas the Comanche Peak nuclear plant reports withdrawal values. Where EIA data differ markedly from TCEQ data and were judged less reliable, that is, highly inconsistent with other plants within the same generator/cooling category, then TCEQ estimates were used. In a limited number of cases, TWDB data were used where data were not available from EIA or TCEQ, or TWDB data were

most consistent with other power plants in similar categories. More detailed information on data comparisons is provided in SI, section 2. In the absence of any water use data or for systems with questionable data, the category weighted average values of similarly configured plants were assigned (representing 18% of consumption and 24% of withdrawal total volume).

Statewide withdrawal required for cooling was calculated separately for once-through systems by multiplying hours of plant operation required to generate reported electricity output at full nameplate capacity by cooling system pump capacity rating specification and represented 66% of reported actual withdrawal derived from the various databases. This comparison indicates that about one-third of water withdrawn for thermoelectric generation in the state is not actually required for cooling. Plants with high capacity factors (nuclear, 92%; coal, 73%) are considered baseload plants and reported withdrawals are equal to (for nuclear ST) or slightly higher than (12% for coal ST) cooling water requirements. However, plants with low capacity factors that operate as peaking plants often have low electrical output levels, that is, are idling in anticipation of meeting a near-term peak demand; however, their cooling circulation pumps can only operate at full capacity, resulting in overestimation of water withdrawal requirements for cooling, particularly for NGST (24% capacity factor) and NGCC (40% capacity factor) plants with once-through cooling systems. Estimated withdrawals required for cooling in these plants were only 16% (NGST) to 33% (ST part of CC plants) of reported withdrawals.

Water Consumption of Thermoelectric Generation.

Water consumption totaled ~ 0.43 maf (0.53 km^3) for thermoelectric generation in Texas in 2010, representing 4.2% of the states' water consumption (10.1 maf, 12.5 km^3 ; 2010) (Tables 1 and 2, Figure 4). This water consumption is much lower than consumption for irrigation (65%), municipal use (17%), and manufacturing (9.2%). Indirectly, water consumption for thermoelectric cooling represents $\sim 5\%$ of typical household water withdrawals (SI, section 3, Figure S3). Although water consumption for thermoelectric cooling represented only 4.2% of total statewide water consumption, locally it can be important if water availability is low.

Water Withdrawal for Thermoelectric Generation.

Water withdrawals for thermoelectric generation vary depending on where the system boundary is defined. EIA classifies cooling systems as once-through, recirculating ponds, and cooling towers. Only two power plants with once-through cooling systems withdraw water directly from a river in Texas (the Guadalupe River, SI, section 4, Figure S4), similar to typical once-through systems in the eastern U.S. (SI Figure S5). The remaining once-through power plants in Texas withdraw water from ponds/reservoirs, which are also found throughout the eastern U.S. (SI Figure S5). There is no systematic variation in terms of storage volume and recirculation estimates (pond storage/withdrawal rate) for systems classified by EIA as once-through systems versus recirculating ponds in Texas (SI Figure S6), suggesting that the classification is somewhat arbitrary and generally lacks physical meaning. Examining Google Earth maps of most cooling ponds/reservoirs shows structures designed to increase recirculation efficiency (SI Figure S7); therefore, we classified all these systems as recirculating ponds/reservoirs for simplicity.

Withdrawals are generally calculated assuming the system boundary is at the power plant, with withdrawals representing water circulation between the cooling pond and power plant

Table 1. 2010 Texas Net Electricity Generation Requiring Cooling (354 TWh) and Cooling Water Consumption and Withdrawal Amounts and Intensities/Rates^a

Grouping		N	NetG	Consumption		Withdrawal	
			(TWh)	(kaf)	(gal/kWh)	(kaf)	(gal/kWh)
Fuel	Nuc	4	41	59.0	0.46	4,619	36
	Coal	39	151	248.4	0.54	12,273	27
	NG	379	160	115.5	0.23	9,289	19
	Oth	21	2	3.8	0.57	4	0.60
Gen Tech	ST	175	219	349.1	0.52	24,316	36
	CC	268	135	77.6	0.19	1,867	4.5
Cool	OT	115	171	251.9	0.48	25,986	49
	T	328	183	174.8	0.31	198	0.35
All	All	443	354	427	0.39	26,184	24

^aValues in bold indicate dominant control of generator technology on water consumption, with combined cycle plants having 63% lower consumption intensities than steam turbines and cooling technology on water withdrawal with once-through cooling ponds having about two orders of magnitude higher withdrawal than wet cooling towers. The statewide estimates are represented by three different approaches: (1) fuel source, (2) generator technology, and (3) cooling system. N: Number of generators. NetG: Net generation in TWh = million MWh; NG: Natural gas; Nuc: Nuclear; Oth: Other; Gen Tech: Generator technology or prime mover; Cool: Cooling system type; ST: Steam turbine. CC: Combined cycle. OT: Once-through. T: Wet cooling tower. Total cooled net generation of 354 TWh represents 86% of 411 TWh total net generation. Consumption of 427 thousand ac-ft (kaf) is equivalent to 0.526 km³. Total water withdrawal of 26 184 kaf is equivalent to 32.3 km³. Because water consumption is affected by generator technology and cooling systems, totals and rates do not only reflect the reported category but are also impacted by other categories. For example, STs are predominantly once-through systems and CCs are mostly cooling towers, both of which affect water consumption. Note water consumption intensity or rate (gal/kWh) is controlled primarily by generator technology (CC 63% lower than ST, shown in bold), and withdrawal intensity or rate (gal/kWh) is controlled primarily by cooling system (towers ~2 orders of magnitude lower than ponds, shown in bold). (Metric version of Table in SI, Table S4).

(Figure 2a). The withdrawal value from analysis of the EIA/TWDB/TCEQ databases for 2010 totaled 26.2 maf (32.3 km³). Withdrawals for thermoelectric generation represent 66% of the state total (26.2 maf +13.4 maf [nonthermoelectric withdrawals] = 39.6 maf, 48.8 km³) (Table 1). However, only about 2% (0.43/26.2 maf) of this water is lost to evaporation from cooling towers or forced evaporation from ponds/reservoirs due to increased temperatures.

The system boundary could also be defined to include the cooling pond (Figure 2a), which may be appropriate for recirculating ponds and in this case withdrawal from the river/lake to the recirculating cooling pond, sometimes referred to as diversion (SI Figure S1), would be much lower, reflecting the net watershed balance for the pond (rainfall + runoff into pond minus natural + forced evaporation). These withdrawals to replenish the pond, termed makeup water, would be closer to water consumption. With the larger footprint (including the pond), water consumption should increase because it would include natural evaporation from the pond. Although initial reservoir impoundment removes a significant amount of water from the river circulation, withdrawals from rivers/reservoirs afterward are only required to replenish the cooling pond.

Table 2. 2010 Texas Net Electricity Generation by Fuel-Generator-Cooling System Configurations and Estimated Cooling Water Consumption and Withdrawal Rates and Volumes^a

Fuel	Gen Tech	Cool	N	NetG (TWh)	Consumption		Withdrawal	
					(kaf)	(gal/kWh)	(kaf)	(gal/kWh)
Nuc	ST	OT	4	41.3	59.0	0.46	4,619	36
Coal	ST	OT	25	103.3	166.4	0.52	12,182	38
		T	14	47.4	82.0	0.56	90	0.62
NG	ST	OT	63	17.1	23.1	0.44	7,406	141
		T	34	6.8	14.3	0.68	15	0.71
		C ¹	9	0.9	0.3	0.12	0.4	0.15
	CC	OT	23	9.8	3.5	0.12	1,779	59
		T	140	75.6	53.8	0.23	61	0.26
		C ¹	44	29.6	13.2	0.14	18	0.20
Oth	ST	T	13	1.7	3.6	0.68	3.8	0.71
		C ²	8	0.4	0.2	0.12	0.2	0.15
NG	ST	C ²	5	0.5	0.2	0.12	0.2	0.15
	CC	C ²	61	19.9	7.1	0.12	9.7	0.16
All	ST,CC	All	443	354	427	0.39	26,184	24
All	All	All	867	411	427	0.34	26,184	21

^aNumber of generators (N), fuel sources include nuclear (Nuc), coal, natural gas (Ng), other (Oth). Generator technologies (Gen Tech) include steam turbines (ST) and combined cycle (CC). Cooling systems (Cool) include once-through (OT), wet cooling towers (T), and cogeneration (combined heat and power, C). (Metric version of Table in SI, Table S5). Assessing impacts of **generator technologies** on water consumption rates with similar cooling systems: once-through ponds, CC 73% lower consumption intensity than ST (0.12 vs 0.44 gal/kWh); wet cooling towers, CC 66% lower than ST (0.23 vs 0.68 gal/kWh). Assessing impacts of **cooling systems** on water consumption rates with similar generator technologies: Coal ST, towers 8% higher than once-through ponds (0.56 vs 0.52 gal/kWh); NGST, towers 55% higher than once-through ponds (0.68 vs 0.44 gal/kWh); NGCC, towers 92% higher than once-through ponds (0.23 vs 0.11 gal/kWh). Note: There are not many examples of NGCC with once-through ponds, accounting for only 2.4% of all net generation and the category represents only 0.8% of all water consumption and 7% of all water withdrawals. Assessing the impacts of generator technology on water withdrawal rates with similar cooling systems: once-through ponds, water withdrawal intensities are 58% lower for NGCC plants relative to NGST plants (59 vs 141 gal/kWh); Cooling towers, water withdrawal intensities are 63% lower for NGCC plants relative to NGST plants (0.26 vs 0.71 gal/kWh). All fuel, all generator technologies, and all cooling systems refer to both thermoelectric and nonthermoelectric generation. Total water consumption of 427 thousand acre feet (kaf) = 0.43 million acre feet = 0.53 km³ = 526 Mm³. 1 km³ = 1.233 maf. Water consumption intensity of 0.34 gal/kWh = 1.3 L/kWh statewide. 1 gal = 3.785 L. ^bCogeneration with reported water use. ^cCogeneration with no reported water use.

Controls on Water Consumption/Withdrawal. A variety of factors can impact water consumption/withdrawal, including fuel type, generator technology, cooling system, thermal efficiency, capacity factor, and age of plant.²¹

Controls on Water Consumption. Water consumption is controlled primarily by (a) generator technology, which is related to thermal efficiency, and by (b) cooling system design with up to 50% higher consumption in cooling towers relative

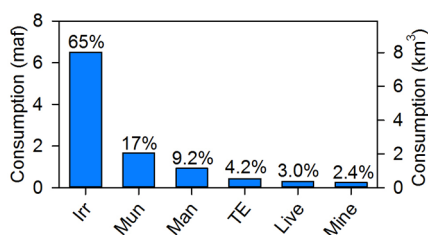


Figure 4. Water consumption for thermoelectric generation (TE) in Texas relative to water consumption for other sectors based on 2010 data from the Texas Water Development Board (www.twdb.state.tx.us). Total water consumption was 10.1 maf (12.5 Mm³). Water consumption was estimated from water withdrawal reported by TWDB by assuming 85% of irrigation water and 85% of manufacturing water was consumed. These percentages are based on comparison of water consumption and withdrawal data for Texas for 1995 from the USGS data.¹² Most water withdrawn for mining in Texas is consumed.²⁹ The only sector with low water consumption is municipal, with an estimated 30% consumed for residential irrigation and 10% lost to leakage in Texas.³⁰ Irr: Irrigation. Mun: Municipal. Man: Manufacturing. TE: Thermoelectric. LS: Livestock. Mine: Mining.

to ponds (Figure 5). (a) Generator technologies impact water consumption through their thermal efficiency, which is defined as the fraction of heat from fossil fuels or nuclear fission that is converted to electricity (electricity output/heat or energy input) (SI, section 5).^{16,17} Increasing the thermal efficiency of a system means that more of the energy from the fuel source is converted to electricity, reducing residual or waste heat requiring cooling. Combined cycle plants have the highest thermal efficiency (NGCC, 44%) because residual heat from the CT part is used by the ST part of CC plants through a heat recovery steam generator (HRSG) system (Figure S8, Table S2). In contrast, thermal efficiencies of coal and nuclear ST plants are lower (both 36%) than that of NGCC plants. Increasing temperatures of cooling ponds would also reduce thermal efficiency; however, this effect is much lower than temperature differentials between different generator technologies (ST, CT, CC).

Total water consumption by generator technology is 82% for STs and 18% for CCs in Texas (Table 1). All traditional ST generation requires cooling, whereas, statewide, generation from CC plants is 71% CT, which does not require cooling, and 29% ST, which requires cooling. Therefore, CC plants should have about 70% lower cooling water requirements than ST plants on average statewide, similar to the 63% found for the 2010 data (CC 0.19 gal/kWh vs ST 0.52 gal/kWh) (Table 1). Comparing similar cooling technologies (once-through and cooling towers) results in water consumption intensities for CC generation being 66–73% lower than for ST generation (Table 2, Figure 5), consistent with that expected from the noted CT to ST ratio in CC plants.

The impact of cooling systems on water consumption was evaluated by comparing cooling systems for plants with similar generator technology. One would expect up to 50% higher water consumption for wet cooling towers relative to once-through ponds, if everything else is the same. Results show that, for NGST generators alone, water consumption intensity is 55% higher for wet cooling towers relative to once-through ponds (Table 2). Similarly, for NGCC generators alone, water consumption intensity for towers is 92% higher than that for ponds. For coal plants, the difference is only 8% higher. The large range in water consumption intensities for different cooling systems may reflect limited data for some categories (Table 2), possible operational differences, (for example, relative use of CT [no cooling] versus ST in CC plants with different cooling systems), or reporting problems. Although wet cooling towers generally consume more water than once-through ponds for a given generator technology, the average statewide consumptive water intensity for all cooling towers (0.31 gal/kWh) is contrarily 35% lower than that of all cooling ponds (0.48 gal/kWh) because most cooling tower generation is associated with CC generators (Table 1), with much lower cooling requirements per kWh than other generator technologies (71% of CC net generation is from CTs, requiring no cooling). These statewide comparisons of once-through systems and towers underscore the dominant role of generator technology (ST, CT, CC) over cooling system technology in controlling water consumption. Water consumption rates from this analysis according to fuel, generator, and cooling system

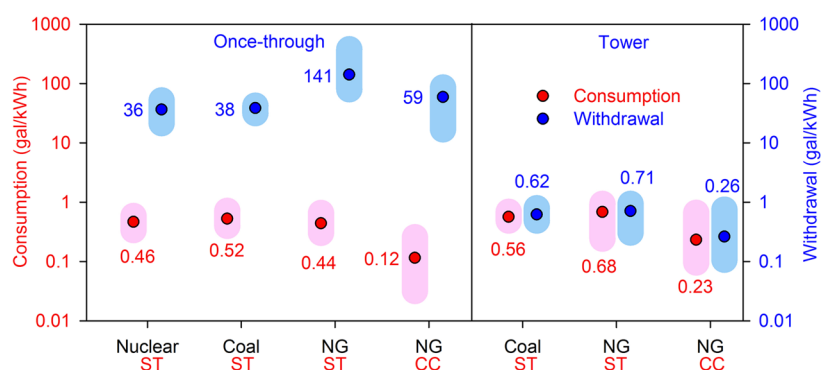


Figure 5. Relationship between water consumption and water withdrawal for different power plants according to fuel type–generator–cooling system combinations (Table 2). Points represent mean values weighted by net generation. Shaded areas represent approximate range of values (0.1–0.9 percentile). NG: Natural gas. ST: Steam turbine. CC: Combined cycle. Note the log scales for consumption and withdrawal intensities or rates. Withdrawal rates are controlled primarily by the cooling systems as shown by the large difference between once-through cooling (mostly recirculating ponds) on the left and cooling towers on the right. Note the trade-off between water withdrawal and consumption rates, with higher withdrawal and lower consumption for once-through systems and lower withdrawal and higher consumption for wet cooling towers. The low withdrawal rates for some NGCC plants with once-through cooling reflect plants that mostly operated the CT parts of CC plants with low capacity factors. Within each cooling system, CC plants have the lowest consumption rates. (Version with metric units in SI, Figure S11).

(Table 2) are generally within the range of those reported from the literature (SI Table S3).³

The age of a plant is also a factor in thermal efficiency and water use.²¹ CC plants were the only plants to show a distinct increase in thermal efficiency based on analysis of decadal data, with less efficient plants constructed before 1990 (~36% efficient) compared to those that have come on-line since (~46% efficient). This increased thermal efficiency should have reduced water consumption.

Controls on Water Withdrawals. Traditionally water withdrawals are calculated from the water source (pond/reservoir) to the power plant, resulting in statewide water withdrawal intensities for 2010 of 49 gal/kWh for once-through systems, more than 2 orders of magnitude higher than withdrawal intensities for wet cooling towers (0.35 gal/kWh) (Table 1). Water withdrawals are also affected to a lesser extent by generator technology or thermal efficiency. For similar cooling systems, water withdrawal intensities are 58–63% lower for NGCC plants relative to NGST plants (Table 2). Withdrawal intensities from this study are generally within the range of reported withdrawals from the literature³ (SI Table S3). Water withdrawal volumes are much higher in the eastern part of the state, where ponds and reservoirs are concentrated (SI Figure S9). Total water withdrawal by cooling system is 99% for ponds and reservoirs (26 maf) and 1% for wet cooling towers (0.2 maf) for 2010 data (Table 1).

There are several issues associated with water withdrawals, including (a) water storage requirements to support withdrawals, (b) impacts of withdrawals on other water users withdrawing water from the same pond/reservoir or on downstream users, (c) discharge temperature issues (Clean Water Act 316A), and (d) effects of cooling water intake structures on aquatic species (CWIS, Clean Water Act 316B). The issues vary depending on whether it is an industrial pond or multipurpose reservoir that is used for power plants and water supply. Of the 43 ponds/reservoirs supplying water directly to power plants in Texas, 25 are industrial ponds and 18 are multipurpose, primarily water supply. The industrial ponds represent only 1 maf (1.2 km³) of the associated water storage but account for 80% of the net electricity generation from ponds, whereas the multipurpose ponds/reservoirs represent 3.4 maf (4.2 km³) of water storage but only 20% of the net electricity generation. Industrial ponds generally have smaller drainage areas (≤ 300 mi², mean 42 mi²) than multipurpose reservoirs/ponds (>150 mi², mean 3700 mi²) (SI Figure S10).

Although reservoir storage must be available to support the large water withdrawals at power plants with once-through cooling systems, less water is required to replenish industrial ponds supporting once-through cooling systems than those supporting wet cooling towers, other factors being equal, because of up to 50% to 100% higher water consumption associated with towers relative to once-through cooling systems. Once-through systems supported by multipurpose reservoirs may reduce water availability for municipal water supplies abstracting water from the same reservoir but can actually increase water available for downstream users because of lower consumption relative to wet cooling towers. Many industrial cooling ponds often need only to meet discharge temperature regulations where the pond physically discharges back to the supplying river/reservoir system (Figure 2a). However, industrial ponds only discharge such water during very high flow periods; therefore, discharge temperatures may

not a concern for many industrial ponds. In fact, industrial ponds may protect larger reservoir/river systems from high temperatures. Cooling water intake structures (CWIS) may affect aquatic species through entrapment and entrainment. Because industrial ponds are man-made, they may or may not be stocked with fish. Impacts on fish can be addressed using Best Technology Available, such as screens etc., where there are concerns about CWIS. Therefore, there are trade-offs between once-through systems, with at least order of magnitude higher water withdrawals and impacts on aquatic species and thermal discharges, relative to wet cooling towers with much lower water withdrawals but up to 50%- to 100%-higher water consumption. Attributes of industrial ponds and multipurpose ponds/reservoirs should be considered when promoting or mandating a particular cooling technology.

Temporal Trends in Power Plant Systems. The long lifespan of power plants (30–50 years) results in the current Texas power plant fleet representing a legacy of past variations in fuel availability and costs, water availability and water rights, and advances in technologies—for example, NGCC systems, which impact trends in water consumption (Figure 6). Fuel

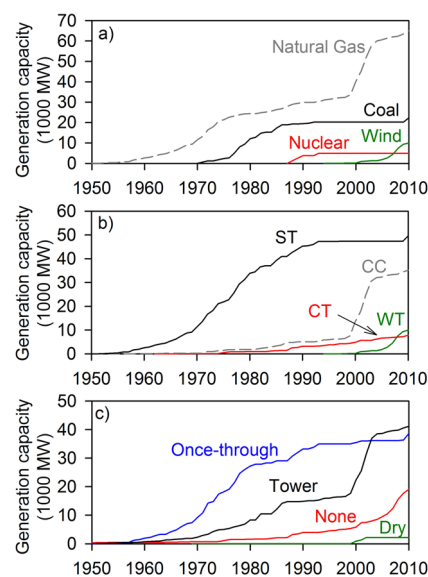


Figure 6. Cumulative generation capacity in 1000s of MW or GW of the existing Texas power plant fleet by (a) fuel type, (b) generator technology, and (c) cooling system type. The total nameplate capacity in 2010 was 117 500 MW. Hindcasts were developed from the current power plant fleet based on information on when the systems came online (www.eia.org). The original fleet consisted mostly of NGST with increasing coal ST and also increasing nuclear ST in the late 1980s in response to the 1973 oil embargo. Natural gas increased markedly from 1998–2004 (85% increase) and consists mostly of combined cycle generators (400% increase 1998–2004) and cooling towers (118% increase). Wind energy increased significantly in mid-2000s related to the Texas Renewable Portfolio Standard and the Federal production tax credit for wind energy, renewed in 2013.

sources varied over time, from predominantly natural gas in the 1960s and early 1970s to coal and nuclear sources following the 1973 oil embargo and more recently to large increases in natural gas generation (85% increase 1998–2004) in response to hydraulic fracturing and low natural gas prices.⁸ The dominant generator technology was STs until the early 1990s; however, CC plants markedly increased in the late 1990s (400% increase 1998–2004). Proliferation of ponds, mostly in

the 1970s and 1980s (340% increase) reflects availability of large quantities of unappropriated surface water and increases in water rights permitting during this time and lower cost and higher cooling efficiency of ponds relative to wet cooling towers.

If future EPA regulations mandate conversion of existing once-through pond cooling systems to tower cooling systems, water consumption would increase by up to 50–100% if everything else (e.g., generator technology etc) remained the same. What we have seen in the past decade and a half is that new plants are mostly NGCC with cooling towers. Reduced cooling requirements associated with CC plants should more than compensate for increased consumption intensity associated with cooling towers because the latter only applies to the ST part of CC generation and should result in net reduction in water consumption intensity.

Future projections of water use are based on Electric Reliability Council of Texas (ERCOT) projections of future net generation for Texas. Historically, annual energy for 2003–2012 grew at an average annual growth rate (AAGR) of 1.5%.²⁷ Forecasted AAGR of energy demand is 1.9% to 2017 and 1% to 2030. Future projections of water use presented here are based on extending the current power plant fleet to 2030 with no retirements except for NGST plants, for which the declining generation rate of ~ -2 MWh/year that occurred between 2004 and 2010 is projected forward to result in no NGST generation by 2023. Finally, applying the forecasted AAGRs results in 30% total growth between 2010 and 2030, with all new generation from NGCC plants with wet cooling towers. Based on these assumptions, water consumption in terms of total volume is projected to grow at an average annual rate of 0.2%, resulting in total water consumption by power plants increasing $\sim 4.6\%$ by 2030 relative to current levels. However, water consumption intensity is projected to decrease by $\sim 19\%$ relative to the overall 2010 rate because of the assumed new power plant type (NGCC with cooling towers). Withdrawal volumes are projected to decline slowly (average -0.8% annually) until 2023, reflecting the NGST retirements, and because the assumed new systems use cooling towers that withdraw at least an order of magnitude less water than ponds, and withdrawal intensity is projected to decrease by $\sim 31\%$ overall by 2030. These projections of water consumption and withdrawal are considered upper bounds in terms of ERCOT projections because retirements of current plants (except NGST plants) were not considered and new generation was assumed to be NGCC, whereas ERCOT²⁸ estimates 36% from NGCT (no cooling requirement) and 64% from NGCC in a Business as Usual (BAU) projection and much more power from renewables in other scenarios (BAU with updated wind shapes, NGCC 10%, NGCT, 19%, solar, 27%, and wind, 45%).²⁸ However, ERCOT projections might change markedly if prices for natural gas increase and generation from coal and nuclear sources increase. In addition, water use would increase if carbon capture is required in the future.

Broader Implications. While the analysis in this study focused on Texas, the results have broader implications. The understanding of controls on water consumption and withdrawal can apply to power plants anywhere and should be considered as various regulatory and economic forces shift emphasis to different technologies, allowing impacts on water resources to be considered. The importance of generator technology controlling water consumption with up to 63% reduction in consumption intensity for NGCC plants relative to

traditional STs (0.19 vs 0.52 gal/kWh) is very important, with projected future expansion of NGCC plants in Texas and throughout the U.S. The use of cooling towers instead of once-through cooling ponds or rivers has been decreasing water withdrawal rates and is expected to continue in the future.

This study emphasized the evolution of the power plant fleet in Texas and the legacy infrastructure that cannot be modified in a short period. Use of once-through cooling ponds is unlikely to expand in Texas in the future as use of ponds essentially leveled off in the early 1990s. Retirement of existing power plants with once-through cooling ponds may be replaced by plants with similar cooling systems because the power plant operators have the water rights and the ponds are being maintained, as seen in the proposed new Ferguson Plant on Lake LBJ. Even when power plants are retired and not replaced, the ponds/reservoirs are often maintained for recreational purposes (e.g., Lake Lady Bird Johnson in Austin). If replacement plants change generator technology from ST to CC along with cooling systems (cooling towers replacing once-through ponds), both water consumption and withdrawal rates will decrease. Projected increases in NGCC plants with cooling towers in Texas based on ERCOT forecasts should further reduce water consumption and withdrawal rates in the state. The results may be applicable to the U.S. in general, with recent increases in NG generation (120% increase 1996–2010) and increasing use of cooling towers reducing water withdrawals in the U.S. (www.eia.org).

Understanding fundamental controls on water consumption and withdrawal of thermoelectric generation within the context of power plant fleets with long lifespans and legacy infrastructure is an essential prerequisite to assessing impacts of water availability on thermoelectric generation and impacts of thermoelectric generation on water resources.

■ ASSOCIATED CONTENT

● Supporting Information

Unit conversions and acronyms, additional information on evaluation of data sources, comparison of indirect water use for thermoelectric generation with residential water use, evaluation of pond/reservoir classification according to cooling type in Texas, thermal efficiency of different fuel and generator technologies, water consumption versus water withdrawal for different power plant technologies, temporal trends in water consumption and withdrawal, and distribution of power plant cooling technologies in the U.S. This information is available free of charge via the Internet at <http://pubs.acs.org/>.

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Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS

CC	combined cycle (generally 2 CT to 1 ST generators)
CT	combustion turbine
CWIS	cooling water intake structures
EIA	Energy Information Administration
kWh	kilowatt hour
MWh	megawatt hour
TWh	terawatt hour (1 TWh = 1 million MWh)
NGCC	natural gas combined cycle
NGST	natural gas steam turbine
ST	steam turbine
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board

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