SUPPORTING INFORMATION

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

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10 figures
4 tables
18 pages
Section 1. Unit Conversions and Acronyms

- 1 gal = 3.785 L
- 1 mile = 1.6 km
- 1 mi² = 2.6 km²
- 1 acre-foot (af) = 325,851 gal = 1.233 million L
- 1000 acre-feet (af) = 1 kaf = 1.233 Mm³ = 1.233 mega m³ = 1.233 million m³
- 1 million acre-feet (maf) = 1.233 km³
- 1 kWh = kilowatt-hour = 3.6 MJ = 3,412 British thermal unit (BTU)
- MWh = megawatt-hour = 3.412 million British thermal unit (MMBTU)
- MMBtu = 1.055 GJ
- 1 MWh = 3.6 GJ


Section 2. Evaluation of Data Sources

2.1 Water Use Data Availability by Source

Net thermoelectric generation of 354 TWh in Texas during 2010 required water for cooling, representing 86% of total net generation (411 TWh). The EIA database provided water consumption for 69% of that power and water withdrawal data for 74% of that power (Table S1). The state agencies (TCEQ, TWDB) provided water consumption for 55% to 59% and water withdrawal data for 55% to 61% of that power. About 11% of net generation requiring cooling had no associated water withdrawal or consumption data from any source.

2.2 Water Consumption and Withdrawal Data Usability by Source

Classification of cooling systems according to EIA is shown in Fig. S1. The EIA data were used as the default data and are the only source of data for many regions in the US. EIA data have been improved in recent years and 2010 data include information on cooling system hours of operation, allowing rates of water use in the different categories to be converted to annual total volumes. Expressed as percentages of the cooled power, an estimated 55% of water consumption and 66% of water withdrawal from the EIA database were considered internally consistent in terms of generator/cooling systems; outliers were often up to an order of magnitude different (Fig. S2). Data from TCEQ and TWDB state agencies provided reliable data for 49% of consumption and 38% to 39% of withdrawals (Table S1). However, in terms of the total water volumes, the EIA, TCEQ and TWDB provided reliable data accounting for 52% to 60% of water consumption and 60% to 64% of water withdrawal.

2.3 Data Comparison among Sources

In many instances, data are available from two or three sources for a given power plant. Agreement among sources varies considerably, which may depend in part on differences in definitions or in how those definitions may have been interpreted by the submitting plant operators. 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 (Fig. 3). Outliers are generally obvious with up to an order of magnitude difference in consumption or withdrawal rates from those of similarly configured power plants in terms of generators/cooling systems. TCEQ and TWDB data also agreed well with 44% of overlapping consumption rates and 73% of overlapping withdrawal rates within 20% (Fig. S2). In fact, when the values are within 10%, they are usually identical. Between the EIA and TCEQ data sources, 23% of overlapping consumption volumes and 56% of overlapping withdrawal volumes are within 20%.
Table S1. Reported water consumption and withdrawal by data source (EIA, TCEQ, and TWDB) expressed as a percentage of the total net generation represented by each data source, including percentages having reported associated data, percentages considered to be reliable, and percentages ultimately used or represented in the final analysis by the respective data sources. Percentages are relative to the total cooled power generation requirement (354 TWh in 2010).

| Data Source | Consumption | Withdrawal |
|-------------|-------------|------------|
|             | Total Net Gen | Total Net Gen | Total Net Gen | Total Net Gen | Total Net Gen |
|             | Reported Data | Reliable Data | Used Data | Reported Data | Reliable Data | Used Data |
| EIA         | 65           | 57          | 53       | 73           | 65          | 65       |
| TCEQ        | 56           | 49          | 21       | 55           | 37          | 10       |
| TWDB        | 58           | 48          | 2        | 61           | 48          | 2        |
| None        | 10           | -           | 24       | 10           | -           | 23       |

EIA data were used as the default values when they were considered reliable, consistent with TCEQ and/or TWDB rates and internally consistent in terms of generator/technology systems. TCEQ data were selected second because they had a category for consumption in their report; however, TCEQ data often corresponded exactly to diversion rates reported by TWDB. In three instances (W.A. Parish, Fayette, and Sim Gideon-Lost Pines), supplemental water use information provided by plant operators was used due to complexities not captured in the reported data to any agency. W.A. Parish plant has 2 fuel sources (coal and natural gas) and 8 separate generator/cooling systems, including tower and once-through systems. Sim Gideon-Lost Pines power plants use the same water intake structure from Lake Bastrop. Also, Fayette and Sim Gideon-Lost Pines receive run-of-river diversions managed by the Lower Colorado River Authority that are not reported to other agencies. Finally, respective estimates of water consumption for 24% of water withdrawals for 23% of the cooled power requirement in the study were based on assumed rates assigned as plant configuration category average values because either no data were available from any source or the available data were deemed inaccurate when compared with similarly configured power plants.
Figure S1. Cooling system definitions from EIA Form 923.

Water from other sources including wells, water utilities, and wastewater treatment plants is considered Withdrawal, not Diversion.

Blowdown from cooling systems which is diverted to ash systems or evaporation ponds is not considered Discharge.
Figure S2. Comparison of a) water consumption and b) water withdrawal intensities for power plants reported by TCEQ and TWDB. Most TWDB consumption (actually reported as “use”) is similar to or somewhat greater than corresponding TCEQ consumption values and may represent diversions that include a component of makeup water to replace natural evaporation. Most TWDB withdrawal values that do not agree with TCEQ values fall below the 1:1 line, reflecting that TWDB values in these cases may also be diversions, while those that are in agreement are virtually identical to TCEQ values. Although this graph compares water consumption between TWDB and TCEQ, in most cases, water consumption and withdrawal in the study were derived from EIA or TCEQ.
Section 3. Comparison of Indirect Water Use for Thermoelectric Generation with Residential Water Use

The water use for thermoelectric generation can also be compared with typical residential water use. Indirect water consumption for thermoelectric generation based on mean annual electricity consumption in a typical household in Texas (2010: 15,600 kWh; http://www.eia.gov/tools/faqs/) and a mean rate of water consumption from this study of 0.34 gal/kWh (1.3 L/kWh; Table 2, Fig. 4) results in indirect water consumption for household electricity of 5,300 gal/yr (20,000 L/yr), equivalent to 14.5 gal/d (55 L/d). Based on mean water withdrawal of a typical Texas household of 2.7 people of 267 gal/d (1000 L/d; [1]), indirect water consumption for thermoelectric generation represents ~5% of typical household water withdrawal, generally lower than most other categories of indoor water use (Fig. S1).

For perspective, landscape irrigation accounts for the highest category of residential water use in Texas and annual water consumption for electrical generation of 5,300 gal/yr (20,000 L/yr) is equivalent to ~1.3 in (3.3 cm) watering of a typical residential lawn area (~6400 ft²; 600 m² lawn size).

Figure S3. Typical household water use categories by percent based on 30% outdoor residential irrigation[1] and percent of other categories from [2].
Section 4. Evaluation of EIA Pond/Reservoir Classification according to Cooling Type

Figure S4. View of Victoria plant that is one of two power plants in Texas with once-through cooling withdrawing water from the Guadalupe River.
Figure S5. Distribution of power plants in the US according to cooling technologies, with once-through (open-loop) systems, including rivers/reservoirs/ponds (red circles), and once-through recirculating ponds (blue circles), and closed-loop systems (wet and dry cooling towers). However, analysis of the Texas data show that there was no physically meaningful distinction between systems classified as once-through and recirculating ponds (Fig. S3). Once-through systems are found mostly in the eastern US and towers are found throughout the US. Data source: www.eia.gov.
Figure S6. Plot showing lack of systematic variation between once-through cooling ponds/reservoirs and recirculating ponds in terms of storage volume versus number of times water is recirculated through the pond/reservoir (storage volume/withdrawal rate). Classification is based on EIA data. EIA water body classifications for once-through cooling systems are shown, including once-through fresh (OF), once-through pond or canal (OC), and recirculating pond or canal (RC). Comparison of EIA categories with images on Google Earth shows that most systems have structures that indicate recirculation.
Figure S7. View of cooling pond for South Texas Project nuclear plant withdrawing water from the Colorado River. This pond is an example of an off-channel reservoir. Although this system is classified as once-through because cooling water moves once through the condenser, water is circulated through the pond, as shown by the structures in the pond, to maximize heat dissipation in this recirculation system. Arrows indicate diversion from the river to the pond to replenish water losses from the pond. Water is rarely discharged to the river, only when the pond is overflowing. This pond is isolated by a berm surrounding the pond; therefore, there is no contribution from runoff from the surrounding land.
Section 5: Thermal Efficiency of Different Fuel and Generator Technologies

Thermoelectric generation requires a heat source and a heat sink. The heat balance described by Rutberg et al. (2011) \[3\] helps understand the cooling water requirements for thermoelectric generation. A fraction of the heat generated from fossil fuel combustion or nuclear fission is converted to electricity (referred to as thermal or energy efficiency), another fraction is lost with flue gasses in the smoke stack for coal and natural gas plants but not nuclear plants, and the remaining heat, termed waste heat or residual heat is dissipated using cooling water. The more heat that is converted to electricity, the less waste heat or residual heat that has to be dissipated through cooling. The thermal efficiency is defined as the fraction of heat from fossil fuels or nuclear fission that is converted to electricity (electricity output/heat or energy input). Therefore, water requirements for cooling are inversely related to thermal efficiency.

The thermal efficiency is ultimately controlled by the laws of thermodynamics. The theoretical efficiency is described by the Carnot cycle which represents a reversible engine:

\[
\text{Carnot Efficiency} = \frac{\text{work produced}}{\text{thermal energy input}} = \frac{(T_H - T_C)}{T_H}
\] (1)

where \(T_H\) is the T of the heat source or heat entering engine and \(T_C\) is the T of the heat sink or of waste heat at the condenser (T in °K). Carnot efficiency is increased by raising the T of the heat source and reducing the temperature of the heat sink. Heat source temperatures are limited by constraints of the materials used for turbines and heat sink temperatures are controlled by climatic variability and water availability\[4\].

Steam turbine generators represented 53% of net generation in 2010. The thermal efficiency of steam turbines can be increased by raising \(T_H\) and/or reducing \(T_C\). Steam can be heated to supercritical (660°C) or ultrasupercritical (720° – 760°C) temperatures; however, \(T_C\) temperatures are controlled by the local climate and are generally about 40°C, resulting in thermal efficiencies up to 70% \([1033°K-313°K]/1033°K\). Compressed air engines or gas turbines have much higher heat source temperatures than steam turbines. Using advances in material technology, temperatures in combustion turbines can extend to 1300°C \[4\]. Typical output temperatures for combustion turbines range from 450° to 650°C; therefore, maximum efficiencies would be up to 65%.

Combined cycle plants combine the output steam from combustion turbines with steam turbines to extend the temperature range to a maximum of 1300° - 40°C and greatly increase theoretical thermal efficiency. Output heat from combustion turbines is used to drive a steam turbine, using a heat recovery steam generator (HRSG) system.

Reported thermal efficiencies represent theoretical efficiencies assuming a reversible engine based on (1); however, true engines are not irreversible and the steam turbines operate according to the Rankine cycle and combustion turbines operate according to the Brayton cycle with useful heat divided by the total heat supplied. Actual thermal efficiencies are calculated by dividing the output (net generation) by the heat input.

The heat balance described by Rutberg et al. (2011) \[3\] helps understand the cooling water requirements for thermoelectric generation. Schematics for the different generator combinations describe the heat balances for the various systems (Fig. S8). The previous section describes the fraction...
of the heat generated from fossil fuel combustion or nuclear fission that is converted to electricity (thermal or energy efficiency), another fraction is lost with flue gasses in the smoke stack for coal and natural gas plants (fossil steam turbine, 12%; fossil combined cycle, 20%; [3]) but not nuclear plants, and the remaining heat, termed waste heat or residual heat is dissipated using cooling water.

Thermal efficiencies for coal and nuclear plants based on this study are similar (36%, Table S2). Natural gas steam turbines (NGST) and combustion turbines (NGCT) have lower efficiencies (29 – 30%) whereas natural gas combined cycle (NGCC) plants have the highest efficiencies (44%). Waste heat from power plants can also be used for nearby space heating and air conditioning or to create process steam in industrial facilities in cogeneration facilities or combined heat and power (CHP) systems, increasing energy efficiency up to 60%.

Table S2. Calculated thermal efficiencies for generators according to fuel source, generator technology based on EIA data on net generation for Texas for 2010. Thermal efficiencies were calculated by dividing the output (net generation MWh) by the heat input (GJ) by multiplying by the conversion factor (3.6 GJ/MWh).

| Fuel    | Heat Input       | Energy (Net Gen.) | Thermal Efficiency |
|---------|------------------|-------------------|--------------------|
|         | GJ               | MWh               | mean %             |
| Nuclear ST | 409,765,319 | 41,335,248       | 36.3               |
| Coal ST   | 1,506,453,030 | 150,172,832      | 35.9               |
| NGST      | 311,614,392   | 25,177,280       | 29.1               |
| NGCT      | 238,539,097   | 19,977,081       | 30.1               |
| NGCC      | 1,115,682,174 | 134,797,521      | 43.5               |

ST: steam turbine; CT: combustion turbine, CC: combined cycle; Net Gen.: net generation.
Conversion factor 1 MWh = 3.6 GJ
Figure S8. Schematic of heat balance for different power plant systems, modified from Ku and Shapiro (2012) [4]. The fraction of heat resulting in electricity is based on analysis of 2010 data for Texas (Table S2). Estimates of heat dissipated through the exhaust in the flue gas is based on those from Rutberg et al., 2011[3]. The fraction of waste heat requiring cooling was calculated as a residual.
Section 6: Comparison of Water Intensities from the Literature

Table S3. Comparison of consumption and withdrawal rates with those from the literature [5] for similar plant configurations.

| Fuel | Prime Mover | Cooling System | Consumption (gal/kWh) | Withdrawal (gal/kWh) |
|------|-------------|----------------|-----------------------|----------------------|
|      |             |                | This Study            | Macknick et al. (2011) | This Study            | Macknick et al. (2011) |
| Nuclear | ST | OT       | 0.46                  | 0.27-0.61             | 36                    | 0.61                  | 36-74 |
| Coal  | ST | OT       | 0.52                  | 0.25-0.55             | 38                    | 12-36                 | 7 |
|        | T       | OT       | 0.56                  | 0.69                  | 0.62                  | 1.0                   |
| NG    | ST | OT       | 0.44                  | 0.24                  | 141                   | 35                    |
|        | T       | OT       | 0.68                  | 0.83                  | 0.71                  | 1.2                   |
| CC    | OT       | CC       | 0.12                  | 0.10-0.24             | 59                    | 6-11                  |
|        | T       | CC       | 0.23                  | 0.20                  | 0.26                  | 0.25                  |
| Other | ST | OT       | 0.68                  | 0.55                  | 0.71                  | 0.88                  |
|        | T       | OT       |                       |                      |                       |                       |

ST: Steam Turbine, CC: Combined Cycle, OT: Once Through, T: Tower.
Figure S9. Distribution of power plants according to cooling technology and net generation for Texas for 2010. Once-through (open loop) cooling systems generally consist of recirculating ponds/reservoirs found in the eastern half of the state whereas closed loop (wet cooling towers) are found throughout the state. There are two once-through plants that withdraw water directly from a river (the Guadalupe River) and two dry cooling tower plants.
Fig. S10. Drainage areas for industrial ponds (≤ 300 mi$^2$, median 11 mi$^2$) and multipurpose reservoirs (> 150 mi$^2$, median 722 mi$^2$) that provide water to power plants.
Section 8. Water Consumption versus Water Withdrawal for Different Power Plant Technologies.

Figure S11. Relationship between water consumption and water withdrawal for different power plants according to fuel type – generator – cooling system combinations. Points represent mean values weighted by net generation. Shaded areas represent approximate range of values (0.1 to 0.9 percentile). NG: Natural Gas, ST: Steam Turbine, CC: Combined Cycle. Note the log scales for withdrawal and consumption intensities or rates. The left half of the diagram represents once-through cooling systems, mostly recirculating ponds and the right half represents wet cooling towers. Note the tradeoff between water consumption and withdrawal rates, with higher withdrawal and lower consumption for once-through systems and lower withdrawal and higher consumption for wet cooling towers. Within each cooling system, combined cycle plants have the lowest water consumption rates.
Table S4. 2010 Texas net electricity generation, cooling water consumption and withdrawal amounts and intensities/rates summarized by fuel type, generator technology, and cooling system type.

| Grouping          | N  | Net generation | Consumption | Withdrawal |
|-------------------|----|----------------|-------------|------------|
|                   |    | (TWh)          | (Mm³)       | (L/kWh)    | (Mm³)      | (L/kWh) |
| Fuel type         |    |                |             |            |            |
| Nuclear           | 4  | 41             | 73          | 1.7        | 5,695      | 136     |
| Coal              | 39 | 151            | 306         | 2.0        | 15,132     | 102     |
| Natural gas       | 379| 160            | 142         | 0.9        | 11,453     | 72      |
| Other             | 21 | 2.0            | 5.0         | 2.2        | 5.0        | 2.3     |
| Generator technology |  |                |             |            |            |
| Steam turbine     | 175| 219            | 430         | 2.0        | 29,982     | 136     |
| Combined cycle    | 268| 135            | 96          | 0.7        | 2,303      | 17      |
| Cooling System    |    |                |             |            |            |
| Once-through      | 115| 171            | 311         | 1.8        | 32,040     | 185     |
| Tower             | 328| 183            | 216         | 1.2        | 244        | 1.3     |
| All               | 443| 354            | 526         | 1.5        | 32,285     | 91      |

Total cooled net generation of 354 TWh represents 86% of total net generation of 411 million TWh. 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, steam turbines have predominantly once-through cooling systems and combined cycle systems generally have cooling towers, both of which affect water consumption.
Table S5. 2010 Texas net electricity generation by fuel-generator-cooling system configurations and estimated cooling water consumption and withdrawal rates and volumes.

| Fuel type     | Generator technology | Cooling System | N  | Net generation (TWh) | Consumption (Mm$^3$) | Withdrawal (Mm$^3$) | Consumption (L/kWh) | Withdrawal (L/kWh) |
|---------------|----------------------|----------------|----|----------------------|----------------------|---------------------|---------------------|---------------------|
| Nuclear       | Steam turbine        | Once-through   | 4  | 41.3                 | 73                   | 1.7                 | 5,695               | 136                 |
| Coal          | Steam turbine        | Once-through   | 25 | 103.3                | 205                  | 2.0                 | 15,021              | 144                 |
|               |                      | Tower          | 14 | 47.4                 | 101                  | 2.1                 | 111                 | 2.3                 |
| Natural gas   | Steam Turbine        | Once-through   | 63 | 17.1                 | 29                   | 1.7                 | 9,131               | 534                 |
|               |                      | Tower          | 34 | 6.8                  | 18                   | 2.6                 | 18                  | 2.7                 |
|               |                      | Cogeneration$^1$| 9  | 0.9                  | 0.4                  | 0.5                 | 0.5                 | 0.6                 |
| Natural gas   | Combined cycle       | Once-through   | 23 | 9.8                  | 4.3                  | 0.5                 | 2,193               | 223                 |
|               |                      | Tower          | 140| 75.6                 | 66                   | 0.9                 | 75                  | 1.0                 |
|               |                      | Cogeneration$^1$| 44 | 29.6                 | 16                   | 0.5                 | 22                  | 0.8                 |
| Other         | Steam turbine        | Tower          | 13 | 1.7                  | 4.4                  | 2.6                 | 4.7                 | 2.7                 |
|               |                      | Cogeneration$^2$| 8  | 0.4                  | 0.2                  | 0.5                 | 0.2                 | 0.6                 |
| Natural gas   | Steam turbine        | Cogeneration$^2$| 5  | 0.5                  | 0.2                  | 0.5                 | 0.2                 | 0.6                 |
|               | Combined cycle       | Cogeneration$^2$| 61 | 19.9                 | 8.8                  | 0.5                 | 12                  | 0.6                 |
| All           | ST, CC               |                | 443| 354.3                | 526                  | 1.5                 | 32,285              | 91                  |
| All           | All                  |                | 867| 410.9                | 526                  | 1.3                 | 32,285              | 79                  |

ST: steam turbine, CC: combined cycle.

$^1$Cogeneration (combined heat and power) with reported water use

$^2$Cogeneration (combined heat and power) with no reported water use

Total water consumption of 427 thousand acre ft (kaf) = 0.43 million acre feet = 526 Mm$^3$ = 0.53 km$^3$; 1 km$^3$ = 1.233 maf; Water consumption intensity of 0.34 gal/kWh = 1.3 L/kWh statewide.
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