Supplemental Material: A Regional Assessment of the Water Embedded in the US Electricity System

Rebecca A.M. Peer¹, Emily Grubert², and Kelly T. Sanders¹

¹ Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA 90089
² School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332
E-mail: peerr@usc.edu

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1. Introduction

This supplementary materials file includes additional detail on methods and results for the letter “A Regional Assessment of the Water Embedded in the US Electricity System” by Peer et al., which estimates US consumptive water intensity for electricity by eGRID region, defined in Table 1 and shown in Figure 1.

2. Primary energy consumptive water intensity

Water consumption embedded in fuel upstream of the point of generation is calculated using a bottom-up approach, aggregating individual generators at power plants up to eGRID region level. To facilitate application of consumptive water intensity values by fuel, using data from [2], Energy Information Administration (EIA) fuel codes for power plants are simplified and categorized. Table 2 provides the translation from reported EIA fuel types to fuel classifications used in this work, adapted from Data File 1, Sheet EIA Definitions in [2]. Water types are defined as in [2].

Fuel inputs to US generators for 2014 are taken from EIA Form 923 Data “Elec Fuel Consumption MMBtu” [3]. This metric excludes fuel inputs for heat at combined heat and power (CHP) plants, unlike the similar metric “Total fuel consumption MMBtu.” Note that by using total electrical fuel consumption, this work only allocates water consumption associated with input fuel at electricity generators to electricity production, rather than across multiple products. Across US electricity generation, the choice is fairly inconsequential: electricity fuel consumption is about 94% of total fuel consumption for generators reporting on EIA Form 923 [3]. The difference is relevant in a few cases, however, mainly for various biomass and oil products (which are often burned in CHP contexts at industrial facilities like pulp and paper plants or refineries) and for midwestern coal. Energy allocated to electricity from bituminous coal is, on
average, 97% of total energy burned at power plants, but in the midwest, it is only 29% [3]. Electricity fuel for natural gas is, on average, about 90% of total natural gas consumed at power plants [3], with limited regional differentiation.

Upstream water consumption for production, processing, and transportation life cycle stages for each fuel is drawn from Grubert and Sanders (2018) [2]. Values calculated in this work are presented in Table 3. For power plants consuming coal, regional water consumption values are applied based on the state where the supplier coal mine is located, based on EIA reporting. Table 4 details the separation of coal-producing states into coal provinces, as defined in Grubert and Sanders [2]. For power plants consuming oil and natural gas, water consumption intensities (1.29×10^{-1} and 2.57×10^{-2} m^3/GJ, respectively, based on supplemental data from [2]) are applied based on the allocation schema of these fuels for electricity generation.

For Kentucky, counties were individually assigned East or West tags based on their geographic location (Table 5) because of varying coal characteristics in the state. Upstream water consumption from imported coal from countries outside the US was excluded, as this analysis only examines the water consumption within the boundaries of the US.

Some US coal is used for steel making, as metallurgical (also called met or coking) coal. This work assumes that all met coal is produced in the Appalachian region and that
consumptive water intensity is identical for met and thermal coal. Met coal accounts for about 6% of US coal energy [2], which is about 14% of Appalachian coal energy, so upstream Appalachian coal water consumption in this work is assumed to be about 86% of the dewatering and processing volumes presented in [2].

Coal is not the only fuel used for multiple purposes. Both oil and natural gas are primarily used for purposes other than electricity in the US. This work thus allocates upstream water consumption from [2] to oil and natural gas proportionally based on the amount of energy used for electricity for each fuel, which is about 6% of total oil energy and about 33% of total natural gas energy.

The water intensity of geothermal plants is particularly site specific. This work specifically allocates plant-specific water consumption for reservoir augmentation to the
### Table 2. EIA fuel code proxies for fuel classifications used in this work.

| EIA Code | EIA Definition                                                                 | This Work Classifies                              |
|----------|--------------------------------------------------------------------------------|---------------------------------------------------|
| AB       | Agricultural By-Products                                                      | Solid Biomass and RDF                             |
| ANT      | Anthracite Coal                                                               | n/a                                               |
| BFG      | Blast Furnace Gas                                                             | Bituminous Coal                                   |
| BIT      | Bituminous Coal                                                               | Bituminous Coal                                   |
| BLQ      | Black Liquor                                                                  | Solid Biomass and RDF                             |
| DFO      | Distillate Fuel Oil. Including diesel, No. 1, No. 2, and No. 4 fuel oils.     | Oil                                               |
| GEO      | Geothermal                                                                    | Geothermal                                        |
| JF       | Jet Fuel                                                                      | Oil                                               |
| KER      | Kerosene                                                                      | Oil                                               |
| LFG      | Landfill Gas                                                                  | Biogas                                            |
| LIG      | Lignite Coal                                                                   | Lignite Coal                                      |
| MSB      | Biogenic Municipal Solid Waste                                                | Solid Biomass and RDF                             |
| MSN      | Non-biogenic Municipal Solid Waste                                            | Solid Biomass and RDF                             |
| MWH      | Electricity used for energy storage                                           | n/a                                               |
| NG       | Natural Gas                                                                   | Natural Gas                                       |
| NUC      | Nuclear. Including Uranium, Plutonium, and Thorium.                            | Uranium                                           |
| OBG      | Other Biomass Gas. Including digester gas, methane, and other biomass gases.  | Biogas                                            |
| OBL      | Other Biomass Liquids                                                         | Solid Biomass and RDF                             |
| OBS      | Other Biomass Solids                                                          | Solid Biomass and RDF                             |
| OG       | Other Gas                                                                     | Natural Gas                                       |
| OTH      | Other Fuel                                                                    | Case-by-case allocation                           |
| PC       | Petroleum Coke                                                                | Oil                                               |
| PG       | Gaseous Propane                                                                | Oil                                               |
| PUR      | Purchased Steam                                                               | Case-by-case allocation                           |
| RC       | Refined Coal                                                                  | Bituminous Coal                                   |
| RFO      | Residual Fuel Oil. Including No. 5 & 6 fuel oils and bunker C fuel oil.        | Oil                                               |
| SC       | Coal-based Synfuel. Including briquettes, pellets, or extrusions, which are   | Bituminous Coal                                   |
|          | formed by binding materials or processes that recycle materials.              |                                                   |
| SGC      | Coal-Derived Synthesis Gas                                                    | Bituminous Coal                                   |
| SGP      | Synthesis Gas from Petroleum Coke                                            | Oil                                               |
| SLW      | Sludge Waste                                                                   | Solid Biomass and RDF                             |
| SUB      | Subbituminous Coal                                                            | Subbituminous Coal                                |
| SUN      | Solar                                                                          | Solar                                             |
| TDF      | Tire-derived Fuels                                                            | Solid Biomass and RDF                             |
| WAT      | Water at a Conventional Hydroelectric Turbine and water used in Wave Buoy     | Hydropower                                        |
|          | Hydrokinetic Technology, current Hydrokinetic Technology, Tidal                |                                                   |
|          | Hydrokinetic Technology, and Pumping Energy for Reversible (Pumped Storage)   |                                                   |
|          | Hydroelectric Turbines.                                                       |                                                   |
| WC       | Waste/Other Coal. Including anthracite culm, bituminous gob, fine coal,       | Bituminous Coal                                   |
|          | lignite waste, waste coal.                                                     |                                                   |
| WDL      | Wood Waste Liquids, excluding Black Liquor. Including red liquor, sludge      | Solid Biomass and RDF                             |
|          | wood, spent sulfite liquor, and other wood-based liquids.                      |                                                   |
| WDS      | Wood/Wood Waste Solids. Including paper pellets, railroad ties, utility poles,| Solid Biomass and RDF                             |
|          | wood chips, bark, and other wood waste solids.                                 |                                                   |
| WH       | Waste Heat not directly attributed to a fuel source                           | Case-by-case allocation                           |
| WND      | Wind                                                                           | Wind                                              |
| WO       | Waste/Other Oil. Including crude oil, liquid butane, liquid propane, naphtha, | Oil                                               |
|          | oil waste, re-refined motor oil, sludge oil, tar oil, or other petroleum-based |                                                   |
|          | liquid wastes.                                                                 |                                                   |
Table 3. Upstream water consumption volumes for each fuel cycle in the electricity sector (m$^3$).

| Fuel Classification                              | Water consumption |
|--------------------------------------------------|-------------------|
| Oil                                              | $4.47 \times 10^7$ |
| Subbituminous coal (northern great plains)       | $8.45 \times 10^6$ |
| Bituminous coal (Appalachia)                     | $1.20 \times 10^8$ |
| Bituminous coal (interior)                       | $4.45 \times 10^8$ |
| Bituminous coal (Rocky Mountain region)          | $3.38 \times 10^7$ |
| Lignite coal (gulf coast)                        | $3.28 \times 10^8$ |
| Lignite coal (northern great plains)             | $4.60 \times 10^5$ |
| Natural gas                                      | $2.41 \times 10^8$ |
| Uranium                                          | $1.07 \times 10^7$ |
| Hydropower                                       | $1.72 \times 10^9$ |
| Wind                                             | $1.96 \times 10^6$ |
| Solid biomass & RDF                              | $7.36 \times 10^7$ |
| Biogas                                           | 0                 |
| Geothermal (excluding California & Nevada)        | $3.56 \times 10^4$ |
| Geothermal (California)                          | $1.49 \times 10^8$ |
| Geothermal (Nevada)                              | $1.04 \times 10^6$ |
| Solar PV                                          | $1.69 \times 10^5$ |
| Solar thermal                                    | $1.76 \times 10^5$ |

Table 4. Definition of coal regions used in this work.

| Province                           | Abbreviation | States                        |
|------------------------------------|--------------|-------------------------------|
| Northern Great Plains              | NGP          | MT, ND, WY                     |
| Appalachia/Eastern                 | APP          | AL, eastern KY, MD, OH, PA, TN, VA, WV |
| Interior                           | INT          | AR, IL, IN, KS, western KY, MO, OK |
| Gulf Coast                         | GFC          | LA, MS, TX                     |
| Rocky Mountain Region              | RMR          | AZ, CO, NM, UT                 |

appropriate eGRID regions, and water removal in the form of steam at The Geysers steam field (CAMX) is also allocated specifically to the appropriate region. Water for well drilling, the remaining upstream water consumer, is allocated across US geothermal sites based on total generation. See [2] for details on how these values were calculated and accounted.

2.1. Water consumed for hydroelectricity

Regional eGRID water consumption rates for hydroelectricity are calculated using the method in Grubert (2016) [4]. Each reservoir associated with a dam defined as having
Table 5. Separation of Eastern and Western Kentucky counties used for defining coal regions in this work.

| FIPS County ID | County Name                        | KY E-W Classification |
|----------------|-------------------------------------|-----------------------|
| 13             | Bell County                         | East                  |
| 19             | Boyd County                         | East                  |
| 25             | Breathitt County                    | East                  |
| 51             | Clay County                         | East                  |
| 59             | Daviess County                      | West                  |
| 65             | Estill County                       | East                  |
| 71             | Floyd County                        | East                  |
| 95             | Harlan County                       | East                  |
| 107            | Hopkins County                      | West                  |
| 115            | Johnson County                      | East                  |
| 119            | Knott County                        | East                  |
| 121            | Knox County                         | East                  |
| 127            | Lawrence County                     | East                  |
| 131            | Leslie County                       | East                  |
| 133            | Letcher County                      | East                  |
| 139            | Livingston County                   | West                  |
| 149            | McLean County                       | West                  |
| 153            | Magoffin County                     | East                  |
| 159            | Martin County                       | East                  |
| 177            | Muhlenberg County                   | West                  |
| 183            | Ohio County                         | West                  |
| 193            | Perry County                        | East                  |
| 195            | Pike County                         | East                  |
| 203            | Rockcastle County                   | East                  |
| 217            | Taylor County                       | West                  |
| 225            | Union County                        | West                  |
| 233            | Webster County                      | West                  |
| NA             | Daviess County (based on coal mine name) | West              |

primary purpose = hydroelectricity in the National Inventory of Dams (NID) [5] is assigned both to its centroid from [4] and to an eGRID region. Hydroelectric facilities that have primary purpose = hydroelectricity in the NID that also appear in eGRID (about 79% of relevant reservoir surface area) are assigned to their reported eGRID region, and others (about 21% of relevant reservoir surface area) are assigned based on a spatial join of NID reported coordinates and the 2016 eGRID boundaries [1] using QGIS. Note that using coordinates to define location for hydroelectric facilities is less straightforward than for single-site power plants, as reservoirs are areally extensive, and dams, powerhouses, and the single-point location of a reservoir might be quite distant from each other.

The water intensity of hydroelectricity is calculated as total water consumption associated with dams with NID primary purpose = hydroelectricity divided by total hydroelectricity generation in the region, regardless of whether the plants are at dams
with primary purpose = hydroelectricity (see [4] for discussion and justification), so water consumption for relevant reservoirs in each eGRID region is calculated based on reservoir surface area, not powerhouse generation. Water consumption from reservoir evaporation upstream of the point of generation (PoG) is calculated using a Penman-Monteith model, with dams aggregated by statistically determined centroids. The values presented in this work are evaporation net of local (nearby) landcover. See [4] for details and a copy of the model.

3. Point of generation consumptive water intensity

Water consumption at the point of generation (PoG) is the water consumed at power plants, mainly for cooling at thermoelectric generating facilities. This work classifies generators by fuel type, prime mover, and cooling system. To simplify calculations and reduce the number of generator codes (fuel-prime mover-cooling system), reported fuel codes, prime mover codes, and cooling system codes from the EIA were reclassified as described in Table 6, Table 7, and Table 8, respectively. Water types are defined in Table 9 and Table 10, based on EIA Form 860.

All gas turbine, wind turbine, and photovoltaic generators are assigned a PoG water consumption rate of zero, as there is no reported operational water consumption for these technologies. Energy storage technologies are also assumed to have zero water consumption. Median water consumption rates from 2014 EIA data [7] were applied for all natural gas, coal, and nuclear (uranium) generating technologies. Generating technologies reporting no cooling system (i.e., “NA”) were assigned a generation-weighted average consumption intensity based on the consumption rates for other technology classifications with the same fuel and prime mover.

Estimates of total water consumed for power plant cooling from Grubert and Sanders [2] are used to assign water consumption rates for biomass, biogas, oil, solar thermal, and geothermal generating technologies. The total estimates reflect data and calculations from the US Geological Survey and the Union of Concerned Scientists [8,9]. These estimates were divided by total water cooled generation for each fuel type for an average water consumption rate to be applied for each generator classification. The source and assumed consumptive water intensity for each PoG classification is presented in Table 11.

| Code (F-PM-CS) | Cooling Rate Assumption | Consumption Rate (m³/MWh) |
|----------------|-------------------------|---------------------------|
| BG-CC-NA       | Water use from [2] for biogas | 1.13                      |
| BG-ES-NA       | No cooling required      | 0                         |
| BG-GT-NA       | No cooling required      | 0                         |
| BG-ST-ON       | Water use from [2] for biogas | 1.13                      |
| BG-ST-RC       | Water use from [2] for biogas | 1.13                      |
| Region        | Description                                                                 | Value  |
|--------------|------------------------------------------------------------------------------|--------|
| BG-ST-NA     | Water use from [2] for biogas                                                | 1.13   |
| BM-GT-NA     | No cooling required                                                          | 0      |
| BM-ST-DC     | Water use from [2] for solid biomass & RDF                                   | 1.82   |
| BM-ST-ON     | Water use from [2] for solid biomass & RDF                                   | 1.82   |
| BM-ST-PN     | Water use from [2] for solid biomass & RDF                                   | 1.82   |
| BM-ST-RC     | Water use from [2] for solid biomass & RDF                                   | 1.82   |
| BM-ST-NA     | Water use from [2] for solid biomass & RDF                                   | 1.82   |
| CL-CC-PN     | Consumption rate for natural gas from [7]                                   | 0.598  |
| CL-CC-NA     | Generation-weighted average of consumption rates for natural gas combined cycle from [7] | 0.713  |
| CL-OT-NA     | Consumption rate for coal from [7]                                           | 1.42   |
| CL-ST-DC     | Consumption rate for coal from [7]                                           | 0.184  |
| CL-ST-ON     | Consumption rate for coal from [7]                                           | 0.772  |
| CL-ST-PN     | Consumption rate for coal from [7]                                           | 1.39   |
| CL-ST-RC     | Consumption rate for coal from [7]                                           | 1.84   |
| CL-ST-NA     | Generation-weighted average of consumption rates for coal steam from [7]     | 1.42   |
| ES-ES-NA     | No cooling required                                                          | 0      |
| GEO-BT-NA    | Water use from [2] for geothermal binary turbine, wet cooled                 | 5.09   |
| GEO-ST-NA    | Water use from [2] for geothermal, wet cooled                                 | 0.193  |
| NG-CC-DC     | 10% of [7] rates for natural gas CC, tower cooled                            | 0.082  |
| NG-CC-HB     | Consumption rate for natural gas from [7]                                   | 0.348  |
| NG-CC-ON     | Consumption rate for natural gas from [7]                                   | 0.712  |
| NG-CC-PN     | Consumption rate for natural gas from [7]                                   | 0.598  |
| NG-CC-RC     | Consumption rate for natural gas from [7]                                   | 0.821  |
| NG-CC-NA     | Generation-weighted average of consumption rates for natural gas combined cycle from [7] | 0.713  |
| NG-CS-DC     | 10% of [7] rates for natural gas CS, tower cooled                            | 0.078  |
| NG-CS-RC     | Consumption rate for natural gas from [7]                                   | 0.776  |
| NG-CS-NA     | Generation-weighted average of consumption rates for natural gas combined cycle single shaft from [7] | 0.428  |
| NG-ES-NA     | No cooling required                                                          | 0      |
| NG-GT-ON     | No cooling required                                                          | 0      |
| NG-GT-NA     | No cooling required                                                          | 0      |
| NG-OT-NA     | No cooling required                                                          | 0      |
| NG-ST-DC     | Consumption rate for natural gas from [7]                                   | 0.315  |
| NG-ST-ON     | Consumption rate for natural gas from [7]                                   | 1.23   |
| NG-ST-PN     | Consumption rate for natural gas from [7]                                   | 1.20   |
| NG-ST-RC     | Consumption rate for natural gas from [7]                                   | 3.15   |
| NG-ST-NA     | Generation-weighted average of consumption rates for natural gas steam from [7] | 1.69   |
| NUC-ST-ON    | Consumption rate for nuclear from [7]                                        | 1.37   |
| NUC-ST-PN    | Consumption rate for nuclear from [7]                                        | 1.93   |
| NUC-ST-RC    | Consumption rate for nuclear from [7]                                        | 2.54   |
| NUC-ST-RT    | Consumption rate for nuclear from [7]                                        | 2.54   |
4. Results

Figure 2 shows generation by fuel in each eGRID region, and Table 12 shows total water consumption by technology for each eGRID region.

Tables 13, 14, and 15 present fuel-specific consumptive water intensity by eGRID region, for upstream, PoG, and overall intensities.
Table 6. EIA fuel code proxies for electricity fuel classifications used in this work [3].

| EIA Code | EIA Definition                                                                 | Proxy for this work |
|----------|-------------------------------------------------------------------------------|---------------------|
| LFG      | Landfill Gas                                                                  | Biogas              |
| OBG      | Other Biomass Gas. Including digester gas, methane, and other biomass gases.  | Biogas              |
| AB       | Agricultural By-Products                                                      | Biomass             |
| BLQ      | Black Liquor                                                                  | Biomass             |
| MSB      | Biogenic Municipal Solid Waste                                                | Biomass             |
| MSN      | Non-biogenic Municipal Solid Waste                                            | Biomass             |
| OBL      | Other Biomass Liquids                                                         | Biomass             |
| OBS      | Other Biomass Solids                                                          | Biomass             |
| SLW      | Sludge Waste                                                                  | Biomass             |
| TDF      | Tire-derived Fuels, excluding Black Liquor. Including red liquor, sludge wood, spent sulfite liquor, and other wood-based liquids. | Biomass             |
| WDL      | Wood Waste Liquids, excluding Black Liquor. Including red liquor, sludge wood, spent sulfite liquor, and other wood-based liquids. Wood/Wood Waste Solids. Including paper pellets, railroad ties, utility poles, wood chips, bark, and other wood waste solids. | Biomass             |
| WDS      | Wood/Wood Waste Solids.                                                       | Biomass             |
| BIT      | Bituminous Coal                                                               | Coal                |
| DFO      | Distillate Fuel Oil. Including diesel, No. 1, No. 2, and No. 4 fuel oils.     | Coal                |
| JF       | Jet Fuel                                                                      | Oil                 |
| KER      | Kerosene                                                                      | Oil                 |
| LIG      | Lignite Coal                                                                  | Coal                |
| PC       | Petroleum Coke                                                                | Oil                 |
| RC       | Refined Coal                                                                  | Coal                |
| RFO      | Residual Fuel Oil. Including No. 5&6 fuel oils and bunker C fuel oil.          | Oil                 |
| SC       | Coal-based Synfuel. Including briquettes, pellets, or extrusions, which are formed by binding materials or processes that recycle materials. Coal. | Coal                |
| SUB      | Subbituminous Coal                                                            | Coal                |
| WC       | Waste/Other Coal. Including anthracite culm, bituminous gob, fine coal, lignite waste, waste coal. Waste/Other Oil. Including crude oil, liquid butane, liquid propane, naphtha, oil waste, re-refined motor oil, sludge oil, tar oil, or other petroleum-based liquid wastes. | Coal                |
| WO       |                                                                               | Oil                 |
| GEO      | Geothermal                                                                    | Geothermal          |
| BFG      | Blast Furnace Gas                                                             | Natural Gas         |
| NG       | Natural Gas                                                                   | Natural Gas         |
| PG       | Gaseous Propane                                                                | Natural Gas         |
| SGC      | Coal-Derived Synthesis Gas                                                    | Coal                |
| SGP      | Synthesis Gas from Petroleum Coke                                           | Natural Gas         |
| OG       | Other Gas                                                                     | Natural Gas         |
| NUC      | Nuclear. Including Uranium, Plutonium, and Thorium.                            | Nuclear             |
| SUN      | Solar                                                                          | Solar               |
| WND      |                                                                               | Wind                |
| ANT      | Anthracite Coal                                                               | n/a                 |
| MWH      | Electricity used for energy storage                                           | n/a                 |
| OTH      | Other Fuel                                                                    | Case-by-case allocation |
| PUR      | Purchased Steam                                                               | Case-by-case allocation |
| WH       | Waste Heat not directly attributed to a fuel source                           | Case-by-case allocation |
Table 7. EIA prime mover code proxies for prime mover classifications used in this work [3].

| EIA Code | EIA Definition                                                                 | Proxy for this work |
|----------|-------------------------------------------------------------------------------|---------------------|
| CA       | Combined-Cycle – Steam Part                                                   | Combined Cycle      |
| CS       | Combined-Cycle Single-Shaft Combustion Turbine and Steam                       | Combined Cycle      |
|          | Turbine share of single generator                                              |                     |
| CT       | Combined-Cycle Combustion Turbine Part                                         | Combined Cycle      |
| BA       | Energy Storage, Battery                                                       | Energy Storage      |
| CE       | Energy Storage, Compressed Air                                                 | Energy Storage      |
| CP       | Energy Storage, Concentrated Solar Power                                       | Energy Storage      |
| ES       | Energy Storage, Other (Specify on Schedule 9, Comments)                       | Energy Storage ES   |
| FW       | Energy Storage, Flywheel                                                      | Energy Storage      |
| PS       | Energy Storage, Reversible Hydraulic Turbine (Pumped Storage)                | Energy Storage      |
| GT       | Combustion (Gas) Turbine. Including Jet Engine design                         | Combustion Turbine  |
| IC       | Internal Combustion (diesel, piston, reciprocating) Engine                    | Combustion Turbine  |
| HA       | Hydrokinetic, Axial Flow Turbine                                              | Hydrokinetic        |
| HB       | Hydrokinetic, Wave Buoy                                                       | Hydrokinetic        |
| HK       | Hydrokinetic, Other                                                           | Hydrokinetic        |
| HY       | Hydraulic Turbine. Including turbines associated with delivery of water by pipeline. | Hydraulic         |
| PV       | Photovoltaic                                                                  | Photovoltaic        |
| BT       | Turbines Used in a Binary Cycle. Including those used for geothermal applications. | Binary Turbine     |
| ST       | Steam Turbine. Including Nuclear, Geothermal, and Solar Steam (does not include Combined Cycle). | Steam Turbine      |
| WT       | Wind Turbine, Onshore                                                         | Wind Turbine        |
| WS       | Wind Turbine, Offshore                                                        | Wind Turbine        |
| FC       | Fuel Cell                                                                     | Energy Storage      |
| OT       | Other                                                                         | Other               |
**Table 8.** EIA cooling system code proxies for cooling system classifications used in this work [6].

| EIA Code | EIA Definition                                           | Proxy for this work |
|----------|---------------------------------------------------------|---------------------|
| DC       | Dry (air) cooling System                               | Dry cooling (DC)    |
| H        | Hybrid (non-specified)                                 | Hybrid (HB)         |
| HRC      | Hybrid: recirculating cooling pond(s) or canal(s) with dry cooling | Hybrid (HB)         |
| HRF      | Hybrid: recirculating with forced draft cooling tower(s) with dry cooling | Hybrid (HB)         |
| HRI      | Hybrid: recirculating with induced draft cooling tower(s) with dry cooling | Hybrid (HB)         |
| HT       | Helper Tower                                           | Recirculating (RT)  |
| O        | Once through (non-specified)                           | Once through (ON)   |
| O + R    | Once through (non-specified) and Recirculating (non-specified) | n/a                |
| OC       | Once through with Cooling Ponds                        | Pond (PN)           |
| ON       | Once through without cooling pond(s) or canal(s)       | Once through (ON)   |
| R        | Recirculating (non-specified)                          | Recirculating (RT)  |
| RC       | Recirculating with Cooling Ponds                       | Pond (PN)           |
| RF       | Recirculating with Forced Draft Cooling Tower          | Recirculating (RT)  |
| RI       | Recirculating with Induced Draft Cooling Tower         | Recirculating (RT)  |
| RN       | Recirculating with Natural Draft Cooling Tower         | Recirculating (RT)  |

**Table 9.** EIA water type code proxies for water type classifications used in this work [6].

| EIA Code | EIA Definition                                           | Proxy for this work |
|----------|---------------------------------------------------------|---------------------|
| SW       | Surface Water (ex: river, canal, bay)                   | Surface Water       |
| GW       | Ground Water (ex: aquifer, well)                        | Groundwater         |
| PD       | Plant Discharge Water (ex: wastewater treatment plant discharge) | Recycled Water      |

**Table 10.** EIA water quality code proxies for water quality classifications used in this work [6].

| EIA Code | EIA Definition                                           | Proxy for this work |
|----------|---------------------------------------------------------|---------------------|
| BR       | Brackish Water                                          | Brackish Water      |
| FR       | Fresh Water                                             | Freshwater          |
| BE       | Reclaimed Water (ex: treated wastewater effluent)       | Freshwater          |
| SA       | Saline Water                                            | Saline Water        |
### Table 12. Summary of regional volumetric water consumption for different generating technology classifications.

| Volumetric Water Consumption (million m$^3$)$^a$ |
|-----------------------------------------------|
| eGRID region | all thermal$^b$ | non-thermal$^c$ fueled$^d$ | non-hydro renewables$^e$ | all renewables$^f$ | no combustion$^g$ |
| AKGD         | 4.7  | 4.7  | 0.0027 | 4.7  | 0.0027 | 0.0027 | 0.0027 |
| AKMS         | 0.46 | 0.46 | 0.00060 | 0.46 | 0.00060 | 0.00060 | 0.00060 |
| AZNM         | 1,400| 260  | 1,100 | 120  | 55     | 1,200  | 1,300  |
| CAMX         | 300  | 250  | 44    | 99   | 120    | 170    | 180    |
| ERCT         | 360  | 360  | 4.7   | 290  | 0.93   | 4.9    | 71     |
| FRCC         | 300  | 300  | –     | 240  | 17     | 17     | 46     |
| HIMS         | 6.4  | 6.4  | 0.0085 | 5.8  | 0.64   | 0.64   | 0.34   |
| HIOA         | 22   | 22   | 0.0040 | 21   | 1.4    | 1.4    | 0.0043 |
| MROE         | 78   | 43   | 35    | 26   | 3.5    | 39     | 48     |
| MROW         | 450  | 230  | 220   | 150  | 8.0    | 230    | 290    |
| NEWE         | 130  | 140  | –6.5  | 52   | 29     | 22     | 51     |
| NWPP         | 360  | 300  | 64    | 250  | 24     | 88     | 100    |
| NYCW         | 45   | 45   | 0     | 19   | 1.4    | 1.4    | 24     |
| NYLI         | 15   | 15   | 0     | 11   | 3.5    | 3.5    | 0.00074|
| NYUP         | 53   | 75   | –22   | 26   | 4.0    | –18    | 23     |
| RFCE         | 410  | 420  | –6.9  | 190  | 13     | 6.4    | 200    |
| RFCM         | 110  | 110  | –2.9  | 75   | 4.7    | 1.6    | 32     |
| RFCW         | 950  | 920  | 22    | 730  | 4.7    | 27     | 220    |
| RMPA         | 93   | 100  | –8.0  | 100  | 0.37   | –7.8   | –8.0   |
| SPNO         | 72   | 72   | 0.19  | 55   | 0.25   | 0.25   | 17     |
| SPSO         | 250  | 210  | 40    | 200  | 6.4    | 45     | 40     |
| SRMV         | 380  | 300  | 84    | 200  | 10     | 94     | 170    |
| SRMW         | 300  | 250  | 44    | 180  | 0.27   | 44     | 120    |
| SRSO         | 370  | 400  | –31   | 290  | 23     | –8.7   | 54     |
| SRTV         | 580  | 530  | 45    | 440  | 4.7    | 50     | 130    |
| SRVC         | 520  | 440  | 79    | 220  | 24     | 100    | 280    |

National$^h$ | 7,500 | 5,800 | 1,700 | 4,000 | 360 | 2,100 | 3,300 |

$^a$Values are rounded to two significant digits. $^b$Biogas, biomass, coal, geothermal, natural gas, nuclear, oil, solar thermal. $^c$Hydroelectricity, solar, wind. Includes solar thermal. $^d$Coal, natural gas, oil. $^e$Biogas, biomass, geothermal, solar, wind. $^f$Biogas, biomass, geothermal, hydroelectricity, solar, wind. $^g$Geothermal, hydroelectricity, nuclear, solar, wind. $^h$National totals may not match generation-weighted values presented in table due to rounding.
Table 13. Summary of regional upstream consumptive water intensity by fuel type, 2014.

| eGRID region | Biogas | Biomass | Coal | Geothermal | Hydro | Oil | Natural Gas | Solar PV | Solar Thermal | Uranium | Wind |
|--------------|--------|---------|------|------------|-------|-----|-------------|----------|---------------|---------|------|
| AKGD         | 0      | 0       | 0.037| 0          | 0     | 1.2 | 0.27        | 0        | 0             | 0       | 0    |
| AKMS         | 0      | 0       | 0    | 0          | 0     | 13  | 0.41        | 0        | 0             | 0       | 0    |
| AZNM         | 0      | 1.6     | 0.21 | 12         | 126   | 1.5 | 0.21        | 0.011    | 0.078         | 0.013   | 0.011|
| CAMX         | 0      | 1.5     | 0.87 | 12         | 2.8   | 1.4 | 0.20        | 0.011    | 0.078         | 0.013   | 0.011|
| ERCT         | 0      | 1.5     | 0.20 | 0          | 13    | 2.1 | 0.20        | 0.011    | 0             | 0.013   | 0.011|
| FRCC         | 0      | 1.7     | 1.0  | 0          | 0     | 1.4 | 0.21        | 0.011    | 0.078         | 0.013   | 0    |
| HIMS         | 0      | 1.0     | 0    | 0          | 0     | 1.4 | 0           | 0.011    | 0             | 0       | 0    |
| HIOA         | 0      | 1.7     | 0.19 | 0          | 0     | 1.2 | 0.15        | 0.011    | 0             | 0       | 0    |
| MROE         | 0      | 1.2     | 0.031| 0          | 33    | 1.2 | 0.22        | 0        | 0             | 0.013   | 0.011|
| MROW         | 0      | 1.4     | 0.013| 0          | 19    | 1.7 | 0.24        | 0.011    | 0             | 0.013   | 0.011|
| NEWE         | 0      | 1.4     | 0.25 | 0          | -0.97 | 1.4 | 0.21        | 0.011    | 0.078         | 0.013   | 0.011|
| NWPP         | 0      | 1.2     | 0.16 | 0.30       | 0.47  | 1.5 | 0.21        | 0.011    | 0             | 0.013   | 0.011|
| NYCW         | 0      | 1.9     | 0    | 0          | 0     | 1.2 | 0.24        | 0        | 0             | 0.013   | 0    |
| NYLI         | 0      | 1.9     | 0    | 0          | 0     | 1.5 | 0.25        | 0.011    | 0             | 0       | 0    |
| NYUP         | 0      | 1.3     | 0.30 | 0          | -0.85 | 1.3 | 0.21        | 0.011    | 0             | 0.013   | 0.011|
| RFCE         | 0      | 1.8     | 0.32 | 0          | -2.2  | 1.5 | 0.22        | 0.011    | 0             | 0.013   | 0.011|
| RFCM         | 0      | 1.3     | 0.06 | 0          | 27    | 1.3 | 0.25        | 0        | 0             | 0.013   | 0.011|
| RFCW         | 0      | 1.0     | 0.51 | 0          | 6.0   | 1.4 | 0.22        | 0.011    | 0             | 0.013   | 0.011|
| RMPA         | 0      | 1.6     | 0.064| 0          | -3.8  | 1.5 | 0.23        | 0.011    | 0             | 0       | 0.011|
| SPNO         | 0      | 1.4     | 0.012| 0          | 0     | 2.1 | 0.30        | 0        | 0             | 0.013   | 0.011|
| SPSO         | 0      | 0.8     | 0.14 | 0          | 12    | 1.4 | 0.22        | 0.011    | 0             | 0       | 0.011|
| SRMV         | 0      | 0.72    | 0.076| 0          | 37    | 1.4 | 0.23        | 0.011    | 0             | 0.013   | 0    |
| SRMW         | 0      | 1.0     | 0.046| 0          | 37    | 1.5 | 0.24        | 0.011    | 0             | 0.013   | 0.011|
| SRSO         | 0      | 1.0     | 0.47 | 0          | -4.6  | 1.5 | 0.20        | 0.011    | 0             | 0.013   | 0    |
| SRTRV        | 0      | 0.52    | 1.8  | 0          | 2.4   | 1.5 | 0.22        | 0.011    | 0             | 0.013   | 0.011|
| SRVC         | 0      | 1.1     | 0.38 | 0          | 21    | 1.5 | 0.21        | 0.011    | 0             | 0.013   | 0    |

| Nationalb   | 0      | 1.2    | 0.40 | 9.5        | 6.8   | 1.4 | 0.21        | 0.011    | 0.078         | 0.013   | 0.011|

*Values are rounded to two significant digits. b National totals may not match generation-weighted averages presented in table due to rounding.
| eGRID region | Biogas | Biomass | Coal | Geothermal | Hydro | Oil | Natural Gas | Solar PV | Solar Thermal | Uranium | Wind |
|--------------|--------|---------|------|------------|-------|----|-------------|---------|--------------|---------|------|
| AKGD         | 0      | 0       | 1.4  | 0          | 0     | 1.9| 0.62        | 0       | 0            | 0       | 0    |
| AKMS         | 0      | 0       | 0    | 0          | 0     | 0  | 0           | 0       | 0            | 0       | 0    |
| AZNM         | 0      | 1.8     | 1.7  | 0.71       | 0     | 2.0| 0.67        | 0       | 2.3          | 2.5     | 0    |
| CAMX         | 0.53   | 1.8     | 1.4  | 0.32       | 0     | 0  | 0.60        | 0       | 5.1          | 1.8     | 0    |
| ERCT         | 0      | 1.8     | 1.4  | 0          | 0     | 0  | 0.22        | 0.74    | 0            | 1.7     | 0    |
| FRCC         | 0.52   | 1.8     | 1.3  | 0          | 0     | 0  | 0.46        | 0.73    | 4.4          | 1.6     | 0    |
| HIMS         | 0      | 1.8     | 1.4  | 1.3        | 0     | 1.9| 0           | 0       | 0            | 0       | 0    |
| HIOA         | 0      | 1.7     | 1.8  | 0          | 0     | 2.3| 0           | 0       | 0            | 0       | 0    |
| MROE         | 0.017  | 1.2     | 1.2  | 0          | 0     | 0  | 0.28        | 0.83    | 0            | 0       | 1.4  |
| MROW         | 0.10   | 1.8     | 1.3  | 0          | 0     | 1.0| 0.68        | 0       | 0            | 0       | 1.6  |
| NEWE         | 0.45   | 1.8     | 1.5  | 0          | 0     | 2.2| 0.53        | 0       | 0            | 0       | 1.6  |
| NWPP         | 0.23   | 1.8     | 1.7  | 3.6        | 0     | 0  | 0.70        | 0.62    | 0            | 0       | 2.5  |
| NYCW         | 0      | 1.8     | 0    | 0          | 0     | 2.1| 0.48        | 0       | 0            | 0       | 1.4  |
| NYLI         | 0      | 1.8     | 0    | 0          | 0     | 1.9| 0.67        | 0       | 0            | 0       | 0    |
| NYUP         | 0      | 1.8     | 0.82 | 0          | 0     | 2.4| 0.69        | 0       | 0            | 0       | 1.7  |
| RFCE         | 0.31   | 1.8     | 1.4  | 0          | 0     | 1.3| 0.71        | 0       | 0            | 0       | 1.9  |
| RFCM         | 0.17   | 1.8     | 1.1  | 0          | 0     | 0.27| 0.74        | 0       | 0            | 0       | 2.5  |
| RFCW         | 0.04   | 1.8     | 1.5  | 0          | 0     | 0.44| 0.87        | 0       | 0            | 0       | 1.9  |
| RMPA         | 0      | 1.8     | 1.4  | 0          | 0     | 0.89| 0.60        | 0       | 0            | 0       | 0    |
| SPNO         | 0      | 1.8     | 1.3  | 0          | 0     | 1.7| 0.96        | 0       | 0            | 0       | 1.9  |
| SPSO         | 0      | 1.8     | 1.5  | 0          | 0     | 0.050| 0.92       | 0       | 0            | 0       | 0    |
| SRMV         | 0      | 1.8     | 1.7  | 0          | 0     | 0.064| 0.75       | 0       | 0            | 0       | 2.1  |
| SRMW         | 0.022  | 1.8     | 1.2  | 0          | 0     | 2.2 | 0.65        | 0       | 0            | 0       | 2.0  |
| SRSO         | 0.40   | 1.7     | 1.5  | 0          | 0     | 0.94| 0.78        | 0       | 0            | 0       | 1.8  |
| SRTV         | 0      | 1.8     | 1.3  | 0          | 0     | 0.51| 0.65        | 0       | 0            | 0       | 1.6  |
| SRVC         | 0      | 1.8     | 1.3  | 0          | 0     | 1.3 | 0.67        | 0       | 0            | 0       | 1.6  |

| National$^h$ | 0.22   | 1.8     | 1.4  | 1.1       | 0     | 1.1 | 0.71        | 0       | 3.5          | 1.8     | 0    |

$^a$Values are rounded to two significant digits. $^b$National totals may not match generation-weighted averages presented in table due to rounding.
| eGRID region | Biogas | Biomass | Coal | Geothermal | Hydro | Oil | Natural Gas | Solar PV | Solar Thermal | Uranium | Wind |
|--------------|--------|---------|------|------------|-------|-----|-------------|---------|--------------|---------|------|
| AKGD         | 0      | 0       | 1.5  | 0          | 0     | 3.2 | 0.89        | 0       | 0            | 0       | 0.011|
| AKMS         | 0      | 0       | 0    | 0          | 13    | 0.41| 0           | 0       | 0            | 0       | 0.011|
| AZNM         | 0      | 3.5     | 1.9  | 0          | 126   | 3.5 | 0.88        | 0.011   | 2.4          | 2.6     | 0.011|
| CAMX         | 0.53   | 3.3     | 2.3  | 13         | 2.8   | 1.4 | 0.81        | 0.011   | 5.2          | 1.8     | 0.011|
| ERCT         | 0      | 3.3     | 1.6  | 0          | 13    | 2.4 | 0.94        | 0.011   | 0            | 1.7     | 0.011|
| FRCC         | 0.52   | 3.5     | 2.3  | 0          | 0     | 1.9 | 0.94        | 0.011   | 4.5          | 1.6     | 0    |
| HIMS         | 0      | 2.8     | 1.4  | 1.3        | 0     | 3.3 | 0           | 0.011   | 0            | 0       | 0.011|
| HOA          | 0      | 3.3     | 2.0  | 0          | 0     | 3.5 | 0.15        | 0.011   | 0            | 0       | 0.011|
| MROE         | 0.017  | 2.4     | 1.2  | 0          | 33    | 1.5 | 1.0         | 0       | 0            | 1.4     | 0.011|
| MROW         | 0.10   | 3.2     | 1.4  | 0          | 19    | 2.7 | 0.92        | 0       | 0            | 1.7     | 0.011|
| NEWE         | 0.45   | 3.2     | 1.8  | 0          | −0.97 | 3.6 | 0.74        | 0.011   | 0.078        | 1.6     | 0.011|
| NWPP         | 0.23   | 2.9     | 1.9  | 3.8        | 0.47  | 2.2 | 0.82        | 0.011   | 0            | 2.6     | 0.011|
| NYCW         | 0      | 3.7     | 0    | 0          | 0     | 3.3 | 0.72        | 0       | 0            | 1.4     | 0    |
| NYLI         | 0      | 3.8     | 0    | 0          | 0     | 3.4 | 0.92        | 0.01    | 0            | 0       | 0    |
| NYUP         | 0      | 3.2     | 1.1  | 0          | −0.85 | 3.7 | 0.90        | 0       | 1.7          | 0.011   | 0    |
| RFCE         | 0.31   | 3.6     | 1.8  | 0          | −2.2  | 2.9 | 0.93        | 0.011   | 0            | 1.9     | 0.011|
| RFCM         | 0.17   | 3.1     | 1.2  | 0          | 27    | 1.6 | 0.99        | 0       | 0            | 2.6     | 0.011|
| RFCW         | 0.04   | 2.8     | 2.0  | 0          | 6.0   | 1.9 | 1.1         | 0.011   | 0            | 1.9     | 0.011|
| RMPA         | 0      | 3.4     | 1.5  | 0          | −3.8  | 2.4 | 0.83        | 0.011   | 0            | 0       | 0.011|
| SPNO         | 0      | 3.2     | 1.3  | 0          | 0     | 3.7 | 1.3         | 0       | 0            | 1.9     | 0.011|
| SPSO         | 0      | 2.6     | 1.6  | 0          | 12    | 1.4 | 1.1         | 0.011   | 0            | 0       | 0.011|
| SRMV         | 0      | 2.5     | 1.8  | 0          | 37    | 1.5 | 0.97        | 0.011   | 0            | 2.1     | 0    |
| SRMW         | 0.02   | 2.8     | 1.2  | 0          | 37    | 3.7 | 0.89        | 0.011   | 0            | 2.0     | 0.011|
| SRSO         | 0.40   | 2.7     | 2.0  | 0          | −4.6  | 2.4 | 0.98        | 0.011   | 0            | 1.8     | 0    |
| SRTV         | 0      | 2.3     | 3.2  | 0          | 2.4   | 2.0 | 0.86        | 0.011   | 0            | 1.6     | 0.011|
| SRVC         | 0      | 2.9     | 1.7  | 0          | 21    | 2.8 | 0.87        | 0.011   | 0            | 1.6     | 0    |

| Nationalb   | 0.22   | 3.0     | 1.8  | 11         | 6.8   | 2.5 | 0.92        | 0.011   | 3.6          | 1.8     | 0.011|

*aValues are rounded to two significant digits. *b National totals may not match generation-weighted averages presented in table due to rounding.
4.1. Technological and fuel variability in water consumption from electricity

Total induced upstream water consumption for coal produced for electricity generation is only 22% of the total life cycle water use illustrated in Figure 3; thus, the coal category is dominated by cooling water use at the point of coal-fired power plant generation. In total, coal represented approximately 22% of total US water consumption associated with upstream production and processing of fuels consumed in power plants, but 48% of total US water consumption at the point of electricity generation.

Because of regional differences in production methods (e.g. underground vs surface extraction) and geological characteristics, such as the accumulated water present in a coal seam, the water consumed for coal mining is non-linear and can vary significantly across regions. Thus, regional water consumption rates for coal production and processing upstream of the point of power generation were utilized. Although the water consumed for coal mining appears to be relatively large in some regions, much of this water consumption is associated with dewatering and depressurization of mines, that is, water trapped within the coal mine is released to facilitate production. We consider this water removal consumptive since water is displaced from its original formation and is not returned. However, unlike many other consumptive uses of water, this water might not directly compete with regional water users as it might not have been produced in the absence of coal mining.

Water consumption for natural gas-fired generators is also dominated by cooling water requirements at the point of generation, which represents 77% of the total life cycle water consumption for the fuel. The introduction of hydraulic fracturing (HF) and horizontal drilling has increased the fraction of generation supplied by natural gas, but the induced water consumption upstream of generation only represents 8% of the national upstream water consumption. Similarly, the water consumption at the point of generation represents 17% of national consumption, highlighting the increased average efficiency of the natural gas generation fleet.

Results indicate that the large volumes of water consumption associated with nuclear power generation are driven by cooling water requirements. The upstream induced water consumption for uranium is relatively small (only 1% of total US upstream water consumption) because the uranium extraction, processing, and refining industry is highly international. [2] In 2014, only 6% of the uranium purchased for nuclear power production originated from the US, with the remaining 94% originating from foreign countries, namely Kazakhstan, Australia, Canada, and Russia. [10] This work only reflects water that is consumed in the United States, therefore the water embedded in upstream process of imported uranium used for electricity generation is excluded. Conversely, the water consumption at the point of generation for nuclear-fueled generation represents approximately one third (31%) of total US point of generation consumption. This consumption is driven heavily by slightly increased consumption rates and the exclusive use of wet cooling systems at nuclear generating facilities.
Hydropower represented approximately 6% of total US electricity generation and 23% of total water consumption in 2014. Water consumption associated with hydroelectricity occurs as evaporative losses upstream of the PoG, i.e., from the reservoir.

The water consumption associated with hydropower generation has noticeably large regional variability, including some regions with negative water consumption. Negative water consumption can occur due to our use of a net water consumption approach for calculating water consumption relative to evapotranspiration from preexisting landcover. This condition applies to about 20% of 2014 generation, mostly in New England and the forested southeast. Hydroelectric generation in the Northeast Power Coordinating Council New England (NEWE), Northeast Power Coordinating Council Upstate NY (NYUP), SERC Reliability Corporation South (SRSO), Western Electricity Coordinating Council Rockies (RMPA), and Reliability First Corporation East (RFCE) eGRID subregions has negative water consumption, indicating that the presence of impoundments in these regions actually result in the net accumulation of water into the environment as a result of human activity.

Although the Western Electricity Coordinating Council Northwest (NWPP) generated more electricity from hydropower than any other subregion in 2014 (54% of total US hydro generation), its net water consumption from this generation is relatively small (3.7% of total US hydropower water consumption). By contrast, the Western Electricity Coordinating Council Southwest (AZNM), represents a relatively small amount (3.5%) of total US hydroelectricity generation, ranking 14th of the 26 eGRID subregions, but its upstream water consumption far exceeds any other subregion (65% of total US upstream consumption for hydroelectricity). As a result, consumptive losses associated with hydropower generation represent 60% of total upstream water consumption despite only accounting for 5.9% of generation within the region. The disproportionate water consumption intensity of hydropower generation in the AZNM region is driven primarily by large dams along the Colorado River (e.g. the Hoover Dam, etc.) that drive net increases in evaporation (as compared to the baseline evapotranspiration in the region).

The total water consumption associated with electricity generation (i.e. upstream and at the point of generation) is driven by cooling thermal power plants in most regions (Figure 3). The cooling water consumption intensity of these thermal generators will vary slightly from facility to facility due to factors such as cooling system, prime mover configuration, power generation efficiency, local climate conditions, and to some extent, regulatory policy [11]. The variability of consumptive rates (i.e. m³/MWh) for wet-cooled facilities is relatively low across generating technologies (e.g. on the same order of magnitude), but is significantly reduced for hybrid and dry-cooled facilities. As such, the calculated water consumption at the point of generation scales largely with the fraction of generation from thermal generation (namely coal, natural gas, and nuclear) in each region. Figures 3 and 4 show electricity generation and water consumption by cooling system type, for context.
In sharp contrast to coal mining, the water consumed at the point of coal-fired electricity generation scales roughly with the amount of electricity generated at coal-fired facilities in each subregion. The same trends are seen for nuclear generators, although their average water consumption rates are slightly higher than coal-fired facilities. Unlike coal-fired generators, nuclear facilities cannot discharge heat through flue gases. Natural gas-fired generators in the US have higher average efficiency than coal-fired and nuclear generation units, in part due to use of combined cycle configurations. Both the higher efficiency and use of gas turbines in a combined cycle configuration contribute to lower cooling water requirements per unit of generation [12]. These trends are evident in Figures 3 and 2, where the water consumed at the point of generation for each type of thermal generator generally scales with its respective fraction of electricity generation in each subregion.
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