# Water Requirements for Existing and Emerging Thermoelectric Plant Technologies

DOE/NETL-402/080108

August 2008 (April 2009 Revision)

# Disclaimer

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# Executive Summary

In light of the critical relationship between power generation and water, it is necessary to understand the water-related impacts associated with deployment of the advanced power platforms included in the National Energy Technology Laboratory (NETL) research program. Table ES-1 shows water consumption and cooling duty factors for several power generation platforms, with and without carbon dioxide ($CO_2$) capture. There is almost a fourfold increase in water consumption per net kWh between the lowest water consuming platform (NGCC) and the highest (Nuclear). Also the addition of $CO_2$ capture and compression increases water consumption by 50% to 90%. Many of the advanced power platforms use less water and have a lower increase in water demand associated with incorporation of $CO_2$ capture equipment than do current technologies.

The water consumption factors in Table ES-1 are based on a cooling system in which the effluent cooling water from the steam cycle condenser and other water coolers is cooled in an evaporative cooling tower and re-circulated. "Consumption" represents water that must be made up to account for both evaporation in the cooling tower and a relatively small amount that is consumed in unit operations within the generation process. Table ES-1 also presents cooling duty factors, or thermal cooling load per kWh of net generation. These factors enable one to estimate the impacts of different cooling water system configurations (e.g., once-through, wet cooling, dry cooling). The percent change with the addition of $CO_2$ capture is different for cooling duty and water consumption because cooling duty does not include process water requirements.

**Table ES-1. Water consumption and cooling duty factors for thermoelectric power plants**[i]

| | Without $CO_2$ Capture | With $CO_2$ Capture | % Change With $CO_2$ Capture |
|---|---|---|---|
| ***Water Consumption Factors (gallons per MWh net power)**** | | | |
| **Nuclear** | 720 | -- | |
| **Subcritical PC** | 520 | 990 | +90% |
| **Supercritical PC** | 450 | 840 | +90% |
| **IGCC, slurry-fed** | 310 | 450 | +50% |
| **NGCC** | 190 | 340 | +80% |
| ***Cooling Duty Factors (MMBtu per MWh net power)*** | | | |
| **Subcritical PC** | 4.7 | 11 | +130% |
| **Supercritical PC** | 4.1 | 9.3 | +130% |
| **IGCC, slurry-fed** | 3.0 | 3.7 | +20% |
| **NGCC** | 2.0 | 4.2 | +110% |

** Based on a cooling water system utilizing wet recirculating cooling towers*

[i] Factors derived from the NETL Report "Cost and Performance Baseline for Fossil Energy Power Plants study, Volume 1: Bituminous Coal and Natural Gas to Electricity"; adjustments described in Appendix A.

The factors in Table ES-1 are developed for the purpose of deriving the water-related impacts from different power plant deployment scenarios, such as those forecasted by the National Energy Modeling System (NEMS) and MarKal models. The body of this report presents the calculation methodologies and data sources used to estimate the factors set forth in Table ES-1. This information will enable analysts to adjust the factors to represent the impact of advanced technologies in the areas of power generation, $CO_2$ capture and compression, and cooling water systems.

# 1 Background

Water, once considered a nearly inexhaustible resource, is increasingly limited, and water requirements for electricity production must compete with other demands, such as agriculture and sanitation. The 2007 drought in the southeastern U.S. underscored this issue with several nuclear power plants in the region reducing their output by up to 50% due to low river levels in August 2007.[1] Future water-related impacts on the industry may also come in the form of regulation. The Environmental Protection Agency is developing regulations under §316(b) of the Clean Water Act that will require the location, design, construction and capacity of cooling water intake structures to reflect the best technology available for minimizing adverse environmental impact.

## 1.1 Water Usage in Thermoelectric Plants

The water-related impacts of fossil fuel thermoelectric power plants are a function of (1) the cooling and process water needs, and (2) the system used to provide the cooling water. Thermoelectric power plants use water primarily to cool and condense the steam used to drive the turbines, with relatively minor amounts of water used for process steam make-up and other water-intensive processes, Figure 1.1-1.

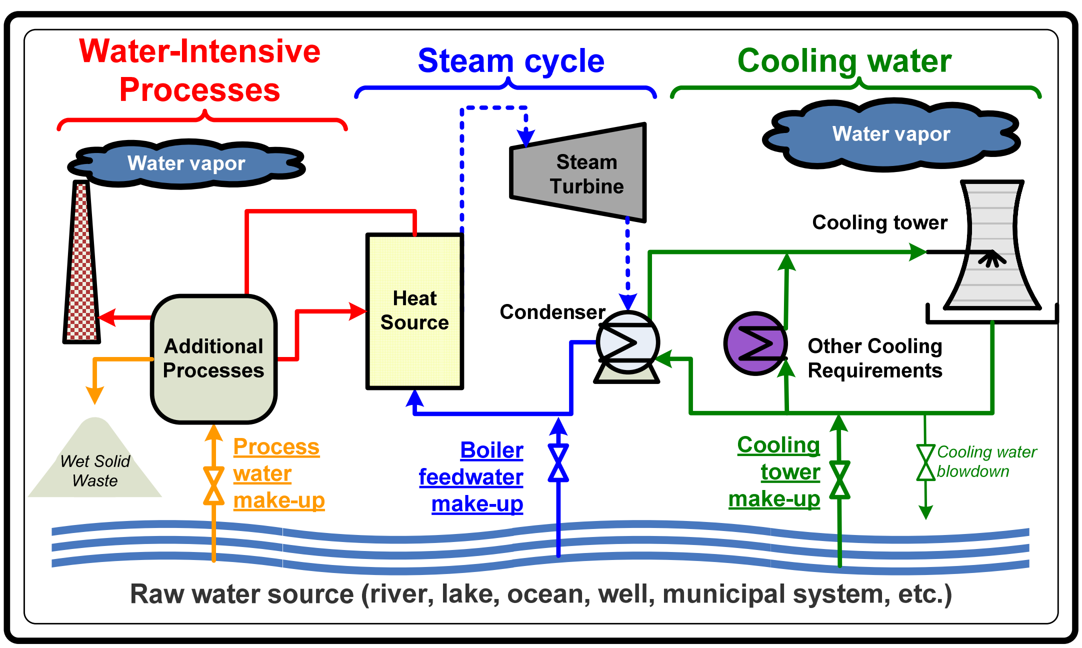



**Figure 1.1-1. Water flow schematic for power plants**

About 43% of existing thermoelectric power plant generating capacity employ a once-through cooling water system where water is drawn from a water body, used to condense steam, and then returned at a higher temperature.[2] More recently once-through cooling water systems have incorporated cooling towers that lower the temperature of the discharge water. Further reduction in water withdrawal can be achieved in a recirculating system where the bulk of the water is cooled in evaporative cooling towers and reused with a lesser amount discharged and made up. A still further reduction in water use is possible in dry cooling systems – beneficial for arid regions – that use closed loop air cooling thus eliminating losses due to evaporation.

### 1.2 Objective

In December 2006, NETL participated in a Department of Energy (DOE)-wide peer review of the analyses that are conducted to show the benefits of the DOE research and development portfolio. One of the recommendations from the peer review panel was for DOE to consider the water-related impacts associated with advanced thermoelectric plant technologies. This report provides the water use factors for use in deriving the water-related impacts from different power plant deployment scenarios, such as those forecasted by the National Energy Modeling System and MarKal models.

### 1.3 DOE Water Reduction Effort

This report highlights the water-related advantages of advanced power platforms within the NETL research portfolio. However, due to the critical relationship between power generation and water, NETL has also initiated a research program to specifically develop advanced technologies to reduce water consumption by thermoelectric power systems. The NETL Existing Plants – Emissions and Capture (EPEC) program contains a diverse research portfolio of water projects that have the potential to significantly reduce the water-related impacts of thermoelectric plants. The EPEC program focuses on four technology pathways: (1) use of nontraditional sources of process and cooling water; (2) innovative water reuse and recovery; (3) advanced cooling technologies; and (4) advanced water treatment and detection technology. Many of the efforts involve integration with existing power plant operations, but are also applicable to advanced thermoelectric technologies. More information on the NETL efforts can be found at: http://www.netl.doe.gov/technologies/coalpower/ewr/water/index.html

## 2 Cooling Water Systems

For a cooling water system, water usage can be described as either *consumption* such as the water evaporated to the atmosphere in a cooling tower or *withdrawal* which is equal to consumption plus any water returned to its source. There are two basic cooling system configurations – once-through and recirculating, Figure 2-1. In a once-through cooling system, water from an external water source passes through the steam cycle condenser and is then returned to the source at a higher temperature with some level of contaminants. This system *withdraws* a significant amount of water, but *consumes* little at the plant site (evaporation may, however, occur after the water is returned to its source). To minimize the thermal impact to the water source, a cooling tower may be added in a once-through system to allow air cooling of the water (with associated losses on site due to evaporation) prior to returning the water to its source.

In a recirculating system, cooling water exits the condenser, goes through a fixed heat sink and is then returned to the condenser. This configuration results in relatively low water *withdrawal*, but *consumption* occurring at the plant site is high relative to a once-through configuration. Typical heat sink options for recirculating systems are mechanical or natural draft cooling towers and cooling ponds. In cooling towers, the water is cooled by the air to near the wet-bulb temperature using the principle of evaporation. Water flows over high surface area packing which serves to increase contact time with the air and maximize heat transfer. Mechanical draft cooling towers use fans to push or pull air through the towers, while natural draft cooling towers utilize large concrete chimneys facilitating a natural air current up the tower. While they require less power, natural draft towers are extremely large and generally only used at facilities with high cooling water requirements.

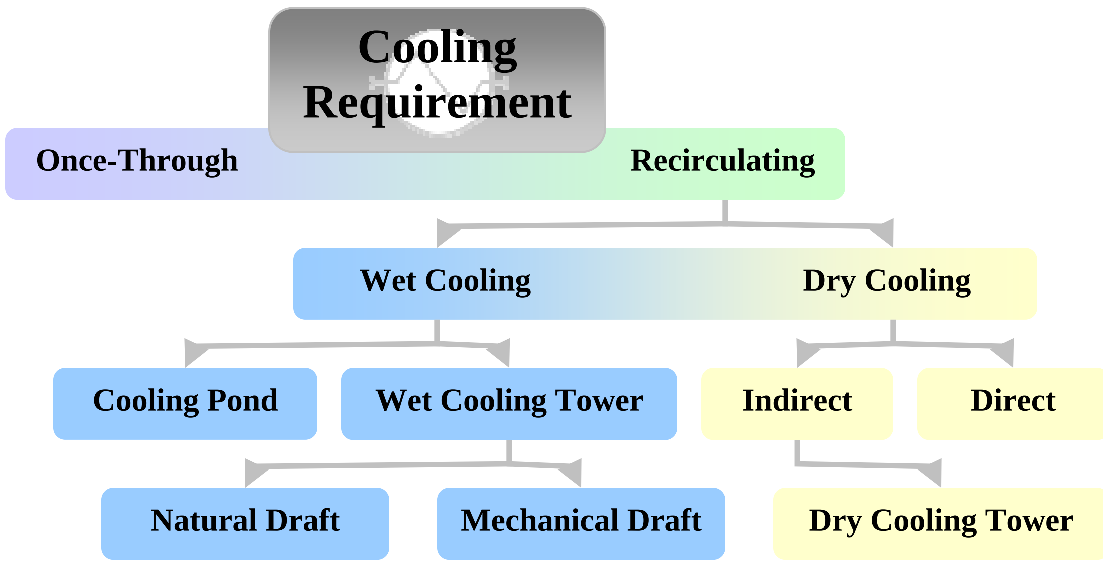



**Figure 2-1. Cooling water system configurations**

Make-up water to the cooling tower is required to replace the water that evaporates to the atmosphere. Evaporation losses are typically the largest contributor to water consumption in a cooling tower system and can be estimated based on the cooling water flow rate and the cooling water temperature rise.

As water evaporates in the cooling tower, any dissolved solids that came in with the raw make-up water will concentrate. To control the water chemistry and thus avoid scale formation and corrosion in the cooling water system, water must be discharged in a "blowdown" process. The required blowdown rate is highly dependent on the make-up water quality and is often determined based on cycles of concentration – the ratio of dissolved solids in the cooling water relative to the make-up water. With poor make-up water quality, the maximum allowable cycles of concentration is low requiring a high blowdown rate. A mid-range blowdown rate (corresponding to a water quality requiring a cycles of concentration of 4) would be one third of the evaporation losses or 25% of the total make-up cooling water flow.[3] The water discharged as part of the blowdown process may be returned to the original source or sent to a water treatment facility. The quantity discharged (the blowdown) is the primary difference between the raw water *withdrawal* and the water *consumption* in a wet recirculating cooling tower system.

When water availability is low, a dry cooling system may be utilized. Dry cooling can be either direct or indirect and in each case uses convective heat transfer to provide cooling, eliminating evaporation losses. In direct dry cooling systems, the turbine exhaust steam enters condenser tubes and is cooled by ambient air. In an indirect system, cooling water is used to condense the steam, as in a wet recirculating system. Then the cooling water flows through tube bundles that are cooled in a mechanical or natural draft cooling tower. Cooling water make-up requirements can be nearly eliminated by use of dry cooling systems, but process and steam make-up water requirements are unaffected.

Wet recirculating systems are roughly 40% more expensive than once-through systems, while dry cooling systems are 3 to 4 times more expensive than a wet recirculating system.[4] Figure 2-2 shows the average total cost and number of cooling systems for fossil/biomass-fueled steam plants in the U.S. for 2005. While most systems currently employ once-through cooling, environmental regulations and permitting requirements will likely push developers to choose recirculating or dry cooling options in the future.

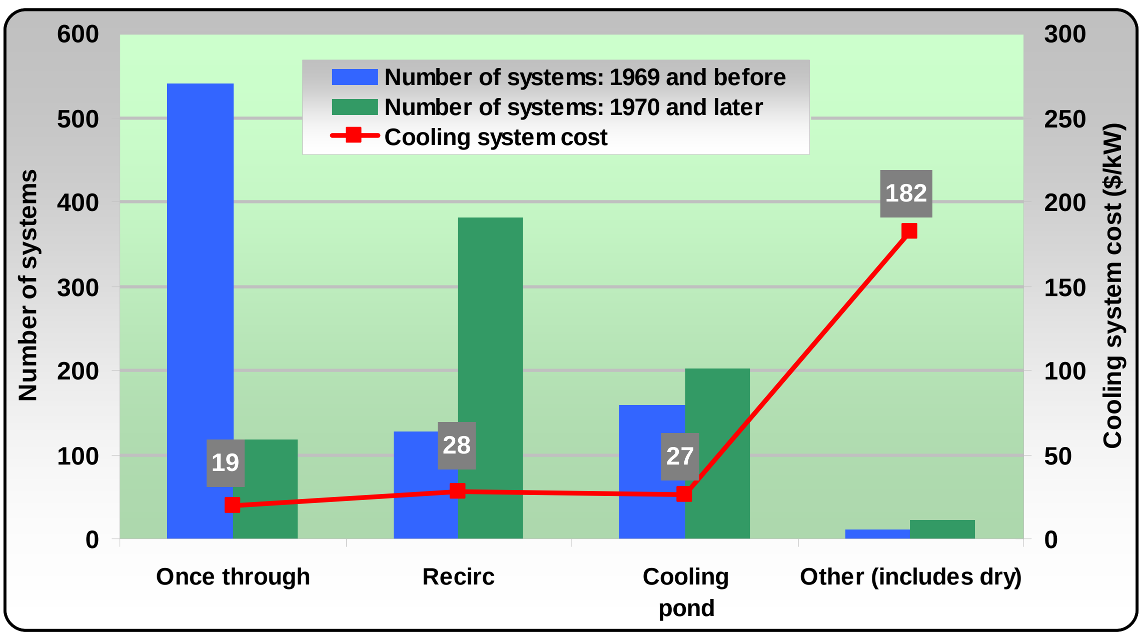



**Figure 2-2. Average total cost and number of cooling systems by type[5]**

# 3 Water Requirements for Power Generation Platforms

## 3.1 Data Sources and Comparison

In the 2007 NETL report, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity" (NETL Baseline), various greenfield thermoelectric plant technologies were designed and costed. Water consumption, while not the primary focus of the NETL Baseline report, was quantified for pulverized coal (PC), natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC) plants. The analysis in Sections 3 and 4 of this report stems from these designs.[ii] For the coal-based platforms, the water use factors are specific to bituminous coal.

Figure 3-1 compares water consumption for six thermoelectric generation platforms using the design water consumption values from the NETL Baseline report (coal- and natural gas-based systems) and a 2002 EPRI report (nuclear). The units are gallons of water consumed per net kWh of generation. All else equal, more efficient platforms will consume less water per kWh of net generation. However, other factors such as the steam cycle conditions, steam turbine contribution to gross power and process water requirements will impact the water usage for each technology.

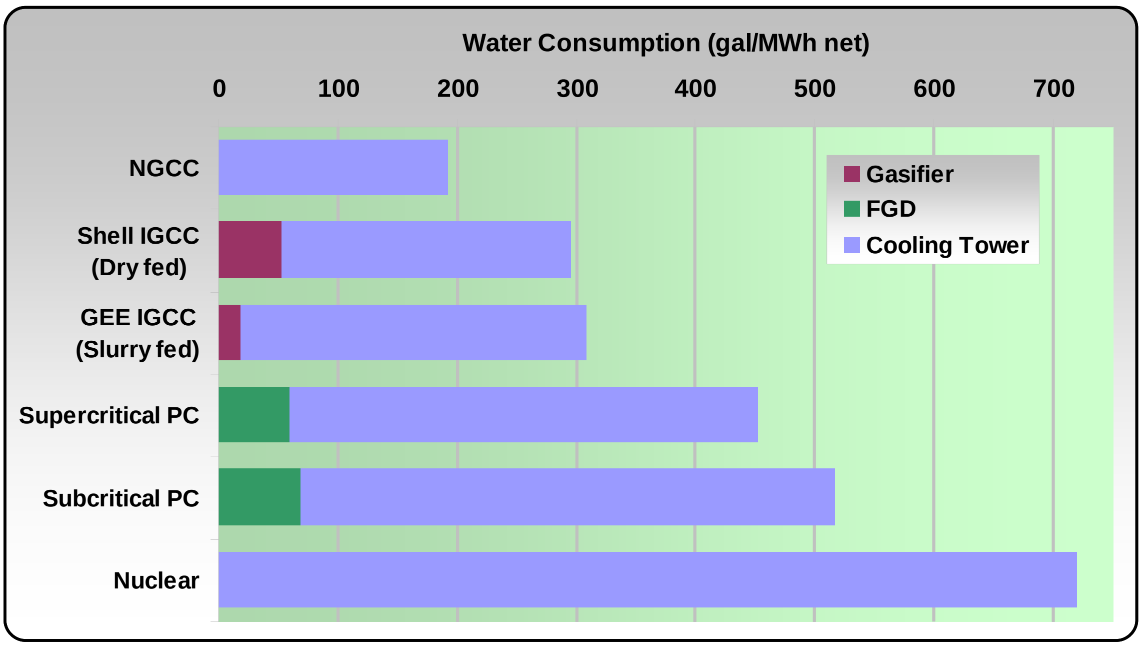



**Figure 3-1. Water consumption for nuclear[6] and greenfield bituminous coal and natural gas thermoelectric power plants utilizing wet cooling towers**

NGCC and IGCC power plants have lower water consumption due to the fact that around 2/3 of a combined cycle power plant's output comes from the combustion turbines which require minimal water when compared to the steam cycle. Like PC plants, nuclear power generation is all from a steam cycle; however, nuclear plants utilize lower pressure and temperature steam, and as a result require more steam and cooling water relative to the power produced.

[ii]The water requirements associated with each technology that were determined by the NETL Baseline report were adjusted based on a more detailed water analysis. The key assumptions related to water consumption and withdrawal used in the original study and a description of the subsequent adjustments are described in Appendix A. These adjusted factors are utilized throughout this report.

## 3.2 Subcritical and Supercritical PC plants

As the least efficient type of fossil fuel power plant examined here, a subcritical PC plant also consumes the most water per kW of power produced. Due to the lower steam pressure as compared to a supercritical plant, less energy can be transferred from the boiler to the turbine, so more steam flow, and thus more cooling water flow is required to generate the same electricity. Schematics highlighting the water flows in a subcritical and a supercritical PC plant with a wet FGD unit can be seen in Figure 3-2 and Figure 3-3.

A PC plant fitted with a wet FGD unit will require make-up water. In an FGD, the flue gas enters a large vessel where it is sprayed with a slurry of about 10% limestone and 90% water. The sulfur in the flue gas and calcium in the limestone create a slurry of calcium sulfate (a gypsum). Although much of the water is removed from the gypsum by a dewatering process and then recycled, some is contained in the gypsum and must be made up.

Water is also lost from the plant in the form of water vapor in the flue gas. Although most of it was generated during combustion or was inherent coal moisture (approximately 11 wt% for bituminous coal), some of this water is from the FGD system.

In the steam cycle, the boiler feedwater (BFW) system requires blowdowns and subsequent make-up water. Because BFW make-up water is treated to remove impurities, the blowdown and make-up rates are not significant compared to the cooling water system requirements.

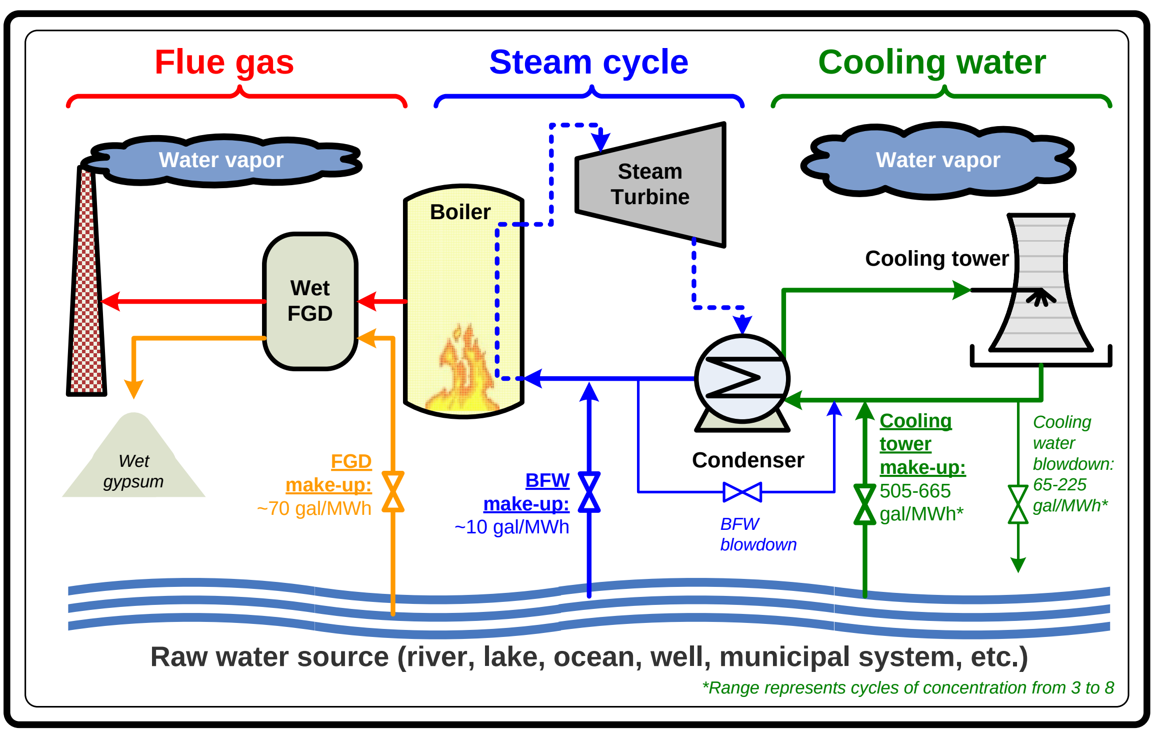



**Figure 3-2. Water flow schematic for a greenfield subcritical pulverized coal power plant utilizing a wet cooling tower and a wet FGD**

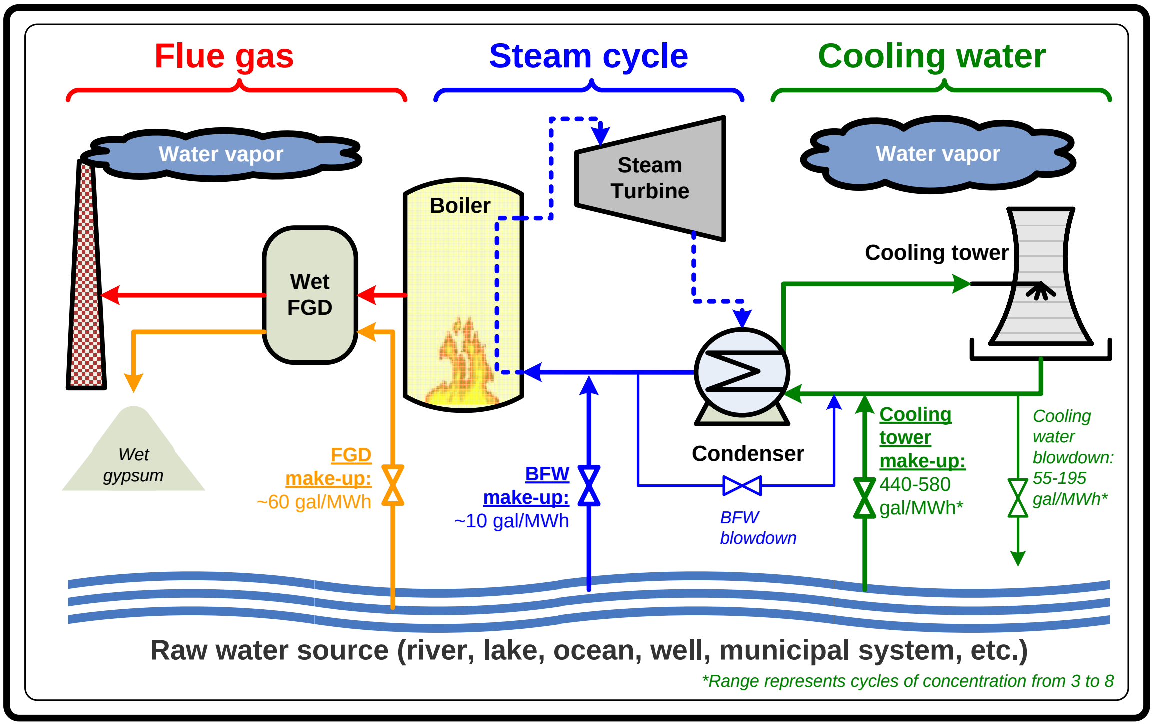



**Figure 3-3. Water flow schematic for a greenfield supercritical pulverized coal power plant utilizing a wet cooling tower and a wet FGD**

## 3.3 IGCC plants

An IGCC power plant's water profile is significantly lower than either sub- or supercritical PC plants as shown in Figure 3-4. This is mainly due to the fact that the gas turbine, which requires minimal cooling water, produces around 60% of the plant's entire electrical output. Hot exhaust gas from the gas turbine passes through a heat recovery steam generator (HRSG) to drive a steam cycle. It is worth noting that an IGCC's steam cycle operates at a lower pressure than a PC plant's does (1800 psig, as compared to 2400 psig for subcritical and 3500 psig for supercritical plants), hence an IGCC plant consumes more water per MWh produced from the *steam turbine* than does a PC plant.[iii]

In addition to the use of cooling water for the steam condenser, an IGCC plant has cooling requirements for several other gas processing steps. In the air separation unit (ASU), cooling water is required to cool compressed air prior to the cryogenic ASU cold box. In an IGCC's acid gas removal (AGR) unit, hydrogen sulfide removal occurs through absorption by a chemical or physical solvent that then must be regenerated using heat. Cooling water is primarily utilized in the regenerator tower condenser and to cool

[iii] For the GEE IGCC configuration modeled in NETL's baseline report, the steam turbine has a capacity of 299 MW and requires 3,485 gpm of make-up water associated with the condenser, yielding 699 gal/MWh gross for just the steam turbine condenser. For the PC plant, the cooling water make-up requirement is lower at 555 gal/MWh gross power. However, if the power output of the entire IGCC plant including the steam and gas turbines is accounted for, then the GE plant's cooling water make-up requirement is 271 gal/MWh gross power.

the regenerated solvent. Finally, a relatively small amount of cooling water is required for compressor intercoolers in the tail gas treating unit (TGTU).

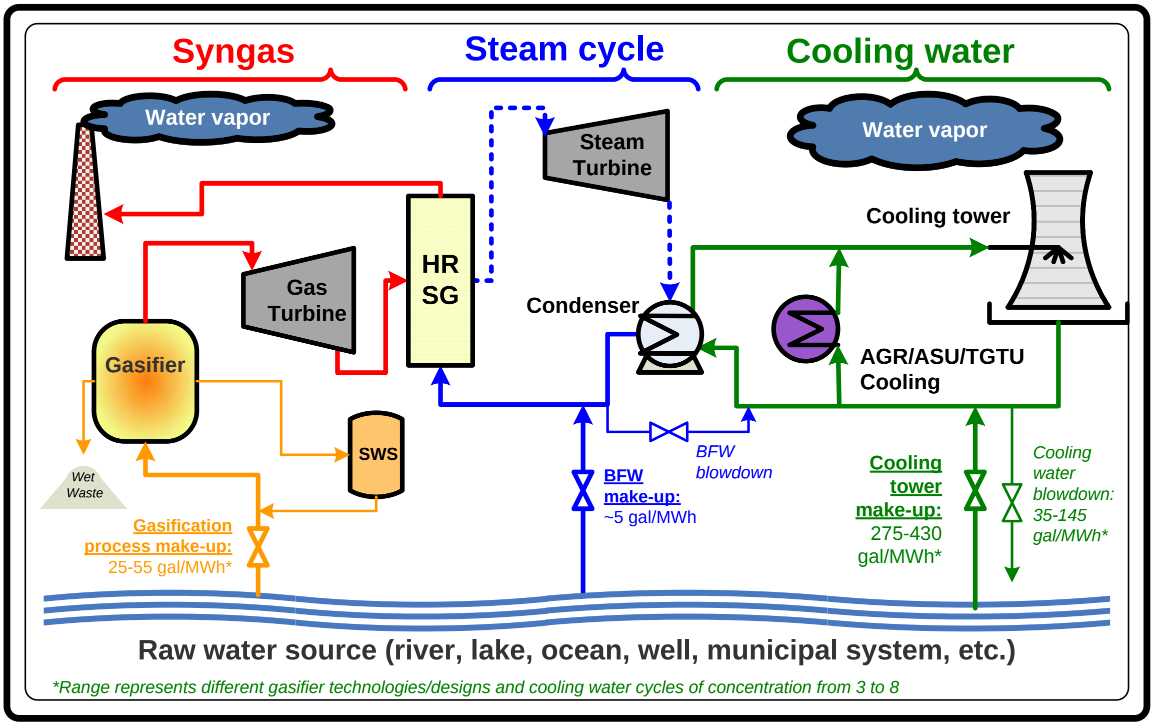



**Figure 3-4. Water flow schematic for a greenfield IGCC plant utilizing a wet cooling tower**

IGCC plants also have water make-up requirements related to the gasification process itself. In the gasifier, coal, oxygen and steam are reacted to produce a combustible gas called syngas. Each of the different IGCC gasifier designs modeled in the NETL Baseline report utilizes water for different sub-processes as shown in Table 3-1. In gasifiers marketed by Shell and ConocoPhillips (E-GAS), humidification of the syngas stream makes up a large portion of the gasifier's water demand. Syngas humidification along with steam and nitrogen dilution of the syngas aids in minimizing formation of $NO_x$ during combustion in the gas turbine burner section. The E-GAS and General Electric Energy (GEE) gasifiers are slurry fed meaning that water is added to the coal prior to gasification. A portion of the water is consumed in the gasification process as it is converted to syngas. For these slurry fed designs, molten slag leaving the gasifier is quenched in water, then the slurry of water and slag drops out of the stream and is disposed of. Although some of the slurry water can be recovered, significant make-up is still required. In each of the designs, scrubbing of the syngas with water occurs.

It was assumed that some process water can be recovered and utilized in other processes or otherwise recycled within the system. For example, the quench and scrubber water are sent to a sour water stripper (SWS) where the impurities are removed from the water. As modeled, a portion of the blowdown from the SWS effluent is recycled to meet other process water needs. Filtering or clean up requirements to facilitate this type of internal recycle were not evaluated in detail in the NETL Baseline report.

**Table 3-1. Water intensive processes utilized by different IGCC gasifier designs**[3]

| | GEE | CoP E-GAS | Shell |
|---|---|---|---|
| Ash Handling | ✗ | ✗ | ✗ |
| Slurry/Slag Handling | ✗ | ✗ | |
| Quench/Scrubber | ✗ | ✗ | ✗ |
| Humidifier | | ✗ | ✗ |
| Gasifier Steam | | | ✗ |
| Gas Turbine Dilution | | | ✗ |

## 3.4 NGCC plants

NGCC plants do not consume water for slurrying or desulfurization and the gas turbine generates 65%-70% of the total plant power output. The result is a configuration with a low water profile. The NGCC design does, however, consume roughly 25% more water relative to power generation from the *steam turbine* than does a subcritical PC plant, despite operating under similar steam conditions. This difference stems from the heat source for the BFW heater systems. In the NGCC design, the BFW heating occurs in the heat recovery steam generator (HRSG). In the PC design, extraction steam must be used for BFW heating. A schematic of a greenfield NGCC plant's water requirement is shown in Figure 3-5.

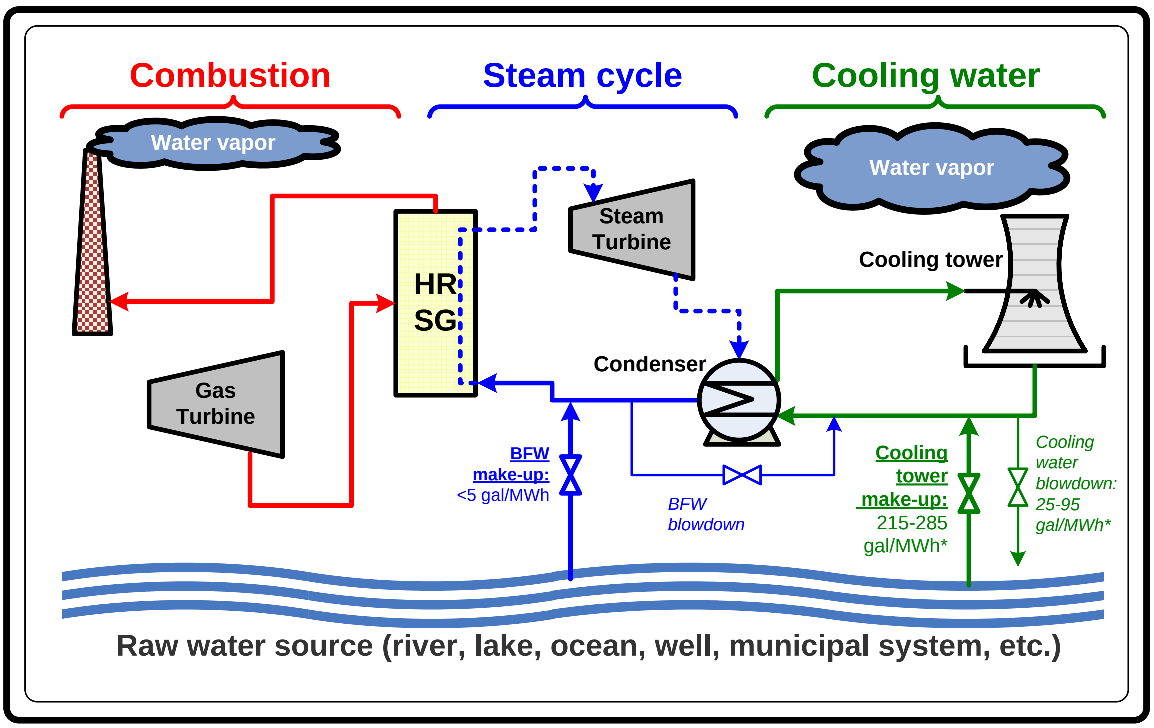



**Figure 3-5. Water flow schematic for a greenfield NGCC plant utilizing a wet cooling tower**

## 3.5 Nuclear Plants

In a nuclear plant, energy from the decay of uranium heats pressurized water which is then used to produce steam in the steam generator (SG). All power produced comes from the steam cycle as it does for PC plants. Nuclear plants have a higher cooling tower load relative to net power generation. This is because the steam conditions are limited by metal brittleness effects from the nuclear reactor thereby reducing efficiency. Figure 3-6 shows the water requirements for a nuclear power plant.

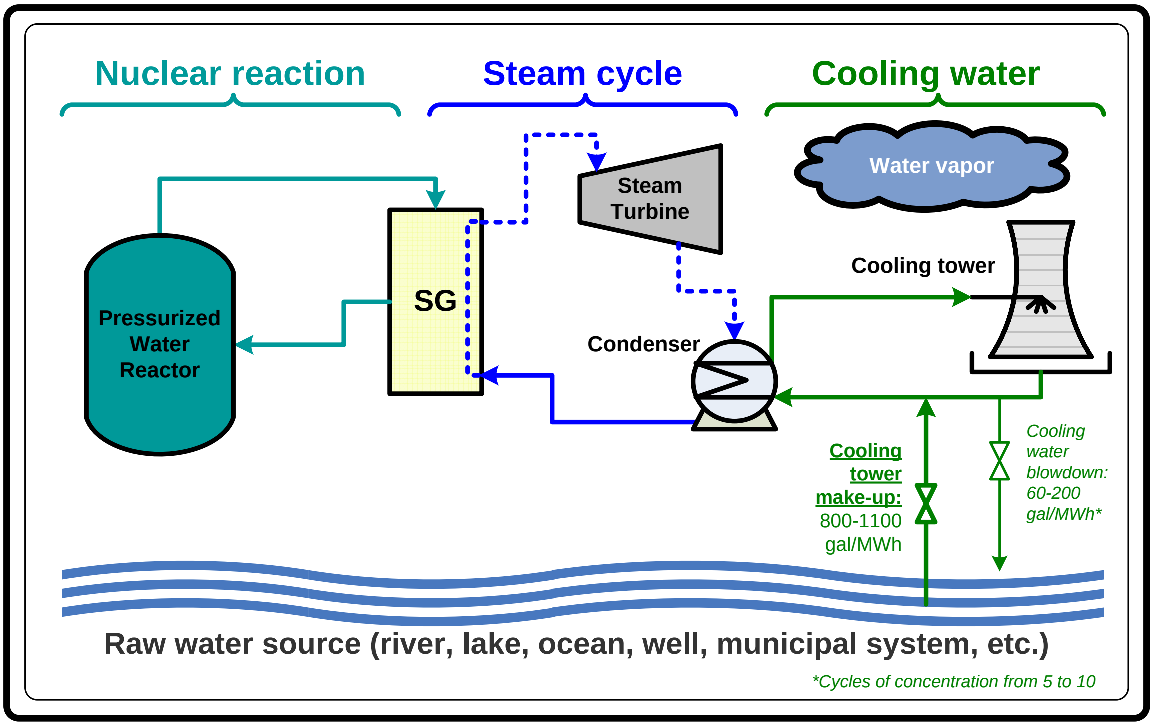



**Figure 3-6. Water flow schematic for a nuclear plant utilizing a wet cooling tower**[6]

# 4 Carbon capture and water usage

The NETL Baseline report designed and costed thermoelectric plants with the capability to capture carbon dioxide for each of the fossil energy plant technologies. Based on the technologies used in these designs, installing carbon dioxide recovery (CDR) equipment increases the water requirement per net power generation of a plant, due both to a reduction in the plant efficiency (Figure 4-1) and to the cooling water and process water requirements associated with carbon dioxide capture and compression.

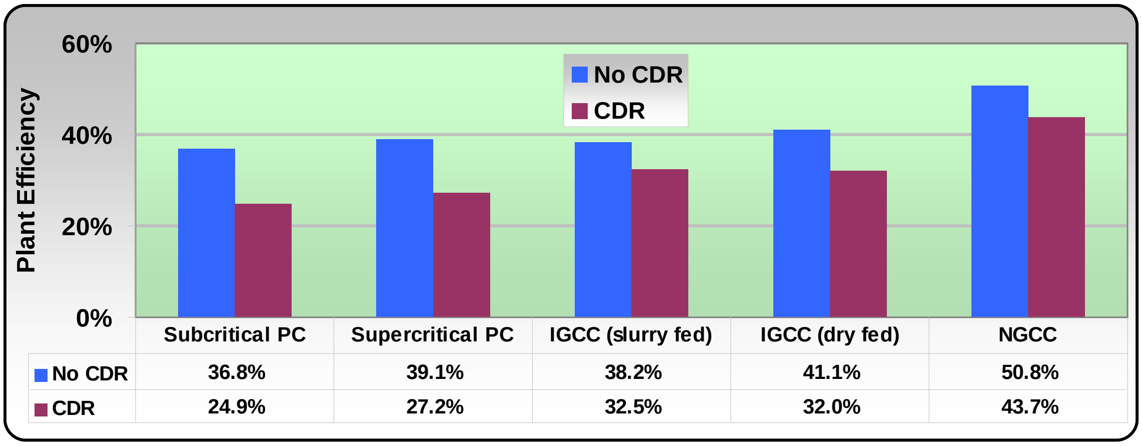



**Figure 4-1. Comparison of net plant efficiencies (HHV basis) with and without CDR**

The $CO_2$ recovery method for PC and NGCC plants used in the NETL Baseline study is a monoethanolamine (MEA) recovery unit based on the Fluor Econamine FG Plus technology. The data presented here are specific to that technology, however, research in this area is ongoing and systems with improved efficiency, costs, and/or water balances are being pursued.

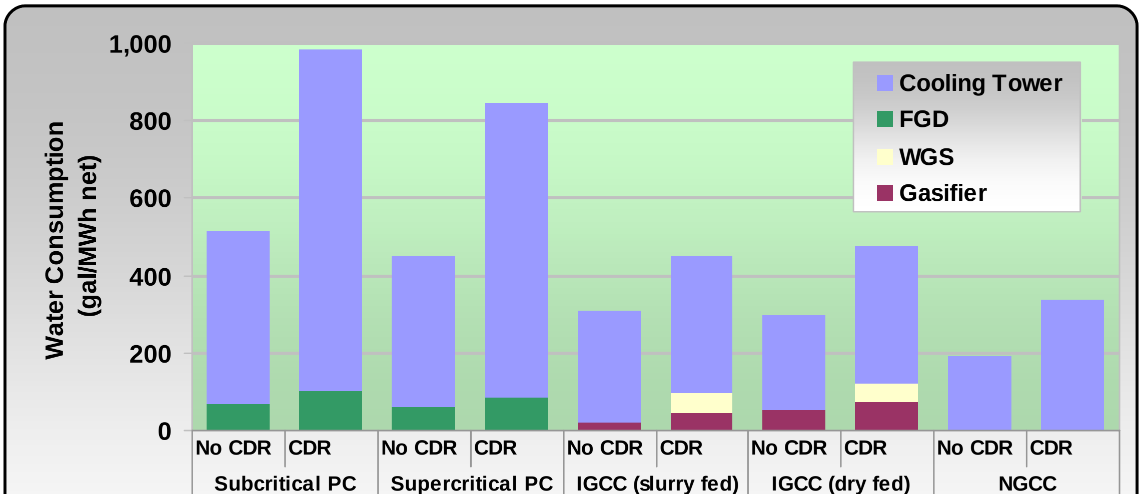
To meet the specifications of the Econamine process, a polishing scrubber simultaneously cools the flue gas and reduces the $SO_2$ concentration to less than 10 ppmv. The gas then contacts the MEA, which absorbs the $CO_2$. The $CO_2$-laden MEA is then steam-heated to release the $CO_2$. The MEA is recovered and reused, and the carbon dioxide is cooled and compressed for shipment. Overall, the CDR facility involves a number of subprocesses which collectively require a significant amount of cooling water. This includes flue gas cooling, water wash cooling, absorber intercooling, reflux condenser duty, reclaimer cooling, the lean solvent cooler, and $CO_2$ compression interstage cooling. At the same time, however, the cooling water requirements associated with the steam turbine condenser are reduced slightly relative to the power from the steam turbine as low pressure extraction steam is routed to the MEA regenerator condenser. In addition, a portion of the cooling water that is evaporated is offset by collecting water that condenses as the $CO_2$ is cooled and compressed. In a plant without CDR equipment, this water would generally leave the stack as water vapor.

For IGCC plants, a high level $CO_2$ recovery will require a water-gas shift reactor and a physical-absorption based scrubber. The water-gas shift reactor increases the $CO_2$ and hydrogen concentration in the syngas stream by converting carbon monoxide to $CO_2$ and hydrogen by the addition of steam over a catalyst bed. $CO_2$ is then removed from the gas stream using a two-stage Selexol process. The greater concentration of $CO_2$ in the IGCC process allows use of this physical-solvent. This results in less of an increase in cooling water requirements compared to the chemical solvent used in the Econamine process for PC and NGCC plants. The remaining increase in cooling duty is due to an increase in the ASU cooling requirements and the addition of $CO_2$ compressor intercoolers.

## 4.1 Water consumption factors[iv]

Utilizing the design conditions and assumptions of the NETL Baseline report, water consumption factors (net of the blowdown from the cooling water system) for each of the plant technologies with and without CDR equipment were developed. Raw water *withdrawal* factors which show the entire volume of water withdrawn for cooling water and process use is provided in Appendix B.

Figure 4-2 compares the water consumption relative to net power generation. In the PC and NGCC cases, water consumption per net generation increases by 90% and 76%, respectively, with the addition of $CO_2$ capture. The bulk of the increase is from higher cooling tower load related to the utilization of the cooling water-intensive chemical-absorption $CO_2$ recovery method at the back end of the power plant. In the IGCC slurry fed case, $CO_2$ recovery occurs prior to combustion so the water consumption factor increases by only 46%. More than half of this increase is due to water-intensive processes in the gasifier and in the water gas shift (WGS) process.




| | Subcritical PC | | Supercritical PC | | IGCC (slurry fed) | | IGCC (dry fed) | | NGCC | |
|---|---|---|---|---|---|---|---|---|---|---|
| | No CDR | CDR | No CDR | CDR | No CDR | CDR | No CDR | CDR | No CDR | CDR |
| Total | 517 | 985 | 452 | 844 | 309 | 452 | 295 | 475 | 192 | 338 |
| Cooling Tower | 449 | 884 | 392 | 759 | 290 | 355 | 243 | 355 | 192 | 338 |
| FGD | 68 | 101 | 59 | 86 | | | | | | |
| WGS | | | | | | 52 | | 49 | | |
| Gasifier | | | | | 19 | 45 | 53 | 71 | | |

**Figure 4-2. Comparison of water consumption factors with and without carbon capture for greenfield plants using wet recirculating cooling towers – net power basis**

The reason for increases in cooling water consumption per net power generation is a combination of the reduction in efficiency and the additional cooling water and process water for CDR equipment. Table 4-1 shows the total increase in water consumption for carbon capture and breaks it down into the expected water increase due to the lower efficiency of the carbon capture platform and the increased water usage due to additional cooling and process water for CDR processes.

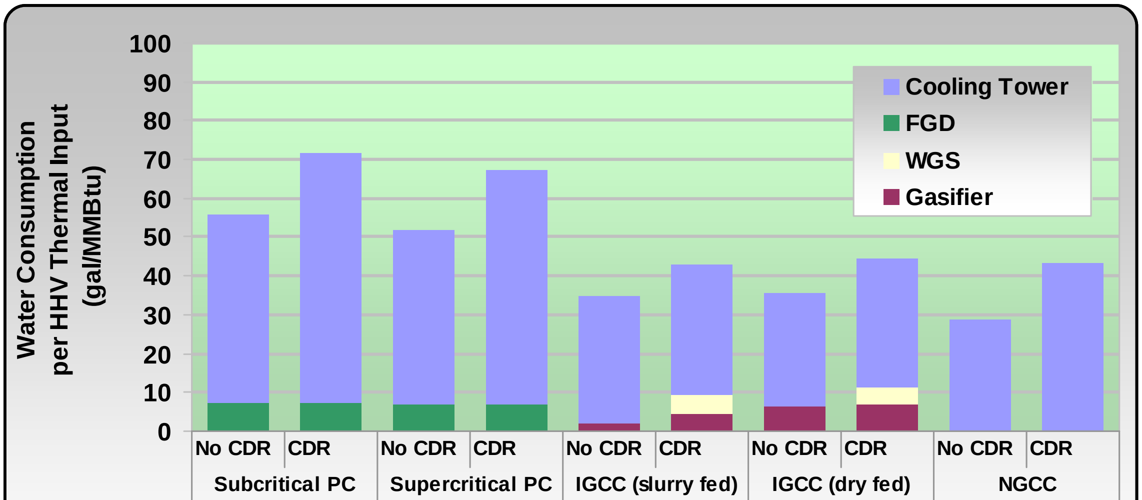
[iv] See Appendix A for key information on the basis for these factors.

**Table 4-1. Impact of efficiency and water use by CDR equipment on water consumption associated with carbon capture for plants using wet recirculating cooling towers**

| Plant Type | Impact of Efficiency | Impact of Water Use by CDR Processes | Total Increase in Water Consumption for Carbon Capture |
|---|---|---|---|
| | *Increase in Water Consumption Due to $CO_2$ Capture, gal/MWh net (%)* | | |
| **Subcritical PC** | 247 (48%) | 221 (43%) | 468 (90%) |
| **Supercritical PC** | 198 (44%) | 195 (43%) | 393 (87%) |
| **IGCC (slurry fed)** | 54 (18%) | 89 (29%) | 143 (46%) |
| **IGCC (dry fed)** | 84 (28%) | 96 (32%) | 180 (61%) |
| **NGCC** | 31 (16%) | 114 (60%) | 146 (76%) |

Figure 4-3 shows the water consumption factors on a HHV thermal input basis which essentially removes the impact of the efficiency reductions and only concentrates on the water use by the CDR equipment. On this basis, most of the increase in water consumption for the IGCC cases is due to process water usage including the addition of the steam for the WGS reaction and water demand associated with gasifier operation. The change in water consumption associated with the cooling water system for the IGCC cases is primarily due to compression cooling.

This information is also useful if policy and economic considerations point to the implementation of carbon capture for existing PC or NGCC plants. Should a plant be retrofitted with CDR equipment, the net power output of that plant would be reduced and thus the increase in water consumption for that specific plant would not increase by the 90% or 76% quoted above. For example, for an existing subcritical PC plant based on the design used in this evaluation, the water consumption assuming a constant coal feed rate would increase by 30% or require roughly 16 gallons of additional make-up water per MMBtu of thermal input (HHV). This additional requirement is almost entirely for the cooling tower load. As a result, if a particular plant has maximized its water draw, the additional water requirements are only associated with the cooling tower load and could thus be achieved with conversion to recirculating or the addition of a dry cooling system.




| | Subcritical PC | | Supercritical PC | | IGCC (slurry fed) | | IGCC (dry fed) | | NGCC | |
|---|---|---|---|---|---|---|---|---|---|---|
| | No CDR | CDR | No CDR | CDR | No CDR | CDR | No CDR | CDR | No CDR | CDR |
| Total | 55.7 | 71.8 | 51.8 | 67.4 | 34.6 | 43.1 | 35.5 | 44.5 | 28.6 | 43.2 |
| Cooling Tower | 48.4 | 64.4 | 45.0 | 60.5 | 32.5 | 33.8 | 29.2 | 33.2 | 28.6 | 43.2 |
| FGD | 7.3 | 7.4 | 6.8 | 6.8 | | | | | | |
| WGS | | | | | | 4.9 | | 4.6 | | |
| Gasifier | | | | | 2.1 | 4.3 | 6.3 | 6.7 | | |

**Figure 4-3. Comparison of water consumption factors with and without carbon capture for greenfield plants using wet recirculating cooling towers – thermal input basis**

## 4.2 Cooling water duty factors[v]

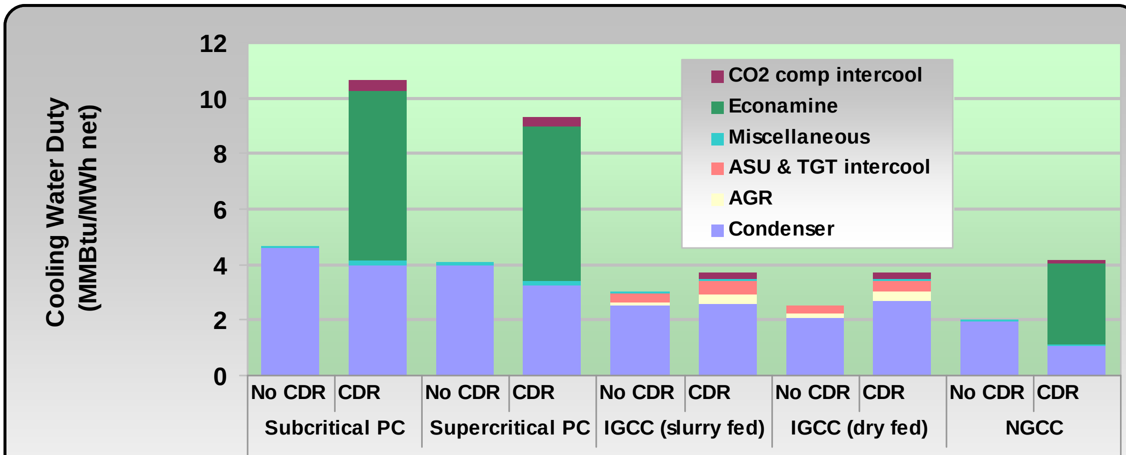
The water consumption factors for the cooling requirements described above can only be applied to wet recirculating cooling towers. Knowing the cooling duty associated with the cooling water systems for plants with and without $CO_2$ capture allows application of this data to once-through or dry cooling systems. Utilizing the design cooling duty from the NETL Baseline report for various processes within the plants, factors for cooling water duty per net power generation and per coal feed rate were developed as shown in Figure 4-4 and Figure 4-5.

The cooling water duty follows a similar pattern to the water consumption factors with the increase related to $CO_2$ capture for NGCC and PC plants being far greater than for the various IGCC cases. For PC and NGCC plants, the increase in the cooling tower load is primarily due to the cooling needed for the amine process with some increased load due to $CO_2$ compressor intercoolers. The condenser duty actually decreases with the addition of CDR equipment both per net power and relative to the coal feed rate. The reason for this decrease is that a portion of the steam from the steam turbine is routed to the Econamine system and condensed in the solvent regenerator reboiler.

For the IGCC cases, a significant portion of the additional water consumption associated with CDR capability is due to the gasifier and WGS process, so the cooling tower load increase is less significant than the overall water consumption increase. The minor increase in additional cooling system load is due to the reduced efficiency of the CDR

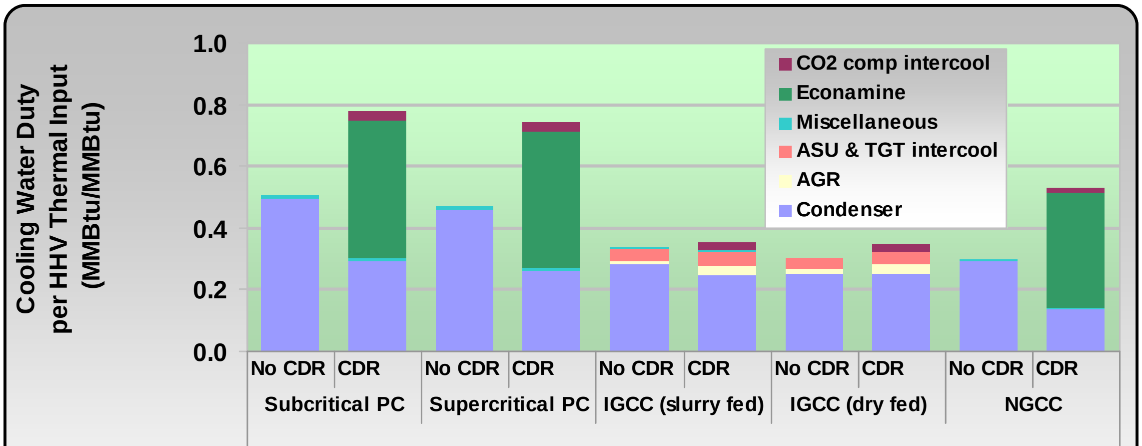
[v] See Appendix A for key information on the basis for these factors.

configuration, additional cooling load on the AGR unit and the addition of $CO_2$ compressor interstage coolers. Again this information can be used to evaluate the cooling water needs for retrofitting an existing PC or NGCC plant with CDR equipment with the added flexibility to evaluate dry and once-through cooling systems.




| | Subcritical PC No CDR | Subcritical PC CDR | Supercritical PC No CDR | Supercritical PC CDR | IGCC (slurry fed) No CDR | IGCC (slurry fed) CDR | IGCC (dry fed) No CDR | IGCC (dry fed) CDR | NGCC No CDR | NGCC CDR |
|---|---|---|---|---|---|---|---|---|---|---|
| Total | 4.7 | 10.7 | 4.1 | 9.3 | 3.0 | 3.7 | 2.5 | 3.7 | 2.0 | 4.2 |
| CO2 comp intercool | | 0.39 | | 0.36 | | 0.25 | | 0.22 | | 0.13 |
| Econamine | | 6.13 | | 5.54 | | | | | | 2.91 |
| Miscellaneous | 0.10 | 0.15 | 0.09 | 0.14 | 0.03 | 0.04 | 0.03 | 0.04 | 0.04 | 0.04 |
| ASU & TGT intercool | | | | | 0.36 | 0.49 | 0.27 | 0.43 | | |
| AGR | | | | | 0.10 | 0.32 | 0.14 | 0.32 | | |
| Condenser | 4.58 | 4.00 | 3.99 | 3.27 | 2.53 | 2.61 | 2.09 | 2.69 | 1.97 | 1.08 |

**Figure 4-4. Comparison of cooling water duty factors for greenfield plants – net power basis**




| | Subcritical PC No CDR | Subcritical PC CDR | Supercritical PC No CDR | Supercritical PC CDR | IGCC (slurry fed) No CDR | IGCC (slurry fed) CDR | IGCC (dry fed) No CDR | IGCC (dry fed) CDR | NGCC No CDR | NGCC CDR |
|---|---|---|---|---|---|---|---|---|---|---|
| Total | 0.50 | 0.78 | 0.47 | 0.74 | 0.34 | 0.35 | 0.30 | 0.35 | 0.30 | 0.53 |
| CO2 comp intercool | | 0.03 | | 0.03 | | 0.02 | | 0.02 | | 0.02 |
| Econamine | | 0.45 | | 0.44 | | | | | | 0.37 |
| Miscellaneous | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| ASU & TGT intercool | | | | | 0.04 | 0.05 | 0.03 | 0.04 | | |
| AGR | | | | | 0.01 | 0.03 | 0.02 | 0.03 | | |
| Condenser | 0.49 | 0.29 | 0.46 | 0.26 | 0.28 | 0.25 | 0.25 | 0.25 | 0.29 | 0.14 |

**Figure 4-5. Comparison of cooling water duty factors for greenfield plants – thermal input basis**

# 5 Next Steps

To extend and improve the factors presented here, the following next steps are recommended:

- Refine the water consumption and withdrawal factors presented here with a specific focus on water requirements. Process simulations will be used as necessary.
- Develop water consumption and withdrawal factors for an integrated gasification fuel cell (IGFC) platform.
- Develop water consumption and withdrawal factors for plant designs with oxy-fuel combustion.
- Develop water consumption and withdrawal factors for low rank coal for each of the coal-based platforms.
- Develop factors for solid residuals for each of the coal-based platforms.

# Appendix A

**Key assumptions in the 2007 NETL baseline report:**

- Raw water makeup is assumed to be provided 50% by a publicly owned treatment works and 50% from groundwater
- Cooling water circulation and losses were determined using the following:
  - Design ambient wet bulb temperature of 51.5 ºF to achieve a cooling water temperature of 60 ºF (8.5 ºF approach)
  - Cooling water temperature range of 20 ºF
  - Evaporative losses of 0.8% of the circulating water flow rate per 10 ºF of range
  - Drift losses of 0.001% of the circulating water flow rate
  - Blowdown rates = evaporated losses / (cycles of concentration – 1)
    - Mid-range cycles of concentration of 4 was used (measure of water quality)
- Blowdown from other processes in the plant were assumed to be routed to the cooling water system, backing out makeup water, as follows:
  - PC and NGCC cases with $CO_2$ capture: condensed water resulting from the cooling and compression of $CO_2$ (for non $CO_2$ capture cases, this water leaves with the flue gas)[vi]
  - All cases: the boiler feedwater blowdown is routed to the cooling water system
- Note that cooling water and process water requirements will vary significantly with process conditions such as temperature

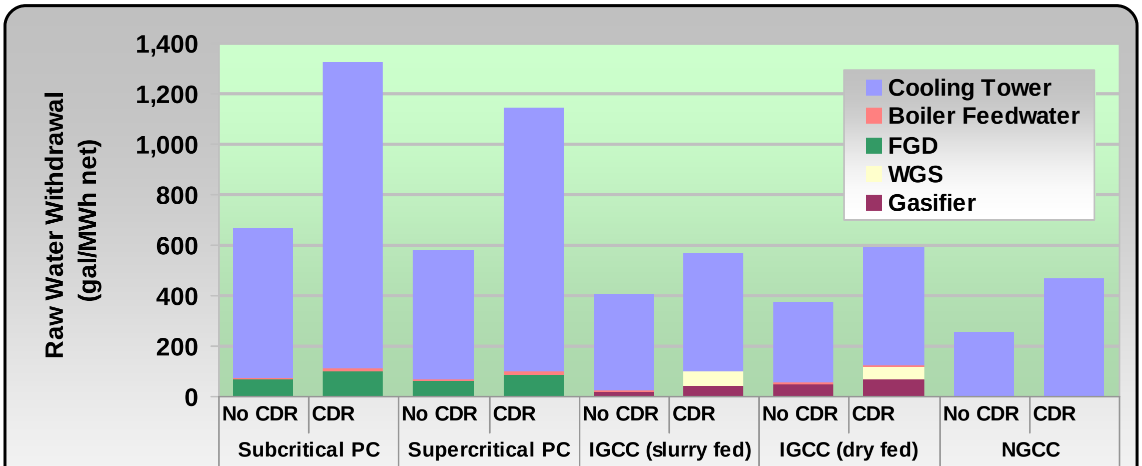
**Adjustments to water requirements detailed in the 2007 NETL baseline report:**

- In the baseline report, for the PC and IGCC cases, an engineering estimate for miscellaneous cooling duty requirements of 100 MMBtu/hr was added (75 MMBtu/hr for the NGCC cases). This number was adjusted in this analysis as follows:
  - PC cases: assumed to be 55 MMBtu/hr for the subcritical no $CO_2$ capture cases and was scaled based on coal feed rate for all other PC cases
  - IGCC cases: assumed to be 20 MMBtu/hr for the GEE IGCC no capture case and was scaled based on coal feed rate for all other IGCC cases
  - NGCC cases: assumed to be 20 MMBtu/hr for both cases
- In the baseline report, cooling duty associated with the ASU and the TGTU intercoolers was documented, but not utilized in determining the cooling water circulation rate. The cooling duty and associated cooling water requirements were added for these processes in this analysis.

[vi] Note that this was a significant change between the May 2007 report and the Revised August 2007 report

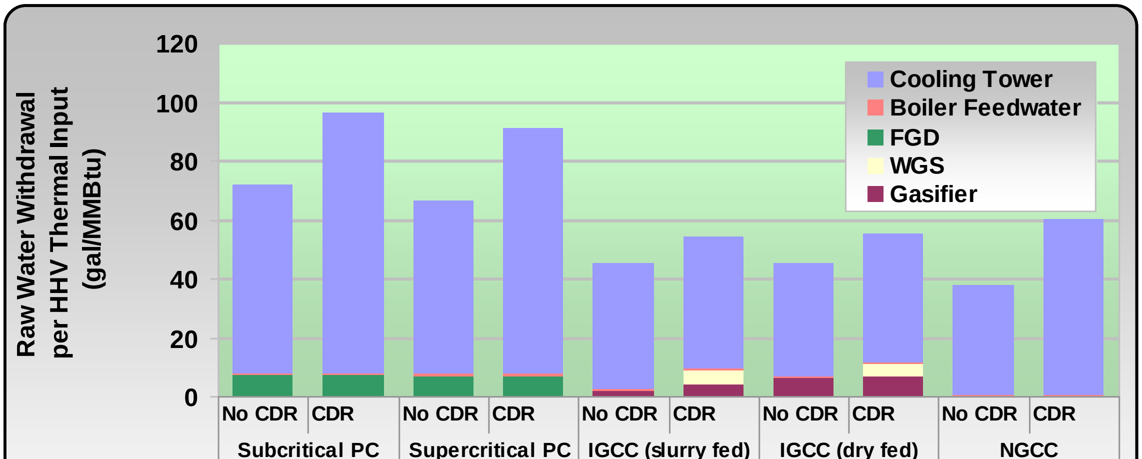
# Appendix B

Below are the raw water *withdrawal* factors corresponding to the discussion in Section 4. This analysis incorporates all water withdrawn for various uses in the plant.




| | Subcritical PC No CDR | Subcritical PC CDR | Supercritical PC No CDR | Supercritical PC CDR | IGCC (slurry fed) No CDR | IGCC (slurry fed) CDR | IGCC (dry fed) No CDR | IGCC (dry fed) CDR | NGCC No CDR | NGCC CDR |
|---|---|---|---|---|---|---|---|---|---|---|
| Total | 667 | 1,326 | 582 | 1,142 | 406 | 571 | 376 | 593 | 256 | 471 |
| Cooling Tower | 590 | 1,213 | 515 | 1,044 | 382 | 469 | 320 | 468 | 254 | 468 |
| Boiler Feedwater | 8 | 12 | 8 | 12 | 5 | 5 | 4 | 5 | 2 | 3 |
| FGD | 68 | 101 | 59 | 86 | | | | | | |
| WGS | | | | | | 52 | | 49 | | |
| Gasifier | | | | | 19 | 45 | 53 | 71 | | |

**Figure B-1. Comparison of raw water withdrawal factors with and without carbon capture for greenfield plants using wet recirculating cooling towers – net power basis**




| | Subcritical PC No CDR | Subcritical PC CDR | Supercritical PC No CDR | Supercritical PC CDR | IGCC (slurry fed) No CDR | IGCC (slurry fed) CDR | IGCC (dry fed) No CDR | IGCC (dry fed) CDR | NGCC No CDR | NGCC CDR |
|---|---|---|---|---|---|---|---|---|---|---|
| Total | 71.9 | 96.6 | 66.7 | 91.1 | 45.5 | 54.3 | 45.3 | 55.6 | 38.1 | 60.2 |
| Cooling Tower | 63.7 | 88.4 | 59.0 | 83.3 | 42.9 | 44.6 | 38.5 | 43.8 | 37.7 | 59.8 |
| Boiler Feedwater | 0.9 | 0.9 | 0.9 | 0.9 | 0.5 | 0.5 | 0.4 | 0.5 | 0.4 | 0.4 |
| FGD | 7.3 | 7.4 | 6.8 | 6.8 | | | | | | |
| WGS | | | | | | 4.9 | | 4.6 | | |
| Gasifier | | | | | 2.1 | 4.3 | 6.3 | 6.7 | | |

**Figure B-2. Comparison of raw water withdrawal factors with and without carbon capture for greenfield plants using wet recirculating cooling towers – thermal input basis**

# References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