WATER USE IN THERMAL POWER PLANTS EQUIPPED WITH CO_2 CAPTURE SYSTEMS

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For enquiries please contact:

BY TELEPHONE: +61 (0)3 8620 7300

BY EMAIL: info@globalccsinstitute.com

BY MAIL: Global CCS Institute, PO Box 23335
Docklands VIC 8012 Australia

Please use the following to reference the report:

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- Anne Carpenter (IEACCC)
- Paul Feron (CSIRO)
- Eric Grol (NETL/DOE)
- Jens Hetland (SINTEF)
- Andy Read (ROAD)
- Stanley Santos (IEAGHG)
- Erik Shuster (NETL/DOE)

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Abbreviations

AGR: Acid Gas Removal

ASU: Air Separation Unit

CCS: Carbon Capture and Storage

CPU: Compression and Purification Unit

DCC: Direct Contact Cooler

FGR: Flue Gas Recycling

FGD: Flue Gas Desulphurisation

IGCC: Integrated Gasification Combined Cycle

NGCC: Natural Gas Combined Cycle

OC: Once-through Cooling

PC: Pulverised Coal

RC: Recirculating Cooling

WGS: Water Gas Shift (reaction)

Units

h: hours

MWe: Megawatt (electric)

MWth: Megawatt (thermal)

MWh: Megawatt per hour

t: tonnes (metric)

Terms and definitions

Water use: indicates generic water use, referring both to withdrawal and consumption

Water withdrawal: extraction of water from a local environment of water utility

Water consumption: portion of water loss during operation

Effluent: water stream returned to the local environment

Cooling water: water for cooling purposes

Makeup water: water reintegrated into a process to compensate operational loss

Normalised water withdrawal or consumption: amount consumed or withdrawn, normalised with respect to the power output of the power plant (ie, t/MWe)

Absolute water withdrawal or consumption: amount actually consumed or withdrawn (ie, t/h)

Percentage increase: increase from A to B, calculated as 100*(B-A)/A

Highlights

- The potential for increased water use has been noted as a challenge to widespread deployment of CCS

- Early studies suggested that addition of a capture system would result in doubling of water use
  - These studies are widely cited
  - These studies reported percentage increases in water use normalised to net power production (t/MWh)

- Application of normalised water use values to individual power production facilities overstates the increase in water use for that specific facility

- An individual facility contemplating installation of a CO_2 capture system should base decisions related to water use on absolute volumes rather than normalised values

- More recent studies show that increased water use can be much lower

- Improvements in capture technologies lead to lower increases in water use

- The type of cooling system used at a facility has significant impacts on increases in water withdrawal and consumption

- Different CO_2 capture systems and approaches lead to different water requirements.

1 Executive summary

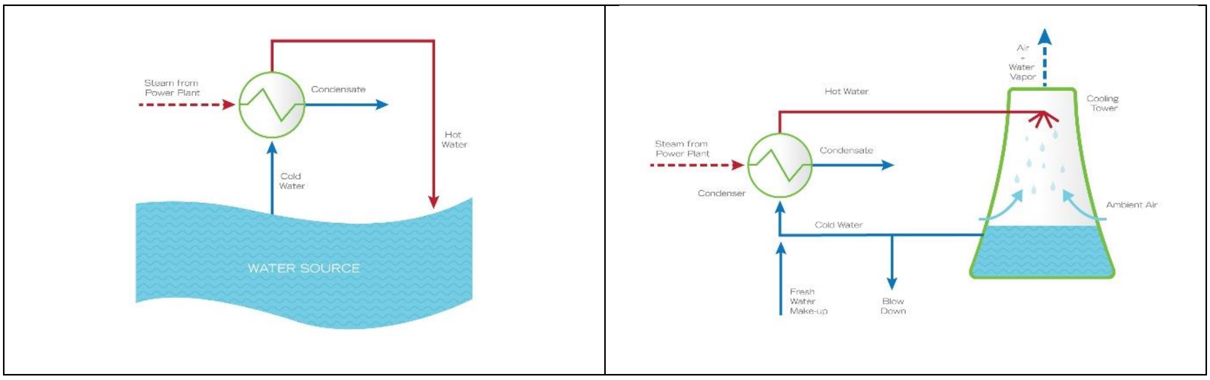
1.1 Introduction

The potential for increased water use has often been noted as a challenge to the widespread deployment of carbon capture and storage (CCS) to mitigate greenhouse gas emissions. Early studies that are widely referenced and cited in discussions of CCS indicated that installation of a capture system would nearly double water consumption for thermal power generation, whilst more recent studies have generated different results. The objective of this report is to clarify the messages regarding water consumption associated with installation of a capture system via a comprehensive review of data available in the literature. Changes in water use estimates over time are discussed in terms of capture technology, cooling systems, and how the data are reported.

Over 80 per cent of industrial water use worldwide is devoted to thermal power generation, while in the US and other industrial countries, the figure rises to almost 90 per cent. A 500 MWe coal-fired power plant can use more than 45,000 cubic meters (12 million gallons) of water per hour (withdrawal).

The largest demand for this water is process cooling. There are two types of cooling water system designs (Figure S.1), once-through (open loop) and recirculating (closed loop). In once-through systems, the cooling water is withdrawn from a local water body such as a lake, river, or ocean and heat is transferred to the cooling water. The warm cooling water is subsequently discharged back to the same water body. In wet recirculating systems, warm cooling water is typically pumped to a cooling tower where the heat is dissipated directly to ambient air by evaporation of the water and heating the air. For a wet recirculating system, only makeup water needs to be withdrawn from the local water body to replace water lost through evaporation.

Figure S.1 Once-through (left) and recirculating cooling systems (right)



The two commonly used metrics to measure water use are withdrawal and consumption. Withdrawal is the total amount of water that is extracted from a particular source. Water that is withdrawn can either be consumed or discharged back into the source or a different waterbody. Consumption is used to describe the loss of withdrawn water.

1.2 Data sources

There are a number of studies that have developed modelling estimates of water use for different types of capture systems and power plants. Table S.1 gives an overview of the most relevant studies available, indicating types of power plants, carbon dioxide (CO_2) capture technologies and cooling systems evaluated. The results of the studies have been synthesised and compared. Details regarding study components and how they were used in this analysis can be found in the original references and in the full report.

Table S.1 Literature reporting water requirements for CO_2 capture systems

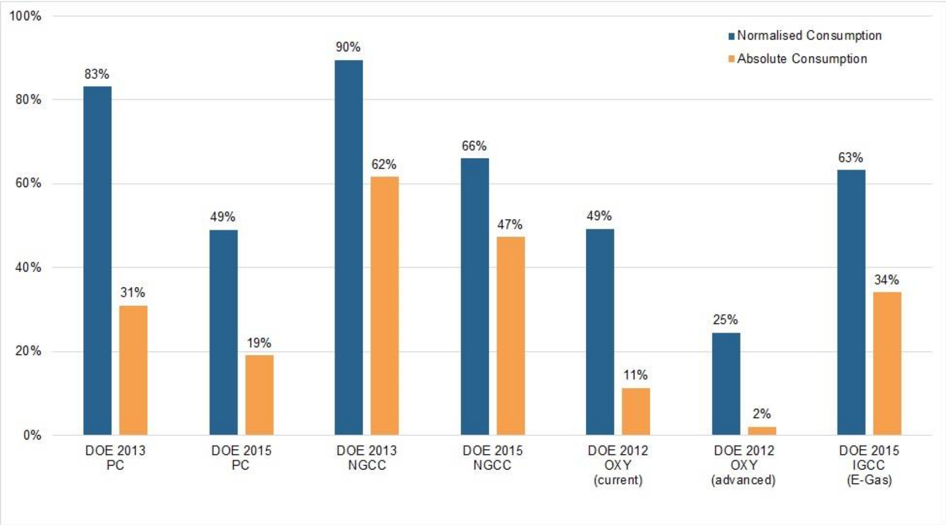
Reference	**Post-combustion**		**Pre-combustion**	**Oxy-combustion**
	PC	NGCC	IGCC	PC
IEAGHG, 2011	OC		OC	OC
DOE, 2012				RC
DOE, 2013	RC	RC		
ROAD, 2014	OC			
DOE, 2015	RC	RC	RC	

Legend: PC = pulverised coal (power plant), NGCC = natural gas combined cycle, IGCC = integrated gasifier combined cycle, RC=recirculating cooling, OC= once-through cooling

1.3 Results for power plant using recirculating cooling

Figure S.2 summarises estimated increases in water consumption associated with addition of a CO_2 capture system to thermal power generation plants employing recirculating cooling. In the documentation for all of the studies cited above, the results are presented in terms of increases in normalised water use – or water use per MWh of electricity produced (blue bars in Figure S.2).

Figure S.2 Estimated increases in normalised and absolute water consumption associated with CO_2 capture systems applied to thermal power plants employing recirculating cooling



Normalised water use can be important for broad planning purposes and for comparisons of CCS versus other decarbonisation technologies via life cycle analysis. However, because carbon capture has significant parasitic power demands, the net power production with CO_2 capture is reduced. By only reporting the water use estimates linked to net power production (ie normalised consumption), the impression given is that supplemental water requirements for a given power production facility are significantly larger than they actually are.

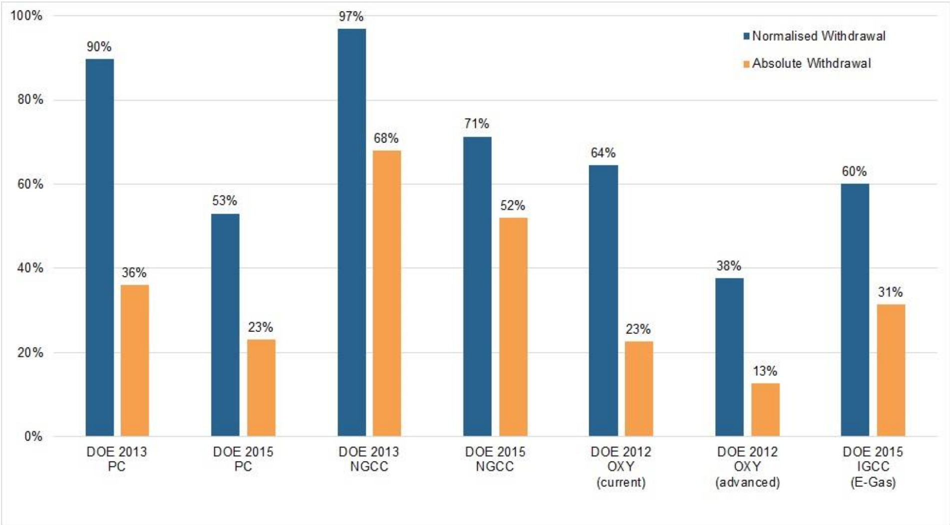
When an individual facility is evaluating the consequences of implementing CO_2 capture, it is more appropriate to consider changes in the total (absolute) volume of water used, as opposed to the normalised value, because any impact on local resources will be associated with the absolute increase in volume of water consumption. As indicated, the percentage increases in absolute water consumption (orange bars in Figure S.2) are lower than the normalised figures across all power production platforms analysed.

Another important outcome of the analysis is illustrated by the difference between the DOE 2013 and DOE 2015 studies for post-combustion systems (PC and NGCC). The 2015 study assumed that a more advanced, less energy-intensive CO_2 capture technology was employed. As indicated, this difference alone resulted in large reductions in normalised and absolute water consumption increase estimates for both PC and NGCC systems. It is reasonable to assume that as capture technologies with further decreases in energy intensity are developed, additional water requirements will decrease as well.

Benefits of capture technology improvements in terms of water consumption are also illustrated in the results for oxy-combustion systems. For these systems, water use estimates are made by comparing water use in oxygen-fired systems to the water use associated with similar air-fired power production systems. The two cases shown include a currently available configuration using cryogenic air separation and an advanced technology employing membrane-based oxygen separation. Percentage of water use increases for currently available oxy-combustion systems are similar to those for the more advanced post-combustion technology tested, and substantially lower for the more advanced oxy-combustion system.

Figure S.2 also includes results for an IGCC system (E-Gas). The DOE 2015 study included analysis of multiple gasification systems with similar water use patterns. The results of the E-Gas system analysis were chosen for presentation in this report, as they were consistent with the other systems evaluated. The major difference between the results for IGCC and combustion-based systems is that makeup water is much more important, as discussed further in the report. Increases in water withdrawal associated with the application of capture technologies on power plants with recirculating cooling are illustrated in Figure S.3. The patterns observed are very similar to those for consumption, although the associated volumes are slightly larger.

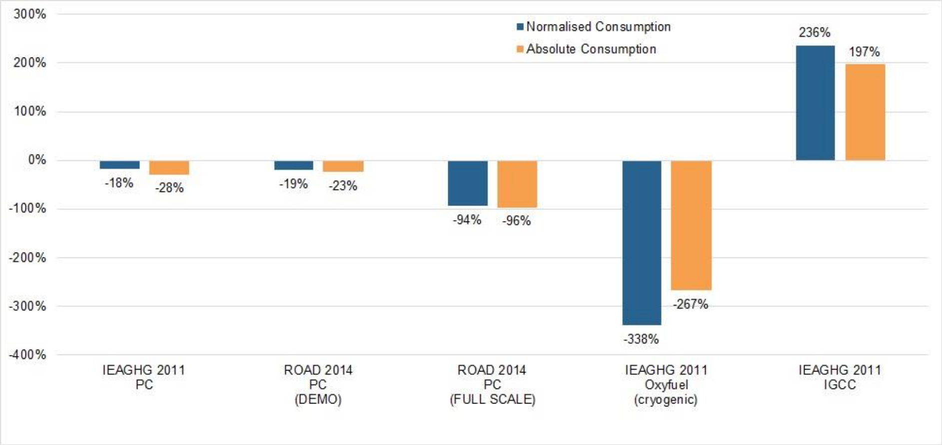
Figure S.3 Estimated increases in normalised and absolute water withdrawal associated with CO_2 capture systems applied to thermal power plants employing recirculating cooling



1.4 Results for power plant using once-through cooling

Figure S.4 summarises estimated increases in water consumption associated with addition of a CO_2 capture system to thermal power generation plants employing once-through cooling.

Figure S.4 Estimated increases in normalised and absolute water consumption associated with CO_2 capture systems applied to thermal power plants employing once-through cooling



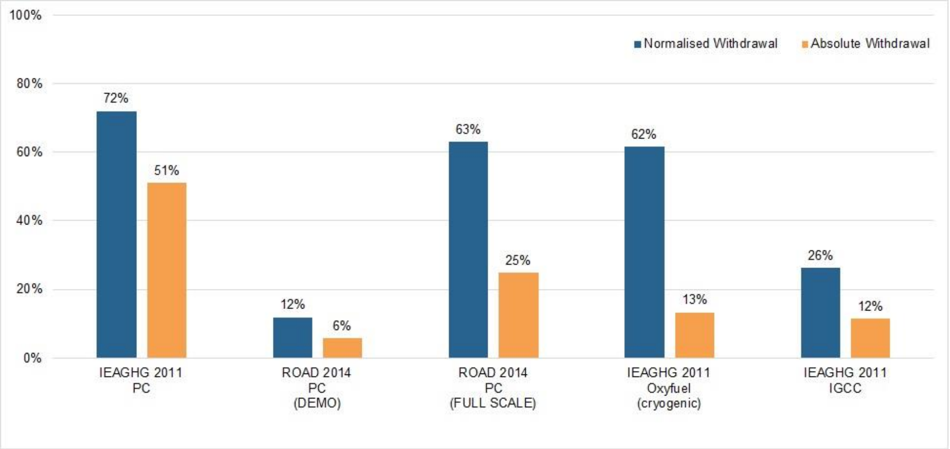
The results are clearly different than those for recirculating cooling. As noted above, the water used in once-through cooling systems is returned to the source, and thus consumption within the power generation facility is low, typically an order of magnitude lower than for plants with recirculating cooling. This is an important distinction when considering the consumption results for once-through systems, and although the percentage differences seem large, they are based on much smaller volumes.

Processes associated with the capture system often require cooling of the flue gas, which results in condensation of water. Thus more water can be returned to the water source following installation of a CO_2 capture system. This results in consumption estimates that are lower with a capture system than without, reflected in the negative numbers in Figure S.4. For oxy-combustion systems, the power production facility can become a net generator of water.

IGCC is the only power production platform analysed that shows an increase in consumption with addition of a capture system. This is because the water gas shift (WGS) reactor required for carbon capture operations in IGCC systems consumes water (steam) to generate additional hydrogen and convert the carbon monoxide in syngas into CO_2. The makeup water needed for WGS drives the increased consumption for IGCC systems reflected in Figure S.4.

Increases in water withdrawal associated with application of capture technologies on power plants with once-through cooling are illustrated in Figure S.5. The total volume of water withdrawal in once-through systems can be as much as two orders of magnitude higher than for recirculating systems. Thus even if percentage differences for once-through cooling are similar or smaller than for recirculating systems, the associated volumes are much larger. While this may have limited impacts in terms of total water resource availability, it can impact operation of intake structures.

Figure S.5 Estimated increases in normalised and absolute water withdrawal associated with CO_2 capture systems applied to thermal power plants employing once-through cooling



1.5 Conclusion

Comparison of the results of multiple studies leads to several significant outcomes:

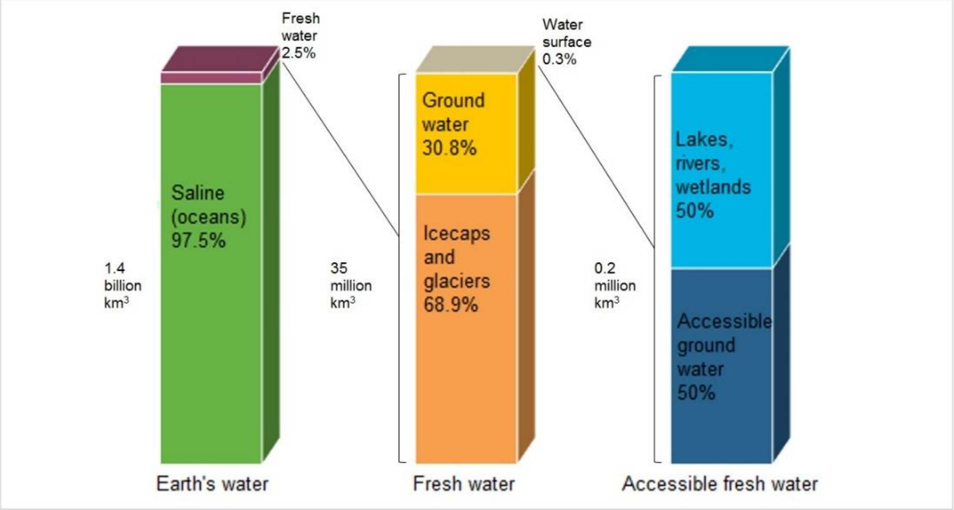
- Early, widely cited studies that suggested that addition of a CO_2 capture system would result in doubling of water use should be re-evaluated in light of multiple factors.
- These studies reported percentage increases in water use normalised to net power production (t/MWh).
- Normalised water use can be important for broad planning purposes and for comparisons of CCS versus other decarbonisation technologies via life cycle analysis. However, this metric is influenced by the reduced power production associated with CO_2 capture.
- By only reporting water use estimates linked to net power production, the impression given is that supplemental water use for a given power plant is significantly larger than it actually is.
- When an individual facility is evaluating the consequences of implementing CO_2 capture, it is more appropriate to consider changes in the total (absolute) volume of water used, as opposed to the normalised value, because any impact on local resources will be associated with the absolute increase in volume of water consumption.
- Improvements in CO_2 capture technologies can lead to lower increases in water use.
- Different CO_2 capture systems and approaches have different impacts, with significant variability among the cases evaluated.
- The type of cooling system used at a facility influences the increases in water withdrawal and consumption.

Given these outcomes, the potential for increased water use to serve as a challenge to widespread deployment of CCS should be reassessed.

2. Introduction

About 70 per cent of the Earth's surface is covered by water. The total worldwide supply of water is about 1.4 billion cubic kilometres. However, only about 2.5 per cent of this total is freshwater. Of the total freshwater, more than 68 per cent is locked up in ice and glaciers, while more than 30 per cent is in the ground. The total quantity of freshwater that is usable by humans and ecosystems is approximately 200,000 cubic kilometres (Figure 2.1).[1]

Figure 2.1 Earth's water distribution[1]



Further complicating issues surrounding water use is the uneven distribution of freshwater. Fifty two per cent of the world's population can be found in the 10 countries with the largest water reserves (approximately 62 per cent of global freshwater resources). The 171 water-scarcest countries together contain only about 10 per cent of the global freshwater supply, but have 30 per cent of the world's population. The uneven distribution of water resources can also be seen within countries. For example, water risks in the arid southwest US are significantly higher than those in the Great Lakes region. Similarly, water risks in China's wet south region are lower than those in the dry north regions.[1]

The uses of water also vary by location. Globally, 70 per cent of water withdrawals are used for agriculture, with 18 per cent industrial use and 12 per cent domestic use. However, in heavily industrialised areas, such as the US and Europe, industrial water use increases to nearly 50 per cent. In less industrialised areas, agricultural use can account for close to 90 per cent.[1]

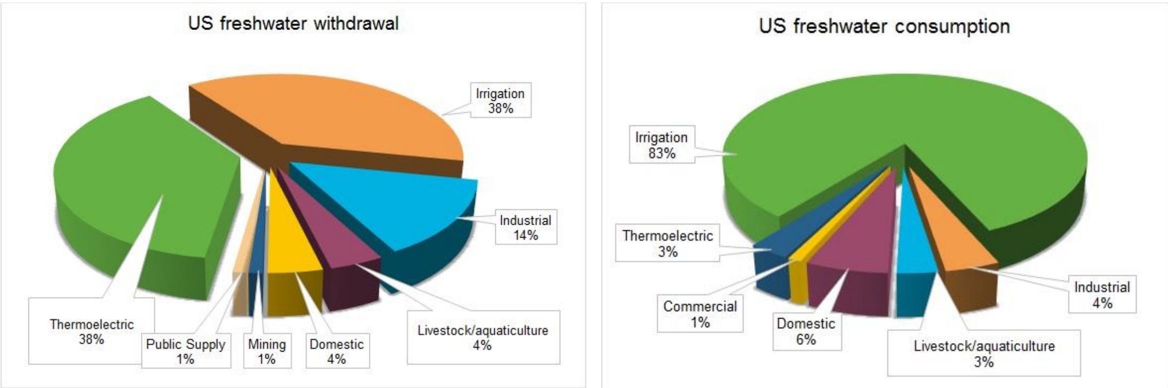
Industrial freshwater use is dominated by thermal power generation. Over 80 per cent of industrial water use worldwide is devoted to power generation, while in the US and other industrial countries, the figure rises to close to 90 per cent. A 500 megawatt (MWe) coal-fired power plant can use more than 45,000 cubic meters (12 million gallons) of water per hour (withdrawal).[2] The largest demand for this water is process cooling.

The two commonly used metrics to measure water use are withdrawal and consumption. Withdrawal is the total amount of water that is extracted from a particular source. The water required for thermal power plant operation is withdrawn primarily from large volume sources, such as lakes, rivers, oceans, and underground aquifers. Water that is withdrawn can either be consumed or discharged back into the source. Consumption is used to describe the loss of withdrawn water, typically through evaporation into the air, which is not returned to the source or some other waterbody.

[1] (SBC Energy Institute, 2014)
[2] (Feeley, et al., 2006)

The United States Geological Survey (USGS) estimated that thermal power generation accounted for approximately 38 per cent of freshwater withdrawals in 2010.[3] The most recent data available indicate that thermal power water consumption (labelled as thermoelectric in USGS documentation) accounted for only 2.5 per cent of total US freshwater consumption (see Figure 2.2).[4] However, even at 2.5 per cent consumption, more than 11 million cubic meters per day (3 billion gallons per day) were consumed.

Figure 2.2 US freshwater withdrawal versus consumption[3,4]



A wide variety of societal issues, policy and regulatory debate, environmental questions, technological challenges, and economic concerns exist at the interface of energy and water. Water is a significant factor in economic development activities. Planning efforts must consider the availability and quality of water resources in a given locality or region to ensure that supplies are available to accommodate existing and future water consumers. Failure to do so can result in growth limitations, inequitable development, and heated public debate and litigation regarding usage priorities.

Power production facilities will increasingly compete with other water users in water-stressed areas. Agriculture and public supply will most likely be the greatest competitors due to their large water withdrawal. As with all resources, trade-offs will occur, and concerns will be raised over which uses are more important, water for drinking and personal use, growing food, or energy production.

The potential for increased water use has often been noted as a challenge[5,6,7] to the widespread deployment of carbon capture and storage (CCS) to mitigate greenhouse gas emissions. Early studies[8,9], that are widely referenced and cited in discussions of CCS, indicated that installation of a capture system would nearly double water consumption for thermal power generation. More recent studies[10] have generated different results. The objective of this report is to clarify the messages regarding water consumption associated with installation of a capture system via a comprehensive review of data available in the literature. Changes in water use estimates over time are discussed in terms of capture technology assumptions and in terms of how the data are reported.

Section 3 provides background information on water use in thermal power plants followed by Section 4, with a description of supplemental water use associated with carbon capture systems. Section 5 presents and discusses literature results, and Section 6 provides a brief overview of approaches to reduce water use in the capture process.

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3 (Maupin, et al., 2014)
4 (U.S. Geological Survey, 1999)
5 (IEA, 2012)
6 (Carpenter, 2015)
7 (Byers, et al., 2016)
8 (DOE/NETL, 2007)
9 (Zhai & Rubin, 2010)
10 (DOE/NETL, 2015a)

3. Water requirements of thermal power plants

3.1 Cooling

Large quantities of cooling water are required for thermal power plants to support the generation of electricity. Thermal generation involves heating water to steam that is used to drive a turbine-generator, a cooling system is required to condense the steam exiting the turbine before it is recycled to the steam generator.

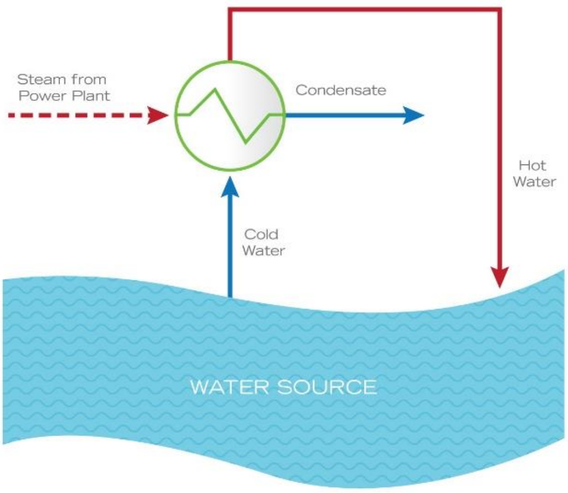
There are three general types of cooling system designs used for thermal power plants, once-through (or direct), recirculating (or closed loop), and dry. They differ in cost, complexity, and in the amounts of water they withdraw and consume.

3.1.1 Once-through cooling

In once-through systems, the cooling water is withdrawn from a local body of water such as a lake, river, or ocean and the warm cooling water is subsequently discharged back to the same water body after passing through the condenser (Figure 3.1). As a result, plants equipped with once-through cooling water systems have relatively high water withdrawal, but low water consumption. Once-through cooling systems are typically used in areas where water is abundant.

In areas with more limited water resources, recirculating cooling systems are typically used. In some jurisdictions (for example, the US) regulations regarding intake structures limit the ability to install once-through cooling systems on new-build facilities even in areas with abundant water resources. In these areas, new-build facilities are likely to use recirculating cooling systems.

Figure 3.1 Schematic representation of a once-though cooling system



3.1.2 Recirculating cooling

The most common type of recirculating system uses wet cooling towers to dissipate heat from the cooling water to the atmosphere. Cooling is achieved by evaporation of a small fraction (1 to 2 per cent)[11] of the recirculating water, which flows in direct contact and counter current to ambient air inside the cooling tower

[11] (EPRI, 2004)

(Figure 3.2). In the process, a portion of the warm water evaporates from the cooling tower and forms a water vapour plume. The evaporation loss is affected by cooling water requirements and atmospheric conditions.

Only part of the water evaporates, while the remainder is returned back to the condenser for a new cycle. The amount of water lost through evaporation is replaced with new water taken from an external source. These evaporative losses can lead to the build-up of minerals and sediment in the water that could adversely affect performance. To prevent this build-up, a portion of the cooling water, known as blowdown, needs to be periodically discharged from the system.

For a recirculating system, the withdrawal rate is only that which is necessary to make up for water loss due to evaporation, drift, and blowdown. As a result, plants equipped with recirculating systems have relatively low water withdrawal, but high water consumption, compared to once-through systems. This withdrawal amount is typically a small percentage (2 to 4 per cent) of the withdrawal rate for once-through cooling systems.[12]

Figure 3.2 Schematic representation of a recirculating cooling system

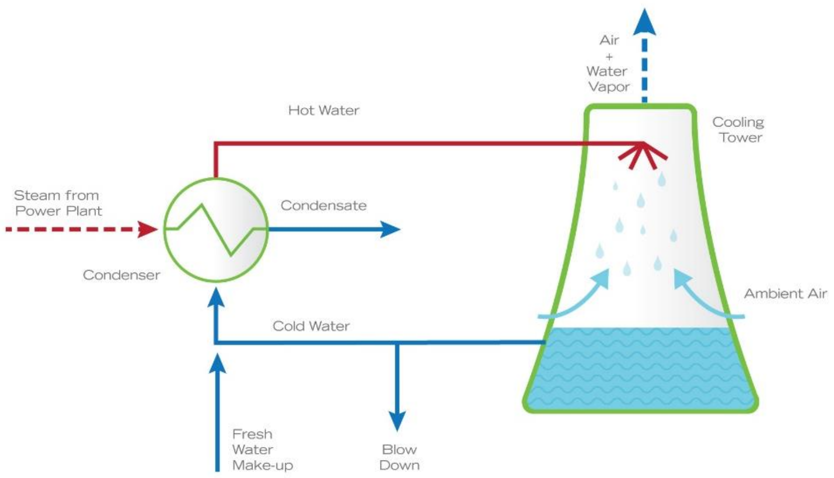


Table 3.1 illustrates typical withdrawal and consumption quantities per MWh of electricity produced in pulverised coal (PC), natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC) power plants for once-through and recirculating cooling systems.

Table 3.1 Typical water withdrawal and consumption for thermal power generation[13] (tonnes/MWh)

	PC		*NGCC*		*IGCC*	
	(min)	*(max)*	*(min)*	*(max)*	*(min)*	*(max)*
Once-through						
Withdrawal	85.7	103.0	28.5	76.0	NA	NA
Consumption	0.2	0.5	0.1	0.4	NA	NA
Recirculating						
Withdrawal	1.8	2.7	0.6	1.1	1.4	2.3
Consumption	1.7	2.5	0.5	1.1	1.2	1.7

NA = data not available

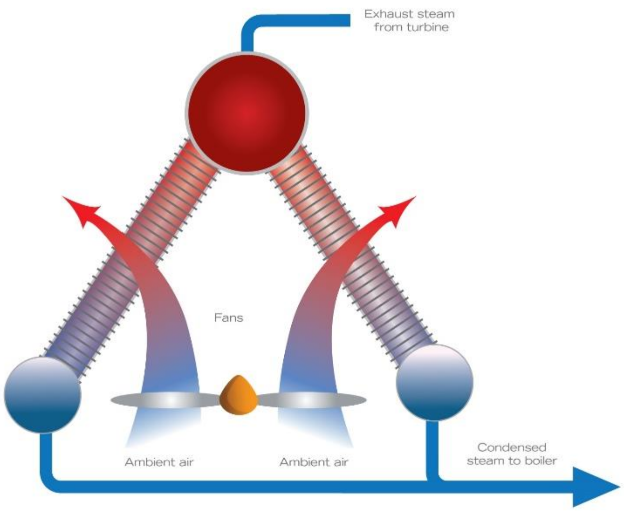
[12] (EPRI, 2004)
[13] (Macknick, et al., 2012)

3.1.3 Dry cooling

Dry cooling systems use air-cooled steam condensers. The turbine exhaust steam flows through air condenser tubes that are cooled directly by conductive heat transfer using a high flow rate of ambient air that is blown by fans across the outside surface of the tubes (Figure 3.3). Therefore, cooling water is not used in the direct air-cooled system.

Dry cooling systems are not as prevalent as wet recirculating cooling systems due to relatively higher capital and operating costs and lower performance. For example, the US Environmental Protection Agency (EPA) estimated capital costs for a dry cooling system to be 6.5 per cent of total plant capital costs (versus 2 per cent for a wet cooling tower).[14] Dry cooling lowers overall plant efficiency by about 2 to 7 percentage points.[15]

Figure 3.3 Schematic representation of a dry-cooling system



3.2 Process makeup water

Process makeup water is also required in power plants. For example, demineralised water is needed to make up for losses incurred in the steam cycle. Another example is freshwater needed to support pollution control systems, like Flue Gas Desulphurisation (FGD). However, the volumes required for process makeup are much smaller than the volumes of water required for cooling.

[14] (U.S. EPA, 2001)
[15] (IEA, 2012)

4. Water use in CO_2 capture systems

Adding a CO_2 capture system to an existing power station will increase water use. This is largely due to capture system cooling requirements and, to a smaller extent, for process makeup water. Carbon capture technologies can be divided into three general categories based on the types of systems to which they are applied: post-combustion, pre-combustion, and oxy-combustion.

Post-combustion refers to capture systems separating CO_2 from the flue gases produced by conventional coal-, biomass- or gas-fired power generation.

Pre-combustion technology is applied to separate CO_2 from the synthetic fuel gas generated in a gasifier in order to obtain two separate streams of near pure CO_2 and hydrogen.

Oxy-combustion is a process in which fossil fuel combustion occurs with an oxidant stream made up of nearly pure oxygen or a mixture of oxygen and recycled CO_2, resulting in an outlet stream that is essentially only CO_2 and water vapour.

Each capture technology has specific water requirements depending on process equipment and configuration. The following sections give a high level description of water requirements for commercially available capture systems. Estimates of post-, pre- and oxy-combustion water use available from the literature are reported in Section 5.

4.1 Post-combustion systems

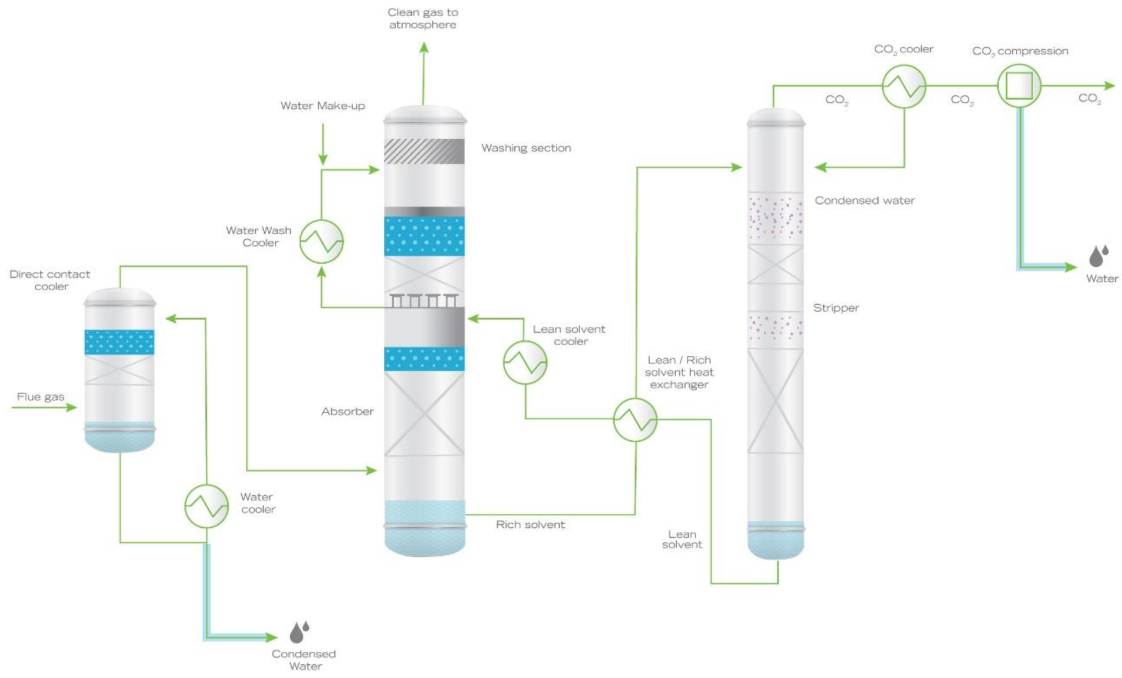
Post-combustion capture systems available commercially or near commercialisation commonly use amine based solvents.[16] These systems are typically installed downstream from conventional pollution control equipment and use a chemical absorption/desorption cycle to separate CO_2 from the flue gas, as illustrated in Figure 4.1. The solvent binds with the CO_2 in an absorber. It is then routed to a stripping column where the temperature is increased, releasing the absorbed CO_2.

Figure 4.1 also shows where process coolers in a standard amine based absorption system might be found. If the capture plant is designed with a different process layout (for example, including absorber intercooling) the number of coolers may vary.

Finally, Figure 4.1 illustrates where makeup water is required and where water is produced. The most significant need for makeup water is associated with the water wash section at the top of the absorber, where fresh water is needed to limit the concentration of amines in the washing loop. The process also produces water by condensation in the direct contact cooler. This water, after proper treatment can be used in the power plant or externally. Since this water is contaminated with flue gas impurities it cannot be reused directly for make-up in the capture process without previous purification.

[16] (Liang, et al., 2015)

Figure 4.1 Simplified process scheme of amine-based post-combustion CO_2 capture indicating the main process coolers and water inflow/outflow streams



4.2 Pre-combustion systems

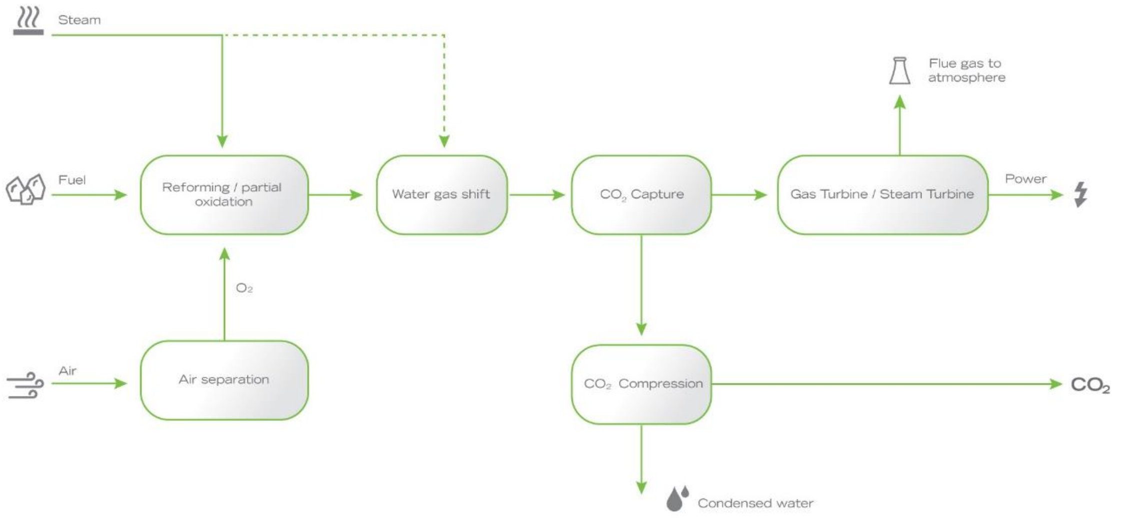
Pre-combustion capture is mainly applicable to gasification plants, where fuel (coal, biomass, or coal/biomass mixture) is converted into syngas, a mixture of hydrogen (H_2), carbon monoxide (CO), and minor amounts of other gaseous constituents.[17] To enable pre-combustion capture, the syngas is further processed in a water-gas shift (WGS) reactor, which converts CO into CO_2 while producing additional H_2, thus increasing the CO_2 and H_2 concentrations.

A two-stage acid gas removal (AGR) system can be used to remove syngas contaminants, and then separate CO_2 from the H_2 using a physical or chemical solvent. After CO_2 removal, the H_2-rich syngas is used as a fuel in a combined cycle to generate electricity or as feedstock for chemical processes. A simplified block diagram illustrating an IGCC with pre-combustion CO_2 capture is shown in Figure 4.2. Increased water use associated with a pre-combustion capture system comes from increased process cooling requirements and increased makeup water needs.

Makeup may play a more significant role for pre-combustion systems compared to post-combustion systems due to the addition of the WGS. In fact, the WGS consumes a significant quantity of water, as steam is required to sustain the shift reaction. In a gasification-based system (ie, IGCC) that does not include CO_2 capture, the syngas can be directly combusted in a gas turbine without going through the WGS reaction.

Figure 4.2 Simplified process flow diagram of a generic IGCC with pre-combustion CO_2 capture

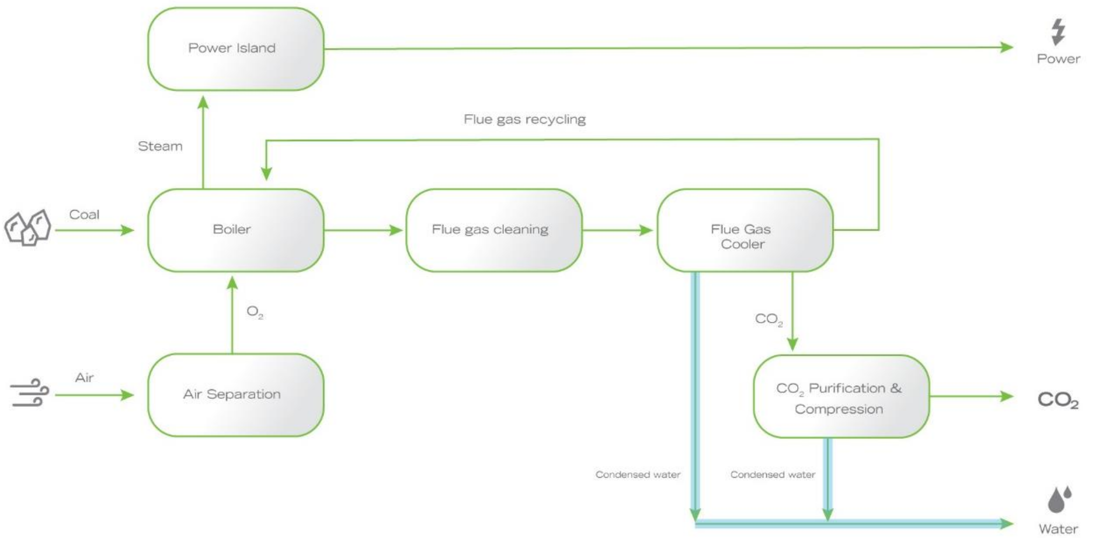
[17] (Jansen, et al., 2015)



4.3 Oxy-combustion systems

Oxy-combustion is applicable to new and existing fossil fuel power plants, although it must be noted that retrofitting an existing coal-fired power plant can present significant technical and economic hurdles.[18] An oxy-combustion system consists of a boiler, a cryogenic air separation unit (ASU), a flue gas recycle (FGR) system, flue gas purification, and CO_2 compression. A simplified process schematic of an oxy-combustion system is shown in Figure 4.3. Increased water use associated with an oxy-combustion system would be related to cooling water employed in the ASU and the FGR system.

Figure 4.3 Simplified process flow diagram of a generic oxy-combustion system



Commercial ASUs use cryogenic distillation to separate oxygen from air, and typically use water coolers for the initial cooling of air and the cooling of compressors. The ultimate separation of oxygen from air is achieved through a distillation process driven by a refrigeration system (as opposed to water-based cooling). Advanced ASU designs attempt to increase process efficiency via effective integration of hot and cold streams.[19]

18 (Stanger, et al., 2015)
19 (Perrin, et al., 2013)

FGR systems are employed to maintain boiler combustion temperatures as well as heat and mass transfer characteristics within design limits. Usually the recirculated gas, or a part of it, is cooled to reduce its moisture content and thus minimise corrosion risk. [20,21] When economically attractive, heat integration can be implemented instead of a simple water cooler. The condensate generated during cooling can be recycled and reused in the power plant.

4.4 CO_2 compression

A common element in any CO_2 capture system is CO_2 compression. It is necessary to enable CO_2 transport and can be treated as a component of the capture system that increases the cooling requirement of the overall capture process.

A typical CO_2 compressor would include a multistage configuration with intercoolers. The extent of external cooling required, however, is dependent on the design of the compressor. American Electric Power evaluated a variety of configurations and approaches for the Mountaineer CCS II Project.[22] The results showed that cooling water requirements can vary by a factor of more than 2, depending on the characteristics of the compressor. In some cases cooling can be (partially) accomplished using steam cycle condensate, reducing the need for external cooling water.

In the CO_2 compression process, water is generated through condensation in coolers installed upstream of the condenser and between multiple compression stages (if intercooled) where vapour contained in the CO_2 stream is condensed and collected. Water can also be produced if a dehydration unit is used to meet vapour content limits imposed by CO_2 transport. All of this water, after proper treatment, can be reused in the system or returned to the environment.

[20] (McDonald, 2013)
[21] (Stanger, et al., 2015)
[22] (American Electric Power, 2011)

5. Water use estimates available in the literature

There are a number of studies where detailed modelling estimates of water use for different types of capture systems and power plants have been developed. Table 5.1 gives an overview of the most relevant studies available, indicating types of power plants, CO_2 capture technologies and cooling systems evaluated. The results of the studies have been synthesised and are compared below.

Table 5.1 Literature reporting water requirements for CO_2 capture systems

Reference	Post-combustion		Pre-combustion	Oxy-combustion
	PC	NGCC	IGCC	PC
IEAGHG, 2011	OC		OC	OC
DOE, 2012				RC
DOE, 2013	RC	RC		
ROAD, 2014	OC			
DOE, 2015	RC	RC	RC	

Legend: PC = pulverised coal (power plant), NGCC = natural gas combined cycle,
IGCC = integrated gasifier combined cycle, RC=recirculating cooling, OC= once-through cooling

The capture systems evaluated include amine-based chemical absorption for post-combustion, physical solvent based absorption systems for pre-combustion, and atmospheric pressure oxy-combustion employing cryogenic air separation.

While the US Department of Energy/National Energy Technology Laboratory (DOE/NETL) studies evaluated recirculating cooling systems in their models, IEAGHG and ROAD used once-through cooling systems. This difference is relevant and thus the results presented below are separated, based on the type of cooling system evaluated. In the following paragraphs, the studies used are briefly described.

5.1.1 DOE/NETL reports

Beginning in 2007[23], DOE/NETL has produced a number of reports estimating water use for PC, NGCC, and IGCC power generation with and without CO_2 capture. Subsequently, several updates have been released providing new results after adjustments in the models and in the assumptions.

The most updated version available is dated July 2015.[24] This last study is of particular interest because, for post-combustion capture, it provides estimates that are based on Shell Cansolv capture technology instead of the Fluor Econamine FG+ technology used in the previous reports. For this reason, the post-combustion capture estimates published in 2013[25] have also been included in this review, to allow for assessment of how the water demand is affected by changes in the capture technology.

For IGCC systems, water use estimates were developed based on four different gasifier configurations (GEE Radiant, GEE Quench, E-Gas, and Shell). All estimates were based on the Selexol capture system. Therefore, only the 2015 version was used in the analyses presented below.
Zhai et al. 2011[26] conducted water use analyses similar to those done in the DOE studies, but using a slightly different approach. Their study yielded results similar to those found in the DOE 2013 analysis, and for this reason the results have not been included in this report.

[23] (DOE/NETL, 2007)
[24] (DOE/NETL, 2015a); (DOE/NETL, 2015b)
[25] (DOE/NETL, 2013)
[26] (Zhai, et al., 2011)

A separate report by NETL/DOE released in 2012[27] provides estimates for oxy-combustion systems. The study evaluated ten different oxy-combustion cases with alternative configurations and technologies employed. Of the ten cases, only two are presented in this study, one representing state of the art oxy-combustion systems, called *Current Technology Case*, and the other representing an oxy-combustion system employing membranes for oxygen separation, called *Advanced Membranes* case.

The *Current Technology Case* provides estimates for supercritical coal fired plants with state of the art oxy-combustion; in this configuration oxygen at 95 per cent purity is produced by cryogenic distillation. Although oxygen membranes are still under development, and thus not yet mature for large scale oxygen production, the *Advanced Membrane* case has been included, as it shows the potential reduction in water use achievable in future oxy-combustion systems employing membranes.

5.1.2 IEAGHG, 2011

In 2011, IEAGHG[28] produced water use estimates[29] for ultra-super critical plants with post- (Fluor Economine FG+), pre- (Selexol), and oxy-combustion systems, providing a rather complete overview. The report provides very detailed information, including heat and mass balance and engineering details of the equipment considered. Cases were run for once-through cooling and air cooling systems. For the purposes of this analysis, only the once-through cooling cases have been reviewed.

5.1.3 ROAD, 2014

Hylkema and Read published an article in 2014 about the water consumption of the Rotterdam Opslag en Afvang Demonstratieproject (ROAD) project. [30] The study illustrates the integration of a 250 MW_e demonstration capture unit with a recently-built 1070 MW_e coal-fired plant, focusing on the requirements for cooling and makeup water. Extrapolation of the result for a full scale plant with similar characteristics and integration philosophy is also provided.

5.2 Evaluation approach

The following sections provide a summary of estimates found in the literature for each of the three groups of technologies: post-, oxy-, and pre-combustion. Since each of the studies use different approaches and units in reporting the results, the data collected have been summarised and presented in a spreadsheet using a common format. A copy of the spreadsheet is included in Appendix A with explanations of all calculations.

The objective is to present the results in a consistent way and to extract the increases[31] in water consumption[32] and withdrawal for each of the cases. The percentage increases in water consumed and withdrawn have been calculated on both a *normalised* and *absolute* basis. Absolute refers to the actual amount of water (ie, t/h), and normalised refers to a quantity of water normalised with respect to the net power output of the power plant (ie, t/MWh). Both of these measures can be important, depending on the types of issues being addressed, as discussed in the following sections.

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[27] (DOE/NETL, 2012)
[28] (IEAGHG, 2011)
[29] Note: in IEAGHG report the term “water use” indicates the amount of water withdrawn.
[30] (ROAD, 2014)
[31] Increase in water withdrawal and consumption, caused by the addition of a CO_2 capture system with respect to a power plant without capture.
[32] Consumption in this report is defined as the net difference between the water extracted and water returned to the environment. The latter includes effluents of sufficient quality to be re-injected in rivers, sea or lakes (such as waste water treatment effluents)

The results are also differentiated on the basis of cooling system type – recirculating versus once-through cooling. Increasing the water requirements for a plant with recirculating cooling means that both withdrawal and consumption will increase. Increasing the requirements for a once-through cooling system results in increased withdrawal rates, but the consumption associated with cooling will remain essentially unchanged (negligible water losses). Consequently, the results are presented separately for systems using once-through and recirculating cooling using four indicators:

- Percentage increase in normalised consumption: measures the percentage increase in normalised water consumption between capture and non-capture cases.
- Percentage increase in absolute consumption: measures the percentage increase in absolute water consumption between capture and non-capture cases.
- Percentage increase in normalised withdrawal: measures the percentage increase in normalised water withdrawal between capture and non-capture cases.
- Percentage increase in absolute withdrawal: measures the percentage increase in absolute water withdrawal between capture and non-capture cases.

5.3 Estimates for post-combustion systems

Water use estimates for post-combustion systems have been sourced from the publications of DOE 2013, DOE 2015, ROAD 2014 and IEAGHG 2011 described above. Several of the studies evaluated water use associated with sub-, super-, and ultra-super-critical systems. However, the differences in water use among different power systems were small. Therefore, in the results presented below, the water use values have been averaged across the different power systems.

5.3.1 Recirculating cooling

Water consumption and withdrawal results for post-combustion systems using recirculating cooling are summarised in Table 5.2, which highlights the differences between capture and non-capture cases. Figures 5.1 and 5.2 provide graphical representations of changes in water withdrawal and consumption.

Table 5.2 **Water use estimates for post-combustion systems (recirculating cooling)**

Case	***DOE 2013 PC***	***DOE 2015 PC***	***DOE 2013 NGCC***	***DOE 2015 NGCC***
Without capture				
Plant power output (MWe)	550	550	555	630
Total water in (t/MWh)	2.32	2.20	0.97	0.95
Total water out (t/MWh)	0.47	0.45	0.22	0.21
Consumed water (t/MWh)	1.84	1.74	0.76	0.74
With 90% capture				
Plant power output (MWe)	395	440	473	559
Total water in (t/MWh)	4.40	3.37	1.92	1.63
Total water out (t/MWh)	1.03	0.77	0.48	0.41
Consumed water (t/MWh)	3.37	2.60	1.43	1.23
Increase in normalised consumption	83%	49%	90%	66%
Increase in absolute consumption	**31%**	**19%**	**62%**	**47%**
of which for cooling	**30%**	**19%**	**61%**	**47%**
of which for makeup	**0.9%**	**0.1%**	**0.1%**	**0.3%**
Increase in normalised withdrawal	90%	53%	97%	71%
Increase in absolute withdrawal	36%	23%	68%	52%

Figure 5.1 **Percentage increase in water consumption for post-combustion capture systems with recirculating cooling**

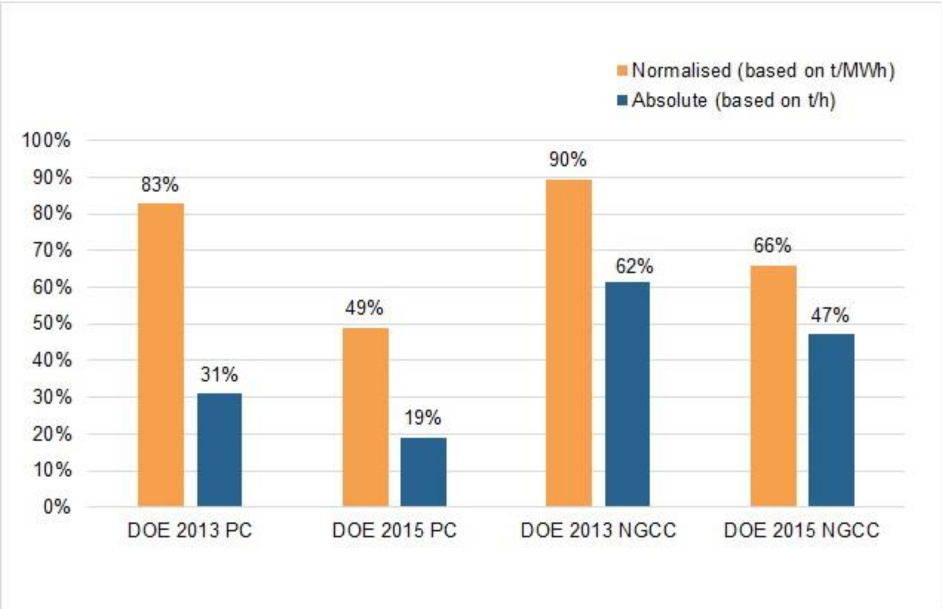
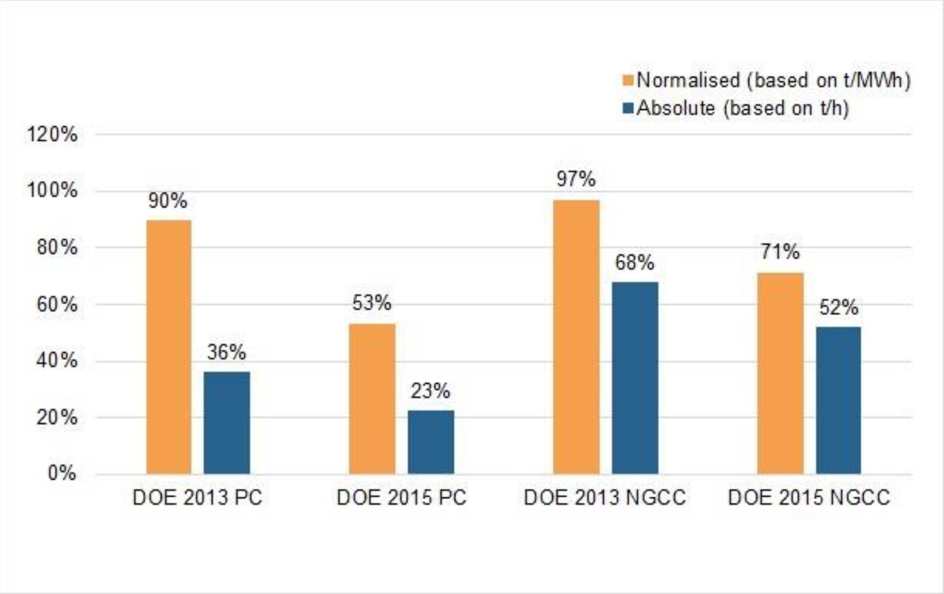


Figure 5.2 **Percentage increase in water withdrawal for post-combustion capture systems with recirculating cooling**



The DOE 2013 results for pulverised coal plants show that normalised water consumption increases from 1.84 t/MWh to 3.37 t/MWh with the addition of CO_2 capture (Table 5.2). This corresponds to a percentage increase of 83 per cent in normalised consumption, and a 31 per cent increase in absolute consumption (Figure 5.1).

However, when we evaluate the DOE 2015 results, the percentage increase in normalised consumption is less than 50 per cent (1.74 t/MWh to 2.60 t/MWh), corresponding to less than a 20 per cent increase in absolute consumption (Figure 5.1). The principle reason for the decrease compared to the DOE 2013 results is the use of a more advanced capture system technology (Shell Cansolv), which employs a more advanced solvent that decreases the energy penalty associated with capture operations. Since the water use estimates reported in all of the studies are normalised to power production, a smaller decrease in power production yields a smaller percentage increase in water requirement.

The difference between normalised and absolute consumption increases points out a limitation associated with just reporting normalised results. As carbon capture has significant parasitic power demands, the net power production with CO_2 capture is reduced. By tying the water use estimates to net power production, the supplemental water requirements appear significantly larger than they actually are.

Normalised water use can be important for broad planning purposes. However, it overestimates the impact for a particular facility. When an individual facility is evaluating whether to pursue a CCS system in order to achieve greenhouse gas reductions, it is more appropriate to consider changes in the total volume (absolute) of water used as opposed to the normalised value because any impact on local resources will be associated with the total increase in volume of water consumption.

Similar analyses of NGCC power plants result in consumption increases that appear even larger than those for coal-based power plants. This, however, is partially a function of how the data are presented. NGCC plants use significantly less water than coal-based plants, and so the addition of a CO_2 capture system has a larger impact on a percentage basis. However, even with CO_2 capture, a NGCC plant consumes less than half the water consumed by a coal-based power plant (about 1.2 t/MWh versus 2.6 t/MWh - Table 5.2). Similarly to the PC cases, the use of an advanced capture system results in significant improvements in terms of water consumption.

The breakdown between process makeup and cooling water included in Table 5.2 shows that increased cooling water consumption is an order of magnitude larger than consumption associated with increased makeup water requirements.

Increases in water withdrawal show similar trends to those observed for consumption, as illustrated in Figure 5.2.

5.3.2 Once-through cooling

Water consumption and withdrawal results for post-combustion systems using once-through cooling are summarised in Table 5.3. Figures 5.3 and 5.4 provide graphical representations of changes in water withdrawal and consumption.

Table 5.3 Water use estimates for post-combustion systems (once-through cooling)

Case	***IEAGHG 2011***	***ROAD 2014 Demo***	***ROAD 2014 Full Scale***
Without capture			
Plant power output (MWe)	758	1070	1070
Total water in (t/MWh)	139.98	86.73	86.73
Total water out (t/MWh)	139.89	86.59	86.59
Consumed water (t/MWh)	0.09	0.15	0.15
With 90% capture			
Plant power output (MWe)	666	1012	822
Total water in (t/MWh)	240.76	97.06	141.01
Total water out (t/MWh)	240.69	96.94	141.00
Consumed water (t/MWh)	0.07	0.12	0.01
Increase in normalised consumption	-18%	-19%	-94%
Increase in absolute consumption	**-28%**	**-23%**	**-96%**
of which for cooling	**0%**	**0%**	**0%**
of which for makeup	**-28%**	**-23%**	**-96%**
Increase in normalised withdrawal	72%	12%	63%
Increase in absolute withdrawal	51%	6%	25%

Figure 5.3 **Percentage increase in water consumption for post-combustion capture systems with once-through cooling**

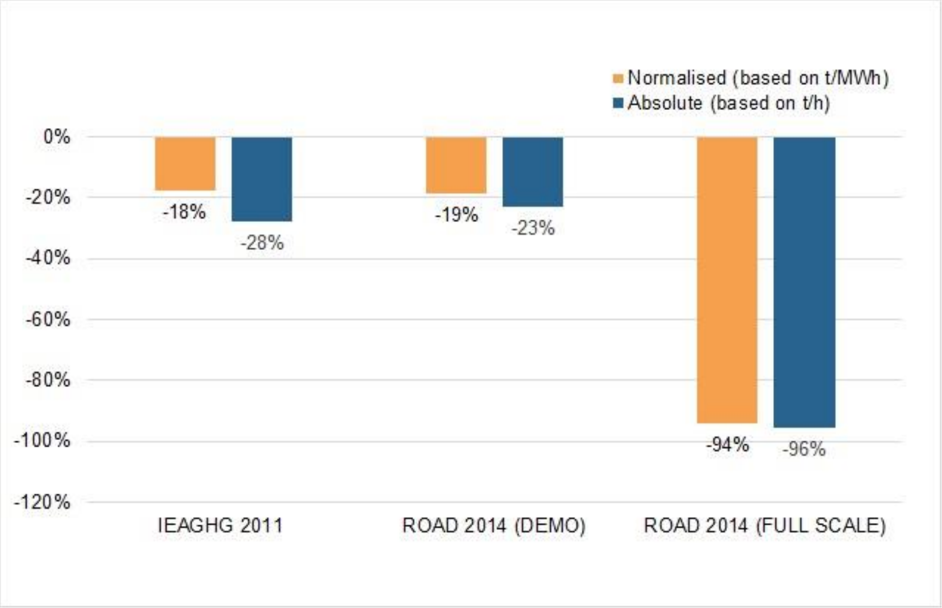
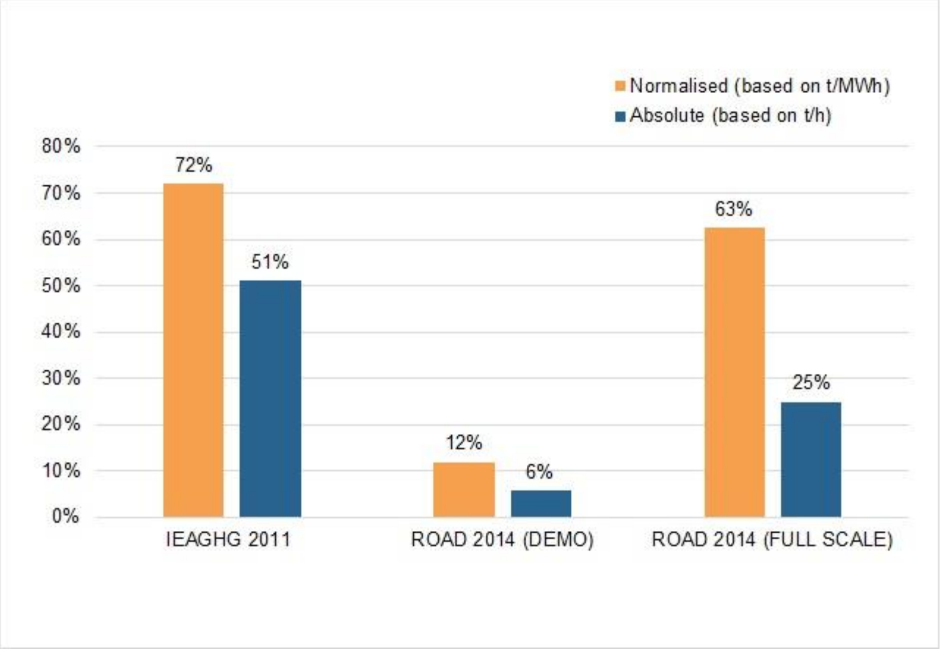


Figure 5.4 **Percentage increase in water withdrawal for post-combustion capture systems with once-through cooling**



Percentage variations reported in Table 5.3 reveal an interesting phenomenon – for once-through cooling, the addition of a post-combustion capture system can actually lead to a reduction in water consumption. For the three cases reported, a reduction is observed. However, it should be noted that the values for water consumption are very low as compared to the values for recirculating systems. Thus, relatively small changes in consumption result in large percentage changes.

IEAGHG calculations show a reduction in normalised water consumption from 0.09 to 0.07 t/MWh. This corresponds to a percentage variation of -18 per cent and -28 per cent in normalised and absolute water consumption, respectively.[33] This occurs because with the addition of a capture system, water is produced in the direct contact cooler (DCC) installed upstream of the absorber, where flue gas water is condensed and collected.

Furthermore, some water is also recovered from the CO_2 compression system. After proper treatment, most of this water can be returned to the local ecosystem, offsetting the increased makeup requirements associated with the addition of the capture system. If this water is recycled rather than returned to the local ecosystem, it would reduce external water supply needs by about 18 tonnes per hour.

ROAD estimates show similar effects – water is recovered in the DCC, but in this case, it is reused in the FGD unit. In the demonstration-scale plant, this would correspond to a variation of about -23 per cent and -19 per cent in absolute and normalised consumption, respectively (Figure 5.3). This corresponds to savings in freshwater consumption of about 44 tonnes per hour.

At full scale, this type of water recycling would lead to a variation of -96 per cent in absolute consumption (-94 per cent normalised), nearly eliminating the need for an external freshwater supply of about 120 tonnes per hour. The water recovery option evaluated by ROAD is explained in more detail in section 6.3.

The ROAD analysis shows a higher water gain compared to the IEAGHG analysis. This difference is related to different assumptions about the temperature of the direct contact coolers, the coal used and the type of flue gas cleaning system applied.

An increase in withdrawal occurs for power plants served by once-through cooling (Figure 5.4). The volumes of the withdrawal are much larger than those associated with recirculating cooling.

5.4 Estimates for pre-combustion systems

Water use estimates for pre-combustion systems have been sourced from the DOE 2015 and IEAGHG 2011 publications described above.

5.4.1 Recirculating cooling

Water consumption and withdrawal values for recirculating cooling in pre-combustion systems are summarised in Table 5.4, which highlights the differences between capture and non-capture cases. In the DOE/NETL report for IGCC systems that serves as the basis for this section, water use estimates were developed based on four different gasifier configurations: GEE Radiant, GEE Quench, E-Gas, and Shell.

While there was some variation among the numerical results for the different gasifier systems, in terms of general principles demonstrated, the results were similar. Thus for simplicity, only the results for the E-Gas case are presented in this section. The results for the other three cases have been included in Table A.2 in Appendix A. Figures 5.5 and 5.6 provide graphical representations of changes in water withdrawal and consumption.

[33] It is worth noting that water consumption variation is almost exclusively associated to make-up requirements since once-through cooling system have negligible water losses.

Table 5.4 Water use estimates for pre-combustion systems (recirculating cooling)

Case	***DOE 2015 IGCC E-Gas***
Without capture	
Plant power output (MWe)	625
Total water in (t/MWh)	1.59
Total water out (t/MWh)	0.33
Consumed water (t/MWh)	1.26
With 90% capture	
Plant power output (MWe)	513
Total water in (t/MWh)	2.55
Total water out (t/MWh)	0.49
Consumed water (t/MWh)	2.06
Increase in normalised consumption	63%
Increase in absolute consumption	**34%**
of which for cooling	**13%**
of which for makeup	**21%**
Increase in normalised withdrawal	60%
Increase in absolute withdrawal	31%

Figure 5.5 Percentage increase in water consumption for pre-combustion capture systems with recirculating cooling

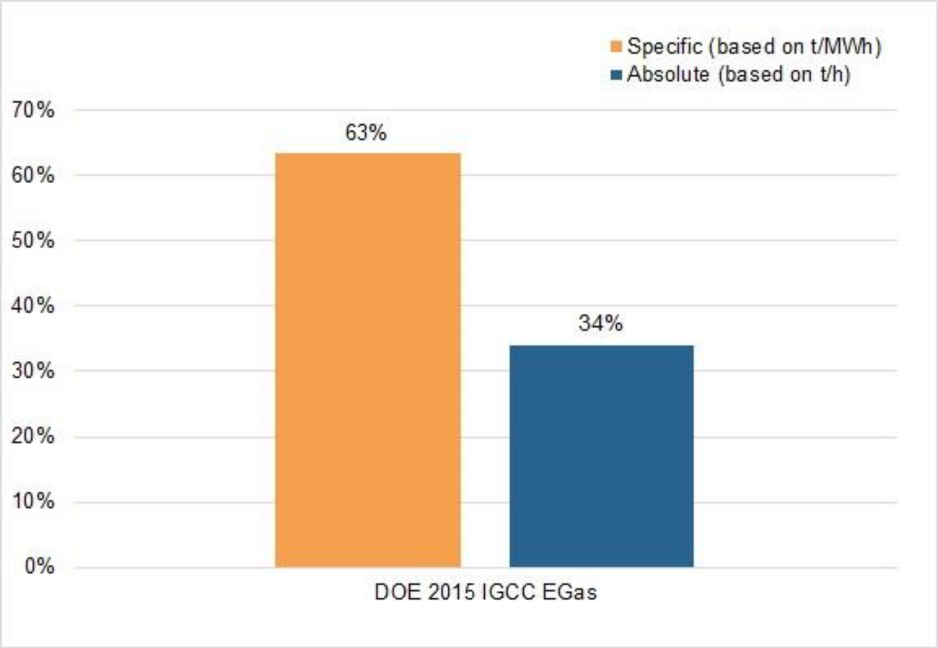
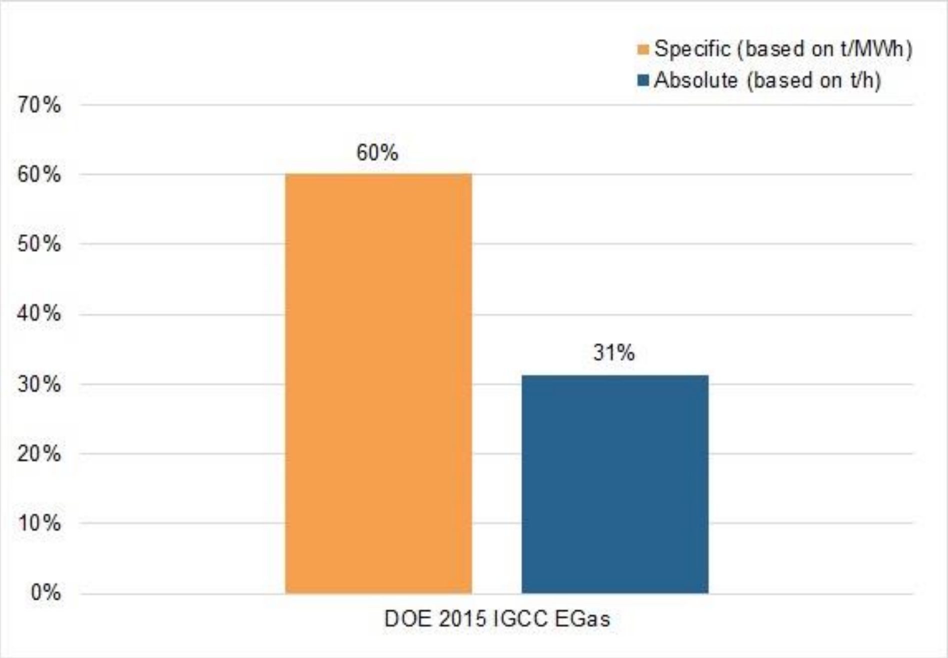


Figure 5.6 Percentage increase in water withdrawal for pre-combustion capture systems with recirculating cooling



Adding a Selexol™ CO_2 removal process to an E-Gas IGCC plant will increase the normalised water consumption around 63 per cent. The corresponding increase in absolute consumption is about 34 per cent. Similar percentage increases are observed for increases in withdrawal.

Looking at the breakdown between process makeup and cooling water in Table 5.4, it is clear that makeup water constitutes approximately two-thirds of the water consumption increase. This is mainly due to the large volumes of water (steam) required in the WGS and illustrates that makeup requirements in pre-combustion systems are much more important than in post- or oxy-combustion systems with respect to the overall water consumption.

5.4.2 Once-through cooling

Water consumption and withdrawal values for once-through cooling in pre-combustion systems are summarised in Table 5.5, which highlights the differences between capture and non-capture cases. Figures 5.7 and 5.8 provide graphical representations of changes in water withdrawal and consumption.

Table 5.5 **Water use estimates for pre-combustion systems (once-through cooling)**

Case	*IEAGHG 2011 IGCC GEE quench*
Without capture	
Plant power output (MWe)	826
Total water in (t/MWh)	147.06
Total water out (t/MWh)	146.94
Consumed water (t/MWh)	0.12
With 90% capture	
Plant power output (MWe)	730
Total water in (t/MWh)	185.67
Total water out (t/MWh)	185.28
Consumed water (t/MWh)	0.39
Increase in normalised consumption	236%
Increase in absolute consumption	**197%**
of which for cooling	**0%**
of which for makeup	**197%**
Increase in normalised withdrawal	26%
Increase in absolute withdrawal	12%

Figure 5.7 **Percentage increase in water consumption for pre-combustion capture systems with once-through cooling**

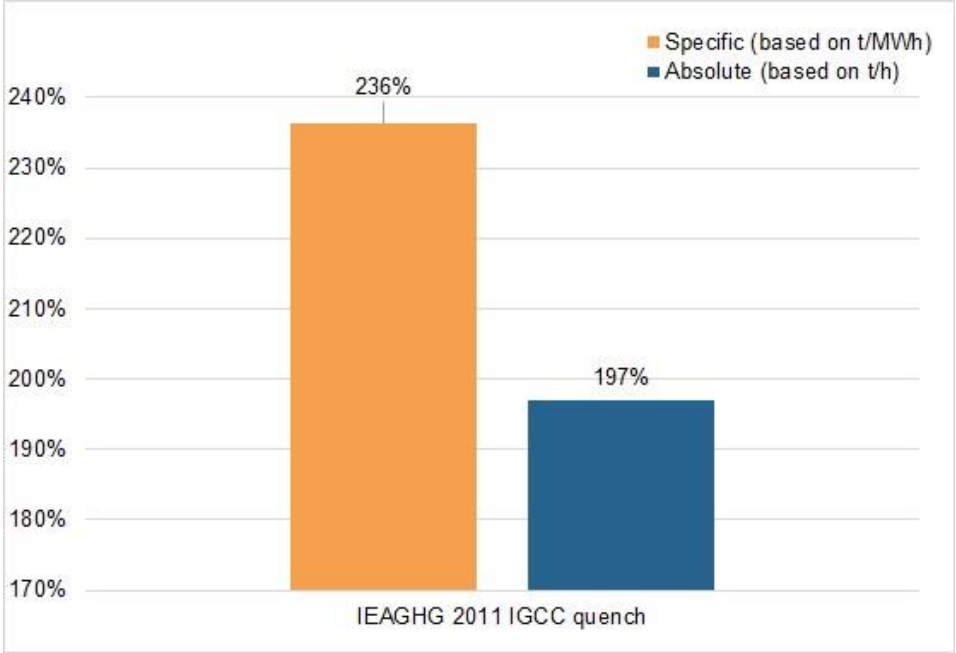
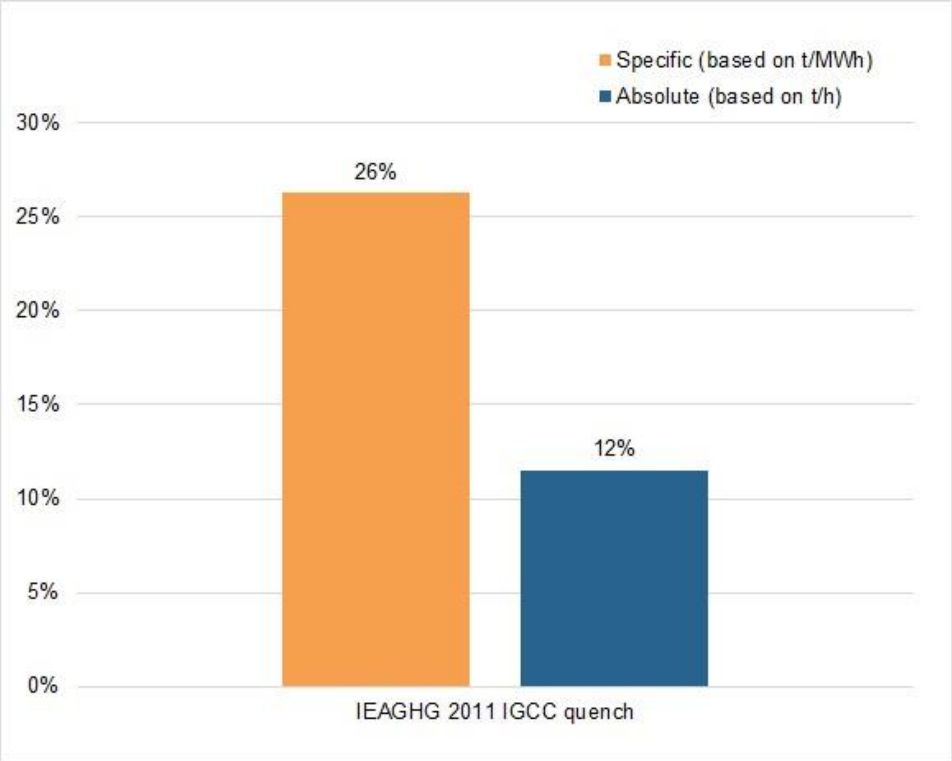


Figure 5.8 Percentage increase in water withdrawal for pre-combustion capture systems with once-through cooling



For the system evaluated changes in consumption are only associated with process makeup, and increase from 0.12 t/MWh to 0.39 t/MWh with the addition of pre-combustion capture (Table 5.5). Percentage consumption increases are almost 200 per cent on an absolute basis and about 240 per cent on a normalised basis (Figure 5.7).

The percentage increases are higher than those for recirculating cooling (Figure 5.5), however this occurs because they are calculated on a smaller initial basis. Despite the higher percentage increase, IGCC with once-through cooling consumes less water than with recirculating cooling, both before and after addition of pre-combustion capture, the difference is approximately an order of magnitude.

5.5 Estimates for oxy-combustion systems

Water use estimates for oxy-combustions systems have been sourced from DOE 2012 and IEAGHG 2011 reports. The estimates differ from those presented for pre-combustion and post-combustion systems in one significant aspect. Whereas for pre- and post-combustion, water use estimates are provided for similar power production facilities with and without CO_2 capture, information is not available that shows water use for an oxy-combustion system that does not include CO_2 capture. Therefore, water use comparisons for oxy-combustion systems are made by comparing their water use to the water use associated with similar air-fired power production systems.[34]

[34] The air fired power plant used as reference has the same characteristics of the super-critical pulverized-coal plant without CO_2 capture defined in (DOE/NETL, 2013).

5.5.1 Recirculating cooling

Water consumption and withdrawal values for recirculating cooling in oxy-combustion systems are summarised in Table 5.6, which highlights the differences between capture and non-capture cases. Figures 5.9 and 5.10 provide graphical representations of changes in water withdrawal and consumption.

Table 5.6 Water use estimates for oxy-combustion systems (recirculating cooling)

Case without capture	**Air-fired PC power plant (reference)**	
Plant power output (MWe)	550	
Total water in (t/MWh)	2.19	
Total water out (t/MWh)	0.45	
Consumed water (t/MWh)	1.75	
Cases with 90% capture	**DOE 2012 oxy-fuel (cryogenic)**	**DOE 2012 oxy-fuel (membrane)**
Plant power output (MWe)	410	450
Total water in (t/MWh)	3.60	3.02
Total water out (t/MWh)	1.00	0.84
Consumed water (t/MWh)	2.61	2.17
Increase in normalised consumption	49%	25%
Increase in absolute consumption	**11%**	**2%**
of which for cooling	**35%**	**26%**
of which for makeup	**-24%**	**-24%**
Increase in normalised withdrawal	64%	38%
Increase in absolute withdrawal	23%	13%

Figure 5.9 Percentage increase in net water consumption for oxy-combustion capture systems with recirculating cooling

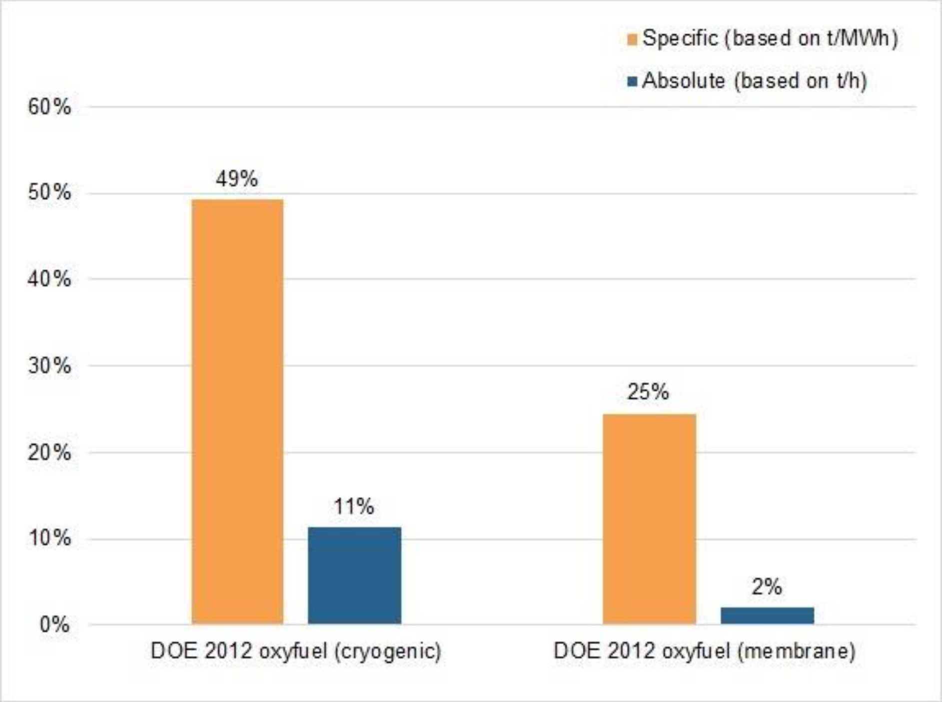
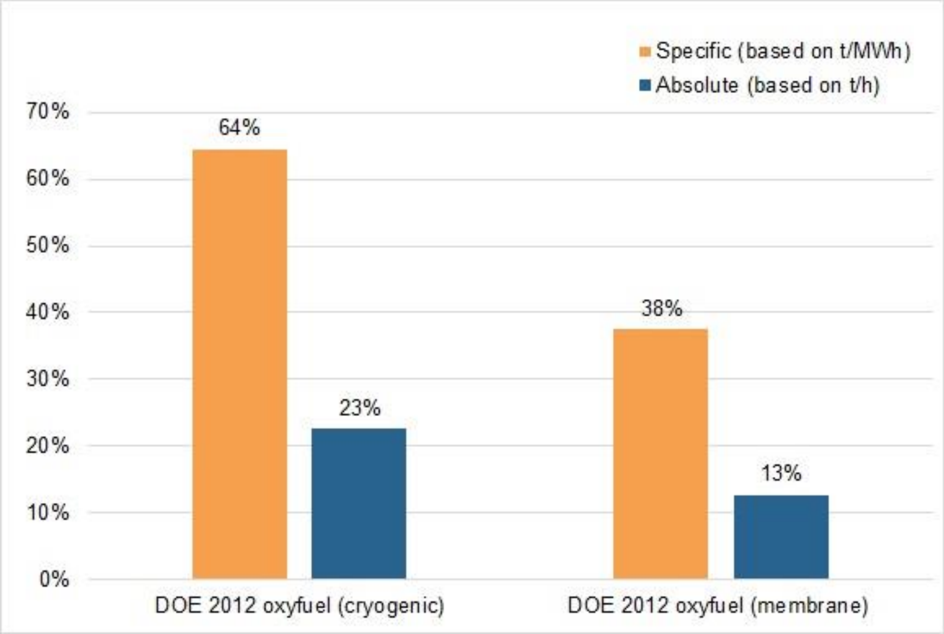


Figure 5.10 Percentage increase in water withdrawal for oxy-combustion capture systems with recirculating cooling



Oxy-combustion systems employing cryogenic oxygen separation show an increase in normalised water consumption of around 49 per cent and 11 per cent in absolute consumption. This is equal to an increase from approximately 1.7 t/MWh to 2.6 t/MWh.

The increase in water use estimated for the *Advanced Membrane* case is even lower – only 2 per cent on an absolute basis, corresponding to a 25 per cent increase in normalised water use. Much of the difference in normalised water consumption between the *Advance Membrane* and the *Current Technology* cases can be attributed to the differences in the associated power output. Differences in absolute consumption can be attributed to the differing cooling requirements associated with cryogenic versus membrane-based oxygen production.

The breakdown between process makeup and cooling water included in Table 5.6, shows that the increase in cooling water consumption is compensated-for by the decrease in makeup water consumption. Makeup water requirements are reduced thanks to internal water recovery in the CO_2 capture cases.

5.5.2 Once-through cooling

Water consumption and withdrawal values for once-through cooling in oxy-combustion systems are summarised in Table 5.7, which highlights the differences between capture and non-capture (ie, air-fired) cases. Figures 5.11 and 5.12 provide graphical representations of changes in water withdrawal and consumption.

Table 5.7 Water use estimates for oxy-combustion systems (once-through cooling)

Without capture	**Air-fired PC power plant (reference)**
Plant power output (MWe)	758.00
Total water in (t/MWh)	139.98
Total water out (t/MWh)	139.89
Consumed water (t/MWh)	0.085
With 90% capture	**IEAGHG 2011 oxy-fuel (cryogenic)**
Plant power output (MWe)	531.40
Total water in (t/MWh)	226.18
Total water out (t/MWh)	226.39
Consumed water (t/MWh)	-0.20
Increase in normalised consumption	-338%
Increase in absolute consumption	**-267%**
of which for cooling	**0%**
of which for makeup	**-267%**
Increase in normalised withdrawal	62%
Increase in absolute withdrawal	13%

Figure 5.11 Percentage increase in water consumption for oxy-combustion capture systems with once-through cooling

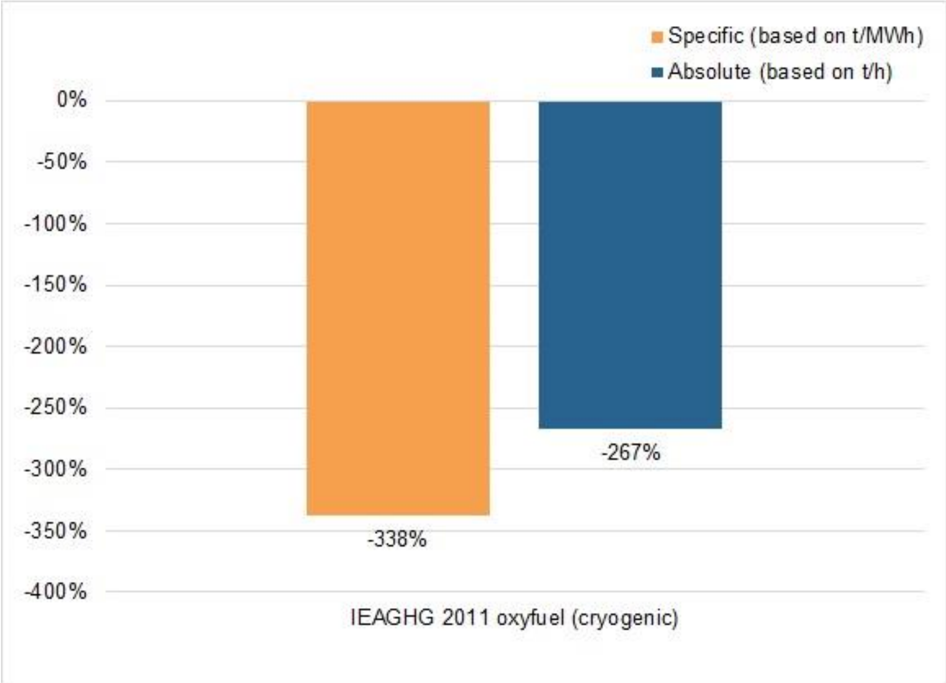
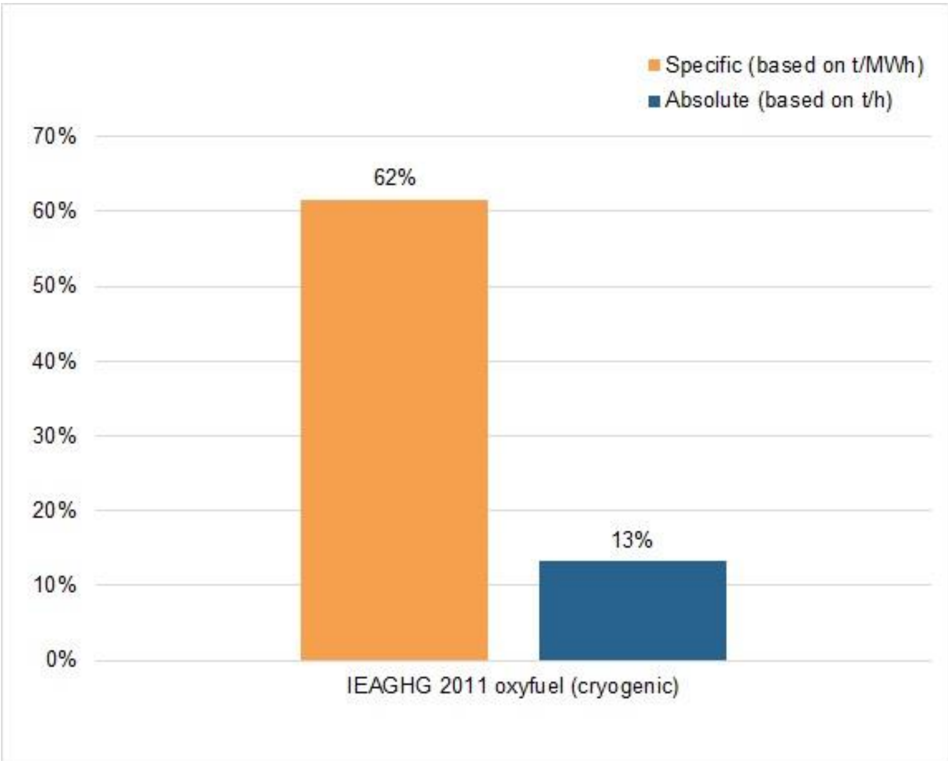


Figure 5.12 Percentage increase in water withdrawal for oxy-combustion capture systems with once-through cooling



The oxy-combustion configuration analysed shows decreases in water consumption of -270 per cent and -340 per cent for absolute and normalised consumption, respectively. Although these percentage variations are large, it must be noted the associated volumes are rather small (Table 5.7). The breakdown between process makeup and cooling included in Table 5.7 shows that this decrease in water consumption is completely attributed to a reduction in makeup water consumption.

With the addition of an oxy-combustion system, the water produced by flue gas cooling and by condensate extraction in the compressor, can be recycled after proper treatment, reducing the need for external freshwater. Makeup water requirements are off-set by the water generated in CO_2 capture cases. Depending on the system design and the fuel employed[35], an oxy-combustion system can actually become a source of water.

Since the cooling duty of the plant increases with addition of oxy-combustion, the volume of water withdrawn for cooling increases by about 13 per cent, corresponding to about 62 per cent more water withdrawn per MWh.

35 (Hetland, 2013)

6. Approaches to reduce water use in CO_2 capture systems

When opportunities for supplying additional water to a power plant to support a CO_2 capture system are limited, options to minimise the additional water consumption need to be considered. For cooling, the most obvious solution is to consider a dry cooling system. Dry systems, however, are expensive in terms of capital and operational costs. Therefore, other solutions could be more cost effective to limit the amounts of water withdrawn or consumed.

6.1 Selection of the capture technology

As seen in Section 5, different capture technologies can have unique impacts on water requirements. This is most vividly illustrated by the significant reduction in water use associated with adoption of a more efficient capture technology. It is reasonable to assume that, as more advanced technologies are developed that result in further reductions in energy requirements, water use requirements may be reduced even further, although the primary target of developers is usually to reduce cost and energy requirements.[36]

An example of a technological innovation that could lead to decreased water consumption is the use of membranes in post-combustion capture processes. Post-combustion capture membranes require minimal cooling[37] and process water, and therefore they have little impact on water consumption. Another example is the Sorption Enhanced Water Shift Reaction (SEWGS) for pre-combustion systems, which combines the WGS reaction with CO_2 separation, reducing the energy and the additional steam required by the CO_2 capture process.[38]

6.2 Waste heat integration

Waste heat integration involves the efficient utilisation of (waste) heat produced by the capture system in other parts of a process rather than dissipating it in coolers. A common approach for post-combustion systems is to use the waste heat of the amine-based capture process in the steam cycle of the host power plant – to warm-up condensate or boiler feed-water in the preheating section of the steam cycle. Such integration is primarily targeted to improve the efficiency of the whole system. However, implementing waste heat integration reduces the cooling duty of the capture system, and thus the volume of cooling water used.

In amine-based post-combustion systems, waste heat is available from the process coolers and/or from the CO_2 compressor. The effectiveness of the integration however depends on the amount and temperature of the heat available. Integration options must be evaluated in terms of effective cost benefit. A comprehensive review of heat integration options for post-combustion systems is presented in a report published in 2015 by the IEA Clean Coal Centre. [39]

Efficiency and water consumption might also be improved in oxy- and pre-combustion systems through implementing waste heat integration. In these systems, waste heat utilisation can occur in many different ways depending on the configurations and the technologies adopted.

[36] (Global CCS Institute, 2015)
[37] (Khalilpour, et al., 2014)
[38] (Jansen, et al., 2013)
[39] (Henderson, 2015)

6.3 Water recovery and recycling

Water recovery and recycling can have significant impacts on the need for process makeup water. In post-combustion systems, water can be recovered in the flue gas cooler, typically a direct contact cooler, installed upstream of the absorber to cool the flue gas to about 30-40°C, in the overhead condenser that cools the CO_2 stream leaving the top of the stripper, and the CO_2 compressor (see Figure 4.1).

Water extracted from the CO_2 capture system can be collected and reused as makeup water in the capture system. Water extracted from the DCC can be reused for other purposes in the power plant, after proper treatment. Use of DCC water as process makeup in the FGD unit for the ROAD project, as described in Section 4, is a good example of this type of approach.[40] Significant amounts of water can also be recovered in the flue gas cooler typically employed in oxy-combustion systems. In the IEAGHG 2011 oxy-fuel case described in Section 4, the water produced is about three times the water required in the plant for makeup. This water can be reused inside or outside the power plant after proper treatment.

The amount of water that can be extracted from flue gas in fossil fuel-fired power plants depends on the process configuration (ie, cooler temperature) and the fuel characteristics. For example, water recovery from a power plant burning anthracite, which has a low moisture content, would not produce as much water as an equivalent plant burning lignite, which has a high moisture content.

Hetland conducted water balance calculations for an amine-based post-combustion capture system and an atmospheric pressure oxy-combustion system using a variety of fuels – natural gas, anthracite, bituminous coal and lignite. [41] The calculations accounted for the water produced by flue gas cooling and consumed for process makeup. The results indicate that plants combusting lignite or natural gas have high potential for water extraction from flue gas, and that water recovery would be higher in oxy-combustion systems than in post-combustion systems burning the same fuel.

[40] (ROAD, 2014)
[41] (Hetland, 2013)

7. Conclusion

Additional water requirements introduced by CO_2 capture processes can be of concern. Estimates available in the literature provide quantification of these requirements. By comparing the estimates produced for different cases, this study highlights relevant aspects to be considered when assessing the impact of a CO_2 capture system on water requirements.

When addressing water use in general, a distinction is necessary between water *withdrawal* and water *consumption*. Withdrawal indicates the amount of water that is extracted from a source, whereas consumption refers to the amount of water actually lost (ie, evaporated). The difference between withdrawal and consumption is the water that is returned to the point of withdrawal. In this report, consumption is calculated as the difference between water withdrawn and the sum of effluents returned to the environment – only the water removed from the local ecosystem or water network is considered consumed.

This distinction between consumption and withdrawal is particularly relevant to understanding the impact of different types of cooling system – recirculating versus once-through – on the quantities of water consumed. Increasing the water requirements for a plant with recirculating cooling means that both withdrawal and consumption will increase. Increasing the requirements for a once-through cooling system results in increased withdrawal rates, but the consumption associated with cooling will remain essentially unchanged.

The objective of this study was to present water use estimates in a consistent way and to compare the increases in water consumption and withdrawal for each of the cases reported. This has been accomplished by looking at the percentage increase in power plant water consumption and withdrawal with and without CO_2 capture. The percentage increases have been calculated on both a *normalised* and *absolute* basis. Absolute refers to the actual amount of water (ie, tonnes per hour), normalised refers to a quantity of water normalised with respect to the net power output of the power plant (ie, tonnes per MWh). Both of these measures are important, depending on the types of issues being addressed.

Early studies that are widely referenced and cited in discussions of CCS, indicated that installation of a post-combustion capture system would nearly double normalised water consumption for thermal power generation using recirculating cooling. More recent estimates, however, show a percentage increase of less than 50 per cent for coal-fired power generation. This decrease results from the use of a more advanced CO_2 capture technology that has better performance, and thus, lower cooling requirements. This highlights the water use impact of selecting one technology as opposed to another. In absolute terms, the percentage increase in water consumed is estimated at less than 20 per cent for coal-fired power plants.

The difference between normalised and absolute consumption increases points out a limitation associated with just reporting normalised results, as has been common in earlier publications regarding the impact of CO_2 capture on water use. Normalised water use can be important for broad planning purposes and for comparisons of CCS versus other decarbonisation technologies via life cycle analysis. However, because carbon capture has significant parasitic power demands, the net power production with CO_2 capture is reduced.

By only reporting the water use estimates linked to net power production (ie, normalised consumption), the impression given is that supplemental water requirements for a given power production facility are significantly larger than they actually are. When an individual facility is evaluating the consequences of implementing CO_2 capture, it is more appropriate to consider changes in the total (absolute) volume of water used, as opposed to the normalised value, because any impact on local resources will be associated with the absolute increase in volume of water consumption.

For coal fired power plants using once-through cooling, the results indicate that increased water consumption is only associated with process makeup water requirements of the capture system. However, since the addition of a post-combustion capture system allows for some recovery of water from the flue gas, the additional makeup requirements are balanced, or off-set, by the water production. For this reason, the percentage variation for coal fired power plants with once-though cooling is negative. Normalised consumption varies from -20 to -96 per cent. These results highlight that, depending on the case considered, CO_2 capture can actually contribute to reducing water consumption.

For oxy-combustion systems with recirculating cooling, normalised water consumption increases by about 50 per cent, which corresponds to 11 per cent in absolute terms. Similar to post-combustion, an oxy-combustion system with once-through cooling can experience a negative percentage variation of water consumption - the amount of water generated in the flue gas cooler can be greater than the amount of makeup water needed.

Adding a CO_2 removal process to an IGCC plant will increase the normalised water consumption in the range of 45-74 per cent with recirculating cooling, depending on the gasification technology employed. The corresponding increase in absolute consumption is in the range of 26-38 per cent. It is noted that for IGCC systems, the contribution of process makeup water to the increase in water consumption is much more significant than for post-combustion or oxy-combustion systems. This is due to the process steam required in the water gas shift reaction.

When opportunities for additional water supply are limited, options to minimise increased water consumption need to be considered. One solution is to employ dry cooling systems. Dry systems however, are expensive in terms of operational costs. Therefore additional measures can be considered. For post-combustion systems, positive contributions in curbing water requirements can be achieved by waste heat integration. One option is to use the waste heat available from the process coolers or the CO_2 compressor to warm-up condensate or boiler feed-water in the preheating section of the steam cycle. Such integration is primarily targeted at improving the efficiency of the whole system, but it does come with a price in terms of capital costs and increased complexity. However it also reduces the overall cooling requirements.

By comparing the results of multiple studies based on different technologies and approaches, this analysis clearly shows that different CO_2 capture systems and approaches have different impacts, with significant variability among the cases presented. The validity of previous assertions that addition of a capture system automatically doubles water consumption is called into question. Variations in capture technologies, cooling systems, and in the way that data are presented (normalised versus absolute consumption) impact the magnitudes of consumption estimates and the conclusions that can be drawn from them. Actual consumption increases must be estimated on a case by case basis, carefully accounting for capture and cooling system characteristics and approaches to reduce water use.

This work is not intended to rank technologies, nor to recommend one technology over another. Its objective is rather to indicate water use increase expected for selected CO_2 capture concepts, and to provide a more complete and accurate representation of the impact that widespread deployment of CCS might have on water resources.

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Appendix A – summary of data collected from literature

Table A.1 Summary of water consumption estimates for post-combustion systems

Please see Table A.4 for explanation of the terms

Note: In reports DOE 2013 and DOE 2015 the net power output in capture cases is kept equal to non-capture cases. Here, in order to simulate the effect of a retrofit, the reduced output is used; it is calculated from the thermal input and the efficiency in CO_2 capture mode.

	PULVERIZED COAL - RECIRCULATING COOLING		NGCC - RECIRCULATING COOLING		PULVERIZED COAL - ONCE THROUGH COOLING		
REFERENCE	DOE 2013	DOE 2015	DOE 2013	DOE 2015	IEAGHG 2011	ROAD 2014	ROAD 2014 (FULL SCALE)
CASE (in reference)	Case 11-12	Case B12A-B12B	Cases 13-14	Cases B31A - B31B	Case 3.21-3.22 - PC wet land	ROAD DEMO	ROAD FULL SCALE
NAME assigned	**DOE 2013 PC**	**DOE 2015 PC**	**DOE 2013 NGCC**	**DOE 2015 NGCC**	**IEAGHG 2011**	**ROAD 2014 (DEMO)**	**ROAD 2014 (FULL SCALE)**
PC plants + CO2 capture							
location	Midwestern US	Midwestern US	Midwestern US	Midwestern US	The Netherlands (coastal)	The Netherlands (coastal)	The Netherlands (coastal)
cooling system	recirculating cooling (evaporative cooling towers)	recirculating cooling (evaporative cooling towers)	recirculating cooling (evaporative cooling towers)	recirculating cooling (evaporative cooling towers)	Once trough (sea water)	Once trough (sea water)	Once trough (sea water)
water source	50% wells / 50% municipal	50% wells / 50% municipal	50% wells / 50% municipal	50% wells / 50% municipal	Sea for cooling, not specified for raw water	Sea-water cooling + fresh-water from nearby lake + demi-water from utility	Sea-water cooling + fresh-water from nearby lake + demi-water from utility
CO2 capture tech.	Fluor ECONAMINE FG+	Shell CANSOLV	Fluor ECONAMINE FG+	Shell CANSOLV	Fluor ECONAMINE FG+	Fluor ECONAMINE FG+	Fluor ECONAMINE FG+
heat integration with capture?	no	no	no	no	coolers of CO2 compressor	overhead coooler capture plant	overhead coooler capture plant
Water balance w/o capture							
Net power generated (MWe)	550	550	555	630	758	1070	1070
Total water withdrawal (t/MWh)	2.318	2.198	0.973	0.954	139.976	86.735	86.735
Withdrawal for cooling (t/MWh)	1.893	1.792	0.962	0.945	139.872	86.589	86.589
Withdrawal for make-up (t/MWh)	0.425	0.406	0.011	0.010	0.104	0.146	0.146
Total water out (t/MWh)	0.475	0.453	0.216	0.214	139.891	86.589	86.589
Cooling water returned to source (t/MWh)	0.475	0.448	0.216	0.214	139.872	86.589	86.589
Water disposal (Effluents) (t/MWh)	0.000	0.005	0.000	0.000	0.019	0.000	0.000
Total net water balance (used water) (t/MWh)	1.844	1.744	0.757	0.740	0.085	0.146	0.146
Net balance cooling water (t/MWh)	1.418	1.344	0.746	0.730	0.000	0.000	0.000
Net balance make-up/effluents (t/MWh)	0.425	0.400	0.011	0.010	0.085	0.146	0.146
Water balance w/ capture 90%							
Net power generated (MWe)	395	440	473	559	666	1012	822
Total water in (t/MWh)	4.396	3.370	1.916	1.635	240.764	97.055	141.011
Withdrawal for cooling (t/MWh)	3.780	2.859	1.902	1.622	240.354	96.937	141.002
Withdrawal for make-up (t/MWh)	0.616	0.511	0.014	0.013	0.410	0.119	0.009
Total water out (t/MWh)	1.025	0.771	0.482	0.406	240.694	96.937	141.002
Cooling water returned to source (t/MWh)	1.025	0.763	0.482	0.406	240.354	96.937	141.002
Water disposal (Effluents) (t/MWh)	0.000	0.009	0.000	0.000	0.340	0.000	0.000
Total net water balance (used water) (t/MWh)	3.371	2.599	1.434	1.229	0.070	0.119	0.009
Net balance cooling water (t/MWh)	2.755	2.097	1.420	1.216	0.000	0.000	0.000
Net balance make-up/effluents (t/MWh)	0.616	0.502	0.014	0.013	0.070	0.119	0.009
Percentage increase of NORMALISED figures							
Based on increase in t/MWh							
% Increase in NORMALISED withdrawal	**90%**	**53%**	**97%**	**71%**	**72%**	**12%**	**63%**
% Increase in NORMALISED net consumption	**83%**	**49%**	**90%**	**66%**	**-18%**	**-19%**	**-94%**
Percentage increase of ABSOLUTE figures							
Based on increase in t/h							
% Increase in ABSOLUTE withdrawal	**36%**	**23%**	**68%**	**52%**	**51%**	**6%**	**25%**
of which for cooling	35%	22%	68%	52%	51%	6%	25%
of which for make up	1%	1%	0%	0%	0%	0%	0%
% Increase in ABSOLUTE net consumption	**31%**	**19%**	**62%**	**47%**	**-28%**	**-23%**	**-96%**
of which for cooling	30%	19%	61%	47%	0%	0%	0%
of which for make up	1%	0%	1%	0%	-28%	-23%	-96%

Table A.2 Summary of water consumption estimates for pre-combustion systems

Please see Table A.4 for explanation of the terms

	IGCC - RECIRCULATING COOLING				IGCC - ONCE THROUGH COOLING
REFERENCE	DOE 2015	DOE 2015	DOE 2015	DOE 2015	IEAGHG 2011
CASE (in reference)	Case B5A - B5B	Case B5A - B5BQ	Case B4A - B4B	Case B1A-B1B	cases 5.05 -5.06
NAME assigned	DOE 2015 IGCC GEE radiant	DOE 2015 IGCC GEE quench	DOE 2015 IGCC EGas	DOE 2015 IGCC Shell	IEAGHG 2011 IGCC quench
PC plants + CO2 capture					
location	Midwestern US	Midwestern US	Midwestern US	Midwestern US	The Netherlands coast
cooling type	evaporative cooling towers	evaporative cooling towers	evaporative cooling towers	evaporative cooling towers	Once trough (seawater temp. 12 C)
water source	50% wells / 50% municipal	50% wells / 50% municipal	50% wells / 50% municipal	50% wells / 50% municipal	Sea for cooling, not specified for raw water
CO2 capture tech.	GEE slurry feed radiant + 2 stage SELEXOL	GEE slurry feed quench + 2 stage SELEXOL	CCB&I E-Gas slurry feed + 2 stage SELEXOL	Shell dry feed + 2 stage SELEXOL	GEE slurry feed quench gasifier + SELEXOL
heat integration with capture?	no	no	no	no	condensate and boiler feedwater are used as cooling medium in ASU and CO2 compression
Without capture					
net power generated (MWe)	622	623	625	629	827
Total water in (t/MWh)	1.735	1.733	1.593	1.499	147.058
Withdrawal for cooling (t/MWh)	1.538	1.535	1.422	1.240	146.932
Withdrawal for make-up (t/MWh)	0.198	0.197	0.171	0.259	0.126
Total water out (t/MWh)	0.360	0.359	0.328	0.284	146.941
Cooling water returned to source (t/MWh)	0.357	0.356	0.327	0.284	146.932
Water disposal (Effluents) (t/MWh)	0.003	0.003	0.001	0.000	0.010
Total net water balance (used water) (t/MWh)	1.376	1.373	1.264	1.214	0.117
Net balance cooling water (t/MWh)	1.181	1.179	1.094	0.956	0.000
Net balance make-up/effluents (t/MWh)	0.195	0.195	0.170	0.259	0.117
With capture 90%					
net power generated (MWe)	543	543	513	497	730
Total water in (t/MWh)	2.440	2.567	2.550	2.582	185.674
Withdrawal for cooling (t/MWh)	1.941	2.021	2.021	2.006	185.263
Withdrawal for make-up (t/MWh)	0.498	0.546	0.529	0.576	0.411
Total water out (t/MWh)	0.452	0.472	0.485	0.467	185.282
Cooling water returned to source (t/MWh)	0.449	0.467	0.482	0.464	185.263
Water disposal (Effluents) (t/MWh)	0.003	0.004	0.004	0.004	0.019
Total net water balance (used water) (t/MWh)	1.988	2.095	2.064	2.115	0.392
Net balance cooling water (t/MWh)	1.493	1.554	1.539	1.543	0.000
Net balance make-up/effluents (t/MWh)	0.495	0.541	0.525	0.572	0.392
Percentage increase of NORMALIZED figures					
Based on increase in t/MWh					
% Increase in NORMALIZED withdrawal	**41%**	**48%**	**60%**	**72%**	**26%**
% Increase in NORMALIZED net consumption	**45%**	**53%**	**63%**	**74%**	**236%**
Percentage increase of ABSOLUTE figures					
Based on increase in t/h					
% Increase in ABSOLUTE withdrawal	**23%**	**29%**	**31%**	**36%**	**12%**
of which for cooling	9%	13%	14%	23%	12%
of which for make up	14%	16%	17%	13%	0%
% Increase in ABSOLUTE net consumption	**26%**	**33%**	**34%**	**38%**	**197%**
of which for cooling	9%	13%	13%	22%	0%
of which for make up	17%	20%	21%	16%	197%

Table A.3 Summary of water consumption estimates for oxy-combustion systems

Please see Table A.4 for explanation of the terms. Note: In report DOE 2012 the net power output in capture cases is kept equal to non-capture cases. Here, in order to simulate the effect of a retrofit, the reduced output is used; it is calculated from the thermal input and the efficiency in CO_2 capture mode.

	PULVERIZED COAL - RECIRCULATING COOLING		PULVERIZED COAL - ONCE THROUGH COOLING
REFERENCE	DOE 2012	DOE 2012	IEAGHG 2011
CASE (in reference)	Current Technology Case	case 1 advanced membranes	cases 3.21 - 4.11
NAME assigned	DOE 2012 oxyfuel (cryogenic)	DOE 2012 oxyfuel (membrane)	IEAGHG 2011 oxyfuel (cryogenic)
PC plants + CO2 capture			
location	Midwestern US	Midwestern US	The Netherlands (coastal)
cooling type	Evaporative cooling	Evaporative cooling	Once trough (seawater temp. 12 C)
water source	50% wells / 50% municipal	50% wells / 50% municipal	Sea for cooling, not specified for raw water
CO2 capture tech.	Oxy-combustion + ASU (2012 tech.)	Oxy-combustion + membranes	
heat integration with capture?	no	no	yes (condensate and boiler feedwater are used as cooling medium in ASU and CO2 compression)
Without capture			
net power generated (MWe)	550	550	758
Total water in (t/MWh)	2.193	2.193	139.976
Withdrawal for cooling (t/MWh)	1.800	1.800	139.872
Withdrawal for make-up (t/MWh)	0.393	0.393	0.104
Total water out (t/MWh)	0.447	0.447	139.891
Cooling water returned to source (t/MWh)	0.447	0.447	139.872
Water disposal (Effluents) (t/MWh)	0.000	0.000	0.019
Total net water balance (used water) (t/MWh)	1.745	1.745	0.085
Net balance cooling water (t/MWh)	1.353	1.353	0.000
Net balance make-up/effluents (t/MWh)	0.393	0.393	0.085
With capture 90%			
net power generated (MWe)	410	451	531
Total water in (t/MWh)	3.607	3.016	226.182
Withdrawal for cooling (t/MWh)	3.513	2.945	226.120
Withdrawal for make-up (t/MWh)	0.094	0.071	0.063
Total water out (t/MWh)	1.001	0.843	226.385
Cooling water returned to source (t/MWh)	0.875	0.742	226.120
Water disposal (Effluents) (t/MWh)	0.126	0.101	0.265
Total net water balance (used water) (t/MWh)	2.605	2.173	-0.202
Net balance cooling water (t/MWh)	2.638	2.204	0.000
Net balance make-up/effluents (t/MWh)	-0.033	-0.030	-0.202
Percentage increase of NORMALIZED figures			
Based on increase in t/MWh			
% Increase in NORMALIZED withdrawal	**64%**	**38%**	**62%**
% Increase in NORMALIZED net consumption	**49%**	**25%**	**-338%**
Percentage increase of ABSOLUTE figures			
Based on increase in t/h			
% Increase in ABSOLUTE withdrawal	**23%**	**13%**	**13%**
of which for cooling	37%	28%	13%
of which for make up	-15%	-15%	0%
% Increase in ABSOLUTE net consumption	**11%**	**2%**	**-267%**
of which for cooling	35%	26%	0%
of which for make up	-24%	-24%	-267%

Table A.4 Explanation of the terms

Terms	ID	Explanations
REFERENCE		Abbreviated name of the literature source
CASE (in reference)		Case's identifier as reported in the literature source
NAME assigned		Case's identifier assigned in this report
PC plants + CO2 capture		
location		Location of the power plant
cooling system		Type of cooling system for power plant and capture plant
water source		Source of water used for cooling and make-up
CO2 capture tech.		CO2 capture technology employed
heat integration with capture?		yes/no waste heat recovery from CO2 capture systems
Water balance w/o capture		
Net power generated (MWe)	*A*	Sourced from reference
Total water withdrawal (t/MWh)	*B*	= C + D
Withdrawal for cooling (t/MWh)	*C*	Sourced from reference (normalised to net power output)
Withdrawal for make-up (t/MWh)	*D*	Sourced from reference (normalised to net power output)
Total water out (t/MWh)	*E*	= F + G
Cooling water returned to source (t/MWh)	*F*	Sourced from reference (normalised to net power output)
Water disposal (Effluents) (t/MWh)	*G*	Sourced from reference (normalised to net power output)
Total net water balance (used water) (t/MWh)	*H*	= I + L
Net balance cooling water (t/MWh)	*I*	Sourced from reference (normalised to net power output)
Net balance make-up/effluents (t/MWh)	*L*	Sourced from reference (normalised to net power output)
Water balance w/ capture 90%		
Net power generated (MWe)	*M*	Sourced from reference, or, if the case assumed to keep the power output constant with CO2 capture, the reduced output M is calculated as A*η1/η2, where η1 and η2 are efficiencies before and after addition of CO2 capture, respectively.
Total water in (t/MWh)	*N*	= O + P
Withdrawal for cooling (t/MWh)	*O*	Sourced from reference (normalised to net power output)
Withdrawal for make-up (t/MWh)	*P*	Sourced from reference (normalised to net power output)
Total water out (t/MWh)	*Q*	= R + S
Cooling water returned to source (t/MWh)	*R*	Sourced from reference (normalised to net power output)
Water disposal (Effluents) (t/MWh)	*S*	Sourced from reference (normalised to net power output)
Total net water balance (used water) (t/MWh)	*T*	= U + V
Net balance cooling water (t/MWh)	*U*	Sourced from reference (normalised to net power output)
Net balance make-up/effluents (t/MWh)	*V*	Sourced from reference (normalised to net power output)
Percentage increase of normalised figures		(Based on increase in t/MWh)
% Increase in normalised withdrawal		= (N - B)/B
% Increase in normalised net consumption		= (T - H)/H
Percentage increase of ABSOLUTE figures		(Based on increase in t/h)
% Increase in ABSOLUTE withdrawal		= (M*N - A*B)/(A*B)
of which for cooling		= (M*O - A*C)/(A*B)
of which for make up		= (M*P - A*D)/(A*B)
% Increase in ABSOLUTE net consumption		= (M*T - A*H)/(A*H)
of which for cooling		= (M*U - A*I)/(A*H)
of which for make up		= (M*V - A*L)/(A*H)