Assessing the undesired impacts on water sustainability from climate change mitigation technologies in fossil-based power generation

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This work investigates the water impact of carbon capture technologies employed in coal and natural gas power generation, viz. integrated gasification combined cycle, oxy-fuel combustion, solid oxide fuel cells and post-combustion solvent-based. The Water Impact per CO_2 Avoided (WICa) metric was developed to understand the tradeoff between water usage and global warming potential, and additionally as a decision-making tool. It relates the impact on available water resources to greenhouse gas reduction over the cradle-to-plant-exit lifecycle by leveraging existing metrics, including the Water Impact Index (WII), water withdrawal, water consumption, water quality, and Water Scarcity Index (WSI). The results show that some carbon capture technologies increase the overall water usage of power generation plants, thereby increasing the water impact per CO_2 avoided. Solid oxide fuel cells and oxy-fuel technology, though not mature in comparison to post-combustion capture, have the least water impact per CO_2 avoided. Furthermore, water withdrawal and consumption are shown to trend with the WII in specific scenarios, implying that, in the absence of water quality and WSI data, the metric's use as a stakeholder decision-making tool remains. The potential to reduce global warming via carbon capture technologies in the power generation industry can create additional water resource challenges for countries if not carefully considered.

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1. Introduction

1.1 Climate Change Mitigation & Water Sustainability

One unintended consequence of most carbon capture (CC) technologies for power generation is the requirement of additional water over the entire cradle-to-plant-exit lifecycle (1–4). Additionally, despite the benefit in reducing greenhouse gas emissions, water data for some of these technologies are not available, and the data that are available cannot be used meaningfully.

Reviews over the last decade are seemingly comprehensive, focusing on differentiating between CC technologies and carbon separation technologies, relative technology readiness and sustainability based on environmental impacts assessments(5,6). The research highlighted and compared different technology requirements and configurations, included optimisation of parameters relative to reduction of greenhouse gas emissions, and reported approximately 90% CO_2 removal for some technologies (Data set of Adams *et al*. (7)). However, all fall short in terms of commentary on water usage which is essential and critical to the operation of these technologies.

To further emphasize the importance of water consideration in carbon capture technology, global water demands projected for 2050 show increases for manufacturing and thermal power generation of 400% and 140% respectively (8). This demand, together with increasing water scarcity and water degradation further strains water resources globally and the impact is far greater in countries with an already depleted water supply. The access to clean water for human activities, including power generation and agriculture, underpins economic and social progress (9), and the adoption of CC technology would “commit humanity” to increased water use. (4)

Choosing between different CC technologies is simple from a greenhouse gas (GHG) emissions perspective but complex from a water impact perspective. The extent of the impact to water resources are user determined by understanding their water usage requirements. Requirements include water body water quality and local water availability. With power generation and similar industries, the impact is expanded to the volume and quality of water that is returned. Fully understanding the impact of CO_2 emissions reduction on water resources is crucial, not only from a volume perspective but from a quality and location perspective.

The value is in knowing the trade-off between green initiatives and their impact on natural resources. Making responsible and accountable decisions on climate change mitigation technology requires a holistic view including its impact on water sustainability.

As an example, the cost of CO_2 avoided (CCA) metric is useful to illustrate the comparative value of unlike CO_2 mitigation processes, with the aim of finding the most cost-effective CO_2 reduction solution. Similarly, mapping the impact to water resources to carbon dioxide avoided will identify carbon capture technologies in power generation that might benefit a region's water resources and conversely will also identify technologies that could place a region's water resources under further stress. While no metrics exist to assess the trade-off between water sustainability and GHG emissions reduction for CC technology in power generation, there are well known metrics available to construct such a model.

i. Volume of water (consumption and withdrawal): In power generation design, water provision is based on the requirements of the facility which are more closely related to withdrawal rather than consumption. Reporting on water withdrawn is critical during project feasibility as a process functions (the design capacity) on volume withdrawn and produces (the operating capacity) on volume consumed especially in the case of cooling technology requirements.

ii. The quality of water in terms of concentration of pollutants: The quality of water is considered as important in industry as volume of water required, as it limits the use of the specific water resource to a narrower set of applications. Large amounts of water available at less-than-optimal quality can impact overall costs and determine whether certain technologies or operations are feasible. Anecdotally, higher water quality is in higher demand which can, and in most cases does, place further strain on stressed resources. Mikosch *et al*. (10) and Pradinaud *et al*.(11) both comment on the challenges and importance of considering water quality when assessing water impact.

iii. Water scarcity, in terms of the degree of water scarcity in the location that water is required: Hydrological irregularities and high human use (catalysed by population growth and urbanisation) contribute to increasing water scarcity. Water scarcity is a global issue affecting all areas of protection and can impact the successful adoption of technology if not properly considered. At the same time, increasing water usage in industrial applications can directly increase water scarcity, as the demand for high quality water increases, and this is especially crucial in a country where water resources are threatened.

1.2 Water Data (un)availability

Water data for CC technology is uncommon and often heterogenous (12–14). Notable work on water usage in power generation include some information on CC technology but does not offer sufficient data to assess the trade-off between water usage from a volume perspective or water impact (because of that usage), and carbon dioxide avoided. Reviews on carbon capture technologies over the last decade concentrate on positioning the best technologies for addressing the global warming potential of power generation. This hierarchy between technologies is based largely on cost (Adams *et al.* (7), and Simpson *et al.* (15) investigated the levelized cost of electricity (LCOE) as well as cost of CO_2 avoided (CCA)), carbon dioxide capture rates as well as heat efficiencies. Water usage data is seldom reported in carbon capture technology studies(5–7).

Generally, natural gas technologies have low literature representation. Meldrum *et al.* (2) cover 18 natural gas plants versus 61 coal plants (utilising various cooling types). Macknick et al. (1) covers 20 natural gas plants versus 55 coal plants. Most research efforts are coal focused because of its higher CO_2 intensity than natural gas (7).

Consumption and withdrawal data are readily available for cooling operations given the recognised contribution of cooling in power generation however data availability is also low for the fuel cycle and other operational activities required for electricity generation, leading to an overall incomplete water requirements understanding (1). Investigations by Macknick *et al.* (1) and Meldrum *et al.* (2) estimate water usage data for coal and natural gas systems including different cooling technologies, based on available literature. Macknick *et al.* (1), focusses on operational water usage only (excludes the fuel cycle) and Meldrum *et al.* (2) covers the full life cycle (fuel cycle and operations). Specifically, these works consolidate water usage for selected power generation technologies and the impact of different cooling methods within them. While the studies do not focus on CC technology, they note that carbon capture has the potential to increase or decrease water consumption depending on the type of cooling.

For example, cooling towers consume twice as much water per unit of electricity generated versus once-through cooling. However, once-through cooling uses a withdrawal of between 10-100x more water than cooling towers(1). The type of cooling technology plays a significant role in water usage for power plant operations and having access to sufficient high-quality water is crucial to power generation plant operations.

Similar observations are noted in Feng *et al*. (16) who reported on water consumption alone in their work on the integration of post combustion CC on a coal-fired power plant in assessments of water use. In their work on water consumption of a retrofitted oxyfuel combustion facility, Zhu *et al.* (17) observed that that once through cooling is superior to recirculating cooling purely based on the water consumption value. However, water consumption alone is only half the picture and relates the water used within the process and does not consider the general water requirements necessary to operate a process which is crucial to determining water impacts.

The lack of general water quality data is also a concern. Part of the problem is the complexity of water quality data and the extensive amount of parameters that need tracking (18). Damania *et al.* (18) found that this is a global issue and regardless of economic status all countries experience the same challenges when it comes to water pollution. In fact, they highlighted that pollution does not decline with economic growth instead the variety of pollutants increases with “prosperity”. Water data is key to being able to assess impacts to water resources, to creating meaningful sustainability metrics and ultimately more sustainable processes.

1.3 Existing Water Sustainability and Climate Change Impact Assessment Methods

Climate change impact assessment methodologies are well documented, robust, and accepted. Using ISO 14044 and the Intergovernmental Panel on Climate Change (IPCC) global warming potentials (GWP), the climate impacts of different chemical emissions are comparable.

Water impact assessment, however, is more challenging. Many variables contribute to the impacts with some being contested. We identify current noteworthy methods and present gaps preventing them from being suitable to assess environmental trade-offs related to water sustainability.

1.3.1 Water footprinting methods

The water footprinting method is presented by the Water Footprint Network (WFN) (19) and in ISO 14046 (20) (the international standard on water footprinting), which approaches water footprinting as a water-targeted approach to life cycle assessment (LCA). LCA methodologies are the most common tool for assessing impacts of processes and products and has been standardised in ISO 14044. Bayart *et al*. (21) point out that the life cycle impact assessment (LCIA) methods on which they rely on do not sufficiently address water specifically “freshwater scarcity” and “availability”. They summarize further limitations and efforts to capture the nuances presented by the quality and scarcity of water within these assessment methods. They point out this similar observation on LCI data. LCI data only offer details on the volume of freshwater used for systems. With often, limited information provided on the type of resource (origin) and nothing about its discharge (fate) in terms of volume and quality. They concluded that these methods overlook the major environmental consequences of the reduction in quality and availability of freshwater. LCA characterise the impact to water from pollutant emissions, as is observed from the impact categories, however impacts from water unavailability are not quantified (22). The Water use in LCA (WULCA) group developed a consensus based method known as AWARE (Available water remaining) which is aimed at addressing the shortcoming of water scarcity, influenced by several parameters, for use in LCA ((23), (24)) as well as water scarcity footprint assessments.

Water quality will impact access to water and intensify water scarcity; therefore, it must be considered to obtain a complete picture of the impact to water resources however the mechanics of including water quality concepts in water impact assessment is still uncertain (11). This is also observed in the Water footprinting where there is no consensus on how to address water quality deterioration (10).

The WFN defines water footprinting as the volume of both direct and indirect freshwater use over the entire supply chain to produce a product(19). It is generally reported as a single value. ISO 14046 defines water footprint as "metric(s) that quantify the potential environmental impacts related to water", reported as single value or set of impact indicators. For non-comprehensive assessments, the environmental impact categories per ISO 14046 are water availability footprint (impact due to high demand on water), water scarcity footprint (when water availability focuses on scarcity) and water footprint that addresses water degradation (environmental impacts due to water quality).

1.3.2 The Water Impact Index (WII)

The WII (25) is a single indicator, based on the Water Footprinting method, used to assess the reduction in available freshwater due to human activities. It integrates water volume, water quality, and water scarcity. Negative values suggest an increase in water availability whereas positive values indicate a decrease in water availability. An index feature is the inclusion of quality in the withdrawal and return terms which creates a penalty for using high quality water and discharging poor quality water. The WII, as defined in Bayart *et al.*(25) is:

$$\mathrm{WII} = \sum_i \left[W_i Q_{W_i} WSI_i\right] - \sum_j \left[R_j Q_{R_j} WSI_j\right] \tag{1}$$

where WII is the Water Impact Index expressed as volume unit water impact index equivalent, W_i and R_j are quantities of water withdrawn from water body i and returned to body j. Q_{Wi} and Q_{Rj} are unitless quality indices of water withdrawn from water body i and returned to body j, and range between 0 (worst quality) and 1 (best quality) (25). WSI_i and WSI_j are unitless water scarcity indices for water bodies i and j, calculated by the water stress index equation outlined in Pfister *et al.* (13) (Further details provided in the electronic supplementary information)

The quality index is based on the chosen penalising pollutant p and takes on the value of 1 when $c_p \leq c_{ref,p}$

$$Q = min\left(1; \frac{c_{ref,p}}{c_p}\right) \forall p \tag{2}$$

where Q is the quality index, $c_{ref,p}$ is the reference concentration of a specific pollutant and, c_p is the actual concentration of that pollutant present in the water body (either withdrawal or discharge.)

This is a modification from the original form of the equation in Bayart *et al.* (25), where in that work p is not a set of many different pollutants considered in the analysis, but rather a single "most penalizing pollutant". In their formulation, p is chosen as "worst case" pollutant p which is the one that the minimum $C_{ref,p}/C_p$ in a set of all possible pollutants. Both approaches will find the same Q, but only if the "most penalizing pollutant" is known *a priori*. This was a known weakness in the formulation as indicated by the authors in their discussion. Therefore, we use a more generalized form that allows the user to consider a set of all pollutants of interest without needing to know the "most penalizing pollutant" *a priori.*

Water quality is central to determining water availability. For water withdrawal, a quality index of 1 means a lower overall water availability for other users because less high quality water is available to them. In the case of water returned – a quality index of 1 means a higher overall water availability (the full amount returned is available to other users at high quality).

The usefulness and meaning of relating water scarcity and water volume has been debated (26). However, in the absence of a holistic method the WII offers a simple way to quantitatively measure the degree of impact.

Additionally, we observe the following about the WII:

i. WSI for water bodies in the same region does not change materially as the WSI is determined based on the ratio of water consumed by all users to total water available. The WSI was developed based on available watershed (feed to a water body) information which were available in aggregate regionally and not per watershed as suggested by the WII definitions. Independent watershed data would be ideal, however, its absence means that the WSI represents a country or region's position and not a single water body. Our approach uses the country WSI for the WSI of the withdrawal and returned water bodies. These are therefore identical in the WII equation.

ii. Once the value is calculated, freshwater availability is indicated without exposing the underlying water quality. A negative value (resulting from the withdrawal term being smaller than the returned term) is interpreted as increase in water availability, however this value cannot distinguish between pollutants. This overall scenario is useful when determining whether water is available for other users.

iii. The WII can aid comparisons of the same system (before and after water treatment or application of other technologies) as with the example presented in Bayart *et al*. (25) and seen later in this work.

1.3.3 Available Water-Carbon Metrics

Rosa *et al*. (4) examined the water footprint of CO_2 captured (in m^3 water per tonne of CO_2 captured) of four CC technologies. Rosa *et al.* (4) acknowledge that high water footprints could exacerbate the water scarcity status in regions however their results indicate water that is solely consumed and not the possible impacts related to the use of that water, dependent on spatial and temporal factors. (27). While the work does confirm quantitatively the water consumption of some CC technology, it does not fully relate the benefit of the reduction in carbon dioxide emissions to water. Additionally, the work does not specify certain parameters that will allow fair comparison such as cooling requirements, heat rate or higher heating values.

The Water-carbon-abated ratio (WCAR) (28) is a similar metric. Its water impact is based on LCA data, specifically water consumption only. This work does include water scarcity footprinting (calculated as the product of water consumption and a WSI factor), however, it is not used in the calculation of the WCAR. The calculation of WCAR has its merits as an indicator of trade-offs between technologies in terms of water consumption and GHG emissions avoided but the lack of factoring of a quality value or a scarcity factor means that there is no understanding of the impact to water once the water is consumed.

Both efforts consider water impact as the availability to other users post consumption, but neither include quality or scarcity directly.

Other work, such as that of Rosa et al. (29) investigated the effects on water scarcity of retrofitting four different carbon capture technologies to existing coal fired based facilities. Specifically: absorption with amine solvents, membrane separation, and adsorption into solid sorbents by either pressure swing adsorption (PSA) or temperature swing adsorption (TSA) processes. They show that while retrofitting does not significantly increase water scarcity; certain regions may lack the water resources to meet the additional water demands of carbon capture technologies. Additionally, they highlight that currently 43% of global coal fired plants experience water scarcity for one month a year while 32% can experience water scarcity for five months or more suggesting that influences to water scarcity must be considered in water impact assessment. Therefore, this work is appropriately positioned and builds on this key finding of Rosa et al. (29)

1.4 Proposed Metric and Contribution of the work

In this work we propose the Water Impact of CO_2 avoided (WICa) metric; an easy, usable, high-impact way to assess the trade-off between reduction of GWP, as CO_2 equivalents emissions avoided, and the impact on water resources for CC technologies in the power generation industry. Previous integrated metrics (Table 1) indicate water that is consumed but lack the impacts related to the use of that water, which also varies temporally and spatially (27). By expanding the consideration beyond volumetric withdrawal, return and consumption to other key parameters such as water quality and water scarcity, we will be able to better understand the impacts of water use. A perspective supported in literature (30,31). Table 1 summarizes and compares the proposed metric to the previously available metrics in the literature and the characteristics they employ to assess water impact. The WICa metric is the first to incorporate all of the major water metric characteristics (consumption, withdrawal, return, quality, and scarcity) as well as the GHG emissions avoided. WICa combines all of these factors into a single number especially useful for the cross comparison of green technologies.

Table 1: Summary of characteristics in water sustainability captured by proposed metrics in the literature.

Characteristics	**Water footprinting (Water Footprint Network)** (19)	**Water footprinting ISO14046**(20)	**Water footprint of CO_2 Captured Rosa *et al.*** (4)	**WCAR Water-carbon-abated ratio Habib** (28)	**WII Water Impact Index Bayart et al.** (25)	**WICa Water Impact of Carbon Avoided (This work)**
Water consumption	✓	✓	✓	✓	✓	✓
Water withdrawal					✓	✓
Water returned					✓	✓
Water quality		✓			✓	✓
Water scarcity		✓			✓	✓
GHG emissions/GHG emissions avoided			✓	✓		✓

The WICa metric is made up of two parts, the numerator is the change in water impact between a base case and green case and the denominator is the change in global warming potential (GWP) between the same base case and green case. Water impact is assessed using the WII, which covers the key variables that are identified as important when understanding water impact. The change in GWP avoided is similar to cost of carbon avoided metric and is calculated as the difference between the CO_2 equivalent emissions of the green case (with CC technology) and the base case (without CC technology).

$$\mathrm{WICa} = \frac{WII_{\text{Green Case}} - WII_{\text{Base Case}}}{\mathrm{GWP}_{\text{Base Case}} - \mathrm{GWP}_{\text{Green Case}}} \tag{3}$$

Where WII is calculated as m^3 water equivalents per MWh (m^3e/MWh) which is based on water data available, and in some cases, estimated, for power generation plants, and GWP is the global warming potential reported as tonne (t = tonne = 1000kg) CO_2 equivalents per MWh (tCO_2e/MWh). The resultant WICa metric units is therefore m^3 water equivalents per tCO_2 equivalents.

The base case and green case subscripts are further described in the following sections. The WII is calculated for the base case at a specified withdrawn and returned water quality and WSI. It is then calculated for the green case at the same water quality (withdrawn, returned and WSI) as the base case. Assuming that only a single water body, *i*, is used for withdrawal and return (discharge) and that the water bodies are in the same regions and share the same WSI value.

We explore the usefulness and value of WICa in a climate change mitigation case study. This will both demonstrate the value of the metric and provide new insights into the water sustainably and GHG emissions trade-offs of several different climate change mitigation technologies for different countries. We assess several of these technologies in fossil-based power plant systems, together with varying water qualities and country water stress indices to put forward the holistic view of their impact on water resources.

2. Case Study: Comparing 65 different low-CO_2 fossil-based power plant systems

Power generation is responsible for over 40% of energy-related greenhouse gas emissions (32) and global water demands projected for 2050 show a 140% increase in thermal power production(8). The incorporation of CC technology, as part of a strategy to reduce this GWP, impacts this global view. The adoption of certain CC technologies increases the energy requirements, reduces efficiency and thereby increasing overall water usage requirements.

Water is required for two purposes: (i) for unit operations as a processing fluid and (ii) for cooling. Typical uses and unit operation interactions for process and cooling water, based on Adams *et al.* (7)and NETL reports referenced in this work. are illustrated in Figures 1 to 4. For detailed water allocation breakdowns see Gerdes and Nichols (33)and, Zhai and Rubin (34). The process water system “block” in Figures 1 to 4 encompasses the water requirements for the boiler feed water system (makeup and blowdown), as well as flue gas desulphurisation (makeup and dewatering) and any other unit operations that require water. Within the CC process this would include CO_2 capture recovery and CO_2 compression knockout.(33). The following subsections describe the five general categories of carbon capture in power plant design, with a focus on how water is used within the process.

2.1 Post-Combustion Solvent-Based Capture from Coal

Post-combustion capture from coal (Figure 1) is the most mature of the CC technologies. It is also the easiest to retrofit to an existing plant (5). It can be retrofitted into current power plant systems without much modification to the original plant as it can be appended to the flue gas system following environmental controls such as NO_x and SO_2 removal. CO_2 reduction is significant, but the overall plant efficiency is reduced due to the additional fossil-fuel consumption. More cooling is required to meet increased energy requirements than plants without carbon capture, thus increasing over all water usage.

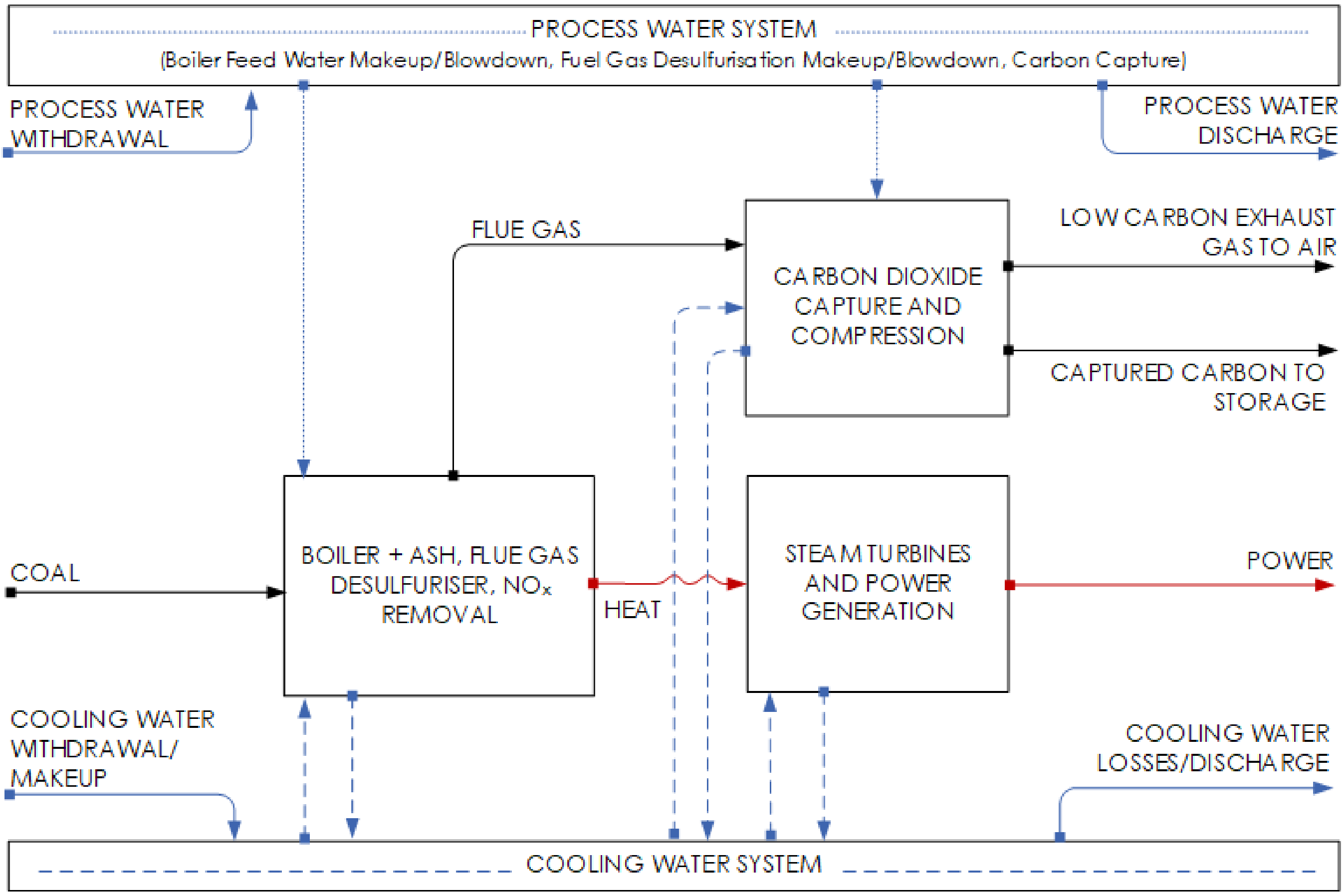

Figure 1. Post combustion schematic for coal-fired plants

Coal is combusted with air in the furnace at high temperature to produce steam at high pressure and high temperature, which produces power via the steam turbine and generator. The flue gas exhaust leaving the furnace generally goes through ash, NOx and sulphur removal. For solvent based CC technologies, gas is sent to an absorber where it comes into contact with the solvent and CO_2 is removed/captured from the gas. The captured CO_2 is then compressed, for transport and storage. The balance of the now low-carbon flue gases are vented to the atmosphere.

2.2 Post-Combustion Solvent-Based Capture from Natural Gas

Based on the example in Adams *et al*. (7), the natural gas combined cycle is an example of post combustion solvent-based capture from natural gas (Figure 2). Both a gas combustion turbine and steam turbine are used to generate power.

A generator converts the mechanical power from the combustion turbine (in which natural gas is combusted with compressed air) to electric power. Additional electric power is created by the steam turbines using steam created by the heat exchange of the high temperature combustion exhaust. CO_2 removal occurs in the absorber column that utilises a solvent to scrub CO_2 from the cooled combustion gas. The rich solvent is regenerated in a stripper column where the lean solvent is recovered, and CO_2 distillate is then compressed for transport.

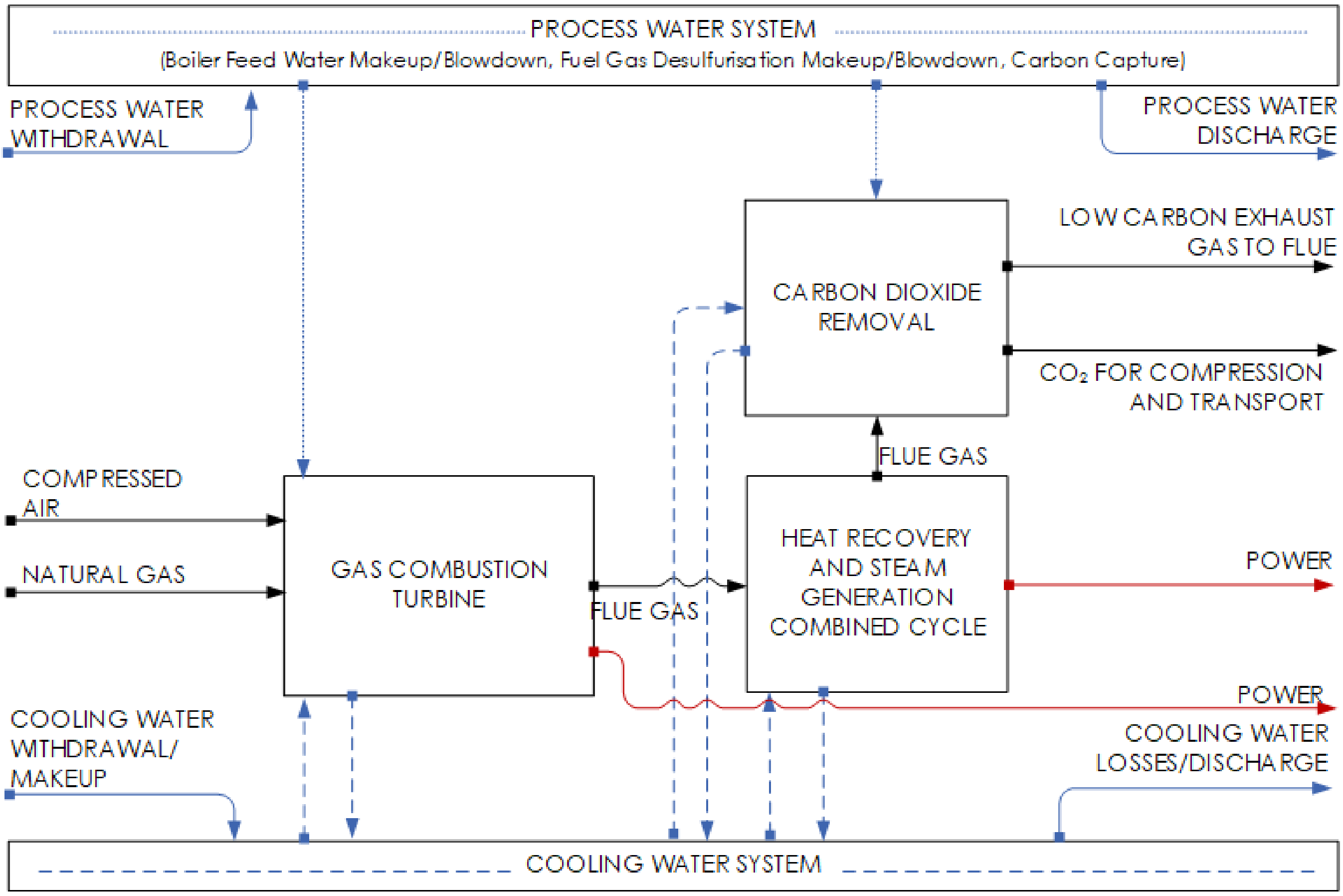

Figure 2. Post combustion capture in natural gas power generation plants

2.3 Pre-Combustion Solvent-Based Capture from Coal

Pre-combustion (Figure 3) is used in coal- gasification power plants and involves the pretreatment of the fuel prior to combustion. In the case of coal, coal is partially combusted in a gasifier in an oxygen-lean environment creating syngas. The syngas goes through the water shift gas shift reaction and series of absorbers to remove H_2S and CO_2 separately. The CO_2 is then compressed, transported, and stored. The sequencing of gasification together with the water gas shift reaction (IGCC) results in a high-energy stream predominantly of H_2 and CO_2 where all the coal ends up as CO_2. Hydrogen is then combusted in gas turbine to produce power. Despite the higher CO_2 capture efficiencies due to the higher pressures and concentrated CO_2 stream, the cost associated with gasification make pre-combustion costly. From a water perspective, and as will be seen in this work, pre-combustion technology uses less water than solvent-based post-combustion for about the same CO_2 emissions, but more than all other technologies investigated in this work.

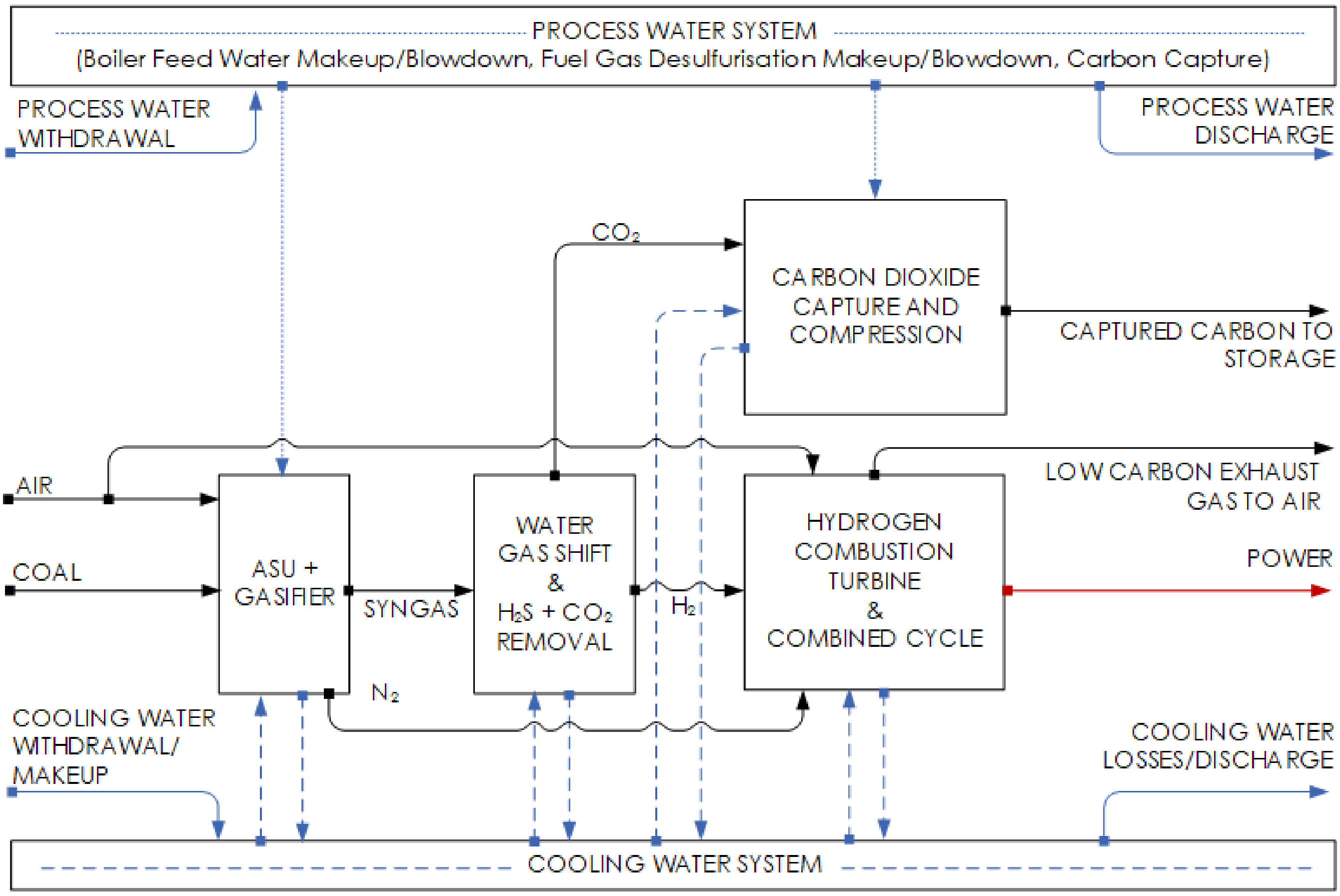

Figure 3. Precombustion capture in coal-fired plants (IGCC)

2.4 Oxy-Fuel Combustion with Post-Combustion Capture from Coal

In oxy-fuel combustion (Figure 4), fuels, typically coal or natural gas, are combusted in a N_2 lean environment. An air separation unit is used to separate O_2 from air, in which the fuel is combusted resulting in flue gasses with high CO_2 and water content (6). The exhaust of the heat recovery and steam generation unit typically contains H_2O and CO_2, which goes through a series of condensers and flash drums that separate the CO_2 and H_2O. Oxy-fuel combustion systems are less mature than post- and pre-combustion options.

2.5 Solid Oxide Fuel Cells with Post- Oxidation Capture from Coal and Gas

Solid oxide fuel cell systems operate similarly to oxy-fuel post- combustion systems. Air is fed directly into the cathode of the SOFC, therefore an air separation unit is not needed. The oxygen in the air migrates to the anode and reacts directly with the fuel. This means that the fuel cell achieves both power generation and air separation. The separation strategy is also similar to that of post-combustion oxyfuels, where unspent fuel is catalytically oxidized, and then water is condensed out of the resulting gas stream, leaving a stream containing high purity CO_2. The CO_2 is compressed for transport and storage. This process means that water recovery is possible and a natural and necessary complementary outcome of the CO_2 capture process. Fuel cell technology in CC is expensive and commercially challenging due to low cell lifetime and manufacturing, however, the low water usage and GHG emissions make it a technology worth exploring.

For detailed reviews on each technology see Adams *et al.* (7).

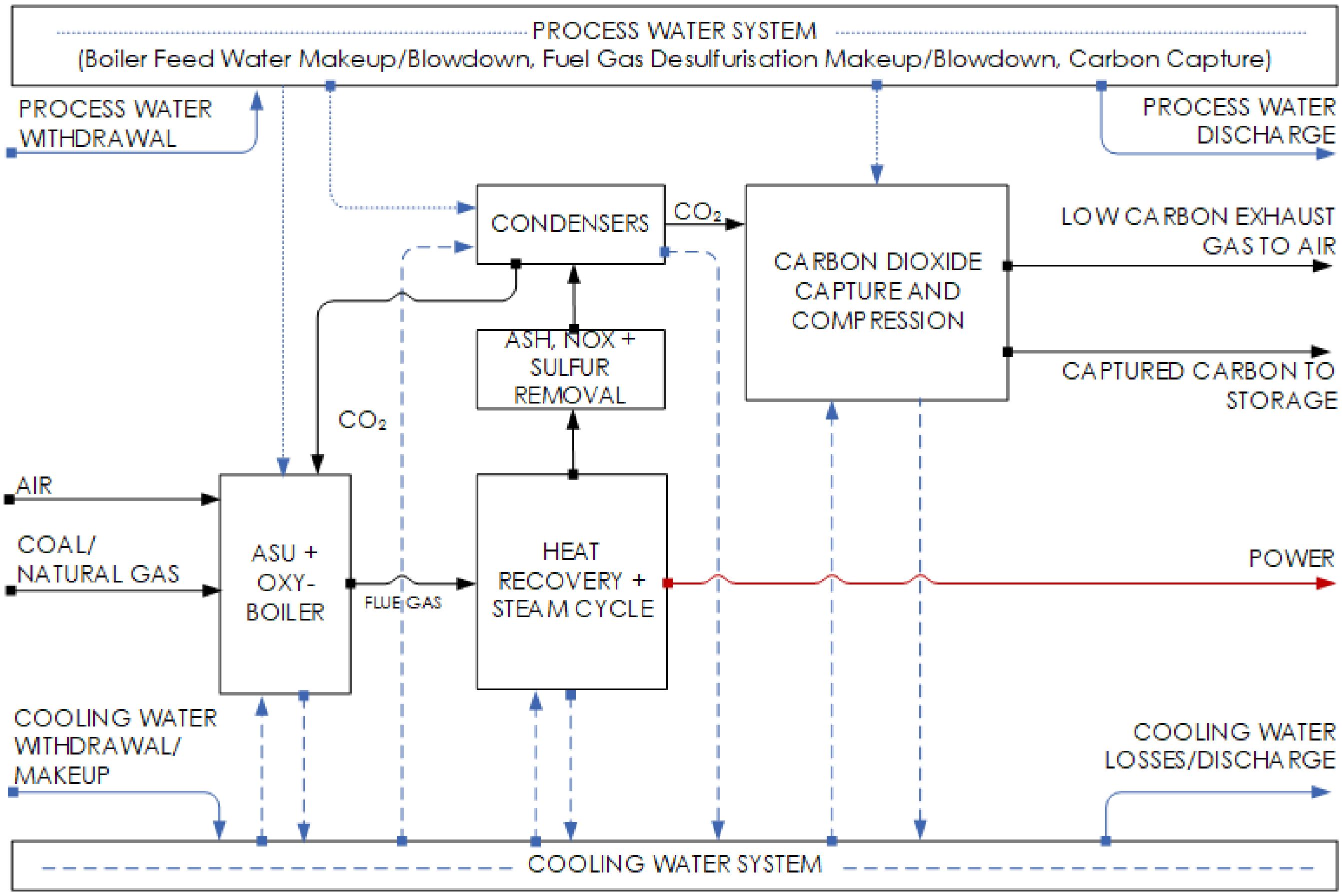

Figure 4. Oxy-fuel combustion schematic for coal- or natural gas -fired plants

3. Research Method

We compare different carbon mitigation technologies using the data set from Adams *et al*. (7). This data set contains a quantitative summary of over 100 proposed coal and natural gas power plants with CC technologies in the literature. The record for each power plant includes information such as efficiency, heat rate, fuel costs, non-fuel costs, and the cradle-to-plant-exit life cycle GHG emissions. The data set was normalized to have consistent supply chains, plant sizes, and boundaries of analyses, such that results taken from across the literature could be compared to each other on a consistent and fair basis. The data set was chosen due to its completeness, wide coverage of CC technologies and the effective consolidation of data by creating a consistent basis of metrics for comparison. However, the data set contained no information related to water consumption and therefore water information had to be determined in this work.

Not all technologies in that data set could be used in our work because relevant water data for the cited works could not be determined from the published information available nor could they be estimated (through methods described later) due to insufficient data. Therefore, our final dataset used in this work includes a subset of 65 data points, covering coal and natural gas power generation plants, with the data being predominantly focussed on coal. The dataset for coal-based CC technologies used in this work includes supercritical pulverised coal (SCPC), integrated gasification combined cycle (IGCC), coal- based oxy-fuel combustion (COXY) and integrated gasification solid oxide fuel cell (IGFC). For natural gas the dataset consists of natural gas combined cycle (NGCC) and natural gas solid oxide fuel cell (NGFC). These technologies are referred to as the green cases. Four categories of data are necessary to compute the WICa metric: (i) CO_2 emissions (avoided) over the cradle-to-plant-exit life cycle for CC technologies; (ii)

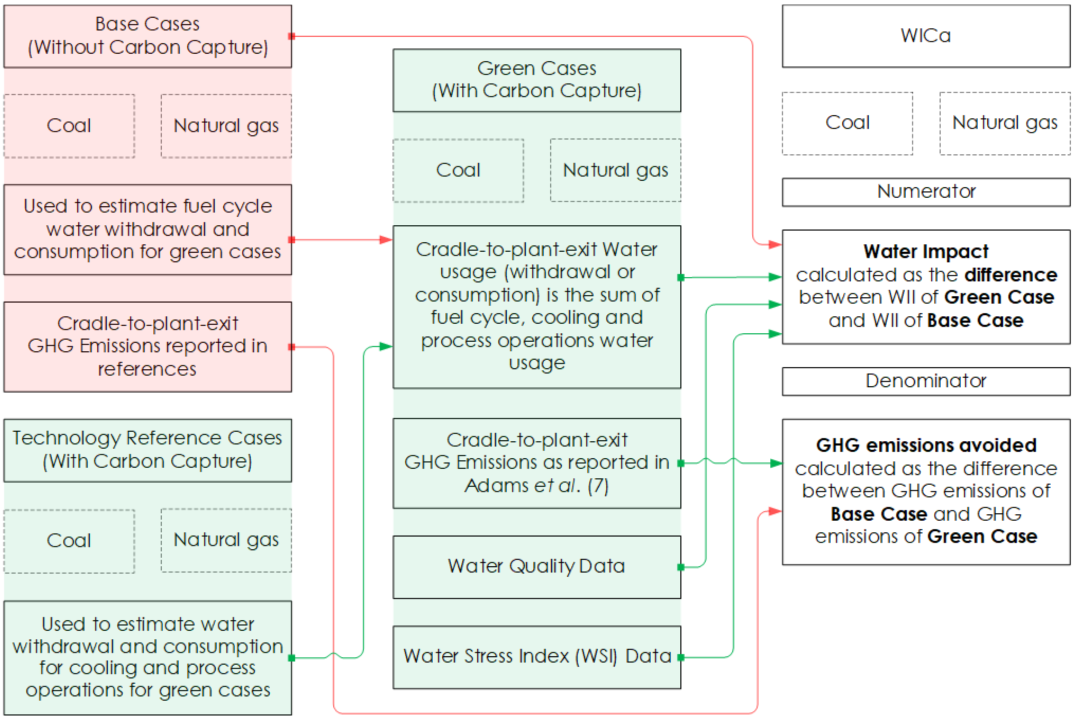

Figure 5. Method for assumptions and calculation of WICa metric

water data necessary to assess the WII which must include water withdrawal, water consumption and water returned (generally calculated by difference) for each stage of the cradle-to-plant-exit life cycle for the CC technologies; (iii) the water qualities; and (iv) regional WSI data.

The methodology used in this work is summarized in Figure 5. First, base cases are selected, one for coal and one for natural gas. These are used as “business as usual” cases. For each of the 65 “green” cases used in this study, the CO_2 emissions avoided are calculated by comparing the base case to the green case. When the information necessary to compute water metrics are not available for the green cases, estimates are computed where necessary. To help with these estimates, we have selected technology reference cases (with carbon capture) which are detailed studies of a single relevant power plant that contains sufficient information about water use in the process. We use that detailed water information to help generate estimates for other green cases where water information is missing, for example, by assuming that water consumption per unit cooling in the green case is the same as in the technology reference case. The details are explained in the following subsections.

Table 2: Base cases for coal and natural gas fuel type

Property/units	Supercritical Pulverised Coal (SCPC)	Natural Gas Combined Cycle (NGCC)
Fuel type	Bituminous Coal	Conventional Pipeline Natural gas
Net Plant power output (MWe)	650	727
Heat rate (MJ_{HHV}/MWh)	8957	6714
Water withdrawal		
Cooling operations (m^3/MWh)	1.938	0.905
Process operations (m^3/MWh)	0.185	0.002
Water Consumption		
Cooling operations (m^3/MWh)	1.477	0.701
Process operations(m^3/MWh)	0.185	0.002
Cradle-to-plant-exit CO_2 emissions (tCO_2e/MWh)	0.950	0.406
Type of cooling	Mechanical Draft, Evaporative cooling tower	Mechanical Draft, Evaporative cooling tower
Reference	Schmitt *et al.* (35)	

Table 3: Literature fuel cycle water usage data (median values) from Meldrum *et al.* (2). ^{b}This value is the ^{a}water use per MWh divided by the heat rate (MJ_{HHV}/MWh from Table 2) which is used in the estimation of the fuel cycle water usage of the green cases described in Section 3.2.1.

Fuel	Subcategory	Water withdrawn		Water consumed	
		$^a m^3$/MWh	$^b m^3/MJ_{HHV}$	$^a m^3$/MWh	$^b m^3/MJ_{HHV}$
Coal (SCPC)	Underground mining	0.216	2.14×10^{-5}	0.212	2.37×10^{-5}
Natural gas (NGCC)	Shale Gas	0.064	9.53×10^{-6}	0.061	9.09×10^{-6}

Table 4:Technology reference cases used to estimate the water use in the cooling operations and process operations where published data are unavailable.

	Coal Cases				**Natural Gas Cases**	
Property/units	Supercritical Pulverised Coal (SCPC)	Integrated gasification Combined Cycle (IGCC)	Coal based oxy-fuel combustion (COXY)	Integrated gasification solid oxide fuel cell (IGFC)	Natural Gas Combined Cycle (NGCC)	Natural Gas solid oxide fuel cell (NGFC)
Classification of process/primary CO$_2$ capture	Bituminous Coal/ Solvent Based – EconFG+	Solvent Based-Selexol	Oxy-fuel	Atmospheric pressure	Solvent Based - Econamine FG+	Atmospheric pressure
Net Plant power output (MWe)	550	497	550	550	559	650
Heat rate (MJ$_{HHV}$/MWh)	11077	11538	11613	9105	7877	6220
Water withdrawal						
Cooling operations (m^3/MJ$_{HHV}$)	2.50 x10^{-4}	1.74 x10^{-4}	1.52 x10^{-4}	7.43 x10^{-5}	2.06 x10^{-4}	1.13 x10^{-4}
Process operations (m^3/MJ$_{HHV}$)	4.36x10^{-5}	5.00 x10^{-5}	1.24 x10^{-5}	1.32 x10^{-5}	1.64 x10^{-6}	8.90 x10^{-6}
Water Consumption						
Cooling operations (m^3/MJ$_{HHV}$)	1.83x10^{-4}	1.34 x10^{-4}	1.09 x10^{-4}	4.55 x10^{-5}	1.54 x10^{-4}	7.72 x10^{-5}
Process operations (m^3/MJ$_{HHV}$)	4.28x10^{-5}	4.97 x10^{-5}	1.24 x10^{-5}	1.20 x10^{-5}	1.64 x10^{-6}	8.90 x10^{-6}
Total Cradle-to-plant-exit GHG emissions (tCO$_2$e/MWh)	0.286	0.251	0.197	0.088	0.115	0.064
Type of cooling	Mechanical Draft, Evaporative Cooling Tower	Mechanical Draft, Evaporative Cooling Tower	Mechanical draft, counter-flow cooling tower	Recirculating Wet Cooling Tower	Mechanical Draft, Evaporative Cooling Tower	Mechanical draft, wet cooling tower
Reference	Fout *et al.* (44) – Case B12B	Fout *et al.* (45) - Case B1B	Haslbeck *et al*. (38) - Case: S12F	Iyengar *et al.* (46) - Case 1-1	Fout *et al.* (44) – Case B31B	Iyengar *et al.* (47) -Case ANGFC0B

Table 5: Water Scarcity Indices for selected countries. [a]WTA values are obtained from Luo *et al.* (36)and are used to calculate WTA*. [b]WTA* as defined in Pfister *et al.* (13) are used to calculate WSI values used in this work. [c]Defined in Luo *et al.* (36), this ranks countries according to their water stress.

Rank[d]	**Country**	**WTA**[a]	**WTA***[b]	**WSI**[b] (used in this work)
1	Unite Arab Emirates	1	1.80	0.999
31	India	0.740	1.33	0.981
46	China	0.637	1.15	0.940
50	South Africa	0.595	1.07	0.906
58	Philippines	0.527	0.95	0.813
76	Poland	0.367	0.661	0.490
87	Finland	0.291	0.523	0.224
96	Canada	0.207	0.37	0.099
115	Norway	0.103	0.19	0.032

3.1 Water stages

The overall water use for each technology case can be categorized into three contributing “water stages” which cover the cradle-to-plant-exit life cycle, as summarized in Figure 6. The first stage is the fuel cycle. Meldrum *et al*. (2) define the fuel cycle activities as fuel extraction, processing and transportation which aligns with the fuel cycle activities defined in Adams *et al*. (7). Cooling operations are cooling services typically provided by cooling towers, such that the water involved is isolated from the process and does not mix with other material streams in the process. Process operations considers any other water stream that is not involved in cooling. For example, this includes water that is a reagent for chemical reactions such as water gas shift or gasification, water recovered from a flue gas that was produced by combustion, and makeup water for losses in steam cycles and absorption cycles.

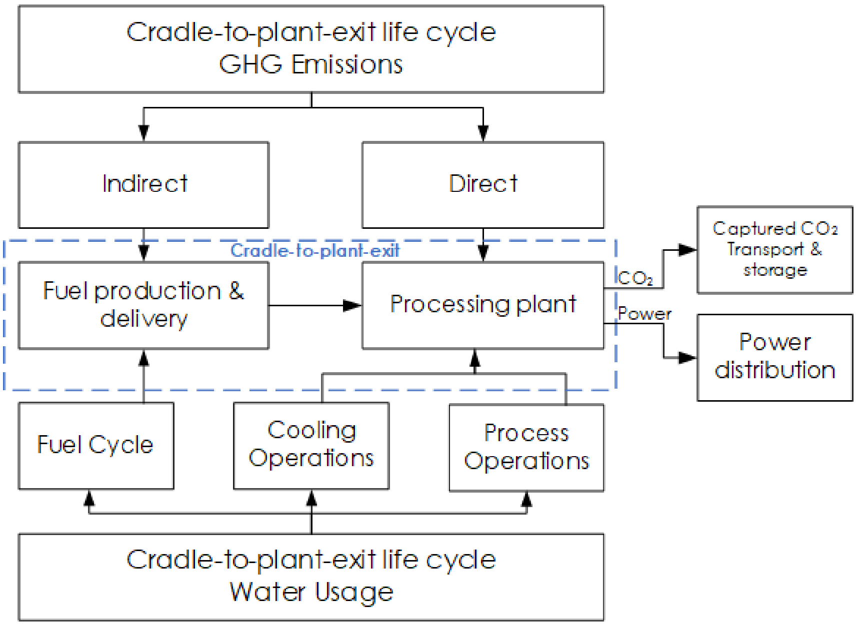

Figure 6. Cradle-to-plant-exit life cycle water stages corresponding to GHG emissions.

3.2 Base cases

Two base cases(35) (power generation plants without CC) are chosen based on water data availability and serves as the primary reference condition when calculating WICa, one for coal and one for natural gas. The coal base case is a supercritical pulverized coal (SCPC) power plant without CC. The natural gas base case is a natural gas combined cycle (NGCC) power plant. It is important to choose a base case that is representative of the “status quo” or “business-as-usual” at the appropriate scale of the study (on the order of 600-750 MW net power output). There must also be sufficiently detailed information about each base case, including mass and energy flows of the process containing all

Table 6: Water quality scenarios used in the sensitivity analysis.

Scenario	Water quality of withdrawn water	Water quality of returned water	Scenario Commentary
1	1	0.01	This scenario describes high quality withdrawal and poor-quality return. It is unlikely that water return would be this low, however we use this as the worse case scenario in this work.
2	0.02	0.02	In these scenarios water qualities are the same and range from low to high values. This means that the concentration of the major pollutant (Cp) ranges from 50 to 0 times more than the reference concentration of the major pollutant in both the withdrawn and returned water.
3	0.5	0.5	
4	0.6	0.6	
5	1	1	
6	0.01	1	This scenario presents the “best case”, creating an overall benefit for the water for the next user—withdraw poor quality water and return high-quality water. It is however unrealistic in the case on power generation. It is an unlikely scenario and is therefore not investigated.

water aspects. The base cases selected in this work are different than those chosen in Adams *et al.* (7) because we chose to use more recently published information, and because the chosen work had detailed water information. The choice of bases case will of course affect the WICa value, and choosing different cases would result in slightly different WICa values. However, since all 65 green cases are compared to the same base cases, very useful conclusions can be made by their direct comparison to each other. Relevant water and emissions data for the base cases are shown in Table 2.

3.2.1 Estimating fuel cycle water withdrawal and consumption

To estimate the water usage of the fuel cycle we first use the heat rate of the base cases (Table 2) and the literature fuel cycle water estimations from Meldrum *et al.* (2) (Table 3) to create a generalised base line. This value is in the form of m^3 water/MJ_{HHV} also presented in Table 3. The fuel cycle water usage of each of the 65 green cases is then calculated by multiplying the heat rate of the green case to this generalised baseline (Equation (4)) and is reported in m^3 water /MWh. Meldrum *et al.* (2) based water estimations for coal underground mining on US mining data and associated activities as described above. For natural gas we used their shale gas estimations which includes drilling, fracturing, processing and transport. We used these conservative estimates opposed to their reported values for conventional natural gas and surface mining. We assumed that the water requirements for the fuel cycle are comparable within each fuel type for the green cases, due to similar activities within the cycle.

$$\text{Fuel\_Cycle\_Water\_Usage}_{\text{Green Case}} = \text{Heat Rate}_{\text{Green Case}} \times \left(\frac{\text{Fuel Cycle Water Estimations}_{\text{Literature}}}{\text{Heat Rate}_{\text{Base case}}}\right)_{\text{Generalised baseline}} \qquad (4)$$

3.2.2 Calculating carbon dioxide emissions avoided

In this work, total cradle-to-plant-exit CO_2 process emissions are the sum of the direct (from the plant itself, including the cooling system) and indirect (from the production and delivery of fuel) emissions (Figure 6). The GWP used to compute the CO_2 emissions avoided and thus the WICa metric, is computed using IPCCs 100-year time horizon and is reported as CO_2 equivalents (CO_2e).

3.3 Technology reference cases

Technology reference cases are chosen to help estimate the water data for any of the 651 green cases where that information is lacking in the literature for that specific green case. This includes information for the cooling and process operations stages of the cradle-to-plant-exit lifecycle. One technology reference case is selected for each type of technology and used to fill in the gaps of missing information in the green cases where needed (Table 4). Details of these cases follow.

3.3.1 Estimating water withdrawal and consumption for cooling and process operations

The water usage estimations for cooling and process operations are calculated similarly to the fuel cycle water usage estimations (discussed in *3.2.1*). We use the heat rate of the technology reference case (TRC) with the reported water data in the literature (*Table 4*) to create a generalised baseline for each withdrawal and consumption for cooling and process operations. The heat rate of the green case is then multiplied by this baseline to estimate the water usage (for each water use and operations). The technology reference cases are chosen based on the availability of water data in the literature. The water data must include withdrawal and consumption for both the cooling and process operations to be used. The resultant baseline values are shown in Table 4 for coal and natural gas in m^3/MJ_{HHV}.

$$\text{Operations\_Water\_Usage}_{\text{Green Case}} = \text{Heat Rate}_{\text{Green Case}} \times \left(\frac{\text{Operations\_Water\_Usage}_{\text{TRC}}}{\text{Heat Rate}_{\text{TRC}}}\right) \tag{5}$$

3.3.2 Variations in Plant Location

The WICa metric considers both water quality and the WSI, which vary from location to location. Therefore, the specific location of each of power plant and its context within the regional or national water supply affect the WICa on a case-by-case basis. We consider water quality and WSI as variables subject to sensitivity analysis.

Water quality data is challenging to source in literature and varies from location to location and implementation to implementation. Site-specific factors include the definitions of what constitutes a pollutant p, its corresponding safe limits $c_{ref,p}$, and the quality of the local water supply from which water is withdrawn. The purpose of this work is to compare the 65 different green cases generally. Therefore, we take water quality as a sensitivity parameter in the form of quality scenarios. The worst-case scenario would be to take high quality water and return poor quality water. The best-case scenario would be to take poor quality water and return high quality water – this is an unrealistic scenario. A likely, best-case scenario would be to return the same quality water as withdrawn. The quality scenarios used are shown in Table 6.

Table 5 shows the water stress data for selected representative countries used in this work. It is assumed that the water bodies for withdrawal and return are located in the same region and thus have the same WSI (calculated per country). The most recent WTA data are available from Luo *et al.*(36) as part of the WRI's Aqueduct water stress projections and is described further in Luck *et al.* (37). These values were calculated based on contributions form 3 sectors: industry, domestic and agriculture. They presented three scenarios: business as usual, optimistic, and pessimistic. We have used the business-as-usual projections for 2020 in Table 5.

The variation factor of 1.8 was used to determine the WTA* for non-strongly regulated flows as described in Pfister *et al.* (13) . This accounts for water stress that may be experienced due to precipitation variability. The resulting WSI values are computed using equation (1) from the electronic supplementary information and presented in Table 5. We note that for studies that have location-specific information and considerations, a WSI specific to that location should be used instead of these general country-level statistics.

Table 7: Water and GHG emissions data for carbon-capture technologies in coal-fired plants. [a]From Adams et al. (7)

Tag	Green Technology/Process	[a]Net Plant output	[a]Electrical Efficiency	[a]Heat Rate	[a]CO_2 Removed	[a]Cradle-To-Plant-Exit GWP	CO_2 avoided	Water withdrawal	Water consumption	Net Water Discharge
(Units)		MWe	%HHV	MJ_{HHV}/MWh	%	tCO_2e/MWh	tCO_2e/MWh	m^3/MWh	m^3/MWh	m^3/MWh
SCPC-2	Solvent Based	525	27.4	13139	90	0.327	0.623	4.18	3.29	0.89
SCPC-3	Solvent Based - Adv.amine	837	36.1	9972	90	0.275	0.675	3.17	2.5	0.68
SCPC-4	Solvent Based - Cansolv	822	33.8	10651	90	0.279	0.672	3.39	2.66	0.73
SCPC-5	Solvent Based - Amine	546	27.2	13235	90	0.323	0.627	4.21	3.31	0.9
SCPC-6	Solvent Based - Adv.Amine	616	36.5	9863	90	0.271	0.679	3.14	2.47	0.67
SCPC-7	Solvent based-Chilled Ammonia	548.7	28.4	12676	90	0.314	0.637	4.03	3.17	0.86
SCPC-8	Solvent based-Chilled Ammonia	549.3	31.5	11429	90	0.292	0.658	3.64	2.86	0.78
SCPC-9	Solvent based-Chilled Ammonia	558.7	27.9	12903	90	0.325	0.625	4.11	3.23	0.88
SCPC-10	Solvent based-Chilled Ammonia	614	36.6	9836	88.4	0.276	0.674	3.13	2.46	0.67
SCPC-11	Solvent Based-Amine	519	25.6	14063	94	0.291	0.659	4.48	3.52	0.96
IGCC-1	Solvent Based-Selexol	543	32.6	11043	90	0.241	0.709	2.74	2.29	0.45
IGCC-2	Solvent Based-Selexol	513	31	11613	90	0.251	0.699	2.88	2.41	0.48
IGCC-4	Data not available	500	29.9	12040	86	0.307	0.644	2.99	2.5	0.49
IGCC-5	Solvent Based-Selexol NS	694	32	11250	90	0.241	0.71	2.79	2.33	0.46
IGCC-6	Solvent Based - Shift + Selexol	455	35.1	10256	94	0.197	0.753	2.55	2.13	0.42
COXY-1	Oxy-fuel	376.1	34.3	10493	91	0.16	0.79	1.98	1.52	0.46
COXY-2	Oxy-fuel	352.9	32.2	11180	90	0.178	0.772	2.11	1.62	0.49
COXY-3	Oxy-fuel	670.3	34.7	10369	94	0.136	0.814	1.96	1.5	0.45
COXY-4	Oxy-fuel with 10% air added	669.3	34.7	10384	94	0.137	0.814	1.96	1.51	0.45
COXY-5	Oxy-fuel with 20% air added	666.2	34.5	10432	94	0.137	0.813	1.97	1.51	0.46
COXY-6	Oxy-fuel with 30% air added	661.2	34.3	10511	94	0.138	0.812	1.98	1.52	0.46
COXY-7	Oxy-fuel with 40% air added	654.1	33.9	10626	94	0.14	0.811	2.01	1.54	0.46
COXY-8	Oxy-fuel with 50% air added	645.1	33.4	10775	94	0.142	0.809	2.03	1.56	0.47
COXY-9	Oxy-fuel	238.5	32.3	11149	90	0.231	0.719	2.11	1.62	0.49
COXY-10	Oxy-fuel	533.2	32.7	10996	93	0.147	0.804	2.08	1.6	0.48
COXY-11	Oxy-fuel w/ compres, dehydration	310	33.8	10648	100	0.091	0.859	2.01	1.54	0.47
COXY-12	Oxy-fuel w/ double flash purification	270.6	29.5	12199	92	0.189	0.762	2.3	1.77	0.53
COXY-13	Oxy-fuel w/ distillation purification	265.8	29	12418	90	0.214	0.737	2.34	1.8	0.54
COXY-14	Oxy-fuel	574	36.6	9836	90	0.203	0.747	1.86	1.43	0.43
COXY-16	Oxy-fuel (Case: S22F)	549	30.1	11960	90.9	0.201	0.749	1.81	1.29	0.52
COXY-17	Oxy-fuel (USC-subbituminous)	509	31.5	11429	90	0.203	0.748	2.16	1.66	0.5
COXY-18	Oxy-fuel (SCPC-bituminous)	501	31	11613	98	0.12	0.83	2.19	1.68	0.51
COXY-19	Oxy-fuel (SCPC-bituminous)	510	31.5	11429	90	0.203	0.748	2.16	1.66	0.5
COXY-20	Oxy-fuel (USC-subbituminous)	833	34.1	10557	90	0.182	0.768	1.99	1.53	0.46
COXY-21	Oxy-combustion Supercrit.	550	29.3	12287	99.5	0.105	0.845	2.32	1.78	0.54
COXY-22	Oxy-combustion Supercrit.	555.1	29.5	12203	99.4	0.104	0.846	2.3	1.77	0.53
COXY-23	Oxy-combustion Supercrit.	549	29.3	12287	96.9	0.132	0.819	2.32	1.78	0.54
COXY-24	Oxy-combustion Supercrit.	548.7	29.2	12329	85.5	0.182	0.769	2.33	1.79	0.54
COXY-25	Oxy-combustion Ultra-supercrit.	550	33	10909	99.4	0.093	0.857	2.06	1.58	0.48
COXY-26	Oxy-combustion Ultra-supercrit.	545.3	32.7	11009	93.2	0.154	0.796	2.08	1.6	0.48
IGFC-1	Minimized CO content in SOFC feed	719	42	8571	100	0.073	0.877	0.96	0.7	0.26
IGFC-2	IGFC-1 w/ seasonal shutdowns	719	42	8571	100	0.073	0.877	0.96	0.7	0.26
IGFC-3	IGFC-1 w/ integrated energy storage	719	41.5	8675	100	0.074	0.876	0.97	0.71	0.26
IGFC-4	IGFC-2 w/ integrated energy storage	719	40.6	8867	100	0.076	0.875	0.99	0.72	0.27
IGFC-5	Cyngas directly in SOFC	719	38.4	9375	100	0.08	0.87	1.05	0.76	0.29
IGFC-6	IGFC-5 w/ seasonal shutdowns	719	38.4	9373	100	0.08	0.87	1.05	0.76	0.28
IGFC-7	IGFC-5 w/ integrated energy storage	719	38	9474	100	0.081	0.869	1.06	0.77	0.29
IGFC-8	IGFC-5 w/ integrated energy storage	719	37.4	9626	100	0.082	0.868	1.08	0.78	0.29
IGFC-9	Atm-Pressure IGFC Plant	253	49.4	7287	99	0.064	0.887	0.82	0.59	0.22
IGFC-10	Pressurized IGFC	253	56.2	6406	99	0.056	0.894	0.72	0.52	0.19
IGFC-11	Part. methane Syngas IGFC (TREMP)	846.6	44.4	8115	99	0.072	0.878	0.91	0.66	0.25
IGFC-12	Part. Methane Syngas IGFC (HICOM)	925	48.5	7425	99	0.07	0.881	0.83	0.61	0.23
IGFC-13	IGFC-DIRECT	865	45.3	7943	99	0.075	0.876	0.89	0.65	0.24
IGFC-14	Liquid-tin anode SOFC	93.9	57.2	6294	100	0.054	0.897	0.7	0.51	0.19

4. Results and Discussion

4.1 Calculated water flows

The raw data used in this study (performance and emissions data), including the results of the water withdrawal, consumption, and discharge calculations, is presented for coal and natural gas in Tables 7 and 8 respectively. These numbers apply to all 65 green cases generally, regardless of where the plant is located. (7)

Figure 7 shows the overall water withdrawal, consumption and process water discharge for all the coal-based CC technologies. The first data bar is the coal base case (SCPC w/o CC). The consumption and process water discharge portions are normalized to withdrawal such that their sum is equivalent to the withdrawal.

SCPC and IGCC technologies with CC have worse water withdrawal than the high CO_2-emitting base case, illustrating the tradeoff between water impacts and CO_2 emissions avoidance. However, the less mature oxyfuel combustion and SOFC technologies have lower water impacts than even the base case, because as a necessary part of the CO_2 capture process, they capture water that would be otherwise emitted in the flue gas. Since this water can be recycled or discharged, it is a positive synergistic benefit on the water cycle. The IGFC technology is superior in terms of water withdrawal for the cradle-to-plant-exit life cycle as compared to all other technologies presented.

Water data for the COXY-16 technology case is obtained from Haslbeck *et al*. (38) and not calculated as described above. All relevant water data is available in the report. We observed that reported water consumed is the same as the reported water withdrawn, implying a zero process water discharge. Nothing about the process suggests the possibility of this outcome and we reason this to be an error in the text. We therefore recalculated the water

Table 8: Water and GHG emissions data for carbon-capture technologies in gas-fired plants. ^{a}From Adams et al. (7)

Tag	**Green Technology/Process**	**^{a}Net Plant output**	**^{a}Electrical Efficiency**	**^{a}Heat Rate**	**$^{a}CO_2$ Removed**	**^{a}Cradle-To-Plant Exit GWP**	**CO_2 avoided**	**Water withdrawal**	**Water consumption**	**Net Water Discharge**
(Units)		MWe	%HHV	MJ_{HHV}/MWh	%	tCO_2e/MWh	tCO_2e/MWh	m^3/MWh	m^3/MWh	m^3/MWh
NGCC-2	Solvent Based - MEA	789.0	46	7809	90%	0.115	0.291	1.69	1.29	0.41
NGCC-3	Solvent Based - Advanced Amine	804.0	47	7660	90%	0.113	0.293	1.66	1.26	0.40
NGCC-4	Solvent Based - Econamine FG+	448.9	43	8451	90%	0.123	0.283	1.83	1.39	0.44
NGCC-5	Solvent Based - Amine	485.0	42	8491	90%	0.122	0.284	1.84	1.40	0.44
NGCC-6	Solvent Based - Amine	389.0	41	8824	94%	0.110	0.296	1.91	1.45	0.46
NGFC-1	SOFC base case	693.0	74	4865	100	0.044	0.362	0.59	0.42	0.18
NGFC-6	Low pressure ATR, 6 parallel SOFC sections. (BASELINE CASE1-1)	550.0	56	6394		0.059	0.347	0.67	0.4485	0.22
NGFC-7	Low pressure ATR, 8 parallel SOFC sections. Smaller ASU (CASE 1-7)	550.0	62	5825		0.053	0.353	0.61	0.41	0.20
NGFC-8	High pressure ATR (CASE 2-1)	550.0	65	5556		0.055	0.351	0.70	0.55	0.15
NGFC-9	High pressure ATR. Smaller ASU (CASE 2-3)	550.0	65	5556		0.055	0.351	0.48	0.31	0.16
NGFC-10	No ATR (CASE 3-1)	550.0	66	5463		0.050	0.356	0.52	0.35	0.17

consumption based on withdrawal and process water discharge data provided in the report and the values are aligned with other oxy-fuel technology cases.

Figure 8 summarizes the results for natural gas. Like the coal case, the post-combustion capture processes had worse water impacts than the base case (without CC) but the SOFC based cases had reduced water impacts since water produced from natural gas oxidation could be captured and returned to the environment.

Figure 9 illustrates the technologies investigated in this work with regard to their total water consumption and their total greenhouse gas emissions. Two key observations from this figure are noteworthy: (1) there are distinct clusters between the different technologies and fuel types; (2) water consumption and greenhouse gas emissions for CC technology for coal-based plants are higher than all natural gas technologies except for IGFC which has lower GHG emissions and water consumption than oxy-fuels, IGCC and solvent based post-combustion technologies (SCPC).

The base cases are also shown for coal and natural gas, creating ideal regions of water consumption and GHG emissions relative to the base cases. All technology cases have reduced total GHG emissions than both base cases as can be seen within the regions created by the vertical and horizontal lines drawn through the base case points. However, SCPC cases and IGCC cases have higher water consumption relative to the SCPC base case. Oxy-fuels and NGCC have lower water consumption than the SCPC base case but higher water consumption than the natural gas base case.

The natural gas based SOFC systems are the best in terms of water consumption and greenhouse gas emissions. Coal based SOFC systems are second in terms of water consumption and greenhouse gas emissions. This trend between NGFC and IGFC, was observed in Adams *et al*. (7) with regard to levelized cost of electricity (LCOE) and greenhouse gas emissions.

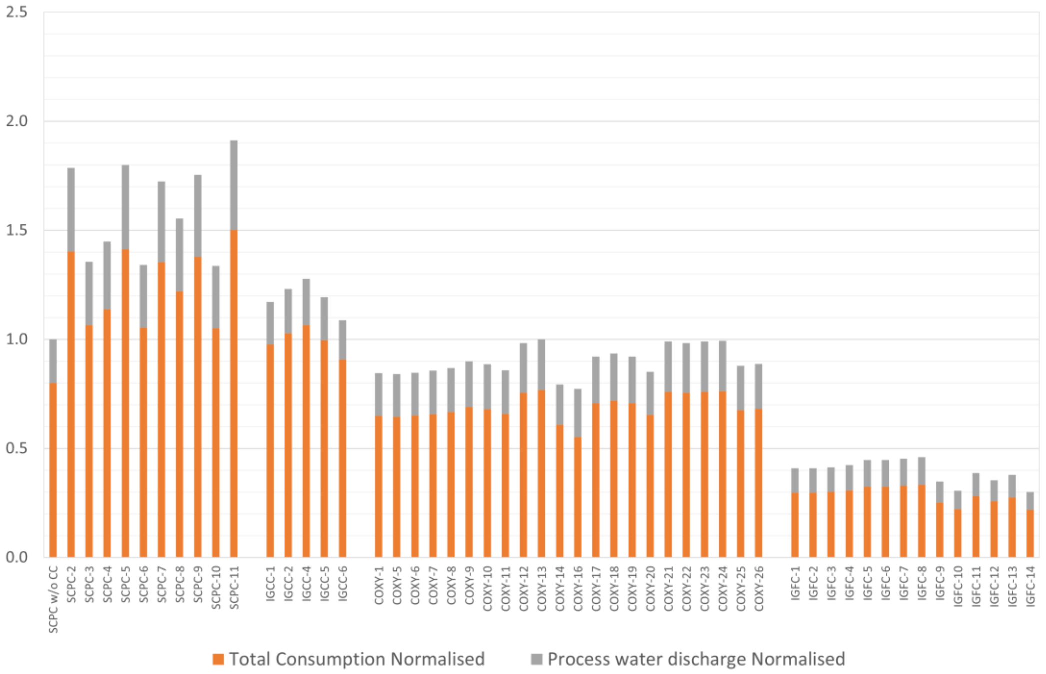

Figure 7: Overall water usage data for carbon capture technologies in coal-fired plants

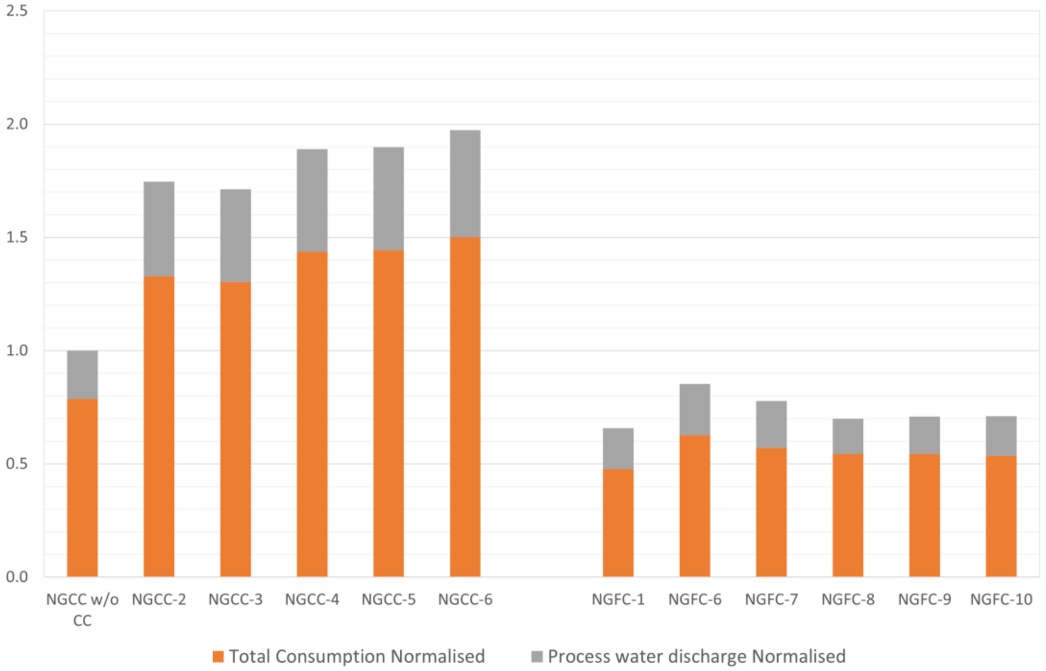

Figure 8: Overall water usage data for carbon capture technologies in gas-fired plants

This figure gives a good broad perspective on the water requirements of the different technologies, relative to their GHG emissions. However, some impacts of these technologies are unclear. What are the impacts to water quality and how does this compare to plants without CC? What are the impacts of consumption in locations with high and low water scarcity? These considerations enhance the decision-making process by creating holistic awareness around technology choices and are examined next.

4.2 Sensitivity analysis of WII to water quality (Q_{Wi} and Q_{Rj})

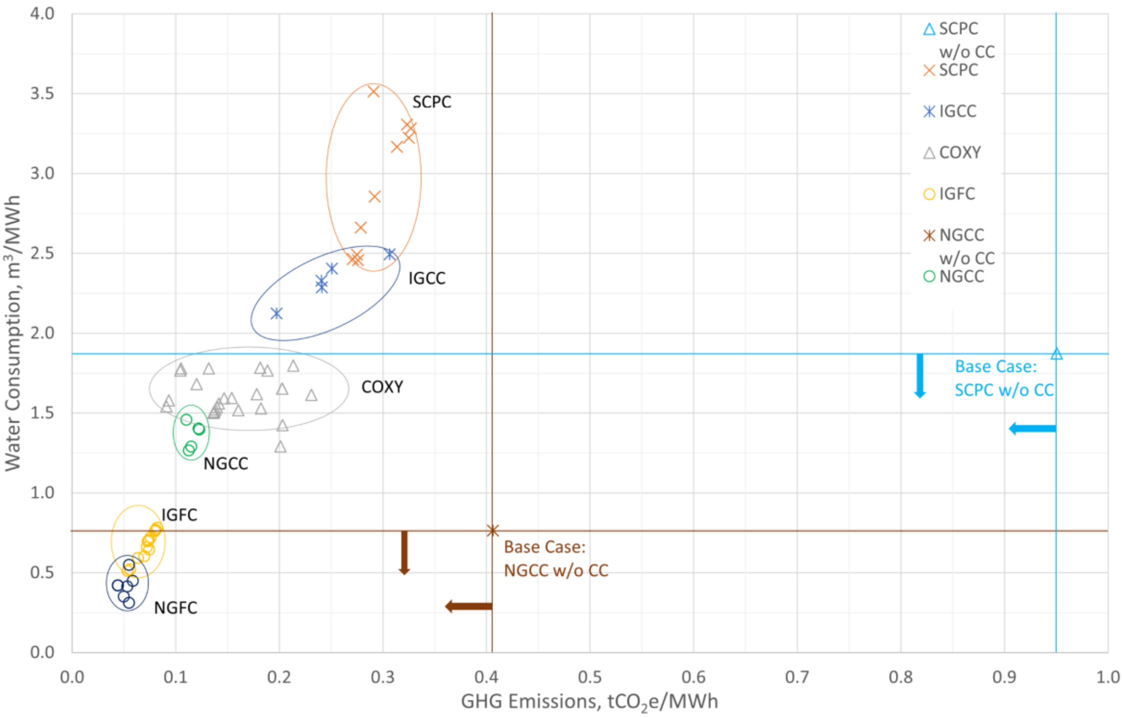

Figure 9: Water consumption vs GHG emissions of coal and natural gas fired carbon capture technologies.

To show the sensitivities to water quality in the withdrawn and returned water, we use WSI = 0.999 (reflecting the highest national water scarcity index in the world). The WII is then calculated for the different withdrawal and return qualities shown in Table 6 at this WSI and shown in Figure 10. For a WSI of approximately 1, the water withdrawal maps the worst-case scenario accurately. This means that water withdrawal can be used to approximate the WII when the water quality is very low. Water withdrawal is also the worst-case upper bound to the WII. When water quality is high (water withdrawn and returned are both equal to 1), the WII correlates to the total water consumption exactly. Thus, water consumption can be used to approximate WII in very high-quality situations, or to form a lower bound on WII. This creates a range of potential water impacts of technologies when data is unknown.

As the quality improves the WII increases (*i.e.* withdrawing higher quality water means less high quality water is available for other users). In the case of water quality = 0.02, the lower impact is misleading. Withdrawing poor quality water might reflect low impact however this water requires pre-treatment to either cooling or process water quality.

Our work assumes that all the cited processes work the same regardless of water quality. Therefore, the impact of that pre-treatment will not be reflected in the results and would ultimately increase the LCOE of the plant.

This raises an important point: the consideration of water quality and pre-treatment in the calculation of LCOE. In the previous study, no standardisation was performed on water quality and how that might affect pre-treatment costs. The water impact in an absolute sense differs greatly depending on the quality of water (see the next section) and the relative water scarcity. Treatment costs may also vary based on these factors. Although out of scope of this study, it should be considered in future work.

The WII results are presented in Figure 11 for different water quality values. The green case is normalised against the base case for the different metrics.

From Equation (3), substituting an equivalent and, for this purpose, arbitrary value of 0.5 for Q_{Wi} and Q_{Rj}, with a $WSI = 0.999$ for the green case the equation is now:

$$WII_{\text{Green Case}} = [(0.5)(0.990)(W_i - R_i)]_{\text{Green Case}} \tag{6}$$

To normalise this, we divide by the WII of the green case with the same water quality and WSI values of the base case. The normalised equation is:

$$WII_{\text{Normalised, same quality}} = \frac{\left[(0.5)(0.999)(W_i - R_j)\right]_{\text{Green Case}}}{\left[(0.5)(0.999)(W_i - R_j)\right]_{\text{Base Case}}} \tag{7}$$

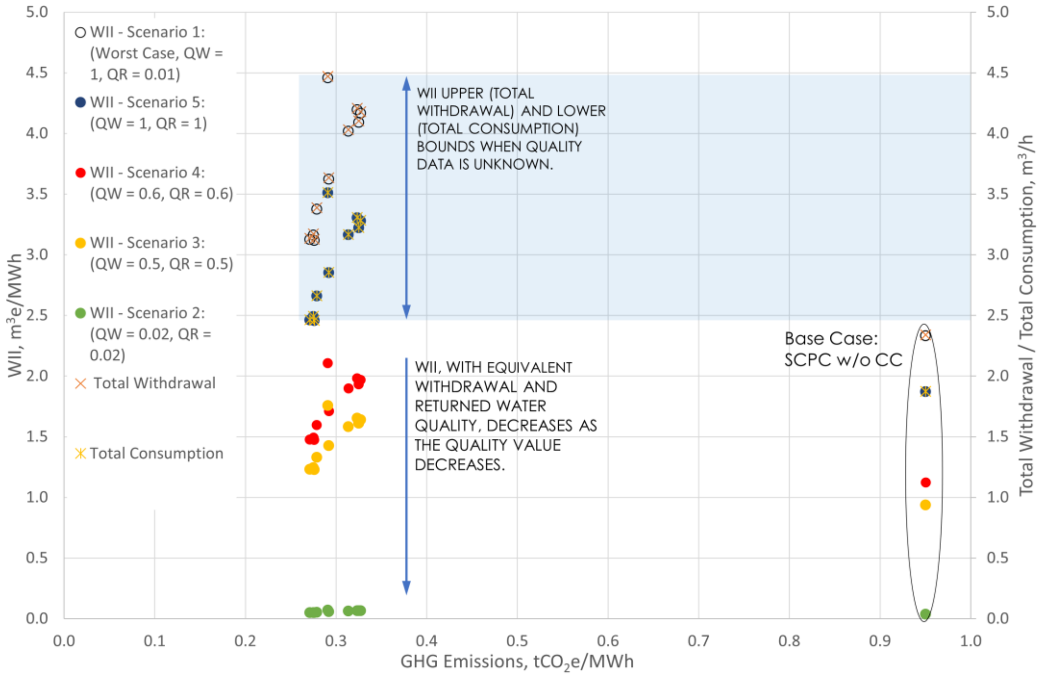

Figure 10: WII vs greenhouse gas emissions for high water scarcity index and varying water qualities for SCPC cases.

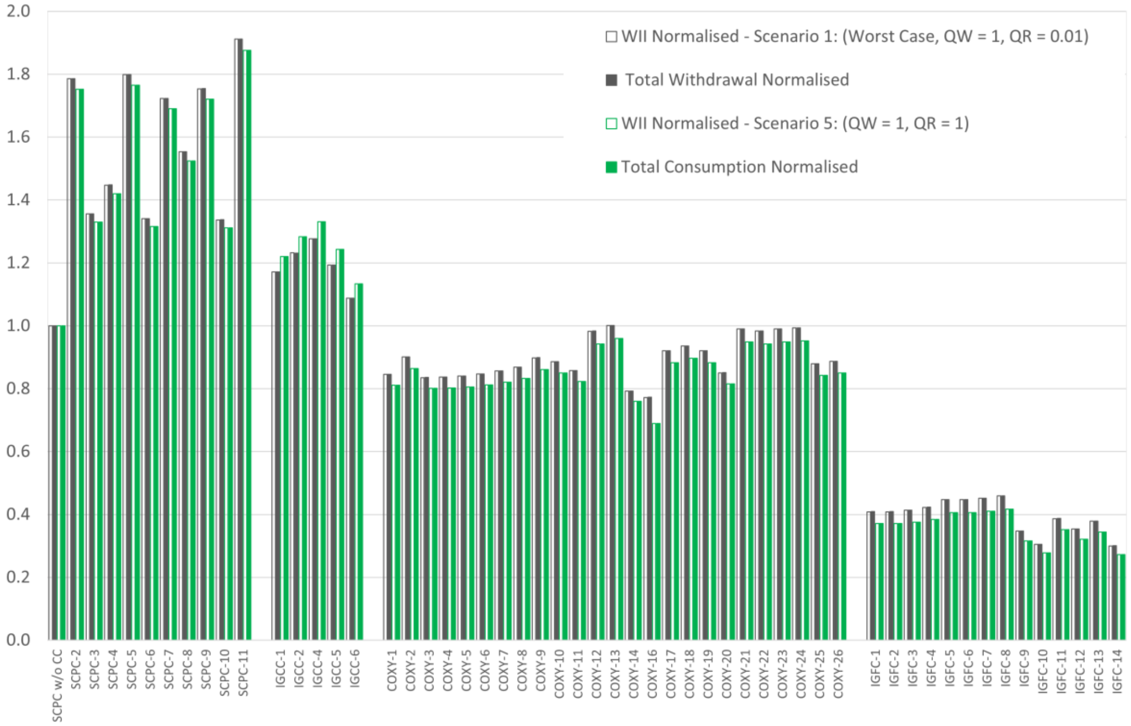

Figure 11: Relationship between normalised WII's and normalised withdrawal and consumption values for coal fired carbon capture technologies at high WSI.

Reduced further:

$$WII_{\text{Normalised, same quality}} = \frac{(W_i - R_j)_{\text{Green Case}}}{(W_i - R_j)_{\text{Base Case}}} \approx \frac{C_{\text{Green Case}}}{C_{\text{Base Case}}} \tag{8}$$

The difference between withdrawal and return is consumption (C_i). The normalised WII for all values of WSI with equal withdrawal and return water qualities are the same, and, are also equal to the normalised consumption values. In the normalised sense, only when the qualities are equal, the qualities and WSI are irrelevant. A similar effect can be seen for the worse-case scenario where Q_{Wi} = 1 (high water quality) and Q_{Rj} = 0.01) low water quality.

We replace these values in equation (7) maintaining the WSI of 0.999:

$$WII_{\text{Normalised, worse case}} = \frac{(W_i - 0.01R_j)_{\text{Green Case}}}{(W_i - 0.01R_j)_{\text{Base Case}}} \tag{9}$$

We can approximate for a returned water of very low quality that:

$$W_i - 0.01R_j \approx W_i \tag{10}$$

Then the normalised WII for the worse case is approximately the normalised total withdrawal:

$$WII_{\text{Normalised, worse case}} \approx \frac{W_{i_{\text{Green Case}}}}{W_{i_{\text{Base Case}}}} \tag{11}$$

The normalised figure below shows these relationship

For IGCC values the normalised consumption value is greater than the normalised withdrawal value which is not observed in other technologies. It is important to remember that this bar graph must be read relative to the base case only and not the other parameters. However, this anomaly is not unusual for IGCC technology. The water data for IGCC reflects that there is a higher percentage of the withdrawn water that is consumed as compared to the base case and compared to all technologies investigated for both coal and natural gas. In the works of Macknick *et al*. (1) and Meldrum *et al*. (2) the percentage of water withdrawn for consumption in IGCC technology with CC is greater than SCPC cases. The additional water consumption can be attributed to the additional absorption steps and the gasifier.

In summary, when water quality and scarcity data is unknown, the data should be normalised to make comparative decisions between the categories. The most reasonable values to use are water qualities from the worst-case scenario. When geographical data is available, absolute values can be used to obtain a more rigorous meaningful result.

It is worthwhile mentioning that the water quality equation presented in (25) does create some boundaries around the water quality, specifically the returned water quality. The equation considers only one penalising pollutant (the worst case one) which has been raised as a challenge by the authors. If we are to consider any local or national regulations on the concentrations of compounds that are considered to be pollutants, these regulations prohibit industries from discharging/returning water with concentrations higher than the concentration of the reference pollutant. Equation 4 is then always 1 in any normal situation in which a plant is operating legally. It is unclear if this is a feasible or realistic approach especially when one pollutant is considered. The idea of improving water quality is not new. Consider desalinisation or inter-basin transfer (39). Within the power generation context however, high volumes of high-quality water is necessary and planning and securing these resources is key to meeting power

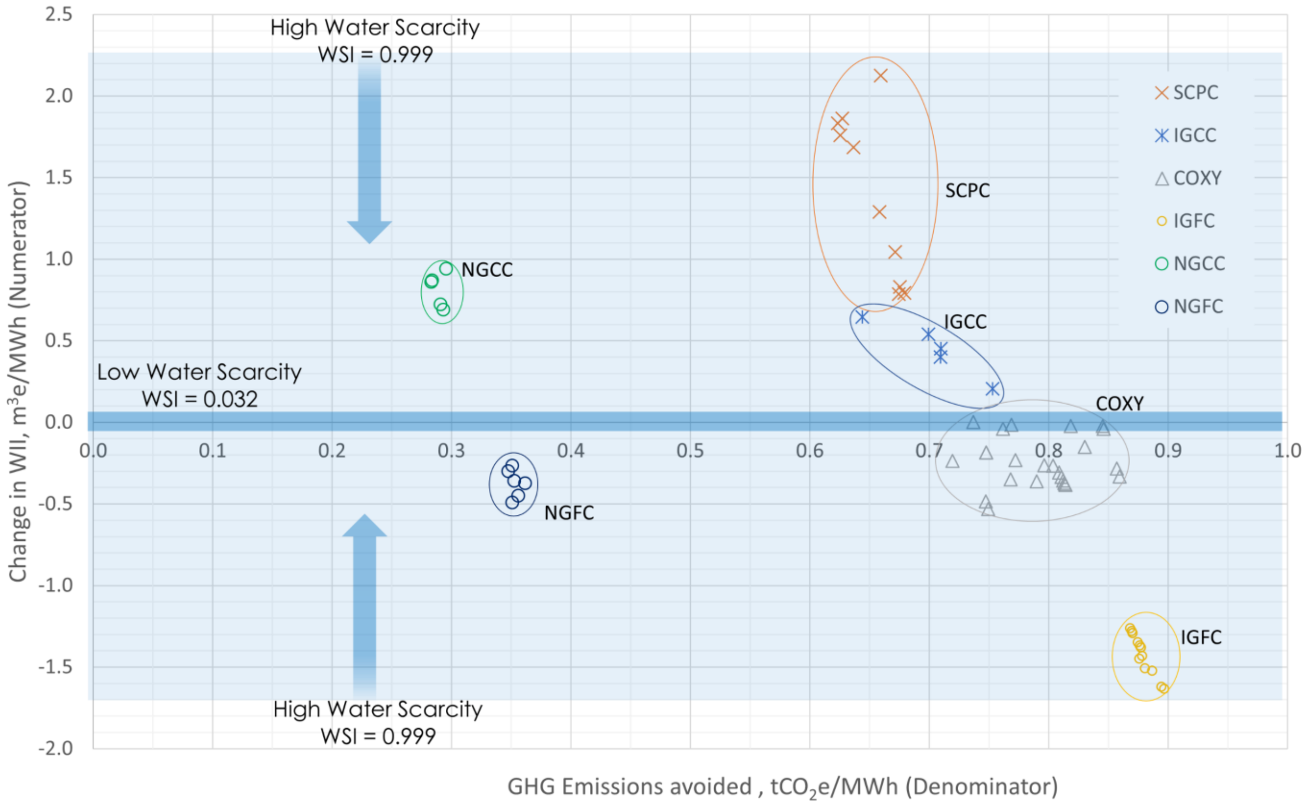

Figure 12: Change in WII relative to carbon dioxide avoided using the worst-case scenario for water qualities and a high water scarcity index (WSI = 0.999). Blue shading reflects the impact of decreasing water scarcity; the data range moves in the direction of the arrows as WSI decreases. See Figure 13 for the magnified version of the darker blue shading at low water scarcity= 0.03

demands. The “basin” is unlikely to be shared with other users. We put forward these various scenarios to emphasize the equal importance of water volume and water quality.

Table 9: Change in WII (numerator of WICa) for different WSI values of countries for SCPC technology, presented in descending order to illustrate the boundary of the impact. These values are based on Scenario 1 (worse-case) quality values.

World ranking	1	31	46	50	58	76	87	96	115
Country	United Arab Emirates	India	China	South Africa	Philippines	Poland	Finland	Canada	Norway
WSI	0.999	0.981	0.940	0.906	0.813	0.409	0.224	0.099	0.032
SCPC-11	2.126	2.087	2.000	1.928	1.731	0.870	0.477	0.211	0.068
SCPC-5	1.863	1.830	1.753	1.690	1.517	0.763	0.418	0.185	0.060
SCPC-2	1.833	1.800	1.725	1.662	1.492	0.750	0.411	0.182	0.059
SCPC-9	1.758	1.727	1.654	1.594	1.431	0.720	0.394	0.174	0.057
SCPC-7	1.686	1.656	1.587	1.529	1.373	0.690	0.378	0.167	0.054
SCPC-8	1.291	1.267	1.214	1.170	1.051	0.528	0.289	0.128	0.042
SCPC-4	1.044	1.025	0.983	0.947	0.850	0.428	0.234	0.103	0.034
SCPC-3	0.829	0.814	0.780	0.752	0.675	0.339	0.186	0.082	0.027
SCPC-6	0.794	0.780	0.748	0.720	0.647	0.325	0.178	0.079	0.026
SCPC-10	0.786	0.772	0.739	0.713	0.640	0.322	0.176	0.078	0.025

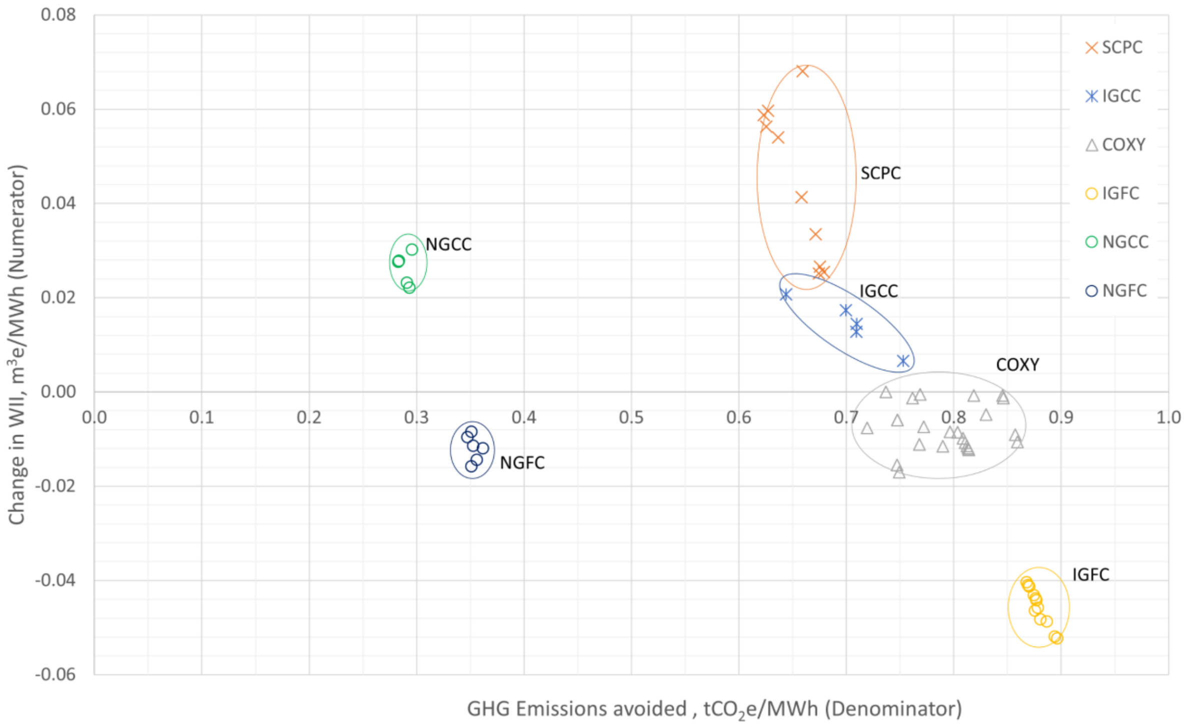

Figure 13: Change in WII relative to carbon dioxide avoided using the worst-case scenario for water qualities and a low water scarcity index (WSI = 0.0.032). The expanded graph at high water scarcity (WSI = 0.999) is shown in Figure 12.

4.3 Sensitivity analysis of WII to WSI

Figure 12 and 13, and Table9 demonstrate, using SCPC technology as an illustrative example, the effect of water scarcity on the overall water impact for different countries. We calculate the WII based on the worst-case quality scenario. In Table9 the technologies have been ordered to show the range of WSI values. This range is shown by the larger blue shading on Figure 12 (WSI = 0.999 (UAE)). As WSI decreases (WSI = 0.032 (Norway)) the impact is lessened as seen by the values in Table9 and the narrower range, shown by the smaller blue shaded region on Figure 12. Figure 13 is a zoomed in version of this smaller darker blue shaded region. The SCPC values in Table9 present varying data with a significant difference between SCPC-11 and SCPC-10 for all values of WSI. As noted earlier, the WII maps the water withdrawal data at the worst-case water quality scenario and a high WSI. This means that the change in WII is in fact the difference in withdrawal rates between the base case and the green case; for SCPC-10 the change is less compared to the change for SCPC-11. For these specific SCPC cases, these values are attributed to, and are proportional to, the differing heat rates of these technology cases (Table 7), SCPC-10 has a heat rate of 9836 MJHHV-/MWh and SCPC-11 has a heat rate of 14063 MJ_{HHV}/MWh. Another difference between these two cases is the type of solvent used; SCPC-10 uses chilled ammonia whereas SCPC-11 is amine based. Depending on the actual mechanism of solvent use (washing steps and heat exchange), water usage can be affected. Matin *et al*. (40), investigated varying concentrations monoethanolamine (MEA) as an amine solvent in their LCA work. It was found that these concentrations do not impact the water consumption impact category as much as the CO_2 emissions.

Table 9 also highlights that, higher water impacts are experienced in regions of high-water scarcity (WSI = 0.999, UAE) as seen in the range of values across the countries for each SCPC technology case. The same trend is observed: when high-quality water is consumed, the impact increases. However, the impact of using high-quality water is far greater in a region with a higher water scarcity index because it is in greater demand (39) .

In the normalised sense, as shown in Figure 11, the value of WSI doesn't not change the normalised impact, however comparative conclusions can still be drawn. In a region with high water stress, withdrawing good quality water will mean less water available to other users. There is a challenge in choosing the most realistic scenario without having a full picture of the process. These graphs show that by varying water quality of withdrawn and returned water, eventually the water impact maps the water withdrawn in the worst-case scenario and then maps the water consumed in the case of the same water quality. In the case of same water quality, we see that the normalised value for the technology is the same and the real difference comes from the worst case scenario (Scenario 1). Additionally, Figure 13, shows that two distinct categories of technologies can be identified. NGFC, IGFC and COXY have a net benefit for the environment in terms of water sustainability whereas the other technologies illustrate the negative trade-off between water impact and GWP.

4.4 Discussion

Figure 12 is the metric presented as the numerator (change in water impact between the green case and base case) against the denominator of the metric (CO_2 emissions avoided) for all technologies investigated. A negative change in WII implies that the WII of the green case is less than that of the base case.

Firstly, we observe the distinct trends between the natural gas-based technologies and the coal-based technologies. It is important to remember that the natural gas based case studies reflect a lower amount of GHG emissions avoided as compared to the coal based case studies purely because the total cradle-to-plant-exit GHG emissions for the natural gas base case is lower than that for the coal base case.

Both coal and natural gas SOFC technology have a negative change in WII but IGFC has a higher GHG emissions avoided, due to the high emissions of the coal base case. The average GHG emissions of IGFC is 0.07 tCO_2e/MWh and NGFC is 0.05 tCO_2e/MWh (Table 7, reported as cradle-to-plant-exit GWP) making NGFC the better choice in terms of average emissions. However, in a feasibility study natural gas might be the only viable option for various reasons. If the base case of a coal plant was used, the numbers for all the natural gas cases would look very different. There would be a greater change in water impact and a higher amount of GHG emissions avoided.

The next best technology is coal based oxy-fuels (COXY) both in terms of change in WII and GHG emissions avoided, however, consumes more water than NGCC NGFC and IGFC (Figure 9). In this situation, with three closely competing technologies (excluding NGCC due to its positive change in WII), considerations on location (access to natural gas/coal, water and other raw materials), emissions regulations and the land footprint required to construct this kind of facility must be considered. Further to this, feasibility studies are necessary and imperative to understand the impacts (economic, environmental, and social) over the entire supply chain to arrive at a suitable technology, this includes the water impact and GHG emissions.

Table 10 lists the final median WICa metric values, based on a worst-case scenario and a high WSI,for all the technologies investigated in this work and is presented in Figure 14 relative to key water and energy metrics.

Table 10: Median WICa values for the technologies investigated presented in ascending order for both coal and natural gas CC technologies

Fuel type	Technology	WICa Value
Coal	IGFC	-1.57
	COXY	-0.33
	IGCC	0.64
	SCPC	2.30
Natural gas	NGFC	-1.03
	NGCC	3.04

Negative WICa values mean that there is a net benefit to water resources and GHG emissions reduction since the WII for the green case is lower than that of the base case. It is interesting to compare the fuel efficiency to the water metrics. Figure 14 shows the anticipated link between electrical efficiency and water usage – higher efficiency technologies have lower water usage - and the overall benefits of less mature but more efficient, technologies. Even though the efficiencies for COXY, IGCC and SCPC technologies are similar, the median water usage are significantly lower for COXY technologies. A closer look, at Table ESI 2 (in electronic supplementary information) shows that the percentage of process operations water withdrawal to total operations water withdrawal (cooling + process) for COXY case studies is 8% whereas for IGCC and SCPC technologies, this percentage is between 15% and 22%. This could suggest two things. Firstly, the water requirements of the individual unit operations are far less than that of SCPC and IGCC. This is a high possibility as solvent based post-combustion and pre-combustion systems have high water requirements. Additionally, due to the complete separation of H2O and CO2, COXY systems have the potential of water recovery. This water can be treated and reused within the system thereby reducing raw water withdrawal ((17), (41)) and is enough, in some instances, to satisfy the full water consumption requirement (41). In the cases investigated in this study, it is unclear if this was done. A similar benefit was noted in van der Spek et al. (42) where the comparison of oxyfuel configuration to post-combustion configuration resulted in lower cooling water intensity due to the integration of the steam cycle with downstream processes.

Secondly, and conversely, the percentage of the cooling operations water withdrawal to total operations water withdrawal for COXY systems in this work, is more than SCPC and IGCC. The actual withdrawal values are, however, significantly lower. Zhu *et al.* (17) investigated the life cycle water consumption of oxyfuel combustion systems, and found that “operations and maintenance”, which includes cooling, consume the most water over the life cycle. However, within “operations and maintenance” they do not distinguish between cooling and other operations making it impossible to determine if cooling or other unit operations contribute the most to water consumption. Again, further validating earlier observations, the technologies with high efficiencies, low water impact and low water consumption are the fuel cell technologies.

5. Conclusions

The objective of this work was to create an easy, usable, high impact way to assess the trade-off between global warming mitigation, as CO_2 equivalents avoided, and the impact on water resources for CC technologies in the power generation industry.

The analysis shows that, overall, CC technology increases water usage except for IGFC and NGFC technologies. This suggests that capturing carbon can be done in a water efficient way by selecting an appropriate technology. The usefulness of the metric is demonstrated in the absence of specific water quality and water scarcity data-a common situation as often noted in the literature (14,43). Our results show that the worst-case scenario (described as scenario 1 in this work), can be used to estimate the WII of different technologies and, in a normalized sense, not knowing the WSI does not impair the comparative conclusions that can be drawn.

Our case study of 65 different low-CO_2 fossil-based power plant systems provided a substantial basis from which to estimate water usage data and draw qualitative and quantitative conclusions. Additionally, the exercise drew attention to the water data availability in the literature versus the availability of other data, such as GHG emissions and economic data. The discrepancy between *needing water* in the power generation CC process, and the *reporting of water usage* data in power generation CC research was emphasised. Additionally, we also recognise that changes in the cooling employed in the technology reference cases would alter the overall water usage image presented here but potentially not impact overall observations.

By varying the quality variable for both water withdrawn, and water returned, for a WSI close to 1 the impact maps the water withdrawal and consumption data points accurately for scenario 1 and the scenarios when the qualities are equivalent. This is especially useful when data are unknown, however it is important to note that the specific impact relies heavily on the water quality. In varying the WSI, we observe greater impact for areas with low WSI versus areas with high WSI. For low impact cases due to poor quality water, considerations related to pretreatment cost must be factored in. These could affect other parameters not included in the scope of this work.

We established that NGFC, IGFC and COXY technologies have the most promising WICa values. However, IGFC and COXY have the highest GHG emissions avoided due to the high GHG emissions of the base case. SOFC based CC has the lowest water usage and GHG emissions on an absolute basis compared to all other technologies investigated further supported by their low WICa values.

Enabling the CC technology decision making for fossil-based power plants with a water resources impact dimension was a further goal of this work. The method presented here translates to other contexts and industries with different water metrics and green initiatives (reducing particulate matter, reducing sulfur etc.). The WICa metric reflects the key characteristics that are necessary in understanding the potential water impacts of reducing GWP, as described in Table 1. It is useful in making general assessments of technologies for specific regions and for specific water qualities. It does not yet include the additional emissions impact for the treatment of water to improve water quality before use and after disposal.

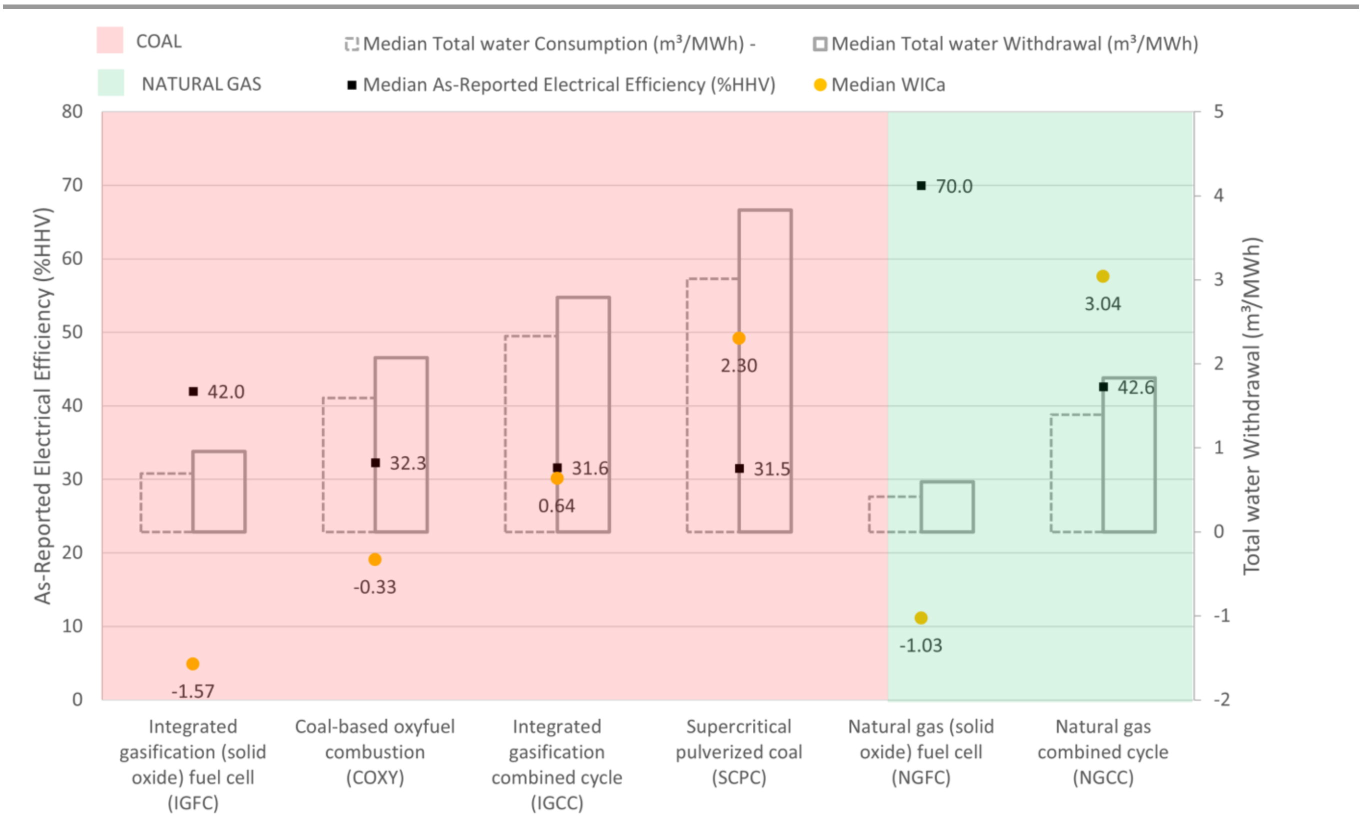

Figure 14: Summary of the relationship between technology efficiencies, water usage and WII.

Author Contributions

P.M. – Formal analysis and writing – original draft; P.M. and T.A.A – Conceptualisation and methodology; T.A.A. and K.H – Writing – review and editing, supervision.

Conflicts of interest

There are no conflicts to declare.

Data Availability

The data supporting this article have been included as part of the Electronic Supplementary Information (ESI).

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Electronic supplementary Information

Electronic Supplementary Information (ESI) supplied as additional document.

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