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Hydrological limits to carbon capture and storage

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Title: Water scarcity exposure of global coal-fired power plants with and without post-combustion carbon capture

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ABSTRACT

Post-combustion carbon capture and storage (CCS) is an important technology to reduce CO_2 emissions from the electricity and industrial sectors. Despite the mounting concerns about global water scarcity and its impact on energy production, the potential hydrological consequences of large-scale CCS have not yet been explored. Here we simulate the impacts on water resources that would result from retrofitting global coal-fired power plants (CFPP) with four different CCS technologies. We find that 43% of global CFPP capacity currently experience water scarcity at least one month per year and 32% experience scarcity for five or more months during the year. Addition of CCS does increase water scarcity, and the extent to which it does so depends on the technology. We show that the choice of what CFPP to retrofit and what CCS technologies to deploy will be essential in preventing additional water scarcity. If CCS were to be pursed, facilities not affected by water scarcity should be selected.

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Globally coal-fired plants account for 38% of electricity generation[1] and 19% (8.9 Gt CO_2 y^{-1}) of total CO_2 emissions[2]. Coal generation is also a primary source of toxic airborne emissions globally[3]. Despite the growing reliance on renewable energy and the recent policy efforts aimed at reducing the use of coal[4], today the global coal dependence for power generation is the same as twenty years ago[1]. Since the turn of the 21st century, population growth, increasing affluence, and industrialization in developing countries have demanded an unprecedented growth in coal consumption (+57%) (ref. 1), leading to a boom in the construction of CFPP[2]. Given that each new coal plant is at least a billion-dollar investment with a 30- to 50-year lifetime[5], currently operating CFPP commit the energy sector to emissions above the levels compatible with 1.5-2º C climate change scenarios[6] and commit fresh water consumption to levels that potentially compete with natural ecosystems and other human uses[7-21]. These commitments ostensibly address the increasing concerns for global water scarcity[22] and humankind's ability to meet its burgeoning food and energy needs[23].

The twin costs of mitigating climate change and competing for water resources are vexing factors in managing energy systems. Although there is a portfolio of technologies that can provide a long-term substitute for coal, any reasonable action for mitigating these factors must curtail CO_2 emissions and water use from CFPP without requiring write-off of these assets and their committed billion-dollar investments[24]. Post-combustion carbon capture and storage (hereunder CCS) is the preferred economically viable technology to reduce CFPP carbon emissions because it can be added to existing plants to reduce emissions without having to decommission power plants[25]. To date, however, a global assessment of the potential impacts of CCS on water resources – should the CFPP existing around the world be retrofitted with CCS technologies – is missing. As we continue to evaluate the cost-effectiveness of different climate change mitigation technologies, the assessment of potential water limits to CCS can provide relevant insights.

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The four main CCS technologies used to retrofit CFPP are based on absorption with amine solvents, membrane separation, solid sorbents adsorption with either pressure swing (PSA) or temperature swing (TSA) capture systems. While amine-based absorption is a proven commercially available technology, membranes and adsorption-based CCS systems appear promising, but they are at a much lower stage of development[26]. All of these CO_2 capture technologies are energy-intensive processes[27] that would impose parasitic power demand on the existing power plant and thus make it less efficient[26]. The additional power generation required for CCS would result in additional water consumption for the CFPP cooling process[28]. Moreover, additional water is required as an integral part to the carbon capture processes[29]. In fact, recent work has assessed that a post-combustion amine absorption process would nearly double

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CFPP's water intensity, decrease net plant efficiency from 38.3% to 26.4%, and increase levelized cost of electricity by 75%[30].

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Previous research has simulated water risks of power generation with CCS in the United States[31-34], Europe[35], and the UK[36]. These studies, however, did not adopt a monthly hydrological model to quantify potential impacts on water resources. Their focus was on regional-scale analyses of water requirements from the absorption process without considering other CCS technologies. As important as these studies are, it remains unclear whether CCS might induce or exacerbate water scarcity at specified times of the year, nor is it clear what the water intensity differences are for the various CCS technologies. This limited hydrological understanding of the potential impacts of CCS adds uncertainties on the environmental consequences of the implementation of CCS worldwide.

Herein we present a global hydrological analysis of the potential impacts on water resources that would result from retrofitting large (> 100 MW of gross capacity) CFPP with four CCS capture systems: amine absorption, solid sorbents pressure swing adsorption (PSA) or temperature swing adsorption (TSA), and membrane systems. This analysis begins with a monthly, regional assessment of water scarcity experienced by current CFPP. For each CFPP, then, we assess its monthly water withdrawal and consumption using the Integrated Environmental Control Model (IECM Version 11.2)[37], and analyze its exposure to water scarcity. A proper assessment of water withdrawals, consumption, and scarcity can facilitate the development of sustainable water management practices and shed light on regional hydrologic impacts of CCS. Our study promotes the understanding of the water requirements of CCS and provides relevant insights to mitigate CO_2 emissions from the electricity and industrial sectors while preserving water resources.

Box 1 | Concepts and definitions about water systems.

Water Consumption is the volume of water that is used by human activities and returned to the atmosphere as water vapor. Therefore, this water becomes unavailable for short-term reuse within the same watershed. Consumptive use of freshwater at inland locations is more critical than consumptive use of seawater. Moreover, consumptive use of freshwater at coastal plants is less critical than consumptive use of freshwater at inland plants, because this influences downstream's water availability.

Water Withdrawal is the total volume of water removed from a water body. This water is partly consumed and partly returned to the source or other water bodies, where it is available for future uses.

Water Consumption Intensity (m^3/MWh) is the volume of water consumed (m^3) per unit power produced (MWh). It is a measure of efficiency of water consumption.

Water Withdrawal Intensity (m^3/MWh) is the volume of water withdrawn (m^3) per unit power produced (MWh). It is a measure of efficiency of water withdrawal.

Blue Water Flows are freshwater flows associated with either surface and groundwater runoff.

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Environmental Flows describe the quantity, timing, and quality of water flows required to sustain freshwater ecosystems.

Available Water is the water sustainably available for human uses. It is calculated as *Blue water flows* minus *Environmental Flows.*

Water Scarcity refers to the condition of imbalance between freshwater availability and demand. Here we define water scarcity based on whether the ratio between *Freshwater Consumption* and *Available Water* is greater than one[22]. Water scarcity corresponds to conditions in which the monthly available water resources are less than total water consumption, and freshwater requirements from coal-fired generation must therefore compete with water uses for domestic and irrigation needs, as well as environmental flow requirements.

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Box 2 | Concepts and definitions about post-combustion carbon capture and storage technologies.

Post-Combustion Carbon Capture and Storage (CCS) consists of retrofitting existing power plants with carbon capture and storage units without having to modify the power plant itself. CCS is used to separate CO_2 from the flue gas of power plants. Once captured, CO_2 is compressed to its supercritical state and transported and injected into a safe geological formation (Supplementary Figure 1).

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Absorption is a CCS technology based on a liquid solvent used to dissolve CO_2 molecules (absorb) into a liquid solution such as aqueous amines. The CO_2-enriched liquid solution is pumped in a regenerator where it is heated to liberate gaseous CO_2 and the lean solution is circulated back to the absorber (Supplementary Figure 2).

Membrane Separation is a CCS technology used to separate CO_2 from the flue gas by selectively permeating it through a membrane material. CO_2 permeates the membrane if its partial pressure is higher on one side of the membrane relative to the other side (Supplementary Figure 3).

Solid Sorbents Adsorption is a CCS technology based on a solid material used to adsorb CO_2 molecules onto the surface of another material. The CO_2-enriched solid sorbent is regenerated using low pressure (***Pressure Swing Adsorption (PSA)***) or high temperature (***Temperature Swing Adsorption (TSA)***) where gaseous CO_2 is liberated and the lean solid sorbent is reused again to capture CO_2 (Supplementary Figure 4 and 5).

Present day monthly, regional water scarcity at CFPP

Global hydrological models are powerful tools to simulate and quantify changes in water availability and consumption. Here, we use water scarcity as an indicator of where, in what period of the year, and for how long, CFPP **without CCS systems** are vulnerable to risks of limited water availability. Our hydrological analysis uses a monthly biophysical water balance model that accounts for water consumption for irrigation, domestic, and coal-fired power generation needs, as well as for environmental flows required to maintain the health of aquatic ecosystems. Although we do consider inter-annual variability in water resources, our main water scarcity results are shown considering long term monthly average available water in the 2011-2015 period.

We find that a surprising number of plants exhibit water scarcity for five or more months per year. About 43% (830 GW) of the world's CFPP are facing regional water scarcity at least one month per year and 32% (625 GW) of CFPP experience water scarcity five or more months per year (Figure 1). Of these 625 GW, 56% are located in China, 15% in India, and 11% in the United States. Other CFPP facing water scarcity for at least five months per year are located in South Africa (34 GW), Australia (12 GW), Russia, (8 GW), Poland (8 GW), and Germany (7 GW).

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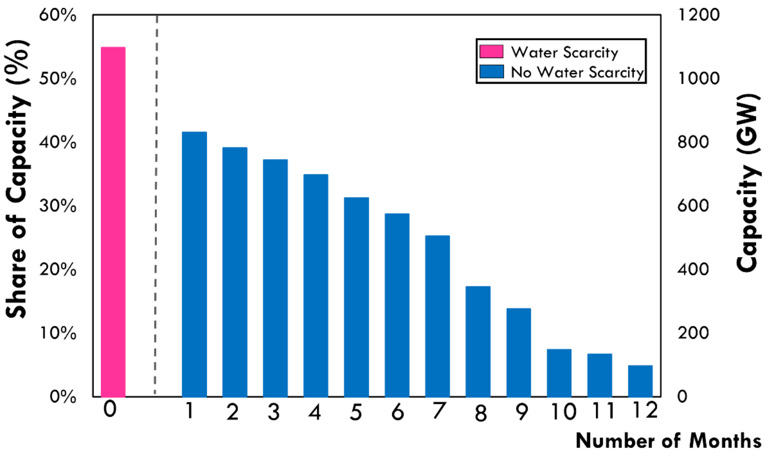

Figure 1. Coal-fired capacity (GW) and share of coal fired capacity (%) facing water scarcity for the specified number of months per year.

Figure 2 shows the geographical distribution, water scarcity duration (in number of months), and cooling technology of CFPP operating in year 2018 worldwide. CFPP are typically built adjacent to water bodies and consume water from nearby lakes, rivers, or oceans where water availability is abundant. Year-round CFPP that do not face water scarcity are located in the Great Lakes region in the North-Eastern United States, Europe, Russia, and South China. Other CFPP not affected by water scarcity are located along the coasts as they use seawater as cooling medium (we assumed that CFPP currently cooled with seawater are not affected by water scarcity).

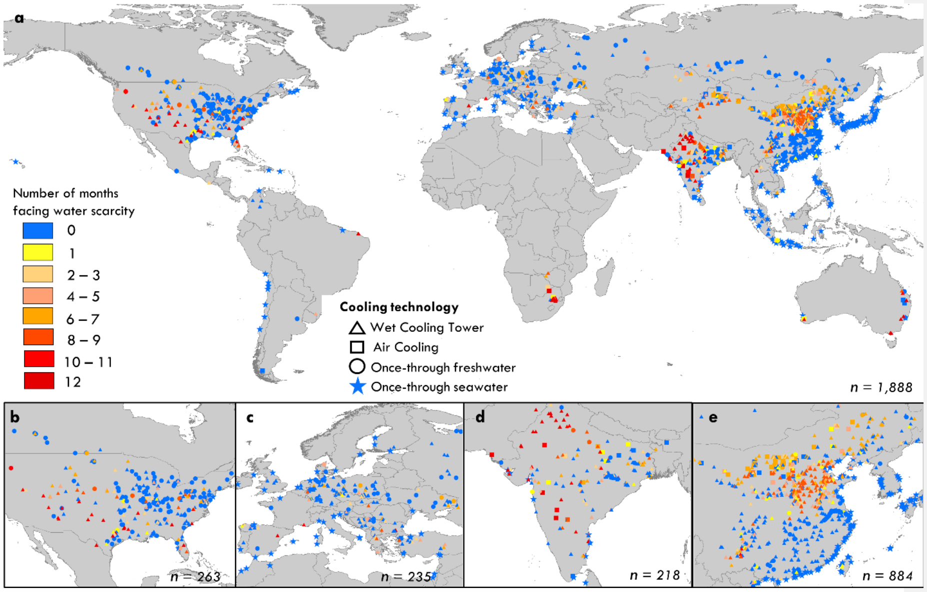

Figure 2. Geospatial distribution of coal-fired plants facing water scarcity in the 2011-2015 period. Detail **(a)** shows location, number of months per year facing water scarcity, and cooling technology of 1,888 coal-fired plants (*n*) worldwide. Details **(b-e)** show the four main regions where coal-fired plants are located (United States, Europe, India, and China). CFPP facing water scarcity appear either in intensively irrigated areas (for example, High Plains in the United States), in high population density regions (Pretoria, Johannesburg conurbations), or in irrigated and populated areas (North China Plain, India). Water scarcity also occurs in arid regions with a well-defined dry season (Western United States, India, Australia, Xinxiang and Inner Mongolia provinces in China). Generating units with once-through cooling are shown distinguishing seawater and freshwater as a cooling medium.

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The analysis of the share of CFPP capacity currently facing water scarcity in different regions of the world and months of the year shows that in China more than 30% of the installed capacity faces water scarcity from March to October (Figure 3a). In the United States at least 20% of coal capacity faces water scarcity from April to November. A similar picture can be found in Europe, where at least 20% of coal capacity faces water scarcity from June to September. More than 40% of India's coal capacity faces water scarcity in the dry season (December to June). CFPP located in other Asian countries are not particularly exposed to water scarcity because of high water availability and their construction along the coast using seawater as a cooling medium. It is worth noting that for those global CFPP that use fresh water for cooling, the predominant cooling technologies are wet cooling towers (60% of total capacity), followed by once-through systems (35%), and air-cooling (5%) (Figure 3b). Air-cooling is a relatively new technology and 90% of its capacity is located at new plants in China and India. About 22% of global coal-fired operating capacity is cooled using seawater, while the remaining 78% uses freshwater.

The analysis of the coal-fired capacity facing water scarcity by cooling technology shows that 60% (728 GW) of the units cooled with wet cooling towers face water scarcity for at least one month per year. Because of their lower water intensity (Figure 4), air-cooled systems are usually implemented in newly built units located in arid and/or water scarce areas. In fact, we find that 72% (67 GW) of CFPP cooled using air-cooled systems are facing water scarcity. While 56% (360 GW) of once-through cooled capacity uses seawater as a cooling medium and therefore is not affected by water scarcity, only 6% (36 GW) of once-through generating capacity is exposed to water scarcity. China has 62% (403 GW) and 74% (53 GW) of its wet cooled and air-cooled coal-fired plants, respectively exposed to at least one month of water scarcity per year (Figure 3b). The United States and India have 60% (89 GW) and 63% (113 GW) of their wet cooled coal-fired units exposed to water scarcity for at least one month per year.

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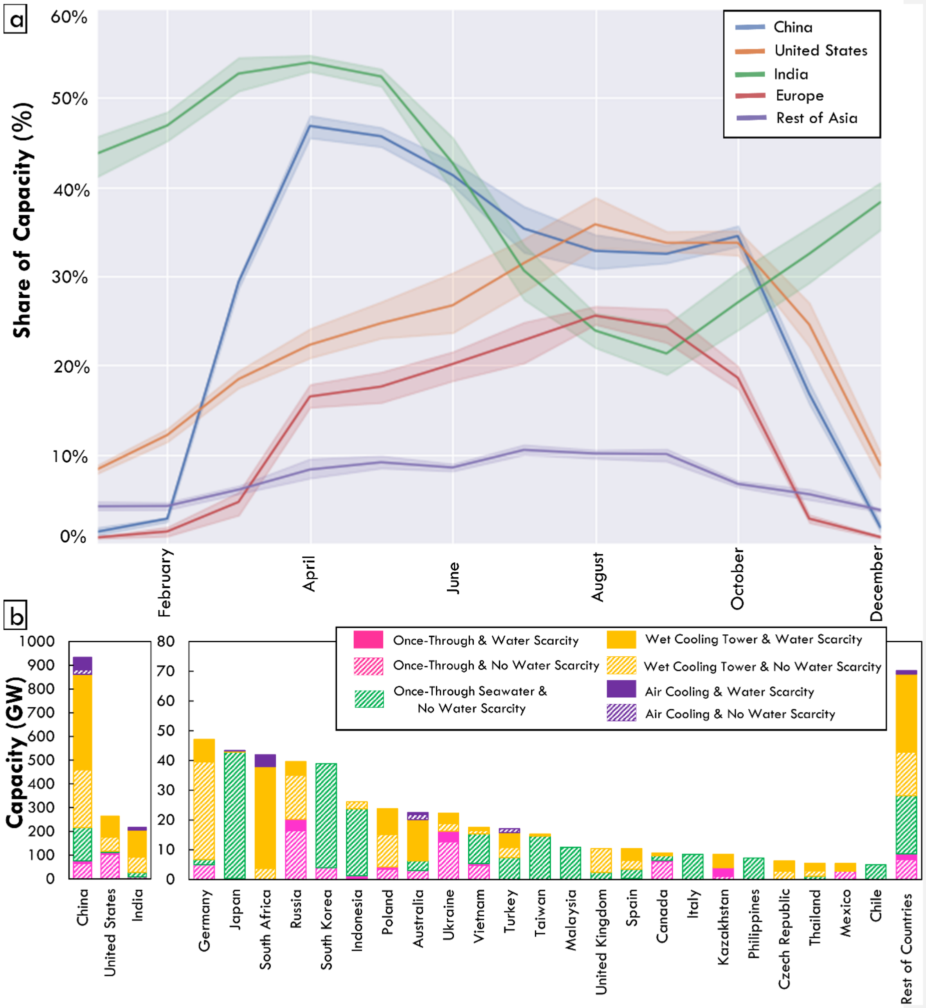

Figure 3. The exposure of coal-fired plants to water scarcity. Panel (a) shows regional share of coal-fired operating capacity facing water scarcity along the year. Solid lines represent average water scarcity in the 2011-2015 period, shaded areas show inter-annual variability of water scarcity in the years from 2011 to 2015. Panel (b) shows coal-fired capacity facing average water scarcity (for at least one month per year) by cooling technology. Panel (b) shows the current installed coal-fired capacity and respective cooling systems by country (or region).

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Future water scarcity with CCS

Using the water balance approach described above, we turn to an important aspect of future decisions regarding CCS, namely to what extent the available freshwater resources would allow for the adoption of CCS as a means to curb carbon emissions by the existing CFPP. Meeting humanity's burgeoning energy and water demand while avoiding an increase in anthropogenic CO$_2$ emissions and protecting environmental flows is one of the most pressing challenges of this century.

Given that old and low-efficiency CFFP without environmental control systems will likely shut down and will not be retrofitted with expensive CCS technologies, we assumed that only 1,093 large (>100 MW) CFPP operating since year 2000 will be retrofitted with CCS and capture 90% of their CO$_2$ emissions by 2020. Because of this relatively short timeframe, we assume that water availability and coal-fired generation would not substantially change compared to current conditions. Although this scenario is not meant to be a realistic representation of the rate of adoption of CCS to CFPP, it allows us to assess the impacts of CCS retrofit on water resources. Moreover, this assumption is in line with the urgent need to drastically reduce global CO$_2$ emissions from CFPP in order to meet climate targets (**Rogelj et al., 2018**). This analysis provides the estimated additional water withdrawals and consumption from coal-fired generators considering 1) current 1,888 CFPP, and 2) four hypothetic scenarios where the 1,093 large CFPP are retrofitted with CCS units.

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Water intensity, consumption, and withdrawals of CCS

Our estimates show that the water intensity of CFPP with and without CCS technologies strongly vary with the type of cooling system and CCS technology (Figure 4). Interval bars show that water intensity from air-cooling and once-through cooling technologies can differ by up to 4% with different air temperatures, relative humidity, and gross power inputs, while for wet cooling it can vary up to 20%. CFPP with wet cooling towers retrofitted with CCS units have the highest water consumption intensity, while CFPP with once-through cooling technology have the highest water withdrawal intensity. Independent of the cooling system, the least water intensive CCS technologies are solid sorbent PSA and membrane systems.

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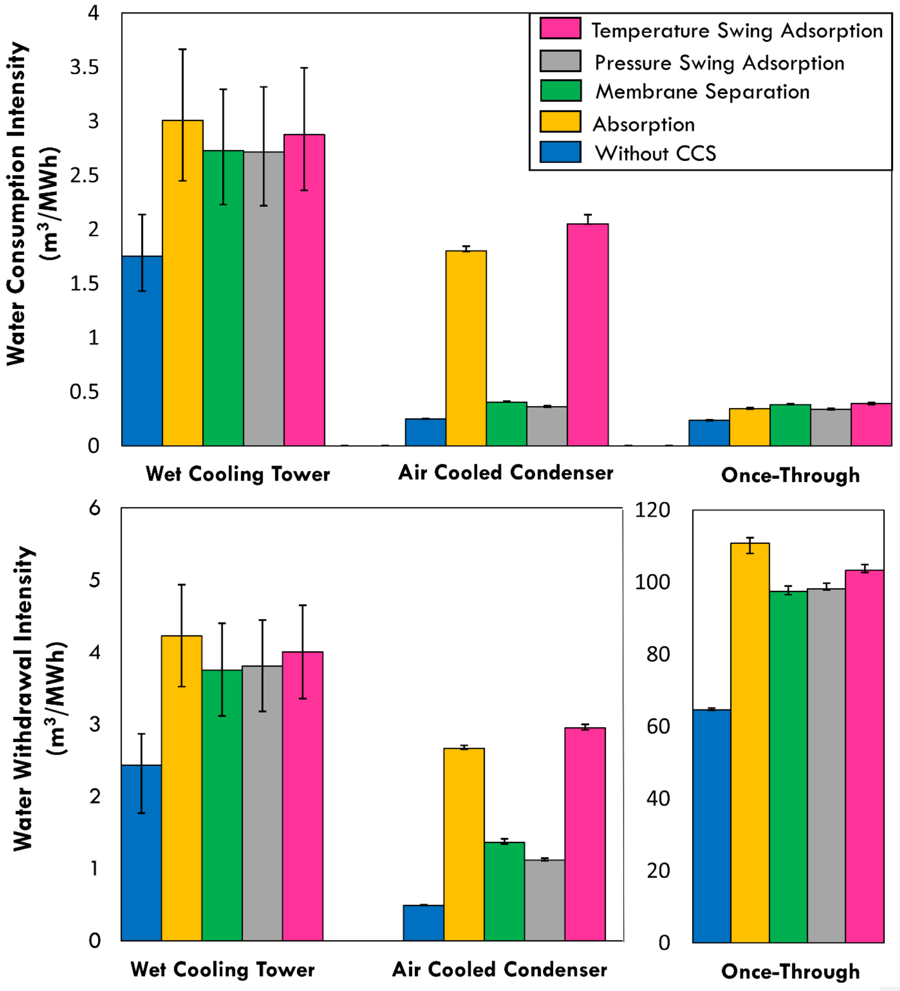

Figure 4. Water consumption and withdrawal intensities of coal-fired plants with and without CCS. The figure was generated running the Integrated Environmental Control Model (IECM Version 11.2)[37] and considering the different monthly air temperatures, relative humidity, and gross power inputs of the 1,888 CFPP considered in this study. Interval bars represent maximum and minimum values of water intensities. Note that water withdrawal intensity with once-through cooling technology is shown using a different scale.

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An analysis of water consumption by CFPP considering current conditions and four future scenarios in which these large CFPP are retrofitted with CCS units shows a substantial increase in water consumption. Current total global water consumption from CFPP is 9.66 km^3 y^{-1}, of this volume 88% is sourced from freshwater, while the remaining 12% is sourced from seawater (Figure 5). China, with 48% of world's CFPP capacity, has also the greatest share in freshwater consumption (53%), followed by India (16%), and the United States (13%). By retrofitting CFPP built after year 2000 with the off-the-shelf amine absorption technology, global water consumption by CFPP would increase by 50% (4.81 km^3 y^{-1}). If CFPP were all retrofitted with membranes, water consumption would increase by 31% (3.00 km^3 y^{-1}). Water consumption would increase by 32% (3.13 km^3 y^{-1}) and 42% (4.07 km^3 y^{-1}) in the case CFPP were retrofitted with solid sorbent PSA, and solid sorbent TSA, respectively. Assuming that current CFPP cooled with seawater will use seawater when retrofitted with CCS, 0.69-1.10 km^3 y^{-1} of this additional water consumption would come from seawater, while the remaining fraction (2.31-3.71 km^3 y^{-1}) would be consumed from freshwater bodies. Similar results can be found in terms of water withdrawals (Figure 5).

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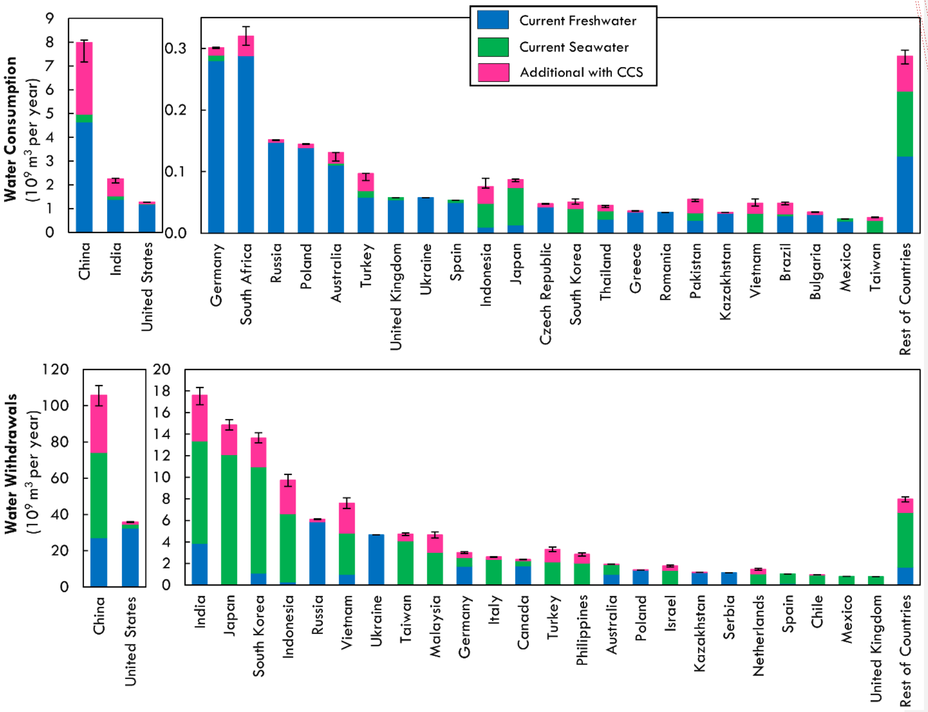

Figure 5. Water consumption and withdrawals of coal-fired plants with and without CCS. Current water consumption and withdrawals from 1,888 CFPP are differentiated between freshwater and seawater. Additional water consumption and withdrawals from the 1,093 CFPP (operating after year 2000) include both freshwater and seawater. Note that countries (or regions) are listed in descending order of current water consumption and withdrawals by CFPP. Interval bars represent the maximum and minimum values of water consumption and withdrawals (seawater and freshwater combined) considering the four CCS scenarios assumed in this study. Current water withdrawals from CFPP total 204 km^3 y^{-1}, of this volume 43% is sourced from freshwater, while the remaining 57% is sourced from seawater. Countries (or regions) where water is primarily withdrawn from seawater are China (63% or 47.1 km^3 y^{-1}), India (71% or 9.5 km^3 y^{-1}), and Japan (99% or 12 km^3 y^{-1}). By retrofitting CFPP with CCS systems, the global water withdrawals (seawater and freshwater combined) would increase by 32% (65 km^3 y^{-1}), 22% (45 km^3 y^{-1}), 23% (47 km^3 y^{-1}), or 27% (55 km^3 y^{-1}), with amine, membranes, solid sorbent PSA, and solid sorbent TSA, respectively.

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Exposure to water scarcity

Retrofitting CFPP with CCS units would create or exacerbate water scarcity conditions compared to current operations. Amine absorption and solid sorbents TSA are the technologies that would have more impacts on water resources. By retrofitting CFPP built after year 2000 with these two technologies, an additional 13 GW of CFPP capacity would face water scarcity. Moreover, an additional 23% (232 GW) of CFPP capacity would be exposed to water scarcity for at least one additional month a year (Figure 6). Because of their lower water intensities, membranes and solid sorbents PSA would exacerbate water scarcity for only 18% and 20% of CFPP capacity, respectively (Figure S9). If CFPP in China and India were retrofitted with the commercially available amine absorption technology, an additional 168 GW and 52 GW of coal fired capacity would be exposed to longer periods of water scarcity every the year (Figure 6b). In other words, in China and India 23% and 37% of CFPP built after year 2000, respectively would be vulnerable to longer periods of water scarcity.

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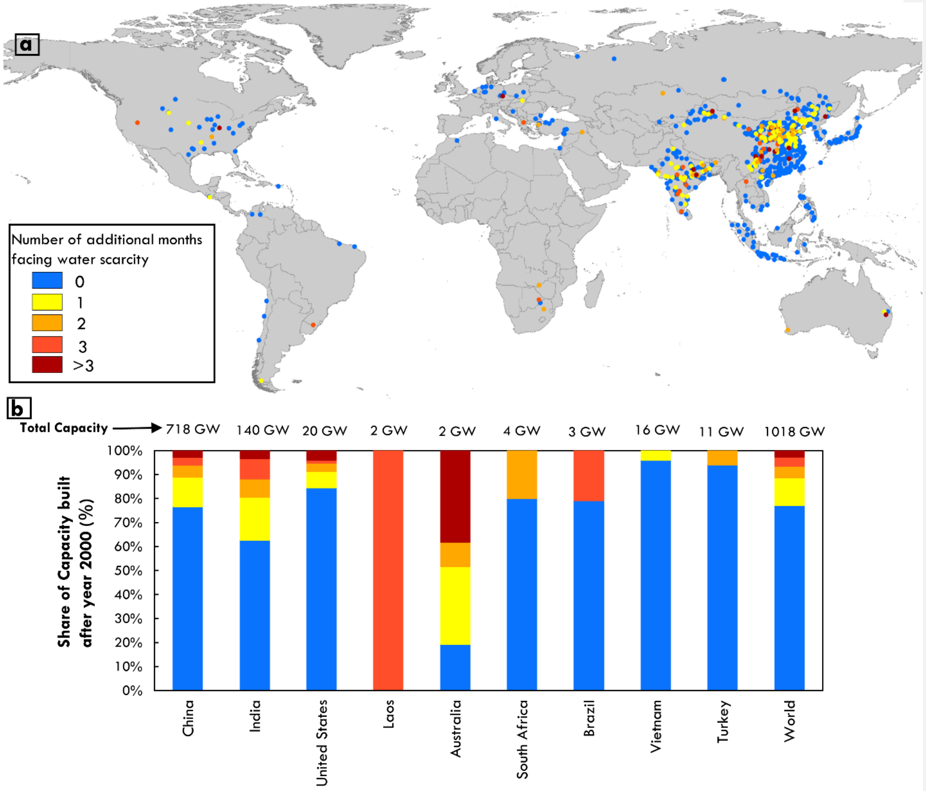

Figure 6. Additional water scarcity with carbon capture amine absorption technology. The figure shows the number of additional months of water scarcity per year that CFPP built after year 2000 would face in the event the were retrofitted with the commercially available amine absorption technology. Detail **(a)** shows the geographical distribution of CFPP built after year 2000 and the number of months of additional water scarcity they would face if retrofitted with amine absorption, **(b)** shows country-specific share of coal fired capacity built after year 2000 that would face additional months of water scarcity if retrofitted with amine absorption. Countries are listed in descending order based on additional capacity facing water scarcity.

DISCUSSION

Tradeoffs between climate change mitigation benefits and water resources

This study highlights the water impacts of coal-fired power generation and the hydrologic impacts of the adoption of CCS to address the associated CO_2 emissions. Our results show that cooling systems and CCS technologies have different water requirements, in terms of both

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consumption and withdrawal. For CFPP located in water scarce areas, the additional water consumption that would be required by CCS (Figure 4) could create a competition for local water resources with other human activities[39,40] and/or generate an unsustainable water consumption at the expenses of aquatic ecosystems and freshwater stocks. Therefore, the choice of cooling and CCS technologies is fundamental to avoid a competition for freshwater with other local human activities, ecosystem health, and at the same time reduce water consumption. It is also important to notice that the global additional water requirements of CCS are dwarfed by freshwater demand from irrigation in the agriculture sector (Table S1). In fact, modest improvements in efficiency in irrigation would free up enough freshwater for aquatic habitats and other human uses such as CCS.

The finding that 32% of CFPP are exposed to water scarcity for at least five months per year shows that these coal-generating units might not be well suited for retrofitting with CCS if alternative water sources are not implemented. If CFPP were to be retrofitted with CCS, it will mainly take place in India and China (Figure 6), where 80% (858 GW) of global CFPP capacity has been built after year 2000 and where 309 additional GW are planned or under construction **(Cui et al., 2019)**. We find, however, that these two countries have already a vast share of CFPP capacity exposed to water scarcity and the addition of CCS would further increase the vulnerability of their CFPP to water scarcity and potentially strand their CCS operations. Decision makers, energy corporations, and investors will have to consider the tradeoffs between the climate change mitigation benefits and the increased pressure on local water scarce resources of CCS.

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Constraints on water availability already influence the location of power plants planned for the near future and the choice of cooling technologies. In China, the need to adapt to growing water scarcity has resulted in fewer water intensive cooling systems in new power plants and the refurbishment of existing ones[16, 46]. Investors are also becoming increasingly concerned with the effects of water scarcity. For instance, because wind and solar power production require less water than once-through coal-fired plants, UBS, a global leading investment firm, is recommending its investors to buy low water intensive wind power assets and sell coal-fired assets to avoid exposure to risks associated with water scarcity[47]. Moreover, energy corporations and investors should pay more attention to water as a risk for their business operations when they plan for investments in coal-fired power plants. As such, our findings have also implications for future investments in the global coal power sector.

We tested the sensitivity of our results to different environmental flow requirements, which are by far the largest factor affecting our results. With the current assumption that 80% of the available water needs to be allocated to environmental flows, we find that 43% and 32% of global CFPP capacity faces water scarcity for at least one and five month per year, respectively. By adopting the less conservative Variable Monthly Flow (VMF) method (**Pastor et al., 2014**), the fraction of CFPP capacity facing at least one and five months of water scarcity decreases to 39% and 23%, respectively.

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In attempting a global analysis like the one presented in this study, some approximations need to be made, and data limitations are inevitable. Water consumption of CFPP can vary up to 20%, depending on coal type, combustion technology, plant efficiency, plant size, and environmental control systems (**Talati et al., 2014**). Because Global Coal Plant Tracker – the dataset containing the CFPP inventory used in this study – does not provide information on these factors, we tested the sensitivity of our water scarcity analysis by increasing and decreasing monthly water consumption estimates of each CFPP by 20%. We find that our results show little sensitivity to this change in water consumption by CFPP. When we increase water consumption, we find that 44% and 34% of global CFPP capacity would face water scarcity for at least one and five months per the year, respectively. By reducing monthly water consumption of each CFPP by 20%, we find that 42% or 30% of global CFPP capacity would by exposed to water scarcity for at least one or five months per year, respectively.

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In an increasingly water scarce and carbon-enriched world, governments will take specific actions targeting CO_2 emissions and water intensive technologies, and investors may want to know whether new environmental policies could reduce viability of coal-fired power generation with CCS systems. Our results enable a more comprehensive understanding of water uses by coal-fired plants and can better inform the management and policy decisions that are critical for a sustainable allocation of water resources in energy production. For coal-fired plants located in water scarce areas, tradeoffs between the climate change mitigation benefits and the increased pressure on water resources of CCS should be weighed. This study shows that the water requirements of CCS technologies should be taken into account while evaluating future CCS

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scenarios because it is crucial to mitigate emissions from the energy sector without compromising on the sustainable use of water resources. Because refineries, natural gas power plants, steel and concrete factories can also be retrofitted with CCS, the analysis presented in this study can be expanded beyond the case of coal-fired power plants.

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METHODS

Global coal-fired plant database

Global Coal Plant Tracker (update as of July 2018) (ref. 48) provides an inventory of all the coal-fired plants with a capacity greater than 30 MW existing around the world. It reports information about location, status, capacity, operating company, plant name, and year of construction of global coal-fired units with a total global estimated operating capacity of 2,003 GW (as for July 2018). The status is classified as “announced”, “pre-permit”, “permitted”, “in construction”, “shelved”, “cancelled”, “operating”, “mothballed”, or “retired”.

Here, we focus only on “operating” coal-fired units with a capacity greater than 100 MW, assuming that investments in CCS retrofitting would not be justified in the case of smaller units. Multiple units belonging to the same coal-fired plant were aggregated into a single power plant. The operating large coal-fired plants that meet the above criteria account for 1927 GW or 96% of total estimated operating capacity from coal-fired plants worldwide[48]. For all these coal plants, we used satellite imageries from Google Earth® to identify cooling types (wet cooling tower, air-cooled condenser, and once-through systems) and the water source used as a cooling medium (seawater or freshwater). Determining cooling technology and cooling water source of coal-fired plants by visual inspection using satellite images has been proved an effective way to fill gaps existing in available data on power plant cooling systems[16]. Wet cooling tower systems are equipped with cooling towers, air-cooled condenser are equipped with air-cooling islands, and once-through cooling systems do not have such cooling systems and are located close to large water bodies. Visual inspection results were also cross-checked when possible with information provided by the operating company listed in the Global Coal Plant Tracker[48].

Assessing water intensities of coal-fired plant with and without CCS

We assessed water consumption intensity and water withdrawal intensity (m^3/MWh) from coal-fired plants using the Baseline Power Plant configuration of the Integrated Environmental

Control Model (IECM Version 11.2) developed by Carnegie Mellon University for the U.S. Department of Energy's National Energy Technology Laboratory (USDOE/NETL)[37]. The IECM Model is a well-documented publicly available model that provides systematic estimates of performance and emissions for fossil-fueled power plants with or without CCS systems[28,37]. Water intensities in the IECM Model do account for the parasitic energy demand of the CCS process. Therefore, the Baseline Power Plant configuration in the model assumes that the additional power required to perform CCS is taken at the expenses of the plant efficiency and therefore less heat and power would be generated. Moreover, the Baseline Power Plant configuration in the IECM Model does consider that each CFPP is retrofitted with environmental control systems (selective catalytic reduction, electrostatic precipitator, and wet flue gas desulfurization). We considered the water use by these environmental control systems both in the scenarios with and without CCS.

For each coal-fired unit, water intensity was assessed considering 1) a current, and 2) four hypothetic future scenarios. In the current scenario, we assessed water intensity of each coal-fired unit considering its cooling system (wet cooling tower, air-cooled condenser, and once-through). In the future scenario we assumed that only CFPP operating after year 2000 (1,093 CFPP or 1018 GW) will be retrofitted with CCS units considering four different CCS technologies: absorption with amine solvents, membrane separation, and adsorption with pressure swing (PSA) and temperature swing (TSA) capture systems. For each scenario and for each unit we assessed water intensity considering local average monthly air temperature and its gross power input. Average monthly temperatures at 5 × 5 arcminute resolution were taken from Fick et al., (2017)[49]. Coal type (anthracite, lignite, bituminous, sub-bituminous), combustion technology (supercritical, sub-critical, ultra-supercritical), plant efficiency, plant size, environmental control systems (selective catalytic reduction, electrostatic precipitator, and wet flue gas desulfurization for removing nitrogen oxides, fly ash, and sulfur dioxide, respectively, from the flue gas), and CO_2 capture level are other factors that influence water intensity of a CFPP (Talati et al., 2014). Because the Global Coal Plant Tracker database used in this study does not contain detailed information about these factors, we tested the sensitivity of our results to ±20% changes in monthly water consumption in each CFPP.

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For each coal-fired unit we assessed monthly water consumption and water withdrawals (m^3/month) by multiplying its monthly water intensity (m^3/MWh) times the coal-fired unit capacity by a 50% capacity factor and the number of hours in each month. The 50% capacity factor is a conservative assumption given that the global average capacity factor of coal-fired plants was 52.5% in year 2016 (ref. 13), and also considering that we are experiencing a reduction in coal use owing to natural gas conversion[50,51].

Water scarcity analysis

Monthly water scarcity (5 × 5 arcminute resolution) was assessed combining the monthly availability and consumption of freshwater resources. Coal-fired plants are located in water scarce areas if the ratio between freshwater consumption (WC) and available water (WA) is greater than one[22]. This methodology to evaluate water scarcity has been extensively validated in studies aiming at analyzing the influence of energy and agricultural production on water resources[39,42,52]. WC accounts for freshwater consumption for irrigation, domestic uses, and coal-fired plants. For this reason, coal-fired plants cooled with seawater were not considered in the water scarcity analysis, because they do not consume freshwater in their operations. Monthly available water (WA) (5 × 5 arcminute resolution, or ~10km at the Equator) was calculated as the difference between monthly blue water flows generated in that grid cell and the environmental flow requirement. Monthly blue water flows (2011-2015 period) were assessed by adding up for every cell routed river discharge and groundwater discharge. Discharge data were taken from PCR-GLOBWB-2 outputs (Sutanudjaja et al., 2018; Wanders et al., 2019). Upstream water consumption and its unavailability for downstream uses were accounted for by considering - for every cell of the landscape - all water uses (agriculture, industrial, municipal, and environmental flows). Irrigation water consumption (at 5 × 5 arcminute resolution) was taken from Rosa et al. (2019) (ref. XX) and was assessed using a process-based crop water model that estimated irrigation water consumption for major crops. Domestic water consumption (at 5 × 5 arcminute resolution) was taken from Hoekstra and Mekonnen (2012) (ref. 45) and assessed using country-specific per capita values multiplied by the local population taken from population density maps. We assumed that coal-fired plants cooled with seawater face no water scarcity and only land-based water plants are at risk of water scarcity.

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Environmental flow is here defined as the minimum freshwater flow that is required to sustain ecosystem functions. Environmental flow requirements were accounted for in our water scarcity analysis[20,39,40,44], assuming that 80% of the monthly blue water flows should be preserved for environmental flows protection (i.e., remain unavailable to human consumption) to maintain ecosystem functions[38].

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Uncertainties, assumption, and limitations

Our results are based on a biophysical model and on assumptions that are always necessary in any global modelling study. First, decisions to retrofit existing plants with CCS are complicated and involve many factors such as plant age and size, economic viability, land restraints, and location close to geological formations suitable for carbon storage. The analysis of these factors falls outside of the scope of this work. We also do not consider the potential impacts that carbon dioxide storage could have on regional groundwater quality and therefore water availability[54,55]. Second, we assumed that current power plants cooled with seawater will also withdraw and consume seawater (in the same proportion) when retrofitted with CCS. Third, while our water balance model considers water consumption and accounts for the need to protect environmental flows that are crucial to the health of freshwater ecosystems, it does not evaluate other environmental and economic impacts associated with water withdrawals from coal-fired plants, which involve local effects that a global analysis fails to assess. Moreover, quantifying water scarcity using water withdrawals might overestimate water scarcity since return flows can be used multiple times. For example, water withdrawals in the Colorado River Basin exceed water availability because of substantial reuse of return flows. Therefore, we assessed water scarcity using water consumption. Fourth, because hybrid-cooling technology (wet cooling paired with air-cooling) is a relatively new technology, we did not consider this cooling technology in our analysis. Fifth, power plants located in water scarce areas are unlikely to remain water stranded in the sense that they are expected to continue their operation in months of water scarcity by sourcing water through inter-basin water transfers, artificial reservoirs, mining non-renewable groundwater, building desalination plants, or using water at the expenses of environmental flows. Alternatively, water stranding can be avoided by lowering power production or by retrofitting coal-fired plants with emerging technologies that have lower water intensity (e.g. air-cooled systems)[16], although, at the expense of increased energy consumption and economic costs[56,57]. Furthermore, there are also opportunities to use desalinated brine from saline carbon dioxide sequestration aquifers to provide alternative freshwater sources and offset the additional water requirements of CCS[33]. These are economic, institutional, and non-biophysical factors that our hydrological model were unable to take into account. Moreover, energy corporations can prevent a shut-down (and associated losses) during periods of water scarcity by buying water from other sectors (typically agriculture, in the presence of tradeable water rights) and paying more attention to water as a risk for their business operations[47]. Today, the reliability of coal-fired generators is quite high in the sense that they rarely experience power losses associated with water availability limitations[15,58]. Curtailments or shutdowns during dry periods are seldom due to constraints in water availability but to the ability to cool down water when its temperature exceeds environmental regulatory thresholds for discharge in water bodies[58,59].

Lastly, our analysis considers the possibility to retrofit global coal-fired power plants with post-combustion carbon capture and storage technologies. However, post-combustion carbon capture and storage is an emerging technology not just for coal-fired generation, but also for other industrial (Kätelhön et al., 2019) and energy CO_2 sources[60,Siegelman et al.,] 2019. Other technologies also could be deployed to capture carbon such as pre-combustion and oxy-combustion[26,61]. Another promising technology is to remove carbon dioxide from the atmosphere and generate negative emissions via Bioenergy with Carbon Capture and Storage (BECCS)[62] or Direct Air Capture (DAC) (Realmonte et al., 2019).

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Conflict of Interest: The authors declare no conflict of interest.

Data Availability: Data used to perform this work can be found in the Supplementary Information and in the reference list. Any further data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPLEMENTARY MATERIALS

Contents:

Table S1 shows global water consumption and withdrawal by sector.

Table S2 shows share of coal-fired capacity facing water scarcity during a given number of months per year considering the different scenarios run in this study.

Table S3 to S4 show water consumption and withdrawals values per month from coal-fired plants.

Table S5 shows country-specific coal fired capacity built after year 2000 that would see an exacerbation in water scarcity by at least one month per year if were retrofitted with off-the-shelf amine based absorption CCS technology.

Table S6 to S10 show design parameters of coal-fired power plants with and without carbon capture and storage (CCS) units. Values reported are from the Baseline Power Plant in IECM model (IECM, 2009).

Figure S1 to S8 show schematic representations of cooling technologies and post-combustion carbon capture and storage technologies.

Figure S9 show additional water scarcity with different carbon capture technologies.

Countries belonging to the regions used in Figure 5:

Europe: Austria, Bosnia & Herzegovina, Bulgaria, Czech Republic, Denmark, Finland, France, North Macedonia, Germany, Greece, Hungary, Ireland, Italy, Kosovo, Moldova, Montenegro, Netherlands, North Macedonia, Poland, Portugal, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Ukraine, United Kingdom.

Rest of Asia: Bangladesh, Cambodia, Indonesia, Japan, Kazakhstan, Kyrgyzstan, Israel, Laos, Malaysia, Mongolia, North Korea, South Korea, Pakistan, Philippines, South Korea, Sri Lanka, Thailand, Turkey, Uzbekistan, Vietnam.

Rest of the World: Argentina, Australia, Botswana, Brazil, Canada, Chile, Colombia, Dominican Republic, Guatemala, Mexico, Morocco, New Zealand, Peru, South Africa, Zambia, Zimbabwe.

Table S1. Global water consumption and withdrawal by sector.

SECTOR	Water Withdrawal ($km^3\ y^{-1}$)	Source	Water Consumption ($km^3\ y^{-1}$)	Source
Agriculture	2,410	(2)	847-1180	(3,4)
Domestic	400-450	(5)	42	(6)
Primary Energy Production	47	(7)	30	(7)
Power Generation (Total)	350	(7)	17	(7)
Coal-fired power plants (current)	204	This Study	10	This Study
Coal-fired power plants retrofitted with CCS	249-269	This Study	13-15	This Study

Table S2. Share of coal-fired capacity **currently** facing water scarcity during a given number of months per year considering the different scenarios run in this study. **1)** water scarcity considering average monthly available water in the 2011-2015 period and 80% environmental flow threshold; **2)** water scarcity considering average monthly available water in the 2011-2015 period and Variable Monthly Flow Method[1] for environmental flow requirements; **3)** water scarcity considering average monthly available water in the 2011-2015 period, 80% environmental flow threshold, and an increase by 20% in water consumption from coal plants; **4)** current water scarcity considering average monthly available water in the 2011-2015 period, 80% environmental flow threshold, and a decrease by 20% in water consumption from coal plants; **5), 6), 7), 8), 9)** water scarcity considering monthly available water in the 2011, 2012, 2013, 2014, 2015, respectively and an 80% environmental flow threshold.

Number of Months per year	**1)**	**2)**	**3)**	**4)**	**5)**	**6)**	**7)**	**8)**	**9)**
Not Facing Water Scarcity									
0	57%	61%	56%	58%	55%	54%	54%	55%	56%
Facing Water Scarcity									
1	43%	39%	44%	42%	45%	46%	46%	45%	44%
2	41%	36%	42%	39%	43%	43%	42%	43%	41%
3	39%	30%	40%	37%	41%	40%	38%	40%	39%
4	36%	27%	38%	34%	39%	38%	36%	37%	37%
5	32%	23%	34%	30%	35%	35%	33%	34%	34%
6	30%	20%	32%	28%	31%	30%	29%	31%	31%
7	26%	16%	28%	25%	27%	27%	26%	28%	27%
8	18%	10%	19%	16%	18%	18%	18%	18%	17%
9	14%	7%	16%	13%	14%	14%	14%	15%	14%
10	8%	4%	9%	7%	9%	8%	7%	8%	8%
11	7%	4%	7%	6%	7%	6%	6%	7%	6%
12	5%	3%	5%	4%	5%	5%	5%	5%	6%

Table S3. Monthly water consumption by global coal-fired plants considering the current and the four CCS scenarios considered in this study.

	Current (×10^9 km^3)	**Absorption (×10^9 km^3)**	**Membrane (×10^9 km^3)**	**Solid Sorbents PSA (×10^9 km^3)**	**Solid Sorbents TSA (×10^9 km^3)**
January	0.70	0.31	0.21	0.22	0.30
February	0.67	0.28	0.21	0.21	0.29
March	0.78	0.33	0.24	0.25	0.33
April	0.81	0.34	0.25	0.26	0.34
May	0.87	0.37	0.27	0.28	0.36
June	0.86	0.37	0.27	0.28	0.36
July	0.90	0.38	0.28	0.30	0.38
August	0.90	0.52	0.28	0.30	0.37
September	0.84	0.49	0.26	0.28	0.35
October	0.83	0.49	0.26	0.27	0.35
November	0.75	0.46	0.23	0.24	0.32
December	0.74	0.45	0.23	0.23	0.32
Total	9.66	4.81	3.00	3.13	4.07

Table S4. Monthly water withdrawals by global coal-fired plants considering the current and the four CCS scenarios considered in this study.

	Current ($\times10^9$ km^3)	**Absorption ($\times10^9$ km^3)**	**Membrane ($\times10^9$ km^3)**	**Solid Sorbents PSA ($\times10^9$ km^3)**	**Solid Sorbents TSA ($\times10^9$ km^3)**
January	17.26	5.58	3.90	4.06	4.75
February	15.59	5.04	3.52	3.66	4.29
March	17.31	5.55	3.87	4.02	4.72
April	16.81	5.33	3.70	3.85	4.53
May	17.42	5.48	3.80	3.95	4.65
June	16.89	5.28	3.66	3.81	4.48
July	17.47	5.45	3.77	3.93	4.63
August	17.46	5.46	3.78	3.93	4.63
September	16.86	5.30	3.68	3.83	4.50
October	17.37	5.51	3.83	3.99	4.68
November	16.75	5.37	3.75	3.90	4.57
December	17.25	5.58	3.90	4.06	4.76
Total	204.44	64.93	45.15	46.99	55.20

Table S5. Country-specific coal fired capacity (MW) built after year 2000 that would see an exacerbation in water scarcity by at least one month per year if were retrofitted with off-the-shelf amine based absorption CCS technology.

	Facing exacerbation of water scarcity (MW)	**Total capacity built after year 2000 (MW)**	**Fraction of total capacity**
Argentina	120	120	100%
Australia	1863	2308	81%
Austria	0	0	-
Bangladesh	0	250	0%
Bosnia & Herzegovina	0	300	0%
Botswana	600	600	100%
Brazil	670	3220	21%
Bulgaria	0	791	0%
Cambodia	0	405	0%
Canada	0	707	0%
Chile	0	1662	0%
China	167936	718001	23%
Colombia	0	487	0%
Czech Republic	405	1155	35%
Denmark	0	0	-
Dominican Republic	0	0	-
Finland	0	0	-

France	0	0	-
North Macedonia	0	0	-
Germany	0	4845	0%
Greece	330	330	100%
Guatemala	300	439	68%
Hungary	0	0	-
India	52090	139702	37%
Indonesia	0	20344	0%
Ireland	0	0	-
Israel	0	2250	0%
Italy	0	1320	0%
Japan	0	16063	0%
Kazakhstan	120	240	50%
Kosovo	0	0	-
Kyrgyzstan	0	300	0%
Laos	1878	1878	100%
Malaysia	0	9198	0%
Mexico	0	0	-
Moldova	0	0	-
Mongolia	0	0	-
Montenegro	0	0	-
Morocco	0	350	0%
Netherlands	0	2400	0%
New Zealand	0	0	
North Korea	0	600	0%
Pakistan	0	4200	0%
Peru	0	0	
Philippines	0	4613	0%
Poland	0	1295	0%
Portugal	0	0	-
Romania	0	0	-
Russia	0	2048	0%
Serbia	0	0	-
Slovakia	192	192	100%
Slovenia	0	0	-
South Africa	794	3970	20%
South Korea	0	15474	0%
Spain	0	0	-
Sri Lanka	0	900	0%
Sweden	0	0	-
Taiwan	0	3995	0%

Taiwan, China	0	800	0%
Thailand	0	2684	0%
Turkey	625	10542	6%
Ukraine	0	0	-
United Kingdom	0	0	-
United States	3143	20264	16%
Uzbekistan	0	150	0%
Vietnam	660	16462	4%
Zambia	450	450	100%
Zimbabwe	0	0	-

Table S6. Design Parameters for the Baseline Power Plant in IECM[8].

Parameter	Value
Plant Type	Supercritical Pulverized Coal
Steam Cycle Heat Rate (kJ/kWh)	7764
Plant Capacity Factor (%)	50
Ambient Air Pressure (kPa)	101.35
Relative Humidity (%)	50
Environmental Control Systems:	
Nitrogen Dioxide	Selective Catalytic Reduction
Particulates	Electrostatic Precipitator
Sulfur Dioxide	Flue Gas Desulfurization
Carbon Dioxide	Carbon Capture and Storage
CO_2 removal efficiency (%)	90
CO_2 Product Pressure (MPa)	13.79
CO_2 Compressor Efficiency (%)	80.00

Table S7. Detailed Performance Parameters of a Baseline Power Plant retrofitted with Amine-based absorption Capture System[8].

Parameter	Value
Amine-based capture system type	Econamine FG+

CO2 removal efficiency (%)	90.0
Sorbent concentration (wt, %)	30.0
Temperature exiting direct contact cooler (ºC)	45
Maximum train CO2 capacity (tonnes/h)	209
Max CO2 compressor capacity (tonnes/h)	299
Lean CO2 loading (mol CO2/mol sorbent)	0.19
Nominal sorbent loss (kg/tonne CO2)	0.30
Liquid-to-gas ratio	3.1
Ammonia generation (mol NH_3/mol sorbent)	1.0
Gas phase pressure drop (kPa)	6.9
Solvent pumping head (kPa)	206.8
Pump efficiency (%)	75
Heat-to-electricity efficiency (%)	18.70
Makeup water for washing (% of flue gases)	0.8
Regeneration heat requirement (kJ/kg CO_2)	3538

Table S8. Detailed Performance Parameters of a Baseline Power Plant retrofitted with Membrane based Capture System[8].

Parameter	Value
Membrane-based capture system type	2-Step with Air Sweep
CO_2 removal efficiency (%)	90.0
CO_2 Permeance (S.T.P)	3500
CO_2/N_2 Selectivity (S.T.P.)	35.00
Vacuum Pressure in Cross Flow Membrane (bar)	0.20
Vacuum Pump Efficiency (%)	85.00
Membrane Operation Temperature (ºC)	50.00

Table S9. Detailed Performance Parameters of a Baseline Power Plant retrofitted with Solid Sorbents adsorption PSA based Capture System[8].

Parameter	Value
Solid Sorbet Type	ZIF-78
CO_2 removal efficiency (%)	90.0
System configuration	Single Stage PSA
Adsorber Temperature (ºC)	35.00
Adsorber Pressure (bar)	1.500
Desorption Pressure (bar)	2.18×10^{-2}
Flue Gas Compressor Efficiency (%)	85.00
Vacuum Pump Efficiency (%)	85.00

Table S10. Detailed Performance Parameters of a Baseline Power Plant retrofitted with Solid Sorbents adsorption TSA based Capture System[8].

Parameter	Value
System Used	CCSI/NETL 32D
CO_2 removal efficiency (%)	90.0
Sorbent Name	NETL 32D
Maximum CO_2 Adsorption Capacity (mol CO_2/ kg sorbent)	3.500
Adsorber Temperature (ºC)	53.00
Regenerator Operating Temperature (ºC)	136.00

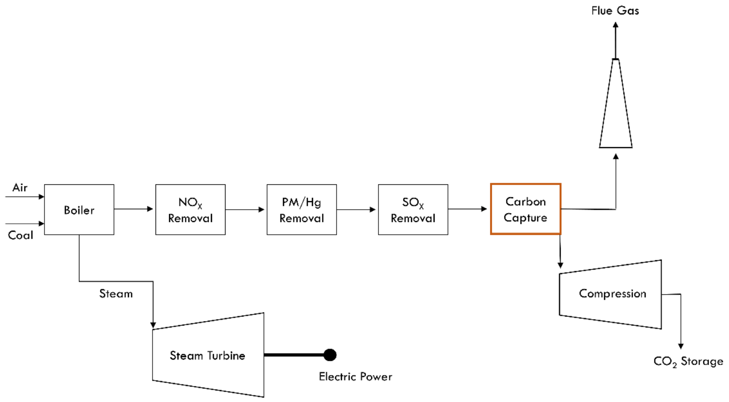

Figure S1. Schematic representation of coal-fired power plant with post-combustion carbon capture. A state-of-the-art coal-fired power plant has environmental control systems to remove nitrogen dioxide (NO$_X$ removal), particulates and mercury (PM/Hg removal), sulfur dioxide (SO$_X$ removal), and carbon capture for carbon dioxide (CO$_2$ removal)^{9}.

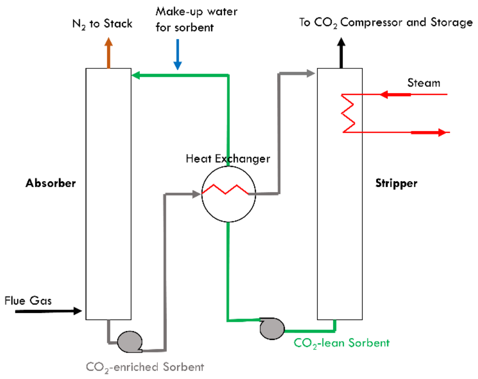

Figure S2. In an absorption process, a solvent is cycled between an absorber, where CO$_2$ is captured, and a stripper where the CO$_2$ is released through heating by steam from a power plant.

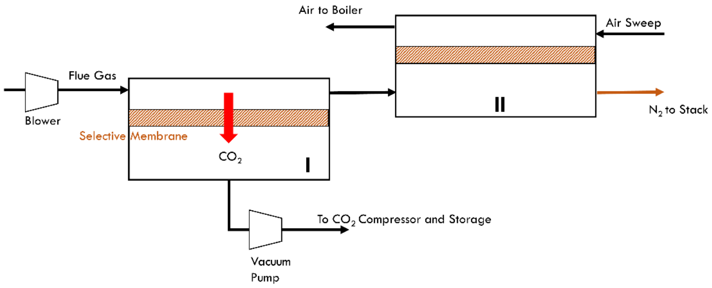

Figure S3. A 2-step counterflow with air sweep membrane separation. In this process, air is used as a sweep gas in membrane module II and hence the air fed to the boiler and burn coal with CO_2-enriched air[9].

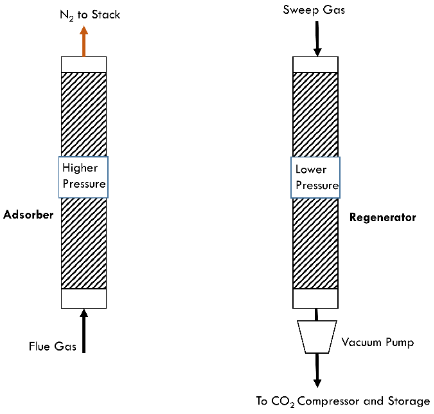

Figure S4. Pressure Swing Adsorption. In a fixed bed absorber, CO_2 is captured in two steps. In the adsorber, CO_2 is selectively adsorbed from the flue gas at high pressure (1.5 atm). Once the adsorbent is saturated with CO_2, the adsorbent is regenerated at low pressure and a pure stream of CO_2 is produced.

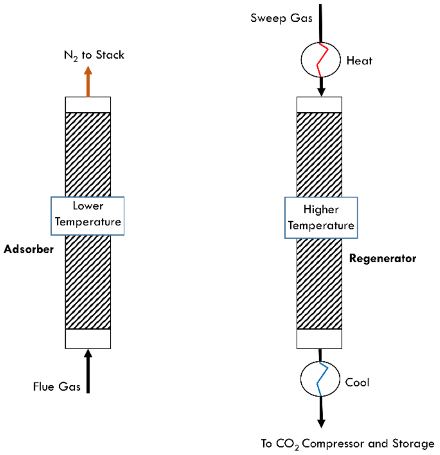

Figure S5. Temperature Swing Adsorption. In a fixed bed absorber, CO_2 is captured in two steps. In the adsorber, CO_2 is selectively adsorbed from the flue gas at low temperature. Once the adsorbent is saturated with CO_2, the adsorbent is regenerated at high temperature and a pure stream of CO_2 is produced.

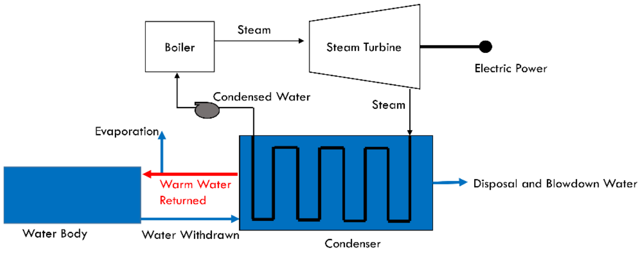

Figure S6. Schematic representation of a once-through cooling system.

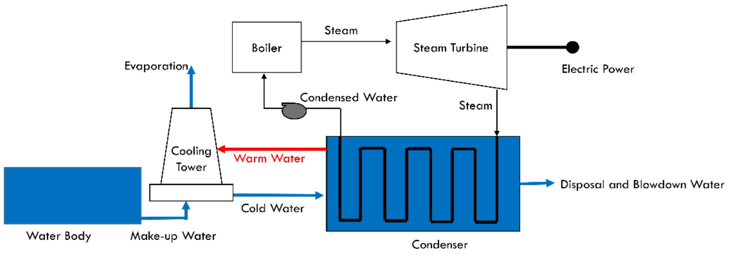

Figure S7. Schematic representation of a wet cooling tower system.

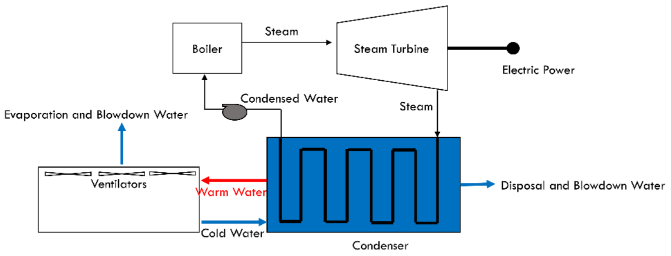

Figure S8. Schematic representation of an air cooled system.

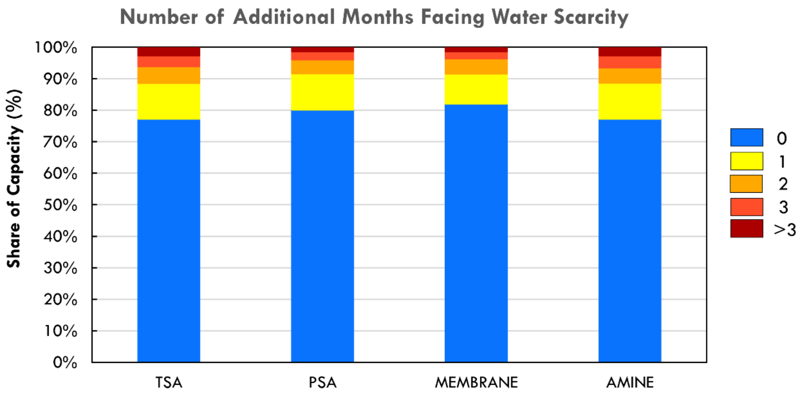

Figure S9. Additional water scarcity with different carbon capture technologies. The figure shows the number of additional months of water scarcity per year that global coal fired power plants (built after year 2000) would face if were retrofitted with the four CCS technologies considered in this study.

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