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

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11

12 **ABSTRACT**

13 **Post-combustion carbon capture and storage (CCS) is an important technology to reduce**
14 **CO₂ emissions from the electricity and industrial sectors. Despite the mounting concerns**
15 **about global water scarcity and its impact on energy production, the potential hydrological**
16 **consequences of large-scale CCS have not yet been explored. Here we simulate the impacts**
17 **on water resources that would result from retrofitting global coal-fired power plants**
18 **(CFPP) with four different CCS technologies. We find that 43% of global CFPP capacity**
19 **currently experience water scarcity at least one month per year and 32% experience**
20 **scarcity for five or more months during the year. Addition of CCS does increase water**
21 **scarcity, and the extent to which it does so depends on the technology. We show that the**
22 **choice of what CFPP to retrofit and what CCS technologies to deploy will be essential in**
23 **preventing additional water scarcity. If CCS were to be pursued, facilities not affected by**
24 **water scarcity should be selected.**

25 Globally coal-fired plants account for 38% of electricity generation¹ and 19% (8.9 Gt CO₂ y⁻
26 ¹) of total CO₂ emissions². Coal generation is also a primary source of toxic airborne emissions
27 globally³. Despite the growing reliance on renewable energy and the recent policy efforts aimed
28 at reducing the use of coal⁴, today the global coal dependence for power generation is the same
29 as twenty years ago¹. Since the turn of the 21st century, population growth, increasing affluence,
30 and industrialization in developing countries have demanded an unprecedented growth in coal

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37 consumption (+57%) (ref. 1), leading to a boom in the construction of CFPP². Given that each
38 new coal plant is at least a billion-dollar investment with a 30- to 50-year lifetime⁵, currently
39 operating CFPP commit the energy sector to emissions above the levels compatible with 1.5-2° C
40 climate change scenarios⁶ and commit fresh water consumption to levels that potentially compete
41 with natural ecosystems and other human uses⁷⁻²¹. These commitments ostensibly address the
42 increasing concerns for global water scarcity²² and humankind's ability to meet its burgeoning
43 food and energy needs²³.

44
45 The twin costs of mitigating climate change and competing for water resources are vexing
46 factors in managing energy systems. Although there is a portfolio of technologies that can
47 provide a long-term substitute for coal, any reasonable action for mitigating these factors must
48 curtail CO₂ emissions and water use from CFPP without requiring write-off of these assets and
49 their committed billion-dollar investments²⁴. Post-combustion carbon capture and storage
50 (hereunder CCS) is the preferred economically viable technology to reduce CFPP carbon emissions
51 because it can be added to existing plants to reduce emissions without having to decommission
52 power plants²⁵. To date, however, a global assessment of the potential impacts of CCS on water
53 resources – should the CFPP existing around the world be retrofitted with CCS technologies – is
54 missing. As we continue to evaluate the cost-effectiveness of different climate change mitigation
55 technologies, the assessment of potential water limits to CCS can provide relevant insights.

56
57 The four main CCS technologies used to retrofit CFPP are based on absorption with amine
58 solvents, membrane separation, solid sorbents adsorption with either pressure swing (PSA) or
59 temperature swing (TSA) capture systems. While amine-based absorption is a proven
60 commercially available technology, membranes and adsorption-based CCS systems appear
61 promising, but they are at a much lower stage of development²⁶. All of these CO₂ capture
62 technologies are energy-intensive processes²⁷ that would impose parasitic power demand on the
63 existing power plant and thus make it less efficient²⁶. The additional power generation required
64 for CCS would result in additional water consumption for the CFPP cooling process²⁸.
65 Moreover, additional water is required as an integral part to the carbon capture processes²⁹. In
66 fact, recent work has assessed that a post-combustion amine absorption process would nearly double.

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

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76 Previous research has simulated water risks of power generation with CCS in the United
77 States³¹⁻³⁴, Europe³⁵, and the UK³⁶. These studies, however, did not adopt a monthly hydrological
78 model to quantify potential impacts on water resources. Their focus was on regional-scale
79 analyses of water requirements from the absorption process without considering other CCS
80 technologies. As important as these studies are, it remains unclear whether CCS might induce or
81 exacerbate water scarcity at specified times of the year, nor is it clear what the water intensity
82 differences are for the various CCS technologies. This limited hydrological understanding of the
83 potential impacts of CCS adds uncertainties on the environmental consequences of the
84 implementation of CCS worldwide.

85 Herein we present a global hydrological analysis of the potential impacts on water resources
86 that would result from retrofitting large (> 100 MW of gross capacity) CFPP with four CCS
87 capture systems: amine absorption, solid sorbents pressure swing adsorption (PSA) or
88 temperature swing adsorption (TSA), and membrane systems. This analysis begins with a
89 monthly, regional assessment of water scarcity experienced by current CFPP. For each CFPP,
90 then, we assess its monthly water withdrawal and consumption using the Integrated
91 Environmental Control Model (IECM Version 11.2)³⁷, and analyze its exposure to water
92 scarcity. A proper assessment of water withdrawals, consumption, and scarcity can facilitate the
93 development of sustainable water management practices and shed light on regional hydrologic
94 impacts of CCS. Our study promotes the understanding of the water requirements of CCS and
95 provides relevant insights to mitigate CO₂ emissions from the electricity and industrial sectors
96 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 one²². 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 CO₂ from the flue gas of power plants. Once captured, CO₂ is compressed to its supercritical state and transported and injected into a safe geological formation (Supplementary Figure 1).

Absorption is a CCS technology based on a liquid solvent used to dissolve CO₂ molecules (absorb) into a liquid solution such as aqueous amines. The CO₂-enriched liquid solution is pumped in a regenerator where it is heated to liberate gaseous CO₂ and the lean solution is circulated back to the absorber (Supplementary Figure 2).

Membrane Separation is a CCS technology used to separate CO₂ from the flue gas by selectively permeating it through a membrane material. CO₂ 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 CO₂ molecules onto the surface of another material. The CO₂-enriched solid sorbent is regenerated using low pressure (**Pressure Swing Adsorption (PSA)**) or high temperature (**Temperature Swing Adsorption (TSA)**) where gaseous CO₂ is liberated and the lean solid sorbent is reused again to capture CO₂ (Supplementary Figure 4 and 5).

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115 **Present day monthly, regional water scarcity at CFPP**

116 Global hydrological models are powerful tools to simulate and quantify changes in water
117 availability and consumption. Here, we use water scarcity as an indicator of where, in what
118 period of the year, and for how long, CFPP **without CCS systems** are vulnerable to risks of
119 limited water availability. Our hydrological analysis uses a monthly biophysical water balance
120 model that accounts for water consumption for irrigation, domestic, and coal-fired power
121 generation needs, as well as for environmental flows required to maintain the health of aquatic
122 ecosystems. Although we do consider inter-annual variability in water resources, our main water
123 scarcity results are shown considering long term monthly average available water in the 2011-
124 2015 period.

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

132
133 **Figure 1. Coal-fired capacity (GW) and share of coal fired capacity (%) facing water**
134 **scarcity for the specified number of months per year.**

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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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165 The analysis of the share of CFPP capacity currently facing water scarcity in different
 166 regions of the world and months of the year shows that in China more than ~~30~~ of the installed
 167 capacity faces water scarcity from March to ~~October~~ (Figure 3a). In the United States at least
 168 20% of coal capacity faces water scarcity from April to November. A similar picture can be
 169 found in Europe, where at least 20% of coal capacity faces water scarcity from June to
 170 September. More than ~~40~~ of India's coal capacity faces water scarcity in the dry season
 171 (~~December~~ to June). CFPP located in other Asian countries are not particularly exposed to water
 172 scarcity because of high water availability and their construction along the coast using seawater
 173 as a cooling medium. It is worth noting that for those global CFPP that use fresh water for
 174 cooling, the predominant cooling technologies are wet cooling towers (60% of total capacity),
 175 followed by once-through systems (35%), and air-cooling (5%) (Figure 3b). Air-cooling is a
 176 relatively new technology and 90% of its capacity is located at new plants in China and India.
 177 About 22% of global coal-fired operating capacity is cooled using seawater, while the remaining
 178 78% uses freshwater.

180 The analysis of the coal-fired capacity facing water scarcity by cooling technology shows
 181 that ~~60~~% (~~728~~ GW) of the units cooled with wet cooling towers face water scarcity for at least
 182 one month per year. Because of their lower water intensity (Figure 4), air-cooled systems are
 183 usually implemented in newly built units located in arid and/or water scarce areas. In fact, we
 184 find that ~~72~~% (~~67~~ GW) of CFPP cooled using air-cooled systems are facing water scarcity. While
 185 ~~56~~% (~~360~~ GW) of once-through cooled capacity uses seawater as a cooling medium and
 186 therefore is not affected by water scarcity, only ~~6~~% (~~36~~ GW) of once-through generating
 187 capacity is exposed to water scarcity. China has ~~62~~% (~~403~~ GW) and ~~74~~% (~~53~~ GW) of its wet
 188 cooled and air-cooled coal-fired plants, respectively exposed to at least one month of water
 189 scarcity per year (Figure 3b). The United States and India have ~~60~~% (~~89~~ GW) and ~~63~~% (~~113~~
 190 GW) of their wet cooled coal-fired units exposed to water scarcity for at least one month per
 191 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

221 Using the water balance approach described above, we turn to an important aspect of future
222 decisions regarding CCS, namely to what extent the available freshwater resources would allow
223 for the adoption of CCS as a means to curb carbon emissions by the existing CFPP. Meeting
224 humanity's burgeoning energy and water demand while avoiding an increase in anthropogenic
225 CO₂ emissions and protecting environmental flows is one of the most pressing challenges of this
226 century.

227
228 Given that old and low-efficiency CFPP without environmental control systems will likely
229 shut down and will not be retrofitted with expensive CCS technologies, we assumed that only
230 1,093 large (>100 MW) CFPP operating since year 2000 will be retrofitted with CCS and
231 capture 90% of their CO₂ emissions by 2020. Because of this relatively short timeframe, we
232 assume that water availability and coal-fired generation would not substantially change
233 compared to current conditions. Although this scenario is not meant to be a realistic
234 representation of the rate of adoption of CCS to CFPP, it allows us to assess the impacts of CCS
235 retrofit on water resources. Moreover, this assumption is in line with the urgent need to
236 drastically reduce global CO₂ emissions from CFPP in order to meet climate targets (Rogelj et
237 al., 2018). This analysis provides the estimated additional water withdrawals and consumption
238 from coal-fired generators considering 1) current 1,888 CFPP, and 2) four hypothetical scenarios
239 where the 1,093 large CFPP are retrofitted with CCS units.

240 **Water intensity, consumption, and withdrawals of CCS**

241 Our estimates show that the water intensity of CFPP with and without CCS technologies
242 strongly vary with the type of cooling system and CCS technology (Figure 4). Interval bars show
243 that water intensity from air-cooling and once-through cooling technologies can differ by up to
244 4% with different air temperatures, relative humidity, and gross power inputs, while for wet
245 cooling it can vary up to 20%. CFPP with wet cooling towers retrofitted with CCS units have the
246 highest water consumption intensity, while CFPP with once-through cooling technology have the
247 highest water withdrawal intensity. Independent of the cooling system, the least water intensive
248 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.

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

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274 in water consumption. Current total global water consumption from CFPP is $9.66 \text{ km}^3 \text{ y}^{-1}$, of this
 275 volume 88% is sourced from freshwater, while the remaining 12% is sourced from seawater
 276 (Figure 5). China, with 48% of world's CFPP capacity, has also the greatest share in freshwater
 277 consumption (53%), followed by India (16%), and the United States (13%). By retrofitting CFPP
 278 built after year 2000 with the off-the-shelf amine absorption technology, global water
 279 consumption by CFPP would increase by 50% ($4.81 \text{ km}^3 \text{ y}^{-1}$). If CFPP were all retrofitted with
 280 membranes, water consumption would increase by 31% ($3.00 \text{ km}^3 \text{ y}^{-1}$). Water consumption
 281 would increase by 32% ($3.13 \text{ km}^3 \text{ y}^{-1}$) and 42% ($4.07 \text{ km}^3 \text{ y}^{-1}$) in the case, CFPP were retrofitted
 282 with solid sorbent PSA, and solid sorbent TSA, respectively. Assuming that current CFPP cooled
 283 with seawater will use seawater when retrofitted with CCS, $0.69\text{--}1.10 \text{ km}^3 \text{ y}^{-1}$ of this additional
 284 water consumption would come from seawater, while the remaining fraction ($2.31\text{--}3.71 \text{ km}^3 \text{ y}^{-1}$)
 285 would be consumed from freshwater bodies. Similar results can be found in terms of water
 286 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 km³ 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 km³ y⁻¹), India (71% or 9.5 km³ y⁻¹), and Japan (99% or 12 km³ y⁻¹). By retrofitting CFPP with CCS systems, the global water withdrawals (seawater and freshwater combined) would increase by 32% (65 km³ y⁻¹), 22% (45 km³ y⁻¹), 23% (47 km³ y⁻¹), or 27% (55 km³ y⁻¹), with amine, membranes, solid sorbent PSA, and solid sorbent TSA, respectively.

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 they 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 CO₂ emissions. Our results show that cooling systems and CCS technologies have different water requirements, in terms of both

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

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

406 Constraints on water availability already influence the location of power plants planned for
407 the near future and the choice of cooling technologies. In China, the need to adapt to growing
408 water scarcity has resulted in fewer water intensive cooling systems in new power plants and the
409 refurbishment of existing ones^{16, 46}. Investors are also becoming increasingly concerned with the
410 effects of water scarcity. For instance, because wind and solar power production require less
411 water than once-through coal-fired plants, UBS, a global leading investment firm, is
412 recommending its investors to buy low water intensive wind power assets and sell coal-fired
413 assets to avoid exposure to risks associated with water scarcity⁴⁷. Moreover, energy corporations
414 and investors should pay more attention to water as a risk for their business operations when they

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418 plan for investments in coal-fired power plants. As such, our findings have also implications for
419 future investments in the global coal power sector.

420 We tested the sensitivity of our results to different environmental flow requirements, which
421 are by far the largest factor affecting our results. With the current assumption that 80% of the
422 available water needs to be allocated to environmental flows, we find that 43% and 32% of
423 global CFPP capacity faces water scarcity for at least one and five month per year, respectively.
424 By adopting the less conservative Variable Monthly Flow (VMF) method (Pastor et al., 2014),
425 the fraction of CFPP capacity facing at least one and five months of water scarcity decreases to
426 39% and 23%, respectively.

427 In attempting a global analysis like the one presented in this study, some approximations
428 need to be made, and data limitations are inevitable. Water consumption of CFPP can vary up to
429 20%, depending on coal type, combustion technology, plant efficiency, plant size, and
430 environmental control systems (Talati et al., 2014). Because Global Coal Plant Tracker – the
431 dataset containing the CFPP inventory used in this study – does not provide information on these
432 factors, we tested the sensitivity of our water scarcity analysis by increasing and decreasing
433 monthly water consumption estimates of each CFPP by 20%. We find that our results show little
434 sensitivity to this change in water consumption by CFPP. When we increase water consumption,
435 we find that 44% and 34% of global CFPP capacity would face water scarcity for at least one and
436 five months per the year, respectively. By reducing monthly water consumption of each CFPP by
437 20%, we find that 42% or 30% of global CFPP capacity would be exposed to water scarcity for
438 at least one or five months per year, respectively.

439 In an increasingly water scarce and carbon-enriched world, governments will take specific
440 actions targeting CO₂ emissions and water intensive technologies, and investors may want to
441 know whether new environmental policies could reduce viability of coal-fired power generation
442 with CCS systems. Our results enable a more comprehensive understanding of water uses by
443 coal-fired plants and can better inform the management and policy decisions that are critical for a
444 sustainable allocation of water resources in energy production. For coal-fired plants located in
445 water scarce areas, tradeoffs between the climate change mitigation benefits and the increased
446 pressure on water resources of CCS should be weighed. This study shows that the water
447 requirements of CCS technologies should be taken into account while evaluating future CCS

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

466 METHODS

467 Global coal-fired plant database

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

474 Here, we focus only on “operating” coal-fired units with a capacity greater than 100 MW,
475 assuming that investments in CCS retrofitting would not be justified in the case of smaller units.
476 Multiple units belonging to the same coal-fired plant were aggregated into a single power plant.
477 The operating large coal-fired plants that meet the above criteria account for 1927 GW or 96% of
478 total estimated operating capacity from coal-fired plants worldwide⁴⁸. For all these coal plants,
479 we used satellite imageries from Google Earth® to identify cooling types (wet cooling tower, air-
480 cooled condenser, and once-through systems) and the water source used as a cooling medium
481 (seawater or freshwater). Determining cooling technology and cooling water source of coal-fired
482 plants by visual inspection using satellite images has been proved an effective way to fill gaps
483 existing in available data on power plant cooling systems¹⁶. Wet cooling tower systems are
484 equipped with cooling towers, air-cooled condenser are equipped with air-cooling islands, and
485 once-through cooling systems do not have such cooling systems and are located close to large
486 water bodies. Visual inspection results were also cross-checked when possible with information
487 provided by the operating company listed in the Global Coal Plant Tracker⁴⁸.

488

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

490 We assessed water consumption intensity and water withdrawal intensity (m³/MWh) from
491 coal-fired plants using the Baseline Power Plant configuration of the Integrated Environmental

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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 hypothetical 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 CO₂ 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 $\pm 20\%$ changes in monthly water consumption in each CFPP.

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Deleted: The main factors affecting water intensity are air temperature and the plant's gross power output (IECM, 2009). Therefore, f

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For each coal-fired unit we assessed monthly water consumption and water withdrawals (m³/month) by multiplying its monthly water intensity (m³/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}.

551

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 one²². 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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596 Environmental flow is here defined as the minimum freshwater flow that is required to
597 sustain ecosystem functions. Environmental flow requirements were accounted for in our water
598 scarcity analysis^{20,39,40,44}, assuming that 80% of the monthly blue water flows should be
599 preserved for environmental flows protection (i.e., remain unavailable to human consumption) to
600 maintain ecosystem functions³⁸.

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602 **Uncertainties, assumption, and limitations**

603 Our results are based on a biophysical model and on assumptions that are always necessary
604 in any global modelling study. First, decisions to retrofit existing plants with CCS are
605 complicated and involve many factors such as plant age and size, economic viability, land
606 restraints, and location close to geological formations suitable for carbon storage. The analysis of
607 these factors falls outside of the scope of this work. We also do not consider the potential
608 impacts that carbon dioxide storage could have on regional groundwater quality and therefore
609 water availability^{54,55}. Second, we assumed that current power plants cooled with seawater will
610 also withdraw and consume seawater (in the same proportion) when retrofitted with CCS. Third,
611 while our water balance model considers water consumption and accounts for the need to protect
612 environmental flows that are crucial to the health of freshwater ecosystems, it does not evaluate
613 other environmental and economic impacts associated with water withdrawals from coal-fired
614 plants, which involve local effects that a global analysis fails to assess. Moreover, quantifying
615 water scarcity using water withdrawals might overestimate water scarcity since return flows can
616 be used multiple times. For example, water withdrawals in the Colorado River Basin exceed
617 water availability because of substantial reuse of return flows. Therefore, we assessed water
618 scarcity using water consumption. Fourth, because hybrid-cooling technology (wet cooling
619 paired with air-cooling) is a relatively new technology, we did not consider this cooling
620 technology in our analysis. Fifth, power plants located in water scarce areas are unlikely to
621 remain water stranded in the sense that they are expected to continue their operation in months of
622 water scarcity by sourcing water through inter-basin water transfers, artificial reservoirs, mining
623 non-renewable groundwater, building desalination plants, or using water at the expenses of
624 environmental flows. Alternatively, water stranding can be avoided by lowering power
625 production or by retrofitting coal-fired plants with emerging technologies that have lower water
626 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 CCS³³. 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 operations⁴⁷. 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 CO₂ sources⁶⁰ 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).

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).

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

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

883

884 **Countries belonging to the regions used in Figure 5:**

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

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

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

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900 **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

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904 **Table S2.** Share of coal-fired capacity **currently** facing water scarcity during a given number of
 905 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 Method¹ 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 ($\times 10^9$ km ³)	Absorption ($\times 10^9$ km ³)	Membrane ($\times 10^9$ km ³)	Solid Sorbents PSA ($\times 10^9$ km ³)	Solid Sorbents TSA ($\times 10^9$ 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

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

	Current ($\times 10^9 \text{ km}^3$)	Absorption ($\times 10^9 \text{ km}^3$)	Membrane ($\times 10^9 \text{ km}^3$)	Solid Sorbents PSA ($\times 10^9 \text{ km}^3$)	Solid Sorbents TSA ($\times 10^9 \text{ km}^3$)
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

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923 **Table S5.** Country-specific coal fired capacity (MW) built after year 2000 that would see an
924 exacerbation in water scarcity by at least one month per year if were retrofitted with off-the-shelf
925 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 IECM⁸.

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 System⁸.

Parameter	Value
Amine-based capture system type	Econamine FG+

CO ₂ removal efficiency (%)	90.0
Sorbent concentration (wt, %)	30.0
Temperature exiting direct contact cooler (°C)	45
Maximum train CO ₂ capacity (tonnes/h)	209
Max CO ₂ compressor capacity (tonnes/h)	299
Lean CO ₂ loading (mol CO ₂ /mol sorbent)	0.19
Nominal sorbent loss (kg/tonne CO ₂)	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 System⁸.

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 (°C)	50.00

Table S9. Detailed Performance Parameters of a Baseline Power Plant retrofitted with Solid Sorbents adsorption PSA based Capture System⁸.

Parameter	Value
Solid Sorbet Type	ZIF-78
CO ₂ removal efficiency (%)	90.0
System configuration	Single Stage PSA
Adsorber Temperature (°C)	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

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944 **Table S10.** Detailed Performance Parameters of a Baseline Power Plant retrofitted with Solid
945 Sorbents adsorption TSA based Capture System⁸.
946

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 (°C)	53.00
Regenerator Operating Temperature (°C)	136.00

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949 **Figure S1.** Schematic representation of coal-fired power plant with post-combustion carbon
 950 capture. A state-of-the-art coal-fired power plant has environmental control systems to remove
 951 nitrogen dioxide (NO_x removal), particulates and mercury (PM/Hg removal), sulfur dioxide
 952 (SO_x removal), and carbon capture for carbon dioxide (CO_2 removal)⁹.

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955 **Figure S2.** In an absorption process, a solvent is cycled between an absorber, where CO_2 is
 956 captured, and a stripper where the CO_2 is released through heating by steam from a power plant.

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959 **Figure S3.** A 2-step counterflow with air sweep membrane separation. In this process, air is used
 960 as a sweep gas in membrane module II and hence the air fed to the boiler and burn coal with
 961 CO₂-enriched air⁹.

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964 **Figure S4.** Pressure Swing Adsorption. In a fixed bed absorber, CO₂ is captured in two steps. In
 965 the adsorber, CO₂ is selectively adsorbed from the flue gas at high pressure (1.5 atm). Once the
 966 adsorbent is saturated with CO₂, the adsorbent is regenerated at low pressure and a pure stream
 967 of CO₂ is produced.

968

969 **Figure S5.** Temperature Swing Adsorption. In a fixed bed absorber, CO₂ is captured in two
 970 steps. In the adsorber, CO₂ is selectively adsorbed from the flue gas at low temperature. Once the
 971 adsorbent is saturated with CO₂, the adsorbent is regenerated at high temperature and a pure
 972 stream of CO₂ is produced.

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

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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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