International Journal of Greenhouse Gas Control 39 (2015) 318–328

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Exploring the potential impact of implementing carbon capture technologies in fossil fuel power plants on regional European water stress index levels

Wouter Schakel[a,*], Stephan Pfister[b], Andrea Ramírez[a]

[a] Copernicus Institute, Utrecht University, 3584CD, Utrecht, the Netherlands
[b] Institute of Environmental Engineering, ETH Zürich, 8092 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 25 February 2015
Received in revised form 24 April 2015
Accepted 21 May 2015
Available online 2 June 2015

Keywords:
CCS
Water stress
Power sector
Cooling water
Prospective scenarios
Europe

ABSTRACT

Equipping power plants with carbon capture technology can affect cooling demand and water use. This study has explored the potential impact of large scale deployment of power plants with carbon capture technologies on future regional water stress in Europe. A database including 458 of European largest power plants with data on location, technology, age, fuel type, amount of electricity generation and cooling method has been developed. This data has been combined with literature data on water use rates and developed scenarios to calculate corresponding water use of these European power plants for 2030 and 2050 under different conditions, such as the penetration level of carbon capture technologies and installed technologies. Water stress methodology based on water withdrawal has been used to explore the impact of carbon capture and storage on future water stress levels. Our findings indicate that by 2030, no considerable increase in water stress is expected due to the instalment of carbon capture technologies. However, when assuming a high penetration level of carbon capture technologies, water stress in 2050 might substantially increase in many regions in Europe. The extent of the increase in water stress strongly depends on penetration level of carbon capture, installed power plant and cooling technologies and applied water stress methodology. When using water consumption to estimate water stress, the results do not indicate significant changes in water stress for the scenarios with carbon capture. Nevertheless, as water stress based on water withdrawal is currently the common method, the results of this study provide reasons for concern regarding the potential impact of carbon capture on future European water stress levels and indicate the need for future research to monitor and possibly prevent potential water stress increases from the instalment of carbon capture technologies.

1. Introduction

Decreasing greenhouse gas emissions (GHG) from energy production while maintaining or increasing energy security will become an enormous challenge in upcoming years. Carbon capture and storage (CCS) offers a potentially low-cost pathway to energy production with low CO_2 emissions (GEA, 2012). The International Energy Agency (IEA) indicates that CCS will be a critical component of energy portfolios with low CO_2 emissions if ambitious measures are undertaken to combat climate change (IEA, 2013). In the 2 °C scenario of the IEA, CCS technology will account for 14% of the CO_2 emissions reductions by 2050 (IEA, 2014). The importance of CCS in future energy systems is also highlighted in other studies (GEA, 2012; IEA, 2012; IPCC, 2012).

Thermoelectric power plants require water, for generating steam to drive turbines, for cooling exhaust steam and for other operations including ash disposal, emissions control and potable use (IEAGHG, 2011). Total freshwater withdrawal of about 224 km^3/yr in North America and 121 km^3/yr in Europe is required for cooling thermoelectric power plants (Van Vliet et al., 2012), accounting for about 40% (King et al., 2008) and 43% (Rübbelke and Vögele, 2011) of total surface water withdrawals, respectively. Water is a limited natural resource and its use reduces availability and results in water scarcity impacts. Generally, water use is differentiated into water withdrawal (which includes water that is released back after use to the water source) and water consumption (water that is evaporated or integrated into products) (IEAGHG, 2011). The effect of water consumption depends on the water availability and current water scarcity level.

Applying CO_2 capture technology in a power plant can further increase water withdrawal and consumption due to additional fuel use to compensate the efficiency decrease induced by CO_2 capture

* Corresponding author. Tel.: +31 302537621.
E-mail address: w.b.schakel@uu.nl (W. Schakel).

http://dx.doi.org/10.1016/j.ijggc.2015.05.031
1750-5836/

and due to the water demanded by the CO_2 capture process itself. When CCS technology is added to a coal fired power plant, the total water use (consumption and withdrawal) is expected to increase by 33 to 90% (EPRI, 2011), depending on the energy conversion technology. Applying CCS in power plants equipped with conventional conversion technologies (such as subcritical pulverised coal) leads to relatively larger water use increases than when CCS is applied in power plants equipped with modern technologies (e.g., ultrasupercritical pulverised coal, IGCC). The range of water consumption increase is also confirmed by other studies (Feeley et al., 2008; Fthenakis and Kim 2010; IEAGHG, 2011; Macknick et al., 2011,b; NETL, 2012a,b) and could become a potential bottleneck in applying CCS technology, especially in water stressed areas (EPRI, 2011).

The importance of water demand and water availability in thermoelectric power production is well documented (Feeley et al., 2008; Koch and Vögele, 2009). Furthermore, it has been shown that both the electricity supply of Europe and the US could be vulnerable to future water scarcity (Van Vliet et al., 2012). However, only few studies have assessed the potential impact of applying CCS to power plants to the water availability at the regional or global level. In the United States, the water demand of the future electricity system has been linked to the water availability (Averyt et al., 2011; NETL, 2010; Sovacool and Sovacool, 2009), identifying potential challenges and water trade-offs of thermoelectric electricity production. Besides, future water withdrawal and consumption of the power sector has modelled for different scenarios (Liu et al., 2014). Furthermore, the potential impact of CO_2 storage in aquifers in the United States has also been investigated (Davidson et al., 2009). A study assessing the future potential impact of CCS on the average global water consumption (Dooley et al., 2013) showed that applying CCS can significantly increase global water consumption. However, this study also concludes that CCS and water availability are not necessarily in conflict as it is expected that future deployment of advanced CCS power plants, such as IGCC-based units and oxy-fired systems, would lead to lower water consumption rates than the water consumption rates of current power plants (Dooley et al., 2013). In Europe, a pilot project assessing the cooling water use of the electricity and industry sector has recently been finished (Ecofys et al., 2014), but research on the impact on freshwater availability is not yet included. Future pathways with high level of penetration of CCS have been identified to increase water consumption in the UK and to intensify risks to the aquatic environment, especially if electricity generation with CCS is clustered (Byers et al., 2014).

To date, no studies are available in the open literature that assess the potential impact of applying carbon capture to power plants on the water availability and water stress in Europe. Such assessment should take into account whether, where and under what circumstances power plants equipped with carbon capture technology could contribute to increases in regional water scarcity. The goal of this study is to explore the potential impact of applying carbon capture on European water stress levels. To achieve this goal, water usage of the 458 major thermoelectric power plants in Europe is spatially matched with water availabilities per watershed. By using prospective scenarios (for 2030 and 2050), varying the amount of CCS installed, power plant technologies, carbon capture technologies and cooling methods, potential bottlenecks of applying CCS on Europe's regional water scarcity levels are explored and discussed.

2. Methodology

This study uses a bottom up approach to regionally relate water demand and availability to assess the impact of implementing carbon capture in fossil fuel power plants on regional water scarcity. Typically, water scarcity is measured based on a ratio between water use and water availability (Kounina et al., 2012). In this study, a water stress index (WSI) developed by Pfister et al. (2009) is used (see Section 2.4).

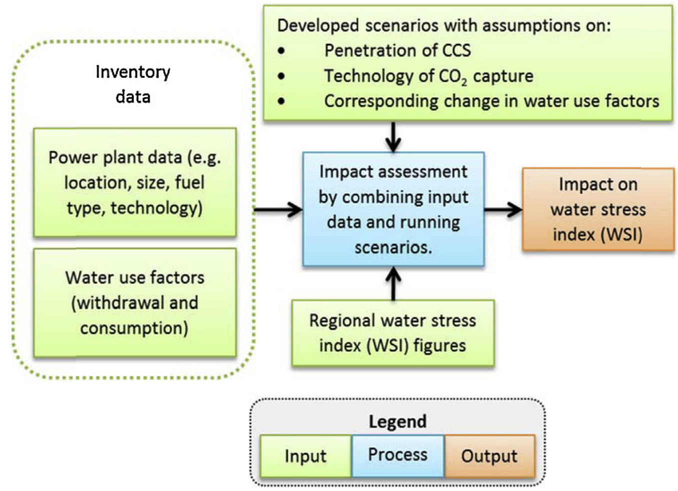

Fig. 1. Schematic overview of the methodology.

Fig. 1 schematically depicts the methodology with the corresponding data flows. Inventory data comprises power plant data (Section 2.1) and water use factors (Section 2.2). Prospective scenarios are developed for 2030 and 2050 which include assumptions on the level of penetration of CCS, CO_2 capture technologies and corresponding changes in the water use of the power plants (Section 2.3). Current regional water stress index figures are used to determine the current water stress. The impact assessment (Section 2.4) consists of a spatial match of water withdrawal levels of the power plants with regional water availability levels to explore the potential impact of the assessed power plants on the water stress index in European watersheds for each scenario. Then, the water stress index levels of the different scenarios are compared to the current situation (base case scenario), which enables exploring the impact of CCS on water stress levels, potential bottleneck areas and the water footprint of electricity production in Europe.

2.1. Power plant database

In this study, a database was developed which includes 458 of the largest power plants (>200 MW) in Europe (including Turkey, excluding Russia). The location of the included power plants is geographically presented in Appendix A (Fig. 7), and the database is made available as supplementary data. The database covers 72% of the EU's electricity generation in 2009[1] and the major power plants (>200 MW) of non-EU European countries.[2] The data was gathered by combining and harmonizing data from several public sources (Carma, 2013; Davis et al., 2013; Industry About, 2013). The initial database, with the names, size, primary fuel type and location of all power plants was obtained from Davis et al., (2013). Missing data on age, cooling method and technology of the power plants has been added using information from Carma (2013) and Industry About (2013). An overview of the type of power plant data that is comprised in the database is presented in Table 1.

The database includes the primary fuel type, combustion technology and cooling method of the power plants. Primary fuel types that are considered are coal (no distinction between black and

[1] 2.3 TWh included in the database out of a total generation of 3.2 TWh (IEA, 2012).
[2] Andorra, Belarus, Macedonia, Moldova, Montenegro, Serbia, Switzerland, Turkey and Ukraine.

Table 1
Power plant data comprised in the database (458 power plants).

Indicator	Unit	Range/Possibilities
Plant Name	–	
Country	–	All countries within Europe (including Turkey, excluding Russia)
Primary fuel	–	Coal/natural gas/oil/uranium
Technology	–	Conventional, pulverised coal, IGCC, CHP, NGCC
Latitude	°N	−15.4–39.3
Longitude	°E	27.8–65.7
Commission year	–	1900–2014
Cooling method	–	Direct cooling/cooling tower/cooling pond[3]/air cooled
Cooled by sea water	–	Yes/no
Electricity generation 2007	MWh	0–40,000,000
Expected electricity generation 2020	MWh	0–40,000,000

brown coal), natural gas, oil and uranium (nuclear power plants). Co-firing biomass and hydro power plants were not taken into account for simplification reasons. Coal-fired power plants are categorized by their combustion technology into subcritical (conventional), supercritical, gasification (IGCC) and combined heat and power (CHP). Gas-fired power plants are either conventional or combined cycle plants (NGCC). Oil and nuclear power plants are not categorized per technology. Power plants are also categorized by their cooling method into direct/once-trough cooling, cooling ponds[3], wet cooling towers and air cooling. The type of cooling method of some of the power plants were not provided by the sources, and have therefore been estimated using google maps to check for the presence of cooling towers and proximity of fresh or sea water. In all cases, either cooling towers were present (assumed method: cooling towers) or the plant was located next to fresh or sea water (assumed method: direct cooling). Hybrid cooling methods, e.g., the combination of direct cooling and cooling towers to enable power plants to flexibly handle varieties in freshwater availability and water use restrictions. Out of the 458 power plants in the database, 112 are directly cooled by sea water and 4 power plants are air cooled. Both sea water cooled and air cooled power plants are assumed to have no impact on the regional water stress index, which addresses freshwater resources only, and have therefore been left out of further analyses.

2.2. Water use factors

There is no open information available on the amount of water use (withdrawal and consumption) of the power plants. To include this information in the database, the total water use (including cooling water, water for steam cycle and flue gas cleaning) of the power plants is estimated using general water use rates based on a literature review. Table 2 presents water withdrawal and consumption ranges per technology and cooling method available in literature as well as the selected value used for each configuration in this study. Most values are selected from the study of Dooley et al. (2013), which provides water use data of the majority of configurations and is the most up to date study available with similar system boundaries as used in our study. When needed, remaining gaps are filled with data from Macknick et al. (2011) and IEAGHG (2011). Water use rates for ultrasupercritical coal-fired, oxyfuel coal fired, and conventional oil/gas fired power plants cooled by pond were not presented in these studies and are taken from (IEAGHG, 2011), (Ikeda et al., 2006) and (Fthenakis and Kim, 2010), respectively. The final gaps are filled by estimating the water use rates assuming similar conversion factors for different configurations (see Table 2).

[3] Cooling pond: Artificial body of water formed for cooling purposes. Sometimes used as alternative for cooling towers or once-trough cooling systems if sufficient land is available.

Some power plants in the database are identified as combined heat and power plants (CHPs). CHPs use part of their excess heat for district heating and require less water for cooling, but also require more make-up water as additional steam has to be produced to distribute the heat. However, the potential change in water use has not been included in this study for two reasons: Firstly, because it is not known for all power plants in the database whether they function as a CHP (due to lack of data) and secondly, because the amount of heat used for district heating is case-specific and might vary seasonally (depending on e.g., location, size, outside temperature), which also makes the amount of water that needs to be allocated to district heating case-specific.

No direct improvement in water use per technology is assumed when assessing the water use rates for 2030 and 2050. However, for the prospective scenarios technology development has been taken into account by upgrading the energy conversion technologies of the power plants to state of the art technologies (see Section 2.3). As these upgraded energy conversion technologies have higher energy conversion efficiency with lower cooling demand, they use less water, and water use is reduced in the prospective scenarios.

2.3. Scenario development

The configuration of future electricity generation is highly uncertain as is shown by the vast amount of different prospective scenarios available (e.g., ERA, 2009; GEO, 2012; IEA, 2012; IPCC, 2012). Consequently, there is a wide range of possibilities regarding the used conversion technologies and the penetration of CCS in the future electricity generation system. In this study, seven different scenarios have been constructed to explore the impact of CCS in the future configuration of electricity generation under different circumstances. The reference (base case) scenario (A0) represents the current situation and water use rates of the power plants. Three prospective scenarios with increased power production are included for 2030: A reference scenario without penetration of carbon capture technologies (B0), one in which all modern (built after 2000) fossil-fuelled power plants are assumed to be retrofitted with carbon capture technology with improved technologies for coal and gas fired power plants (B1) and one with the same amount of retrofitted CCS but without technology improvement for coal fired power plants (B2). For 2050, three scenarios are included: A reference scenario without CCS penetration (C0) and two scenarios in which CCS penetration levels are assumed to match the 2DS base 2050 scenario from the IEA's roadmap (IEA, 2012). The applied scenarios are presented in Table 3.

Note that the goal of the scenarios is to explore the potential impact of CCS penetration on water use by power plants. Therefore, the aim is to produce conservative and optimistic scenarios to assess a widespread range in future electricity production and not to accurately predict the future electricity production configuration in Europe. As such, assumptions are included to reduce complex-

Table 2
Overview of water use rates reported in literature and of values selected in this study.

Fuel type	Combustion technology	Cooling method	Water withdrawal (L/kWh)		Water consumption (L/kWh)	
			Literature[a]	Value selected	Literature[a]	Value selected
Coal	Generic/sub-critical	Once-trough	102.5–158.0	158.0[b]	0.4–1.0	1.0[b]
		Cooling pond	46.3–67.9	53.2[b]	2.1–3.0	2.1[b]
		Cooling tower	2.0–4.4	3.8[b]	1.7–4.4	2.6[b]
	Sub-critical + CCS	Once-trough	241.0	241.0[b]	1.3	1.3[b]
		Cooling tower	4.2–5.6	4.8[b]	3.2–5.0	3.6[b]
	Supercritical	Once-trough	85.5	85.5[c]	0.1–0.5	0.4[c]
		Cooling pond	57.0	57.0[c]	0.2	0.2[c]
		Cooling tower	2.3–3.9	2.3[c]	1.9–3.9	1.9[c]
	Supercritical + CCS	Once-trough		212.1[d]		1.1[d]
		Cooling tower	4.3–4.9	4.3[c]	3.2–4.4	3.2[c]
	Ultrasupercritical	Once-trough	139.9	139.9[e]	0.1	0.1[e]
		Cooling tower		2.5[f]	1.8–2.0	2.0[e]
	Ultrasupercritical + CCS	Once-trough	240.5	240.5[e]	0.4	0.4[e]
		Cooling tower		4.6[g]		3.4[g]
	IGCC	Once-trough	147.0	147.0[b]	0.1	0.1[b]
		Cooling tower	0.9–3.1	1.5[b]	0.7–3.1	1.4[b]
	IGCC + CCS	Once-trough	185.2–186.0	186.0[b]	0.4	0.4[b]
		Cooling tower	2.2–2.6	2.2[b]	1.8–2.1	2.0[b]
	Oxyfuel + CCS	Once-trough	226.1	226.1[e]	0.3	0.3[e]
		Cooling tower		4.9[h]	3.7	3.7[i]
Oil/Gas	Conventional	Once-trough	85.9–152.0	152.0[2]	0.3–0.9	0.9[2]
		Cooling pond	4.6–29.9	29.9[j]	0.4–3.1	0.4[j]
		Cooling tower	0.9–4.6	4.6[b]	0.6–3.1	3.1[b]
Gas	NGCC	Once-trough	34.1–76.0	49.5[b]	0.0–0.4	0.4[b]
		Cooling pond	22.5–25.9	25.9[b]	0.9	0.9[b]
		Cooling tower	0.6–1.0	1.0[b]	0.5–1.0	0.8[b]
	NGCC + CCS	Once-trough	62.5	62.5[b]	0.7	0.7[b]
		Cooling tower	1.9–2.1	1.9[b]	1.4–1.9	1.4[b]
Nuclear	Conventional	Once-trough	95.0–230.0	193.0[b]	0.5–3.4	1.0[b]
		Cooling pond	1.9–30.7	30.7[b]	1.7–3.4	2.3[b]
		Cooling tower	3.0–4.2	4.2[b]	2.3–3.4	2.5[b]

[a] Range of values reported in literature (Dooley et al., 2013; Feeley et al., 2008; Fthenakis and Kim, 2010; IEAGHG, 2011; Ikeda et al., 2006; Macknick et al., 2012; Macknick et al., 2011; NETL, 2012a,b; Yu et al., 2011).
[b] Dooley et al., 2013.
[c] Macknick et al., 2011.
[d] Value is calculated by multiplying the water used by the cooling tower with a conversion factor equal to the ratio between once-trough water use and cooling tower water use of subcritical + CCS.
[e] IEAGHG, 2011.
[f] Value is calculated by multiplying the water consumption with a conversion factor equal to the ratio between water consumption and water withdrawal of cooling tower supercritical.
[g] Value is calculated by multiplying the water use rates of ultrasupercritical without CCS with a conversion factor equal to the ratio between water use of supercritical with and without CCS.
[h] Value is calculated by multiplying the water consumption with a conversion factor equal to the ratio between water consumption and water withdrawal of cooling tower supercritical + CCS.
[i] Ikeda et al., 2006.
[j] Fthenakis and Kim, 2010.

ity and to deal with data unavailability. In general, no switching between fuel types is considered between the scenarios. Power plants maintain their current fuel type in every prospective scenario. The type of cooling technology is assumed to be constant as well: Power plants maintain their current cooling technology in all prospective scenarios, except power plants equipped with cooling ponds which are assumed to be replaced with power plants with cooling towers in the 2050 scenarios. Increases in efficiency and reductions in water use per individual technology are not considered. Instead, technological development is taken into account in the scenarios, to some extent, by changing the conversion technologies of the power plants into more modern technologies in future scenarios (for example USPC and oxyfuel). These more modern technologies increase efficiency and generally require less cooling water. As such, overall water consumption per kWh produced decreases.

For the 2030 scenarios, the expected electricity generation figures of the power plants for 2020 (Davis et al., 2013) are used as a proxy, because these figures distinguish between individual power plants (e.g., planned added capacity, planned shutdown). For 2050, an average relative increase in electricity generation is assumed for each power plant site following the 2DS base 2050 IEA roadmap scenario (IEA, 2012). For the 2050 CCS scenarios (C1 and C2), no distinction between CCS penetration rates between countries is considered, as no country specific data is available. For each country, coal and gas fired power plants are replaced with power plants with CCS starting from the newest to the oldest, because the oldest power plants are expected to be replaced the soonest and are not likely to be carbon capture ready. This is done, up until the point the penetration rate is reached. In scenario C2, half of the coal fired power plants that are replaced by power plants with CCS are assumed to be IGCCs and half are assumed to be oxyfuel stations. In the database, random sampling is applied to select which power plants in each country are replaced by IGCCs and oxyfuel stations, respectively.

2.4. Impact on water scarcity (water stress index)

Water stress is commonly defined by the ratio of total annual freshwater withdrawals (WU) to hydrological availability (WA), as

Table 3
Key characteristics of the assessed scenarios.

Scenario	Year	CCS deployed	CCS penetration	Carbon capture technology	Technologies power plants without CCS
A0	Current	No	No	–	Current technologies
B0	2030	No	No	–	Technology improvement for coal and gas fired power plants[a]
B1	2030	Coal and gas power plants built after 2000[b]	19% (89 out of 458 power plants)	Retrofitted with post-combustion capture	Technology improvement for coal and gas fired power plants[a]
B2	2030	Coal and gas power plants built after 2000	19% (89 out of 458 power plants)	Retrofitted with post-combustion capture	No technology improvement for pulverised coal fired power plants
C0	2050	No	No	–	Replaces: - Coal-fired power plants with USPC - Gas-fired power plants with NGCC - Nuclear/Oil power plants with same type of technology as defined in database
C1	2050	Coal and gas fired power plants[c]	87% of coal-fired power plants and 33% of gas-fired power plants[d]	Replaces: - Coal-fired power plants with USPC with post-combustion capture - Gas-fired power plants with NGCC with post-combustion capture	Replaces: - Coal-fired power plants with USPC - Gas-fired power plants with NGCC - Nuclear/Oil power plants with same type of technology as defined in database
C2	2050	Coal and gas fired power plants[c]	87% of coal-fired power plants and 33% of gas-fired power plants[d]	Replaces: - Coal-fired power plants with IGCC with pre-combustion capture and oxyfuel (50%/50%) - Gas-fired power plants with NGCC with post-combustion capture	Replaces: - Coal-fired power plants with USPC - Gas-fired power plants with NGCC - Nuclear/Oil power plants with same type of technology as defined in database

[a] Subcritical pulverised coal plants are assumed to be upgraded to supercritical pulverised coal plants. Cooling water rates of NGCCs are used instead of conventional gas fired power plants.
[b] All power plants with building year 2000 or later are assumed to be retrofitted with carbon capture technology.
[c] Power plants are assumed to be replaced with power plants with CCS starting from the newest to the oldest, as the oldest power plants are replaced the soonest and are not likely to be capture ready, until penetration rates are reached.
[d] 2DS base 2050 scenario from IEA roadmap (IEA, 2012).

is described by the withdrawal-to-availability ratio (WTA) in Eq. (1) (Alcamo et al., 2003).

$$\mathrm{WTA} = \frac{\mathrm{WU}}{\mathrm{WA}} \tag{1}$$

This concept is enhanced by temporal variation and storage of water availability (VF) to calculate a water stress index (WSI) that accounts for seasonality, ranging from 0 to 1 (Pfister et al., 2009). The WSI serves as one option for a characterization factor of the suggested midpoint category water deprivation in Life Cycle Impact Assessment (Kounina et al., 2012). Moderate and severe water stress is expected above a threshold of 20 and 40% WTA, respectively. These figures are expert judgments and thresholds for severe water stress might vary from 20 to 60%. In the WSI method, the WTA thresholds of 20, 40 and 60% are translated into WSI of 0.09, 05 and 0.91. The WTA of current state is taken from the WaterGAP2 global model (Alcamo et al., 2003), which models global water use and availability for over 10,000 individual watersheds.

In this research, the changed water use rates of the power plants in each scenario (k) are spatially matched with the watersheds i for which the water stress index (WSI) is defined. Consequently, the $\mathrm{WTA_i}$ is recalculated for each scenario k:

$$\mathrm{WTA}_{i,k} = \frac{\Sigma_i \mathrm{WU}_0 i + \mathrm{dWU}_{k,i}}{\mathrm{WA}_i} \tag{2}$$

In which $\mathrm{WTA}_{i,k}$ is the ratio of annual freshwater withdrawal to hydrological availability, $\mathrm{WU}_0 i$ the current annual freshwater withdrawal for watershed i, $\mathrm{dWU}_{k,I}$ the change in water withdrawal in scenario k for watershed i and WA_i the hydrological availability. The updated WTA values are consequently used to recalculate WSI and the difference of WSI (dWSI) based on Pfister et al. (2009):

$$\mathrm{WSI} = \frac{1}{1 + 99 \times \mathrm{e}^{-6.4 \times \mathrm{WTA} \times \mathrm{VF}}} \tag{3}$$

As WSI is scaled to represent the impact, the value of dWSI can directly be compared among watersheds and regions to determine the level of additional or decreased water stress caused by the change in the power production system. Additionally, the water stress index levels of the different scenarios can be compared to the current situation (reference scenario), which enables exploring the impact of CCS on water stress levels and potential bottleneck areas.

The original WSI accounts for water stress in a watershed as a function of the withdrawal-to-availability ratio and therefore also indirectly accounts for water stress caused by changed water quality and competition for withdrawals. As such, the WSI might overestimate the effect of once-through cooling systems. Other indicators focus on consumption-to-availability (CTA) ratios that only account for water scarcity caused by consumptive water use (Kounina et al., 2012) and therefore underestimate total water stress. This issue is addressed by adjusting the WSI to a CTA based indicator as suggested by (Gomez and Pfister, 2012). This adjustment of the constant in the exponent from −6.4 to −17.4 is based on the approach described by Pfister and Bayer (2014):

$$\mathrm{WSI} = \frac{1}{1 + 99 \times e^{-17.4 \times CTA \times VF}} \tag{4}$$

The CTA for each scenario are calculated in the same availability data as WTA. For the current water consumption apart from power production, the results of the WATCH project (Flörke and Eisner, 2011) are used to which the modelled water consumption of power production in each scenario is added.While globally, a comparison of the power plant's impact on water scarcity (dWSI) is of most interest, the contribution of the power sector to total water use is interesting from a more local perspective, as even if the water stress level is low, the relative impact compared to the other users might be relevant. Therefore, the share of power production of the total water withdrawals and consumption in each watershed is also

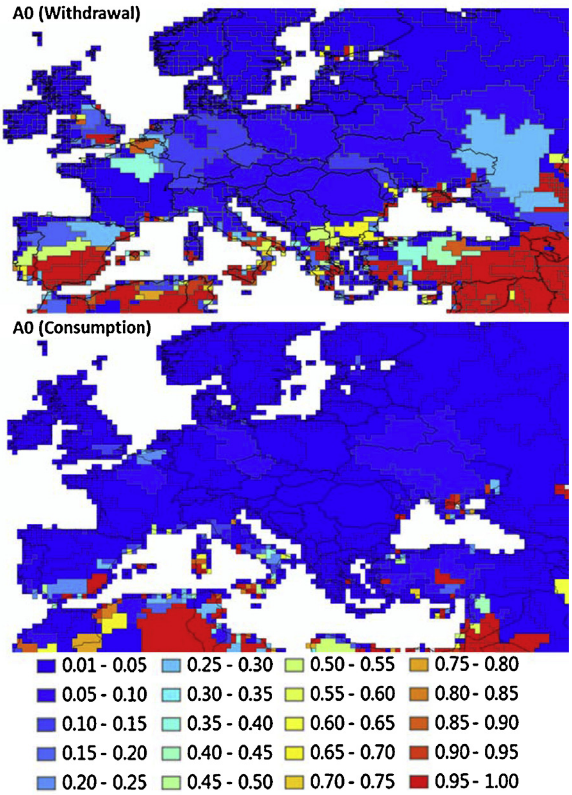

Fig. 2. Withdrawal and consumption based current water stress index levels in Europe (reference scenario A0).

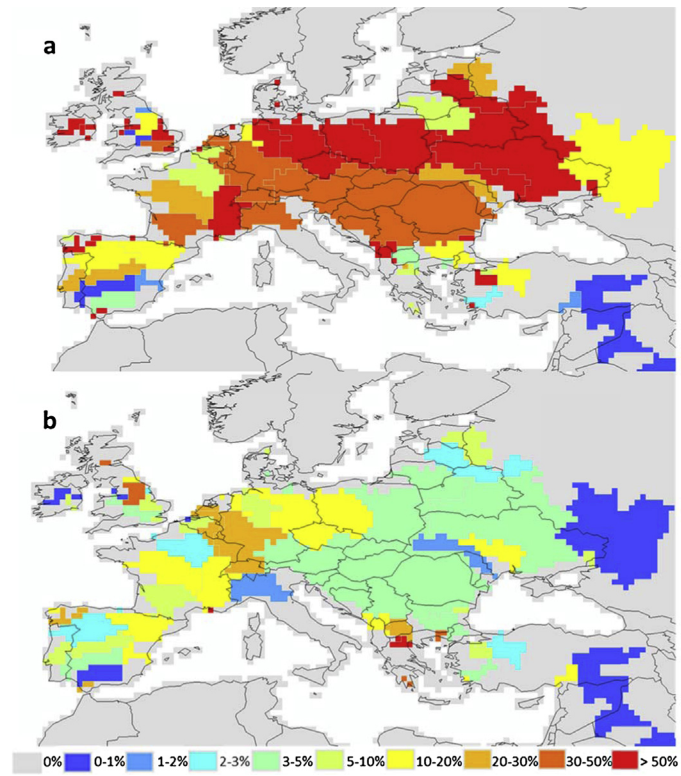

Fig. 3. Relative share of water use in the power sector over total water use including all sectors for water withdrawal (a) and water consumption (b).

analysed, which indicates to what share the water scarcity is caused by the power sector.

3. Results

3.1. Current water stress

Fig. 2 illustrates the current water stress index following the reference (base case) scenario (A0) based on water withdrawal methodology and based on water consumption methodology. Water stress indexes are relatively low in the majority of Europe. However, several regions in Southern Europe, Eastern Europe, Belgium and the London area already have high withdrawal based water stress index levels. WSI based on water consumption is much lower throughout Europe and only high in small areas in southern Europe. In general, consumption based WSI is much lower than withdrawal based WSI in Europe, which implies that absolute changes in water consumption have to be much higher to significantly affect the WSI. A map with the WSI and the locations of the assessed power plants is presented in Appendix A.

3.2. Contribution of power sector

The share of water use in the power sector over total water use depends to a large extent on the geographical location and can provide a first indication of the local contribution of the power sector to water stress. Fig. 3 presents the relative share of water withdrawal (a) and water consumption (b) of the power sector over the total water withdrawal and contribution for all European watersheds.

In coastal regions, the share of water use of the power sector is non-existent, as in these areas power plants are generally cooled by sea water and do not contribute to freshwater withdrawal or consumption. In arid regions, irrigation typically plays a more significant role and therefore water use in power production contributes to a relatively lower extent. In the remaining areas, the share of water withdrawal of power production is dominant, exceeding 50% in many areas in the UK and Central and Eastern Europe.

The share of the power sector of water consumption is much lower than the share of water withdrawal due to the extremely high withdrawal rates for once-trough cooling systems. As such, much more water is withdrawn than consumed in the power sector, and because this difference is lower in other sectors (e.g. agricultural, industrial) the water withdrawal share of the power sector is much larger than the water consumption share. Nevertheless, the share of water consumption of the power sector is already significant (>30%) in some areas in Europe, such as the area surrounding London, the area surrounding the river Rhine and small areas in Spain and Greece.

3.3. Water stress in 2030 scenarios

Fig. 4 presents absolute changes in withdrawal based WSI compared to the reference scenario A0 for scenarios B0–B2. Overall, there are only minor changes in WSI levels. On European average, the WSI levels even decrease by 0024, 0009 and 0.007 points in scenario B0, B1 and B2 respectively. In the scenario without CCS (B0), WSI is slightly reduced in parts of the Benelux, France, Eastern Europe, Bulgaria and Turkey. This reduction is the result of a decrease in water use by coal and gas-fired power plants (due to the assumed upgrade in energy conversion technology). Overall, this decrease in water use compensates the increase in water use due to the growth in electricity production in 2030. Only in central Spain and Portugal water stress increases, as in this area the increase in water use due to additional electricity production is not compensated by technology upgrade (no technology upgrades are considered in 2030 as relative modern power plants (NGCC and SCPC) are already in place).

When penetration of carbon capture technologies is added (scenario B1), the rise in water use due to CCS only significantly increases the water stress in Spain and south-east UK. In these areas, multiple power plants are retrofitted with CCS following the B1 scenario boundaries, which increases the water withdrawal and the water stress. For the rest of Europe, the CCS penetration rate (19%) appears to be too low to compensate the decrease in water use due to the upgrade in energy conversion technologies and subsequently, to increase the WSI.

In scenario B2, equal CCS penetration to scenario B1 is assumed but no technology improvement for coal-fired power plants is included. Only small differences can be observed compared to scenario B1: WSI only slightly increases in Spain and central Europe (Rhine area).

While in general the presented WSI reduction in 2030 strongly depends on the type of technologies installed in 2030, the impact of CCS seems limited. The CCS penetration level of 19% for the B1 and B2 scenario appears too low to significantly increase withdrawal based water stress in the majority of Europe.

3.4. Water stress in 2050 scenarios

Fig. 5 illustrates the absolute change in withdrawal based WSI in 2050 compared to the base case (A0) for scenarios C0, C1 and C2. Contrary to 2030, WSI levels now increase in almost all watersheds. On average, WSI levels increase with 0.013, 0.100 and 0.063 for scenarios C0, C1 and C2, respectively. Overall, the WSI increases due to the assumed growth in electricity generation in Europe. The effects of the growth in electricity generation are not compensated by the instalment of new technologies with higher cooling efficiencies (as was the case in 2030).

When no CCS penetration is considered (scenario C0), WSI levels slightly increase in parts of the UK, Germany, Spain and Portugal, Eastern Europe, Bulgaria and Turkey. Only the increase in central Spain and Portugal exceeds 0.10, which is much larger than the average rise in WSI (0.013). This is because in this area, multiple fossil fuelled power plants are located and the assumed increase in electricity generation in prospective scenarios causes a rise in water use and consequently in water stress.

When CCS is added to the electricity mix (scenario C1), WSI increases in more parts of Europe, such as in the north-west of Spain, the north of France, Benelux, southern Germany, Poland and the Baltic countries. Besides, the increase in WSI also grows, resulting in more red areas (increase > 0.10), mainly in the Benelux, Poland, Eastern Europe and part of Turkey.

In scenario C2, WSI also increases compared to C0, but to a lesser extent than in scenario C1. In regions such as the north-west of Spain, the north of France, Poland, Eastern Europe and the Baltic countries the increase in WSI levels is less dramatic. On average, the WSI increase compared to the base case (A0) is 0.064,

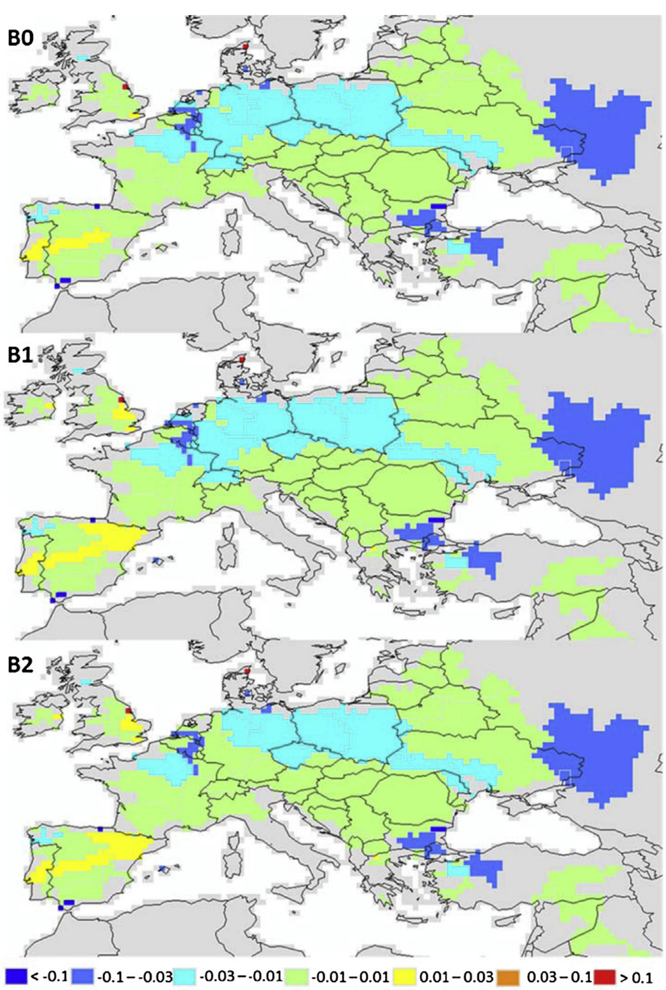

Fig. 4. Absolute change of withdrawal based water stress index levels (Δ WSI) of 2030 scenarios B0 (no CCS), B1 (with CCS) and B2 (with CCS without technology improvement for coal fired power plants), compared to base reference scenario (A0).

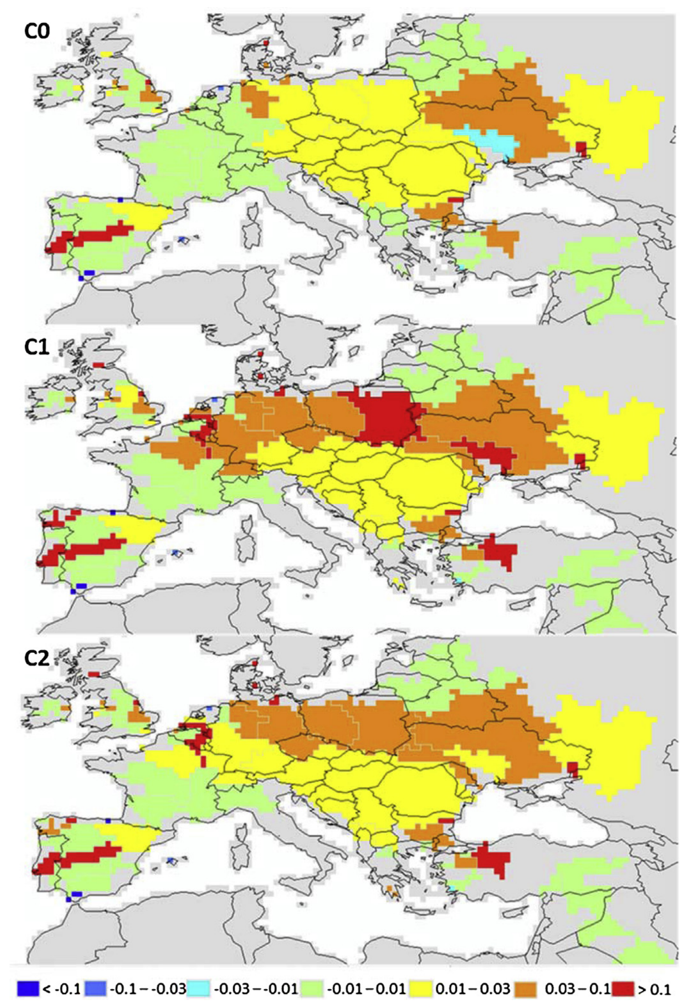

Fig. 5. Absolute change of withdrawal based water stress index levels (Δ WSI) in 2050 for scenarios C0 (no CCS), C1 (CCS with USCPC) and C2 (CCS with oxyfuel and IGCC) compared to base case scenario (A0).

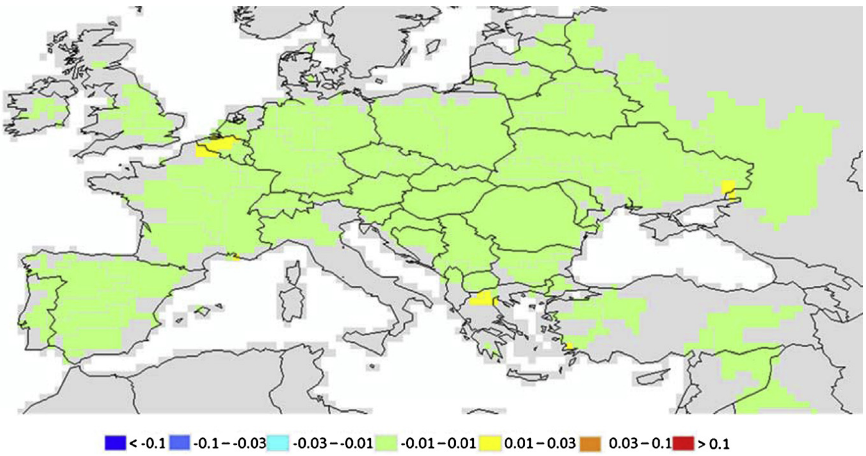

Fig. 6. Absolute change of water stress index levels in 2050 of scenario C1 (CCS with USCP) compared to base case scenario (A0) based on water consumption instead of withdrawal.

approximately 36% less than in scenario C1. Scenario C2 lowers the increase in WSI compared to scenario C1 because in C2 carbon capture coal-fired power plants are assumed to be oxyfuel and IGCC plants, whereas in C1 ultrasupercritical pulverised coal power plants (USCPC) with post combustion capture are considered. With current water use rates, oxyfuel and especially IGCC plants are more efficient than USCPC (Table 2), resulting in lower water use of these power plants and less contribution to WSI in scenario C2.

4. Discussion

4.1. Total water use power plants

The first step in our methodology was to estimate the water use of the power plants in Europe. In total, 109 km^3/year fresh water is withdrawn and 3. km^3/year fresh water is consumed by the power plants included in the database in the reference scenario (the database is provided in the supplementary information). These figures are slightly below the reported fresh water withdrawal and consumption figures of the entire electricity sector in Europe in 2005 of 120 km^3/year (56–152.6 km^3/year) and 6.0 km^3/year (4.5–8.3 km^3/year), respectively (Davies et al., 2013). Only 72% of Europe's electricity production is included in the database which explains why the total water use figures in the database are lower. Nevertheless, the bottom up calculated total water withdrawal and consumption rates of the reference scenario in this study seem to be fairly in range with the values reported in the study of Davies et al. (2013).

4.2. Water stress methodology

The use of water stress index is a methodology that is still under development. To date, no common agreement among scientists exists on which available method would be best suited for assessing water stress (Mertens et al., 2015). Mertens et al. (2015) compared water stress results using different methods, among others the method used in this study, and showed that the chosen method can have a large impact on the final result. It is therefore important to further discuss the advantages and drawbacks of the methodology used in this study.

4.2.1. Withdrawal versus consumption

The WSI results in this paper are based on water withdrawal WSI methodology. This methodology is originally based on water withdrawal and does not specifically target water consumption. As a result, power plants using direct cooling systems (very high withdrawal rates with low consumption rates) affect the WSI to a larger extent than power plants with cooling towers (medium withdrawal and consumption rates). It can be argued that water consumption has a higher impact on water stress than water withdrawal, as the used water is not returned to its source. This would imply that power plants with cooling towers should impact the WSI more than plants with direct cooling systems. On the other hand, water scarcity is also affected by overall withdrawals, as the power plants need the cooling water, even if they do not consume it, and therefore other users are limited in their consumptive use.

The contribution to WSI of water withdrawal compared to water consumption is still debated in literature (Kounina et al., 2012) and not all effects contributing to water stress are yet included. For instance, once-through cooling systems are thermally polluting the water to a high level and therefore add by quality-degradation to water stress. As thermal pollution is not yet taken into account in LCA methodologies, taking this effect into WSI is an option to indicate overall water stress by water use of cooling systems. Based on the results published by Verones et al. (2010), heat releases of once-through cooling systems are of similar importance for freshwater ecosystem quality concern as water consumption in areas with low water scarcity, such as many regions in Europe.

4.2.2. Consumption based WSI

Due to the issues regarding consumption based water stress (Section 4.2.1) and comparability to previous publications, this study focused on the analysis of withdrawal based water stress. Nevertheless, a consumption based analysis of the water stress has been carried out for comparison purposes. Fig. 6 shows the change in consumption based water stress in the most intensive water use scenario C1 (2050, high penetration of CCS with USPC coal power plants) compared to the reference scenario A0 (current water stress). Surprisingly, there are no significant changes in the consumption based WSI in Europe, which is opposite to the findings from water withdrawal based WSI change in the same scenario (Fig. 5, Section 3.4). The most important reason for this difference is the large amount of water withdrawal rates for once-trough cooling systems (in the order of 100 L/k Wh) compared to the water consumption rates, regardless of cooling technology, in general (<5 L/kWh). On average, consumption to withdrawal is approximately 3% for the analysed power plants. In other sectors (e.g., agricultural), this difference between withdrawal and consumption is considerably lower: the average global consumption to withdrawal ratio is 35–40% (Flörke and Eisner, 2014). As such, absolute change in water withdrawal are much larger then changes in water consumption in the power sector leading to more substantial increases in WSI based on withdrawal increases compared to WSI based on consumption. Besides, because consumption based water stress is much lower than withdrawal based water stress in Europe (see Section 3.1), changes in the water consumption of the power plants have to be much higher compared to changes in water withdrawal to significantly increase the consumption based water stress in Europe.

4.3. Database limitations

The database includes 458 of the largest power plants in Europe, accounting for 72% of EU's power production. Although all included information is of high value, several simplifications have been applied for feasibility reasons as discussed in Section 2.1. As a result, uncertainties in actual water use rates of the power plants in the database are high and the database can therefore not be used for a precise estimation of water use of the individual power plants. However, it provides a good estimate of the water use of the power sector in the assessed areas (watersheds). The aim of this study is to explore potential future water stress issues when applying CCS on a large scale, and not to predict future water use of the power sector with a high level of detail. It is therefore concluded that the data in the database is considered to be of sufficient quality for the purpose of this study.

4.4. Cooling methods/water use factors

In this study, water use factors obtained from literature were used to calculate the water use of the power plants. As it was difficult to find data distinguishing between plant technology and cooling method, as much data as possible was taken from the most recent study to ensure a harmonised dataset for all power plant technologies and cooling method configurations. However, the selected water use factors were generally at the higher side of the literature ranges, and as such, total water use and consequently the impact on water stress of the power plants might have been overestimated, both in the base case and in the scenarios. Together with the conservative approach used for the development of 2050 scenarios, the results might represent a worst-case estimate for the impact of CCS on future water stress levels in Europe, which falls well within the goal of this study to explore the impact of CCS on water stress under different conditions.

Some assumptions had to be made to use general figures for all power plants. For instance, hybrid cooling is not considered in this study. In reality, some power plants are equipped with both a direct cooling system and a cooling tower (Ecofys et al., 2014), enabling to shift between the cooling systems depending on varieties in freshwater availability throughout the year. In this study, power plants equipped with a cooling tower are assumed to always use the tower for cooling.

Air cooled power plant have also not been included. When sea water is not available, air cooling or dry cooling is the best performing cooling technology to avoid fresh water withdrawal and consumption, (IEAGHG, 2011). Air cooled power plants would drastically decrease the impact on water stress of these plants, regardless of whether carbon capture is included. This method has not been considered in this study as no scenario analysis is needed to deduce that implementation of air cooled power plants, especially in regions with high water stress, will improve the water stress index. Although the potential benefits of air cooling in dry regions are evident, adverse consequences exist for the technical and economic performance of the power plant, such as a decrease in energy efficiency, and consequently an increase in life cycle CO_2 emissions as well as power plant costs (IEAGHG, 2011). The consideration whether the decrease in water stress outweighs these adverse impacts is power plant specific, and falls beyond the scope of this study.

Finally, future improvements in cooling efficiency are not included. Current cooling rates for all technologies have also been used in the future scenarios. Although some learning in cooling methods could be expected, data on the prospected learning is not available in literature.

4.5. Scenarios

The scenarios in this study were developed to create a comparison of scenarios with deployment of CCS and base case, or business as usual, scenarios in which no CCS is deployed. For 2030, intermediate scenarios have been developed to explore whether a small penetration of CCS already impacts the WSI. The results indicate that this small penetration does not significantly affect WSI levels throughout Europe. In fact, WSI levels even decrease compared to the base case (current) situation. However, the latter result might be too optimistic for two reasons: firstly, because expected electricity generation figures for 2020 are used (while figures for 2030 might be significantly higher) and secondly, the assumption that all old subcritical coal-fired power plants and conventional gas-fired power plants are replaced with newer technologies might not be valid for all power plants. Although the effect of technology upgrade for coal-fired power plants is explored using scenario B2 (in which no technology improvement is considered), this has not been done for gas fired power plants as much less data on cooling demand of gas fired power plants per technology is available. As such, the assumed reduction of the large water withdrawal rates of direct cooled conventional power plants in 2030 might be argued together with the presented reduction of WSI. However, regardless of assumed technology improvement, the potential expected increase in WSI due to installed CCS in 2030 can still be considered relatively low.

The goal of the 2050 + CCS scenarios was to explore the potential impact of applying CCS with a conservative approach. To do so, 2DS base 2050 scenario from IEA roadmap (IEA, 2012), in which a high penetration level of CCS is assumed, has been used for constructing these scenarios. Under this conservative approach, results indicate concerns that large scale deployment of CCS will substantially increase WSI levels in large parts of Europe. However, the applied scenarios are very static with little flexibility toward e.g. fuel types, locations and cooling methods and adding more flexible scenarios might improve the results.

4.6. Impact of climate change on water stress

This study has not included the potential effect of the rising CO_2 concentration in the atmosphere on the water availability in the future. The rising CO_2 levels increase the earth's temperature and are expected to increase water stress in the future (Murray et al., 2012; Schewe et al., 2013). Although this could also potentially change the impact of applying CCS on the water stress, this paper aimed to explore the potential impact of CCS on water stress levels in Europe and not to provide an accurate prediction of future water stress levels by including future changes in all the numerous contributions to water stress.

5. Conclusion

Applying carbon capture on power plants can increase the total water withdrawal and consumption of the power plants. This study aimed to explore the potential impact of future deployment of carbon capture technologies on the water stress in Europe. A database which includes existing power plants has been developed to assess water use of these power plants. The water use of these power plants has been varied using different scenarios for 2030 and 2050 varying the electricity generation and CCS penetration in Europe.

Using a water stress method based on water withdrawal rates, the effect of the water demand of the assessed power plants (with and without carbon capture technology) on the water stress in Europe in 2030 and 2050 is explored.

The analyses show that water stress can be an issue of concern in certain European areas. By 2030, applying carbon capture technologies in power plants is not expected to significantly increase water stress in Europe, because the expected penetration of CCS in 2030 is relatively low and the increase in water demand due to more electricity consumption is likely to be compensated by a reduction in water demand of the power plants due to instalment of improved technologies which require less cooling water. However, in 2050, large scale penetration of CCS showed substantial increases in local water stress levels in Europe, especially by once through cooling systems. The combination of an increase in electricity production and installed carbon capture technologies give reasons for concern regarding the water stress in many areas in Europe, including the UK, Spain and central and Eastern Europe. The increase in water stress can significantly be lowered when more IGCC and oxyfuel coal-fired power plants are installed instead of ultrasupercritical pulverised power plants.

When water stress is estimated using water consumption, the impact of CCS is not significant and almost no increase in water stress can be observed for 2030 and 2050. However, as water stress depends on both water withdrawal and water consumption, the insignificant impact of CCS on consumption based water stress does not provide sufficient substantiation to ignore or underestimate future water stress in Europe, as water stress depends on both water withdrawal and water consumption.

As this study has only provided an exploration of the potential impact of CCS on the water stress in Europe, associated uncertainties are relatively high. Recommended steps to improve this research are:

- Improvement of WSI methodology, taking both water withdrawal and consumption as well as thermal pollution into account
- Potential future changes in water availability (due to e.g. climate change)
- Changes in water use of other sectors than the electricity sector
- Improvement of power plant data
- Expansion and Improvement of scenarios by including:
  - shift in cooling methods
  - shift in fuel types
  - shift in power plant locations
  - more country specific data (CCS penetration, nuclear policy)
  - cooling efficiency improvement
- Take into account different policies and priorities regarding electricity production throughout Europe
- More focus on smaller areas (country, region or individual power plant) for more accurate assessment of the impact of carbon capture on water stress.

Several measures are available that could substantially reduce the impact of CCS on the water stress in the future. Measures such as installing more sea water cooled power plants, consider the use of dry cooling in areas with high water stress and integrate and optimise the different water streams in the power plant (e.g. recycle cooling water for flue gas flue gas treatment or carbon capture) have not been taken into account in this study but could reduce future fresh water use of power plants with and without carbon capture.

Finally, it is important to continue to assess the potential impact of CCS on the future water availability in Europe and other regions, as this can help to explore, identify and prevent potential areas with high water stress. Besides, additional research is required to further investigate possibilities to optimise water use of power plants with carbon capture by recycling water and to facilitate discussion on how to sustainable, in terms of water stress, include carbon capture in the European power sector.

Acknowledgements

This research has been carried out as part of the FP7 PROSUITE project and the EDDiCCUT project.

PROSUITE (2009–2013) is a European project on sustainability assessment methodology of prospective technologies. The project was funded by the European Commission under the 7th Framework Programm.

EDDiCCUT is a 4 year research project (2012–2016) aiming to assess the environmental performance of carbon capture and utilization technologies. The project is led by the Industrial Ecology Programm at Norwegian University of Science and Technology in collaboration with the Copernicus institute at Utrecht University and Tel-Tek in Porsgrunn. Project is supported by Gassnova and industrial partners.

Appendix A. Locations of power plants

Fig. 7 presents the current water stress index based on water withdrawal methodology together with the geographical location of the power plants included in the database.

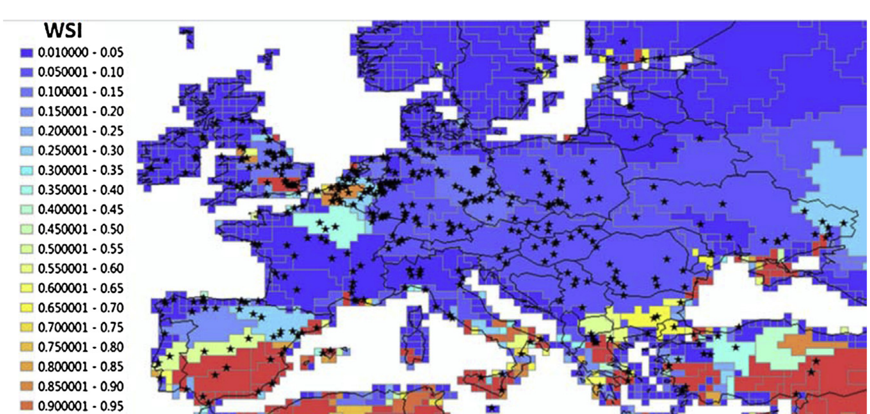

Fig. 7. Current WSI based on water withdrawal and power plant locations (represented by the stars).

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijggc.2015.05.031

References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., Siebert, S., 2003. Development and testing of the WaterGAP 2 global model of water use and availability. Hydrol. Sci. J. 48 (3), 317–337, http://dx.doi.org/10.1623/hysj.48.3.317.45290

Averyt, K., Fisher, J., Huber-Lee A., Lewis, J., Macknick, N., Madden, J., Tellinghuisen, S. (2011). Freshwater Use by U. S. Power Plants: Electricity's thirst for a precious resource.

Byers, a, E., Hall, J.W., Amezaga, JM, 2014. Electricity generation and cooling water use: UK pathways to 2050. Global Environ. Change 25, 16–30, http://dx.doi.org/10.1016/j.gloenvcha.2014.01.005

Carma. (2013) Carbon Monitoring for Action. Center for Global Development. Retrieved from www.carma.org

Davidson, C.L., Dooley, J.J., Dahowski, R.T., 2009. Assessing the impacts of future demand for saline groundwater on commercial deployment of CCS in the United States. Energy Procedia 1 (1), 1949–1956, http://dx.doi.org/10.1016/j.egypro.2009.01.254

Davies, E.G.R., Kyle, P., Edmonds a, J., 2013. An integrated assessment of global and regional water demands for electricity generation to 2095. Adv. Water Resour. 52, 296–313, http://dx.doi.org/10.1016/j.advwatres.2012.11.020

Davis, C.B., Chmieliauskas, A., Nikolic, G.P.J., 2013. Enipedia. Energy & Industry Group. Faculty of Technology, Policy and Management, TU, Delft, The Netherlands, Retrieved from http://enipedia.tudelft.nl

Dooley, J.J., Kyle, P., Davies, E.G.R., 2013. Climate mitigation's impact on global and regional electric power sector water use in the 21st century. Energy Procedia 37, 2470–2478, http://dx.doi.org/10.1016/j.egypro.2013.06.128

Ecofys, TNO, Deltares. (2014). Pilot project on availability, use and sustainability of water production of nuclear and fossil energy – Geo-localised inventory of water use in cooling processes, assessment of vulnerability and of water use management measures. Utrecht. Retrieved from http://ec.europa.eu/environment/archives/water/adaptation/pdf/InventoryCoolingWaterUse.pdf

EPRI. (2011). Cooling Requirements and Water Use Impacts of Advanced Coal-fired Power Plants with CO2Capture and Storage. Retrieved from http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001024495

ERA. (2009). The impact of fossil fuels. Greenhouse gas emissions, environmental consequences and socio-economic effects.

Feeley, T.J., Skone, T.J., Stiegel, G.J., McNemar, A., Nemeth, M., Schimmoller, B., Manfredo, L., 2008. Water: A critical resource in the thermoelectric power industry. Energy 33 (1), 1–11, http://dx.doi.org/10.1016/j.energy.2007.08.007

Flörke, M., Eisner, S., 2011. Global spatially detailed estimates of sectoral water requirements, past, present and future, including discussion of the main uncertainties. Risks Vulnerabilities Hum. Water Demand.

Fthenakis, V., Kim, H.C., 2010. Life-cycle uses of water in U. S. electricity generation. Renew. Sustain. Energy Rev. 14 (7), 2039–2048, http://dx.doi.org/10.1016/j.rser.2010.03.008

GEA, 2012. Global Energy Assessment – Toward a Sustainable Future. Cambride University Press, Cambridge UK and New York, NY, USA, and the International Insitute for Applied Systems Analysis, Laxenburg Austria.

GEO, 2012. Global Energy Assessment Toward a Sustainable Future. Cambridge University Press, Cambridge UK and New York, NY, USA, and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Gomez, M., Pfister, S. (2012). VEOLIA-ETH collaboration on improving Water Stress Index (WSI): Final report of phase 1. Retrieved from http://www.ifu.ethz.ch/ESD/downloads/reports/wsi_veolia_eth.pdf

IEA. (2012). Energy Technology Perspectives. International Energy Agency.

IEA. (2013). Technology Roadmap Carbon capture and storage. International Energy Agency.

IEA. (2014). Energy Technology Perspectives 2014. International Energy Agency.

IEAGHG. (2011). Evaluation and Analysis of Water Usage of Power Plants with CO2 Capture. International Energy Agency.

Ikeda, E., Lowe, A., Spero, C., Stubington, J.F., 2006. Comparison of technical performance of fossil fuel-based electric power generation technologies under Australian conditions. Aust. Inst. Energy Natl. Conf. – Energy Crossroads.

Industry About. (2013). Search and find the world's largest industrial facilities. Retrieved from www.industryabout.com

IPCC. (2012). Renewable energy sources and climate change mitigation: special report of the Intergovernmental Panel on Climate Change. Choice Reviews Online (Vol. 49). 32 Avenue of the Americas, New York, NY 10,013-2473, USA: Cambridge University Press. doi:10.5860/CHOICE 49-6309.

King, C.W., Holman, A.S., Webber, M.E., Geology, E., Box, X., 2008. Thirst for energy. Nat. Geosci. 1 (May), 283–286.

Koch, H., Vögele, S., 2009. Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. Ecol. Econ. 68 (7), 2031–2039, http://dx.doi.org/10.1016/j.ecolecon.2009.02.015

Kounina, A., Margni, M., Bayart, J.-B., Boulay, A.-M., Berger, M., Bulle, C., Humbert, S., 2012. Review of methods addressing freshwater use in life cycle inventory and impact assessment. Int. J. Life Cycle Assess. 18 (3), 707–721, http://dx.doi.org/10.1007/s11367-012-0519-3

Liu, L., Hejazi, M., Patel, P., Kyle, P., Davies, E., Zhou, Y., Edmonds, J., 2014. Water demands for electricity generation in the U. S.: Modeling different scenarios for the water?energy nexus. Technol. Forecasting Soc. Change, http://dx.doi.org/10.1016/j.techfore.2014.11.004

Macknick J., Newmark R., Heath G., Hallett K.C. (2011). A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies, (March).

Macknick, J., Newmark, R., Heath, G., Hallett, K.C., 2012. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ. Res. Lett. 7 (4), 045802, http://dx.doi.org/10.1088/1748-9326/7/4/045802

Mertens, J., Prieur-Vernat, A., Corbisier, D., Favrot, E., Boon, G., 2015. Water footprinting of electricity generated by combined cycle gas turbines using different cooling technologies: a practitioner's experience. J. Cleaner Prod., 201, http://dx.doi.org/10.1016/j.jclepro.2014.08.046

Murray, S.J., Foster, P.N., Prentice, I.C., 2012. Future global water resources with respect to climate change and water withdrawals as estimated by a dynamic global vegetation model. J. Hydrol. 448–449, 14–29, http://dx.doi.org/10.1016/j.jhydrol.2012.02.044

NETL.(2010). Water Vulnerabilities for Existing Coal-fired Power Plants. National Energy Technology Laboratory, U.S. Department of Energy.

NETL. (2012a). Greenhouse Gas Reductions in the Power Industry Using Domestic Coal and Biomass Volume 1: IGCC (Vol. 1). National Energy Technology Laboratory, U.S. Department of Energy.

NETL. (2012b). Greenhouse Gas Reductions in the Power Industry Using Domestic Coal and Biomass Volume 2: Pulverized Coal Plants (Vol. 2). National Energy Technology Laboratory, U.S. Department of Energy.

Pfister, S., Bayer, P., 2014. Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production. J. Cleaner Prod. 73, 52–62, http://dx.doi.org/10.1016/j.jclepro.2013.11.031

Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43 (11), 4098–4104, Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/19569336

Rübbelke, D., Vögele, S., 2011. Impacts of climate change on European critical infrastructures: the case of the power sector. Environ. Sci. Policy 14 (1), 53–63, http://dx.doi.org/10.1016/j.envsci.2010.10.007

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Kabat, P., 2013. Multimodel assessment of water scarcity under climate change. Proc. Natl. Acad. Sci. 111 (9), 3245–3250, http://dx.doi.org/10.1073/pnas.1222460110

Sovacool, B.K., Sovacool, K.E., 2009. Identifying future electricity-water tradeoffs in the United States. Energy Policy 37 (7), 2763–2773, http://dx.doi.org/10.1016/j.enpol.2009.03.012

Van Vliet, M.T.H., Yearsley, J.R., Ludwig, F., Vögele, S., Lettenmaier, D.P., Kabat, P., 2012. Vulnerability of US and European electricity supply to climate change. Nat. Clim. Change 2 (9), 676–681, http://dx.doi.org/10.1038/nclimate1546

Verones, F., Hanafiah, M.M., Pfister, S., Huijbregts, M.A.J., Pelletier, G.J., Koehler, A., States, U., 2010. Characterization factors for thermal pollution in freshwater aquatic environments. Environ. Sci. Technol. 44 (24), 9364–9369.

Yu, F., Chen, J., Sun, F., Zeng, S., Wang, C., 2011. Trend of technology innovation in China's coal-fired electricity industry under resource and environmental constraints. Energy Policy 39 (3), 1586–1599, http://dx.doi.org/10.1016/j.enpol.2010.12.034.