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Water use in the Chinese coal industry

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Abstract

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Freshwater resources are getting increasingly scarce throughout the world. In 21th century China, coal is the fuel of the nation's economic growth. Coal is also the nation's largest source of industrial water use. The objective of this thesis is to project water use in the Chinese coal industry up until 2035 by presenting two scenarios simulating two different approaches to water management policies.

Literature studies makes up the base for estimating water use in three stages in the coal's life cycle; mining, washing, and combustion. Through univariate sensitivity analysis, significant parameters are identified and included in the scenario modeling. Key for the study is the separation of water withdrawal rates and water consumption rates.

The results indicate that future coal production and electricity demand have strong influence on water consumption. The coal industry's water consumption is expected to have increased by 18-28% by 2035 depending on water use policies. By 2035, a business-as-usual scenario (BAU) will have increased annual water consumption by 24-63% from current levels, compared to an increase of 6-35% in a water saving scenario (WS). In terms of water withdrawal by 2035, the results show a 18-47% increase in the BAU scenario and a 9% decrease to 13% increase in the WS scenario. It is concluded that water management has high potential in mitigating and reducing water withdrawal rates, but failure to do so may result in a significant increase.

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Populärvetenskaplig sammanfattning

Brist på färskvattenresurser ökar i världen. I 2000-talets Kina är kol bränslet bakom landets explosiva ekonomi, och är samtidigt även den främsta källan till industriell vattenanvändning. Det här examensarbetet syftar till inventera vattenåtgången i Kinas kolindustri samt att prognostisera denna fram till år 2035. Prognostiseringen genomförs genom att simulera två scenarion med olika förhållningsätt till vattenresurshantering. Dessa varieras även med olika uppskattningar för kolproduktion och kolbaserad elektricitetsgenerering.

Kina klassas generellt som ett land med brist på färskvattenresurser, men detta varierar beroende på vilken del av landet man avser. Den nordöstra delen av landet där en stor del av kolindustrin är koncentrerad är färskvattenbristen som mest påtaglig. I dessa regioner är volymen tillgängligt färskvatten per capita många gånger under det internationella genomsnittet. Då kolindustrin samtidigt är vattenkrävande uppstår en problematik som ofta hamnar i skymundan i diskussioner kring kolets utveckling i Kina.

Kinas miljö- och energipolitik i relation till kol handlar i hög grad om att minska utsläpp av växthusgaser och hälsofarliga partiklar från landets kolkraftverk. Denna studie påvisar att befintliga åtgärder ligger till grund för en signifikant ökning av kolindustrins totala vattenkonsumtion. Med andra ord visar denna studie ett samband mellan förebyggande hantering av luftföroreningar och ökad vattenkonsumtion.

I detta examensarbete ligger litteraturstudier till grund för att uppskatta vattenanvändning i tre faser i kolets livscykel; gruvbrytning, tvättning, samt förbränning. Genom univariat känslighetsanalys identifieras signifikanta parametrar som utgör grunden för modellering av de scenarion som presenteras. En viktig beståndsdel i studien är att separera vattenuttag från vattenkonsumtion, som refererar till icke-konsumerande och konsumerande vattenanvändning.

Resultaten visar att kolproduktion och elbehov i hög grad påverkar vattenkonsumtion, som inte enbart kommer att kunna justeras med hjälp av förbättrad vattenresurshantering. År 2035 kommer ett *business-as-usual* (BAU) scenario att ha bidragit med en 24-63% ökning av vattenkonsumtion jämfört med idag. För ett *water saving* (WS) scenario uppskattas ökningen till 6-35%. Vattenuttaget vid 2035 kommer att öka med 18-47% i BAU-scenariot, samt falla med upp mot 9% eller öka med upp mot 13% i WS-scenariot. Det kan då konstateras att vattenresurshantering främst har hög potential för att lindra eller minska vattenuttaget. Vidare kan försummande av vattenresursanvändning i kolindustrin ge upphov till stora ökningar av både vattenkonsumtion och vattenuttag.

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1. Introduction

As of today, China has the largest coal industry in the world (BP, 2014). China produces and consumes half of the world's coal (BP, 2014), and will continue to be a prominent actor in the global coal industry for decades to come. Coal power is often associated with greenhouse gas emissions (Hong and Slatick, 1994), but is also an energy source that uses large amounts of freshwater (EPA, 2014a). While freshwater is a renewable resource, the greater part of China's coal industry is situated in water scarce areas (Wood Mackenzie, 2013). Displacement of coal and water resources is a growing challenge; where poor water management and overconsumption of water pose threats for both humans and the environment (Luo et al, 2013).

World coal production is currently at an all-time high, but at the same time, a recent publication by BP (2014) noted that China just saw its weakest coal production growth in 13 years, as pictured in Figure 1. While there are several factors affecting coal production rates, such as electricity demand, imports, and environmental regulations; water requirements is becoming an increasingly relevant limiting factor and concern (Pan et al, 2012). Part of understanding the relation between coal and water, and perhaps finding strategies for mitigating growing water needs, is to investigate where water is actually used. It is of particular interest to study water use in China's coal industry given the country's role as the world's largest coal actor.

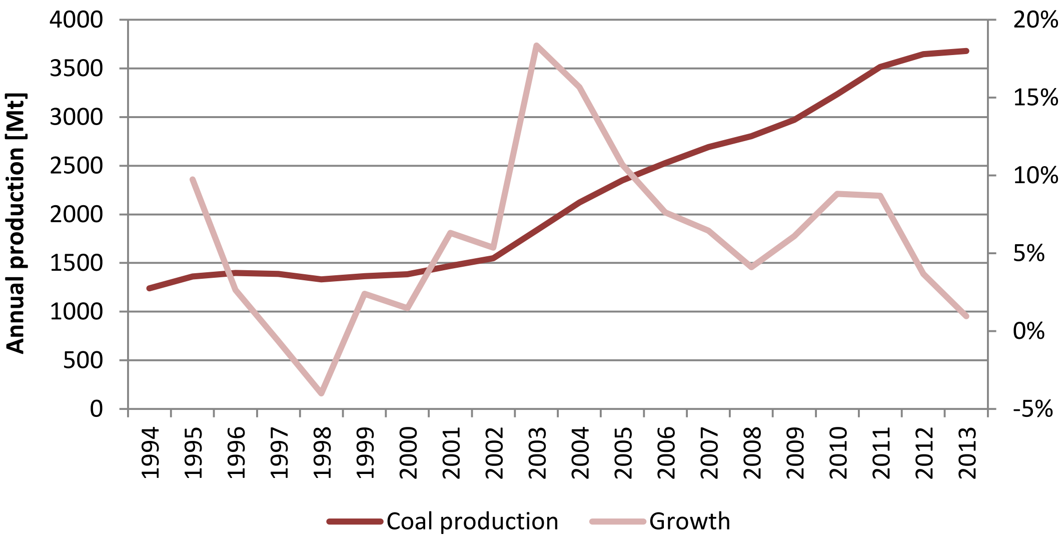

Figure 1: Annual coal production in China plotted against annual relative growth in coal production, 1994-2013 (BP, 2014).

Three parts of the Chinese coal industry is accounted for in this study. These are coal mining, coal washing, and coal combustion. Other uses, such as coal gasification and coal liquefaction, are not covered in this study. While coal uses not covered in this study may amount to significant water use per unit coal used (Pan et al, 2012), their water use in absolute numbers is relatively small. This study focuses on the largest contributors to water use within the coal industry and discusses these in relation to the Chinese energy political agenda. Coal gasification, coal liquefaction, and other coal uses occupy neither of these areas, and is therefore not included in the study.

1.1 Purpose of study

The purpose of this study is to investigate water use in the Chinese coal industry and assess possible water saving measures that may reduce future water use. This is done by developing projections for water withdrawal and water consumption up until 2035. The projections are divided into two scenarios; a business as usual (BAU) scenario and a water saving (WS) scenario. These scenarios are in turn been split into intervals based on production outlooks for coal production and coal-fired electricity generation. As a base for the study, the coal mining, coal washing, and coal combustion phases are investigated to quantify and estimate water use in three stages of the coal's life cycle. Estimating water use in the coal industry is done by summarizing literature studies, where a sensitivity analysis decides relevant parameters to include in the projections.

This study also intends to develop basic methodology for estimating water use for coal mining, washing, and combustion, that may be used in future studies that seek to estimate water use. A current issue in the water-coal debate is that discussions are commonly based on studies that use widely different methodological approaches to calculating water use. As a result, the numbers constituting water use in the coal-water debate are often seen to greatly differ. This study intends to tackle this inconsistency and develop a methodological framework that may also be used in future studies.

2. Background

2.1 Water resources

About 97.5 % of the water on our planet is saline (Shiklomanov, 1993). Saline water can generally not be used in agriculture, so we cannot rely on it for food security (FAO, 2002a). The use of saline water in energy production is also limited as coastal proximity is required (WNA, 2014). The remaining 2.5 % constitute the earth's freshwater. Freshwater is generally found in either glaciers and ice caps, or under the earth's surface in the form of ground water (Shiklomanov, 1993; NGWA, 2014). A fraction of the earth's freshwater make up the rivers, lakes, and wetlands we see around us; the earth's surface water (Shiklomanov, 1993). The amount of surface water in a region constantly changes due to varying precipitation and seasonal climate. This leads to surface water being a fluctuating resource with annual availability subject to constant change. FAO (2010) refers to surface water availability by long-term average estimates, and uses these to calculate annual per capita availability. The fluctuating nature of surface water availability in China is seen in Figure 2, where total surface water resources in China increased by one third between 2009 and 2010, only to drop by just as much the following year.

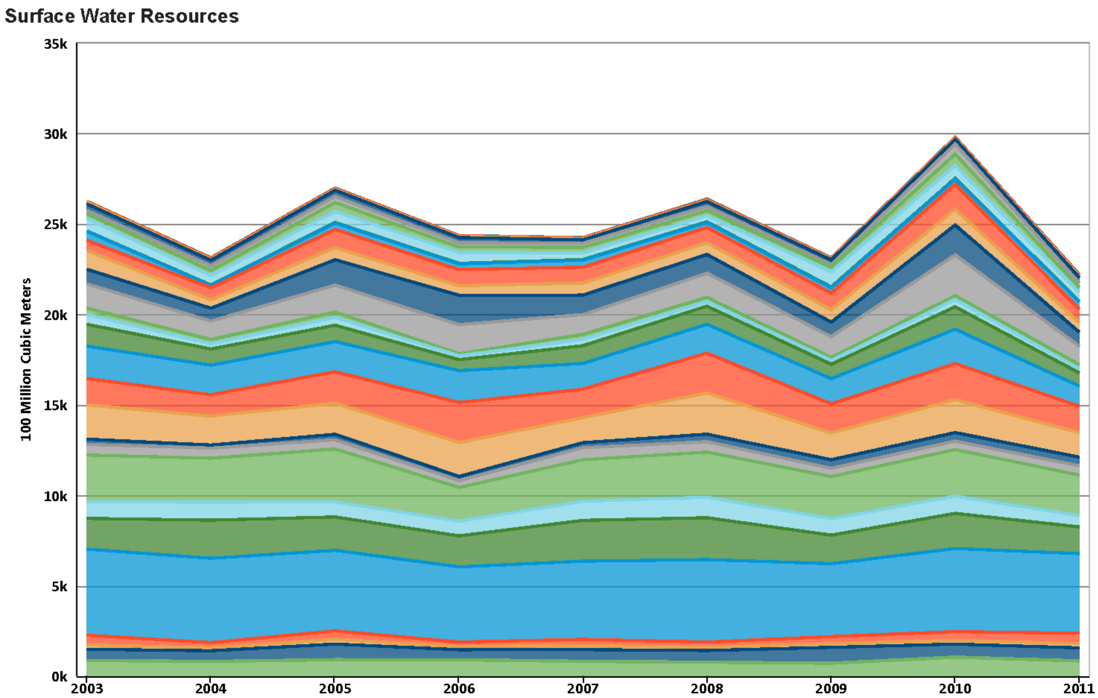

Figure 2: China's total surface water resources over time illustrated by the aggregate amount of provincial water resources. Data and image generated from World Data Bank (2014).

While surface water is the water on the earth's surface, groundwater refers to the water resources found under the earth's surface. When rain falls, part of the rain seep into ground and gets stored among sand, rocks, and clay in the soil (EPA, 2012). Ground water that is relatively close to the surface is referred to as the water table – the water that vegetation and life on the earth's surface rely on (USGS, 2001). The water table rises and falls depending on variations in climate and changes to the landscape on the surface (USGS, 2001). While some consider water stored in glaciers and ice caps to fall in the same category as groundwater (The Rethink Water Network, 2013), the two are generally separated (NGWA, 2014).

Groundwater use is mostly found in agriculture, where 38% of agriculture equipped with irrigation is equipped for groundwater use (Siebert et al, 2010). While ground water availability is affected by drought and changes in climate (USGS, 2001), it is more resilient than that of surface water. By drilling or digging wells, it is possible to extract ground water even in areas that are generally dry and where the water table is quite low (USGS, 2001). Groundwater availability makes industrial activity in arid areas a possibility, but the situating of water intensive industrial activities in arid areas tend to spread contaminants to the groundwater (Teaf et al, 2006). Additionally, high consumption rates tend to raise a number of geological concerns, as commented on by China Geological Survey (2013). It is noted that groundwater depletion has made land subsidence, land fissure, karst collapse, and seawater intrusion fairly common occurrences throughout different parts of China. Surface water and ground water resources overlap to some extent (USGS, 1998). Groundwater drainage into rivers and seepage from rivers into aquifers are both counted as overlapping freshwater resources (UN, 2009). When calculating the total freshwater resources in a country or region, this overlap is generally accounted for and subtracted from the total.

Groundwater is an important asset for industrial and municipal water supply, and the coal industry is not an exception. Pan et al (2012) notes that significant amounts of groundwater are pumped and drained to the ground surface in underground mining operations in China. Gao and Hu (2011) point out that with groundwater resources becoming increasingly contested, water demand will increase exponentially. The same authors note that due to population growth and changing diets, China's irrigated hectares should increase by 2.2% between 2010 and 2020 in order to meet adequate levels food security. They further suggest that the increase in extreme draughts and floods caused by climate change are contributing to the elevation of food security demands. A related issue is the decreasing quality of the country's groundwater resources. A 2014 study by the Chinese government revealed that 60% of the country's monitored groundwater areas had "very poor" or "relatively poor" water quality (Mu, 2014). Contamination of surface water and groundwater near sites for coal activities is a known issue, with drainage from mine sites, sediment runoff, oil spills, fuel spills, and effluents being primary sources (Tiwary, 2001).

In line with the observations by Gao and Hu (2011), McDonald et al (2014) state that growth in freshwater demand is a direct effect of urban growth. Displacement of water needs and water availability further gives way to water trade. However, instead of importing fresh water, urbanized water scarce regions tend to import water intensive products (Zimmer and Renault, 2003). Agricultural products like butter, beef, and soybean oil are prime examples, requiring extensive amounts of water in their production cycle (Renault and Wallender, 2000). The water used in the production of a commodity is referred to as virtual water (Zimmer and Renault, 2003). Indirect water flows of this kind are commonly referred to as virtual water flows, or virtual water trade (Hoekstra, 2003). In China, virtual water flows in the energy sector are characterized by virtual water being transferred from the water scarce north to large cities in the form of coal-fired electricity (Wood Mackenzie, 2013). For the majority of countries, the net virtual water import and export do not amount zero (Mekonnen and Hoekstra, 2011). Countries where the economic value of imports and exports reach an equilibrium can at the same time have extremely uneven virtual water flows. For instance, South Korea, Japan, and Mexico have some of the world's highest virtual water imports per capita (Mekonnen and Hoekstra, 2011).

Water use, whether domestic, industrial, or agricultural, can be specified to further indicate to which extent water is consumed. A general term for water use is water withdrawal, and refers to the temporary withdrawal of water from a resource (Kohli et al, 2012). Water withdrawal encompasses all types of water extraction from a water source. In this study, water withdrawal is considered to be synonymous with water extraction from freshwater resources. Water withdrawal can further be divided into consumptive and non-consumptive water use.

The consumptive share of withdrawn water indicates the share of water that is not returned to its original source after use (Kohli et al, 2012). For instance, withdrawing water from a source and transporting or storing it will often come with some losses in the form of evaporation or leakage, amounting to a certain share of consumptive water use. Other consumptive water uses include incorporation of water in products. Irrigated agriculture is a prime example, where effectively all the withdrawn water used in the process is consumed (Kohli et al, 2012). Siebert et al (2010) highlight that agriculture accounts for 70% of global water withdrawals and 90% of global water consumption.

The non-consumptive water use of an activity refers to the withdrawn water that is returned to its source after having been used. Industries using constant in- and outflows of water to remove system generated heat are examples of non-consumptive water use (Kohli and Frenken, 2011). In the coal industry, power plants that utilize once-through cooling technology fall in this category.

China has 1.35 billion inhabitants, equivalent to 19% of the world's population (Geohive, 2014), but only 6% of the world's freshwater resources (Guan and Hubacek, 2008). Relative abundance in the south is contrasted with scarcity in the north, as shown in Figure 3. On a national level, China's surface water resources per capita are a third of the world average. In northern China, the same figure is 1/25 of world average (Guan and Hubacek, 2008). Freshwater availability continuously changes as precipitation fluctuates. Together with a monsoonal climate, China is highly subject to droughts and floods that can even take place in different regions at the same time (FAO, 2010). Compared to most East Asian and Southeast Asian countries, China's water withdrawal per capita is rather low (Gleick et al, 2007). Yet, China is considered to face significant challenges in terms of water shortage; at large due to geographical spread of water resources (Chen et al, 2009; Wang et al, 2009). Although population growth is diminishing, high levels of economic growth, high urbanization, and increasing living standards are currently fueling an increasing demand for resources and energy (CIIC, 2014).

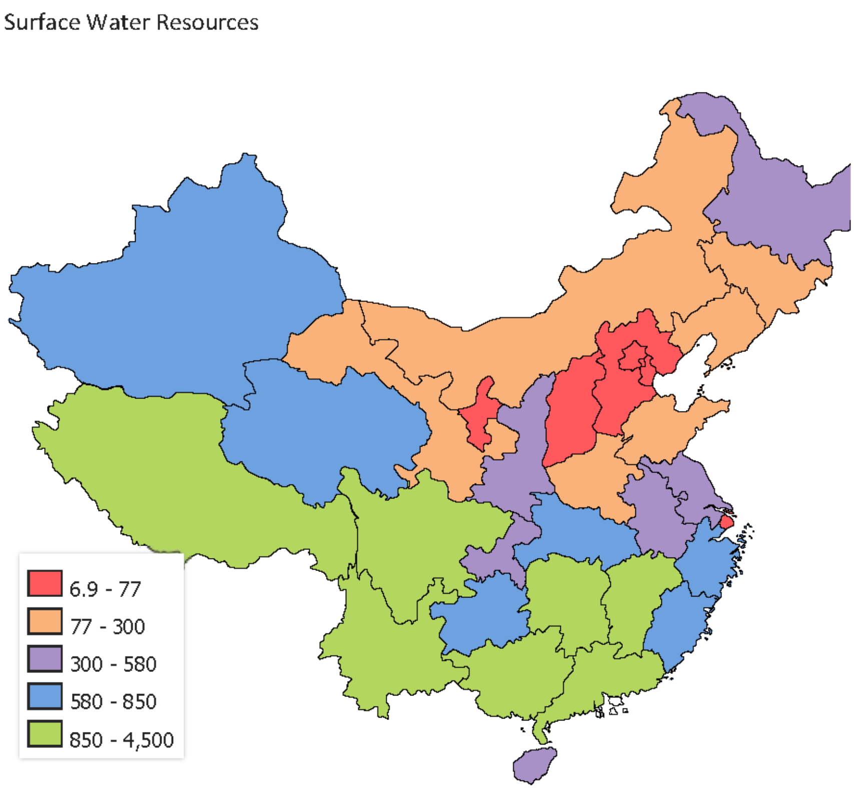

Figure 3: Disparity in surface water resources among provinces measured in 100 million m^3. Data and image generated from World Data Bank (2014).

In terms of sources of water use, agriculture has always been the dominant source of both withdrawal and consumption of freshwater. In 1982, agriculture represented 88% of national water withdrawal, while in 2011, the same figure dropped to 65% according to FAO (in Indexmundi, 2014). Over the same time period, industrial water withdrawal has grown from 10% to 23% (FAO in Indexmundi, 2014). According to the National Bureau of Statistics (in Pan et al, 2012), half of industrial water use in China is directly connected to the coal industry. According to Wood Mackenzie (2013), 70% of coal-fired power plants, as well as the majority of active coal mines, are located in provinces with medium to extremely high baseline water stress, a measure of demand and supply for freshwater. Wang et al (2013a) shows that a significant amount of coal production projections predict a coal production peak to occur within 2020-2035, further indicating that water demand and water challenges will continue to grow from current levels.

Hydrologists typically assess freshwater scarcity in countries and regions by measuring freshwater availability per capita (UN, 2012). A region or country is said to experience water stress when annual availability falls below 1,700 m^3 per person. Furthermore, water availability at or below 1,000 m^3 per person denote water scarcity (UN, 2012). To accommodate for water stress and water scarcity, henceforth referred to as only water scarcity, coal-fired power plants in water scarce regions are often constructed with cooling towers that reuse cooling water, as opposed to once-through cooling techniques that rely on a constant in- and out flow of water (Zhang et al, 2014).

2.2 Coal mining and washing

Coal mining can at large be divided into surface mining and underground mining (WCA, 2014a). Surface mining, also known as opencast or opencut mining, is employed when the coal is close to the surface, and involves breaking up the overburden of soil and rock with explosives (WCA, 2014a). Soil and rock are then removed systematically until coal seams are exposed. This type of mining is common in Australia and the U.S., where surface mining accounts for 80% and 67% of production respectively (WCA, 2014a). According to Meng et al (2009), 95% of Chinese coal production since 1949 comes from underground mines. China's coal resources are generally located at a depth of several hundred meters (Pan, 2005). The recovery rate of mined coal is around 75% in underground mining and around 90% in surface mining (WCA, 2014a). Meng et al (2009) mention that underground mining lead to higher water resource losses compared with that of surface mining. This translates into underground mining having higher water consumption rates. Meldrum et al (2013) present similar findings, estimating water use in underground mining to be 2.5 times the water use in surface mining operations. In Guan and Hubacek (2008), the State Statistical Bureau of China report that 38% of the 1997 water consumption in Northern China's "coal mining and processing" originated from ground water sources.

Water used in coal mines is generally not returned to its source after use and treatment, meaning that water use in coal mining is considered to be of consumptive nature (Mielke et al, 2010). According to Chadwick et al (2013), the principal water consumer in underground mining is dust control. Other sources of water use are fire protection, tunnel washing, and revegetation (Pan et al, 2012; Davis and Wood, 1974). Revegetation of mining sites in China is mentioned as a source of water use in Li (2005) and Gao et al (1998). Water legislation related to coal mines is primarily related to wastewater treatment in effort protecting and enhancing the status of nearby ecosystems, wetlands, and groundwater (EU, 2000). As outlined by Brown et al (2002), there are different methods for wastewater treatment. China's national share of mine water that undergoes treatment is unknown. It is however known that where water treatment takes place, it is generally active mine water treatment in the form of metals separation through pH-raising with limestone addition in sedimentation ponds (Zhang et al, 2010). This type of waste water treatment is expected to yield high water recovery, as stated by INAP (2012) and Günther and Mey (2006). In this study, water use in mines is measured in cubic meter water used per metric tonne coal produced; m^3/t. As part of lowering the water use intensity of a mine, The State Government of Victoria (2014) lists onsite water recycling and water reuse as priorities in their guidelines for water management in mines and quarries.

Coal washing, or coal preparation, includes sizing and cleaning coal in order to meet market demands and specifications. In terms of water use, coal washing uses water to reduce the concentration of ash, sulfur, and other unwished impurities in coal (EIA, 2014a). While coal washing improves the fuel efficiency of the coal and reduces emissions that occur during combustion in coal-fired power plants, coal washing produces water slurry referred to as blackwater (Parekh and Groppo, 1993). According to Parekh and Groppo (1993), half of the solid composition of the blackwater consists of unrecovered coal, and the other half of metals and impurities. Part of the water is generally recovered and reused, while the solids are stored or disposed of (Parekh and Groppo, 1993). Leakage of waste produced in coal preparation plants, henceforth referred to as CPPs, is highly toxic and a source of environmental concern (Ward, 2014).

In early 2013, China Coal Processing & Utilization Association estimated that 55.4% of China's coal was washed (China Coal Resource, 2013). Of thermal coal, i.e. coal that is used in electricity generation, less than 40% was reported to be washed, up from 35% in 2010 (China Coal Resource, 2013). In comparison, the washing rates of Chinese coal twenty years ago were 19% for all types of mined coal and 10% for thermal coal specifically (Chadwick and Kennedy, 1995). Economic incentives to increase the share of thermal coal washed are said to be few, as current penalties and fines for excess pollutant discharge are low (China Coal Resource, 2013). On a contrasting note, MEP (2013) announced a plan to reduce air emission levels in north-eastern China by 2017, indirectly suggesting that coal washing rates and emission penalties are to be set higher.

China's coal production amounted to 3680 Mt in 2013 (BP, 2014), totaling more production than the rest of the world's top ten coal producers combined (WCA, 2014c). Having been a net coal exporter for more than two decades, China became a net coal importer in 2009 with Indonesia and Australia supplying the majority of the country's coal imports as of 2012 (EIA, 2014b). China is experiencing a decline in absolute consumption growth, but still managed a 67% share of global coal consumption growth in 2013. More recently, China Coal News (2014) observed a decreasing trend in monthly coal imports from August 2013 to August 2014 compared to that of the previous year. In November 2014, the Chinese government issued an energy development plan where annual coal consumption is set to peak at 4200 Mt in 2020, 16.3 % higher than that of 2013, translating into an annual growth rate of 1.5% (Shanghai Daily, 2014).

At the end of 2013, China had nearly 13% of the world's proven coal reserves (BP, 2014). Of the coal production in China, over 70% was mined in China's top three coal producing provinces; Inner Mongolia, Shanxi, and Shaanxi, according China National Coal Association (in China Coal Resource, 2013). These provinces are also among the more water scarce provinces in China, which has led to raised concerns about endangering of water resources (The Guardian, 2013; Bloomberg, 2013). With coal-fired power plants often situated in the proximity of mines (WNA, 2013), it is difficult to avoid regional concentration of water use. Water challenges related to quality and use are receiving increased attention both domestically and worldwide, but at the same time, concerns regarding air pollution are China's primary focus in terms of environmental politics. This is highlighted in the 12th Five Year Plan issued in 2010 (CPCCC, 2010), in the more recent Action Plan on Prevention and Control of Air Pollution (MEP, 2013), and in the U.S.-China joint announcement on climate change; aiming to peak national CO_2 emissions by 2030 (The White House, 2014). Several of the measures planned involve increasing water consumption.

A prime example of this is filtering of harmful particles in coal-fired power plants (MEP, 2013).

2.3 Coal-fired power

2.3.1 Plant technologies

Most coal-fired power plants in the world are steam-electric power plants. They rely on heating and pressurizing steam that is used to drive a turbine, after which the steam is condensed to water in a condenser (WCA, 2014e). Different steam-electric power plants use different types of fuels that are combusted for heat (EPA, 2008). The water needs of a coal-fired power plant can be divided into coolant water and process water, where the former normally represent almost all the cumulative freshwater use in the plant (Carney et al, 2008). Power plants utilizing air or saline water for cooling purposes will therefore have comparatively low freshwater demands.

Currently, most coal-fired power plants rely on pulverizing coal before combustion for increased efficiency (Nalbandian, 2009). Newer boiler technologies aim to heat and pressure the steam to higher pressures and temperatures to reach higher degrees of fuel efficiency. Pulverized-coal plants utilizing modern, high efficiency boilers is already the backbone of world coal-fired power generation, and will according to Nalbandian (2009) in all likelihood continue to dominate the world's power plant fleet as they, despite higher initial costs, often prove economically attractive due to lower fuel needs. IEA (2012b) named coal-fired power plants utilizing ultrasupercritical (USC) boilers, the current flagship of steam-electric power plant boiler technology, the most efficient High Efficiency Low Emission-technology (HELE) available. Currently, China and India are among the foremost proponents for USC technology.

Aside from traditional pulverized-coal plants, there are Integrated Gas Combination Cycle (IGCC) plants that gasify coal before combustion. Heat in the combustion gases is used to heat steam that is used in a steam turbine for additional electricity generation (WCA, 2014b). Combined cycle plants generally reach high degrees of fuel efficiency, but have higher water demands due to water needs in the gasification process (NETL, 2013). Due to higher efficiency, IGCC power generation systems also produce lower CO_2 emissions than conventional pulverized coal-fired power plants do (Gnanapragasam et al, 2009). As the ongoing improvement of the efficiency of pulverized-coal plant technology outpaces the one of IGCC technology, widespread commercialization of IGCC is still far from certain (IEA, 2012b). Cost is another challenge, as traditional power plant designs are significantly cheaper (WCA, 2014b).

Carbon Capture and Storage (CCS) is a technology that involves capturing CO_2 emissions produced in power plants. According to Thorbjörnsson et al (2014), coal-fired power plants equipped with CCS experience efficiency losses ranging from 15-32% depending on the type of carbon capture method used. The authors further suggest that coal consumption in coal-fired power plants with CCS can be up to 31% higher compared to conventional coal-fired power plants. Coal-fired power plants utilizing CCS technology also require more water than conventional coal-fired power plants do. Zhai et al (2005) show that with CCS, power plants with wet cooling towers will approximately double their water consumption. In a related study, Meldrum et al (2013) point out that CCS can increase water consumption by 77% and water withdrawal by between 83% and 97% in the life cycle of pulverized coal. Studies of the barriers and incentives for implementation of CCS in China generally do not bring up implications that are connected to efficiency losses or increases in coal- and water demand (Liu and Gallagher, 2009; Liang and Wu, 2009).

2.3.2 Cooling systems

The water cooling of a power plant represents a power plant's primary source of water use (Carney et al, 2008). The water withdrawn or consumed for cooling purposes varies with different types of water cooling techniques (NETL, 2011). Cooling of a steam-electric power plant is directly related to power plant efficiency, or lack thereof, as optimal conditions for the electricity generating turbine depend on steam condensate temperature (Burns and Micheletti, 2002). While there are many variations on power plant designs, the most common archetypes are accounted for in this study.

Once-through freshwater cooling is employed in power plants near rivers or lakes, where large amounts of water is withdrawn to support a constant in- and outflow that transports heat back to the water source. Consumption figures for once-through cooling are relatively low due to low evaporation (NETL, 2011). Once-through freshwater cooling systems may also utilize saline water, enabling coastal coal-fired power plants, ideal recipients for imported coal from e.g. Australia or Indonesia – China's two largest trading partners for imported coal (Du, 2013). Power plants utilizing once-through cooling are cheaper to construct than recirculating systems are (Dorjets, 2014). They also have lower operating energy requirements, making them more fuel efficient than their recirculating counterparts (NETL, 2001).

Wet recirculating cooling is another type of cooling system, commonly accompanied by large cooling towers at the power plant sites where wet recirculating cooling is used. Similar to power plants utilizing once-through cooling, wet tower systems condense the power plants' steam by using water to remove heat. The cooling water is cooled by evaporative cooling in the water towers (NETL, 2011). Wet recirculating systems have low water withdrawal rates compared to once-through cooling as most water is reused. On the other hand, wet recirculating systems have relatively high water consumption rates due to water continuously evaporating from cooling towers. The evaporation rate is linked to the power production of the plant; increased production means increased heat load which results in greater evaporation (NETL, 2011). Some wet recirculating systems use ponds instead of towers for evaporative cooling (NETL, 2001). Cooling ponds require significantly more land but have slightly lower water consumption rates than cooling towers have (IAEA, 2012).

Dry recirculating cooling systems are, together with saline based once-through cooling systems, the most freshwater efficient type of cooling system. Dry recirculating systems operate by using air rather than water for cooling. A major drawback with air cooling is that the power plant rate of efficiency is lower than that of its freshwater counterparts, and thus consumes more coal than water cooled power plants do for the same amount of electricity production (GAO, 2009; Yu et al, 2011). Higher coal consumption results in more pollution and more water use in mining and washing, and faster draining of coal reserves. While imports may offset an increased domestic demand for coal, environmental effects would still occur elsewhere. It should also be mentioned that dry cooling systems are typically much more expensive to construct and maintain than freshwater based cooling systems are (GAO, 2009). IEA (2012c) estimate that the cost of a thermal power plant utilizing dry cooling is 3-4 times more expensive than of those utilizing wet recirculating systems.

Different cooling systems also have different energy requirements, meaning that some cooling systems use more energy to operate. This is referred to as the energy penalty, and includes all types of energy requirements of a power plant. Although the term is not restricted to cooling equipment alone, cooling equipment are significant sources of energy penalty in conventional coal-fired power plants. A study by EPA (2001) reported that energy requirements to operate air cooling equipment in fossil fuel plants amounted to 2.43 % of power output. The figures for wet tower cooling and once-through cooling were 1.18 % and 0.45 % respectively. GAO (2009) note that air cooled power plants are more sensitive to outside air temperature than their water cooled counterparts. This can be explained by the specific heat capacity of water being higher than that of air (USGS, 2014). Water requires more energy than air does to have its temperature increased, making water a more efficient coolant. Keeping the temperature of the coolant low is desired as cooling effectiveness decreases when the coolant temperature increases (GAO, 2009). Burns and Micheletti (2002) mention that daily and seasonal fluctuations in air temperature make air cooled power plants comparatively difficult to design and operate.

Aside from cooling water, a coal-fired power plant utilizes water for a range of other purposes, like boiler feed makeup water, ash handling, and flue gas desulfurization (FGD). FGD entails removal of SO_2 prior to exhaust gases being released to the environment (NETL, 2013). In a case study by NETL, a dozen coal-fired power plants with wet tower cooling technologies were studied, and FGD stood out as the main source of process water use among pulverized coal plants (NETL, 2013). This suggests that the FGD water use is the deciding parameter in process water use in Chinese coal-fired power plants. It should also be noted that all FGD water use in the NETL study is of consumptive use. Zhai et al (2011) points out that boiler feed makeup water represents a considerable part of process water use in wet tower power plants utilizing supercritical boilers. The same authors also note that process water use amount to 24% of water withdrawal and 16% of water consumption in power plants utilizing wet recirculating cooling. The cooling water data in this study is assumed to include boiler feed makeup water unless mentioned separately.

In July 2012, the Chinese government unveiled plans to construct 363 new coal-fired power plants across the country, most of which are planned to be situated in water scarce areas (WRI, 2012). IEA reports that between 2011 and 2035 China will add 553 GW of coal-fired electricity generation while the capacity of retiring coal-fired power plants will amount to 68 GW (IEA, 2012a). In comparison, the nation had 801 GW coal-fired power installed in 2013 according to China's National Energy Agency (in Davidson, 2013). Pulverized-coal with USC technology will likely see an increased growth worldwide, driven by commitments from China and India in particular (Modern Power Systems BRIC, 2013). Since 2010, Chinese power plants with a capacity of more than 600 MW are required to utilize supercritical or ultrasupercritical techonology (Chen and Xu, 2010). In 2011, China's electricity mix consisted of 79% coal power. Between 1991 and 2011, this share hovered around 75-80%, and is expected to decline over the coming decades (EIA, 2014b).

2.3.3 Environmental impacts

Environmental impacts of coal combustion include emissions of air toxics, like SO_2, NO_x, fly ash, lead, cadmium, and mercury. These air pollutions can travel long distances, which spurred EPA (2014b) to issue the Clean Air Interstate Rule in 2005, which serves to protect downwind states from SO_2 and NO_x emissions in upwind states in the Eastern U.S. Similarly, coal combustion in China affects air quality in provinces that do not engage in coal combustion. In the U.S., coal combustion was as of 2011 the greatest source of air pollution in the electric generation sector (NESCAUM, 2011).

No direct water pollution similar to that of coal mining or coal washing occur during the combustion phase, as water and steam is physically separated from the burning of coal (Duke Energy, 2014). Indirect water pollution still occurs as toxic air emissions are spread with coal ash, affecting land, rivers, and other water courses (PSR, 2010). Pollution of water courses with mercury is a known health concern, affecting both humans and animals through food consumption (NRDC, 2014). EPA (1998) concluded in a study that there is still a "plausible link between mercury emissions from anthropogenic combustion and industrial sources and mercury concentrations in air, soil, water and sediments".

Madden et al (2013) points out that power plants utilizing once-through cooling are not only high water withdrawers, but sources of thermal pollution to the lakes or rivers they withdraw water from. The authors refer to several studies that suggest that thermal pollution from power plants have significant impact on aquatic organisms. A joint U.S. DOE (2002) study on energy penalties in cooling water intake structures mentions the occurrence of fish and other organism being trapped in the intake structure of once-through cooled power plants, or if small enough, passing through the cooling system with the coolant water. In the U.S., once-through cooling is rarely used in new power plants due to the need to control thermal pollution (Hamilton, 2013).

3. Methods

3.1 Water use

3.1.1 Estimating water use in coal mining and washing

Water consumption in coal mining has been estimated using data of the following parameters:

- Water use intensities, mining (m^3/t)
- Coal production (Mt)

Coal production represents the total annual coal production in China. It includes all types of domestic coal mining activity as measured by IEA (2010). It does not include coal imports. Water use intensity is measured in m^3/t, or cubic meters per metric tonne mined coal. Data concerning water use intensities have been gathered through literature studies. As surface mining is not prevalent in China, estimates of surface mining water use have been disregarded.

The total water consumption in China's coal mines has been calculated as:

$$Wc_m = Cp \cdot Wui_m \tag{1}$$

where Wc_m is water consumption in mining operations, Cp is coal production, and Wui_m is water use intensity in mining operations.

For coal washing, the following parameters have been used:

- Water use intensities, washing (m^3/t)
- Coal production (Mt)
- Coal washing prevalence

Coal washing prevalence denote the share of mined coal that undergoes coal washing.

The total water consumption in the coal washing phase has been calculated as:

$$Wc_w = Cp \cdot Wui_w \cdot cwp \tag{2}$$

where Wc_w is water consumption in washing operations, Cp is coal production, Wui_w is water use intensity in washing operations, and cwp is coal washing prevalence.

3.1.2 Estimating water use in coal-fired power plants

Nation level estimates of water use in mining and washing are relatively resilient to fluctuations in coal production and changes in energy politics. Similar estimates for water intensities in coal-fired power plants are however strongly connected to the context in which they were estimated. For instance, process water use have increased manifold over the past decade in an attempt to reduce air emissions from coal-fired power (Wang and Hao, 2012a).

The following parameters have been used to estimate water use:

- Coal-fired electricity generation (TWh)
- Share of coal-fired power plants utilizing once-through freshwater cooling
- Share of coal-fired power plants utilizing wet recirculating cooling
- Water withdrawal intensity, once-through cooling (m^3/MWh)
- Water withdrawal intensity, wet recirculating cooling (m^3/MWh)
- Water consumption intensity, once-through cooling (m^3/MWh)
- Water consumption intensity, wet recirculating cooling (m^3/MWh)
- Flue Gas Desulfurization (FGD) water intensity (m^3/MWh)
- Flue Gas Desulfurization (FGD) prevalence

In short, these can be summed up as:

1) Estimated electricity generation
2) Cooling water requirements
3) Process water requirements

Total water withdrawal and consumption in China's coal-fired power plants has been calculated as:

$$Ww_{cfpp} = Ep \cdot \left((S_{ot} \cdot Wwi_{ot}) + (S_{wr} \cdot Wwi_{wr}) + \left(Fgd_{pr} \cdot Wci_{fgd}\right) \right) \qquad (3)$$

$$Wc_{cfpp} = Ep \cdot \left((S_{ot} \cdot Wci_{ot}) + (S_{wr} \cdot Wci_{wr}) + \left(Fgd_{pr} \cdot Wci_{fgd}\right) \right) \qquad (4)$$

where Ww_{cfpp} is water withdrawal and Wc_{cfpp} is water consumption for coal-fired power plants, Ep is coal-fired electricity production, S_{ot} is the share of once-through cooling used and S_{wr} is the share of wet recirculating cooling used. Wwi_{ot} and Wwi_{wr} are water withdrawal intensities for once-through cooling and recirculating cooling systems. Wci_{ot}, Wci_{wr} and Wci_{fgd} are water consumption figures for once-through cooling systems, recirculating cooling systems, and FGD, respectively. Fgd_{pr} denotes the prevalence of FGD in coal-fired power plants.

Since China employs several different cooling systems in their coal-fired power plants, an assumed current distribution of cooling systems, pictured in Figure 4, has been used in calculations. China Electricity Council (2013a) estimated that 58.54% of the nation's coal-fired electricity generating capacity was used in 2013. This number, the capacity factor, has been used in this study to convert estimates of generating capacity (W) to electricity generation (Wh). For example, if a coal-fired electricity generation capacity estimate is $6.00 \cdot 10^{12}$ W for a given year, this is may be described in annual electricity production by multiplying the capacity estimate with the amount of hours in a year. With 8760 h in a year, the results in 52.56 · 10^{15} Wh, or 5256 TWh. A capacity factor of 58.54%, results in electricity generation in the example reaching an annual 3077 TWh.

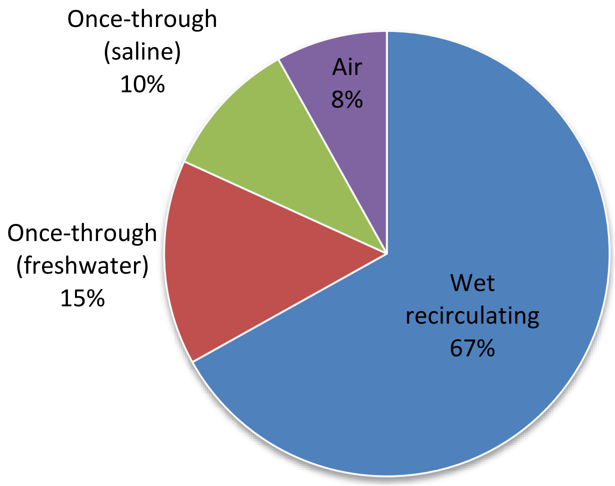

Figure 4: Assumed share of cooling systems in China's coal-fired power plants as of 2014. Figure adopted from Yu et al (2013).

The distribution of cooling systems in China's coal-fired power plants changes as power plants are continuously retired and constructed with the preference of cooling type also changing. China currently has a coal-fired power plant fleet of which 69% of installed capacity is built during the 2000s (IEA, 2012a). Combined with aggressive expansion plans, most of the changes to China's distribution of cooling systems over the coming years will come through additions. Based on its New Policies scenario, IEA (2012a) predicts that more than 8 MW will be constructed for each MW retired in the time interval 2011-2035.

3.2 Sensitivity analysis

After having gathered estimates for parameters that impact overall water use, these parameters have been weighted against each other in a univariate sensitivity analysis. As Marshall (1998) explains, this type of analysis displays how the uncertainty of different parameters impact the overall outcome. Coal production, power plant cooling water needs, and FGD prevalence are instances of parameters that all affect water use. A sensitivity analysis also helps distinguishing between parameters that have large impact on water use and parameters that have less of an impact.

The sensitivity analysis has been carried out by increasing and decreasing the value of single parameters by ±20%, ±40%, ±60%, ±80%, and ±100%, while keeping all the other parameters unchanged. The process has been repeated for every parameter, and subsequently visualized in a diagram, where the slopes of the lines indicate their sensitivity to change and overall impact on water use.

3.3 Explorative scenarios

In order to model China's future water use in the coal industry, two scenarios, illustrated by two intervals, have been constructed based on the results and findings of the study. The intervals modeled are referred to as the business-as-usual (BAU) scenario and the water saving (WS) scenario. These intend to reflect two different energy political directions, where the former is focused on mitigating emissions and the latter on preserving water resources. The BAU and WS scenarios are each built on estimates for high and low coal production and coal-fired electricity generation. The high scenarios represent high coal production and coal-fired electricity generation, while the low scenarios represent low coal production and coal-fired electricity generation. Water use in the BAU and WS scenarios have then been described with numeric intervals in an effort to include plausible variations in production of coal and coal-fired electricity.

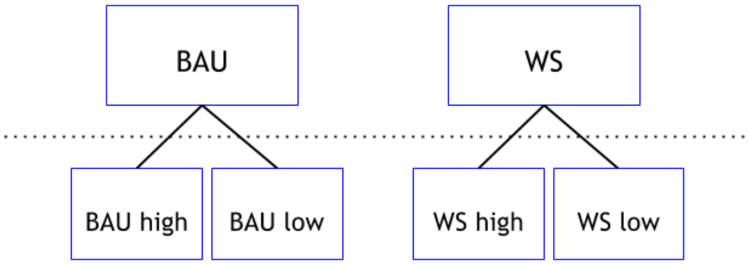

Figure 5: The left side shows the BAU scenario being built on the interval between BAU high and BAU low, two sub-scenarios with different production data to accommodate for different outlooks in Chinese coal production and coal-fired electricity generation. The right side shows the equivalent for the WS scenario.

Overall, the parameters used to model the different water use scenarios are:

- Coal production
- Water use intensity (mining)
- Water use intensity (washing)
- Washing prevalence
- Coal-fired electricity generation
- Prevalence of the wet recirculating cooling
- Prevalence of the once-through freshwater cooling

The constellation of cooling systems is central for the scenarios. In the coal industry as a whole, cooling water needs are recognized as the primary source of water withdrawal. Aside from cooling system constellations; electricity generation, coal production, coal washing rates and water recycling rates have been tailored to follow trends illustrated in the different scenarios. Water recycling, or water reuse, have been modeled by adjusting the water use intensities, as falling water use intensity would suggest improved water management, which in turn relates to recycling and reuse of water. The coal-fired electricity generation forecasts are gathered from findings relating to the estimation of water use in coal-fired power plants.

The coal production forecasts are based on the low production case in Höök et al (2010) and the forecast made in Wang et al (2013a). The estimates for cooling system shares in the power plant fleet are based on the scenarios constructed in Yu et al (2011). Coal washing prevalence in the BAU scenarios are assumed to follow a 2011-2015 growth trend forecasted by China National Coal Industry Association (Wang, 2011). Water use intensity is assumed to follow developments in water reuse and water recycling. In the WS scenario, water use intensity reaches half of today's levels by 2035, suggesting significant improvements in water reuse and water recycling in coal mines and preparation plants. In summary, the BAU and WS scenarios are illustrated as projected intervals for future water use where parameters are altered to fit with two assumed energy political directions. The scenario modeling is done to contextualize results of this study and to model how different energy policies may impact aggregate water use of the Chinese coal industry.

The BAU scenario consists of a gradual increases in tower based wet recirculating cooling systems, i.e. wet tower cooling. As extensive official plans for new power plants in water scarce areas have been made, this study assumes that a majority of these will employ low water withdrawal cooling techniques. The growth of once-through cooling installations in the BAU scenario gradually declines, while the air cooling share slowly increases. A rapid expansion of air cooled power plants is discouraged by rising electricity demand and high initial investment. The water recycling rate remains the same while coal washing prevalence increases by 3 percentage units annually before stagnating at 95% in 2025.

The WS scenario involves mitigating water withdrawal and water consumption rates while encouraging water recycling. This is partly expected to occur through rapid, and in some cases pre-mature, retirement of once-through cooling power plants. In the WS scenario, prevalence of once-through cooling will drop from the current 14.9% to 8.8% in 2035. Air cooling grows rapidly, resulting in high investment costs, both due to the design of air cooled power plants and due to the additional generation capacity needed from the loss in thermal efficiency. Coal demand rises as an effect, but does not impact coal production estimates, as it is assumed that increases may be offset by imports. Both wet tower cooling and saline based cooling grows faster in the WS scenario than in the BAU scenario. Coal washing prevalence remains same in the WS scenario over the next 20 years in order to preserve water. Encouragement of water recycling lowers the water use intensities in coal mining and washing, reaching half their current levels in 2035.

4. Results

The results of this study are presented in three parts. The first part illustrates the results of the literature studies, where estimations of water use in mining, washing, and combustion, as well as estimated forecasted coal-fired electricity use, are presented. The second part shows the results of the parameter analysis, where the impact of the estimates drawn up in the first part are compared and evaluated in relation to the coal industry's total water use.

The third part shows the results of the scenario modeling, where the projections for future water use are illustrated and described based on the findings of the parameter analysis.

4.1 Data results

4.1.1 Water use in mining and washing

As depicted in Figure 6, the majority of the gathered estimates for water use in coal mines are below 0.50 m^3/t. The two highest data points are found at 2.30 m^3/t and 3.00 m^3/t, significantly higher than the median of the average value for each data point, constituting 0.26 m^3/t. It is further notable that the four estimates originating from outside of China are among the lowest estimates. With all the estimates for coal mining water use taken into consideration, the average water use is approximately 0.69 m^3/t.

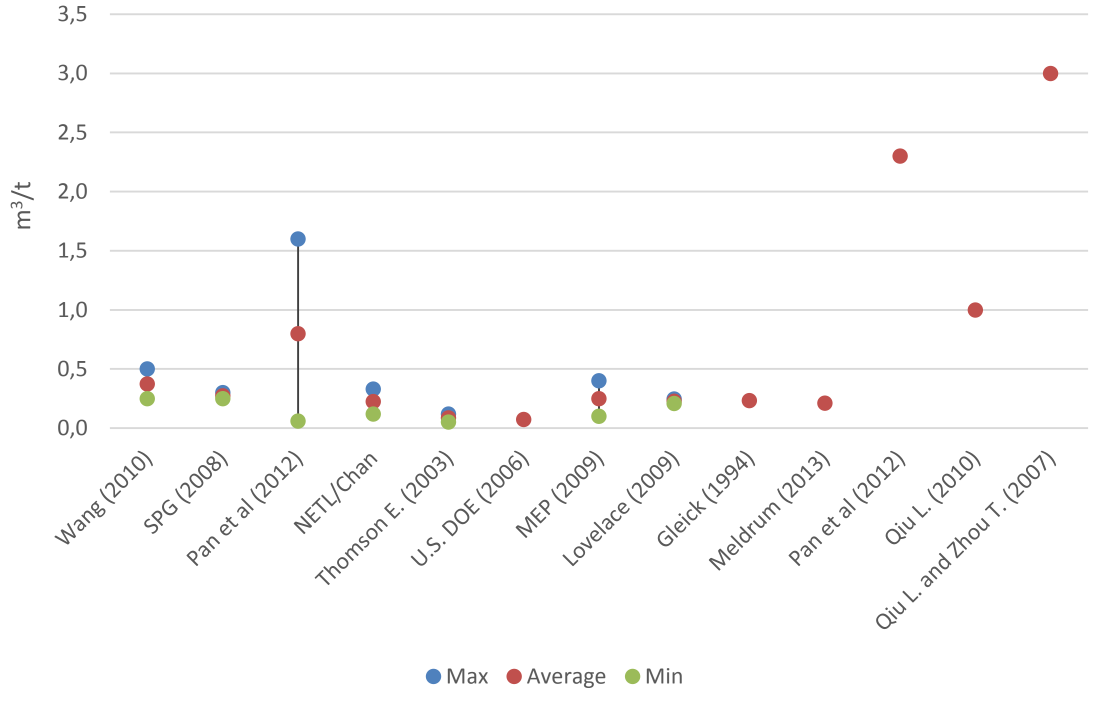

Figure 6: Freshwater use in coal mining operations.

For water use in coal washing, as described in Figure 7, there is a significant spread among the gathered estimates. Notably, the estimates are divided into one cluster at 0-0.5 m^3/t and another at 2.5-4.0 m^3/t. The average water use in the coal washing process, all data considered, amount to 1.3 m^3/t.

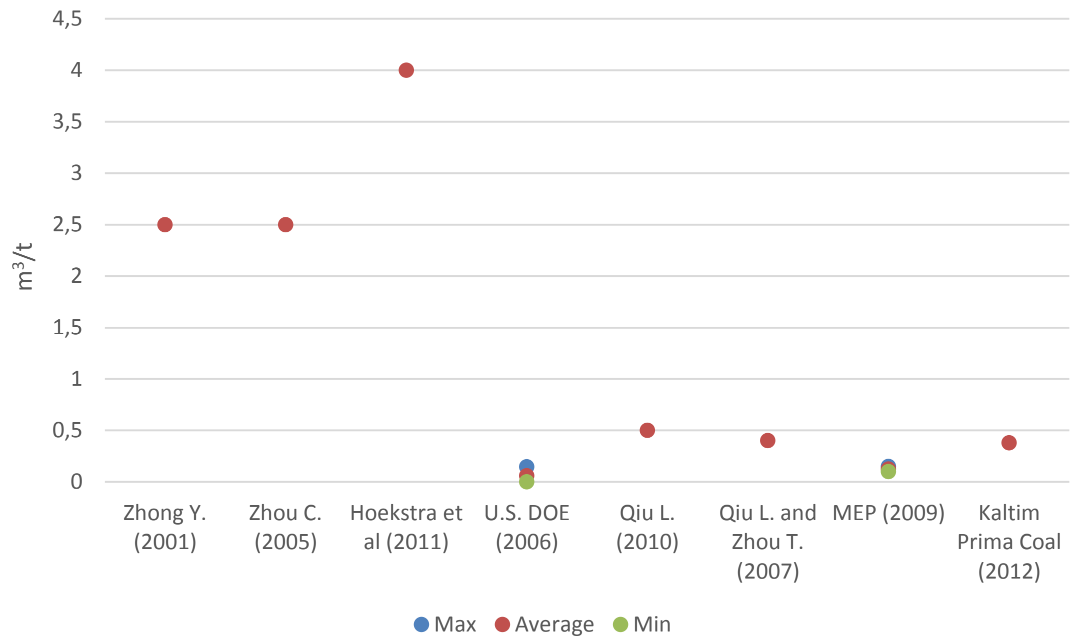

Figure 7: Freshwater use in coal washing operations.

Water use in coal-fired power plants are estimated at 130.9 m^3/t water withdrawal and 1.1 m^3/t water consumption for once-through cooled power plants. In wet recirculating coal-fired power plants, the average water use has been estimated to 2.8 m^3/t water withdrawal and 2.3 m^3/t water consumption.

Table 1: Estimates of withdrawal and consumption intensities for once-through cooling. All estimates are in m^3/MWh.

		Withdrawal	Consumption	
Once-through	Kyle et al (2012)	158	0.95	
	Greenpeace (2013)		1.2	
	BP (2013)	129.6	1.224	
	NREL (2011	137.6	0.95	Generic
	NETL (2011)	83.4	0.0227	Subcritical & supercritical average
	ERPI (2002)	75.5-189.3	1.135	Fossil/bio/waste
	CEC (2002)	113.6-170.3		Fossil
	Gleick (1994)		1.2	
	Yu et al (2011)	133.3		Supercritical
	Average[a]	130.9	1.1	

[a]The NETL estimate of 0.0227 has been disregarded.

Table 2: Estimates of withdrawal and consumption intensities for wet recirculating cooling. All estimates are in m^3/MWh.

		Withdrawal	Consumption	
Wet recirculating	Kyle et al (2012)	3.8	2.6	
	Greenpeace		4.2	
	BP (2013)	2.3	1.944	
	NREL (2011)	3.8	2.6	Generic
	NETL (2011)	2	1.48	
	ERPI (2002)	1.14-2.28	1.14-1.81	Fossil/bio/waste
	CEC (2002)	2.27-3.41		Fossil
	Gleick (1994)		2.6	
	Zhai et al (2011)	1.93		Supercritical
	Yu et al (2011)		3.03	Supercritical
	WNA (2009)	1.75-2		Fossil
	Average	2.8	2.3	

Some of the estimates for withdrawal and consumption intensity used in this study involve other types of power plants than coal-fired ones. In addition, some studies have specifically stated that the estimates made only involve power plants using supercritical, subcritical, or generic boilers. This information is shown in the rightmost column in Table 1 and 2.

4.1.2 Projected coal-fired electricity generation

Data concerning estimated coal-fired electricity generation has been gathered from IEA's World Energy Outlook (2013), China Renewable Energy Society (CRES, 2013) – a private Beijing-based company formerly specialized in solar energy, China Electricity Council (CEC, 2012) – a joint organization of China's power enterprises and institutions, China Development Bank (CBD, 2013) – a government-owned financial institution/policy bank, and the National Development and Reform Commission (NDRC, 2013) – a governmental macroeconomic management agency.

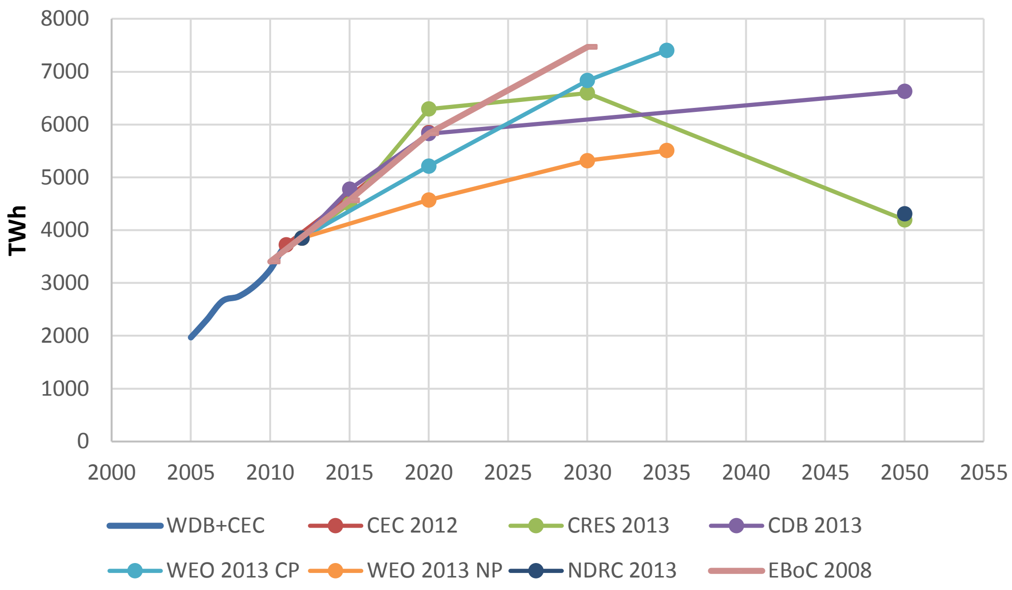

Figure 8: Estimates of coal-fired electricity generation in China.

As visible in Figure 8, there are significant discrepancies in estimations for future coal-fired electricity generation in China. Notably, the 'New Policies' scenario developed by the IEA is lower than every Chinese governmental estimate used in this study. The 'Current Policies' estimate by IEA appears to inhibit slower growth than the Chinese estimates, but reaches higher peak generation at 2035 or later. Up until 2013, the Chinese estimates seem to be more in line with actual measurements of coal-fired electricity generation than IEA's estimates are. It is notable that of the three estimates including 2050 in their estimates, CDB's estimate is significantly higher than that of NDRC and CRES. The CDB estimate of 6631 TWh is 64 % higher than that of today (China Electricity Council, 2013). Noteworthy is that 14 out of 15 coal production forecasts in Wang et al (2013a) predict that the coal production rates of 2050 will be lower than that of today. Regardless of where the coal-fired electricity generation peak occurs in CDB's scenario, it can be assumed that the estimation is made with unparalleled coal production rates in mind. As the Chinese estimates are calculated from capacity figures based on the national capacity factor of China Electricity Council (2013a), a change in utilization hours will affect electricity generation figures of the estimates.

4.2 Parameter analysis

In the sensitivity analysis it is evident that two parameters are extremely sensitive to fluctuations and contingency; electricity generation and water withdrawal intensity for once-through cooling plants. These parameters also significantly affect overall water withdrawal. Water withdrawal intensity in once-through cooling is affected by the share of power plants that use this type of cooling. Changes to this parameter, which is currently estimated at 15% of the Chinese coal-fired power plant fleet, affects total withdrawal rates proportionally to that of mentioned withdrawal intensity. Aside from the two most prominent parameters in Figure 9, the coal production parameter and the parameter for water withdrawal intensity in wet recirculating cooling affect overall withdrawals marginally more than other parameters do. Changes to the estimates for coal washing, coal mining, and FGD do not affect the coal industry's total water withdrawal by much.

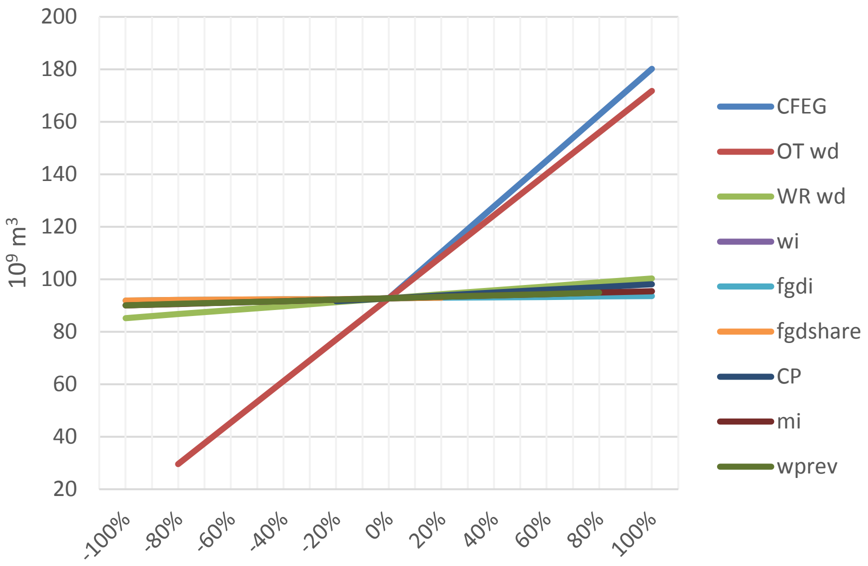

Figure 9: The water withdrawal impact of significant water use parameters in the Chinese coal industry.

In Figure 9, *CFEG* is coal-fired electricity generation. *OT wd* is once-through cooling water withdrawal, and *WR wd* is wet recirculative cooling water withdrawal. In Figure 10, *wd* is replaced with *cs* to denote water consumption for the different cooling types. Coal washing water intensity is denoted by *wi*, and coal mining water intensity is denoted by *mi*. *CP* stands for coal production, and *wprev* stands for coal washing prevalence. *fgdi* denotes FGD intensity, while *fgdshare* marks the share of power plants that uses FGD.

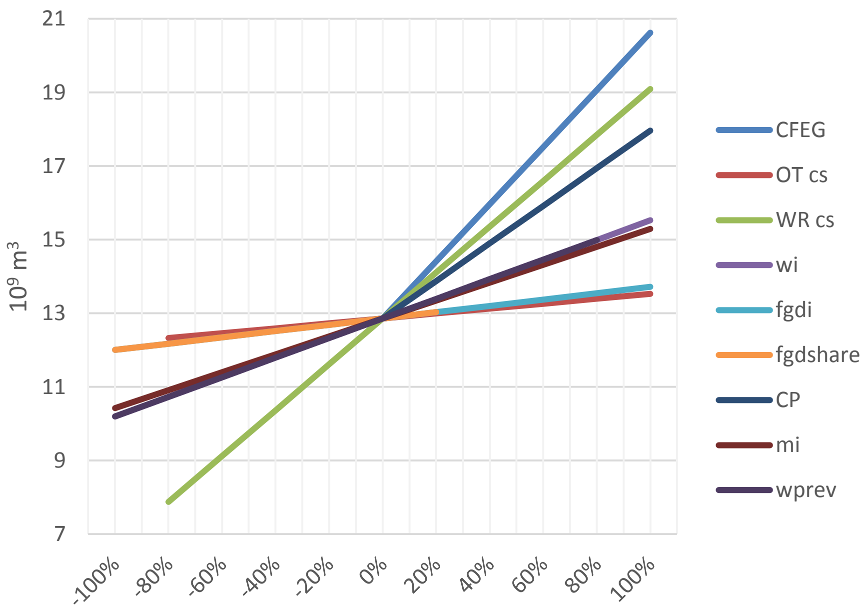

Figure 10: The water consumption impact of significant water use parameters in the Chinese coal industry.

As Figure 10 displays, electricity generation and coal production are heavy drivers for increased water consumption in the coal industry. One can also point out that most of the water consumption occurs in coal-fired power plants. Water intensity of wet recirculating cooling is a highly sensitive parameter, and prone to contingencies similar to those of once-through cooling withdrawal rates. Aside from increases in production of electricity and coal, we see that mining and washing intensities affect overall consumption to a relatively large extent. An increase in washing prevalence from 56% to 100% (an 80% increase in Figure 10) would result in water consumption of the entire coal industry increasing by over 15%. Similarly, decreasing washing rates may result in extensive reductions of water consumption.

Water consumption intensities for mining and washing, measured in m^3/t, can in contrast to water use intensities power plant cooling be mitigated through increased water recycling. For this reason, changes to the *mi* and *wi* parameters are significantly more likely than changes to *OT cs* or *WR cs*. The final cluster of parameters, consisting of FGD and once-through cooling intensity, are aside from displaying low sensitivity not expected to see large changes anytime soon.

4.3 Scenario modeling

The parameters used and their values used in modeling of the scenarios are presented in Table 2 and 3. The BAU high scenario is modeled based on the *CP ref* (coal production) and *CFEG high* (coal-fired electricity generation) parameters. The BAU low scenario is modeled using *CP low* and *CFEG low*. *mi* denote mining water use intensity, while *wi* denote washing water use intensity. *wprev* denote washing prevalence, i.e. the share of coal-fired electricity generation that is produced from washed coal. The bottom four parameters refer to the constellation of cooling systems at the given years. The base year is modeled from data originating from 2011-2014. As Table 2 and 3 display, the WS high and WS low scenarios are modeled identically to the BAU scenarios in terms of coal production and coal-fired electricity generation.

Table 2: Modified parameters in the BAU scenario.

	Base year	2015	2020	2025	2030	2035
CP low (Mt)	3680	3680	3374	3163	2731	2196
CP ref (Mt)	3680	3732	4048	4109	3900	3472
mi (m3/MWh)	0.69	0.69	0.69	0.69	0.69	0.69
wi (m3/MWh)	1.39	1.30	1.30	1.30	1.30	1.30
wprev	0.55	0.65	0.80	0.95	0.95	0.95
CFEG low (TWh)	4051	4300	5212	6000	6100	6000
CFEG high (TWh)	4051	4600	6295	6596	7470	7404
Wet Recirc. (%)	66.9	68.1	68.9	69.3	69.5	69.7
Once-through (%)	14.9	13.5	12.6	12.2	11.9	11.7
Sea water (%)	10.1	9.9	9.7	9.6	9.5	9.4
Air (%)	8.1	8.5	8.8	8.9	9.1	9.2

Table 3: Modified parameters in the WS scenario.

	Base year	2015	2020	2025	2030	2035
CP low (Mt)	3680	3680	3374	3163	2731	2196
CP ref (Mt)	3680	3732	4048	4109	3900	3472
mi (m3/MWh)	0.69	0.62	0.55	0.48	0.41	0.35
wi (m3/MWh)	1.30	1.17	1.04	0.91	0.78	0.65
wprev	0.55	0.55	0.55	0.55	0.55	0.55
CFEG low (TWh)	4051	4300	5212	6000	6100	6000
CFEG high (TWh)	4051	4600	6295	6596	7470	7404
Wet Recirc. (%)	66.9	68.5	70	70.3	70.3	70.6
Once-through (%)	14.9	12.5	10	9.5	9.2	8.8
Sea water (%)	10.1	9.8	9.5	9.3	9.2	9.1
Air (%)	8.1	9.2	10.5	10.9	11.3	11.5

Building on Figure 11, water withdrawals should not to exceed 110 Gm^3, and possibly not even 100 Gm^3, given that China employ strategies included in the WS scenario. It is also seen that given a low production WS scenario, China's water withdrawal rate in the coal industry may already be at its peak. Improved water recycling in mines and CPPs, combined with aggressive restructuring of China's coal-fired power plant fleet, may offset the water withdrawal need that arises from future increases in coal- and electricity production. In Figure 11, it is further notable that the production intervals for water use in the BAU and

WS scenarios do not overlap. This indicates that water saving measures, unrelated to production data, have significant potential in reducing overall water withdrawal. By the end of 2015, it is notable that a decrease in overall water withdrawal by 2015 is entirely possible given a low production scenario. This is primarily due to wet tower cooling being prevalent among newly added power plants while once-through cooling being retired at a quicker rate than it is added at. By comparing the base year estimates to the 2035 estimates, it is seen that the water withdrawals by 2035 amount to a 18-47% increase in the BAU scenario and a 9% decrease to 13% increase in the WS scenario. This again suggests that the impact that water management policies may have on water withdrawals is significant.

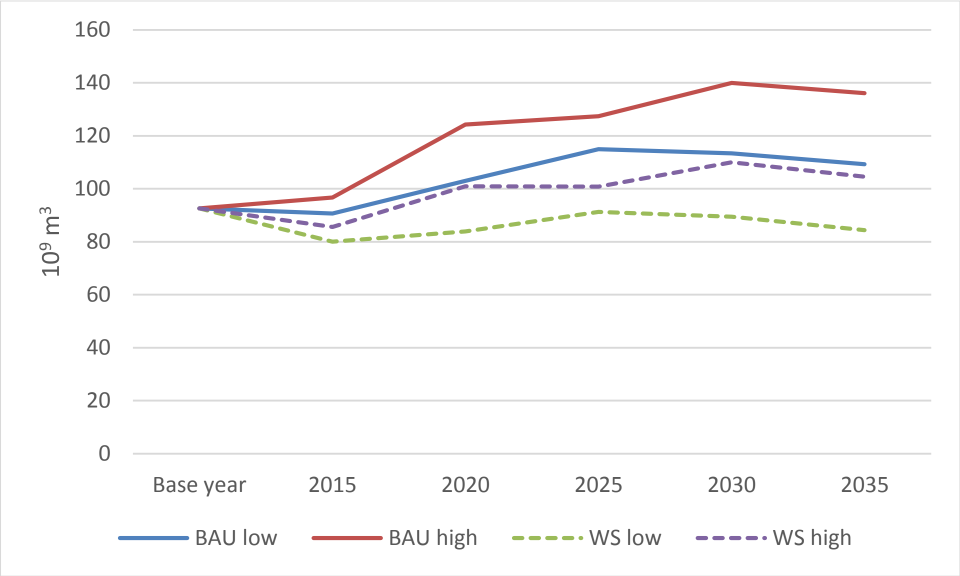

Figure 11: Water withdrawal in the BAU and WS scenario given by high and low coal/electricity production. The BAU scenario is illustrated as the interval between the two continuous lines. The WS scenario is illustrated as the interval between the dotted lines.

For water consumption, Figure 12 displays an overlap between the BAU and WS intervals. This indicates that a future coal production and electricity demand have strong influence on water consumption. Even if the water saving measures suggested for the WS scenario are implemented, there is no guaranteed decrease to water consumption growth. Water management policies alone cannot fully offset the expected increases in coal production and coal-fired electricity generation. By 2035, the expected water consumption in the BAU scenario is an increase by 24-63% from the consumption rate of the base year. In the WS scenario, this increase amount to 6-35%.

Figure 12 further shows that the coal industry will see an overall increase in absolute water consumption over the coming two decades. At 13 Gm^3 today, the consumption rate may surpass 20 Gm^3 as soon as 2025 given a high production BAU scenario. In contrast to the water withdrawal projections, the water consumption in the WS scenario is expected to be consistently higher than the BAU scenario given high coal production and coal-fired electricity generation. This is mainly due to a shift from water withdrawal intensive coal power to water consumption heavy coal power being necessary if coal-fired electricity is to continue to grow in the foreseeable future – even in water resource oriented outlooks. When measuring the water consumption relative to water withdrawal, 14.7-15.5% of the annual water withdrawal by 2035 is consumed in the BAU scenario. In the WS scenario, 16.3-16.7% of withdrawn water is consumed. This reflects assumptions made in the designing of the WS scenario, namely that water saving oriented policies will not necessarily involve decreasing overall consumptive water use, and that a trade-off between water withdrawal and water consumption is necessary to sustain a continued growth of the industry. Currently, 14.0% of the withdrawn water in the coal industry is consumed.

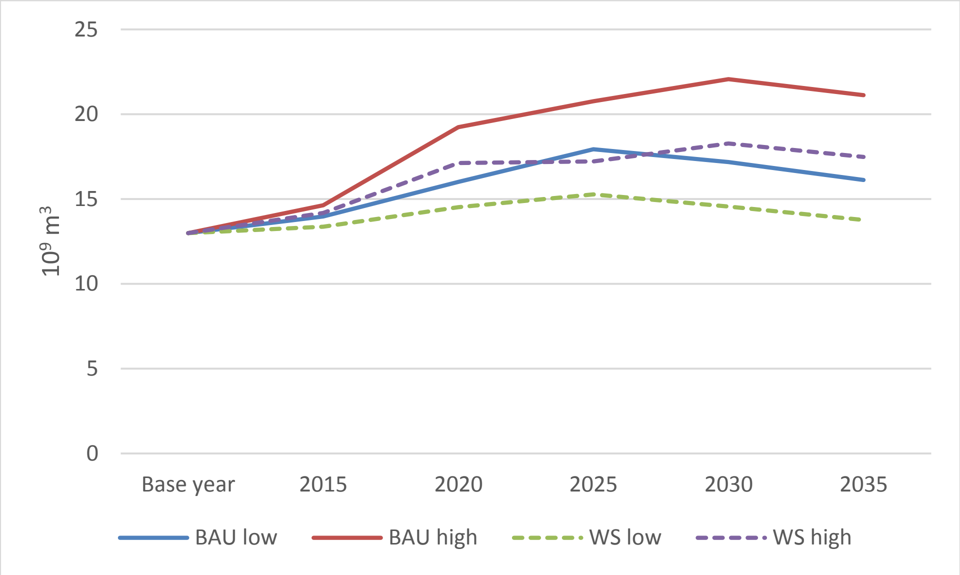

Figure 12: Water consumption in the BAU and WS scenario with high and low coal/electricity production. The two continuous lines make an interval that represents water consumption in the BAU scenario. The dotted lines are the equivalent for the WS scenario.

5. Discussion

The findings of this study are discussed in two parts. The first part revolves around the sensitivity analysis and projected water use. The second part briefly discusses data contingency.

5.1 Future water use in China

Freshwater cooling represents the largest source of water withdrawal in the Chinese coal industry and in Chinese industry as a whole. In a response to growing freshwater demand and diminishing freshwater availability, China is expected to reduce its once-through cooled power generating capacity and increase the prevalence of recirculating cooling. Together with increased coal washing, an influx of wet recirculating cooling will mark a significant increase in the coal industry's consumptive water use. Aside from coal washing and power plant cooling, the parameter analysis in Figure 10 shows that coal production and coal-fired electricity generation are among the most important parameters in estimating total water consumption. Essentially, high coal production and high coal-fired electricity generation leads to high water use. Building on this notion, China's official plans to peak in coal production by 2020 suggests that water use will diminish over time. This study finds that this is not the case, and that there is more complexity to the coal-water relation. For instance, Figure 12 shows that water consumption will increase regardless of high or low production outlooks. It should also be noted that limits to domestic coal production can be offset by coal imports. Future coal-fired electricity generation is therefore not limited by projected coal production. Figure 10 shows that limiting coal production is an effective way of reducing the coal industry's water consumption. A low coal production however only part of limiting water consumption, as the majority of water consumption is found in power plants.

In the WS scenario, technological advancements are expected to gradually improve water recycling in coal mines and CPPs. Similar improvements, i.e. reduction of water use, are not expected to be made in coal-fired power plants. Most of the consumptive water use in the industry can be attributed to evaporative cooling in coal-fired power plants, of which the cooling effectiveness is primarily affected by the surrounding climate. If local air temperatures were to increase, the effectiveness of evaporative cooling would decrease. Air cooled power plants consume significantly less water than water cooled power plants do. They also have a lower rate of efficiency. If China rapidly installs new air cooled power plants as described in the WS scenario, the efficiency of the entire power plant fleet would reach historically low levels. In effect, there would be raised demand on coal production, coal imports, or other sources of electricity generation to make up for efficiency losses in the air cooled power plants.

China's energy political line over the past years has been characterized by maximization of fuel efficiency and emission control. Increasing fuel efficiency of coal power has to some extent been realized through a significant increase in coal washing, which in turn increases water consumption. Figure 10 illustrates how raising the coal washing rate from the current 56% to 95% would result in a 17% increase in total water consumption of the coal industry. If the coal washing growth rate for 2011-2015 predicted by China National Coal Industry (Wang, 2011) persists, 95% will be reached by 2025. Together with the other developments modeled in the BAU scenario, coal washing would significantly attribute to the 23-64% increase in total water consumption projected for 2035.

The recent joint China-U.S. emission agreement (The White House, 2014) showed that reduction of air emissions, CO_2 emissions in particular, is of nation concern in contemporary China. One of the steps that China has taken toward reducing emissions has been rapid installments of FGD units in the coal-fired power plant fleet. This study finds that mitigating power plant air emissions through FGD accounts for a considerable water use. More specifically, Figure 10 shows that removal of currently installed FGD would result in a 7% decrease of total water consumption, indicating that efforts to combat air emissions from coal-fired power plants should not be dismissed as water inexpensive. Keeping in mind that

FGD was first started to get implemented in China during the early 2000s, the growth of FGD is exemplifying for the interchangeability of water resource use and air emissions.

The WS scenario shows that carrying out significant reductions in water use growth is possible, but due to the structural inertia of the industry, such commitment must be made as soon as possible. While difficult to model or predict the effects of continued negligence of water resources, this study shows that water availability plays a significant role in shaping the way China produces energy and approaches environmental challenges. The BAU scenario is equaled to ranking freshwater availability as a low priority concern, which with China's current freshwater scarcity, is not far from treating freshwater as an infinite resource. The issue here lies not only with energy production, but also in avoiding environmental disasters and limiting the already growing thresholds of food security.

5.2 Data contingency

A limitation and challenge in this study has been the lack of systematically consistent datasets. Water use is currently not measured in individual power plants, mines, and coal preparation plants in China in a consistent manner. Another issue encountered is lack of transparency and availability of data. A large portion of data used in this study originates from studies carried out in the U.S., where governmental studies of water use in the power sector are available to the public to a greater extent. Even so, Macknick et al (2011) note that water use in the U.S. power sector is poorly documented and lack standardization. Water use is often generalized from micro scale estimates, such as from a case study in a single mine, rendering many of the layered complexities that constitute water use in the coal industry unacknowledged.

6. Conclusions

By 2035, water consumption in China's coal industry is expected to have increased from current levels regardless of water resource policies and coal production outlooks. The increase in water consumption will primarily occur due to an assumed shift from once-through cooling to wet tower recirculating cooling. Water oriented policies and low coal production coupled with low coal-fired electricity generation will decrease the growth of overall consumption, but will not manage to halt it. This study expects water saving policies to be able to lower water consumption in 2035 by 18-28% relative to a business-as-usual scenario.

The growth of non-consumptive water use, i.e. water withdrawal, is expected to decrease as China transforms its power plant fleet. Water withdrawal growth may even turn into a declining trend in a low production scenario, as shown in Figure 11, given that suggested water saving measures are taken. Such trend could persist throughout both the peak in coal production and the peak in coal-fired electricity generation given that China implements water saving policies outlines in this study. Despite the large potential savings in the industry’s total water withdrawal, water withdrawal rates remain volatile, with small changes to power plant constellation and electricity generation bringing about significant changes. This study finds that a business-as-usual approach to water use, coupled with high coal production and coal-fired electricity generation, may result in water withdrawal rates increasing by up to 47% by 2035.

Current coal power discussions in relation to China frequently revolve around air emissions. This study highlights the interchangeability of air emissions and water use, finding that measures to combat air emissions in China since the early 2000s have attributed significantly to the coal industry’s water use. FGD currently represents about 7% of the coal industry’s current consumptive water use, and coal washing has grown to consume more water than coal mining does. Effects of negligent water resource use already shows in environment and society, but tends to manifests itself locally. It is in the interest of China to make sure that the water scarcity of today does not become the pollution issues of tomorrow.

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