Energy Policy 82 (2015) 131–143

Contents lists available at ScienceDirect

Energy Policy

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

China's energy-water nexus – assessment of the energy sector's compliance with the “3 Red Lines” industrial water policy

Ying Qin [a,*], Elizabeth Curmi [a], Grant M. Kopec [a], Julian M. Allwood [a], Keith S. Richards [b]

[a] *Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK*
[b] *Department of Geography, University of Cambridge, Downing Place, Cambridge, CB2 1 PZ, UK*

HIGHLIGHTS

- A whole systems analysis of current and future water used for energy is presented.
- The energy sector's compliance with the “3 Red Lines” water policies is assessed.
- Future energy plans could conflict with the “3 Red Lines” industrial water policy.
- Water used for energy is highly dependant on technology choices.
- Co-benefits and trade-offs between future energy and water plans are identified.

ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form
11 March 2015
Accepted 14 March 2015
Available online 2 April 2015

Keywords:
Energy
Water
Nexus
Scenario analysis

ABSTRACT

Increasing population and economic growth continue to drive China's demand for energy and water resources. The interaction of these resources is particularly important in China, where water resources are unevenly distributed, with limited availability in coal-rich regions. The “3 Red Lines” water policies were introduced in 2011; one of their aims is to reduce industrial water use, of which the energy sector is a part. This paper analyses current water withdrawals and consumption for all energy processes and assesses the sector's compliance with the industrial water policy under different scenarios, considering potential future policy and technological changes. The results show that future energy plans could conflict with the industrial water policy, but the amount of water used in the energy sector is highly dependant on technology choices, especially for power plant cooling. High electricity demand in the future is expected to be met mainly by coal and nuclear power, and planned inland development of nuclear power presents a new source of freshwater demand. Taking a holistic view of energy and water-for-energy enables the identification of co-benefits and trade-offs between energy and water policies that can facilitate the development of more compatible and sustainable energy and water plans.

1. Introduction

Energy and water resources are closely interlinked and are both critical to the development of human society. Water is required for the production of energy, and energy is needed for the supply, treatment, desalination and distribution of water resources. Hoff. (2011) emphasises the need for integrated resource planning for energy and water, which is becoming increasingly recognised by international institutions, national governments and businesses. However, energy and water policies are still mostly developed in isolation from each other (Hussey and Pittock, 2012; Siddiqi et al., 2013). China is a unique case study to assess the dynamic interactions between these resources and the policies related to them. The country has 22% of the world's population but only 6% of the world's freshwater resources (Guan and Hubacek, 2008). Some areas already suffer from severe water issues; the Chinese Academy of Sciences (2007) found that two-thirds of China's 669 cities have water shortages and up to 40% of rivers are severely polluted. Rapid economic development has seen the country's total primary energy production more than double between 2000 and 2010 (NBSC, 2011), with an energy profile dominated by coal. Growth of China's economy and its emerging middle class continue to drive the country's growing energy and water demands. The energy–water interaction is further intensified in China because the majority of coal reserves are found in the country's driest regions.

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[*] Corresponding author.
E-mail addresses: yq209@cam.ac.uk (Y. Qin), ec459@cam.ac.uk (E. Curmi), gmk28@cam.ac.uk (G.M. Kopec), jma42@cam.ac.uk (J.M. Allwood), ksr10@cam.ac.uk (K.S. Richards).

http://dx.doi.org/10.1016/j.enpol.2015.03.013
0301-4215/

Water constraints have already impeded energy developments in China, as plans to build dozens of coal-to-liquid (CTL) plants were abandoned in 2008 because of local water scarcity (IEA, 2012).

The Chinese government, recognising the importance of water to the country's socio-economic development, announced its most stringent water management plan to date in 2011, as part of the Central No 1. Document known as the “3 Red Lines” water policies. These policies were fully implemented in 2012 with targets on total water use, water use efficiency for industry and agriculture, and water quality improvements on a national as well as on a regional scale (i.e. river basins, provinces, cities and even counties), for 2015, 2020 and 2030. These policies aim to address China's regional imbalance in water availability, and to encourage the sustainable use of water resources. Liu et al. (2013) emphasise that the realisation of these goals will bring positive long-term benefits for China's water system.

The future development of China's energy landscape has global implications and is the subject of great academic, policy and media attention. To meet growing energy needs and the pressure to reduce greenhouse gas emissions, China's future energy plans include an increase in the proportion of natural gas, nuclear and renewables in the energy mix, as well as encouraging energy efficiency improvements. However, Pan et al. (2012) and Wang et al. (2014) emphasise that coal is still expected to play a significant role. Recognising the need to reconcile coal use and water supply, the Chinese government added the “water-for-coal” plan to the “3 Red Lines” water policies in 2013, requiring future large-scale coal projects in water scarce regions to be developed in partnership with local water authorities. This is significant progress, but other energy processes should also be considered in a wider “water-for-energy” plan. Given the interdependence between energy and water and the lack of full integration in future plans, the “3 Red Lines” industrial water policy may conflict with future energy plans. The purpose of this paper is to undertake a detailed analysis of the uses of water in the energy sector in order to understand this potential policy conflict. The following section evaluates previous research on water and energy, to define the specific questions that need to be addressed by this analysis.

1.1. Previous work – assessing the water use for energy

In recent years, literature on the water–energy nexus has increased, with most of the research integrating the two resources in terms of physical linkages, planning and policy. This demands a clear understanding of how energy processes use water, and methods for calculating the water impact of different energy technologies, as recommended by NETL (2011) and Hadian and Madani (2013). Most research and data on water-for-energy seem to derive from the United States, and focus on power generation.

Meldrum et al. (2013) and Macknick et al. (2012) have carried out comprehensive reviews of water withdrawal and consumption intensities for a range of power technologies. Macknick et al. (2012) focus on water use for the operational phase (cooling, cleaning and other process-related needs), whereas Meldrum et al. (2013) review life-cycle water use. Both papers found that the cooling of thermoelectric power plants is an intensive water use and that power generation from solar photovoltaic (PV) and wind turbines have the lowest water requirements. However, both studies highlight that for most generation technologies, estimates vary significantly and are based on few sources. There is general agreement in the literature (Mielke et al., 2010; Averyt et al., 2013; King et al., 2013) that there is a need for better quality data, which is collected and monitored consistently to allow more robust water-for-energy research.

It is important to understand the difference between water withdrawals and water consumption, as both are key indicators for assessing water use in the energy sector, especially in power generation. However, Macknick et al. (2012) stress that state agencies often do not use consistent methods or definitions in measuring water use by the energy sector. The literature is equally inconsistent; Grubert et al. (2012) use water consumption as a performance indicator for investigating the effect of switching from coal-fired to gas-fired power generation in the US, whereas Yu et al. (2011) consider water withdrawal when assessing coal-fired power generation in China. Meldrum et al. (2013) also note that reports often fail to specify whether it is withdrawal or consumption that is being analysed. This study classifies water withdrawal as water removed from the ground or diverted from a surface water source for use, and water consumption as that fraction of the water withdrawn that is removed from the immediate water environment (Kenny et al., 2009); for example, water that is evaporated from cooling towers.

Research on water use for fuel extraction and processing is included in life-cycle assessments of power generation. Meldrum et al. (2013) highlight that the operational phase dominates the life-cycle water use for most power generation pathways, and that for coal, natural gas and nuclear power, the fuel cycle contributes a small but non-negligible amount to total life-cycle water use. However, aside from these life-cycle assessments, there appears to be minimal literature on water used for the extraction and processing of energy sources, compared to studies on power generation. Mielke et al. (2010) and Williams and Simmons (2013) assess water use in the whole energy sector including water use for extraction and processing. Although water has always been understood to be a potential constraint for thermal power generation, its importance in fuel production processes is becoming more apparent (Mielke et al., 2010).

Water-for-energy nexus studies have been carried out in Spain, the Middle East-North Africa (MENA) region, Jordan and the United Kingdom as well as in the United States. It appears that data from the United States are often used when local data are unavailable; this applies for the United Kingdom (Byers et al., 2014) and the MENA region (Siddiqi and Diaz, 2011). These case studies of region-specific water-for-energy connections and stresses help to highlight the importance of carrying out water–energy analysis on a regional scale, as emphasised by Schnoor (2011).

The literature on water-for-energy in China is focused mainly on coal. Pan et al. (2012) provide China-specific quantitative information on water withdrawals, consumption, wastewater recycling and treatment for the various processes used within the coal industry, including coal extraction and power generation. An average water-use intensity figure is used for each coal industry process, but the effects of different technologies within each process are not considered. Pan et al. (2012) use these data to analyse future scenarios, and conclude that the compliance of the coal industry alone with the future industrial water policy would require the adoption of many water-saving measures.

Yu et al. (2011) use a technology-based, bottom-up model to assess how future policies and technological changes may affect the coal-fired power sector's coal consumption, water withdrawals, SO_2 and CO_2 emissions. The authors conclude that technology innovation is key to resource conservation, but acknowledge that technological maturity and high installation costs are likely bottlenecks. However, the additional technological detail and future scenario assessment by Yu et al. (2011) is only for coal-fired power generation and water withdrawals. Zhang and Anadon (2013) assess life-cycle water withdrawals, consumptive water use, and wastewater discharge in China's energy sectors, and their environmental impacts. This analysis has a strong spatial component highlighting provincial water usage, but does not include future assessments.

This review shows the need to consider all current and potential future energy processes that use water when comparing the sector's water use with the industrial water targets. For example, currently nuclear power plants are found on the coast and use saline water for cooling with only small amounts of freshwater, but China is planning to develop inland nuclear power plants which will require freshwater for cooling. There appears to be no holistic analysis of water used in the energy sector by different technologies in China, assessing both water withdrawal and consumption now and in the future. This study aims to address this issue and answer a key question; is it likely that the energy sector will comply with the “3 Red Lines” industrial water policy? To answer this general question, more specific research questions are addressed: (1) How is water currently used in China's energy sector?; (2) How might the energy sector and its water use develop up to the 2030s?; (3) How is the answer to (2) influenced by technology and policy changes?

The importance of assessing technology for each energy process, in particular for power generation is clearly highlighted in the literature. Macknick et al. (2012) emphasise that the amount of water used in power generation depends on the type of plant, the fuel used and also on the cooling technology. Given the complexity of the energy system and the importance of the technology mix, this study adopts a technology-based, bottom-up integrated resource approach to develop a holistic analysis of current and future energy and water-for-energy in China (Fig. 1).

2. Methods – energy and water-for-energy analysis

To undertake a holistic analysis of both energy and water-for-energy resources, the authors trace the use of current and future energy and water-for-energy from the initial resources to the services that they provide, and in the case of water to their relevant sinks. Similar methodologies have been adopted by Cullen and Allwood (2010) in tracing global energy use from source to service, by Ma et al. (2012) in a similar study of China's energy use in 2005, and by Curmi et al. (2013) in a holistic analysis of global water use.

2.1. *Current energy analysis (2010)*

The data structure used to analyse energy use from source to service was adapted from the methodology developed by Ma et al. (2012). Energy is traced from its initial sources (e.g. imported crude oil, domestically produced coal) through the technologies that transform it *via* conversion devices and passive systems, through to the final services they deliver (e.g. transport, industry). Table SI1 in the Supplementary Information provides more information on the energy data structure. To undertake such an analysis, data were gathered from multiple sources, as described in detail below.

Data on imports, exports and domestic production were extracted mainly from the International Energy Agency (IEA) databases (IEA, 2014), supplemented with data from the China Energy Statistical Yearbook 2010 (NBSC, 2011) and China Analysis Brief (US EIA, 2014). There were some inconsistencies in export values between the IEA and China energy balance sheets (NBSC, 2011), so IEA data were used to ensure consistency with most of the other data. The data on the different energy sources used for power generation in China were obtained from IEA datasets (IEA, 2012). Electricity generation losses were calculated by balancing the total primary energy demand, power generation, and total final consumption data, together with the thermal efficiency for coal-fired power generation plants, as shown in Table 1. More detail on coal-fired generation can be found in Section 2.3.

Data were available on the initial sources of energy and on final consumption by sector, however there was very little detailed information on the technologies used to transform this energy. Cullen and Allwood (2010) introduce the distinction between end-use conversion devices which convert energy into useful forms, and passive systems where useful energy is lost as low grade heat in exchange for final services. Given the need to develop future scenarios and to maintain consistency between current and future scenarios, conversion devices and passive systems were each separated into four broad categories. These are, for conversion devices; combustion devices, burners, electric motors and electric appliances; and for passive systems; vehicles, driven systems,

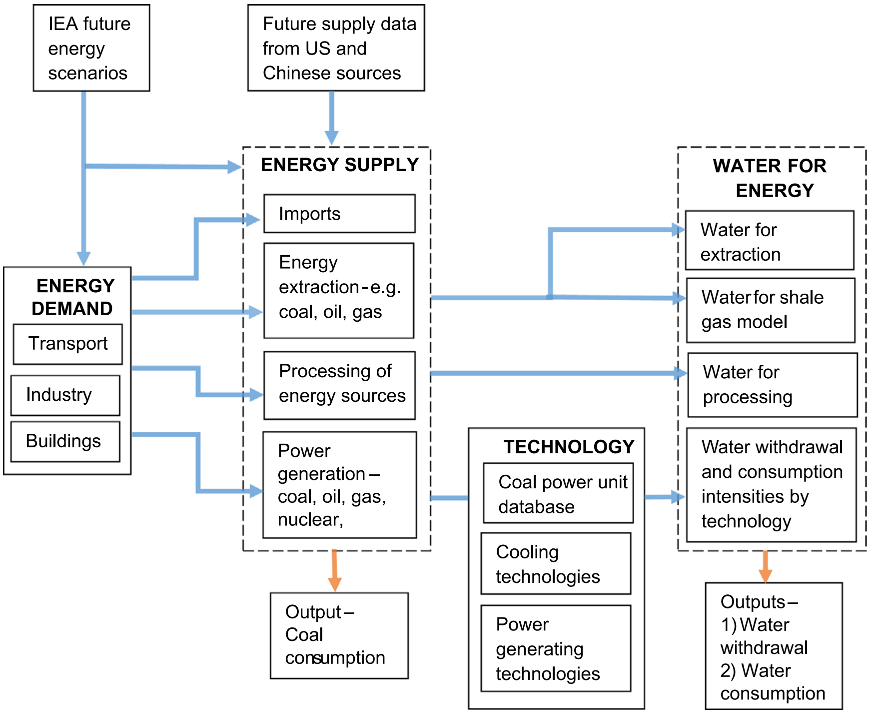

Fig. 1. Model framework used to assess the energy sector's water use.

Table 1
Thermal efficiency for different coal fired generation plants (Yang et al., Unpublished results).

	Thermal efficiency (%)
Ultra supercritical-Once through cooling	42.5
Ultra supercritical–Wet tower cooling	42.2
Ultra supercritical–Dry cooling	38.9
Ultra supercritical–Saline	42
Supercritical–Once through cooling	40.2
Supercritical–Wet tower cooling	40.2
Supercritical–Dry cooling	37.6
Supercritical–Saline	40
Subcritical 600 MW–Once through cooling	38.5
Subcritical 600 MW-Wet tower cooling	39.6
Subcritical 600 MW–Dry cooling	36.8
Subcritical 600 MW–Saline	39
Subcritical 300 MW–Once through cooling	37.1
Subcritical 300 MW–Wet tower cooling	37.1
Subcritical 300 MW–Dry cooling	36
Subcritical–Saline	37

industrial heat systems and building systems. IEA data on final energy consumption by sector and information on Chinese conversion devices and passive systems from Ma et al. (2012) were used to calculate the energy flows through conversion devices and passive systems. More information can be found in Section SI2 in the Supplementary Information.

Energy use was measured as Tonnes of Coal Equivalent (TCE), which is commonly employed in Chinese energy statistics. A Sankey diagram (see Fig. 2) showing the flow of energy from source to final service was used to visualise the whole of China's energy landscape in 2010.

2.2. *Current water-for-energy analysis (2010)*

Water is traced from its initial source (e.g. freshwater withdrawals, recycled water) through to all the energy processes that use water (e.g. coal extraction, oil refining, and nuclear power generation), and then to the sinks (e.g. atmosphere, discharge to river systems). Sections 2.2.1–2.2.3 below describe the methodology and data employed to calculate water used in the various energy processes.

2.2.1. *Water used for extraction of energy resources*

Table 2 provides the data and description on water withdrawals and consumption for the extraction of oil, gas and coal resources. Data on coal extraction are from Chinese sources, but there do not appear to be any data on the amount of water used in the extraction of oil and gas resources in China, so other data sources have to be used. China also extracts an unconventional source of gas known as coal-bed methane, which is produced when methane is adsorbed onto the surface of coal and trapped between seams (Williams and Simmons, 2013).

2.2.2. *Water used for preparation, refining and processing*

Table 3 provides the data and description on water withdrawn and consumed in the preparation, refining and processing of energy sources.

2.2.3. *Water used in power generation*

The majority of the water used in power generation is for cooling purposes. Several cooling technologies may be used, including once-through cooling, wet-tower cooling and dry (or air) cooling systems. The majority of power generation in China is coal-fired and the amount of water withdrawn and consumed depends not only on the cooling system used but also on the size and type of unit (for example ultra super-, super- and sub-critical coal power generation units). Data on withdrawal and consumption of water from different generation technologies were gathered from various sources and are shown in Table 4. Details on freshwater used in inland nuclear power generation can be found in Section 2.4.2.

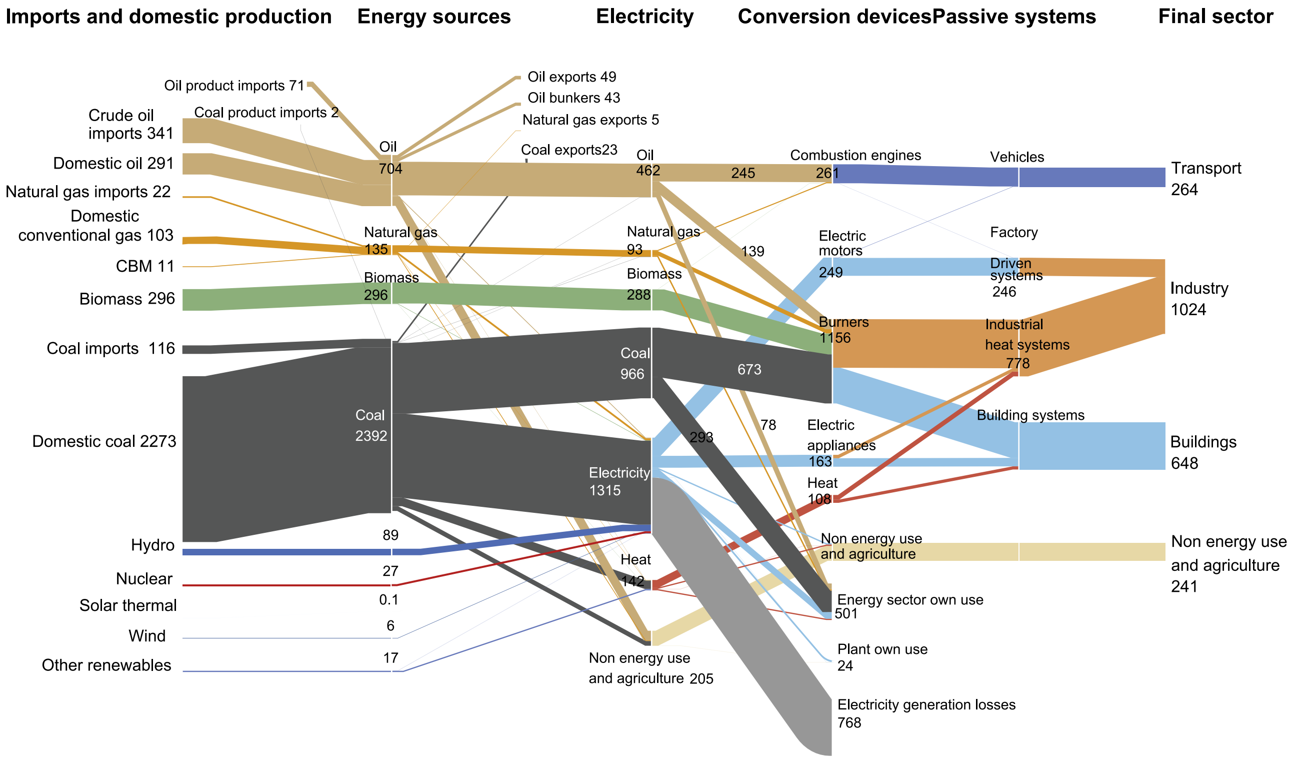

Fig. 2. 2010 Energy Sankey diagram for China showing the flow of energy from initial source to final service. Numbers are given in million tonnes of coal equivalent (Mtce).

Table 2
Water used in the extraction of oil, gas, coal and coal-bed methane.

Process	Produced water [a]	Water withdrawals	Water consumption	Description	Reference
Oil (barrels of water per barrel of oil)	5	1	1	China's largest oil fields are mature and production has peaked, leading companies to invest in enhanced oil recovery (EOR) techniques to maintain oil flow (US EIA, 2014). As a field matures, the ratio of water to oil produced increases. The average figure for Eurasia was used to calculate the produced water, and it was assumed that most of this water was re-injected into the well for EOR with a replacement value equal to one barrel of water. Over 80% of oil wells were onshore requiring freshwater, whiles the rest of the oil wells were allocated offshore and assumed to use saline water (US EIA, 2014).	Williams and Simmons, (2013)
Gas (m^3/TJ)	N/A	1.6	1.6	Water is mainly used for drilling and processing, and will depend on the lifetime production of such a well. This study assumes that gas production is being produced in gas reservoirs and not in combination with oil.	Williams and Simmons (2013)
Surface Coal Mining (m^3 per tonne)	N/A	1.2	(22% is recycled and reused, the rest is embodied in the product, evaporated, returned to the river system)	Water used for the extraction of coal is required for machine cooling, dust repression, tunnel washing and other uses (Pan et al., 2012). The amount of water which is recycled and reused is expected to increase to 30% in the future.	Tsinghua-BP Clean Energy Centre, (2011)
Underground coal mining (m^3 per tonne)	N/A	3.4	(22% is recycled and reused, the rest is embodied in the product, evaporated, returned to the river system)	95% of the coal mines in China are underground mines and these use more water than surface mining.	Tsinghua-BP Clean Energy Centre, (2011)
Coal Bed Methane (barrels of water per MCF)	0.55	N/A		Water is not needed for the extraction of the methane from coal seams, but is co-produced during this extraction. The water that is produced varies widely between different coal basins and therefore is difficult to assess with any certainty. The median range is used for this study. The fate of this water is not known; it can be recycled and reused for another process, returned to the system treated or untreated or disposed in regulated rejection wells.	USGS, (2000)

[a] Produced water is water that is produced from the extraction of oil and gas and is assumed to be re-injected on site to increase pressure in oil and gas reservoirs, and water that is co-produced during the extraction of coal-bed methane.

Table 3
Water used in the preparation, refining and processing of energy.

Description	Water withdrawals	Water Consumption	Description	Reference
Coal washing (m^3/tonne)	2.50	0.2	Coal washing is a process of removing minerals from raw coal, improving the quality of the coal so that the overall thermal efficiency is enhanced. However water constraints in some of China's coal provinces have limited the availability of water for this process, and therefore current coal washing rates are estimated at 43% of total coal extracted (Tsinghua-BP Clean Energy Centre, 2011) and it is assumed that this would increase to 95% in 2035 (Pan et al., 2012).	Pan et al. (2012)
Coal to gas (m^3 of water per m^3 of gas)	0.08	–	Water is used to process coal into gas.	Yang and Jackson, (2013)
Coal to liquids (m^3/tonne)	10	–	Water is used to process coal into hydrocarbon liquids.	Tsinghua-BP Clean Energy Centre, (2011)
Biomass to liquids (m^3/TJ)	128	128	Water is used to convert biomass to liquid for biofuels. Due to lack of data, the water withdrawal factor used assumes all biomass feedstock is corn.	Williams and Simmons, (2013)
Oil refining–Once Through Cooling m^3 per TJ	273	13	Much of the water used in refineries is employed to produce steam for heating and water for cooling. Similar to power generation, the technology used for cooling in refineries could either be once-through cooling where the majority of the water withdrawn is returned to the system at a higher temperature, or wet-tower cooling systems which withdraw less water but consume more due to their high evaporation rates. There are no data on whether refineries in China use once-through or wet-tower cooling, however for this study, and due to the lack of data on wet-tower cooling systems in refineries, it is assumed that once-through cooling is used.	Williams and Simmons, (2013)

China also uses some renewable energy resources for power generation. Water requirements for current renewable power generation technologies (solar photovoltaic (PV), wind) are negligible, and involve small amounts of water for cleaning and panel washing (IEA, 2012, Meldrum et al., 2013). These are not included in the analysis.

2.3. Coal consumption, water withdrawals and consumption in power generation

Coal-fired power generation is a major water user and has the largest potential for water saving. A database of current coal-fired power generating units in China was constructed to enable a better understanding of the amount of water used in this sector. The database contains information on location (province), unit capacity, cooling technology (once-through, wet-tower, dry cooling), coal-power technology (ultra-supercritical, supercritical, subcritical), water withdrawal and water consumption, thermal efficiency, power generated, power supplied and in-plant electricity use for each individual coal power generating unit. This database was used to validate average water withdrawal and consumption figures, coal consumption and power generation loss values taken from the literature, and to improve the understanding of how coal power and cooling technology affects coal and water use. Data were extracted from the China Electrical Council's (CEC) annual statistical yearbooks (CEC, 2011a; 2012), the Annual Development Report of China's Power Industry (CEC, 2011b), and the Thermal Power Unit Benchmarking and Competition Database (CEC, 2013a, 2013b). Data on the parameters listed above were not available for all power generating units, so averages and values from the literature (as in Table 4) were used to fill in some of the missing data (see Section SI4 in the Supplementary Information).

2.4. Future energy and water for energy analysis

Four future scenarios (1a, 1b, 1c and 2) were developed to assess future energy supply and water demand in the energy sector in 2035, combining IEA data on the future supply of and demand for energy, with technology choices for coal-fired power generation, and cooling technologies for inland nuclear power plants. IEA scenarios are projected up to 2035, while the “3 Red Lines” water policy specifies targets for 2030. We extrapolate the latter to match the dates (see Section 2.5).

2.4.1. Future energy system

IEA has developed three future energy scenarios for China up to 2035; the Current Policies, New Policies and ‘450’ scenarios. The first two of these scenarios are considered in this study. The Current Policies scenario adopts the policies enacted in China's 12th Five-Year Plan, and acts as a baseline. The New Policies scenario takes into account broader policy commitments and plans that the Chinese government has announced to tackle energy-related challenges. The IEA scenarios were supplemented by data from other sources to provide a fuller picture of China's future energy landscape. Data on future energy imports and domestic production, and on unconventional oil and gas reserves, were extracted from the US Energy Information Administration's China Analysis Brief (US EIA, 2014); and production targets for shale gas, marine and geothermal power generation were taken from China's 12th Five-Year Plan for energy development (State Council, 2013). The scenarios also include China's plans to expand the production of coal-to-gas and coal-to-liquids, given its abundance of coal but limited supply of natural gas and oil.

2.4.2. Future water for energy

The corresponding requirements for water used in the energy sector were calculated using the data on water withdrawal and consumption rates from the 2010 water-for-energy analysis. However, the assessment of water use for future energy processes required additional analysis, such as water used for the extraction of shale gas, and technology choices for cooling for inland nuclear plants.

There are limited data available on the amount of water used for hydraulic fracking in shale gas production in China, mainly due to the infancy of this energy source in the region. The amount of water is highly dependant on the type of shale and the fracturing techniques used. Fracturing a well also requires the management of flowback water, produced immediately after fracking and before gas production, and of produced water, produced alongside the production of gas over the lifetime of the well (Clark et al. 2013). A model was developed (see Section SI3.1 in the Supplementary Information) to predict the total water demand per well for fracking, flow back water, and produced water over time, taking into account the rate of gas production, nominal decline rates and hyperbolic exponent per well. The number of wells needed to meet shale gas production figures in the energy scenarios was determined, and the cumulative water demand was calculated. It is difficult to determine the initial shale gas production rates in individual wells, as these are still under exploration. There are data on shale gas profiles and water use from the United States where shale gas is currently being commercially produced. This study assumes shale gas profiles in China are similar to the Marcellus shale, which is an average shale gas profile in the United States.

Data on future nuclear power plants in China were sourced from the World Nuclear Association (WNA, 2014), and include current and future nuclear plant locations (coastal or inland), status (operational, under construction, planned, proposed), and plant capacity. Using the assumption that future coastal plants will be built before inland plants for each of the “status” categories, the total power plant capacities for future inland and coastal nuclear plants were calculated. This location difference is critical to understanding whether fresh or saline water is being used for nuclear power generation. From 2015 to 2035, the nuclear demand for each scenario (provided by IEA, 2012) is met by the nuclear plants from the WNA database, with a clear distinction between inland and coastal locations. The cooling technology that future inland nuclear power plants will use is uncertain, but Section SI3.2. in the Supplementary Information provides estimates for the water withdrawal and consumption rates assumed.

For future renewable electricity generation technologies, water withdrawal and consumption rates required for wet-tower cooling in geothermal power generation are estimated as 2000 and 1400 gallons of water/MWh_e respectively (Pate et al., 2007). The cooling process for concentrated solar power (CSP) generation can be wet-tower or dry cooling and the estimated water consumption rates are 780 m^3/TJe and 30 m^3/TJe respectively (Williams and Simmons, 2013). The water withdrawal rates are assumed to be equivalent to the consumption rates. The operational freshwater use for marine power generation is negligible and is not included in this analysis.

2.4.3. Future scenarios

Table 5 summarises the four different scenarios and the technological assumptions made about coal-fired power generation and inland nuclear plants. Detailed descriptions of each of the scenarios can be found in the Supplementary Information together with a table on the different technologies adopted in each scenario (Section SI5). This study recognises that future technological improvements are likely to result in better efficiencies in coal and water use, but what these improvements will be for each coal

Table 4
Water withdrawal and consumption rates for coal fired power generation (Yang et al., Unpublished results; NREL, 2011).

	Water withdrawals (m^3/kwh)	Water consumption (m^3/kwh)
Ultra supercritical-Once through cooling	0.08	0.00023
Ultra supercritical–Wet tower cooling	0.0023	0.00211
Ultra supercritical–Dry cooling	0.00031	0.00023
Supercritical–Once through cooling	0.09	0.00026
Supercritical–Wet tower cooling	0.0023	0.00195
Supercritical–Dry cooling	0.0004	0.0004
Subcritical 600 MW–Once through cooling	0.1	0.00029
Subcritical 600 MW-Wet tower cooling	0.0026	0.00196
Subcritical 600 MW–Dry cooling	0.00029	0.00029
Subcritical 300 MW–Once through cooling	0.1	0.00037
Subcritical 300 MW–Wet tower cooling	0.0026	0.00231
Subcritical 300 MW–Dry cooling	0.00035	0.00035

power and cooling technology, and the combination of the two, is not known. Therefore, available coal power technology efficiencies, and water withdrawal and consumption rates, are used for future calculations. Other coal technologies are also being developed in China including IGCC (integrated gasification combined cycle) and CCS (carbon capture and storage) but these are not widespread and are still in their developmental stage, so are not included in this study.

2.5. Energy sector's compliance with the industrial water policy

To assess the energy sector's compliance with the industrial water policy, both water withdrawal and consumption under the four scenarios are compared to the industrial water allowed target, as set by the “3 Red Lines” water policies. As the water targets are linked to future Industrial Value Added (IVA) as part of GDP, the target will change depending on future economic development. IVA/GDP decreased from 46% in 2004 to 40% in 2009, and based on historic ratios of IVA/GDP and changes in China's economic structure, future IVA as a percentage of GDP is expected to decrease further. This study uses the Pan et al. (2012) assumption that that GDP will be 100,000 billion RMB in 2030, IVA will account for 30%, and IVA will therefore be 30,000 billion RMB. The industrial water allowed target of 120 billion m^3 in 2030 was derived by scaling up the industrial water target of 40 m^3 of water usage per 10,000 RMB of IVA to 30,000 billion RMB. In this study, we assess future energy scenarios up to 2035 (the year to which future IEA energy pathways are projected), and a 2035 IWA was estimated by continuing a linear trend in IWA using the 2015, 2020 and 2030 targets, giving an IWA target of 104 billion m^3. The targets for 2030 and 2035 are both used for comparison with the energy sector's water demands in the four scenarios.

3. Results

In order to answer the main question of the energy sector's compliance with the industrial water policy, the three specific research questions introduced in Section 1 were assessed and the results are presented in the following sub-sections. This section also compares the results with those of other similar studies, and also summarises a set of sensitivity analyses.

3.1. How is water currently used in China's energy sector?

Fig. 2 presents the current use of energy in China. The diagram shows that coal contributes 68% of China's total energy supply, mainly for power generation and industrial processes. 88% of the country's power output was coal-fired in 2010, the rest being made up of hydropower, gas, and nuclear (7%, 2%, and 2% respectively). China is largely energy self-sufficient with 84% of its total energy supply coming from domestic production. However, because of limited domestic oil resources, 60% of demand for oil is met by imports. 52% of China's final energy demand is from industry, mainly for the production of materials for building infrastructure, and for producing goods and services (mainly for export).

Fig. 3 shows the corresponding water use in the energy sector. In 2010 thermal power generation was the largest user of water, responsible for 84% of total water withdrawn, 99% of which was in coal-fired power generation. However, 91% of this water returns to

Table 5
Description of the four scenarios. Key changes made in each scenario are highlighted. The scenarios are cumulative and build on the previous one. WTC is wet-tower cooling and OTC is once-through cooling.

	Scenario 1A	Scenario 1B	Scenario 1C	Scenario 2
Objective	Baseline for analysis, taking no consideration of policy changes or technological improvements	Considering the impact of coal power restructuring on coal and water use	Considering the impact of dry cooling expansion on coal and water use on top of efficiency gains by coal power restructuring	Considering the impact of efficiency improvements, dry cooling expansion with policy changes (demand reduction and further increase in non-fossil fuels) on coal and water use
Energy pathway	IEA Current policies	IEA Current policies	IEA Current policies	IEA New policies
Coal power technologies	Same mix as 2010	50% reduction in subcritical 300 MW units(increase in ultra-supercritical and supercritical units)	50% reduction in subcritical 300 MW units(increase in ultra-supercritical and supercritical plants)	50% reduction in subcritical 300 MW units(increase in ultra-supercritical and supercritical plants)
Nuclear	50% WTC and 50% OTC	50% WTC and 50% OTC	100% WTC	100% WTC
Dry cooling (% of power generated)	12%	12%	30%	30%

the system and only 7% is actually consumed (2% is recycled). Coal extraction was the second largest water user, using 8.2% of water withdrawn; 58% of this water was returned to the system, usually polluted. Water withdrawn in 2010 for the energy sector was 70 km^3 (Fig. 3), 11% of which was consumed. Total water withdrawal for the industrial sector in 2010 was 145 km^3 (Ministry of Water Resources, 2011) which means the energy sector was responsible for roughly half of the water withdrawn by the industrial sector, with the rest being used by other industries such as steel, cement and iron production.

3.2. *How might future energy and water for energy develop?*

Fig. 4 summarises the future demand for energy resources in 2035 under the four different scenarios. More detailed results, and visualisations of scenario 1a using Sankey diagrams, can be found in the Supplementary Information (Section SI7). Significant increases in energy demand are observed for all four scenarios. New energy sources in the form of shale gas, oil shale, geothermal and marine energy are exploited in the future but contribute relatively small amounts to the total energy supply (4%, 0.4%, 0.03% and 0.005% respectively for scenario 2). To meet growing electricity demands, there is significant development of nuclear power generation, with increases of 1121% and 1247% compared to 2010 for scenarios 1(a,b,c) and 2 respectively. However, coal remains the dominant energy fuel source under all four scenarios, even in scenario 2 in which it makes up 53% of the total energy supply.

The corresponding water-for-energy analysis shows increased water demand for almost all energy processes, with substantial increases for coal washing, thermal and nuclear power generation (Fig. 5). Water needed for the extraction of shale gas appears to be minimal when compared to other processes in the energy sector, contributing only 0.05% of total water withdrawals in Scenario 2. Renewable resources in general are not major water users under the four scenarios, with solar CSP and geothermal energy requiring small amounts of water (0.01% and 0.2% respectively of total water withdrawn in Scenario 2). Withdrawn water that is not consumed may be returned to the system, for example, the majority of the water used in once-through cooling technologies in power plants is usually discharged back into river systems. It can also be recycled and reused (e.g. 30% of water in coal washing is estimated to be recycled) or injected into the ground. Details of these results are provided in the Supplementary Information (Table SI7).

Given that IWA is estimated at 104 billion m^3 in 2035, and measures water withdrawal, this analysis shows that under scenario 1a (business as usual), the energy sector would not comply with the target. Increasing demands for electricity will be mainly met in 2035 by coal-fired power generation whose water demand alone will exceed the IWA. However, the development of inland nuclear power plants will create a new and potentially large source of freshwater use in the energy sector. If future inland nuclear plants use 50% wet-tower cooling and 50% once-through cooling, this new demand will be the second largest water withdrawal in the energy sector, estimated at 11% of total water demand.

3.3. *How might future energy and water for energy be influenced by technology and policy changes?*

Scenarios 1b, 1c and 2 investigate the effects that changes in technology and policy may have on the energy sector's coal and water use. A restructuring of coal power technology (increase in supercritical and ultra-supercritical units, and a decrease in smaller units) under scenario 1b helps to reduce water use but not enough to comply with the IWA target, given an assumption that water intensities are the same as today's. The effect may be greater as technologies and water withdrawal intensities improve. What appears to make a difference in reducing water use and compliance with the IWA is the choice of cooling technology. An expansion to 30% dry cooling for coal-fired power generation and 100% wet-tower cooling for inland nuclear power generation (scenario 1c) can significantly decrease the energy sector's water withdrawals, to 89% of the IWA. The amount of water used for

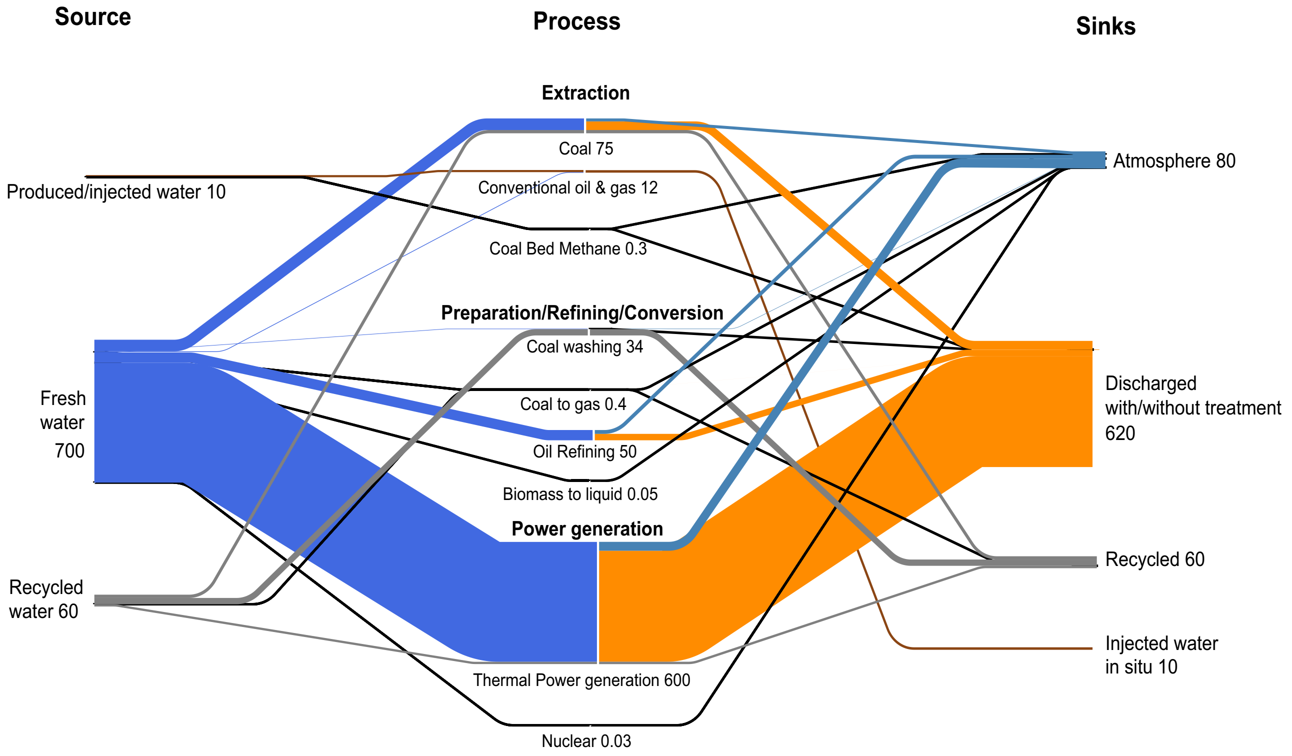

Fig. 3. 2010 water-for-energy Sankey diagram, corresponding to the energy diagram in Fig. 2 (10^8 m^3).

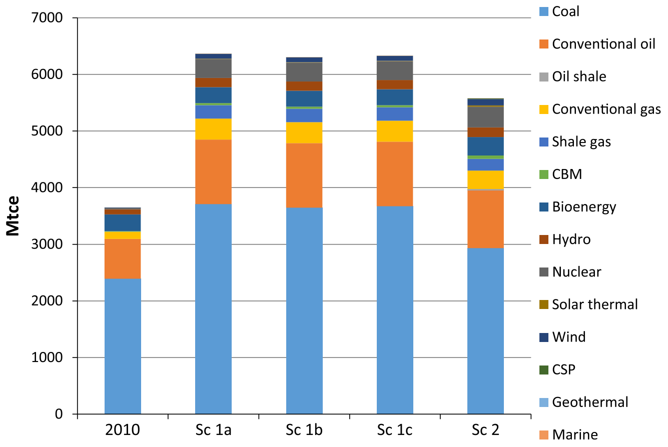

Fig. 4. Comparison of the current and future energy mix.

energy is highly linked to technology; the choice of coal power technology (subcritical, supercritical, ultra-supercritical) and cooling technology (once-through, wet-tower and dry cooling), and the combination of the two will affect both water withdrawal and consumption. Scenario 2 builds on scenario 1c and the results show that, beyond changes in cooling technologies, the implementation of policies to reduce demand and to further increase the proportion of non-fossil fuels in the energy mix would contribute to a decrease in the energy sector's water demand. Nevertheless, coal power generation remains the major water user. In this scenario, the energy sector uses 67% of the industrial water target.

The use of dry cooling instead of once-through or wet-tower cooling can significantly reduce water use, but it will also increase coal consumption, as it is less energy efficient, as well as being more costly and demands higher in-plant electricity usage. Based on an average efficiency loss of 2.4% from wet-tower and once-through cooling to dry cooling calculated from the coal-fired power generating units database, an extra 26 Mtce would be required to generate 1310 TWh of electricity to allow an expansion of dry cooling to 30% of all coal-fired power generation. This would require an extra 36 million tonnes of raw coal. However, it is important to note that extra coal consumption as a result of dry cooling could be significantly higher than calculated in this study (Fig. 6). 2% is often cited as the average efficiency loss in the change from wet-tower cooling to dry cooling (NETL, 2011), but dry cooling towers are highly sensitive to local climate. Efficiency losses ranging from 2–25% have been reported in various studies (Guan and Gurgenci, 2009; Xu et al., 2013; Wurtz and Nagel, 2010), with higher losses in hot weather. More power generating units would be needed as a result of the efficiency losses from implementing dry cooling.

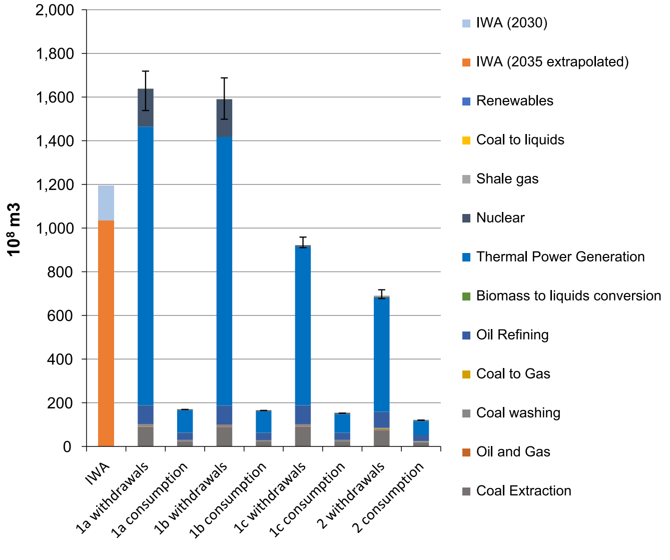

Fig. 5. Comparison between the Industrial Water Allowed (IWA) target and future water withdrawal and consumption by the energy sector under the different scenarios for 2035. The units for water withdrawals and consumption are shown in 108 m^3 to allow the breakdown of water consumption values to be visible. Maximum and minimum bars are included in the water withdrawal columns to show how the use of low and high water intensities reported for coal fired and nuclear power generation (NREL, 2011, Williams and Simmons, 2013) may affect the results. The range of water intensity factors is provided in the Supplementary Information (Table SI8).

3.4. *Comparison with other studies*

Other studies have been carried out on water-for-energy in China. Table 6 compares our current and future estimates with these studies, mainly for coal-fired power generation for which there are comparable results. The calculations for current coal consumption, water withdrawal and water consumption are similar to those in other studies and the baseline (BAU) scenario also shows similar coal and water results for coal-fired power generation when compared to the BAU scenarios carried out in other studies.

3.5. *Sensitivity analysis*

A key parameter influencing the results is the water intensity factor used for each energy process to calculate total water withdrawal and consumption. As the IWA measures water withdrawal and the amount of water which is consumed is relatively small, a sensitivity analysis was carried out on the impact of water intensities on water withdrawals. A range of water intensity factors is provided in NREL (2011) for different cooling technologies used in nuclear and coal-fired power generation (refer to Supplementary information Section SI8). Using the low and high water intensities, water withdrawals for coal-fired and inland nuclear power generation were calculated for the four scenarios to assess the range of possible withdrawals. These are shown as error bars in Fig. 5.

Uncertainties associated with individual coal power units for present and future water demands in China's energy sector were assessed. Using the range of water intensities for coal-fired power generation in NREL (2011) and the number of units with different technologies for 2010 and scenario 1a, approximate estimates of standard deviation and uncertainties for each technology group were calculated. It was found that the water intensities of once-through cooling systems have very low relative variabilities (< 1%), while the wet-tower cooling systems have variabilities of c. ±5% and ±13%, depending on their scale. An overall uncertainty estimate weighted by the different numbers of plants with each technology would be about ±8–9%, since there are relatively fewer once-through cooling systems. However, the uncertainties in water intensity of once-through cooling units are surprisingly, and perhaps improbably low in the NREL (2011) data. If they are instead assumed to be ±5%, the weighted overall uncertainty increases to ±16%. The weighted uncertainties would be less than these if weighted by the amounts of water withdrawn for cooling (rather than the number of units), because the water intensities of once-though cooled units (with lower variability in intensities between individual units) are fifty times greater than those of wet-tower cooled units. More information and a table showing the approximate uncertainty at 95% for each technology group can be found in the Supplementary information (Section SI8).

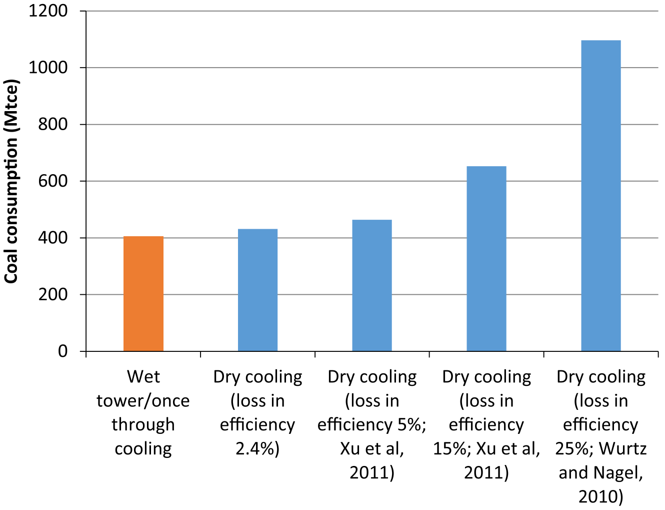

Fig. 6. Comparison of extra coal consumption that would be required for scenario 1c using different efficiency losses from literature.

A sensitivity analysis was also carried out to assess how future improvements in technology, and water intensities, might affect the results (Fig. 7). Two levels of future improvement were assessed for coal-fired and nuclear power generation which are the two largest water users; 10%, and 25% (1% average improvement each year).

Future improvements in technology can help to reduce the energy sector's total water demand, but even under the unlikely assumption that all future coal power and inland nuclear power generating units will have improved technology, the impact is still not as significant as technology choice and demand reduction. Yu et al. (2011) also conclude that the choice of cooling technology is the key factor in controlling coal-fired power generation's water withdrawals, especially the proportion of once-through cooling plants.

4. Discussion

The results presented in Section 3 lead to an assessment of the energy sector's compliance with the industrial water policy which is discussed in Section 4.1. The results also prompt a discussion on the distinction between water withdrawals and consumption in assessing the energy sector's water use. Other aspects of the energy–water nexus are also discussed in this section.

4.1. The energy sector's compliance with IWA

The results show that under a Business As Usual scenario, the energy sector will exceed the IWA target. However, the amount of water-for-energy is highly dependant on technology choice, and the results show that a number of energy- and water-saving measures which have been enacted and are planned for the future, such as changing coal power technologies, and the expansion of dry cooling and wet tower cooling, can help to reduce the energy sector's total water demand. These can complement stricter policies on increasing non-fossil fuels and reducing demand. On top of these measures, increased recycling, treatment and reuse of water will also help to reduce total water use by the energy sector.

4.2. The use of water withdrawal and consumption in assessing the energy sector's water use

According to Pan et al. (2012) the IWA is based on water withdrawals, but as the results show (Fig. 5), while the energy sector withdraws a significant amount of water, the actual consumption is quite small. For example, in scenario 1a only 10% of water is actually consumed, and the rest that is returned to river systems may be at a temperature 6–11 °C higher than when withdrawn (Vine, 2010). There are also trade-offs between water withdrawals and consumption, depending on the cooling technology used. This is evident when comparing scenarios 1b and 1c, where the conversion from 50% wet-tower and 50% once-through cooling to 100% wet-tower cooling in nuclear power generation sees a 97% decrease in water withdrawal for this energy source from 17 billion m^3 to 600 million m^3. However, in scenario 1b, only 2% of the withdrawn water is consumed (400 million m^3) compared to 84% of the withdrawn water in scenario 1c (500 million m^3). Another consideration for cooling technology is cost, as cooling systems which withdraw less water tend to have higher capital and operational costs (Bryers et al., 2013). If the underlying assumption is that the return flows are re-usable, this should prompt a discussion on whether the use of a water withdrawal limit is acceptable as a policy mechanism for the energy sector. However, water withdrawals are easier for policy makers to monitor and measure (through abstraction licences etc.) than water consumption.

4.3. Other considerations for the energy–water nexus

This study focuses on demand for water in the energy sector, but the choice of technology adopted in power generation should really depend on location and water availability. The available supply of water should also be considered, to allow the assessment of whether the availability of water could limit future energy targets. An example is shale gas; at the national scale and in the context of the whole energy sector, shale gas extraction does not appear to be a major water user. However, this may be very different at a regional scale, especially since a proportion of shale gas reserves are located in water-stressed areas.

It is also important to consider other water users, including agricultural and domestic water demands and environmental flows, to provide a holistic assessment of the water sector and assess the trade-offs between water demands in different sectors. Another key consideration is the quality of return-flow water deriving from the energy sector's water use. For example, water used for coal extraction and washing is often heavily polluted with chemicals and impurities; the distinction between withdrawal and consumption is less clear-cut if the return flow is unusable without expensive treatment. Produced water is another source of pollution and is considered a waste product that can have serious effects on water quality if it is not treated properly (McMahon and Price, 2011). However, monitoring of such operations is often inconsistent and difficult to track.

Schnoor (2011) emphasises the growing importance of the energy–water nexus, and in both directions. Energy-for-water has not been covered in this study, but is also important, especially in China where practices employed to relieve water stress all use energy e.g. inter-basin water transfers, extraction of groundwater, desalination and reuse of wastewater.

5. Conclusions and policy implications

This study has calculated the water withdrawal and consumption of the entire energy sector in China for current and future (2035) scenarios. If business continues as usual, China's energy sector will not comply with the “3 Red Lines” industrial water policy. Coal-power generation alone would exceed the target and future energy developments e.g. inland nuclear power plants, will require new sources of water-for-energy. As competition for water

Table 6
Comparison of our results with other similar studies.

	Current Coal consumption for power generation (Tce)	Current power generation (TWh)	Thermal efficiency (gce/kwh)	Current water withdrawals factor (m^3/kwh)	Current total water withdrawal (km^3)	Current water consumption factor (m^3/kwh)	Current total water consumption (km^3)	Future coal fired power generation (Twh)	Future coal consumption for power generation (Mtce)	Future water withdrawals factor (m^3/kwh)	Future water withdrawals for coal fired power generation (km^3)
Pan et al. 2012 (Coal)[a]		(2008) 2759		0.0285	79	0.00285		(2030) 6605		0.01	188 (BAU)[e]
Yu et al. 2011 (Coal)	(2007)[b] 1,214,310,000		345	0.133 (OTC)[c] 0.00303 (WTC) 0.00027 (Dry)	67			(2030) 7470	2500	0.0023 (non-OTC) 0.015 (OTC)	135 (BAU)
Zhang and Anadon, 2013 (Energy)		(2010) 2567		0.0189	49 **54**[d]	0.00084	5 **7**				
This study (Energy)	(2010) 1,151,640,000	3297	315	0.0925(OTC) 0.00245 (WTC) 0.00034 (Dry)	59 **70**	0.00029 (OTC) 0.00208 (WTC) 0.00032 (Dry)	4 **8**	(2035) 7629	2446	Same as current	128 (BAU)

[a] Pan et al. (2012) focus on the coal industry, Yu et al. (2011) on coal fired power generation and Zhang and Anadon (2013) consider the whole energy sector.
[b] The baseline and future years considered in each study are given in brackets
[c] OTC represents once through cooling and WTC represents wet tower cooling
[d] Current water withdrawals and water consumption for the whole energy sector are highlighted in bold
[e] Pan et al. (2012) only use one overall water withdrawal intensity factor for coal fired power generation

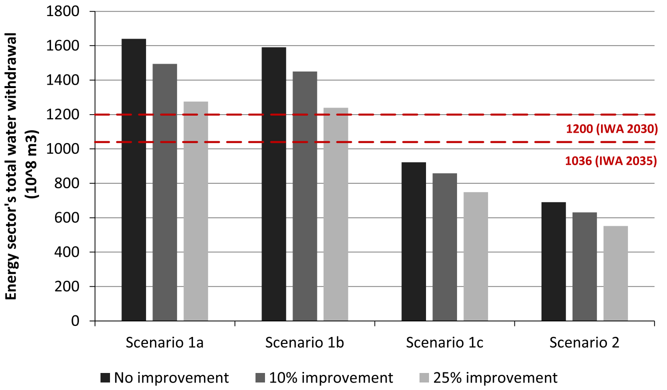

Fig. 7. The impact of future improvements in water withdrawal intensities for coal-fired and nuclear power generation on total water demand by the energy sector under the four scenarios and the energy sector's compliance to the "3 Red Lines" industrial water target.

use between the industrial, domestic and agricultural sectors intensifies and strict water targets are put in place, there is a need to assess the energy sector holistically, understand how water is used in each of its processes, and evaluate competing needs and benefits.

The sector's compliance with the IWA target is likely to require several measures for which there are co-benefits as well as trade-offs for both water and energy. Replacing small, inefficient plants with larger more efficient plants will enable savings of both resources, as will policies to control demand and increase the fraction of electricity supplied by gas and renewables. However, some policies that relieve stress on one resource may have unintended effects on other resources, as shown by the expansion of inland nuclear power plants in the energy mix to meet growing energy demands and reduce GHG emissions. These will significantly increase the energy sector's total water demand, depending on the cooling technologies chosen.

Potential conflict also arises with the expansion of dry cooling. This is intended to relieve local water stress in six identified provinces which also have hot summers that lead to high power demands. This is likely to place significant limitations on the efficiency and power output of dry-cooled plants and will result in more coal consumption (and therefore more water requirements for coal extraction and processing). Yu et al. (2011) highlight that this trade-off in coal consumption blocks the spread of dry cooling technology nationwide, but as most of China's coal reserves and future coal-related projects are located in these provinces, the potential impact on coal consumption and future energy plans could be significant.

The holistic view of water used in the energy sector adopted in this study has demonstrated why the need for integrated resource policies is important for the governance of energy and water resources. Understanding how technology and policies can affect the energy sector's coal and water use enables the identification of co-benefits and trade-offs between energy and water policies which can lead to the development of more compatible and sustainable water and energy plans.

Acknowledgements

The authors would like to thank EPSRC and BP (Grant no. RG60538) for their funding support as well as co-investigators and members of the Foreseer team for their support and invaluable insights.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2015.03.013.

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