Potential water sources for coal-fired power plants

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Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

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Abstract

Global energy demand is rising, while water is becoming a scarcer commodity in many parts of the world due to overexploitation, droughts, heat waves, and other factors. Meeting the growing demand will place increasing stress on limited fresh water resources. The power generation industry is typically the largest industrial user of fresh water in a country. Consequently, the vulnerability of the power generation industry to constraints in water availability can be expected to increase. Hence non-fresh water sources will become increasingly important. This report examines the availability and use of potential non-fresh water sources in China, India, South Africa and the USA. These are the four top thermal coal consuming countries in the world. The alternative sources are municipal waste water, brackish and sea water, mine water, produced water from oil and gas wells (including coalbed methane wells), and water extracted from deep saline aquifers during CO_2 storage. In certain cases, and with suitable design of the on-site water treatment plant, a coal-fired power plant could become a supplier of both energy and fresh water, instead of a water consumer.

Acronyms and abbreviations

bbl	barrels
BOD	biochemical oxygen demand
CBM	coalbed methane
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
COD	chemical oxygen demand
DWA	Department of Water Affairs (South Africa)
EIA	Energy Information Administration (USA)
EPA	Environmental Protection Agency (USA)
EWR	enhanced water recovery
FGD	flue gas desulphurisation
GL	billion (10^9) litres
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
kL	thousand (10^3) litres
L	litres
LT-MED	low temperature multi-effect distillation
MD	membrane distillation
MED	multi-effect distillation
ML	million (10^6) litres
ML/d	million (10^6) litres per day
MSF	multi-stage flash (distillation)
MWW	municipal waste water
NETL	National Energy Technology Laboratory (USA)
NMC	Nagpur Municipal Corporation (India)
OTEC	ocean thermal energy conversion
ppm	parts per million
R	rand (South Africa)
RCSP	Regional Carbon Sequestration Partnership
RMB	reminbi (China)
RO	reverse osmosis
Rs	rupees (India)
SRO	spiral-wound reverse osmosis
SWRO	sea water reverse osmosis
t	tonnes
TDS	total dissolved solids
TL	trillion (10^{12}) litres
TSS	total suspended solids
TVC	thermal vapour compression
US$	United States dollars
USDOE	United States Department of Energy

Conversions

1 m^3 = 1000 litres

1 bbl = 158.99 litres

1 t water = 1 m^3

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1 Introduction

Water and energy are basic necessities for human well-being and prosperity. They are mutually dependent, with energy production requiring large volumes of water and the water infrastructure requiring large amounts of energy. This interdependency has been called the 'water-energy nexus' or 'energy-water nexus', and is explored more fully in an earlier report (Carpenter, 2015). Future demand for both water and energy is expected to rise as a consequence of population and economic growth, and higher living standards, particularly in the emerging economies. Global water demand is projected to grow by 55% between 2000 and 2050, due mainly to rising demands from manufacturing, thermal power generation and domestic use (OECD, 2012). In the New Policies Scenario of the International Energy Agency (IEA), global energy demand is projected to increase by 35% between 2010 and 2035, with the demand for electricity expanding by 70% (IEA, 2012). The Scenario takes into account existing and planned government policies.

The majority (over 90% in 2010) of energy-related water withdrawal is for power generation, which is dominated by water-intensive thermal electricity production from coal, natural gas and nuclear. Water withdrawals for power generation are projected by the IEA in their New Policies Scenario to rise from 540 billion m^3 in 2010 to 560 billion m^3 in 2035 (a 3.7% increase), whilst consumption (the volume withdrawn and not returned to source) may increase by almost 40% (IEA, 2012). These trends are driven by a shift towards higher efficiency power plants with more advanced cooling systems that reduce withdrawals but increase consumption per unit of electricity. The majority of the water used at thermal power plants is for cooling purposes (cooling towers). Water is also needed at coal-fired power plants for flue gas desulphurisation (FGD), boiler feed water, handling ash, and for other applications around the plant. The amount required varies depending on the type of plant (subcritical, supercritical or ultra-supercritical), the cooling system employed, the FGD process and other factors. For example, wet FGD systems consume some 250 L/MWh of make-up water in subcritical power plants and around 220 L/MWh in supercritical plants; semi-dry FGD technologies consume approximately 60% less water (Carpenter, 2012).

The vulnerability of the power generation industry to constraints in water availability is widespread and growing (Carpenter, 2015). Regions where water is scarce face obvious risks, but even regions with ample resources can face constraints due to droughts, heat waves, seasonal variations and other factors. Power plants have had to temporarily curtail or cease production because of a lack of water. For example, the Parli coal-fired power plant in India had to shut-down in February 2013 because of a severe water shortage. The number of plants affected is likely to increase in the future, with serious economic consequences. Ground water supplies are diminishing with an estimated 20% of the world's aquifers already over-exploited (WWAP, 2015). Competition between users for limited water resources will probably escalate, and climate change may exacerbate the situation. Regulatory restraints by governments may impose limits on, or increase the cost of, fresh water usage by power plants. The current strain on fresh water supplies and escalating demand is leading the power generation industry to look for alternative or supplementary sources. Moreover, utilising these sources will help conserve fresh water for other uses, such as drinking and agriculture.

This report examines the availability and use of alternative (non-fresh) water sources for coal-fired power plants in China, India, South Africa and the USA. These are the four top thermal coal consuming countries in the world, and all have water-stressed regions. The alternative sources covered are waste water from municipal water treatment plants, brackish and sea water, mine water, produced water from oil and gas wells (including coalbed methane wells), and water from deep saline aquifers.

Evaluation of the use of alternative water sources in existing or for new power plants is complex. Key issues to be considered include:

- quantity. Power generation needs an abundant, reliable, secure and predictable source of water that is available over the lifetime of the plant;
- quality. Typically, alternative water sources have a lower quality than fresh water, and therefore require treatment before use to avoid operational problems. For example, poor water quality can lead to scaling, corrosion and fouling of pipes and cooling equipment;
- location. Transporting water to power plants is expensive (especially if infrastructure has to be built). Therefore, the source needs to be close enough to the power plant to allow for economic collection and transport;
- overall economics; and
- legal and regulatory constraints.

The alternative water source can cost more than traditional surface and ground water sources, because of the higher treatment and transport costs. Nevertheless, the economic viability of treating lower quality water should increase as traditional fresh water resources dwindle, and treatment costs diminish due to technology developments. Costs will be site-specific and consequently, are only discussed in general terms.

This report continues a series relating to water and the power generation industry. The previous one looked at where water stress is occurring in the world today, before it examined the availability and consumption of water within China, India, South Africa and the USA. It also discussed central government energy, climate and water policies and how they affect the coal-fired power generation sector in these four countries (Carpenter, 2015). The next report in the series will look at water conservation within coal-fired power plants. An earlier report covered low water FGD technologies (Carpenter, 2012).

2 Municipal waste water

Municipal waste water (MWW, also called reclaimed water) is the effluent from MWW treatment plants, which process water from domestic use (including sewage), surface runoff (from storm drains), and sometimes industrial waste water. It is widely available, especially in urban areas, and could potentially provide a plentiful and secure supply of water for nearby power plants. MWW may deliver a drought-resistant source as domestic water use is usually one of the last uses to be curtailed. In many areas of the USA, for example, the utilisation of MWW is exempt from drought-induced water use restrictions. Both power plant operators and municipalities can benefit environmentally and financially from this arrangement, especially if they are reasonably close to each other. Rising urbanisation and population growth will increase the demand for domestic water and hence, the volume of MWW available in the future.

MWW is already successfully used at thermal power plants in cooling towers, as boiler make-up water and in FGD systems. For instance, the Eraring power plant, in New South Wales, Australia, utilises MWW from the Dora Creek sewage treatment works as boiler feed (Anderson, 2003). However, the biggest use is as make-up water in closed-loop (recirculating) cooling towers. The amount of MWW blended with fresh water varies, with only a relatively few power plants using treated MWW as the dominant source. Municipal water treatment plants are designed to handle specific design flows. Thus they can supply a defined quantity of water of relatively consistent quality to a power plant. However, increasing demand and competing uses for municipal water could strain supplies in the future.

2.1 Viability of use

Using MWW is not without its challenges as it is of lower quality than typical fresh water sources. The presence of nutrients and other contaminants can cause corrosion, scaling and biofouling in piping and on heat exchange surfaces. Fouling of the condenser's heat exchange surfaces is of particular concern in closed-loop cooling towers, because evaporative cooling concentrates the contaminants present in the recirculating water. A loss of heat exchanger performance can decrease the efficiency of the plant's steam power cycle, which lowers the amount of power generated per unit of coal fed, and ultimately results in loss of revenue. There are a variety of ways of controlling these operational issues. Plastic piping and higher recirculation rates may be helpful (Cooper, 2012), or operators could adjust the flow volumes of blowdown and make-up in the cooling tower to maintain the required chemistry in the recirculating water (Munson and others, 2009). Alternatively, the waste water is treated before it is used (*see* Section 2.1.1). Most waste water from municipal plants will need some treatment to prevent operational issues. The treatment can be carried out at the power plant or the municipal plant operator can be paid to provide the necessary extra treatment. Costs have been estimated in the USA at around 1–2% of electricity sales revenues to manage fouling, condenser cleaning, and reduced generating efficiency (Stillwell and Webber, 2014). Some power plants, though, have reported no problems when switching to this water source.

The possible emission of biological (viruses and bacteria) and other trace contaminants in aerosols emitted from the cooling tower have led to public health concerns since the aerosols can travel beyond the vicinity of the power plant. For example, the Legionella pneumophilia bacteria can cause Legionnaires' disease. However, the aerosols can be controlled by the use of drift eliminators within the cooling tower. Advanced water treatment processes are also available to help remove the unwanted constituents (Cooper, 2012).

Legal and regulatory issues need to be considered before utilising MWW. For example, water ownership and right of use may complicate its use if interstate or interbasin water transfer is involved. Blowdown from the cooling towers may require additional treatment before discharge or, if returned to the MWW treatment plant, it may pose toxicity problems from a higher total dissolved solid load, biocides, or other power plant treatment chemicals (Cooper, 2012).

2.1.1 Water quality and treatment

Effluent treatment at municipal treatment plants is accomplished in a series of steps that have different levels of complexity. The conventional sequence goes from primary, secondary to tertiary treatment, not all of which are carried out at every facility. Primary treatment involves basic processes, such as settlement tanks to remove suspended solids (by up to 60%) from the water and to reduce biochemical oxygen demand (BOD) by 20–30%. Secondary treatment entails biological degradation that allows bacteria to decompose constituents more (further reducing nutrient levels and BOD), secondary clarification and disinfection. Up to 85% of BOD and total suspended solids (TSS) can be removed (Hsu and others, 2014). Tertiary treatment reduces the residual organic, ammonia, suspended solids, and toxic chemical levels (Pakzadeh and Zbacnik, 2015).

Secondary-treated MWW still contains appreciable amounts of phosphorus (phosphates), nitrogen (in the form of ammonia, nitrates and nitrites) and residual organic matter, such as bacteria (*see* Table 1). These can lead to biofouling of heat exchangers and other equipment surfaces (Dzombak and others, 2012; Vidic and others, 2009). The primary constituents that can result in scaling are calcium, magnesium, sulphate, alkalinity, phosphate, silica, and fluoride (EPA, 2012). Constituents influencing corrosion include ammonia and phosphates (Li and others, 2011). Ammonia, for example, can corrode copper, copper alloy and other metals. It is also a nutrient for microbes, and irreversibly reacts with chlorine. Therefore, secondary-treated effluent typically requires further treatment before it can be utilised in the power plant. Tertiary treatment can be carried out at the MWW treatment plant prior to its transport, as is the case at the Cherokee power plant (*see* Section 2.2.4). But even so, chemical additives, such as biocides, may still be necessary (Dzombak and others, 2012). Otherwise, the treatment is performed at the power plant. In this case, the plant operator has more control over its quality. Tertiary treatment is expensive. Consequently, secondary-treated MWW is more commonly available.

Table 1 Typical quality of secondary-treated MWW in the USA (Vidic and others, 2010)

Parameter	Range
pH	7–8
BOD_5, mg/L	3–30
COD, mg/L	40–80
TDS, mg/L	130–1600
TSS, mg/L	10–50
Alkalinity (as $CaCO_3$), mg/L	100–500
Ca, mg/L	28–185
Mg, mg/L	23–150
NH_3-N, mg/L	3–73
NO_3-N, mg/L	10–30
SO_4, mg/L	60–293
PO_4, mg/L	0.6–51
Conductivity, µS/cm	0.2–1.2

Common water quality requirements for cooling tower and boiler make-up applications (Wilson and others, 2014) include:

- low ammonia (often <2 mg/L or even below detectable limits);
- low total dissolved solids (TDS), especially for boiler feed applications;
- chloride less than 150 mg/L;
- low phosphorus (<0.5 mg/L); and
- low iron and manganese (<0.5 mg/L).

Advanced treatment of MWW to meet the quality requirements can include biological, filtration and disinfection processes, as well as pH adjustment. Biological processes are becoming more common, and include membrane bioreactors, moving bed biofilm reactors, integrated fixed-film activated sludge systems, and biological aerated filters. A membrane bioreactor, for example, provides biological and filtration treatment in one process within a small footprint. It has a high removal efficiency for contaminants such as nitrogen, phosphorus, bacteria, BOD and TSS. A description of membrane bioreactors, moving bed biofilm reactors and biological aerated filters, along with their advantages and disadvantages, is given by Pakzadeh and Zbacnik (2015).

Separate filtration technologies that have been used at power plants include continuous backwash sand filters and cloth filtration. Cloth disk filters have had problems operating on poor quality secondary effluents (low solids retention time), and typically are not applicable for chemical phosphorus removal. Disinfection with sodium hypochlorite or chloramination is commonly included to limit biological re-growth (Wilson and others, 2014). Ultraviolet filtration is also employed to control biofouling. MWW for use as boiler make-up is often further treated in a reverse osmosis system (*see* Section 3.3.2) to remove salts, TDS and larger particles. For example, a power plant in Inner Mongolia, China, combines membrane bioreactor ultrafiltration modules with reverse osmosis to provide make-up water for the boilers. The plant has a capacity of 18 ML/d (Koch Membrane Systems, 2014).

Alternatives to tertiary treatment, such as chemical dosing of secondary effluents, could lower the cost of using MWW in cooling towers. However, these involve trade-offs because low-scale water has high corrosivity, and anti-scalants are compromised by the use of free chlorine to control biofouling (Li and others, 2011; Stillwell and Webber, 2014). Free chlorine can directly attack metals and metal alloys, and degrades tolytriazole, a commonly used corrosion inhibitor. Moreover, free chlorine tends to react with the organic matter to form undesirable disinfection by-products (Li and other, 2011). Consequently, chloramine may be used instead of free chlorine. The most cost-effective approach to the use of MWW as make-up water in power plants will depend on its quality, and is likely to involve a combination of on-site tertiary treatment and chemical addition. Research funded by the USDOE National Energy Technology Laboratory (NETL) on the treatment and use of MWW for cooling systems at power plants is reviewed by Munson and others (2009).

Process simulation models are being developed to predict water quality in the recirculating cooling loop when utilising secondary- and tertiary-treated MWW as the make-up water. For instance, the process model developed by Safari and others (2013) predicts water quality in the cooling loop as a function of operating parameters and the make-up water quality. It can be used to evaluate the potential performance and treatment needs for MWW, and the economic implications.

The blowdown from wet towers could be returned to the MWW plant for further treatment. This may address discharge concerns (Cooper, 2012). Economies can be achieved for new facilities by laying the supply and return pipelines in the same trench.

2.1.2 Economics

The economic feasibility of using MWW depends on the distance between the power plant and municipal treatment facility, the price of water, its treatment costs, and operational factors. Consequently, costs are site-specific, as can be seen in the case studies discussed in Section 2.2.

A conceptual cost model has been developed to estimate the life cycle costs for the construction and operation of tertiary treatment units and treated water delivery for use in power plant cooling systems (Dzombak and others, 2012; Theregowda and others, 2013). It was applied to selected tertiary treatment processes, which included filtration, nitrification, softening, acidification and chemical conditioning (biocide and corrosion inhibitors). Total costs for treating 29.3 ML/d (the amount of water required by a 550 MW coal-fired power plant closed-loop cooling system) were estimated to be in the range US$0.24-0.35/kL (2009 $US) in the USA, excluding taxes and overhead costs. This range lies between the rate charged for river water withdrawal with filtration and chemical conditioning (US$0.20/kL in some areas) and the national average rate for potable city water (US$0.78). The treated water supply and chemical conditioning costs dominated the overall costs.

Walker and others (2013) have evaluated the combined treatment and fouling costs associated with the use of tertiary-treated MWW in the closed-loop cooling systems of thermal power plants. They incorporated the above work of Dzombak and others (2012) and Theregowda and others (2013), with the methodology of Walker and others (2012) for evaluating the economic impact of condenser fouling. Their analysis indicated that if the price differential between fresh water and treated MWW is more than $0.14/kL (2009 US$), than it is economically advantageous to use the waste water, even with the added cost of condenser fouling. The total combined cost of using such water for closed-loop cooling is estimated to be US$3–3.2 million/y for a 550 MW subcritical coal-fired plant that consumes make-up water at a rate of 29.3 ML/d. This translates to a fresh water conservation cost of US$0.26/kL, making it a cheaper way to conserve fresh water than a dry cooling system; dry cooling had a fresh water conservation cost of US$1.5/kL. Moreover, it is below the NETL 2020 fresh water conservation cost target of US$0.74/kL.

2.2 Water availability

This section examines the availability of MWW in China, India, South Africa and the USA, and its use in power plants. These are the four countries covered in an earlier report on water availability and policies for the coal power sector (Carpenter, 2015).

2.2.1 China

China is the world's most populous country, with almost 20% of the world's population. It is the second largest user of water, but the largest producer of waste water. In 2012, China discharged 68.5 billion m^3 of municipal and industrial waste water, with the former accounting for around 68% (46.6 billion m^3) (Hu and others, 2014). The amount of MWW is expected to grow with rising urbanisation and population growth.

There were 3836 waste water treatment facilities in urban areas with a total operational capacity of 149 million m^3/d in 2012 (Hu and others, 2014). By the end of 2010, MWW treatment rates had reached 77.5% in the cities, 60.1% in the counties and less than 20% for townships. These are targeted to increase to 85% in urban areas, 70% for counties and 30% for townships by the end of 2015 in the Five Year Plan for Construction of MWW Treatment Facilities and Infrastructure (available at http://www.gov.cn/zwgk/2012-05/04/content_2129670.htm). A large proportion of MWW remains unused that could potentially supply nearby power plants. Only 8% of treated MWW was reused in 2008, 24% of which was accounted for by industry (mainly for cooling) (Yi and others, 2011). According to the Aquastat database (*see* http://www.fao.org/nr/water/aquastat/data/query/), 3.37 billion m^3 of treated MWW was reused in 2010. This was about 11% of the collected water, not all of which was treated. The aforementioned Plan has set a target of utilising 15% of MWW in urban areas.

The Chinese government has recognised the importance of fully utilising its MWW resources. The waste water treatment targets have been raised to 95% for cities and 85% for counties in the Action Plan for Water Pollution Prevention and Control, issued by the State Council in April 2015 (available at http://www.gov.cn/zhengce/content/2015-04/16/content_9613.htm). By 2017, municipalities, provincial capitals, and municipalities with independent planning status are required to collect and treat all waste water. This could increase the amount available to nearby power plants. In addition, all urban waste water treatment facilities should reach relevant discharge standards, although this may not be of sufficient quality to enable its direct use in a power plant. The utilisation ratio of recycled water is targeted to exceed 20% in water-deficient cities, and 30% in Beijing, Tianjin and Heibei by 2020; the recycled water will mainly be used for domestic purposes. Water applications from thermal power plants will be rejected if all available sources of recycled water (not just MWW) have not been used.

Although the waste water treatment rates are increasing, it is difficult to determine the real treatment rate as some treatment plants do not fully operate, or even operate at all, and some also suffer from under-developed supporting structure, such as incomplete sewage pipelines (Hu and others, 2014). Under-utilisation has been officially recognised by some provinces, which have set targets for improving the utilisation rate of existing treatment plants, as well as building new ones.

MWW is used at a number of coal-fired power plants, such as the Gaojing power plant in Beijing (Dow Water and Process Solutions, 2012) and the Jinqiao plant in Inner Mongolia (da Silva and Lin, 2012). The Baotou Donghua power plant in Inner Mongolia uses tertiary-treated effluent from the local municipal plant, which has a capacity of 40,000 m^3/d. The treated water is transported along a 7 km pipeline to the power plant, where it is further treated before being added as make-up water to the cooling circuit. The treatment includes lime softening, pH adjustment, and the addition of an anti-scalant and disinfectant. Operating costs are RMB0.6/m^3 of reclaimed water. The capital costs of the project were RMB1.0/m^3 when calculated with a 10% interest rate, and depreciation periods of 15 years for the electromechanical equipment and 20 years for the civil works. Therefore, the total operating costs added RMB1.6/m^3, still a significant saving over the fresh water costs of RMB3.3/m^3. A considerable amount of fresh water was also saved (Lahnsteiner and others, 2007).

2.2.2 India

India is the second most populous country in the world with over 1.2 billion people, and is expected to pass China to become the most populated nation by 2025 (WWAP, 2014b). Water is fast becoming a scarce commodity. The per capita availability of 1600 m^3 in 2011 (WWAP, 2014b) is below the United Nation's threshold for water stress of 1700 m^3 per person per year. The demand for water (and electricity) by a rapidly industrialising economy and urbanising society comes at a time when the potential for augmenting supply is limited, quality is declining, and water tables are falling. In light of increasing water scarcity, the Indian government has started to emphasize reuse and recycling. For instance, the National Water Policy of 2012 (*see* http://wrmin.nic.in/forms/list.aspx?lid=1190), states that the 'recycle and reuse of water, after treatment to specified standards, should be incentivized through a properly planned tariff system'. In January 2016, the Cabinet government approved a new tariff policy which, among other things, has made it mandatory for power plants to use treated MWW available in their vicinity (within a 100 km radius) (Press Information Bureau, 2016).

Almost 80% of the water supplied for domestic use in urban areas is released as waste water. A large proportion of this is untreated, causing pollution of rivers and other water bodies. India's largest cities (population over 50,000) generated an estimated 38.254 million m^3 of sewage each day during 2008–09, out of which 11.787 million m^3/d (~30%) was treated in 269 plants (Central Pollution Control Board, 2010, 2015). In 2014–15, the number of MWW treatment plants in India had risen to 816, with a total capacity of 23.277 million m^3/d. Of these, 522 were operational (total capacity 18.883 million m^3/d), 79 non-operational, 145 under construction and 70 were proposals (Central Pollution Control Board, 2015). However, many of the facilities do not operate properly due to a lack of qualified staff, poor maintenance, overloading of facilities and irregular power supply. Building more treatment plants, and more efficient operation of existing ones, could help mitigate water pollution, conserve fresh water, and provide a secure water supply to nearby power plants.

Power plants are turning to MWW to resolve water availability issues. Currently, only 100 MW or 120 MW units are using this source. This will change with the construction of three 660 MW supercritical coal-fired units (units 8, 9 and 10) at the existing Koradi power plant near Nagpur. The Maharashtra State Power Generation Co. (Mahagenco) had an allocation of 55 million m^3/y of water from the Pench River, but required an additional 58 million m^3/y for the new units, which were due to be commissioned in 2015. Following a request from Mahagenco, the water allocation was increased to 67 million m^3/y, with a maximum use of 75 million m^3/y within a 10% variation. But this was projected to be insufficient for all three units, and there was no additional fresh water allocation available. The feasibility of using high quality tertiary-treated waste water from the city of Nagpur's treatment plant was assessed by USAID in its project titled Water Energy NEXUS Phase – II (WENEXA – Phase II). The city generates about 450 ML/d of sewage, but only treats some 80 ML/d. A pilot plant built under the USAID project showed that MWW reuse was effective and feasible. The tertiary-treated water from the pilot plant could be used for ash handling without further treatment or for condenser cooling when treated with disinfectant. Mahagenco signed a memorandum of understanding with Nagpur Municipal Corporation (NMC) to supply 40 million m^3/y (110 ML/d) of treated waste water (with a 10% overloading capacity). NMC would be paid Rs150 million (15 crores) every year for the next 15 years as a royalty fee. In addition, Mahagenco is constructing a new 130 ML/d sewage treatment plant at Bhandewadi, Nagpur, with tertiary treatment capability, and associated pipelines to supply the new units (Kelkar and Balakrishnan, 2012; Mahagenco, 2013; Pradhan, 2014).

The Maharashtra state government is also planning to supply MWW to six additional coal-fired power plants (Parli, Paras, Bhusawal, Chandrapur, Nashik and Khaparkheda) to help prevent situations where power plants have shut-down due to non-availability of water, and to conserve fresh water for its cities (Kulkarni, 2015). For instance, the 1130 MW Parli power plant shut-down in February 2013 due to water shortages; it could obtain MWW from Nanded city.

2.2.3 South Africa

South Africa is a semi-arid, water-stressed country, with limited fresh water resources. With a population of over 54 million, there is less water per person than countries considered to be much drier. There is also a growing gap between water supply and demand, with a potential deficit of 2.7 billion m^3 projected for 2030 (2030 Water Resources Group, 2009). South Africa depends mainly on its surface water resources, which are highly developed in many parts of the country. There are few major ground water aquifers that can be used on a large scale owing to the country's geology. In the northern parts of the country, both surface and ground water resources are nearly fully developed and used (Government Communications, 2015a). This is where the majority of coal-fired power plants are located; most operate in Mpumalanga province.

The reuse of water is low – it accounts for only ~14% of total water use, mostly through waste water returned to rivers for downstream use. Little MWW is currently utilised. Consequently, water reuse is regarded by the government as an important strategy to balance availability with requirements in the future. The Department of Water Affairs (DWA), now the Department of Water and Sanitation, produced a *National Strategy for Water Re-use*, published in June 2011, to encourage informed decisions about water reuse. The strategy is included as an annex in the second National Water Resources Strategy (NWRS2). A key priority in NWRS2 is water conservation (DWA, 2013).

An incentive-based regulation system (Green Drop) was introduced in 2008 to improve the management of waste water quality as many treatment plants were (and still are) not complying with the relevant effluent quality standards; they were releasing raw sewage into the country's rivers. The 2014 Green Drop progress report (Department of Water and Sanitation, 2016) found that the 824 municipal plants assessed treated a total of 5000 ML/d of waste water or 1825 GL/y (*see* Table 2). The total excludes the flow from the 450 plants that do not report or measure their operational flows. However, about a quarter of these plants (212) are in a critical state, whilst 259 are at high risk and 218 at medium risk. Only 135 plants (~16%) were categorised as low risk. The poor performance of the majority of the plants is mainly due to poor maintenance, and lack of funding and qualified staff.

Table 2 MWW treatment plants (Department of Water and Sanitation, 2016)

	Micro size, <0.5 ML/d	Small size, 0.5–2 ML/d	Medium size, 2–10 ML/d	Large size, 10–25 ML/d	Macro size, >25 ML/d	Undetermined	Total
Number of plants	168	269	232	65	62	28	824
Total design capacity, ML/d	37.55	256.88	1019.73	939.90	4178.30	28 plants	6432.36
Total daily inflows, ML/d	9.39	85.43	485.65	496.05	3923.06	450 plants	4999.58

Over 80% (669) of the municipal plants treat less than 10 ML/d, and so could not produce the amount of water required by a power plant cooling system to make it economically worthwhile. In addition, the majority of coal-fired power plants are located at or near coal mines, away from the metropolitan areas, making MWW transport expensive and impractical. Most large coal power plants are operated as zero effluent discharge facilities, and therefore recycle treated sewage effluent generated on-site. It is used to supplement river water in the cooling system or for other purposes.

MWW is utilised for cooling purposes at three power plants, which were, or are, owned by the municipality. The Kelvin power plant is supplied with water from the Northern Works in Johannesburg. The City of Tshwane, a metropolitan area that includes Pretoria, provides chlorinated MWW to the Rooiwal and Pretoria West power plants. The former uses 8.6 ML/d in the closed-loop towers pumped from the Rooiwal waste water treatment plant. The treatment plant currently reuses nearly half of its treated waste water; it also has a long standing operational agreement that the neighbouring farmers must get 8 ML/d (Department of Water and Sanitation, 2015). The Baviaanspoort treatment plant supplies the Pretoria West power plant.

2.2.4 USA

The USA is the third most populous country (after China and India), with a population of over 321 million at the end of 2015 (*see* www.census.gov/popclock/), and is the world's third largest water user. Water availability is becoming an important issue with the growing demand for water and energy, and the increasing prevalence of droughts and heat waves in some parts of the country. A report by NETL found that 347 coal-fired power plants, out of an analysis set of 580 plants, are located in areas subject to water stress, that is, with limited supply and/or competing demand from other sectors (Elcock and Kuiper, 2010). About a third of the vulnerable plants are situated in the southeast. Even in areas with relative abundance, the water may already have been fully allocated, and therefore is unavailable for future coal-fired power plants.

An estimated 115–150 GL/d of waste water is treated in the USA, making it a plentiful source that is widely distributed (Stillwell and Webber, 2014). Of course, in many areas treated MWW is already in use for maintenance of stream flows, irrigation and other purposes, and may not be available to local power plants. The National Research Council (2012) estimated that some 45 GL/d of the 121 GL/d of MWW discharged nationwide in 2008 could be beneficially reclaimed and reused. This was the amount discharged to an ocean or estuary, and therefore would not be needed by downstream cities that rely on the discharges to augment their water supplies.

An analysis published in 2009 found that nearly 50% of the 407 existing coal-fired power plants have sufficient MWW available within a 16 km radius to meet their cooling water needs, and 75% have sufficient available within a 40 km radius. It was assumed that all the power plants had wet towers. Of the 110 proposed plants (proposed in 2007), some 81% could meet their cooling water needs within the 16 km radius and 97% within 40 km (Vidic and others, 2009).

Figure 1 shows the location of coal-fired power plants in relation to publically-owned municipal water treatment plants that treat over 3785 L/min (5.5 L/d). It shows that the majority of power plants are situated near to a MWW source. The corresponding internet-based geographic information system catalogue, the 'Alternative Water Source Information System' was posted on the internet in 2011 (*see* www.all-llc.com/projects/coal_water_alternatives/). It provides data on the location and volume of MWW within a 24 km radius of existing coal-fired power plants (Arthur, 2011). There are no plans to update the database, and it is only searchable using older versions of Internet Explorer or other browsers, such as Firefox.

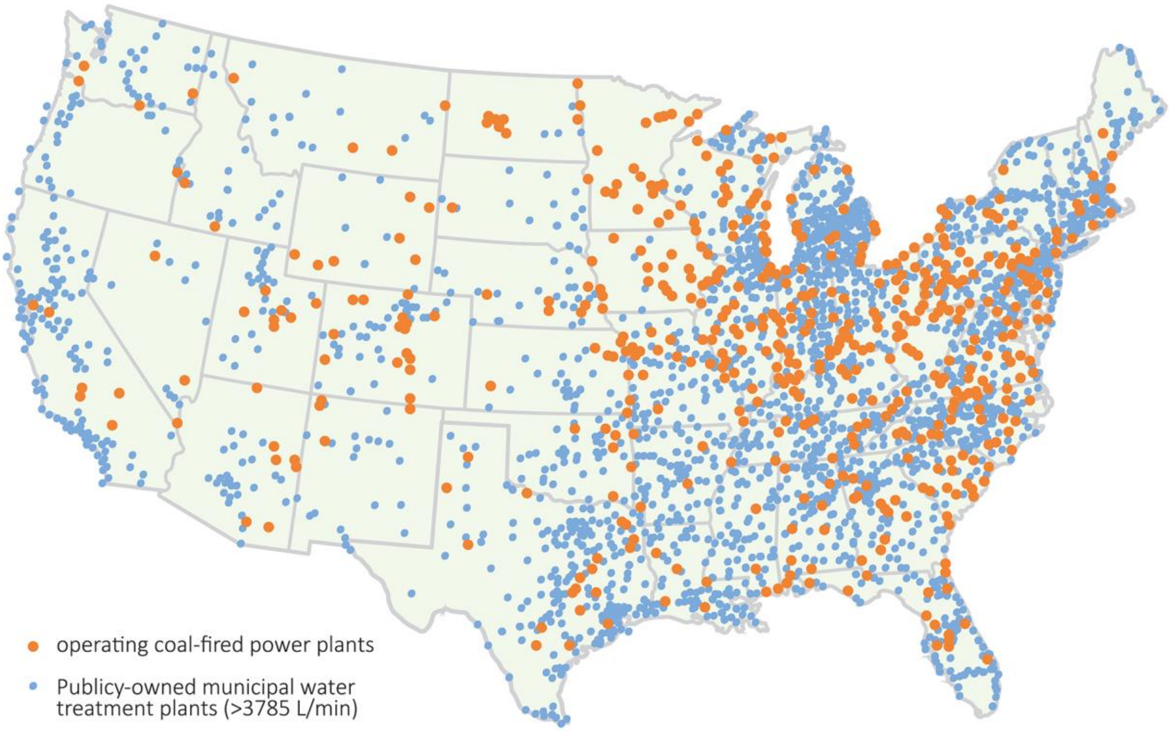

Figure 1 Location of publically-owned MWW treatment plants and coal-fired power plants (from http://www.all-llc.com/projects/coal_water_alternatives/page.php?13#potw)

A later 2013 assessment of MWW and shallow brackish ground water resources found that while neither resource on its own could meet the future demands of thermal power generation, they could significantly augment existing fresh water supplies (Zemlick and others, 2013). Tidwell and others (2014) report that the availability of MWW is sporadically distributed across the drier western states, with the highest availabilities associated with metropolitan areas. But it did tend to be available in watersheds with limited water supply. However, competition from other water users, such as agriculture, could constrain supplies in the future. Sandia National Laboratories is currently developing a water atlas which will include estimates of MWW availability, cost and future demand at the watershed level for the lower 48 states (*see* http://www.netl.doe.gov/research/coal/project-information/proj?k=FWP-14-017626). Availability and cost for 17 western states can be found at http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/water-availability-cost-and-use/.

MWW is the most used alternative water supply at US thermal power plants, with around 5% of the 1709 existing cooling systems currently using it. The number is increasing as 25% of the proposed 60 systems scheduled to come online between 2013 and 2022 plan to utilise this source (Bauer and others, 2014). Most of the power plants using MWW are in states with fresh water shortages, such as Florida, California, Texas and Arizona. Arizona currently uses some 256 ML/d and California 86 ML/d at power plants (Maupin and others, 2014). Stillwell and Webber (2014) found that sufficient resources exist within 40 km to supply an additional 92 power plants in Texas, potentially saving over 1135 ML/d of fresh water. The total cost of retrofitting these plants to enable waste water cooling is estimated to be US$151 million/y, the bulk of which is due to on-site treatment of the waste water. Many of the plants are located in areas with highly or moderately constrained water resources. Consequently, using MWW could be an effective water management strategy.

What is required when designing, developing and operating an optimal and adaptable system for MWW reuse in power plants is outlined by Pack and Brindle (2012). This includes the need for a compilation of best practices for MWW reuse, and technology guidelines to encourage power plant operators to use this source. According to Federal regulations, all MWW must be treated to secondary standards before it can be released from the treatment facility (EPA, 2012). Water reuse standards are the responsibility of the states. State regulations or guidelines can include restrictions on the quality of the reclaimed water that can be used for cooling. These generally focus on protection of public health and the environment. Power plant operators in these states may have to obtain a permit before they can use MWW and will need to meet the regulations. The Environmental Protection Agency's 2012 Guidelines for water reuse (EPA, 2012) provides an inventory of state regulations and guidelines, and describes MWW reuse in the USA and elsewhere. It discusses waste water treatment, the funding of water reuse systems, and includes case studies (such as MWW usage at power plants). Water ownership and right of use could complicate the use of MWW if interstate or interbasin transfer is involved (Li and others, 2011).

One plant utilising MWW is the 717 MW Cherokee coal-fired power plant, near Denver, Colorado. Historically, the 393 million m^3/y of water used for cooling came from nearby rivers. Today, Cherokee uses multiple sources to provide a diverse, reliable and affordable water supply. This includes up to 227 million m^3/y of MWW from the Denver Water Recycling Plant located ~0.8 km away. The Denver Water Recycling Plant purifies secondary effluent from the Metro Wastewater Treatment Plant using a biological aerated filter to nitrify ammonia, followed by conventional drinking water treatment to remove high phosphorus and turbidity. Unit processes in this treatment train include coagulation, flocculation, sedimentation, filtration and disinfection. The treated waste water is transported to the power plant, where it is mixed with raw water in the large reservoir before feeding it to the cooling towers; bleach is added as a biocide. Blowdown from the cooling tower is treated before discharge to the nearby river. In 2012, Cherokee was paying US$0.29/$m^3$ for the waste water, and a monthly service charge (Holmquist and Higham, 2012).

The Polk Power plant in Mulberry, Florida, is situated in an area with depressed aquifer levels, which has caused salt water intrusion, reduced river flows, and lowered lake levels. Tampa Electric entered into a partnership with the city of Lakeland to use MWW to offset its ground water use. The company also recognised that it would need additional water for its expansion plans. Lakeland already uses some of its MWW for cooling purposes at the McIntosh power plant (18 ML/d in 2010). A 24 km pipeline was built by Tampa Electric to transport the waste water from Lakeland's wetland treatment system to the power plant, where it is treated in a three-stage process, namely, settling and clarification, gravity flow filtration, and reverse osmosis. The clean water is then used for cooling, and the waste water from the treatment process is injected deep underground. Initially, some 19 ML/d will be transported and treated, with the capability of increasing to 64 ML/d. Tampa Electric will receive the water at no cost for at least the first 20 years, saving $4 million in water charges it would have paid. The $120 million project was co-funded by the Southwest Florida Water Management District ($45 million), and fully commissioned in March 2015. All of Lakeland's MWW is now beneficially reused, and the project has the additional benefit of cleaning up Tampa Bay by diverting the previously discharged MWW. It also allowed Lakeland to obtain a rare 20-year water permit to use additional ground water for drinking as the city grows. A second phase is to transport MWW from the Polk County (initially some 4 ML/d) and city of Mulberry (initially some 2 ML/d) treatment plants to the power plant; this phase is scheduled for completion in 2017 (Ramoy, 2012; Tampa Electric, 2015).

The Brandon Shores power plant in Maryland uses MWW as make-up water for the wet limestone FGD system (Peltier, 2010). A tertiary water treatment facility was constructed that includes settling and clarification, chemical treatment and biological treatment for nitrogen reduction, as well as ultraviolet disinfection. The process can clean up to 18,170 L/min during peak use (*see* http://www.bowenengineering.com/portfolio/948/).

2.3 Comments

MWW is generally plentiful in urban areas and could provide a drought-resistant source for thermal power plants situated near to municipal treatment facilities. There is certainly potential for more power plants to use this source, especially in China and India where many municipal plants are non-operational or under-utilised for various reasons. More efficient operation of these facilities would increase the amount of MWW available, as well as conserving fresh water and mitigating water pollution. Human health concerns over the possible emission of bacteria and other trace contaminants in the aerosols can be minimised with proper control and management of power plant cooling operations. Operational problems associated with the use of MWW (such as corrosion, scaling and biofouling) can be controlled with adequate water treatment. The treatment costs will be site-specific. Both power plant operators and municipalities can benefit financially and environmentally from the reuse of MWW. However, there is a lack of data on its availability, quantity and quality – there appears to be no single organisation in any country that collects this information.

3 Brackish water, sea water and desalination

Brackish ground water provides an important water resource for nearby inland and coastal coal-fired power plants, whereas sea water could supply the needs of coastal power plants. Both brackish and sea water can be used directly (with minimal treatment) for cooling purposes instead of fresh water, provided the plant is designed for its use. However, desalination is required to supply their fresh water needs, such as boiler make-up water. This chapter discusses brackish and sea water resources before describing the main desalination processes, and the integration of power plants with desalination plants. Integration can bring economic, ecological and other benefits.

3.1 Brackish water

Nearly 1% of the world's water exists as brackish or saline ground water (National Research Council, 2008). The definition of brackish and saline water varies, and is not always clear. According to the US National Ground Water Association, brackish water contains between 1000 and 10,000 ppm of TDS (salts), compared to over 35,000 ppm for sea water. Saline water commonly refers to any water having a TDS concentration greater than 1000 ppm, and includes the brackish concentration range; it is further classified as slightly, moderately or highly saline (*see* http://www.ngwa.org/media-center/briefs/documents/brackish_water_info_brief_2010.pdf).

Brackish ground water (and even brackish surface water) is an important resource for coal-fired power plants in water-scarce regions. It can provide a reliable and secure water source, although long periods of droughts could affect its availability. Some 183 billion m^3 of saline water (with a TDS content of over 1000 ppm) was withdrawn in the USA in 2010, about 14% of the total water withdrawals. Most of it was sea and brackish coastal water used for thermal power. Florida withdrew the most, accounting for 18% (Maupin and others, 2014). Overall, the highest percentage of brackish water withdrawals is by the northeast states and Texas, whereas the drier southwest states and Texas withdraw the most saline water (*see* Figure 2).

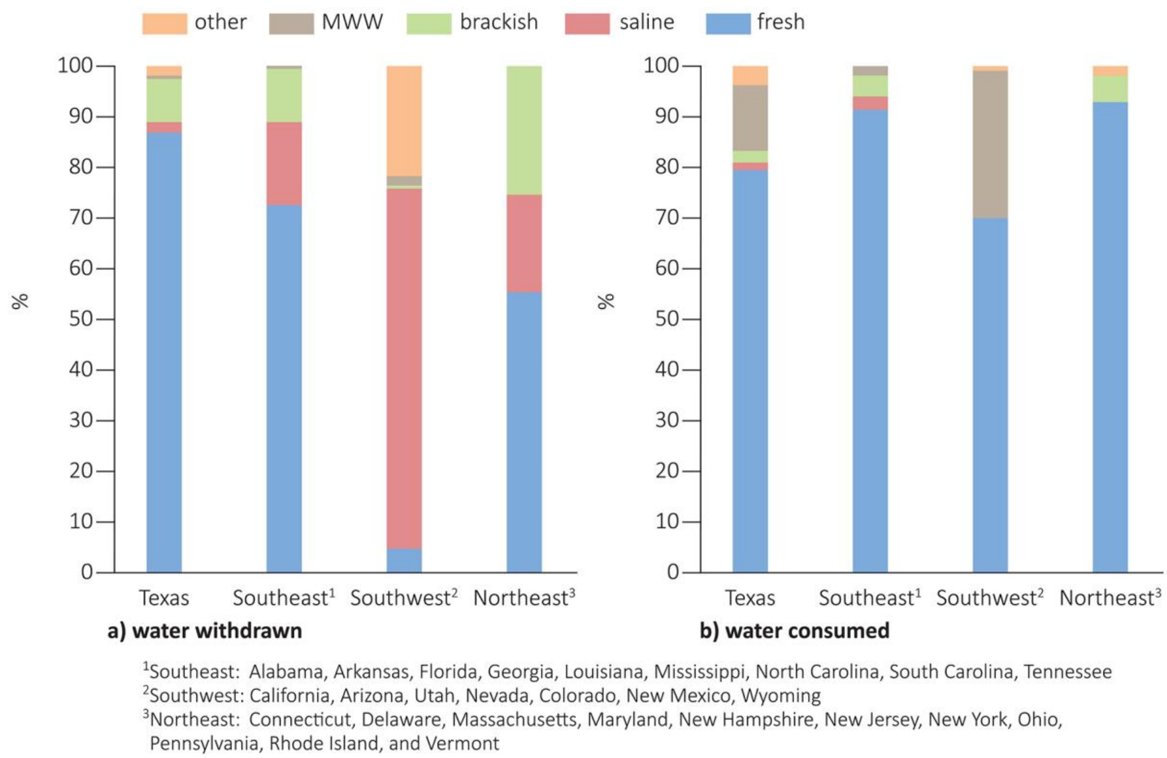

Figure 2 Percentage of water withdrawn and consumed at thermal power plants by water type in four regions of the USA (Bauer and others, 2014)

Data on countries' brackish water resources is poorly documented. National compilations of the distribution, quantity and quality of this source could potentially allow its greater utilisation and provide a better basis for policy decisions. The US Geological Survey is currently conducting a national assessment (*see* http://water.usgs.gov/ogw/gwrp/brackishgw/). Sandia National Laboratories is developing a water atlas which will include estimates of shallow brackish ground water availability, cost and future demand at the watershed level for the lower 48 states in the USA (*see* http://www.netl.doe.gov/research/coal/project-information/proj?k=FWP-14-017626). The relative availability and cost of using shallow (no deeper than 760 m) brackish ground water (with a salinity between 1000 and 10,000 ppm of TDS) have already been mapped for over 1200 watersheds in 17 western states. Deeper and higher salinity water would generally be very expensive to exploit. Brackish ground water underlies around 70% of the country. It is available throughout much of the west, except in the northwest. The highest availabilities are in Arizona, New Mexico and Texas, where detailed studies have been conducted. However, mapped availability is more an indication of what is known and currently used, rather than an indication of the actual resource in the ground (Tidwell and others, 2014). Availability and cost of brackish ground water for the 17 states can be accessed at http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/water-availability-cost-and-use/.

Annual brackish ground water resources are estimated to be some 20 billion m^3 in China, although not all may be exploitable (Gao and Liu, 2011). The water is widely distributed across the country, especially in the drought-prone north, northwest and coastal areas. The quantity, quality and sustainability of ground water in India is being mapped in the National Project on Aquifer Management under the auspices of the Central Ground Water Board (*see* http://cgwb.gov.in/Aquifer-mapping.html). Shallow (within a 500 m depth) saline and brackish ground water occur in many of the water-stressed states in India, including the inland and coastal regions in the northwest and southeast, and coastal regions in the east (Central Ground Water Board, 2010; Mukherjee and others, 2015). South Africa is relatively poorly endowed with ground water. There are areas of natural salinisation due to the geology, including western and southern parts of the Western Cape; but there are no coal-fired power plants in this region. Maps of its aquifers and ground water quality are available at https://www.dwa.gov.za/Groundwater/ACSA.aspx.

A rise in sea levels could increase the salinisation of coastal aquifers worldwide, increasing the volume of available saline water. Pollution is also raising the salinity of ground water in regions across the world. However, thermal power plants could face increasing competition for limited supplies from other users (such as agriculture, and the oil and gas industry) in some areas, especially as aquifers become over exploited.

Withdrawing more brackish water than can be recharged may deplete the ground water resource, create subsidence, increase salinity (in coastal aquifers) or affect the quality and quantity of adjacent water bodies or aquifers. Since the hydrology of ground water, lakes, streams, and wetlands are frequently interconnected, the removal of water from one source means less water for one or more of the other sources. In addition, withdrawal from brackish water sources can stress slowly replenishing aquifers.

The chemical composition of brackish and saline water varies depending on its hydrogeological origin. In most inland cases, ground water salinity results from the dissolution of minerals present in the subsurface. Brackish water in coastal aquifers is created from the natural mixing of sea water with ground water that is discharging to the ocean. Thus the cost of desalination depends on the location. Less energy is required for desalination of brackish water than sea water because of its lower salinity. But inland desalination projects have fewer waste brine and sludge disposal options than coastal plants, and hence brine management (*see* Section 3.3.2) may be more costly for these plants. The US Brackish Groundwater National Desalination Research Facility (*see* http://www.usbr.gov/research/AWT/BGNDRF/) is one organisation that is developing technologies for the desalination of inland brackish ground water.

3.2 Sea water

Sea water constitutes a relatively infinite resource. China, India, South Africa and the USA all have long coastlines and hence available sea water. A number of thermal power plants in these countries already use sea water for cooling and for desulphurisation of flue gas. New power plants are being built on the coast in China and India to allow sea water cooling systems to be employed. However, discharge of the warm water can adversely affect the local marine ecosystem. This could be alleviated by employing closed-loop cooling systems (Bauer and others, 2014). Fresh water requirements could be met by desalination of sea water.

3.3 Desalination

Desalination has been carried out at commercial scale for decades. Capacity has increased significantly over the last 20 years as countries try to augment fresh water supplies, and is expected to continue to grow as technology developments lower energy consumption and costs. Desalination consumes at least 75.2 TWh/y, or about 0.4% of global electricity consumption (WWAP, 2014a). As of June 2013, there were some 17,277 desalination plants worldwide, with a production capacity of 80.9 million m^3/d (Chen and Zhang, 2014). About two-thirds of the world's capacity is processing sea water, and a third brackish water. Desalination of sea water can supply the fresh water needs of coastal power plants, whereas desalination of acid mine drainage (*see* Section 4.1.2), other saline mine and industrial effluents, or brackish ground or surface water could potentially supply the requirements for nearby inland power plants. This could also turn water pollution liabilities into a water resource as desalination technologies not only remove salts from water, but also other pollutants such as metals, nutrients and organics.

3.3.1 Policy

Desalination is seen as an important option in China for securing alternative water resources to ease its mounting water crisis. The 12th Five-Year Plan for Desalination (*see* http://www.sdpc.gov.cn/fzgggz/hjbh/hjjsjyxsh/201212/t20121225_520021.html) set a target of at least 2.2 million m^3/d of online capacity by 2015. This is due to rise to over 3 million m^3/d by 2020. If achieved, this would place China alongside the world's desalination leaders, Saudi Arabia and Israel. The powerful National Development and Reform Commission has been delegated with the task of spearheading the development of the desalination sector to ensure that it meets its targets. Energy consumption and unit costs for desalination are scheduled to fall by 20% by the end of 2015 (Patterson, 2014). Even if this target is achieved, the increased demand for power by the desalination industry to produce 3 million m^3/d of water will be difficult to meet.

The country's 103 sea water desalination plants were producing just over 0.9 million m^3/d of fresh water at the end of 2013 (Patterson, 2014). The desalinated water is supplied mainly to municipal users and the power industry. Desalination plants at coal-fired power plants are among the top 10 largest desalination plants (capacities 14,400–100,000 m^3/d). This is partly due to the policy that requires new power plants in coastal regions to use sea water desalination to supply their fresh water requirements. Total unit costs for nine desalination plants ranged from RMB4.3 to 6.3/m^3 of water (Zheng and others, 2014).

Desalination has also been recognised by the Indian Government as an important means of augmenting water supply to meet growing demand in its 12th Five-Year Plan (*see* http://planningcommission.nic.in/plans/planrel/fiveyr/welcome.html) and 2012 National Water Policy (*see* http://wrmin.nic.in/forms/list.aspx?lid=1190). Among the aims of the National Water Mission is to promote desalination of brackish and sea water, and develop desalination technologies (Ministry of Water Resources, 2011). This includes the use of low grade heat from power plants in the desalination facility. A number of district administrations, such as the one in Tuticorin, have asked industries in their area to install desalination plants so that water allocated to them can be diverted for domestic use. Hence a 10 ML/d reverse osmosis desalination plant is planned at the 1050 MW (five 210 MW units) Tuticorin power plant in Tamil Nadu (Tamil Nadu Generation and Distribution Corp Ltd, 2015).

There are around 1100 desalination plants in India, with capacity predicted to grow at a compound annual growth rate of 22% over the next five years (Kinny, 2014; Sharma, 2014). Gujarat has the highest desalination generation capacity in the country, followed by Tamil Nadu; both of these states are water-scarce (Kinny, 2014). Prices have been decreasing over the last few years, with desalinated water costing around Rs55–60/1000 L or 5.5–6 paise/L depending on the type of technology, capacity of the plant, location and cost of electricity (Sharma, 2014). The prices include the finance, plant, operating and maintenance, and all other overhead costs. Water costs just 2 paise/L from the Nemmeli sea water desalination plant in Chennai, Tamil Nadu. The plant cost Rs533 crore to build and reached full generating capacity in December 2013 (Madhavan, 2014).

Desalination is likely to play an important role in future water security for South Africa. It is one of the strategies recognised in the revised National Water Resource Strategy (NWRS2) for ensuring a sustainable water balance. In May 2011, the Department of Water Affairs published a National Desalination Strategy, which describes a strategic approach to the planning, development and implementation of desalination for water reuse, and as an additional water resource (DWA, 2013). Eskom, the state-owned utility, employs desalination to treat mine water (*see* Section 4.2.3) for reuse at the Tutuka and Lethabo power plants, and for zero liquid effluent discharge. Sea water cooling is used at only one plant, the Koeberg nuclear power plant. Desalination of waste water for use at new wet-cooled power plants could be a cost effective solution in the water-stressed Waterberg area instead of employing dry-cooled plants, where water savings come at the detriment of a lower thermal efficiency. The savings in thermal efficiency could compensate for the energy costs of pumping and desalinating either sea or waste water; that is, on a R/MWh basis, a wet-cooled plant using desalinated water could be cost and carbon equivalent to a dry-cooled plant (The Green House, 2013a).

Prices are decreasing, with reverse osmosis membrane technology costing R6–10/m^3 of water, or less in some circumstances (The Green House, 2011). However, escalating electricity costs could be a deterrent due to the energy requirements. The use of renewable energy sources, such as solar and wind energy, to power desalination plants is under investigation. The development and commercialisation of desalination technologies in niche markets (such as mining and industrial waste water) will be supported by the government as South Africa aims to become an international leader in the field (DWA, 2013).

There is no national desalination policy in the USA, although there are federal initiatives to support it. For example, a national *Desalination and Water Purification Technology Roadmap* was developed in 2003 and updated by Sandia National Laboratories in 2010 (*see* https://www.usbr.gov/research/AWT/s_t_publications/Desalination%20Implementation%20Roadmap%201-26-2010_c_web.pdf). It identified the research and development needs of desalination. States control the decision making and regulations on desalination, including the administration of federal regulations. For example, desalination forms part of California's Water Plan (*see* http://www.waterplan.water.ca.gov/cwpu2013/final/index.cfm). The Plan also covers the legal and regulatory framework of desalination. There are over 2000 desalination plants in the USA (Leven, 2013). They are mostly of small capacity and produce desalinated water from ground water for industrial uses. This is changing with the building of some large municipal sea water desalination plants.

3.3.2 Processes

Commercial desalinisation processes can be categorised into four main groups:

- membrane processes, such as reverse osmosis (RO), where the saline water is passed through semi-permeable membranes to filter out the dissolved solids;
- thermal distillation processes where the saline water is heated to produce a vapour, which is then condensed. Processes include multi-effect distillation (MED), multi-stage flash distillation (MSF), mechanical vapour compression (MVC) and thermal vapour compression (TVC);
- ion exchange processes in which the saline water passes through an ion exchange resin bed or column. These processes are typically used where very low salinity water is required, such as for boiler feed water. They are generally only economic when a small amount of salt needs to be removed, and so are used as the final 'polishing' step. They have also been used to treat brackish water; and
- hybrid processes, which involve a combination of thermal distillation and membrane techniques in a single unit or in sequential steps. Examples include membrane distillation (MD), and RO combined with MSF or MED processes.

A number of power plants use desalination to supply their fresh water needs. The following discusses the principal technologies that are used in conjunction with coal-fired power plants. The strengths and weaknesses of various desalination processes are outlined by Bauer and others (2014).

Reverse osmosis

Reverse osmosis is the most widely used process to treat sea and brackish water. It involves mechanically forcing the feed water under pressure through semi-permeable membranes that restrict the passage of dissolved salts. The feed water needs to be pre-treated, which involves filtering the water to remove suspended solids, and adding chemicals to prevent fouling and blockage of the membrane surfaces. The pressure requirements of a RO system increase with water salinity, resulting in higher electrical consumption. The use of high-efficiency energy recovery devices that recover the pressure energy in the RO concentrate stream reduces energy consumption. Energy demand for sea water RO (SWRO) with energy recovery is between 3.5 and 5 kWhe/m^3 of water (Gude, 2015a), although lower figures have been quoted in the literature. However, RO only requires electricity to operate, making it less energy-intensive overall than MSF and MED. Regular cleaning of the membranes is essential, and the service life of the membranes is limited. Recovery (that is, permeate produced divided by the feed water flow rate) is typically between 30% to 60% for sea water, and 50% to 80% for brackish water (Bauer and others, 2014). Co-locating SWRO facilities by existing power plants can take advantage of the warmer sea water available from the plant's cooling water discharge to increase the desalination process efficiency. This is done at the Tampa Bay desalination plant in the USA (*see* Section 3.3.3).

One power plant using a RO system is the 4620 MW Mundra power plant at Gujarat, India. Sea water is used in the closed-loop cooling tower and as the absorbent in the FGD system. The RO plant produces 47 ML/d of fresh water for boiler make-up and other purposes (Bana, 2014). The sea water is pre-treated in lamella clarifiers and two-stage pressure filters with dual media and sand filters, before it is fed to the SWRO units. Part of the desalinated water is further treated in a RO system for boiler feed make-up. The concentrated brine is discharged back into the sea (Aquatech, nd[a]).

Multi-stage flash distillation

MSF distillation uses a series of chambers, or stages, each with successively lower temperature and pressure, to rapidly vaporise ('flash') water from the saline source. The vapour is condensed by tubes containing the inflowing feed water, thereby recovering energy from the heat of condensation. Each stage is essentially a counter-current heat exchanger. The number of stages used is directly related to how efficiently the system will use and reuse the heat with which it is provided. A typical MSF plant can contain from 4 to about 40 stages. Low grade heat (steam) from an adjacent power plant can supply the thermal heat for the process. Energy consumption is higher than MED and RO. But MSF has a longer life, greater reliability, and lower water quality requirement (less pre-treatment) than RO (Deng and others, 2010).

Multi-effect distillation

The MED process uses multiple vessels (called effects) connected in series, each maintained at a lower temperature than the last one. Because the boiling point of water decreases as pressure decreases, the vapour boiled off in one vessel can be used to heat the saline water in the next one, and only the first one (at the highest pressure) requires an external source of heat, such as waste heat from a power plant (*see* Section 3.3.3). The final vessel uses the incoming saline water to condense the vapour. The highest evaporation temperature is generally below 70°C in the low temperature MED (LT-MED) system. Some plants incorporate thermal vapour compression (TVC) where the pressure of the steam is used (in addition to the heat) to improve the efficiency of the process, and reduce the costs of water production. Power consumption is typically lower than MSF distillation. MED is characterised by high heat transfer efficiency, low pre-treatment requirement (generally simple screening and chlorination), simple operation, and high reliability; but capital costs are higher than for RO (Chen and Zhang, 2014; Daniels, 2012).

Cohen and others (2001) calculated that the waste heat of flue gases upstream of a wet FGD system in a 575 MW power plant could be used in a sea water MED facility to generate 8500–10,000 m^3 of treated water. Moreover, a significant amount of water would be saved at the power plant due to the reduction of the flue gas temperature and therefore, lower water evaporation in the FGD scrubbers.

Membrane distillation

MD is a thermally-driven membrane separation process in which only vapour from heated saline water is allowed to pass through a microporous hydrophobic membrane. The vapour is then condensed and the fresh water collected. The process operates at atmospheric pressure, and typically at temperatures below 70°C (the feed water only needs to be evaporated and not boiled), and can be driven by a 10–20°C temperature difference between the hot and cold solutions (Drioli and others, 2015; Gude, 2015b). Low grade heat from power plants could provide the required heat for the process. MD is simple to operate, uses no chemicals, and has a high product recovery. It needs less energy input than RO and MSF since it operates at atmospheric pressure, and is not subject to the osmotic pressure driven limitations of RO (Morrow and others, 2011). Less expensive membranes than those for RO can be employed because of the lower operating pressure. Plastic membranes, for example, will alleviate corrosion problems (Alkhudhiri and others, 2012). Scaling, fouling and wetting of membranes can still occur, and the heat lost by conduction can be quite large. Recent advances in MD technology, and the variety of configurations being developed, are reviewed by Drioli and others (2015) and Wang and Chung (2015).

Morrow and others (2011) calculated that 168 kg/s (13,892 L/min) of treated water could be produced in a coal-fired supercritical 550 MW (net) power plant by incorporating MD units between the steam condenser and cooling tower. The waste heat removed during low pressure steam condensation by the cooling water system is used to heat brackish water from 21°C to 32°C before it enters the MD unit. This system is the largest source of waste heat in a power plant. The produced water is used as make-up in the cooling tower system. Furthermore, the total cooling tower make-up water is reduced from 304 kg/s to 59 kg/s.

All processes

Desalination facilities can have an adverse impact on aquatic life in the area around the intake pipes. Fish and other organisms can get sucked into the pipes or become trapped against the screens that remove suspended solids. There is also the problem of disposal of the concentrated brine solution generated through the treatment process. The solution may contain chemicals, which have been added to control scaling, fouling and/or corrosion. For sea water plants, the concentrated brine is usually discharged back into the sea. If the desalination plant is co-located with a power plant, then the concentrate can be blended and diluted with the power plant discharge or treated waste water effluent before being returned to the sea, reducing the potential for salinity stress in organisms in the receiving water. The impact on the marine ecosystem is also reduced as the discharge temperature is lower.

The disposal of concentrated brine is more expensive for inland plants, even though its salinity is lower than that from treated sea water (a result of the lower salinity of the brackish source water). If it is discharged to surface waters, it can pose risks to aquatic organisms. In addition, the brine may contain a high concentration of toxic contaminants, which can have a serious detrimental effect on human life and agriculture. The concentrate can be disposed of through deep injection wells. Otherwise it could be evaporated in salt fields or treated by freeze crystallisation (*see* Section 4.1.2) to produce saleable salt.

Incorporation of MD into other desalination processes (such as RO and MED) can decrease the amount of brine discharged, as well as increasing water recovery (Wang and Chung, 2015).

The main parameters of RO, MSF, MED, LT-MED and MD are compared in Table 3.

Table 3 Comparison of desalination technologies (Gude, 2015b)

	RO	MSF	MED	LT-MED	MD
Raw water pre-treatment requirement	high	low	low	low	low
Pressure, kPa	2027–6080	101–203	10–51	10–41	atmospheric
Operating temperature, °C	<45	80–-120	50–90	40–70	40–80
Typical fresh water recovery, %	35–50 (sea water) 50–90 (brackish)	35–45	35–45	35–45	not available
Main energy source	electricity	thermal, electricity	thermal, electricity	thermal, electricity	thermal, electricity
Energy needs, kJ/kg	120	200–350	150–250	not available	111
Energy costs, US$/m^3	0.3–0.6	0.35–1.1	0.08–1.15	not available	not available
Capital costs, US$/m^3/d	900–1700	1600–2300	550–2100	not available	not available
Fresh water costs, US$/m^3	0.55–2.37	0.77–1.85	0.87–1.95	not available	0.26-36

Energy consumption and costs have been a barrier to desalination, with around 30% of the cost of water resulting from the energy requirements (for sea water desalination). These are expected to fall with improvements in desalination technologies (including energy recovery) and the development of new techniques. Desalination will also become more cost effective with rising water tariffs. Moreover, integrating power plant operations with desalination can lower production costs for both water and electricity. However, compliance with stricter environmental regulations could increase costs.

3.3.3 Integration of power plant and desalination operations

The co-location of power plants and desalination facilities can have economic and, in some cases, environmental benefits.

Shared intake/outflow structures

The direct connection of the desalination plant intake and/or discharge facilities with those of an adjacent power plant can eliminate the need for separate intake structures, pipelines and screens, and separate ocean discharge facilities. This can bring economic and environmental benefits, such as infrastructure savings, decreased water intake and discharge costs, lower pumping energy, and reduced fish impingement on the intake screens. Furthermore, integrated pre- and post-treatment can reduce energy and chemical consumption. The power plant's discharge flow needs to be larger than the capacity of the desalination plant for co-location to be cost-effective and feasible. It is only feasible for power plants with open-loop (once-through) cooling systems (National Research Council, 2008). But the higher temperature of the cooling water discharge may provide ideal conditions for biological growth on RO membrane modules causing biological fouling.

The Tampa Bay sea water desalination plant in the USA (*see* Figure 3) obtains its source water from the once-through cooling system discharge of the coal-fired Big Bend power plant. Up to 5300 ML/d of sea water is withdrawn and discharged by the power plant, of which the desalination plant removes up to 167 ML/d. The water is 3°C to 8°C warmer than the ambient ocean water. This is a significant benefit because the RO process requires around 5% to 8% lower feed pressure when the influent sea water is an average of 6°C warmer, reducing energy consumption (National Research Council, 2008). If the cooling water is too hot, then the desalination plant can withdraw sea water from the power plant's intake supply. The 72 ML/d discharge from the desalination process is returned to the power plant's discharge system, where it is blended with up to 5300 ML of cooling water. The discharge is then mixed with sea water in the discharge canal to further reduce salinity, and released to the ocean (*see* http://www.tampabaywater.org/tampa-bay-seawater-desalination-plant.aspx). The desalination plant produces up to 95 ML/d of drinking water for the surrounding area.

Similarly, the Claude 'Bud' Lewis Desalination Plant in San Diego County, CA, USA (*see* http://carlsbaddesal.com/), uses the intake and discharge facilities of the Encina Power Plant. The desalination plant, which began operating in 2015, desalinates 379 ML/d of sea water by RO to produce 189 ML/d of drinking water.

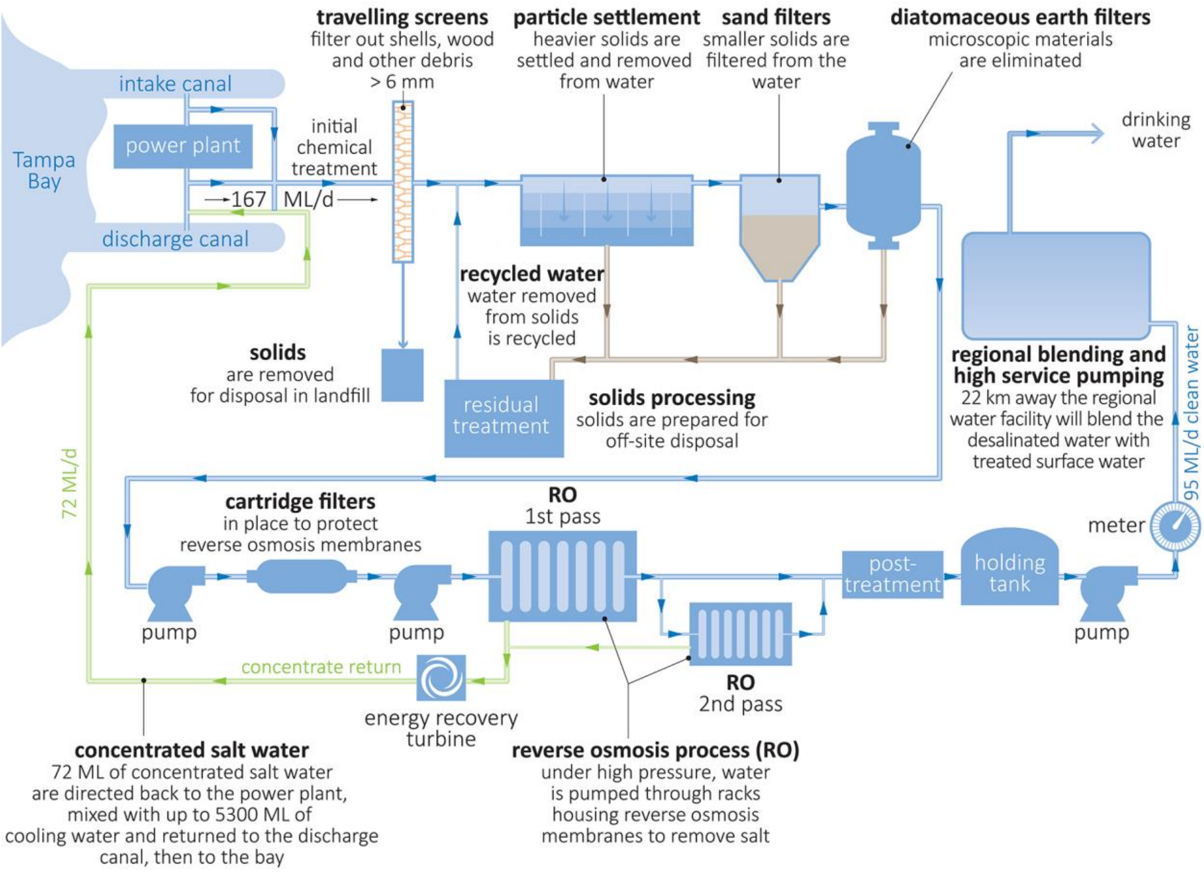

Figure 3 **Tampa Bay desalination plant** (from http://www.tampabaywater.org/tampa-bay-seawater-desalination-plant.aspx)

Tamil Nadu Generation and Distribution Corporation (TANGEDCO) is proposing to build a SWRO desalination plant at its Tuticorin power plant in India that will utilise the power plant's existing intake and outflow structures. This will allow the river water, currently used for cooling, to be employed for domestic and other uses (Tamil Nadu Generation and Distribution Corp Ltd, 2015).

Waste heat utilisation

The majority of the thermal energy needs of a desalination plant employing thermal distillation or MD processes could be met by utilising waste (or low-grade) heat from the adjacent power plant. This improves the efficiency and lowers the electricity and water production costs of the desalination plant. At the same time, it decreases the volume of cooling water required in the power plant. Using desalinated water for boiler feed also lowers the power plant's costs due to its high purity – further softening of the desalinated water is simpler and cheaper, compared to the treatment of traditional water sources (Chen and Zhang, 2014). Moreover, the intake and outflow structures of the power plant can be shared. With suitable design and capacity, excess water could be generated converting the power plant into a supplier of both electricity and fresh water (a cogeneration or dual-purpose power plant). This is widely done in the Middle East. The main disadvantage is that the integrated system is harder to operate due to seasonal variability in electricity demand.

Models for optimising the design of cogeneration plants have been developed, for example, Wu and others (2013, 2014). The latter paper indicated that total annual costs are reduced by 16.1–21.7% when operating a coal-fired power plant integrated with MSF and RO processes compared to separate production units.

Gingerich and Mauter (2015) estimated that the thermal (coal, natural gas and nuclear) power plants in the USA discharged some 18.9 billion GJ of waste heat in 2012, 4% (803 million GJ) of which was discharged at temperatures greater than 90°C. The rest (96%) is condenser heat discharged to the environment at temperatures below 42°C. Further implementation of FGD technologies at coal-fired power plants (with their higher temperature exhaust gases) and the higher quality heat generated in the exhaust of natural gas fuel cycles could increase the availability of waste heat generated by 10.6% in 2040. Some of this waste heat could be utilised in an adjacent desalination plant.

The Tianjin LT-MED–TVC plant at Hanju on the northwest coast of the Bohai Sea is the largest desalination plant in China, with a capacity of 200,000 m^3/d. It consists of eight desalination units, each with a capacity of 25,000 m^3/d. Steam from the adjacent 4 x 1000 MW ultra-supercritical coal-fired Tianjin Beijiang power plant is used to drive the LT-MED process. The desalination plant was designed to operate under a range of steam supply conditions, including varying temperatures and pressures, whilst maintaining full capacity. This is because of load cycling by the power plant. During peak power demand, low pressure steam is extracted from the sixth bleed of the low pressure turbine, at pressures between 0.12 and 0.23 MPa. On the other hand, during peak water demand, medium pressure steam is extracted from the fifth bleed at pressures ranging from 0.6 to 0.31 MPa. These extraction pressures represent a load variance of 100% to 50% in power production over varying power plant efficiencies. Two thermal vapour compressors are employed to handle the wide range of steam pressure for the four LT-MED desalination units built in phase 1, whereas one varying nozzle thermal vapour compressor is used for the other four units built in the second phase. A 'desuperheating' system on the steam lines controls the temperature, which varies from 300°C to 120°C (depending on the pressure).

The temperature of sea water supplied to the desalination plant as feed water can vary between -2°C and 33°C during the course of the year. The plant product and brine streams are used for heating the sea water during cold periods, whilst cooling water from the power plant cooling tower is used during hot periods. The plant was designed to maintain a brine salinity of 6.6% as the brine is evaporated to produce table salt. Discharge of the brine is prohibited since the facility is in an enclosed bay. The water produced is used for boiler make-up, in industrial processes and as drinking water in the local city (Efrat and Yu, 2013; Shemer, 2011). The cost of water for phase 1 (4 x 25,000 m^3/d desalination units) of the project, including operational costs and equipment amortisation, was RMB8/t of water (Levy, 2011). Steam consumption in the four units was about 68.5 t/h and power consumption was 1.3 kWh/m^3 of water (Deng and others, 2010).

Direct sea water cooling is used for all the condensers at Shenhua's Hebei Guohua Cangdong 2520 MW Power Plant, which has four coal-fired units (2 subcritical and 2 supercritical). Desalination provides the ~3.2-4.4 million m^3 of fresh water consumed every year as feed for the boilers, and for desulphurisation and other processes. The two desalination units (12,500 m^3/d and 25,000 m^3/d) currently operating not only meet the needs of the power plant, but also supply fresh water (currently nearly 10 million m^3/y) to other users, helping to alleviate water shortages in the surrounding area. The quality of the desalinated water is higher than other fresh water sources, and consequently, the product offers a price advantage to industrial users.

Steam from the power plant's generator turbine provides the heat source for the LT-MED process (*see* Figure 4). Part of the steam passes through a heat exchanger and into the first stage (effect) evaporator. The rest enters the thermal vapour compressor to increase the pressure of some of the low pressure steam generated through sea water evaporation, and transfers it to the first stage as the heating source. This improves the efficiency and reduces the cost of water generation. The cost of energy is the most important factor influencing the price of desalinated water – it accounted for about 40–50% of the water production costs. Along with about 0.1 t of steam consumed for every 1 m^3 of fresh water produced, some 1.2 kWh is also used in the LT-MED process (Chen and Zhang, 2014).

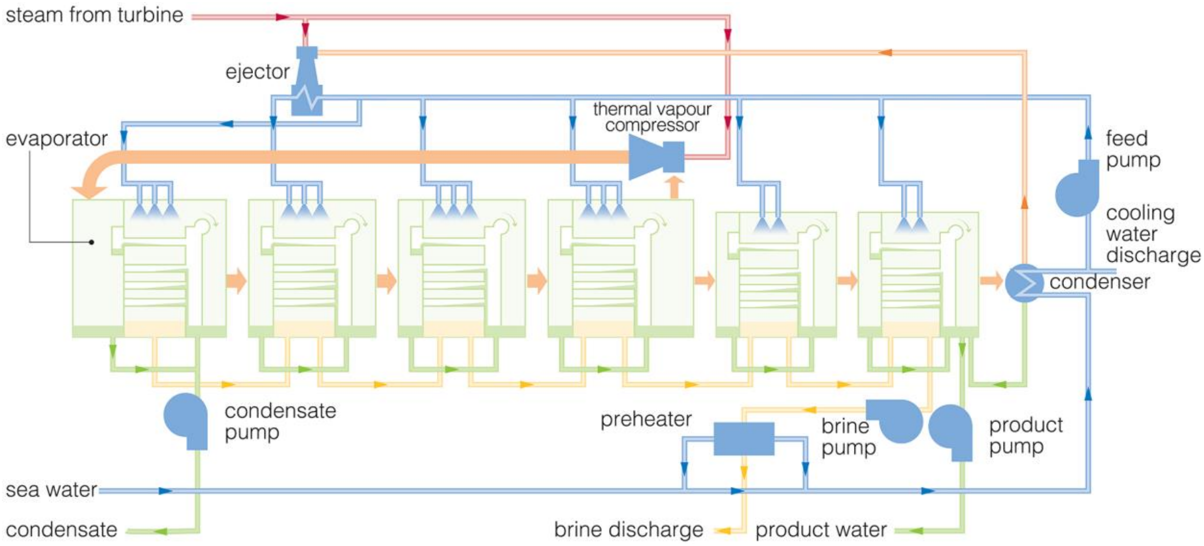

Figure 4 LT-MED–TVC process (Chen and Zhang, 2014)

The National Institute of Ocean Technology in India has developed a Low Temperature Thermal Desalination (LTTD) process, which uses the temperature difference between two bodies of water to flash evaporate the warmer water at a low pressure and condense the resulting vapour with the colder water to obtain fresh water in a single stage process. Waste heat in the warm cooling water discharge from power plants (instead of steam) can be utilised. A 150 m^3/d demonstration plant was commissioned in 2009 at a coastal 600 MW coal-fired power plant in North Chennai, Tamil Nadu. Ambient sea water (at ~27°C) is heated by the power plant condenser discharge to ~36°C before it is flash evaporated and the vapour condensed using the ambient sea water. The resultant fresh water was suitable for drinking purposes and for use in the boilers. Environmental benefits included the reduction of thermal pollution from the release of discharge water to the sea, and no discharge of concentrated brine solution at high temperatures (Press Information Bureau, 2010; Venkatesan and others, 2013). A second 2 ML/d (2 x 1 ML/d units) demonstration plant is being constructed at the 1050 MW Tuticorin lignite power plant; it is expected to consume ~6 kWh/m^3 of water (Desalination & Water Reuse, 2014; Venkatesan, 2014). The power plant currently uses river water, which is scarce in summer. The cost of a LTTD plant at a coastal power plant is estimated to be Rs400 million when producing 2 ML/d of fresh water (Press Information Bureau, 2012).

Desalination plants could also be integrated with dry-cooled power plants that use air instead of water to condense the steam. Gude and others (2014) suggest using the waste heat in a combined-cycle power plant to drive an absorption refrigeration system (ARS) that maintains the chilled water temperature in a thermal energy storage (TES) tank (*see* Figure 5). The chilled water is used to pre-cool the inlet air to the air-cooled condenser. This will improve the efficiency of the power plant during hot summers (the effectiveness of ambient air cooling decreases with increasing temperature). The chilled water produced in a 500 MW combined-cycle power plant could also meet the cooling needs of a 950 m^3/d MED brackish water desalination plant. Furthermore, the MED is solely driven by the waste heat available in the stack gases, lowering energy consumption. The thermal energy storage system holds any waste heat created by the power plant that is not needed immediately. It is used to maintain the cooling efficiency of the air-cooled condensers during hot days, and enables power plant operation at the rated power, instead of suffering power loss due to increased steam turbine back pressure. Overall, the integrated system enables energy conservation and water desalination at the power plant.

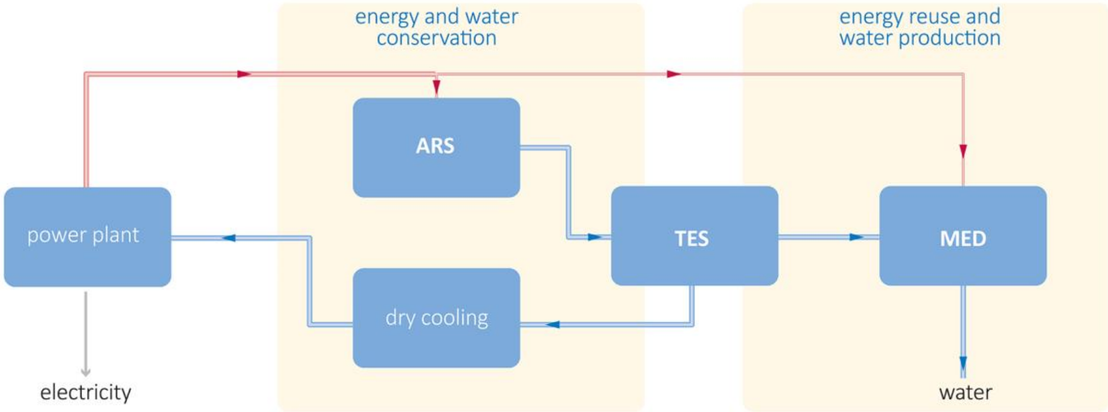

Figure 5 Dual-purpose power-desalination with thermal energy storage (Gude and others, 2014)

A different concept has been proposed by Soto and Vergara (2014) in which a thermal power plant is coupled with an Ocean Thermal Energy Conversion (OTEC) hybrid facility. The OTEC facility uses the temperature difference between surface and deep sea water to generate both electricity and desalinated water. Surface sea water flows through the evaporator of the cycle, providing enough energy to evaporate the working fluid (ammonia). The vaporised working fluid drives the turbine-generator system to generate electricity (*see* Figure 6). The fluid leaves the turbine and is condensed by the cold sea water captured from a depth that is sufficiently cold. Warm water from the power plant condenser discharge heats a second surface sea water stream, which is flash evaporated in a desalination unit. The authors calculated that such a system could enhance power output by 25–37 MW, depending on the season, if incorporated at the proposed Punta Alcalde 740 MW coal-fired power plant in Chile, without adding to the CO_2 emissions. The power plant efficiency would be enhanced by 1.3%. Some 5.8 Mt/y of desalinated water could be produced.

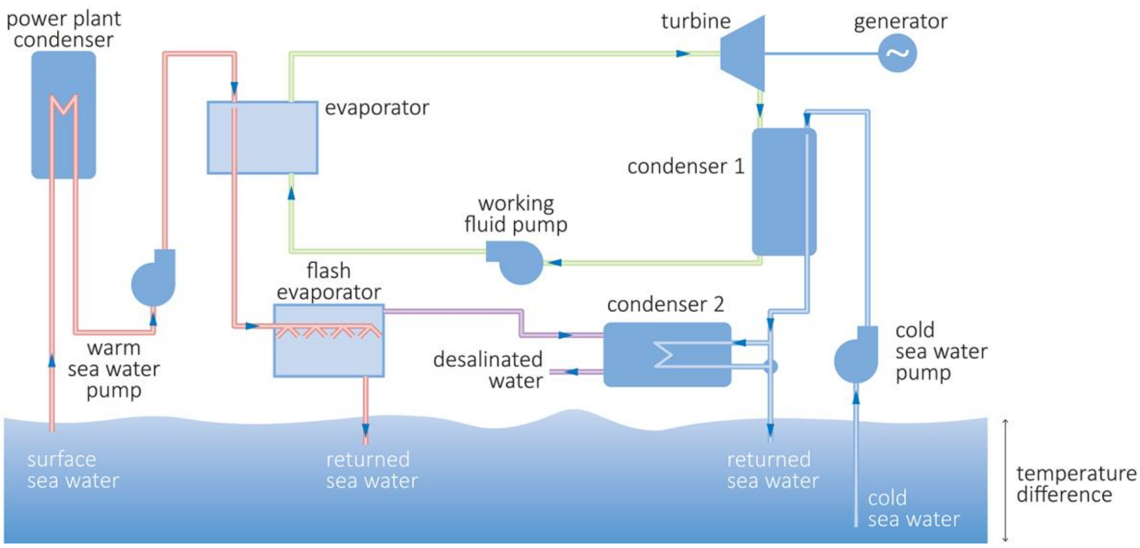

Figure 6 Proposed OTEC cycle using power plant condenser discharge (Soto and Vergara, 2014)

3.4 Comments

The water policy of some countries is likely to see an increase in desalination of brackish and sea water. These water sources can provide a drought resistant, stable and reliable source for nearby power plants, although long periods of drought could affect the availability of brackish water. Better national data compilations on the distribution, quantity and quality of brackish water are needed. This could increase its utilisation, as well as providing a better basis for policy decisions.

Integrating power plants with desalination units has economic and environmental benefits. The majority of the energy needs of a desalination plant using thermal processes can be met by utilising waste or low-grade heat from the power plant. Energy consumption and costs have been a barrier to desalination, but using waste heat would reduce these. Furthermore, the efficiency of the desalination plant is improved, and the volume of cooling water required in the power plants is lowered. The desalinated water can supply the fresh water requirements of the power plant and, if the desalination plant is designed with excess capacity, the power plant can become a co-producer of power and water, instead of a water consumer. Desalination of brackish water could also allow existing power plants in semi-arid and arid regions to continue to use wet cooling systems. But the disposal of the brine concentrate can be problematic, although it could be evaporated in ponds, or treated by freeze crystallisation, to produce saleable salt. Withdrawal of brackish water could put a stress on slowly replenishing aquifers. The main disadvantage is that the integrated system is harder to operate due to seasonal variability in electricity demand.

4 Mine water

Dewatering is necessary when mining below the water table. Water remaining after environmental needs and mine site requirements have been met could provide a source for nearby power plants in regions where such water is abundant and accessible. Whether a mine is a net consumer or generator of water depends on its geological setting. The excess water could be pumped directly to the power plant – coal power plants are often sited at or near coal mines. Otherwise the excess water is discharged (after any necessary treatment) into a neighbouring river for use by downstream plants. When underground mines are closed and pumping ceases, ground water accumulates in the voids left by the mining operations, creating large pools of mine water. These pools could also provide a water source, as could surface mine water filled pits and lakes.

As well as reducing fresh water requirements, utilising mine water reduces or even eliminates acid mine drainage (which pollutes streams, rivers and ground water). Consequently, a water pollution liability can be turned into a resource. Mine water could act as a drought-proof water source for power plants. Furthermore, the cool water from underground mines is not subject to summer heating like surface water, and is therefore a more efficient cooling agent if it can be used without treatment (otherwise it would be exposed to surface temperatures during the treatment process). The main disadvantage is the cost of its treatment. In addition, the withdrawal of significant volumes of water from a mine pool, in excess of the pool's recharge rate, may increase the likelihood of subsidence.

4.1 Viability of use

The term mine water refers to water resulting from dewatering operations, water in surface mine pits, water pumped out of abandoned underground mine pools, and surface runoff from the mine area.

As with other potential water sources, the key factors that affect the viability and cost of using mine water include:

- volume and security of supply;
- quality; and
- location. Transportation costs can be greater than treatment costs (especially if infrastructure has to be built), so unless a power plant is nearby, the use of mine water would be uneconomic.

Moreover, power plants using mine water will need to comply with any relevant regulations. For example, operators in the USA would need to meet the provisions of their National Pollutant Discharge Elimination System permits, as well as any other discharge requirements that may have been made (Munson and others, 2009).

4.1.1 Mine water volume

The amount of water discharged from active mines or taken from abandoned mine pools needs to be sustained at an adequate rate, and over a long enough timeframe, to serve as a reliable source of cooling water for a power plant. If water is withdrawn at a rate significantly higher than the rate of ground water recharge to the underground mine pool, even with a large initial volume, its ability to supply cooling water over a long time period might be jeopardised (Munson and others, 2009). Water may need to be brought in from two or more mine pools to meet the power plant's requirements, increasing transport costs.

Mine dewatering volumes from active mines can vary both in the short and long term, depending on a number of factors. For instance, the amount of ground water flowing into a mine varies at different stages of its development. Water supply could cease when the mine closes and dewatering stops. In some cases, pumping may continue to allow the collection and treatment of mine water in order to avoid pollution of local rivers and ground water through the decanting of mine water.

4.1.2 Mine water quality and treatment

The quality of mine water varies between mines, and over the life of a mine as water is abstracted from different parts and from different depths. Water quality varies within abandoned mines depending on factors such as the length of time the mine has been flooded, and whether or not it has had its first flush. For instance, water quality can significantly improve over time (20–40 years) due to natural attenuation, resulting in little or no treatment being required (Muhlbauer and Fisher, 2015). The initial discharge is generally more acidic if the mine has not had its first flush. Mines in Pennsylvania in the USA that had recently been flooded tended to have higher sulphate levels compared to those that have been static for a longer period of time (Arthur, 2011).

Factors affecting the mine water characteristics include mineralogy of the coal and overburden, quantity of water flowing through the mine and its residence time, availability of oxygen in the water, and the mine design and method of mining (Veil and others, 2003). Mine water is often acidic and can have a high salinity, metals and total dissolved solids content. It becomes acidic from the reaction of oxygen and water with iron sulphide minerals in the coal. The presence of calcareous minerals, such as calcite ($CaCO_3$), can lead to near-neutral pH mine water.

The water needs to be treated before it can be used for cooling purposes and/or as boiler feed water. Generally, acidic water is more expensive to treat then near neutral or alkaline sources. Treatment can include clarification to remove suspended solids, pH adjustment, coagulation, flocculation to remove metals, filtration and desalination (*see* Section 3.3.2). Reverse osmosis (RO) is often employed for desalination (*see* Section 4.2). An overview of selected mine water treatment technologies for use in remediation efforts at mine sites is given in EPA (2014). The review includes both passive and active treatment technologies. Desalination of mine water is less costly than desalination of sea water due to its lower salinity. It may be possible in some cases to dispose of the brine concentrate in an underground compartment of the mine.

Eskom has built a 100 L/d pilot eutectic freeze crystallisation plant at its innovation centre in Gauteng, South Africa, that produces a dry salt cake. This is easier and cheaper to handle than concentrated brine solutions. The process first cools the water to -2°C to remove calcium sulphate, then to -15°C to extract sodium sulphate, and finally to -23°C to remove mixed salts (mainly sodium chloride). RO reject water will be treated in the first trial and acid mine water in the second one. The salt by-products could be sold to offset costs (Gericke and Tamane, 2016).

Bench- and pilot-scale tests of passively treated mine water from an abandoned mine in Pennsylvania, USA, showed that corrosion, scaling and biofouling can be controlled in cooling towers by the addition of suitable chemicals. However, aluminium was not a suitable construction material for cooling systems as severe pitting corrosion occurred (Vidic and others, 2009). Examples of power plants using mine water are covered in the following section.

4.2 Mine water policy, availability and use

This section discusses the availability and use of mine water in China, India, South Africa and the USA, and their policies on its utilisation.

4.2.1 China

China currently has some 14,000 coal mines (Li and others, 2014a). Around 70% are located in five provinces and autonomous regions in the north of the country, namely Shanxi, Shaanxi, Inner Mongolia, Gansu and Ningxia (World Coal Association, 2014a). This area's per capita water resource is just 927 m^3, which is below the United Nation's per capita threshold of 1000 m^3 for water scarcity. During coal mining, ~0.5 t of water is consumed to produce 1–2 t of coal, whilst on average 4 t of water is drained. Overall, coal mining produces ~3–6 Gt/y (3–6 billion m^3/y) of waste water, which includes mine drainage (Li and others, 2014a). Using this source would save a large volume of water. This has been recognised by the Chinese government, which has set a national target to increase the mine water utilisation rate to 75% by 2015. The average utilisation rate was 65% in 2013, up from 59% in 2010 (Thieriot, 2015).

The Water Allocation Plan for the Development of Coal Bases (*see* www.mwr.gov.cn/zwzc/tzgg/tzgs/201312/t20131217_520799.html and http://chinawaterrisk.org/notices/mwr-announces-for-coal-plan/), published by the Ministry of Water Resources in December 2013, requires large coal bases to reach a mine water reuse rate of:

- 100% in water-scarce regions;
- 90% in less water-stressed areas; and
- 80% in water-rich areas.

However, the more recent National Energy Administration's Action Plan for Clean and Efficient Utilisation of Coal covering 2015–20 (*see* http://zfxxgk.nea.gov.cn/auto85/201505/t20150505_1917.htm), released in April 2015, has set lower targets for mine water reuse, namely, 95% in water-scarce regions, 80% in less water-stressed areas, and 75% in water-rich areas (Thieriot, 2015).

The Water Allocation Plan also stated that coal power plants and mines must coordinate water utilisation. New power plants in North China have been given priority access to mine drainage and recycled water. The policy to site new power plants near coal mines in North China will therefore encourage the use of mine water (where possible). It will be more expensive than traditional surface or ground water due to treatment and transport costs.

Power plants have been using mine water for cooling purposes for a number of years, for example, at the Huayu circulating fluidised bed plant in Shanxi province (*see* http://zmsxhy.com/n47/n84/c47508/content.html). Water from the Jining no.3 coal mine in Shandong province is desalinated using electrosorption, and supplied to the closed-loop cooling system of the nearby power plant (Sun and Hwang, 2012).

Wu and others (2010) modelled water management in a coal mining basin in North China (Henan Province). They concluded that the optimal scenario of the twelve studied was to intercept the recharge water going to the upper coal layers of the three mines and use it to supply the planned nearby Jiulishan power plant, rather than other water users.

The Shenhua Group, China's largest coal producer, conserves mine water by storing it underground in the goaf, the space left by the extraction of coal. Water that would otherwise be lost by evaporation is instead available for local power plants, industry, agriculture and municipal users. The natural coal pillar dams are reinforced and connected with artificial dams to provide storage space. The mine water is naturally filtered and purified as it seeps through the gangue, the bed of non-valuable material left behind in the goaf after the coal is extracted. The water, though, still needs some treatment before it can be used. Shenhua established the world's first goaf water storage facility in 1998 that could hold 50,000 m^3 of water. They built the first distributed underground reservoir in Daliuta coal mine in the Shendong mining area in 2010. The four interconnected reservoirs can hold 7.1 million m^3 of water. The company now operates 32 underground reservoirs, with a total capacity of 32 million m^3. Between 2011 and 2013, these reservoirs saved 85 million m^3 of water. More are being built elsewhere in China (World Coal Association, 2014a).

4.2.2 India

In March 2014, India had 536 operating coal mines and 16 lignite mines (Coal Controller's Organisation, 2015). In addition, a number of small coal mines were operating in the state of Meghalaya (the wettest region in the country). Four states (Chhattisgarh, Jharkhand, Odisha and Madhya Pradesh) accounted for some 76% of coal production (excluding lignite). Some of the mines are in water-stressed states, in particular, the lignite mines which are in Gujarat, Rajasthan and Tamil Nadu. Surplus water drained from the coal mines could provide a source for local power plants. The Central Pollution Control Board (2011) provides figures on the amount of water discharged in the areas it surveyed. The water is mostly discharged into local streams or rivers where it is available for downstream users. The amount of water is likely to increase with the Government's plan to double coal production to 1 Gt by 2019 in order to meet its goals of suppling round-the-clock electricity to all Indians and to reduce reliance on imports. Many of the planned new mines are in water-stressed regions.

The Indian government does not appear to have set any targets for mine water utilisation rates, as the Chinese government has done. Ground water use by power plants is not generally allowed. Water policy is under the jurisdiction of the States – the central government can only provide guidance, funding and broad policy frameworks (Carpenter, 2015). Reusing mine water would help to meet the goal of improving water use efficiency by at least 20% that was set out in the National Water Mission (*see* http://wrmin.nic.in/forms/list.aspx?lid=267). Recycling and reuse are important measures for increasing the efficiency of water use.

Few power plants in India currently use mine water. The Neyveli Lignite Corporation is one company that does. It operates three lignite mines and two linked power plants at Neyveli, Tamil Nadu. On average, some 60 million m^3/y of water is used at the power plants, and total water consumption is ~5 m^3/MWh (Kanchan, 2015). Ground water pumped out from the aquifers below the lignite seams that is not reused at the mines is sent to artificial lakes for use in the power plants. Storm water from rain and mine seepage is collected and stored in the mine sumps. Part of the clear water from Mine-I is treated and supplied to the Neyveli Township for domestic use. A second water treatment plant capable of treating 56780 L/min of the collected storm water and mine seepage from Mine-II for use in Thermal Power Station-II, and its expansion, is under construction (Velan, 2013). Clear water from the mines is also supplied to surrounding villages for agricultural activities, thus avoiding some of the need for ground water pumping.

Coal India Ltd has started converting mine voids left from underground mining into water storage bodies (Sengupta, 2015). These will act as potential sources of water for the future. Water treatment costs should be low since, in general, the mine water in India is not acidic, unlike some other countries.

4.2.3 South Africa

There were 64 coal mines operating in South Africa in 2004 (*see* http://www.energy.gov.za/files/coal_frame.html). Production is concentrated in large mines with 11 accounting for 70% of output (Government Communications, 2015b). The majority of these mines are in the Mpumalanga region (Central Basin), which is already experiencing water stress. This is also where most of Eskom's coal-fired power plants are situated. Many of the coal mines in the region are nearing exhaustion. Consequently, new mines will need to be opened in the Waterberg coalfields in northern Limpopo, and elsewhere. Water will have to be brought in to support the development of the Waterberg coalfield and the operation of new coal power plants.

Coal mining uses on average 133 L of water per tonne of coal mined (Pulles and others, 2001). Surface mining requires on average ~160 L/t coal and produces ~1.2 L of liquid effluent/t coal (Wassung, 2010). About 49% of coal is produced by surface mining, whilst the rest comes from underground mining. It has been estimated that 440 GL/d of water from coal and metal mining is potentially available for reuse in South Africa (Braid and others, 2011). Figure 7 indicates the estimated amount of mine water generated from the coal mines in the Highveld coalfields and the projected installed mine water treatment capacity. The Highveld coalfields are in the Upper Olifants River catchment area. Treated mine water discharged to rivers will be available to downstream power plants (and other water users). Moreover, treating mine water (including acid mine drainage) will be cheaper than importing water from other catchment areas.

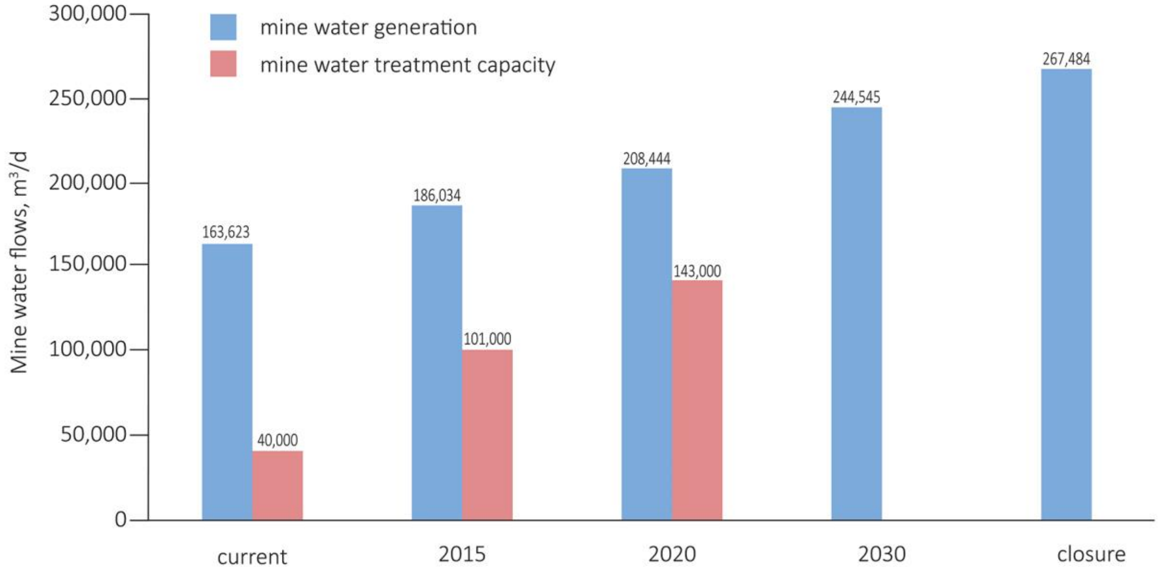

Figure 7 Projected mine water generation and installed treatment (Synman and van Niekerk, 2013)

Recovering water from acid mine drainage and the reuse of mine water are recognised by the government in its second National Water Resource Strategy (NWRS2) as important ways of increasing water availability (DWA, 2013). Acid mine drainage from defunct and active coal and metal mines is a major concern. The water in the Olifants catchment area (Mpumalanga region) is generally too polluted for industrial use because of acid mine drainage. Consequently, Eskom has to transfer water from other catchment areas to supply certain of its power plants (The Green House, 2013b). The Department of Water and Sanitation has started to assess and quantify the problem, and to ensure that new mines, and mines that are still active, take steps to mitigate acid mine drainage. The Minister recently announced that an internal Acid Mine Drainage and Mine Water Management Unit is going to be established to ensure an integrated approach (Mokonyane, 2015). The government has imposed strict regulations in the form of environmental impact assessments and mine closure insurances on operating mines to avoid future water pollution problems. Moreover, the implementation of the Waste Discharge Charge System (which is based on the polluter-pays principle) should increase the treatment of mine water effluent and its use.

Acid mine drainage and reuse projects could utilise the large storage available in underground mine workings to avoid evaporation loss of water. Several acid mine drainage treatment and reuse projects have been implemented, demonstrating the technical feasibility, financial viability and acceptance of such projects. The Witbank (eMalahleni) coalfields, for example, produce 123,250 ML/d (45 million m^3/y) of excess water; this could equate to about 119,000 ML/d at a 97% recovery rate (Braid and others, 2011). Anglo American has built a water treatment plant that desalinates 25–30 ML/d of underground water from four of the coal mines in this region (Fisher and Naidoo, 2014; World Coal Association, 2014b). The clean water supplies 12% of the eMalahleni Local Municipality's daily water needs, as well as the coal mines' water requirements. The treatment capacity of the plant is being increased to 50 ML/d (due to be completed in 2016), enabling the plant to treat water from up to six coal mines. The project was designed to take into account the remaining 20–25 year life of contributing mines, and to cater for post closure liabilities. This will require the desalination of mine water in excess of 30 ML/d. The plant uses the Keyplan Hi recovery Precipitating Reverse Osmosis (HiPRO) desalination process to achieve over 99% of water recovery.

The R545 million water treatment plant at the Optimum coal mine complex (largely surface mining) in Mpumalanga treats 15 ML/d of water in a RO process with a 98% water recovery rate. The long-term decant volume is projected to be 35.1 ML/d (Cogho and van Niekerk, 2009). The water is again supplied to the local municipality. Exxaro has built the R250 million Robert Clarke Water Treatment Plant at the Matla mine, near Kriel in Mpumalanga, to treat 10 ML/d of water pumped out from mined-out underground workings. Some 2.5 ML of the potable treated water will be reused at the mine and by the surrounding communities, and the remaining 7.5 ML discharged into the nearby Olifants River for downstream use (Odendaal, 2015).

Eskom, which runs the majority of coal-fired power plants in South Africa, uses mine water at two of its power plants, namely Lethabo and Tutuka. Some 16 ML/d of mine water from the nearby New Denmark Colliery and 6 ML/d of cooling tower water are treated in the spiral-wound reverse osmosis (SRO) desalination plant at the Tutuka power plant, near Standerton in Mpumalanga (Lalla and others, 2012). The brine waste stream from the desalination plant was disposed of by mixing it with ash on the dry ash dump. This solved the dust problems and prevented salts in the brine from polluting the environment as they are encapsulated in the ash. The dry ash dump has a limited capacity for brine, and therefore the excess was historically sent back to the mine for disposal in an underground compartment. To achieve Eskom's policy of zero liquid effluent discharge, the brine is now treated in a 3 ML/d concentration plant. The final brine concentrate (0.6 ML/d) is sent to an evaporation pond. Overall, the treated water recovery rate is 97% (SRO plus brine concentration plant). The treated water is reused as cooling tower make-up.

The Lethabo power plant in Sasolburg in the Free State uses raw water from the Vaal River, mine water from the New Vaal colliery, and treated sewage water as make-up water for its cooling towers. The cooling water blowdown is desalinated in three SRO units with a total capacity of 12 ML/d (Eskom, 2014). Part of the clean water is reused in the cooling system, and the rest is utilised as boiler make-up after further desalination in an ion exchange process. The brine is disposed of on the dry ash dump by mixing it with ash. Treated and untreated mine water comes from the New Vaal colliery. The untreated water is desalinated in the SRO facility at the power plant before it is used. The treated mine water is desalinated at the colliery by reverse osmosis; a freeze-crystallisation facility has been installed that removes 40 t/d of salt from the brine waste stream (Kolver, 2013).

4.2.4 USA

In 2013, there were 1032 coal mines operating in the USA, 395 underground and 637 surface mines. Three States that are part of the Appalachian region (Kentucky, Pennsylvania and West Virginia) accounted for 70% of coal production (EIA, 2015a). There are also thousands of abandoned mines in which water has accumulated – in underground mine pools and in surface mine water filled pits and lakes.

These could provide a water source to nearby thermal power plants in regions where it is abundant and accessible. This is limited to a few coal (and metal) mining states, principally in the Appalachian and Illinois-Indiana coal mining regions (*see* Figure 8). However, competition for the water is likely to increase as Pennsylvania's Department of Environmental Protection is encouraging the use of acid mine drainage for hydraulic fracturing of shale gas (Walton, 2013).

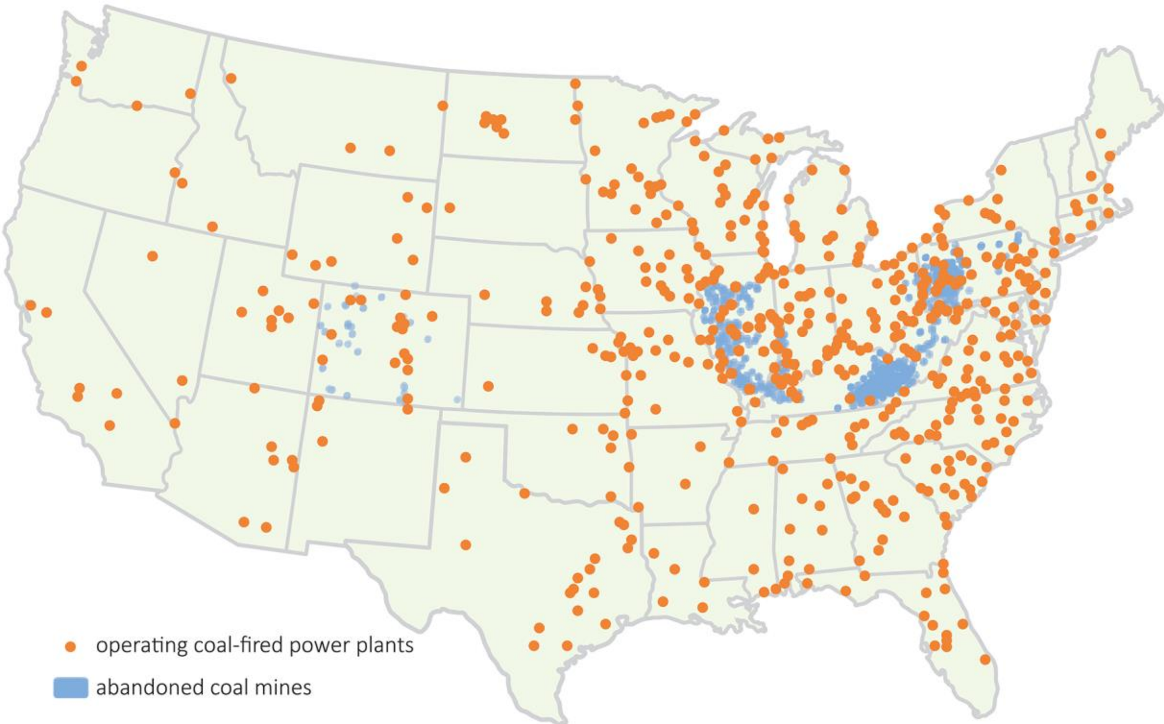

Figure 8 Location of abandoned coal mines and operating coal-fired power plants (Arthur, 2011)

There is no comprehensive inventory of mine pools in the USA, although some evaluations for particular areas have been carried out. The Eastern Pennsylvania Coalition for Abandoned Mine Reclamation (EPCAMR) is developing a geographic information system database of the location, flow rate, quality and other parameters relating to acid mine drainage from underground coal mines in Eastern Pennsylvania (*see* http://epcamr.org/home/current-initiatives/mine-pool-mapping-initiative/). The 'Alternative Water Source Information System' (*see* www.all-llc.com/projects/coal_water_alternatives/) provides some data on the location and volume of mine pool water in abandoned mines within a 24 km radius of existing coal-fired power plants in Pennsylvania, although the data is out-of-date.

It has been estimated that over 4900 GL of acid mine water is ebbing and flowing in abandoned mines beneath Fayette, Greene, and Washington counties in Pennsylvania and in Monongalia County in West Virginia, alone (Veil and Puder, 2006). Over 1.1 million m^3/d (1.1 GL/d) of contaminated water flows from Pennsylvania's abandoned mines, polluting some 5,500 streams (Walton, 2013). There are between 10,000 and 15,000 abandoned underground mines in Pennsylvania, and 100,000 (including small mines) in West Virginia (Veil and others, 2003). The combined storage volume of just 130 mines in these two states was estimated to be 946 GL. The abandoned mines in the Pittsburgh Coal Seam could potentially produce 359,614 L/min, which would be enough to supply all the make-up water for twenty-two 500 MW coal-fired power plants employing a closed-loop cooling system (Arthur, 2011). There is an estimated 4.1 billion m^3 of water in the void space in 60 counties in Illinois, Indiana and Kentucky, that is, the Illinois Basin (Knutson and others, 2012). In Illinois alone, there are some 1615 abandoned coal mines. Work sponsored by the USDOE on the volume, yield, quality, treatment and use of mine pool water for power plant cooling systems is summarised in Munson and others (2009).

Utilising alkaline mine water for cooling tower make-up in a conventional 600 MW plant was found to be competitive with a river source in a comparable-size water cooling system under the economic conditions of the time (Donovan and others, 2004). On the other hand, utilisation of acidic water would have a 12% higher operating cost. This did not take into account any environmental benefits that would accrue due to the treatment of acid mine drainage, in many locations an existing public liability. The analysis was carried out for three sites in the Pittsburgh Coal Basin. Widespread adoption of mine water utilisation for power plant cooling would require the resolution of potential liability and mine water ownership issues.

A different approach in which cool water from the mine is used in the cooling systems and the resultant warm water is injected back into the same or adjacent mine has been investigated for the Pittsburgh Coal Basin (Donovan and others, 2004). The warm water is cooled by recirculation through the underground mine. Thus the flooded mine acts as a heat sink, as well as a supplier of water. This design would avoid the use of a cooling tower since the mine water passes once through the power plant condensers (open-loop system). The analysis found that it would not be feasible for a 600 MW power plant, but could be possible, under the right conditions, for a power plant of 200 MW or less. Capital costs are lower for this type of operation than conventional methods, but operating costs would be higher due to increased water pumping and treatment requirements.

Six cogeneration plants in northeast Pennsylvania are using treated mine pool water (Veil and Puder, 2006), five of which use it as make-up water in the closed-loop cooling system. Some also employ the water for boiler feed and other plant operations. The plants typically burn anthracite culm in circulating fluidised-bed boilers. Their rated capacity ranges from 31 to 83 MW, and the volume of mine water used varies from 378 to 4164 L/min. For instance, Gilberton Power Company's 80 MW John B. Rich Memorial Power Station in Frackville, Pennsylvania, utilises 4.5 ML/d of acid mine drainage, withdrawn from a nearby mine pool. The pH of the water is adjusted before it passes through a flocculation tank, clarifier, and mixed-bed filters; it is then used as make-up water (Aquatech, nd[b]).

The National Mine Land Reclamation Center (2010) at West Virginia University has developed a computer-based design aid for assessing the costs, technical and regulatory aspects, and potential environmental benefits of using mine water at power plants. It was applied to the proposed 300 MW Beech Hollow plant in Champion, Pennsylvania. Building the water collection and treatment system was estimated to cost US$11.1 million, with annual operating costs of US$619,000. This translates into a water acquisition cost of about a sixth of that from the local municipal supply. The project appears to have been cancelled.

Instead of pool water from abandoned mines, the discharge from an active coal mine could be utilised, after treatment, at power plants. Most mines in the Illinois Basin are considered to be dry compared to the Appalachian Region coal mines. However, Knutson and others (2012) identified three active mines in southern Illinois with a significant amount of mine discharge. Water from the Galatia/Millenium mines (1.9 ML/d) and Pattiki mine (1.6 ML/d) could supply 10% of the demand for two 200 MW power plants (assuming a consumption rate of 2.65 L/kWh). About 5% of the water demand of one 200 MW plant could be met from the Royal Falcon mine (0.6 ML/d). Treatment of the Galatia mine water by reverse osmosis with zero liquid discharge was estimated to cost US$16 per 3800 L of purified water in a 1.9 ML/d water treatment plant. The zero liquid discharge scenario (where the brine is sent to crystallisation units) was less expensive than treatment without this option. This is due to the high costs of underground disposal. Costs would decrease if a higher flow rate is treated (and by selling the produced salt). However, transportation costs tend to be greater than treatment costs, so unless a power plant is nearby, mine discharge would be uneconomic.

4.3 Comments

Mine water from abandoned and active mines could prove to be an important source for nearby power plants, either as a supplemental or sole source, in regions where such water is abundant and accessible. Its use could turn a water pollution liability into a water resource. Cool water withdrawn from underground mine pools is a more efficient cooling agent (if it can be used without treatment at the surface) than surface water that is subject to summer heating, thus improving power plant efficiency. The main disadvantage is the higher treatment costs compared to river water. Moreover, the withdrawal of significant volumes of water from a mine pool, in excess of the pool's recharge rate, could affect the local hydrology or increase the likelihood of subsidence.

The technical feasibility and economic viability of utilising mine water can be seen in the number of power plants currently using it for cooling purposes. China is the only country discussed that has set targets for the reuse of mine water. Furthermore, new power plants in North China have been given priority access to mine drainage and recycled water.

There are no comprehensive inventories of mine pools available in China, India, South Africa and the USA, hampering its use. More information on the quantity, quality, flow rate and other parameters of water in mine pools is required. Regulatory and fiscal incentives would also encourage further usage of mine water.

5 Produced water

Water from oil and gas wells, called produced water, could become a significant source for nearby power plants, especially if oil and gas development continues to grow. Moreover, beneficial use reduces the environmental impacts (and associated cost) of its disposal. Some 69.8 billion barrels (11.1 TL)/y of produced water were generated worldwide in 2007 (EPA, 2012), of which the USA accounted for about 20.9 billion bbl (3.3 TL)/y (Clark and Veil, 2009). Currently the majority of produced water is injected underground (for enhanced production or disposal) – some 98% of the water generated onshore in the USA in 2007 (Clark and Veil, 2009). The main barrier to its use in power plants is the cost of treatment, as the water is often highly saline. In addition, collecting water from each well within a field, transporting it, and managing the variability in water flow over time can make it difficult, and expensive, for power plant operators to utilise.

One power plant currently using produced water is the 140 MW combined-cycle Condamine power plant near Chinchilla in Qld, Australia. The plant fires coalbed methane (CBM, also called coal seam gas) from the Surat Basin. Water withdrawn from the CBM fields is treated on-site in a 6 ML/d plant and used for cooling and steam production (Thorndon Cook, 2015; Western Downs Regional Council, 2011). Other power plants in the region are also utilising the water for operational purposes. Another use for CBM water is for coal washing. For example, untreated CBM produced water is employed at the washing plant at the Wilkie Creek coal mine in Australia (RPS Australia East, 2011).

5.1 Viability of use

Produced water includes the water that is in the reservoir and is brought to the surface during hydrocarbon extraction (formation water), and the water that is injected as part of the drilling, development and extraction process that returns to the surface. The water returning to the surface over the first few days or weeks from initial hydraulic fracturing is termed flowback. Assessments of produced water can include this water – the two sources are not always distinguished. Residual water from hydraulic fracturing that returns to the surface over the longer term is usually included in the definition of produced water.

As with other potential sources, the viability of produced water use depends on its availability, quality, quantity, reliability and duration of supply, location, economics, and regulatory factors. The following sections will examine the quantity and quality of water generated from on-shore conventional oil and gas wells, and from unconventional shale gas and CBM wells, and its treatment.

5.1.1 Produced water volume

The quantity (and quality) of produced water varies considerably depending on the geographic location of the field, the geologic formation, the type of hydrocarbon product being produced, and the lifetime of the reservoir. Based on experience in the USA, drilling a single well needs 0.2–2.5 ML of water, whilst hydraulic fracturing (fracking) requires 7–23 ML per well (Reig and others, 2014). The volume of water returned to the surface varies depending on the characteristics of the geological formation. It can be as low as 15% and as high as 300% of the injected volume in hydraulic fracturing (WWAP, 2014a). The quantity of produced water also increases as oil and gas production declines over the lifetime of the conventional reservoir. This is the opposite of a typical production cycle of CBM and shale gas wells where water production decreases over time. Generally, deeper coal seams contain less water than shallower ones, and the salinity of the water is higher (Guerra and others, 2011).

Some 7 to 10 barrels (1060–1515 L) of water is produced per barrel (159 L) of oil in the USA (Guerra and others, 2011). Oil reservoirs commonly contain larger volumes of water than gas reservoirs. Advances in drilling techniques have led to an increase in production water from unconventional gas formations, including coal seams, tight sand and shale deposits. These techniques produce some 8 barrels (1272 L) of water for every barrel of oil (EPA, 2012). Water from coal seams is generally produced from shallower formations than conventional oil and gas resources. Experience in Queensland, Australia, found that individual CBM wells initially produced between 0.2–0.8 ML/well each day, decreasing substantially over a 10-year period. However, produced water volumes are dependent on local hydrogeological conditions, and water production at a well may depend on the rate of recharge or whether water levels have been previously drawn down prior to drilling. Therefore, other areas may be far more or less productive than this range. For example, the 89 gas-producing wells in the Camden Gas project in New South Wales, Australia, only generate some 0.01 ML/day of water in total. Thus the total rate of water production will depend on the number of producing CBM wells in the development area and the average production rate from each well (Khan and Kordek, 2014).

5.1.2 Produced water quality and treatment

The quality (chemical and physical properties) of produced water varies widely. It depends on a number of factors, including the geographic location, the local and regional geology and hydrology, the type of hydrocarbon being extracted, and the extraction process. For example, chemicals added to the fracturing fluids can contaminate the water. Moreover, the quality can vary between wells in the same field, and over time from the same well. Shale gas water in the USA starts out with moderate to high TDS, which increase as time passes (Veil, 2015).

The depth at which the hydrocarbons are found influences the salt and mineral content of produced water, and, in general, the deeper the formation, the higher the salt and mineral content (Government Accountability Office, 2012). Salinity (TDS) can vary from drinking water quality to ten times that of sea water (which could make it uneconomic to treat and reuse). For example, CBM water from some areas of the Gunnedah basin in New South Wales, Australia, has a TDS content as low as 4000 mg/L, while in other areas of the same basin it can be as high as 31,000 mg/L (Khan and Kordek, 2014). In the USA, some 99% of unconventional wells have a TDS content below 50,000 mg/L. The TDS concentration in conventional oil and gas produced water in the western part of the country can vary between 1,000 and 400,000 mg/L (Guerra and others, 2011). Typically, the salinity of water from unconventional CBM wells is lower than that from conventional ones because it is often produced from shallower formations that may interact with fresh water aquifers (Dahm and others, 2014). Consequently, it may be cheaper to treat for use in power plants.

Produced water from oil production in the USA generally has a pH of 6–7.7, while discharge from gas production is more acidic (3.5–5.5). Chloride concentrations are typically 12–100 g/L from oil production and from less than 1 to 198 g/L in water from gas wells (Tetra Tech Inc and DiFilippo, 2008). Produced water often contains high concentrations of scale-forming constituents, including barium, calcium, iron, magnesium, manganese and strontium (Kargbo and others, 2010). Oil and grease can occur in oil and gas produced water but is less of a concern in CBM water. Other constituents that may be present include organic compounds, silica, boron, trace metals, sulphates, carbonates, bicarbonates, nitrates, fluorides, radionuclides and production chemicals. The latter can include surfactants, biocides to prevent growth of microorganisms, and additives to prevent corrosion and scaling. Some of these will need to be removed before the water can be used in power plant cooling systems.

A principal component analysis of the produced water composition from three major CBM fields in the Rocky Mountain Region in the USA (Dahm and others, 2014) found that the variability in quality was related to three factors:

- aquifer recharge that dilutes constituent concentrations (37% of variability);
- dissolution of soluble aquifer minerals such as sodium, and exchange of calcium and magnesium (13.8%); and
- coal depositional environment influence on chloride and trace metal fractions (14% of variability).

This could help in predicting produced water quality and its variability from CBM wells, and in assessing its use. Davies and others (2015) have recently reviewed the factors influencing the chemical composition of CBM produced water.

The treatment of produced water generally requires multiple treatment processes to remove the different constituents before it can be used for cooling or other purposes within a power plant. It is commonly treated at the production site before it is reused and/or to meet discharge regulations. The treated water (at the required quality) could be transported to a nearby power plant. The water is sometimes transported to a local municipal plant for treatment. Otherwise it can be treated at the power plant.

The required treatment processes depend on the chemical composition of the produced water, but commonly involve de-oiling (removal of dispersed oil and grease, when present), desalination, removal of suspended particles, sand, soluble organics, dissolved gases, and naturally occurring radioactive materials (NORM), disinfection and softening (to remove excess water hardness). Sulphate removal may be required for some sources since sulphates can cause formation of stress-induced cracks in stainless steel and can corrode concrete (Knutson and others, 2012).

Produced water often has a high salinity, making it difficult and expensive to treat (WWAP, 2014a). When treated at the production site, the heat or pressure that is sometimes available in produced water could be used either to generate electricity or to drive the water treatment processes, such as reverse osmosis

(RO) or thermal distillation (Bauer and others, 2014). RO (*see* Section 3.3.2) has been employed to treat water with a lower salinity, such as that from CBM operations. For example, the CBM water is treated at the Condamine power plant near Chinchilla in Queensland, Australia, by clarification, microfiltration, RO, and continuous electrodeionisation (Thorndon Cook, 2015). Thermal distillation could be used for higher salinity water, and waste heat from the power plant utilised to lower the energy consumption (*see* Section 3.3.3).

The use of two membrane separation technologies (electrodialysis and electrodeionisation) to treat make-up water (produced water) and cooling tower blowdown were investigated by Gill (2010). Inhibitors were added to prevent scaling. The cost of water desalination using electrodeionisation was estimated to be US$0.05/bbl of water. The University of Illinois is currently investigating the integration of a supercritical system for treating high salinity (30,000–200,000 mg/L) produced water by membrane distillation, and recovering the salt and minerals in a zero liquid discharge plant. Membrane distillation is also being investigated by the Research Triangle Institute (fouling resistant membranes) and the University of Pittsburgh (utilising waste heat) for power plant use, whilst a multi-phase turbo-expander-based water desalination process is being researched by the General Electric Company (NETL, 2015a). All of these projects are funded by the USDOE.

Forward osmosis and reverse electrodialysis membrane technologies are currently being investigated as pre-treatment options for RO to lower energy demand, and thus reduce operating costs. Dewvaporation is used to treat produced water from oil and gas operations in Pennsylvania, USA (Bauer and others, 2014). Shaffer and others (2013) review mechanical vapour compression, membrane distillation and forward osmosis techniques for desalination of high salinity shale gas water. Processes for treating produced water from oil and gas wells are compared by Igunnu and Chen (2014).

Desalination generates a concentrated brine residue that requires disposal (*see* Section 3.3.2). Technologies are available to enable zero liquid discharge. Moreover, constituents, such as salts, calcium, magnesium, iron, bromide and iodide, within the brine may have economic value, and thus their sale would reduce treatment costs. Lithium, an important element in the production of batteries, and iodide (the largest source of iodine within the USA) are being extracted from some produced waters and sold (Engle and others, 2014; Healy and others, 2015). Sodium bicarbonate, sodium carbonate (soda ash) and sodium chloride (common salt) may be recoverable in commercial quantities (depending on their concentration). For example, the use of saturated CBM brine as feedstock for the production of sodium hydroxide using membrane electrolysis is being investigated at the University of Wollongong in Australia (Davies and others, 2015; Khan and Kordek, 2014).

5.2 Produced water policy, availability and use

The availability and use of produced water in China, India, South Africa and the USA are discussed in the following sections.

5.2.1 China

According to the US Energy Information Administration (EIA), China has 24.6 billion bbl and 4.6 trillion m^3 of proved oil and natural gas reserves, respectively. Nearly 4.6 billion bbl/d of petroleum, of which 92% was crude oil, was produced in 2014. Oil production is forecast to rise to around 5.7 billion bbl/d by 2040. Natural gas production was about 125 billion m^3. Most of the largest oilfields are located in the northeast and north central regions of the country, whilst the primary onshore natural gas fields are in the southwest, the northwest, and the north (EIA, 2015b). There is little publically available information on the amount and quality of produced water in China. Some of the water is reinjected for enhanced production. At some sites, the produced water is utilised in the oil refinery. For example, a ten month pilot-scale test was carried out at the 18th well area of Fengcheng Oilfield Work Zone in the Karamay oilfield, Xinjiang, to reuse the water (some 40,800 m^3/d is produced) as boiler feed water (Dong and others, 2015).

China has large reserves of unconventional oil and gas – some 32.2 billion bbl of technically recoverable shale oil resources (third largest worldwide), 31.2 trillion m^3 of technically recoverable shale gas (excluding CBM and tight gas), the largest in the world (EIA, 2013), and nearly 40 trillion of CBM resources, of which 10 trillion m^3 is technically recoverable (Andrews-Speed and Len, 2014). The figures for CBM include resources from surface well extraction and coal mine methane, which is drained by coal operators for safety reasons. The shale oil and shale gas resources are principally in basins in the northwest, northeast and southwest areas of the country (EIA, 2013). The CBM basins are in the northwest, northeast, north, east and southwest (*see* Figure 9). CBM is currently commercially produced in the Eastern Ordos and Qinshui basins in Shanxi, a water-stressed province. Some 2.57 billion m^3 of CBM were produced from surface wells in 2012 (Meng and others, 2014).

Figure 9 Coal bearing basins and CBM resources in China (Meng and others, 2014)

Because of the large reserves, the Chinese government is supporting unconventional gas development as a means of energy security and to alleviate air pollution from coal-fired power plants. The 12th Five Year Plan for Shale Development (2011–15), issued in March 2012, set a production target of 6.5 billion m³ for 2015 (Kwok, 2012). More information about the plan can be found (in Chinese) at http://www.nea.gov.cn/zwhd/wszb20120316/. The 12th Five Year Plan for the Development and Utilisation of CBM (2011–15), released in December 2011, aimed to produce 30 billion m³ by 2015, with 16 billion m³ coming from CBM surface wells and 14 billion m³ from coal mines (*see* http://www.nea.gov.cn/131337364_31n.pdf). Two major CBM bases will be built in Shanxi and Inner Mongolia (both water-stressed provinces) by 2015, with other bases following later. The target of 60 billion m³ of shale gas by 2020 was halved to 30 billion m³ by the State Council in the Energy Development Strategic Action Plan (2014–20), released in 2014 (*see* http://www.gov.cn/zhengce/content/2014-11/19/content_9222.htm). This Plan also sets a 30 billion m³ target for CBM by 2020.

The targets for shale gas and CBM have been reduced due to the slow pace of exploration and development, lack of infrastructure, and economic and regulatory restraints. The shale gas deposits are commonly deeper than those in the USA and are in geologically more complex formations, making them more challenging to exploit (Liu and others, 2015). Over 60% of the shale resources are in areas subject to high to extremely high levels of water stress or arid conditions (Reig and others, 2014). Even in water-rich areas, shale gas development may have to compete with other water users. Necessity may force

China to further develop and use waterless fracking (such as using nitrogen or propane gas). In this case, only formation water will be generated. In addition, not many coal-fired power plants may be near a produced water source.

The shale oil is typically buried deep underground and in hard, thick geologic formations. Therefore, it requires large inputs of energy and water to extract, but would yield substantial quantities of contaminated produced water. Difficult reservoirs and geological complexity are also posing technical challenges for CBM development.

Published literature suggests that the daily volume of produced water from CBM ranges from 10 to 271,280 L/well (*see* Table 4), and the concentration of TDS ranges from 691 to 93,898 mg/L (Meng and others, 2014). The quantity of water will decline over the lifetime of the well. The quantity and quality data are mainly available for the Eastern Ordos and Qinshui basins, and are lacking for other basins.

Table 4 Volume of produced water from CBM basins (Meng and others, 2014)

Basin (location)	Stratigraphic unit	Daily water production, L/well†	Number of wells
Qinshui (Fanzhuang)	Shanxi	100–45,000 (4,750)	>400
Qinshui (Panhe)	Shanxi	800–48,600 (10,400)	>200
Qinshui (Zhengzhuang)	Shanxi	1,790–40,000 (12,000)	>200
Qinshui (Heshun)	Taiyuan	120–11,640 (1,000)	>20
Ordos (Baode)	Shanxi	10,000–50,000	–
Ordos (Liulin)	Shanxi	3,500–42,630	–
Ordos (Liulin)	Taiyuan	41,630–271,280	–
Ordos (Wupu)	Shanxi, Taiyuan	4,710–89,080	>6
Ordos (Daning-Jixian)	Shanxi	(4,400)	–
Ordos (Daning-Jixian)	Taiyuan	(13,100)	–
Ordos (Sanjiao)	Shanxi	3,000–5,000	>40
Ordos (Sanjiao)	Taiyuan	20,000–30,000	>15
Ordos (Yanchuannan)	Shanxi, Taiyuan	400–12,000 (7,000)	>16
Southern Ningwu	Shanxi, Taiyuan	10–100	>6

† Data in parenthesis represent average data

No assessment of the amount and quality of produced water near to Chinese coal-fired power plants has yet been made.

5.2.2 India

At the end of March 2014, the estimated reserves of oil in India were 762.7 Mt (5.6 billion bbl), of which 43% were offshore (Offshore Western Region), and 57% were onshore in Assam (23%), Gujarat (18%), Eastern Onshore Region (7%), Rajasthan (6%), Andhra Pradesh (2%) and Tamil Nadu (1%). Some 37 Mt of oil was produced. Estimated onshore and offshore natural gas reserves were 1427.2 billion m^3, of which 7% was CBM. These gas reserves are mainly offshore, in the Eastern Offshore (37%) and Western Offshore (30%) Regions, with some 33% onshore. This includes Assam (10%), Gujarat (5%), Andhra Pradesh (3%), Tamil Nadu (3%), Tripura (3%), and Rajasthan (1%). Natural gas production was 35.4 billion m^3 (Central Statistics Office, 2015). Statistics on the total amount of produced water generated from the onshore oil and gas wells could not be found.

India has some 87 billion bbl of shale oil resources, out of which the technically recoverable resources are 3.8 billion bbl. Shale gas resources (excluding CBM and tight gas) are 16.5 trillion m^3, of which 2.7 trillion m^3 are technically recoverable (EIA, 2013). Onshore and offshore CBM reserves are 100.8 billion m^3 (Central Statistics Office, 2015). The shale gas and CBM reserves are larger than the conventional natural gas reserves. Thus the country is looking at developing its shale gas and CBM resources to reduce the amount of imported natural gas, and help meet growing energy demand. The Government announced in August 2015 that CBM production will increase fivefold by 2017–18 to reach 2.1 billion m^3/y (Tanchum, 2015); total CBM production in 2013 was about 164 million m^3 (EIA, 2014). However, the shale gas deposits are in geologically complex areas, and the lack of a fresh water and transport infrastructure are hampering development.

The prospective shale gas basins (EIA, 2013) are the Krishna-Godaveni and Cauvery basins in the south, the Cambay Basin in Gujarat (northwest) and the Damodar Valley. Many of the deposits are in water-stressed areas, particularly the shale gas and shale oil deposits. The 2012 draft policy for the exploration and exploitation of shale gas states that the waste (produced) water must be treated in line with Central/State Ground Water Authority regulations before it is discharged, and that the reuse and recycling of water should be the preferred method for water management (Bastra, 2013).

Figure 10 shows the CBM areas in India, most of which are in the eastern parts of the country. There is little published information on the quantity of water produced from CBM wells. In the Raniganj Basin in the Damodar Valley, West Bengal, Essar Oil is producing over 0.1 million m^3 of gas from 25 wells, and Great Eastern Energy Corporation over 0.25 million m^3 from 40 wells, along with over 10 m^3 of water per well each day. The water has a low salinity, with TDS content varying from 2070 to 3082 mg/L (Mendhe and others, 2015). The TDS content in produced water from eight wells in the Jharia Block ranged from 900 to over 3000 mg/L, and up to 5700 mg/L in the Bokaro Block; both blocks are in the Damodar Valley. These values are lower than those reported from the San Juan Basin in the USA. Daily water production varied from 2 to 300 m^3/well (Basumatary and others, 2010). More wells are planned which will increase the amount of produced water available. However, no assessment of the quantity and quality of produced water available near to coal-fired power plants has yet been published.

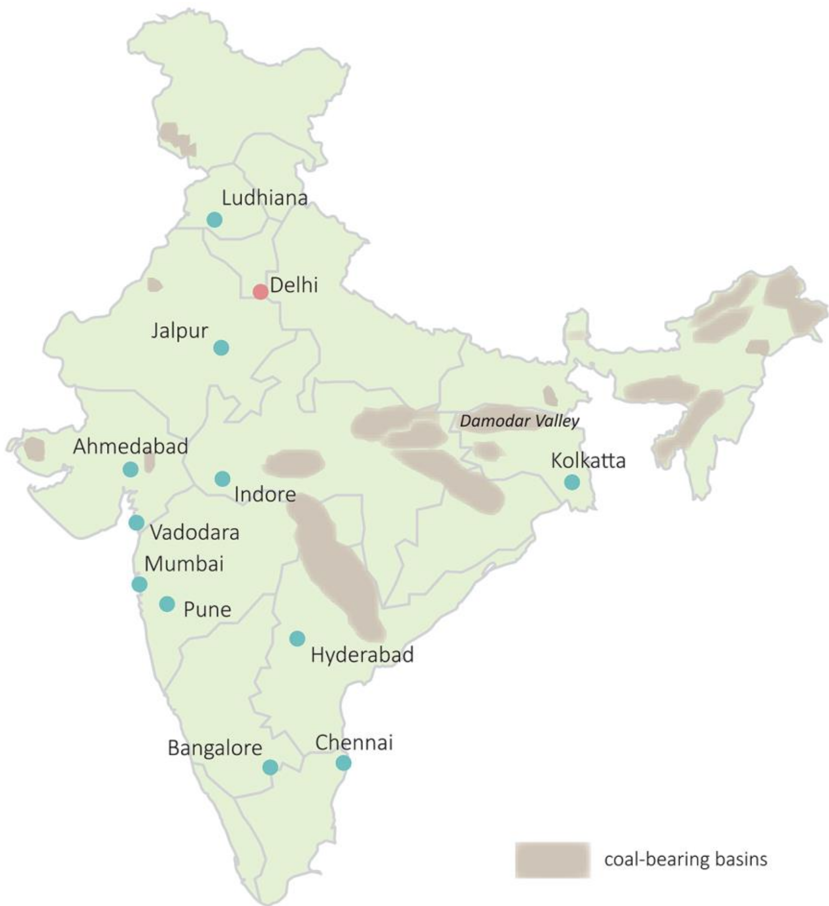

Figure 10 CBM areas in India (Yerramilli and Yerramilli, 2008)

5.2.3 South Africa

South Africa has limited proved reserves of conventional oil and gas, but large reserves of coal. All of the proved oil reserves of some 15 million bbl are offshore (EIA, 2015c). Proven conventional gas reserves were 27.2 million m^3 in 2014 (SAOGA, 2016), mostly offshore. However, the country has large shale gas resources – some 11 trillion m^3 of technically recoverable resources, the eighth largest in the world (EIA, 2013). But according to the Petroleum Agency SA's estimates, only some 1.39 trillion m^3 are recoverable (Pietersen and Kanyerere, 2014). Exploration for shale gas is only just starting, and until sufficient exploration wells are drilled, the resource will remain unknown and unproven.

Shale gas could reduce the country's dependence on imported natural gas and enhance energy security, as well as providing an alternative fuel to coal. However, regulatory uncertainty and environmental concerns are delaying exploration. South Africa is a water-stressed country, and questions have been raised over the availability of water for hydraulic fracturing. Waterless hydraulic fracturing could be used, if economically viable. The major sedimentary basin containing shale gas is the Karoo Basin in central and southern South Africa. But it contains significant areas of volcanic intrusions (dolerite sills) that impact the quality of the shale gas resources, and increase the risk of shale gas exploration.

The southern portion of the Karoo Basin (a water-stressed area) is considered to have the most potential for shale gas (EIA, 2013). However, there are no coal-fired power plants in this area. In addition, there is little information on gas or water flow rates since few exploration wells have yet been sunk. In 1968, a well in this area yielded a gas flow rate of 51,820 m^3/d for 23 h (*see* http://www.petroleumagencysa.com/index.php/petroleum-geology-resources/frontier-geology).

Estimated CBM resources were 0.57–0.85 trillion m^3 in 2014, the twelfth largest in the world (SAOGA, 2016), although initial studies by the Petroleum Agency SA indicate a conservative estimate of around 0.28 trillion m^3 (Pietersen and Kanyerere, 2014). One area which contains significant volumes of CBM is the Waterberg coalfield, located north of Lephalale, Limpopo Province (in the northern part of the country, *see* Figure 11). Coal mining is likely to focus on the shallower coal seams in the western part of the coalfield (there is already one coal mine, the Grootegeluk surface mine). CBM in the deeper coal seams in the eastern part have the potential to be economically exploited. Anglo American Coal South Africa has a pilot-scale project where CBM (and water) is extracted via five wells in this area. Some 28.3 billion m^3 of technically recoverable CBM reserves are reported in their exploration area (Pietersen and Kanyerere, 2014). The produced water is treated by RO and used for game watering. The company has proposed building a further 37 wells in the same area. The wells would require 5841 m^3/d of water for hydraulic fracturing, whilst some 1000 m^3/d is abstracted. It is again planned to treat the produced water in a RO treatment plant to generate 800–850 m^3/d of clean water, which would be utilised on site and on local farms for game watering. The amount of water produced would decrease over time as the water in the coal seam is depleted. Some 10 MW of electricity is to be generated from the methane gas (Golder Associates Africa, 2011). There are no coal-fired power plants planned in this part of the coalfield. The Medupi coal-fired plant is some distance away in the western portion, and the Matimba power plant is situated near Lephalale.

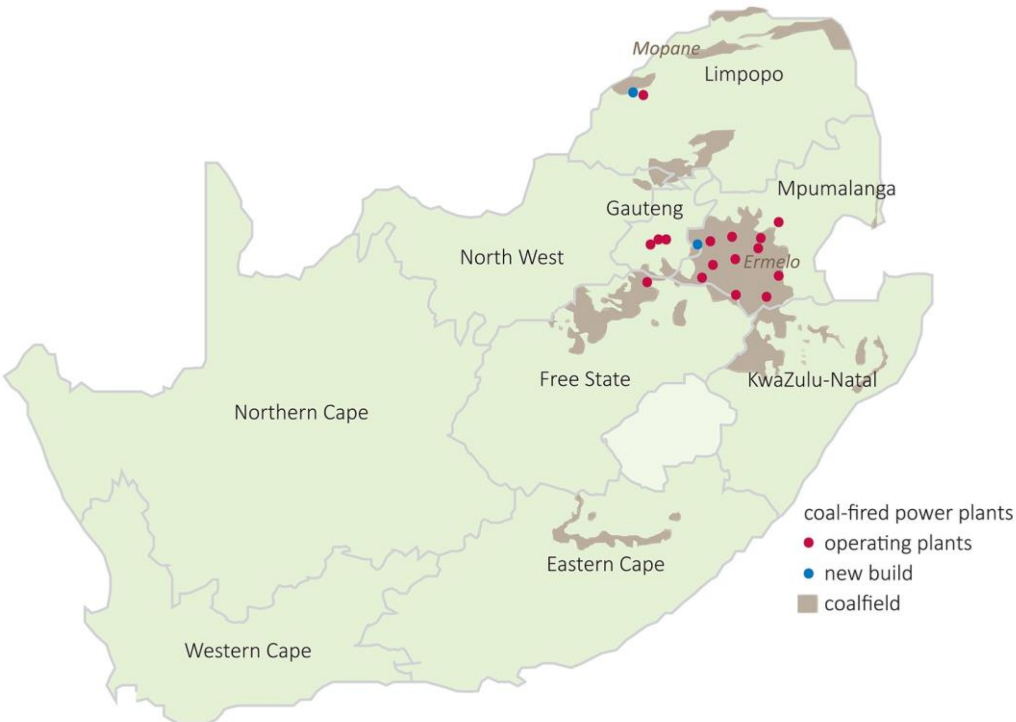

Figure 11 Location of coalfields and operating coal-fired power plants

Among other coalfields being considered for exploitation of CBM are the Ermelo coalfield, about 200 km from Johannesburg, and the Mopane coalfield, about 420 km northeast of Johannesburg (Pietersen and Kanyerere, 2014). However, there are no coal-fired power plants near the Mopane coalfield (*see* Figure 11). No assessment of the quantity and quality of produced water from shale gas or CBM surface wells that could be utilised by nearby coal-fired power plants has yet been carried out. It seems unlikely that produced water would be desalinated and used at power plants since there is so much acid mine water in the areas around the coal-fired power plants. It seems more likely that the acid mine water would be treated and used (as is currently done, *see* Section 4.2.3), as it solves the dual issue of acid mine pollution and water use for power generation (Fisher, 2016).

5.2.4 USA

The USA has extensive reserves of oil, natural gas and coal. At the end of 2014, onshore and offshore proved crude oil reserves were 39.9 billion bbl (including proved reserves of 13.365 billion bbl of tight oil). Proved reserves of onshore and offshore natural gas were 11.01 trillion m^3, which includes 5.65 trillion m^3 of shale gas and 0.445 trillion m^3 of CBM (EIA, 2015d). Technically recoverable resources of shale gas (unproved resources) were estimated to be 16.06 trillion m^3 in 2013, the fifth largest in the world (EIA, 2013). Over 35% of the shale gas resources are in areas that are either arid or under high or extremely high baseline water stress (Reig and others, 2014).

Unconventional oil and gas production has been increasing significantly over the last few years amid concerns of energy security, with forecasts predicting that the country will become a net exporter of natural gas by 2017 (EIA, 2015e). Consequently, produced water from oil and gas wells, as well as from CBM activities, could potentially become a significant source of water. However, available data on the quantity and quality of produced water in the country are incomplete and difficult to obtain. Responsibility for managing and regulating most aspects of oil and gas development is assigned to individual states, rather than to the federal government. Each state can have its own set of regulations, rules, and requirements for monitoring and reporting oil, gas, and water volumes from producing wells. These requirements can range from reporting of detailed water information for each well to no water reporting at all (Veil, 2015). A national database of the volumes, sources, chemical characteristics and ultimate destinations of water used in oil and gas production is needed. Standardisation of the definitions and measurements would help data collection and reporting (Bauer and others, 2014). The US Geological Survey currently maintains a geochemical database that provides details on the location, geologic setting, and chemical composition of produced water samples from seven different well types (conventional oil and gas, shale gas, tight oil, tight gas, CBM, geothermal and ground water) from various locations in the USA (*see* http://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822349-data). This could, for example, help assess potential scaling in a power plant cooling system from a produced water source.

Veil (2015) estimated that some 21.2 billion bbl (3371 GL) of water (including flowback) was generated from onshore and offshore oil and gas wells in 2012, of which 20.56 billion bbl (3269 GL) came from onshore wells. The five states with the greatest produced water volumes were Texas (35%), California (15%), Oklahoma (11%), Wyoming (11%) and Kansas (5%). These include the drier states in the west of the country. The report includes a state-by-state summary of the volumes of produced water, as well as from federal and tribal lands, and provides details on where the information was obtained. It has been predicted that the produced water volume will reach ~34 billion bbl (5406 GL) annually by 2025 (Lyons, 2014).

It is often assumed that with unconventional oil and gas production increasing, the total volume of produced water generated will also rise significantly. But this was not the case. Although oil production increased by 29% and gas production by 22% from 2007 to 2012, water production rose by less than 1%. 2007 was the baseline year for the previous report on produced water volumes by Clark and Veil (2009). It was found that for three states where water produced from conventional and unconventional wells could be distinguished (North Dakota, Arkansas and Pennsylvania), the unconventional wells may generate less produced water per unit of hydrocarbon output than conventional ones.

Most of the produced water from onshore wells (93%) is injected underground (including for enhanced oil recovery (46%), disposal in non-commercial injection wells (40%), and in offsite commercial disposal wells (7%)). Less than 1% was beneficially reused for hydraulic fracking of new wells, irrigation and livestock watering (when the water has a low salinity) or for dust and ice control on roads. Veil (2015) states that it is likely that a higher percentage was reused but the data were not available to quantify the amount. The utilisation of produced water will become more important as oil and gas development continues to grow.

Barriers to increasing the use of produced water include ownership, regulatory and liability issues, and lack of financial incentives (Lyons, 2014). It is not clear whether ownership falls to the oil, coal or gas producer or to the landowner, state or another entity (Munson and others, 2009). Direct beneficial reuse of produced water discharged to surface bodies from production sites west of the 98th meridian is limited to agricultural or wildlife watering under 40 CFR 435 of the Clean Water Act (Shaffer and others, 2013). No discharge is allowed in the states east of the meridian. Thus delivery of produced water to power plants via rivers is not possible. The Effluent Limit Guidelines mandated in the Clean Water Act for conventional and unconventional oil and gas discharges do not apply to CBM extraction.

In 2002, some 350,000 bbl/d (55.6 ML/d) of treated produced water from the Kern River oilfield in California was being sent to cogeneration facilities for use as boiler feed water (Brost, 2002).

Figure 12 shows the location of coal-fired power plants operating in 2006 in relation to the produced water areas. It shows that this water would be an impractical alternative source for many power plants along the east coast and elsewhere due to their distance from the oil and gas production areas. However, it could provide a source for some power plants in the west, such as those in the Rocky Mountain region and the central area of the country (Arthur, 2011). Moreover, produced water from the Rocky Mountain region tends to have a TDS content of below 10,000 ppm, making it cheaper to treat than water from basins in the central and southern parts of the USA that can have a TDS content of over 200,000 ppm.

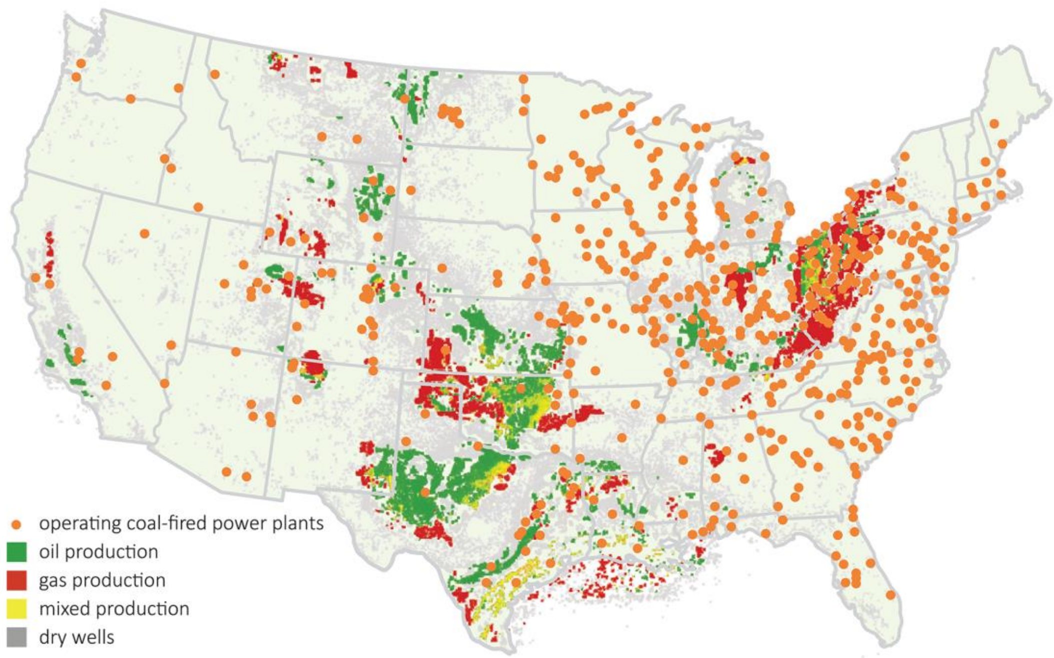

Figure 12 Location of produced water and operating coal-fired power plants (Arthur, 2011)

The corresponding internet-based geographic information system catalogue, the 'Alternative Water Source Information System' was posted on the internet in 2011 (*see* www.all-llc.com/projects/coal_water_alternatives/). It provides data on the location and volume of produced water from oil and gas production within a 24 km radius of the coal-fired power plants (Arthur, 2011). The cost of accessing the water to supplement or replace current supply can be evaluated, as well as availability for future power plants. There are no plans to update the database.

The Electric Power Research Institute (EPRI and others, 2006) evaluated the feasibility of using produced water from conventional oil and gas wells and CBM wells in the San Juan Basin to meet up to 10% of the water needs of the 1800 MW San Juan power plant near Farmington, New Mexico. This source of water could become important in future drought years. The power plant currently withdraws some 75.7 ML/d of fresh water from the San Juan River, most of which is used as cooling tower make-up. A high efficiency RO process, in combination with brine concentrators, treating a blend of produced water and purge water from the FGD absorbers was the most economical treatment system of those evaluated; capital costs were estimated to be US$14.1 million, with operating costs of US$2.98 million per year. The treated water could be used for cooling tower make-up, as bottom ash sluice water, as fly ash wetting water, and for FGD absorber make-up. The latter option was the least costly use for the treated water. The total capital cost of collecting, transporting (via pipelines) and treating the water at the power plant was estimated to be US$43.1 million. Revenue would be generated by reducing the oil and gas field operators' water disposal costs. A New Mexico law was signed in March 2004 that allowed the San Juan power plant to treat and utilise produced water as process water within the plant's boundaries. The law was written so that the New Mexico Oil Conservation Division would consider the water as being disposed of at the power plant, thereby exempting it from other environmental regulations administered by the Office of the State Engineer (Munson and others, 2009). However, the project was not implemented.

The EPRI study additionally examined costs for plants in other parts of the USA. It was estimated, for example, that a coal-fired power plant in a Rocky Mountain state located 4 km from CBM production wells would have total installed costs of US$15 million for the produced water treatment plant and pipeline, and operating costs ranging from US$0.169 to US$0.371 per barrel. The plant would treat 40,000 bbl (6.4 ML)/d of produced water.

Knutson and others (2012) investigated the potential use of produced water to supplement fresh water cooling sources at coal-fired power plants in the Illinois Basin (which covers parts of Illinois, Indiana and Kentucky). They found that although current produced water availability within the water-rich Illinois Basin is not large, flow rates of up to 257 ML/d are possible if CO_2-enhanced oil recovery and CBM recovery are implemented on a large scale. However, treatment and transport is expensive, with transportation costs tending to be the greater because of the distances between the water source and power plants. Estimated costs for treating the produced water ranged from US$2.6 to US$10.5/m^3. Using this water resource will be much more expensive than the source currently used. Building future power plants nearer to the areas with large volumes of produced water should lower costs and may make it economically viable, especially if water prices rise significantly.

5.3 Comments

As the need for fresh water becomes more acute and treatment technologies and their costs improve, produced water could become a valuable source of cooling water. Only a few power plants, mainly in Australia, are utilising this water source. However, it is a limited resource as it is only available over the life of the extraction project. Moreover, collecting water from each well within a field, transporting it, and managing the variability in flow over time can make it difficult, and expensive, to use. Some regulatory issues, such as water ownership in the USA, need to be addressed before produced water is more widely used at power plants. Financial incentives are a key to encourage its use.

Publically available data on the quantity and quality of produced water is lacking, particularly in China, India and South Africa. Even in the USA, where this information is available for some states, a national database is required. Standardisation of the definitions and measurements would facilitate data collection and reporting. National databases would help power plant operators to assess potential nearby water sources.

6 Water from deep saline aquifers

Saline aquifers could potentially provide an alternative or supplementary water source for nearby power plants, provided the water can be economically treated. Limits on the amount of CO_2 that can be emitted from fossil-fuel power plants have been implemented in Canada, and are likely to be introduced elsewhere. Capturing the CO_2 and its geological storage in saline aquifers would not only help to mitigate global warming, but could also produce water for power plant use. Adding carbon capture and storage (CCS) to a power plant can lead to significant increases in water demand. For instance, the addition of a solvent-based CO_2 capture system to a wet-cooled supercritical coal plant increases water consumption by 0.7 ML/GWh, whilst the increase for a dry-cooled pulverised coal plant is 0.72 ML/GWh (Neal and others, 2013). The water extracted from a saline aquifer may be sufficient to meet, or even exceed, the increased water requirements of carbon capture.

Deep saline formations constitute the largest potential global resource for underground storage of CO_2. They are typically filled with water that is too saline to serve as potential drinking or irrigation sources. Storing CO_2 in these aquifers may require the removal of water (also known as extracted, formation or produced water) in order to manage storage reservoir pressure, avoid induced seismicity, improve storage efficiency, reduce pressure on the caprock, and guide the movement of CO_2 plumes (Buscheck and Bielicki, 2015; Klapperich and others, 2014a). The heat and pressure in the extracted water present opportunities for energy recovery. However, potential deleterious effects of injecting CO_2 into the saline formation may include a decrease in pH, a resultant increase in metal concentrations, and increased salinity due to the reaction of CO_2 with the saline formation minerals (Kobos and others, 2011). In this report, water removed from saline aquifers is called extracted water to distinguish it from oil and gas production water.

There are a number of issues still to be resolved before CCS is commercially deployed. These include technical, economic, regulatory and legal issues, monitoring and validation, and public acceptance. Monitoring and measurement systems must be implemented to ensure that any escaping CO_2 is detected and leaks plugged. Some of the challenges for CCS are outlined in Court and other (2011). Geological storage of CO_2 does not present insurmountable technical barriers. There are a number of CO_2 injection projects in commercial operation, the majority of which use CO_2 for enhanced oil recovery. The Boundary Dam project in Canada is the first major coal-fired power plant scheme where the captured CO_2 that is not used for enhanced oil recovery will be injected into a saline aquifer at the nearby Aquistore site. Some 90% of the CO_2 emissions (~1 $MtCO_2$/y) will eventually be captured from a 110 MW unit.

This chapter discusses the availability and use of extracted water from the storage of CO_2 in onshore saline aquifers. It is unlikely that extracted water from storage locations in offshore or coastal areas would be utilised as the potential cost savings of using extracted water in place of sea water for desalination appears too small, even for a salinity as low as 10,000 mg/L TDS. In addition, sea water would provide a more reliable and long-term water source than a CO_2 storage project (Klapperich and others, 2014a).

6.1 Viability of use

Injecting CO_2 into saline aquifers and the resultant water production has been called enhanced water recovery (EWR). In the USA at least, it is likely that CO_2 storage will be restricted to formations with a TDS content greater than 10,000 mg/L in order to protect potential drinking water sources (Munson and others, 2009). Furthermore, CO_2 can be more effectively stored in deeper formations (below ~800 m) where it stays in a supercritical state. The extraction rate of the formation water depends on site-specific factors, such as the geology, confining layer permeability and heterogeneity, and reservoir pressure, as well as project design features such as the desired CO_2 injection rate.

6.1.1 Extracted water volume

Saline aquifers have been, or are being mapped, in a number of countries as part of their assessment of geological formations for the underground storage of CO_2. However, the volume and flow of water from the aquifers are not usually included in the assessment, so it is difficult to estimate the potential available volume of extracted water. Klapperich and others (2014a) calculated that the geologic storage of 9.12 $GtCO_2$/y (targeted for 2050 by the IEA to limit the global temperature rise to 2°C) could produce 11.4 billion m^3/y of water (or 31.2 million m^3/d). It is assumed that 1 t of injected CO_2 (800 g/L density at about 100°C and 5 MPa) would displace 1.25 m^3 of formation water. However, a large amount of the extracted water would be too saline to be economically treatable for beneficial use.

A number of projections of the amount of water that could be extracted when storing CO_2 from power plants have been made. Depending on the storage formation depth, an extraction ratio of one (which is a volumetric balance between injected CO_2 and the net extraction (extraction minus reinjection) of water) requires the removal of between 1.25 and 1.5 m^3 of water per tonne of injected CO_2. For a 1 GW coal-fired power plant this would require the net removal of about 10–12 million m^3/y of water from the storage formation (Buscheck and others, 2012). Some 1 billion m^3 of water could be extracted over a 50 y cycle of CO_2 injection from a 2.1 GW power plant into a single reservoir unit, if the pressure in the reservoir is to be maintained below the caprock fracture pressure (Sullivan and others, 2013). The volume of extracted water (after treatment) may be sufficient to replace or even exceed the increased water requirements of some CO_2 capture processes.

Bourcier and others (2011) estimated that a capture system on a 1 GW coal power plant might remove 6 $MtCO_2$/y for injection into a saline aquifer. This could displace some 8 million m^3/y (or about 22,000 m^3/d) of water. Reverse osmosis treatment with 40% recovery might generate some 3.2 million m^3/y of fresh water. This would provide half of the water usage of a typical 1 GW IGCC power plant, based on a plant use of about 2000 L/MWh.

Some 30% of the water requirements for a coal-fired power plant utilising wet cooling could be supplied by water extracted at a 1:1 volume ratio of CO_2 and water (CO_2 density is 800 g/L) based on storage of the captured CO_2 (Klapperich and others, 2014a). Water demand of power plants could be decreased to levels below the extracted water production volume if dry cooling and, possibly, even hybrid cooling were used instead of wet cooling. Thus these plants could become suppliers of both power and water.

An economic and engineering analysis of the capture of 90% of the 18.1 Mt/y of CO_2 emitted from four pulverised coal-fired power plants and one burning coal seam gas in southeast Queensland, Australia, indicated that water production from CO_2 injection could supply and/or offset their water requirements; the plants consume almost 36 GL/y. The CO_2 is transported some 190 km or 400 km to the Surat and Bowen Basins. Water production reduced the cost of CO_2 injection. The cost of treating the extracted water was relatively small when compared with the costs of CO_2 transport and storage. The water could instead be sold to provide some supplementary revenue for the CCS operator (Neal and others, 2013).

6.1.2 Extracted water quality and treatment

The quality of the extracted water varies between and within saline formations, and over time. It is highly dependent on the characteristics of the geologic formation. Data on water quality from saline formations suitable for carbon storage is scarce. Where available, it shows that salinity can vary from low to higher than sea water (which has a TDS content of ~23,000 mg/L). The extracted water from a saline aquifer in the Teapot Dome in Wyoming, USA, has a TDS content of 9263 mg/L, whereas that from the Ketzin CCS project in Germany is over 200,000 mg/L (IEAGHG, 2012). An analysis by Harto and Veil (2011) of deep saline formations in the USA found that the mean pH was between 7 and 7.5, and TDS content ranged from less than 5000 mg/L to over 300,000 mg/L. The majority of the formation waters was dominated by sodium chloride. Other common constituents included sulphate, magnesium, nitrate, potassium, calcium, bromine and bicarbonate. Minor constituents included silica, barium and fluorides. However, significantly less data were available for the minor constituents. More data on the chemical composition of deep saline aquifer waters need to be collected.

The extracted water requires treatment before it can be used in order to avoid corrosion and scaling problems in power plant cooling systems. The treatment system must be designed to manage the volumes and rates of extracted water from CO_2 storage. Extraction rates depend on site-specific factors, as described earlier. Desalination technologies are described in Section 3.3.2. Aines and others (2011) examined the treatment of extracted water using reverse osmosis. Water with a TDS content up to 85,000 mg/L could be treated in standard RO systems, whereas a TDS content of 85,000–300,000 mg/L would require a multi-stage process. High salinity water with TDS over 300,000 mg/L is unlikely to be treatable. Costs could be lower than the treatment of sea water if the aquifer pressure is utilised in the RO process.

Research is being carried out to reduce the cost of treating extracted water. This includes USDOE funded projects on supercritical membrane distillation (NETL, 2015a). Water treatment costs can be reduced by utilising waste heat from the coal power plant to drive thermal desalination processes (*see* Section 3.3.3). Energy obtained from excess pressure at the well head could be used to drive RO processes, which use a pressure gradient across a semi-permeable membrane to produce desalinated water (Bourcier and others, 2011). Extracted water may be warm enough to power low temperature geothermal generation, which could cover part of the treatment plant's energy penalty. The heat could also drive thermal desalination processes. The salinity gradient could provide a source of electricity that might offset some of the treatment costs when the TDS content is above that of sea water (Bauer and others, 2014).

The disposal cost of the residual concentrated brine would be minimal if it is re-injected back into the saline aquifer to help steer the CO_2 plume. Otherwise the brine could be injected into a separate formation or crystallised out to produce saleable salt. Recovery of rare earth metals and other by-products from the extracted water for sale could also help lower costs for the operator. Costs for treating extracted water at CCS sites in China and the USA are discussed in Sections 6.2.1 and 6.2.4, respectively.

6.2 Extracted water policy, availability and use

The following sections discuss the policy for and availability of extracted water in China, India, South Africa and the USA.

6.2.1 China

China's high and rising energy demand, underpinned by fossil fuels, has resulted in the country becoming the world's largest emitter of CO_2. Some 4.13 GtCO_2 were emitted from electricity and heat production in 2012 (IEA, 2014). Coal accounted for 78.5% (3784.9 TWh) of the electricity generated and emitted 948 gCO_2/kWh. Capturing and storing the CO_2 in saline aquifers, where possible, could potentially generate significant volumes of water.

The Chinese government has a set a target of peaking its CO_2 emissions before 2030. The importance of CCS for mitigating climate change has been recognised in its policies and funding of research and development (*see* Carpenter (2014)). The focus also encompasses the utilisation of CO_2, with the term carbon capture, utilisation and storage (CCUS) now being employed. For example, the *National 12th Five Year Special Plan for Carbon Capture, Utilisation and Storage Technology Development* (*see* http://www.most.gov.cn/tztg/201303/t20130311_100051.htm) was launched by the Ministry of Science and Technology in March 2013. In April 2013, the National Development and Reform Commission (which is responsible for China's overall policy/long-term planning) issued the *Climate [2013] Document No. 849 on promoting carbon capture, utilisation and storage pilot and demonstration* (*see* www.globalccsinstitute.com/publications/notice-national-development-and-reform-commission-ndrc-promoting-carbon-capture). It includes developing pilot projects for CO_2 storage in saline aquifers. A Roadmap for CCS demonstration and deployment has been produced by the Asian Development Bank in cooperation with the Chinese government (*see* http://www.globalccsinstitute.com/publications/roadmap-carbon-capture-and-storage-demonstration-and-deployment-peoples-republic-china). There are nine large-scale CCS projects at the planning stage, of which four are power generation projects (*see* https://www.globalccsinstitute.com/projects/large-scale-ccs-projects). A number of small-scale CCS projects are in operation.

CO_2 storage capacities in saline aquifers in China are uncertain due to limited geological knowledge, different assessment approaches and definitions (such as storage efficiency and CO_2 trapping mechanism), and other factors. Dahowski and others (2009) estimated a total theoretical storage volume of 3067 $GtCO_2$, of which the 16 onshore basins account for 2288 Gt. A higher theoretical estimate of 3016 $TtCO_2$ has been quoted, but due to security, economics and other factors, the actual available capacity reduces to ~0.119 Tt (Li and others, 2014b, 2015). This could potentially provide 4.09 Gt of extracted saline water (*see* Table 5). Other estimates of aquifer storage capacities are lower (Tang and others, 2014; Viebahn and others, 2015).

Table 5 CO_2 storage capacity associated with deep saline water recovery potential (Li and others, 2015)

Sedimentary basin	CO_2 storage capacity, Mt	Water recovery potential, Mt
Western Region		
Junggar Basin	4436	202
Tarim Basin	44688	1320
Turpan-Hami Basin	1542	51
Erdos Basin	4331	171
Qaidam Basin	10483	238
Jiuquan-Minle Basin	559	17
Qinshui-Linfen Basin	113	4
Eastern Region		
Hailar Basin	670	39
Songliao Basin	2075	167
Erlian Basin	1147	71
Bohai Bay Basin	6552	220
Northern Yellow Sea Basin	441	18
Southern Yellow Sea Basin	4925	199
East China Sea Basin	12600	508
Taixi Basin	1512	61
Taixinan Basin	2142	86
Pearl River Mouth Basin	7100	249
Beibuwan Basin	1125	53
Subei Basin	1691	59
Southern Region		
Nanxiang Basin	536	17
Sichuan Basin	9072	289
Jianghan Basin	953	34
Dongtinghu Basin	504	16

Saline basins are generally widely distributed in China. An analysis by Dahowski and others (2009) found that of the 1623 large point sources that each emitted at least 0.1 $MtCO_2$/y in 2007 (giving a total of 3890 $MtCO_2$), 54% had a storage basin within their immediate vicinity (*see* Figure 13). Some 83% had a storage formation within 80 km, and 91% within 160 km. The large point sources included 629 fossil fuel power plants, with the 585 coal-fired units accounting for ~2800 MtCO_2. A more up-to-date map of the location of coal power plants can be found in the Coal Power Atlas database, compiled by the IEA Clean Coal Centre (*see* http://www.iea-coal.org.uk/site/2010/coal-power-atlas). The storage basins investigated by Dahowski and others included depleted oil and gas basins, and unmineable coal seams, although these options are relatively limited. Deep saline aquifers will provide the majority of the storage capacity. More than 80% of the emissions from the large point sources could be captured, compressed, transported and stored at a cost of under US\$70/tCO_2 (Dahowski and others, 2012). The authors did not examine the amounts of extracted water that would be produced. But if all the CO_2 from the coal-fired power plants (2800 Mt) is stored in saline aquifers that generate water, then some 3.5 billion m^3 could be extracted (assuming 1 t of injected CO_2 displaces 1.25 m^3 of water).

Figure 13 Location of deep saline aquifers and large CO_2 sources in China (Li, 2014)

Viebahn and others (2015) estimated in their base case that between 34 and 221 GtCO_2 could be captured from coal-fired power plants to be built by 2050. Some 192 GtCO_2 could theoretically be stored as a result of matching these sources with suitable sinks, if optimistic assumptions about China's storage potential are applied. Under a more cautious approach, this figure falls to 29 GtCO_2. Even this lower figure could potentially generate some 36.3 billion m^3 of water (using the same assumptions as above), if stored in saline aquifers.

Over 60 coal power and chemical projects are operating in the eastern region of the Junggar Basin, Xinjiang. This province has the second largest coal reserves in China, after Shanxi, that are open to exploitation. Using a three-dimensional injection-extraction model, Li and others (2014b) estimated that 173 Mt of saline water could be produced when injecting 5 $GtCO_2$ into a typical formation. This is assuming there is sufficient water present. Thus 1 t of injected CO_2 displaces 3.46 m^3 of water. The extracted water would be enough for a large-scale chemical industry to operate for 10 years.

A CO_2 storage site has been identified in the Ordos Basin some 70 km from the proposed Shenhua Guohua oxyfuel combustion plant demonstration project. A strategic approach has been proposed and costed, whereby 10% of the expected 1 $MtCO_2$/y captured is sold for enhanced oil recovery and the remaining 90% is stored in the saline aquifer, which is close to the oil field. At the same time, the extracted water is sold for desalination in this water-stressed region, thereby generating additional revenue, alongside that for enhanced oil recovery (Minchener and others, 2015).

The USA and China are jointly funding a CO_2-EWR project at the GreenGen IGCC plant near Tianjin through the US-China Clean Energy Research Center (*see* http://www.us-china-cerc.org). About 0.1 Mt/y of CO_2 is currently captured at the plant; under future plans this will increase to between 1–2 Mt/y. A pre-feasibility study investigated two target aquifers in the Bohai Bay Basin, namely the Guantao and Dongying formations; the Guantao Formation was considered to be the better one. The water production well could be placed within 2 km of the CO_2 injection well (0.1 Mt/y injection rate for 10 y) and not encounter breakthrough of the CO_2 into the extracted water. It would need to be 6–8 km away from the injector well for the 1 Mt/y case to ensure limited breakthrough. Water would be extracted for 6 months before injection begins. Thereafter, CO_2 injection would be accompanied by ongoing water removal. A preliminary assessment put water treatment costs at RMB14–18 (US$2.1–2.7)/$m^3$. The water could be used as IGCC boiler water or for cooling purposes (Stauffer, 2014a,b). The next stage is a full feasibility study.

As part of the GreenGen project, Sullivan Graham and others (2014) evaluated the cost of treating the extracted water from the Dongying Formation for use as cooling and boiler water feeds. The costs were evaluated using the CO_2-PENS water treatment model and are based on US (and not Chinese) cost databases. The analysis used a salinity (TDS) range of 1,300–16,000 mg/L, and the desalination technologies considered were RO, nanofiltration, MSF and MED-TVC (*see* Section 3.3.2). Costs ranged from a low of US$1.12/$m^3$ for membrane treatments below 45°C (with ocean disposal of residual brine concentrate), to a high of US$6.23/$m^3$ for thermal treatment and a zero-liquid discharge disposal scenario. Expected recoveries from various treatments were all 90% or greater. Costs are likely to be lower when economies of scale are included for a full-scale, higher volume treatment facility (up from the 400 m^3/d pilot plant). The acid rate for pre-treatment, zero liquid discharge disposal, feed water temperature, and water transportation costs were found to be the most important factors within the total system costs.

6.2.2 India

India is the world's third largest emitter of CO_2 from fossil fuel combustion due to its reliance on coal. Some 1.04 $GtCO_2$ were emitted in 2012 from electricity production, when 1127.6 TWh of electricity was generated. Coal accounted for 71.1% (801.3 TWh) of electricity generation or 1219 gCO_2/kWh (IEA, 2014). Coal is likely to remain the mainstay for electricity generation for the foreseeable future. Thus capturing and storing CO_2 in saline aquifers could generate significant volumes of water if suitable saline aquifers are available nearby, as well as helping to lower emissions and mitigate climate change. Although the Indian government is funding research into, and development of, CCS (*see* Carpenter (2014)), it seems unlikely that CCS will be taken up until it is successfully demonstrated and implemented elsewhere in the world. No demonstration of coal-fired power plants with CCS is planned.

The assessment of CO_2 storage capacity in deep saline aquifers in India is still in its early stages. There is a lack of publically available geological data, and therefore calculations of storage capacity are speculative. The theoretical storage capacity in two papers quoted in Viebahn and others (2014) ranged from 102 to 360 $GtCO_2$. A more detailed assessment by Holloway and others (2008) qualitatively classified the sedimentary basins as having good, fair or limited saline aquifer CO_2 storage potential, because of insufficient geological information. The basins rated as good and fair contain hydrocarbon-bearing formations where saline water bearing sedimentary rocks are known to occur. Their total theoretical CO_2 storage potential is estimated to be 63.3 Gt. A more recent mapping of the Nagaur-Bikaner Basin in Rajasthan by Global Hydrogeological Solutions suggests that 500 $MtCO_2$ could potentially be stored in deep saline aquifers up to a depth of 1100 m below ground level (Chadha, 2014). This study was funded by the Department of Science and Technology as part of its programme to identify deep saline aquifers and their suitability for CO_2 storage.

Figure 14 shows that the sedimentary basins where saline aquifers can be found are located around the margins of India, and are mainly offshore. The onshore basins are in the states of Gujarat and Rajasthan in the northwest, and parts of south and southeast India (including Tamil Nadu and Andhra Pradesh). There are a number of industrial plants (including power plants), each emitting over 0.1 $MtCO_2$, that are located near to the saline basins. Although not shown in the Figure, it includes three of the ultra-mega coal power plants planned at this time (2006). There are not many coal power plants operating today that are near to the saline aquifers. Their location can be found on the Coal Power Atlas (*see* http://www.iea-coal.org.uk/site/2010/coal-power-atlas). There is some CO_2 storage potential in the states in the northeast portion of the country (Assam, Tripura and Mizoram), but there is only one coal-fired power plant in this region. The Ganga Basin, which lies beneath the Ganges Plain, was considered to have limited CO_2 storage potential because of the possible conflict of interest with the use of (relatively shallow) ground water for potable water supply and agriculture. The central part of India is considered to be unsuitable for CO_2 storage since basalt or crystalline basement rocks occur at the surface. It is possible that sedimentary rocks may occur beneath the basalt in some areas, but imaging problems would probably prevent effective site characterisation and monitoring (Holloway and others, 2008).

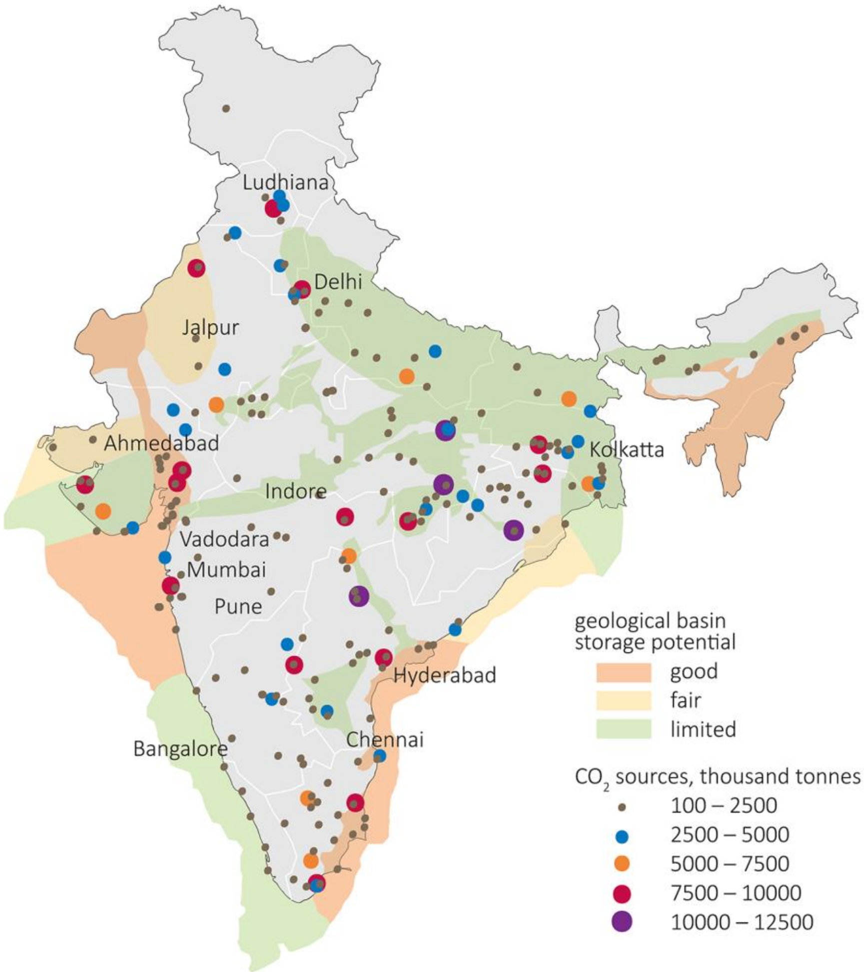

Figure 14 Relationship between existing large CO_2 sources and sedimentary basins (deep saline aquifers) in India (Holloway and others, 2008)

Viebahn and others (2014) estimated, under different energy scenarios, that between 13 and 111 $GtCO_2$ may be captured from coal-fired power plants to be built by 2050. Some 75 $GtCO_2$ could theoretically be stored in nearby (up to 500 km away) oil and gas fields and saline aquifer basins if optimistic assumptions about the country's CO_2 storage potential are applied. If a cautious approach is taken that considers the effective storage potential, then only a fraction may potentially be stored. In practice, this potential will decrease further with the impact of technical, legal, economic and social acceptance factors. Consequently, the amount of extracted water from saline aquifers may be limited.

No assessments have yet been made of the potential water recovery from the saline basins. An estimate of the CO_2 storage capacity of the basins categorised as good and fair by Holloway and others (2008) is given in Table 6. It was assumed that one or more deep saline aquifers suitable for CO_2 storage were present over 50% of the basin and that the basins have an average storage density of 0.2 $MtCO_2/km^2$. The water recovery potential has been calculated using the assumption that 1 t of injected CO_2 displaces 1.25 m^3 of water. The amounts are speculative as, among other factors, the quantity of water in the basins is unknown and no demonstration of CO_2 injection into the aquifers has yet occurred. In addition, the assessment includes offshore portions of the basins.

Table 6 Estimated saline aquifer CO_2 storage capacity (Holloway and others, 2008)

Sedimentary basin	Estimated CO_2 storage capacity, Mt	Estimated water recovery*, million m^3
Assam Basin	5600	7000
Assam-Arakan Fold	6800	8500
Mahanadi Basin	8600	10750
Krishna-Godavari Basin	4000	5000
Cauvery Basin	6000	7500
Mumbai Basin	12000	15000
Cambay Basin	5600	7000
Barmer Basin	1000	1250
Kutch Basin	7100	8875
Jaisalmer Basin	3000	3750
Bikaner-Nagaur Basin	3600	4500
Total	63,300	79,125

* Calculated assuming 1 t of injected CO_2 displaces 1.25 m^3 of water

6.2.3 South Africa

South Africa is heavily reliant on coal to meet its energy needs. In 2012, nearly 94% (239.3 TWh) of its electricity was generated from coal, which emitted 233 $MtCO_2$ or 973 gCO_2/kWh (IEA, 2014). If it is possible to capture and store the CO_2 in nearby saline aquifers, then a significant amount of water may potentially be extracted.

CCS is one of the technical approaches to mitigate global warming that is being supported by the South African government. To better understand the potential of CCS in the country, the government established the South African Centre of Carbon Capture and Storage (SACCCS) in 2009 (with assistance from international governments and industry). The SACCCS (*see* http://www.sacccs.org.za/) helped to develop a CCS roadmap, which aims to establish an operational CCS demonstration plant by 2020 (*see* www.sacccs.org.za/roadmap/). Commercial operation is planned for 2025. The Roadmap was subsequently endorsed by the government. An atlas on the geological storage of CO_2, and accompanying technical report, were published in 2010 (Cloete, 2010; Viljoen and others, 2010).

Results from the Atlas indicate that South Africa has ~150 Gt of theoretical CO_2 storage capacity, of which some 98% is in offshore basins. Only two onshore basins were identified that are likely to contain saline formations – the Algoa and Zululand Basins, with storage potentials of ~0.4 $GtCO_2$ and ~0.46 $GtCO_2$, respectively. The Zululand Basin on the east coast is the nearest one to the coal power plants (*see* Figure 15). The Algoa Basin is too far away to be economically viable.

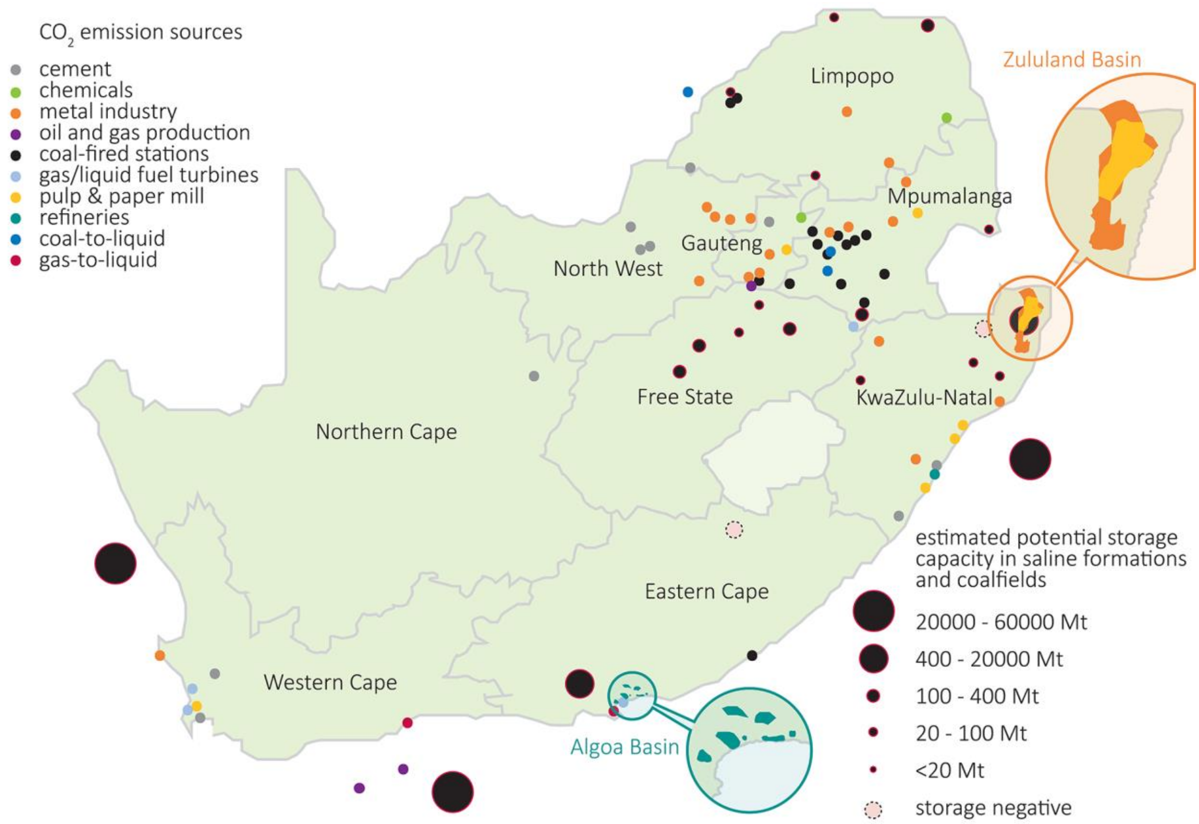

Figure 15 CO_2 emission large point sources and potential storage sites in South Africa (Vincent and others, 2013)

Water recovery from the saline formations has not been investigated. Assuming 1 t of injected CO_2 displaces 1.25 m of water, then some 575 million m^3 may possibly be extracted from the Zululand Basin. The salinity of the water varies from about 13 to 38 g/L (Viljoen and others, 2010). But even so, the basin is some 500 km away from the power plants in Mpumalanga province, making the water expensive to transport (no infrastructure has yet been built), and the amount of water would not last very long. The storage capacity would only be sufficient for the 4110 MW Majuba power plant, the nearest one to the basin, emitting 22.1 MtCO_2/y for 20 years (this requires a storage capacity of ~0.44 Gt). The location of the various coal power plants can be found on the Coal Power Atlas (*see* http://www.iea-coal.org.uk/site/2010/coal-power-atlas). The basin is being investigated further due to limited and poor geological data availability (Chabangu and others, 2014). This could increase estimates of its storage capacity.

Although parts of the Karoo Basin may be nearer to some power plants, the CO_2 storage potential is poor (Cloete, 2010; Viljoen and others, 2010), and therefore water recovery would be low. This is because of the presence of extensive dolerite intrusions, and the low porosity and permeability of the sandstones in the deep saline formations.

To conclude, it seems unlikely that extracted water from deep saline formations will be able to provide an alternative water source for coal power plants in South Africa.

6.2.4 USA

The USA is the second largest global emitter of CO_2. Some 2087 $MtCO_2$ was released from electricity and heat production in 2012, with electricity generation accounting for 481 gCO_2/kWh (~2054 $MtCO_2$); electricity output was 4270.8 TWh. Coal accounted for nearly 38% of electricity generation, and generated 912 gCO_2/kWh (~1468 $MtCO_2$). There is a large volume of saline aquifers in many regions of the USA that could potentially store the CO_2, and probably generate water. The latest Carbon Storage Atlas V estimates CO_2 storage capacity in onshore saline aquifers at 1710 to 14,528 Gt (NETL, 2015b).

The Federal government, through the Office of Fossil Energy and NETL, is supporting research into and the development of CCUS (*see* Carpenter (2014)), and various CCS technology development roadmaps have been published. Research topics include water treatment, especially desalination (*see* Section 6.1.2). In September 2015, the USDOE announced the selection of five projects that will study the feasibility of using saline water from CO_2 storage sites to produce fresh water. Following the feasibility and design phase, one of the recipients will be selected for a pilot project to validate water treatment technologies and reservoir management. These projects will also support the clean energy and climate goals announced by President Obama (USA) and President Xi (China) in November 2014 (USDOE, 2015). A goal of reducing net greenhouse gas emissions by 26–28% below 2005 levels by 2025 was announced by President Obama (The White House, 2014). Both the US and Chinese governments are funding research into CO_2 storage and EWR through the Advanced Coal Technology Consortium of the joint US-China Clean Energy Research Center (*see* http://www.us-china-cerc.org/Advanced_Coal_Technology.html).

As well as researching the technology, NETL is investigating the infrastructure and regulations necessary to implement large-scale CCS from a regional perspective through its Regional Carbon Sequestration Partnership (RCSP) programme. One of the working groups formed by the RCSPs, is the Water Working Group, whose goals are to address the concerns of the public and industry regarding CCS technology and its potential relationships with water resources (Klapperich and others, 2014b).

The largest demonstration of the capture of CO_2 from a coal power plant in the USA, and its transport and storage in a saline aquifer, is the Citronelle project. A small amount of flue gas (equivalent to the amount produced when generating 25 MW of electricity) is diverted to the CO_2 capture unit at the James M. Barry plant in Bucks, Alabama. The resultant CO_2 is transported via a ~19 km pipeline to the injection well in the Citronelle oil field (*see* https://sequestration.mit.edu/tools/projects/citronelle.html; Koperna and others, 2014; NETL, 2015b). Originally, this was a three-year project to test CO_2 flow, trapping and storage mechanisms, and to monitor post-injection storage. But CO_2 is continuing to be captured. Some 115,000 tCO_2 (as of June 2015) has been stored in the aquifer; injection began in August 2012. However, water was not intentionally extracted in this project.

Two commercial coal-fired power plants with CCS are currently under construction, but both will use the captured CO_2 for enhanced oil recovery. These are the Kemper County IGCC facility (~3.5 $MtCO_2/y$) near Meridian, Mississippi, and the W A Parish power plant (~1.4 $MtCO_2/y$) in Fort Bend County, Texas, both of which are due to become operational in 2016.

A large number of power plants across the country are located above saline aquifers, which may potentially provide an alternative water source (*see* Figure 16). The Figure was created through NETL's National Carbon Sequestration Database and Geographic Information System (NATCARB) viewer (*see* http://www.netl.doe.gov/research/coal/carbon-storage/natcarb-atlas). Data in the NATCARB database are supplied through the RCSPs and the site characterisation projects funded by the American Recovery and Reinvestment Act. It includes information on the geochemistry of the saline water, but has little information on the quantity. Most of the saline data, especially those associated with deeper formations, came from locations associated with oil and gas exploration. The US Geological Survey has a National Produced Waters Geochemical Database that contains data on the composition of saline water brought to the surface through oil and gas exploration (*see* http://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822349-data).

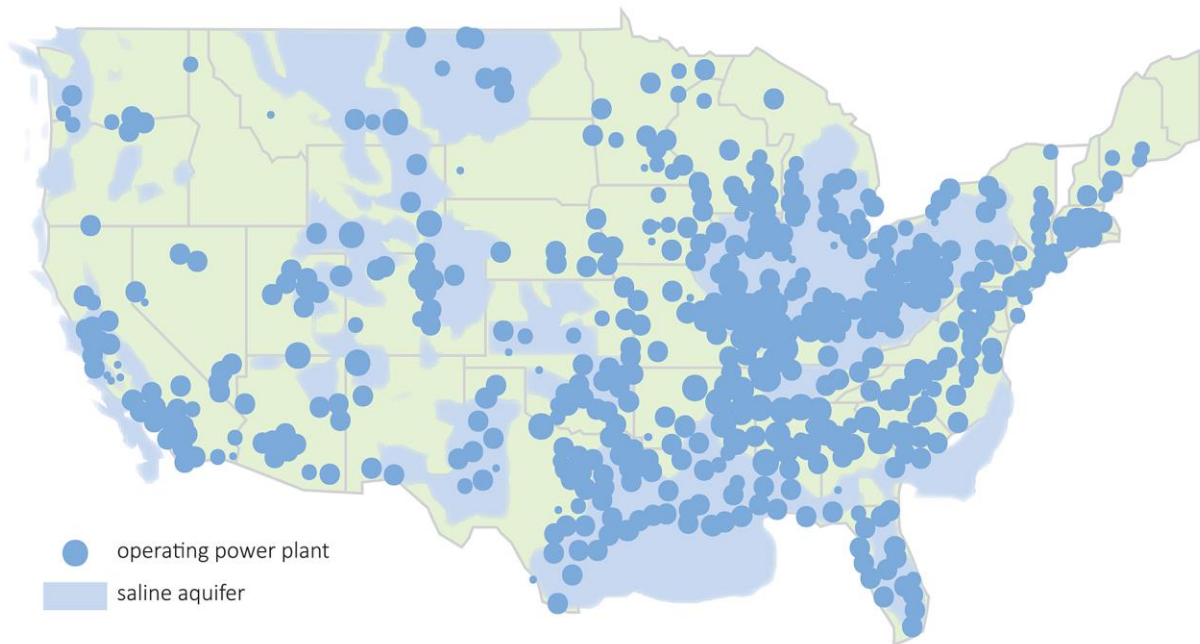

Figure 16 Location of US power plants and saline aquifers (derived from http://natcarb.netl.doe.gov/)

An earlier internet-based geographic information system, the 'Alternative Water Source Information System', was compiled to identify potential sources of saline water for coal-fired power plants that were operating in 2006 (*see* www.all-llc.com/projects/coal_water_alternatives/; Arthur, 2011). Since the data were obtained from the NATCARB database, only the location and quality of the saline water is included. Arthur (2011) reports that while several government agencies, including the US Geological Survey and the USDOE, publish national ground water data, there is no single set containing the location, quality and quantity data necessary to determine the availability of saline water for use at thermal power plants.

The cost of managing water will be an important factor in determining if it makes sense to extract water from a given formation. These costs will vary significantly depending upon the location, specific water characteristics, and the management strategy selected. The NETL has developed a CO_2 Saline Storage Cost Model, which is a spreadsheet that estimates the revenues and capital, operating and financial costs for a

CO_2 storage project in a saline reservoir (*see* http://www.netl.doe.gov/research/energy-analysis/analytical-tools-and-data/co2-saline-storage). Design choices in the baseline case values were developed to be consistent with the power plant designs developed by NETL in their baseline power plant cost studies. Over 550 Gt of potential storage capacity is estimated to be available for under US$10/t$CO_2$ (US$ year 2011). This is more than the 315 Gt storage capacity required if 90% of the CO_2 emissions from power plants and stationary industrial sources were captured over the next 100 years (Morgan and Grant, 2014). The model is being expanded to include cost data for water extraction, utilisation and disposal.

The Water, Energy, and Carbon Sequestration Simulation Model (WECSsim™), developed by Sandia National Laboratories and NETL, can be used at a local, regional or national scale to assess combining a coal- or natural gas-fired power plant with CO_2 capture, transport and storage in deep saline aquifers, along with water extraction and treatment for use in the power plant. The model includes sensitivity analyses of the capital, variable, and CO_2 and water treatment systems costs. The overall cost to capture, transport and store CO_2 at a national scale range from US$74 to US$208/t stored (US$96 to US$272/t avoided emissions) for the first 25 to 50% of the 1126 power plants in the database. Costs rise to US$1585 to over US$2000 (US$2040 to well over US$2000/t avoided emissions) for the remaining 75 to 100% of power plants, which includes all the natural gas-fired plants in the USA (Kobos and others, 2014). At a local scale, CCS and associated water extraction and treatment costs can be evaluated for individual power plants under different scenarios.

The WECSsim™ model can select the CO_2 sink that has the lowest cost for a specified power plant from information input by the user about the plant (such as how much CO_2 capture is required, and aspects of saline water extraction and treatment). For example, the levelised cost of electricity rises from ~US$0.067/kWh before CCS to ~US$0.15/kWh if the San Juan Generating Station near Farmington, New Mexico, utilises the Morrison Formation within the San Juan Basin. However, the model selects the Estrada Formation primarily because of the lower levelised cost of electricity (~US$0.13/kWh). This is despite the cost of treated water for the Morrison Formation being slightly lower (US$5.68/t) then that for the Estrada Formation (US$5.69/t). The US$ year is 2010.

An earlier paper (Kobos and others, 2011) evaluating CO_2 storage in the Morrison Formation found that ~1500 L of saline water may be displaced for every tonne of CO_2 stored. A total of 5.3 ML/d of potential treated water could be produced when capturing 50% of the CO_2. This represents 6% of the San Juan Generating Station's annual demand for water. Water present in the formation could supply the power plant for about 162 years.

An analysis by Bourcier and others (2011) indicated that RO plants for treating extracted water with a similar salinity to sea water (up to 85,000 mg/L TDS) can be built and operated for about half of the cost of sea water desalination. This is provided sufficient over-pressure (from CO_2 injection) exists to supply the pressure needed to drive the RO process. Costs are estimated at US$0.32–0.40/$m^3$ permeate produced when generating 23,000 m^3/d of fresh water. Without well-head energy recovery, costs rise to US$0.60-.80/$m^3$ permeate produced, similar to conventional sea water desalination. The analysis included all surface facilities, transfer pumps, and piping. It did not consider the cost of water extraction and disposal of the residual brine back into the aquifer as these are site dependent. For the net removal of 1.25 to 1.5 m^3 of water per tonne of injected CO_2, the treatment costs translate to US$0.40 to US$1.20/tCO_2 (Buscheck and others, 2012). Offsetting the cost would be the market value of the produced fresh water.

Sullivan and others (2013) used a systems approach to evaluate water treatment costs at three potential CO_2 storage sites (two formations in the Rock Springs Uplift, Wyoming, and the Frio Formation, Texas). Costs (which include residual brine disposal) typically fell within the range US$0.50–2.50/t$CO_2$ injected, but could reach US$30/t$CO_2$ under certain residual brine disposal conditions. The thermal treatment methods (MED and MSF distillation) were more cost effective than membrane ones in many cases, although pressure recovery methods for RO could mitigate this. The authors concluded that the costs indicate that treatment of extracted water may be feasible when compared with overall CO_2 storage costs. The treatment costs could become even more advantageous when the treated water is used to replace fresh water power plant consumption. Moreover, the cost can be offset by other savings (fewer wells, less monitoring, lower insurance costs) and the economic and permitting advantages that arise from reducing uncertainty (Buscheck and Bielicki, 2015).

6.3 Comments

The storage of CO_2 in saline aquifers may require substantial quantities of water to be extracted in order to reduce the risk of induced seismicity, CO_2 leakage, and subsidence, and to improve storage efficiency and CO_2 plume guidance. The volume extracted may be sufficient to replace, or even exceed, the increased water requirements of carbon capture and, in some cases, may even enable a power plant to become a net producer of both water and electricity. Numerous power plants are situated near saline aquifers that are widely distributed in China and the USA. However, this is not the case for India and South Africa, where onshore saline aquifers are less extensive, and few power plants are located nearby. There is a lack of data on the quantity and quality of water in saline aquifers, the suitability of aquifers for carbon storage, and their proximity to power plants, particularly in China, India and South Africa. This needs to be remedied.

The extracted water will require treatment before it can be utilised at a power plant. The technology and costs will be site specific, and if the salinity is too high, may be economically unviable. The heat, pressure and salinity in the extracted water may provide opportunities for energy recovery, which could help lower water treatment costs. Moreover, there may be opportunities for synergistic integration of thermal power plants and water treatment systems, which could also reduce treatment costs. The large volumes required for cooling needs could result in large collection and transport costs, depending on the distance between the extraction wells and power plant.

The geological storage of CO_2 in saline aquifers with EWR is still in its infancy with few projects planned. There are still a number of issues to be resolved, such as technical, economic, regulatory and legal concerns, before CO_2 storage with EWR is deployed. Knowledge gaps and areas where additional and continued research are needed are listed in IEAGHG (2012). It is likely that the use of extracted water at power plants will be exploited first in regions where water resources are limited.

7 Discussion and conclusions

Energy demand is rising, while water is becoming a scarcer commodity in many parts of the world due to overexploitation, droughts, heat waves and other factors. Meeting the growing demand will place increasing stress on limited fresh water resources. The power generation industry is typically a country's largest industrial user of fresh water. Consequently, the vulnerability of the power generation industry to constraints in water availability can be expected to increase. Hence non-fresh water sources will become increasingly important as an alternative or supplementary source.

Power plants need a reliable supply of water, of a specified quality, that is available over the lifetime of the plant (which can be over 40 years). The economic feasibility of using alternative water sources largely depends on the distance to the power plant, the amount of water available, its price, and treatment costs. Costs will be site-specific. All of the non-fresh water sources discussed in the report are typically of lower quality than fresh water, and therefore, require treatment before use. This is to avoid corrosion, scaling and fouling of pipes and cooling equipment. Treatment, such as desalination, can be energy-intensive and expensive. Water with too high a salinity, such as some produced water from oil and gas wells or from saline aquifers, may be too costly to treat and use. Municipal waste water (MWW) is probably the most economically viable alternative or supplementary source due to its quality and abundance. In addition, its quality is often less variable than other sources. The quality of produced water, for instance, can vary over time. Water treatment plants are designed for a specified water quality, and so are more efficient, and cost effective, with the designed quality. New treatment technologies that can meet the quality requirements of power plants at a much lower energy input (and cost), and new materials that can withstand lower water qualities still need to be developed. This could accelerate the use of alternative water sources.

Sea water can provide an unlimited supply of water for coastal power plants. Desalination could deliver their fresh water requirements, which will be lower for those designed to use sea water in the cooling towers and for flue gas desulphurisation. Integrating the power plant and desalination units has both economic and environmental benefits. The majority of the energy needs of a desalination plant using thermal processes can be met by utilising waste or low-grade heat from the power plant, reducing energy costs. Furthermore, the efficiency of the desalination plant is improved, and the volume of cooling water required in the power plant is lowered. If the desalination plant is designed with excess capacity, the power plant can become a co-producer of power and water, instead of a water consumer. The main disadvantage is that the integrated system is harder to operate due to seasonal variability in electricity demand.

Desalination of mine water, produced water from oil and gas wells, extracted water from saline aquifers, or brackish ground or surface water could potentially supply the requirements of inland power plants. This could also turn water pollution liabilities into a water resource as desalination technologies not only remove salts from water, but also other pollutants such as metals, nutrients and organics. The disposal of the resultant brine concentrate could be an issue for inland power plants or coastal plants situated in enclosed lagoons or bays. The production of saleable salt through, for example, evaporation or freeze crystallisation, could help offset treatment costs.

Treated MWW is one of the more promising alternative water sources because of its abundance and often wide geographic distribution within a country. It could provide a drought resistant, plentiful water source to nearby power plants as the use of domestic water is usually one of the last to be curtailed. Rising urbanisation and population growth will increase the demand for domestic water and hence, the volume of MWW available in the future. Both power plant operators and municipalities can benefit financially and environmentally from its reuse. A number of power plants worldwide are already successfully utilising MWW for cooling purposes. Human health concerns over the possible emission of bacteria and other trace contaminants in the aerosols from cooling towers can be minimised with proper control and management of cooling operations. However, competition for its use is increasing in some areas, with multiple users seeking the same MWW source.

Utilising mine water from abandoned or active mines could turn a pollution liability into a resource. The technical feasibility and economic viability of exploiting this source can be seen in its use at mine-mouth power plants. Cool water withdrawn from abandoned underground mine pools is a more efficient cooling agent than surface water that is subject to summer heating, thus improving power plant efficiency. However, the volume of water withdrawn should not be in excess of the pool's recharge rate as this could affect the local hydrology or increase the likelihood of subsidence.

Produced water from oil and gas wells is a limited resource as it is generally only available over the lifetime of the extraction project. Moreover, collecting water from each well within a field, transporting it, and managing the variability in flow and quality over time can make it difficult, and expensive, to use. Nevertheless, the combination of heat, pressure and salinity in the produced water may provide opportunities for energy recovery, and help lower the cost of its treatment. Where available, the elevated pressure could drive reverse osmosis processes. Some water may be warm enough to power low temperature geothermal generation or drive thermal desalination processes. In cases where the salinity is higher than sea water, then the salinity gradient could provide a source of electricity that might offset some of the treatment costs. However, work is required to bring these potential applications to the marketplace. Some regulatory issues, such as water ownership in the USA, still need to be addressed. Only a few power plants are currently exploiting this source. These are mainly in Australia where power plants are firing coalbed methane (CBM) and utilising the produced water from the coalfield for cooling purposes.

Another approach to minimise fresh water use at coal power plants is to take advantage of the possible need for CO_2 storage to mitigate global warming. This synergistic approach could, depending on site specific conditions, use deep saline formations as both a CO_2 storage site and as a source of water. Extracting water from the aquifers can improve CO_2 storage efficiency, and reduce the risk of induced seismicity, CO_2 leakage and subsidence. As with produced water, utilising the heat, pressure and salinity in the extracted water, where possible, could help lower water treatment costs. No power plant is yet utilising this water source, although a few projects are planned. There are still a number of issues to be resolved, including technical, economic, regulatory and legal concerns, before CO_2 storage with enhanced water recovery is deployed.

The Chinese government has recognised the need to use more non-fresh water sources, with targets set for the reuse of recycled water (which includes MWW) and mine water. The majority of MWW is currently discharged (some 46.6 billion m^3 in 2012), with only a small proportion reused (some 8% in 2008). Therefore, it could potentially provide a plentiful water source to local power plants, especially as municipalities, provincial capitals, and municipalities with independent planning status are required to collect and treat all waste water by 2017. New power plants in North China have been given priority access to recycled water and mine drainage. The policy to site new power plants near coal mines in North China will therefore encourage the use of mine water and MWW (where possible).

The utilisation of desalinated sea water is likely to increase as a result of the policy that requires new power plants in coastal regions to use this source to supply their fresh water requirements. China already has experience in utilising the waste heat from coal-fired power plants to drive the thermal desalination processes. In some cases, excess water is generated to supply drinking water to the local city. There is a lack of publically available data on the quantity and quality of produced water from conventional oil and gas wells, which needs to be filled. China is beginning to exploit its large resources of unconventional gas (including CBM), but progress is slow due to unfavourable geological conditions, lack of data, and other factors. Saline aquifers are widely distributed across the country, and could potentially serve as both a CO_2 storage site and water source for the numerous power plants located above or nearby. The feasibility of CO_2 storage with water extraction is being investigated at the GreenGen integrated gasification combined cycle power plant. Dahowski and others (2012) calculated that over 80% of CO_2 emissions from large point sources (including 2.8 Gt from coal-fired power plants) could be captured, compressed, transported and stored at a cost of under US\$70/tCO_2.

Water is fast becoming a scarce commodity in India; a number of coal-fired power plants have had to reduce output, or even shutdown, at times of drought. The principal non-fresh water sources available are MWW, and mine and sea water. The government has started to emphasize the need to reuse and recycle water. In January 2016, the Cabinet government approved a new tariff policy which, among other things, has made it mandatory for power plants to use treated MWW available in their vicinity (within a 100 km radius). Maharashtra is one state that is planning to supply MWW to six of its coal power plants. Almost 80% of the water supplied for domestic use in urban areas is released as waste water, a large proportion of which is untreated. Many of the municipal plants are non-operational for various reasons or under-utilised. More efficient operation of these facilities would increase the amount of MWW available for beneficial reuse, as well as conserving fresh water and mitigating water pollution.

Desalination has also been recognised by the Indian Government as an important means of augmenting water supply to meet growing demand. A number of district administrations, such as the one in Tuticorin, have asked industries in their area (including coal power plants) to install desalination plants so that water allocated to them can be diverted for domestic use. Few power plants currently use mine water, which is mostly discharged into local streams or rivers. The amount available will increase with the government's goal of doubling coal production by 2019, although availability will depend on the location of the power plant. Water treatment costs should be lower than some countries as generally, the water is not acidic.

There are only a few coal power plants that could use produced water from conventional oil and gas fields, or extracted water from saline aquifers, as these sources are located around the margins of India, and are mainly offshore. This is also the case for some of the prospective shale gas basins. Power plants located by the coast are more likely to prefer desalinated water since sea water provides an infinite resource. The CBM areas are mostly in the east of the country, where nearby coal power plants could potentially exploit the produced water. Mapping of India's shale gas and CBM basins (and saline aquifers) is at an early stage. More needs to done to quantify the amount and quality of the water present in the basins.

South Africa is a semi-arid country, with limited fresh water resources. In the northern parts of the country, where the majority of the coal-fired power plants are located, both surface and ground water resources are nearly fully developed and used. There are few alternative or supplementary non-fresh water sources available for use at the power plants, principally acid mine drainage. It has been estimated that 440 GL/d of water from coal and metal mining is potentially available for reuse, some of which is available to nearby power plants. Mine water is currently employed at two power plants, Tutuka and Lethabo. Although water reuse is regarded by the government as an important strategy to balance availability with requirements, the majority of large coal-fired power plants are not located near to the metropolitan areas. This makes MWW transport expensive and impractical. MWW is employed for cooling purposes at three power plants (Kelvin, Rooiwal and Pretoria West), which were, or are, owned by the municipality. It seems unlikely that produced or extracted water will be used due to the distance of the shale gas deposits and saline aquifers from the coal power plants. The exploitation of CBM from the Ermelo coalfield, about 200 km from Johannesburg, and the Mopane coalfield, about 420 km northeast of Johannesburg, may possibly allow the use of some produced water. In addition, there are no coal power plants on the coast that could employ desalinated sea water. It seems most likely that acid mine water would be the first choice, despite the need for desalination, since there is so much acid mine water in the areas around the coal-fired power plants (this is currently done); it solves the dual issue of water use for power generation and acid mine pollution mitigation. Moreover, recovering water from acid mine drainage and the reuse of mine water are recognised by the government in its second National Water Resource Strategy (NWRS2) as important ways of increasing water availability.

Water availability is becoming an important issue in the USA with the increasing prevalence of droughts and heat waves in some parts of the country. MWW is the most used alternative water supply at thermal power plants; around 5% of the 1709 existing cooling systems are currently using it. The number is growing with 25% of the proposed 60 systems scheduled to come online between 2013 and 2022 planning to utilise this source (Bauer and others, 2014). Nearly half of existing coal-fired power plants have sufficient MWW available within a 16 km radius to meet their cooling water needs, and 75% have sufficient available within a 40 km radius (Vidic and others, 2009).

Coal power plants in the Appalachian and Illinois-Indiana coal mining regions have access to water that has accumulated in the thousands of abandoned mines in this region. Six small cogeneration plants in northeast Pennsylvania are already using treated mine pool water. Produced water from oil and gas wells could potentially become a significant source of water for coal power plants in the west, such as those in the Rocky Mountain region, and the central area of the country. Furthermore, the water from the Rocky Mountain region tends to have a total dissolved solids (TDS) content (salinity) of below 10,000 ppm, making it cheaper to treat than water from basins in the central and southern parts of the USA that can have a TDS content of over 200,000 ppm. Currently less than 1% of the produced water from onshore wells is beneficially reused (although 46% is injected underground for enhanced oil recovery); the amount generated is expected to grow in the future. Barriers to increasing the use of produced water include ownership, regulatory and liability issues, and lack of financial incentives. For instance, direct beneficial reuse of produced water discharged to surface bodies from production sites west of the 98th meridian is limited to agricultural or wildlife watering under 40 CFR 435 of the Clean Water Act.

A large number of coal power plants across the USA are located above saline aquifers. The latest Carbon Storage Atlas V estimates CO_2 storage capacity in onshore saline aquifers at 1710 to 14,528 Gt. The amount of water that could potentially be extracted with CO_2 storage has not yet been assessed, but could be considerable. The US Department of Energy is funding research into CO_2 storage with enhanced water recovery. In September 2015, it announced the selection of five projects that will study the feasibility of using saline water from CO_2 storage sites to produce fresh water. The Department is also continuing to fund research into the various alternative water sources, including desalination technologies.

There is a global need for more and better publically available data on the amount and quality of the alternative water sources, and their location relative to coal fired-power plants. National databases are generally lacking, and in countries where the data does exist, it is incomplete, often outdated, and is frequently based on estimates, rather than actual measurements. Standardisation of definitions and measurements would facilitate data collection and reporting. Good data would help power plant operators to assess the potential of nearby water sources. Regulatory and fiscal incentives would also encourage usage of non-fresh water.

The utilisation of economically treated non-fresh water by coal-fired power plants will reduce the burden on a nation's fresh water supplies, whilst enabling the plants to continue to deliver the energy that the nation requires. In certain cases, and with a suitable design of the on-site water treatment plant, a coal-fired power plant could become a supplier of both energy and fresh water, instead of a water consumer.

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