Water Energy Nexus: Coal- Based Power Generation and Conversion – Saving Water

Energy Working Group

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EXECUTIVE SUMMARY

This report was commissioned by the Asia-Pacific Economic Cooperation (APEC) to compile and analyse information on technology developments, best practices and current policy measures related to water use for coal-power generation and clean coal technologies in APEC economies. Information was collected from publicly available policy documents, research papers, technical reports, trade publications and supplemented by DNV GL's internal knowledgebase. The information from documents in the public domain was supplemented by contacting major utilities such as Enel and Eskom to get additional information on their publications.

Modern energy and water systems are interdependent. Rapid urbanization, economic growth and anthropogenic climate change are expected to place further pressure on energy and water resources. More than half of the APEC economies generate a significant (>33%) portion of their electricity from coal. However, the focus on clean development will necessitate a change in the status quo use of both coal and water resources.

The volume of water required for power generation depends on several factors, such as the generation technology, type of cooling deployed and site operating conditions. Cooling water use consumes the largest volume of water for a typical existing coal power plant, particularly ones using cooling towers. This is followed by wet Flue Gas Desulphurization (FGD) and boiler make-up water. It is also noted that newer low emission/high efficiency technologies, such as integrated gasification combined cycle (IGCC), circulating fluidized bed (CFB) and Carbon Capture and Storage (CCS) are not always more water efficient compared to conventional generation. The water used for these plants in turn consumes considerable amounts of energy as this water needs to undergo various physical and chemical treatment processes.

Four emerging technology categories for reducing water use in coal power generation were covered. First, water vapour can be captured from exhaust flue gas. Here, liquid sorption is the process that gives the best output water quality but the use of heat exchangers (i.e., condensate cooling) is the most mature technology and is also more energy efficient. The use of membranes for vapour capture is also being investigated by industry players. Second, re-use of water and Zero Liquid Discharge (ZLD) can be implemented using effluent municipal wastewater or industrial third-party wastewater. This can realize water savings, but only when using stable water quality sources, such as Cooling Tower (CT) blowdown or Reverse Osmosis (RO) brine as raw water. DNV GL finds that ZLD is most often implemented by power stations where discharge is either too expensive or not permitted and thus alternatives were required. Third, cooling water requirements can be optimized through operational improvements. Cooling ponds can help improve power plant efficiency and lower overall emissions when compared to cooling towers but are often overlooked. The use of advanced anti-fouling coatings is well known for cooling water conduits and their application has also shown promise for use in condenser tubes and heat exchangers. Fourth, membrane technologies are being used for forward osmosis to produce make-up water at a lower operating cost. In areas of high water stress, power plants can adopt dry cooling technologies or deploy non-fresh water sources for cooling. Other water-saving approaches, like matching appropriate water quality to the desired end use, will also reduce water pinch, for example surface run-off water for reuse in emission control technologies, such as FGD.

This report also highlights the research initiatives undertaken by APEC economies to address water use in coal technologies. Leading among these is the U.S.-China Clean Energy Research Center's (CERC) Water-Energy Technology funding to develop new approaches to reduce water consumption and CO_2 emissions from thermoelectric plants. The U.S. government is also supporting water efficiency research and demonstration projects through the Department of Energy's National Energy Technology Laboratory (NETL). In addition, the Electric Power Research Institute (EPRI) in the United States is supporting technology demonstrations as a member-funded organization of primarily U.S. electric utilities.

Many APEC economies, such as Australia; China; Hong Kong, China; New Zealand; and the United States intend to diversify their power generation mix in the future to significantly reduce the use of coal. This may lead to a decline in the water consumption for electricity generation depending on the technologies adopted and the demand growth. However, in some economies, such as China, the expanding use of coal conversion (into liquid or gas) technologies will place further stress on water resources due to their high water consumption. Some APEC economies (Malaysia; Russia; Viet Nam etc.) also expect to have coal dominate the growth of their power generation mix. The importance of adopting clean coal technologies has been strongly emphasized in respective planning documents of these economies, but the same level of emphasis has not been placed on addressing water stress emerging from this transition. However, the same economies are also considering replacing coal-fired with gas-fired power generation because combined cycle gas power plants are usually less water intensive. In addition, recent technological advancements indicate a higher maturity level for ZLD technologies for application in gas-fired compared to coal-fired power plants.

Table of Contents

LIST OF ACRONYMS

NEDO	New Energy & Industrial Technology Development Organisation
ACC	Air-Cooled Condenser
AIF	Annual Intake Flow
ALARA	As Low As Reasonably Achievable
AMBIO	Advanced Nanostructured Surfaces for the Control of Biofouling
APCO	Air Pollution Control Ordinance
APEC	Asia-Pacific Economic Cooperation
API	American Petroleum Institute
APS	Arizona Public Service Electric Company
APVMA	Australian Pesticide and Veterinary Medicines Authority
AS	Fly Ash Stabilizer
ASU	Air Separation Unit
BAT	Best Available Technology
BC	Brine Connector
BCL	Brown Coal Liquefaction
BDP	Biocidal Product Directive
BFBC	Bubbling Fluidized Bed Combustion
BLCC	Building Life-Cycle Cost
BMCC	Biomass and Clean Coal
BREF	Best Available Techniques Reference
BSER	Best System of Emission Reduction
Ca	Calcium
CA	Cellulose Acetate
CAA	Clean Air Act
CAPEX	Capital Expenditure
CAPWA	Capture of Evaporated Water with Novel Membranes
CBM	Coal Bed Methane
CBP	Chlorination By-Products
CCGT	Combined Cycle Gas Turbines
CCPI	Clean Coal Power Initiative, USA
CCS	Carbon Capture and Storage
CCT	Clean Coal Technologies
CCTDP	Clean Coal Technology Demonstration Program, USA
CCUS	Carbon Capture Utilization and Storage
CDS	Circulating Dry Scrubber
CEP	Conservation Efficiency and Productivity
CERC	U.S.-China Clean Energy Research Center
CERC-WET	CERC Water-Energy Technologies
CFBC	Circulating Fluidized Bed Combustion
CFE	Commission Federal de Electricidad, Mexico
CIC	Central Interconnected System
CIP	Clean In Place
CO	Carbon Monoxide
COACH	Cooperation Action with CCS China-EU
COC	Certificate of Compliance
COC	Cycles of Concentration
COS	Carbonyl Sulphide
CPO	Chlorine-Produced Oxidants
CPP	Clean Power Plan, USA
CPP	Condensate Polishing Plant
CPU	Condensate Polishing Unit
CRY	Crystallizer
CSA	Clear Skies Act, USA
CSC	Convective Syngas Cooler
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSLF	Carbon Sequestration Leadership Forum

CT[1]	Cooling Tower
CTG	Coal to Gas
CTL	Coal to Liquids
CTSL	Catalytic Two-Stage Liquefaction
CWA	Clean Water Act, USA
CWIS	Cooling Water Intake Structures
CZV BOD	Chemisch Zuurstof Verbruik Biological Oxygen Demand
DCFC	Direct Carbon Fuel Cell
DCL	Direct Coal Liquefaction
DENR	Department of Environment and Natural Resources
DICE	Direct Injection Carbon Engine
DOE	US Department of Energy
EA	Environmental Assessment
EAD	Environment Agency Abu Dhabi, UAE
ECC	Environmental Compliance Certificate
ECN	Energy Research Centre of Netherlands
EDI	Electro Deionization
EDTA	Ethylene-Diamine tetra-Acetic Acid
EEA	European Environmental Agency
EMACC	Enhanced Modular Air-Cooled Condensers
Enel	Ente nazionale per l'energia elettrica, Italy
ENIT	Ecole Nationale d'Ingenieurs de Tunis
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency, USA
EPC	Engineering Procurement and Construction
EPRI	Electrical Power Research Institute, USA
ERC	Energy Regulation Council
ESP	Electrostatic Precipitator
ETS	Emission Trading Scheme
EU	European Union
FAC	Florida Administrative Code
FAC	Flow Accelerated Corrosion
FBC	Fluidized Bed Combustion
FCC	Force Circulation Crystallization
FGD	Flue Gas Desulphurization
FO	Free Oxidant
FOA	Funding Opportunity Announcement
FRC	Free Residual Chlorine
FT	Fischer–Tropsch
GAC	Granulated Activated Carbon
GDP	Gross Domestic Product
GE	General Electric
GHG	Greenhouse Gas
GIS	Geographic Information System
GOJ	Government of Japan
GTI	Gas Technology Institute
H_2	Hydrogen
H2SO4	Hydrogen Sulphate
H_3O^+	Hydrogen Ion
HCL	Hydrogen Chloride
HCN	Hydrogen Cyanide
HF	Hydrogen Fluoride
HHV	Higher Heating Value
HNO_3	Hydrogen Nitrate
HRI	Heat Rate Improvement
HRSG	Heat Recovery Steam Generator
HTI	Hydrocarbon Technology, Inc
HTRI	Heat Transfer Research, Inc
IEA	International Energy Agency
IEC	Israeli Electric Corporation
IED	Industrial Emission Directive
IED	Industrial Emission Directive

IGCC	Integrated Gasification Combined Cycle
IPPC	Integrated Pollution Prevention Council
IPPC-FDM	IPPC- Food Drink and Milk
IRR	Internal Rate of Return
ITG	Independent Task Groups
ITRI	Industrial Technology Research Institute
IX	Ion Exchange
JCOAL	Japan Coal Energy Centre
JWP	Joint Work Plan
KEMA	Keuring van Elektrotechnische Materialen te Arnhem
KEPCO	Korean Electric Power Company
KETS	Korean Emission Trading Scheme
KSC	Kennedy Space Centre
LSE	Liquid Solvent Extraction
LUVO	hydrodynamic cleaning of rotary air
MAC	Magaldi Ash Cooler
MATS	Mercury and Air Toxic Standards, USA
MB	Mixed Bed
MED	Multi Effect distillation
MF	Microfiltration
MGD	Million Gallons per Day
MLD	Million Litres per Day
MOE	Ministry of Environment, Japan
MOEABOE	Ministry of Economic Affairs, Bureau of Energy
MSF	Multistage Flash
MSP	Mesoporous Silica Particles
MVA	Monitoring Verification and Accounting
MVC	mechanical vapour compression
MZ	Mixing Zone Guidance
NCEDA	National Centre of Excellence in Desalination, Australia
N-compounds	Nitrogen Compounds
NDRC	National Development and Reform Commission
NEPC	National Environment Protection Council, Australia
NEPM	National Environment Protection Standards, Australia
NETL	National Energy Technology Laboratory, USA
NF	Nano-Filtration
NIMBY	Not In My Backyard
NIST	National Institute of Standards and Technology
NJIT	New Jersey Institute of Technology
NO_x	Nitrogen Oxides
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NSPS	New Source Performance Standards
NWI	National Water Initiative
NZEC	Near zero emission coal
OEM	Original Equipment Manufacturer
OH^-	Hydroxide Ion
OP	Operational Policy
OPEC	Organization of Petroleum Exporting Countries
OPEX	Operational Expenditure
P-C	Pulse-Chlorination®
PCC	Pulverized Coal Combustion
PDP	Philippines Development Plan
PEP	Philippines Energy Plan
PF	Pulverised Fuel
PFBC	Pressurized Fluidized Bed Combustion

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Philippines DOE	Philippines Department of Energy
PHS	Priority Hazardous Substances
PLN	Perusahaan Listrik Negara, Indonesia
PM_{10}	Particulate matter 10 micrometres
POTW	Privately Owned Treatment Works
PS	Priority Substances
PUBCRIS	Public Chemical Registration Information Systems, Australia
RACC	Reheat Air combined cycles
RD&D	Research, Development and Demonstration
RO	Reverse Osmosis
ROI	Return of Investment
RSB	Regulatory & Supervisory Bureau, Abu Dhabi
RSC	Radiant Syngas Cooler
RSCP	Regional Carbon Sequestration Partnership
SCR	Selective Catalyst Reduction
SD	Spray Dryer
SDS	Spray Dry Scrubbing
SEC	Softening Evaporation Crystallization
SENER	Secretaria de Energia, Mexico
Si	Silicon
SING	Sistema Interconectado del Norte Grande, Chile
SIR	Savings-to-Investment
SNG	Synthesis Gas
SOFC	Solid Oxide Fuel Cell
SO_x	Sulphur Oxides
SS	Disulphide
TCEP	Texas Clean Energy Project
TDS	Total Dissolved Solids
THM	Tri-Halo Methane
TM	Technical Memorandum
TMC	Transport Membrane Condenser
TOC	Total Organic Carbon
TPC	Taiwan Power Company
TRC	Total Residual Chlorine
TRO	Total Residual Oxygen
TWG	Technical Working Group
UCLA	University of California Los Angeles
UF	Ultrafiltration
UIC	Underground Injection Control
UMD	University of Maryland
USEPA	United States Environment Protection Agency
VAB	Vehicle Assembly Building
VCE	Vapour compressor evaporators
WFD	Water Framework Directive
WQC	Water Quality Criteria
WRI	World Resources Institute
WWTP	Wastewater Treatment Plant
ZLD	Zero Liquid Discharge
ZLED	Zero Liquid Effluent Discharge

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LIST OF EXHIBITS

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1 INTRODUCTION

1.1 Background

Modern day energy and water systems are intrinsically intertwined. The use of water is ever present in energy production – extraction, refining, transport of fossil fuels, power generation, and in the growing of feedstock for biomass generation. On the other hand, the use of energy is indispensable in modern water treatment and distribution systems.

Rapid urbanization and economic growth have mounted pressures on both energy and water resources. For the coming decades, it is forecasted that these trends will continue. Also, the anthropogenic climate change will lead to changes in local weather patterns and in turn affect the availability of water in a region.

In a world where scarcity of water is a very important and a growing concern, meeting future energy needs could be constrained by availability of water. This is in recognition of the fact that power generation from conventional power plants consume and/or withdraw a considerable amount of water. For this reason, many power plants are located near large water bodies to ensure continuous access to large quantities of water. When water levels drop, especially during the period of droughts or very hot summers, electricity production may also need to be reduced. The problem is often compounded because hot summers are typically associated with high energy consumption. Some prominent examples of curtailed electricity production in APEC economies due to water stress are highlighted in Exhibit 1. These examples clearly show that policymakers need to address energy and water use in an integrated manner.

Location (Year)	Description
Philippines (2010)[1]	The El Niño weather phenomenon caused a drought that lasted several months, reducing hydro generation and causing electricity shortages.
China (2011)[1]	Drought limited hydro generation along the Yangtze river, contributing to higher coal demand (and prices) and lead to power cuts and blackouts.
USA (2012)[2]	Nuclear-power production hit its lowest seasonal levels in 9 years as drought and heat forced nuclear power plants from Ohio to Vermont to slow output.
Chile (2014)[3]	Persistent drought caused the average electricity bill to become 20% higher compared to 2010.

Exhibit 1: Examples of water impacts on electricity production in APEC economies

It is expected that 'business as usual' will further increase the magnitude and scale of such occurrences. This is because many regions in the world will be under greater water stress. A study by the World Resources Institute (WRI) concluded that among APEC economies Australia; Chile; China; Indonesia;

[1] International Energy Agency - World Energy Outlook Chapter 17, 2012.

[2] United States Department of Energy - Impacts of Long-term Drought on Power Systems in the U.S. Southwest, July 2012.

[3] The Economist - Energy in Chile - Keeping the lights on, June 2014.

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Mexico; Peru; the Philippines; Singapore; and the United States will face high to extremely high water stress by 2040 if current development patterns persist (see Exhibit 2)[4].

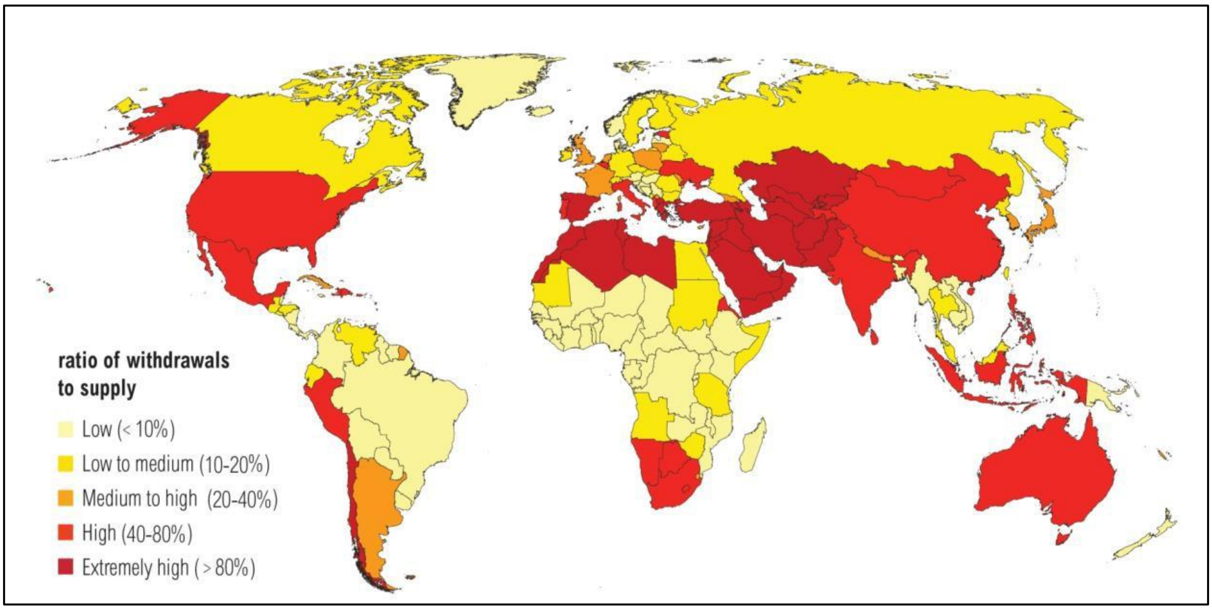

Exhibit 2: Water stress by country in 2040 under "business as usual" scenario[4]

It is in these scenarios when water and energy are interdependent on each other, policymakers will face complex challenges. Topics, like equitable allocation of water for energy production, among competing sectors, such as agriculture and industry, are now surfacing across APEC economies. It is estimated that thermoelectric power production alone comprises 41% of the total freshwater withdrawals in the United States, which is a bigger share than the agriculture sector[5]. In the case of China, power generation in 2010 was the largest industrial water user, accounting for approximately 10% of the economy's total water withdrawal[6]. On a global level, the International Energy Agency (IEA)[7] reported that water withdrawals for energy production in 2010 constituted 15% of the world's total water withdrawals.

Policy decisions for these sectors will have a profound impact on the business, environment and sustainability going forward. Policymakers need access to transparent and realistic information for making decisions beneficial to the society and environment in the long run. However, most of the information pertaining to the water energy nexus in general and moreover specifically to the coal-fired power sector is fragmented and difficult to compare and analyse. Various publications employing different levels of assumptions make it difficult for policy makers to clearly identify the specific dynamics of the water energy nexus.

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[4] Luo, T., R. Young, and P. Reig. 2015. "Aqueduct projected water stress rankings." Technical note. Washington, DC: World Resources Institute, August 2015.

[5] Dodder, R. S. (2014). A review of water use in the US electric power sector: insights from systems-level perspectives. Current Opinion in Chemical Engineering, 5, 7-14.

[6] Seligsohn, Deborah, et al. (2015). Opportunities to Reduce Water Use and Greenhouse Gas Emissions in the Chinese Power Sector, World Resources Institute.

[7] IEA (2012). Water for Energy Is energy becoming a thirstier resource?

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1.2 Definitions

It is important here to clearly define terms that are used throughout the report.

Water use:	This term can be generally characterized as withdrawal, consumption and discharge[8]
Water withdrawal:	Water removed from the ground or diverted from a surface water source—for example, an ocean, river, or lake—for use by the plant. This definition is similar to that provided by Kenny *et al.* 2009[9]. Although *water abstraction* would be more appropriate here.
Water consumption:	The portion of the water withdrawn that is no longer available to be returned to a water source, such as when it has been evaporated, or bounded in by-products, like wastewater sludge or gypsum. Kenney *et al*., 2009 define it slightly different by stating that consumption is the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment.
Water discharge:	The return of water to its original source or a new source. Water discharge represents the difference between withdrawals and consumption. For many thermoelectric power plants globally, much of the water they withdraw is later discharged, although often at higher temperatures, for example, as cooling water[10].
Base load:	Base load is the minimum level of electricity demand required over a period of 24 hours. It is needed to provide power to components that keep running at all times (also referred as continuous load). Base-load power plants will only be turned off during periodic maintenance, upgrading, overhaul or service.
Mid merit:	A power plant that fills the gap between base and peak load.
Peak load:	Peak load is the time of high demand. These peaking demands are often for only shorter durations. Peak demand could be understood as the difference between the base demand and the highest demand.

Exhibit 3: Key definitions for the report

[8] Energy-Water Nexus, Improvements to Federal Water Use Data Would Increase Understanding of Trends in Power Plant use by United States Government Accountability Office (GAO).

[9] Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J. K. and Maupin, M. A., 2009. Estimated Use of Water in the United States in 2005 (U.S. Geological Survey Circular, Vol. 1344) (Reston, VA; USGS).

[10] DNV GL makes a distinction between cooling water and wastewater discharge.

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1.3 Report objectives and structure

APEC economies must resolve the challenges of three paradigms. First, energy and water demand is rising which will need to be addressed holistically because of the intertwined nature of the two resources. Second, many of the economies have significant coal reserves which they would want to utilize for provision of energy. Third, the focus on clean development will necessitate a change from the status quo use of both coal and water resources. It is in this context that this report will share information on the latest technology developments, best practices and policy measures related to water use for coal power generation and production of synthetic natural gas (SNG) and chemicals from coal, including carbon capture and storage (CCS). A short overview of the adopted approach has been illustrated below:

a. Desktop research for compiling all the latest information pertaining to deployment of clean coal and water saving technologies across various member economies of APEC.
b. Review and analysis of relevant research papers and published case studies on adoption of latest water saving and Zero Liquid Discharge (ZLD) technologies for coal-fired power plants.
c. Generation of case studies along with sensitivity analysis for different scenarios.
d. Analysis of public information from DNV GL's internal database and on-going Research & Development projects for identifying cutting edge water reduction technologies for coal-fired power plants.
e. Objective analysis of the complied information by DNV GL's relevant subject matter experts and way forward.

Section 2 gives an introduction on coal generation, while Section 3 explains where water is used in the various process steps of coal fired generation, including coal conversion technologies and CCS. Section 4 lays out the emerging technologies for water use in coal generation under several broad categories with the use of case studies. Section 5 reviews individual APEC economies for recent/proposed regulation in energy-water/clean-coal and recent relevant technological deployments. Section 6 presents APEC initiatives for energy-water nexus topics including R&D setups, economy partnerships and work done in APEC. Section 7 concludes by drawing together content from the previous sections. Finally, the appendices provide additional information on the application of water savings techniques in gas-fired plants and water discharge limits for selected non-APEC economies.

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2 COAL POWER GENERATION AND WATER USE

Coal has been one of the world's most abundant and widely used fossil fuels with substantial global coal reserves. Coal fuels a substantial portion of world's electricity generation and dominates the power generation mix of several APEC economies as shown below. Generation from gas- and oil-fired and nuclear power plants are classified under 'Other thermal' and 'REN' covers generation from solar, wind, tidal, biomass and hydro power stations. More than half of the APEC economies generate a significant (>33%) portion of their electricity from coal.

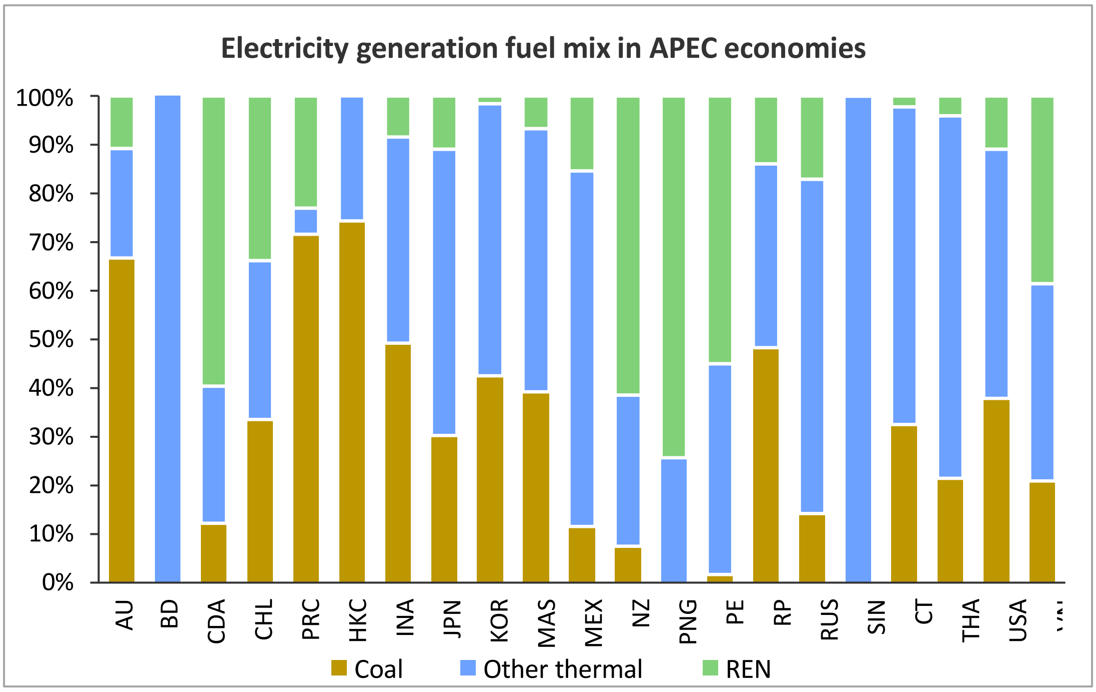

Exhibit 4: Share of major fuel types in electricity generation in APEC economies

Coal based power generation[11] is generally water intensive compared to some other forms of energy generation from alternative sources. Production of coal uses a substantial amount of water mainly for mining activities such as coal cutting and suppression of dust. The amount of water used for the processing of coal depends upon the type of mine (surface or underground) and on the processing and transportation requirements. Washing of coal reduces ash content and improves the combustion efficiency, however, at the cost of additional water consumption.

The volume of water required for power generation depends on several factors, including the generation technology, type of cooling technology deployed, type of environmental controls and the electricity demand profile. Exhibit 5 and Exhibit 6 show how the median water consumption and withdrawal differ widely for the different coal power generation technologies[12].

[11] This is with reference to coal-based power generation deploying conventional subcritical and supercritical combustion technologies.

[12] Data from Meldrum, James, et al., "Life cycle water use for electricity generation: a review and harmonization of literature estimates." Environmental Research Letters 8.1 (2013): 015031.

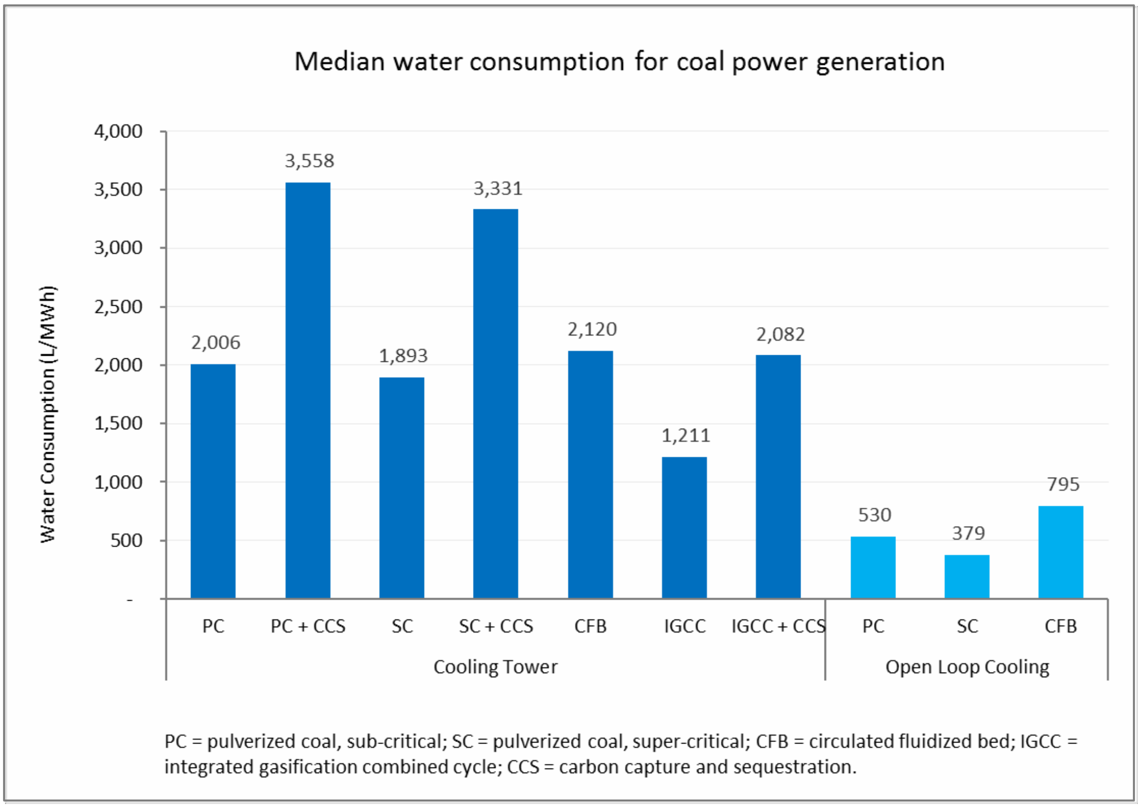

Exhibit 5: Median water consumption in different coal power technologies

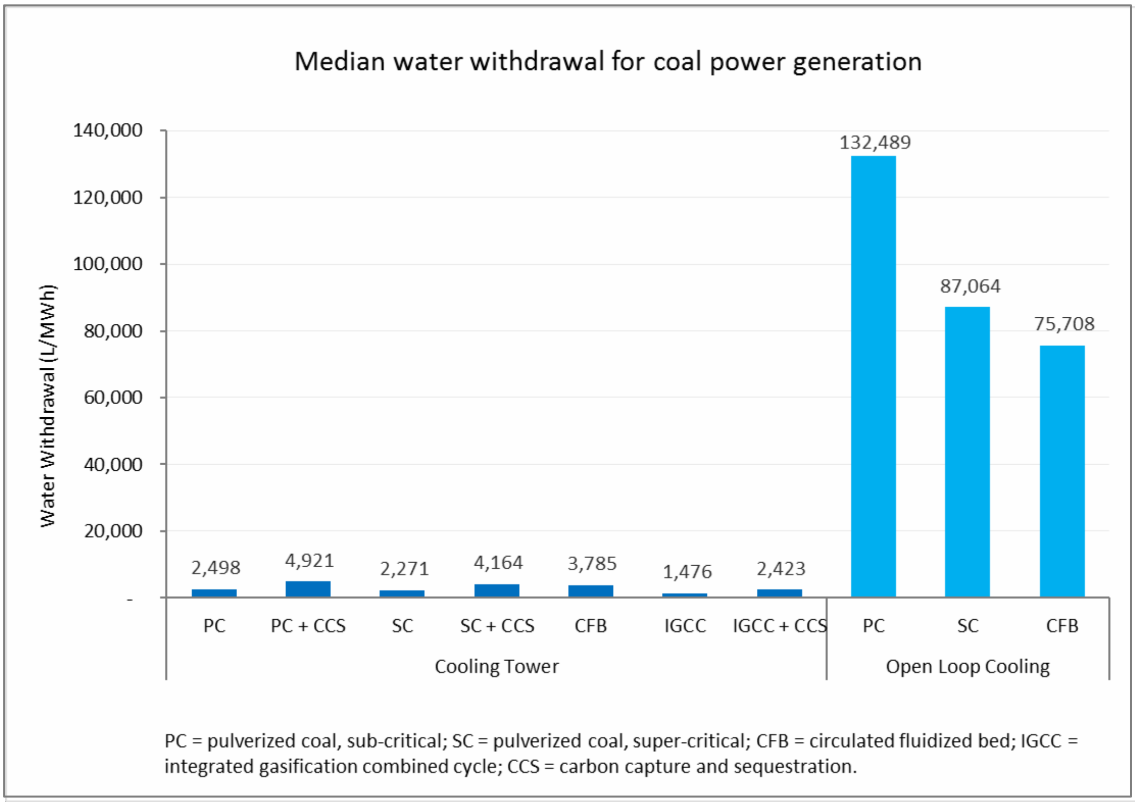

Exhibit 6: Median water withdrawal in different coal power technologies

From the above exhibits, it is clear that cooling towers have a higher water consumption compared to open loop cooling but the reverse is true when comparing the water withdrawal of the technologies. For open loop cooling, this is the opposite. The choice of technology depends on various engineering considerations, water availability and quality, overall economic viability and regulatory policies. Also, observed in the exhibits is that newer low-carbon technologies[13] are not always more water efficient compared to conventional generation. The water for these low-carbon generation plants in turn consumes considerable amounts of energy as it undergoes various physical and chemical treatment processes.

It is estimated[14] that four APEC economies (Australia; China; Russia; and United States) together account for about two-thirds of the world's total proven coal reserves. This indicates that they could invest significantly in clean coal technologies as part of their energy security goals. Exhibit 7 shows the extent to which APEC economies plan to expand coal-fired power generation.[15] The green bars show the plants already under construction (as of July 2016) as a percentage of installed capacity and blue bars show planned capacity (announced and pre-permit) as a percentage of installed capacity.

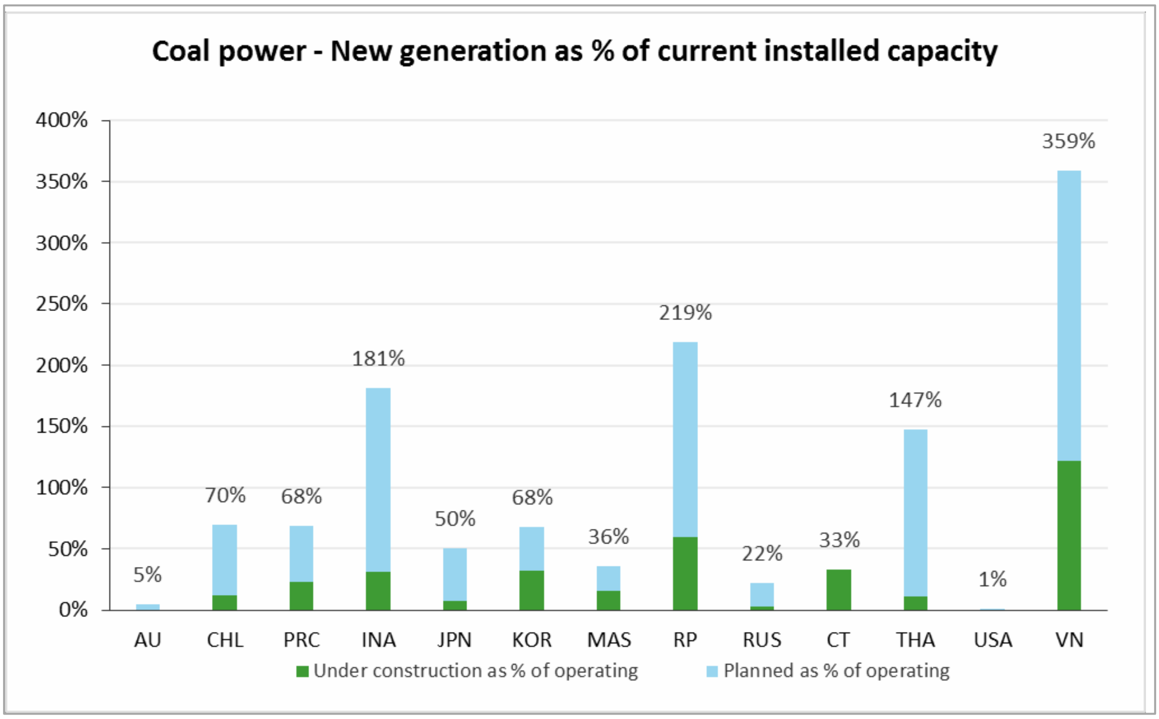

Exhibit 7: Level of new coal developments in APEC

Given the increased focus on cleaner energy following the Paris Agreement, this suggests that major APEC economies will focus on developing clean coal technologies to maximize availability of domestic energy resource while meeting climate goals. The water issue in coal technologies is critical because of the trends explained above.

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[13] This is also applicable for supercritical coal power plants equipped with CCS.

[14] BP Statistical Review of World Energy, June 2016

[15] Proposed Coal Plants by Country (MW) - July 2016 http://endcoal.org/global-coal-plant-tracker/

3 WATER USE IN COAL POWER GENERATION

The previous section highlighted the importance of water in power generation, specifically coal-fired power plants. This section expands on the water requirements in different process steps of generating electricity from coal.

3.1 Cooling Water Use

In industrial plants that use a once-through cooling water system, the cooling water is not 'consumed', but undergoes chemical and thermal changes before being discharged back into the water body.

Cooling for large combustion plants is very well described in two Integrated Pollution Prevention and Control (IPPC) documents under the Directive 2010/75/EU on industrial emissions[16] as listed below:

- Industrial cooling systems (December 2001)
- Large Combustion plants (July 2006)

Herein, best available techniques are described for the different types of cooling technologies, namely Once-through, Wet, Hybrid and Dry Cooling[17], as indicated in Exhibit 8.

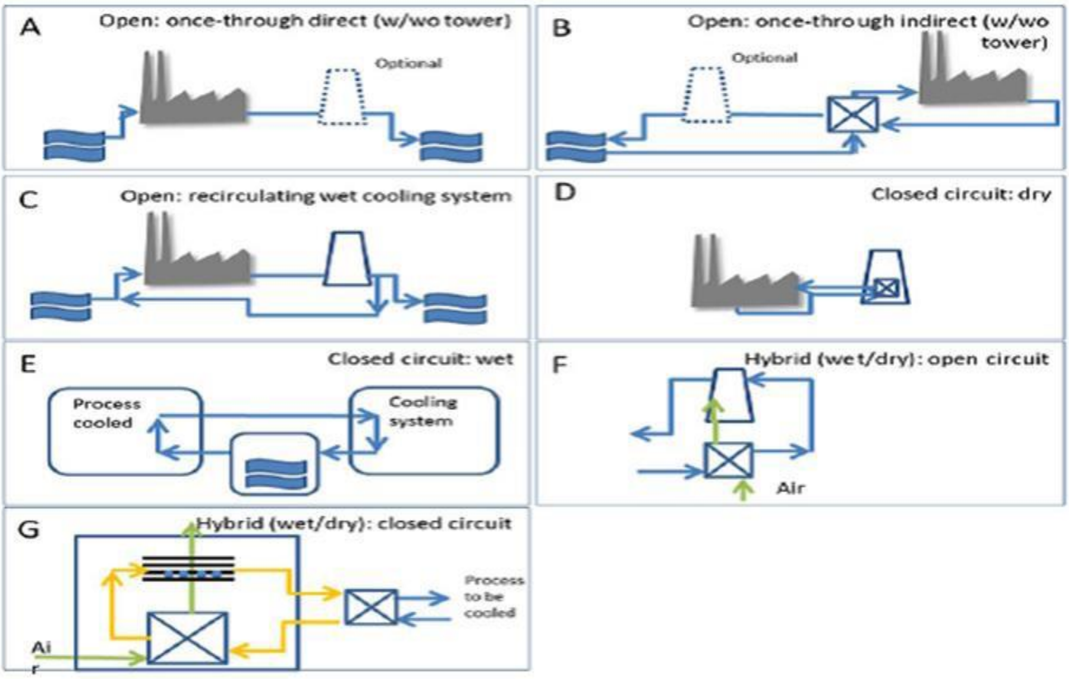

Exhibit 8: Types of Cooling Systems[18]

[16] Directive 2010/75/EU of the European Parliament and the Council on industrial emissions (the Industrial Emissions Directive or IED) is the main EU instrument regulating pollutant emissions from industrial installations. The IED was adopted on 24 November 2010. It is based on a Commission proposal recasting 7 previously existing directives (including, in particular, the IPPC Directive) following an extensive review of the policy. The IED entered into force on 6 January 2011 and had to be transposed by Member States by 7 January 2013.

[17] Air-Cooled Condensing

[18] BREF Cooling, 2001, Integrated Pollution Prevention and Control (IPPC) Reference Document on the Application of Best Available Techniques (BAT) to Industrial Cooling Systems, December 2001.

The Best Available Techniques Reference (BREF) also supplies an overview of in the typical costs associated with cooling as per Exhibit 9. These reference values are more applicable to smaller installations, but in general provide a broad overview of the difference in total operating costs for various cooling technologies.

Cooling System	Total investment (€/MW_{th})	Operational cost (€/MW_{th})	Interest and depreciation (€/MW_{th})	General total annual costs (€/MW_{th})
Once-through	77 - 227	8 - 16	10 - 30	18 - 46
Indirect once-through	100 - 269	10 - 19	13 - 37	23 - 56
Recirculating with open wet cooling tower	89 - 266	19 - 41	11 - 35	30 - 76
Indirect recirculating open wet cooling tower	112 - 331	20 - 43	14 - 43	34 - 86
Dry air cooling	105 - 288	3 - 9	14 - 38	17 - 47
Indirect air cooling	123 - 351	5 - 14	16 - 46	21 - 60

Exhibit 9: Initial and Operating Costs for Different Types of Cooling Systems[18]

Withdrawal & Consumption Among each cooling technology, there is a sizeable difference with respect to water withdrawal and consumption. According to Daniels (2001), the amount of water consumption by U.S. power stations is about 2% of the 3300 million gallons of the daily water used. Most of this water is abstracted and returned except for about 2% evaporation loss in cooling towers[19]. In the same study, the concern of water extraction and its affects are also discussed, for instance, in coastal areas groundwater extraction easily leads to salt intrusion in the aquifer.

A study done by Macknick et al. (2012)[20] provides data on water consumption and withdrawal in the United States for various power generation technologies, such as renewables, thermal and nuclear. Even though the study provides extensive data, it also stipulates the difficulty in acquiring proper values for critical parameters impacting water consumption and withdrawal. For instance, the geographical location of a plant would impact the operational efficiency of cooling tower and ultimately the water withdrawal or consumption. Yet, how this is done cannot be extrapolated out of the article based on the listed information.

[19] D. Daniels, Power plants need to learn to reuse, recycle. Power Magazine Sept/Oct. 2001 pages 45 – 54.

[20] J. Macknick, R. Newmark, G. Heath and K.C. Hallett; Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature, Environ. Res. Lett. 7 (2012) 045802.

Additionally, no distinction is made between recycled wastewater, fresh water[21] and saline water[22]. Nevertheless, some useful trends in the data have been identified which provides a good overview of actual withdrawal and consumption for various cooling technologies in one of the APEC economies, i.e. the United States.

National Energy Technology Laboratory (NETL) did a study in 2010 on water vulnerabilities for existing coal-fired power plants and arrived at similar water withdrawal and consumption figures for sub-critical boilers[23].

It is known that China coal-fired power plants generally operate between 5000 to 6000 hours annually. This scenario is lower than normally associated with coal power plants in other locations[24]. This, in turn, affects the water availability as more water would be consumed due to inefficient operation. In China, there is no independent body that conducts performance testing at overall plant efficiency levels, which implies that actual power plant efficiencies could be possibly lower.

Studies providing information on power plant location and cooling type for the USA were conducted by Elcock and Kuiper (2010) and Macknick, et al. (2012). Similar studies in Europe were conducted by Ecofys in 2013. More studies of similar nature need to be carried out for other APEC economies, like Australia, China, Japan and Korea[25].

Description	Withdrawal (m^3/MW)	Consumption (m^3/MW)	APEC economy - sources
Once-through	86 – 138	0.39 – 0.95	USA: Macknick, et al. 2012
	98	0.37	USA: Elcock & Kuiper, 2010
	80-100	0.23 – 0.29	China: Yang, et al. 2011[26]
		0.40 – 0.6	China: Liu, 2012
Cooling tower	2.3 – 3.8	1.87 - 2.6	USA: Macknick, et al. 2012
	2.0	1.7	USA: Elcock & Kuiper, 2010[27]
	2.3 – 2.6	1.95 – 2.1	China: Yang, et al. 2011

[21] This is applicable to both surface and ground water.

[22] This is applicable to both sea and ground water.

[23] D. Elcock and J.A. Kuiper, Water vulnerabilities for existing coal-fired power plants, DOE/NETL-2010/1429

[24] Generally, most coal power plants have annual operating hours varying from 7000 to 8000.

[25] Similar studies conducted already for the said APEC economies are not in the public domain for us to comment or discuss.

[26] Qin, Y., Curmi, E., Kopec, G. M., Allwood, J. M., & Richards, K. S. (2015). China's energy-water nexus–assessment of the energy sector's compliance with the "3 Red Lines" industrial water policy. Energy Policy, 82, 131-143.

[27] Reported for recirculation cooling tower.

		2.1 – 2.8	China: Liu, 2012[28]
Pond	46 – 68	0.15 – 2.9	USA: Macknick, et al. 2012
Dry-cooling	0.29 – 0.4	0.23 – 0.4	China: Yang, et al. 2011
		0.6 – 0.8	China: Liu, 2012[29]

Exhibit 10: Summary of Water Withdrawal and Consumption Statistics[30]

Various examples of water conservation methods deployed at coal-fired power stations in Australia were identified in the web research which is discussed in the later sections of the report. Based on our understanding of the region, it is evident that most of the coal-fired power stations in the APEC region currently deploy either once-through cooling, hybrid and wet cooling towers.[31] Coal-fired power plants in the region surrounding North-West Coal Basin in China typically deploy dry cooling.[32] According to Liu (2012), the water situation is indeed challenging for 40% of the coal mines and power stations that experience severe water shortages.

The limiting values of water consumption set out in the Five Year Plan are 2.8 cubic metres per MW (m^3/MW_e). This is currently not being met by a majority of power plants regardless of their cooling method. In China, many power stations are located near coal mines wherein water is inefficiently utilized. Liu (2012) points out two examples to reduce water consumption, the first being to apply dry cooling, and the second being efficiency improvements in power generation. The latter would have a positive effect further down the coal and energy chain due to reduced water consumption for coal washing. It is estimated that this would typically save about 86.7 million m^3 of water (or 0.1% of water use in coal sector). Although it is difficult for DNV GL to assess if these figures are correct, nevertheless they do seem reasonable. The water pinch for air-cooled condenser (ACC) as presented by Liu (2012) is 0.6 m^3/megawatt hours (MW_h); whether this MW_h is based on thermal energy or electrical efficiency (43%) is unclear. Nevertheless, both are too high when compared to respective numbers in the previous exhibit as well to the applicable number for Dutch power stations.

In this report, DNV GL has discussed the various water-saving methods to reduce this water pinch to less than 0.1 m^3/MWe. Some of these relevant methods, which at times get overlooked, are listed below -

1. The use of cooling tower systems substituting once-through cooling water systems
2. Increase of the cycles of concentration in cooling tower systems
3. Recycling of boiler condensate and process condensate
4. Recycling of treated sewage and industrial wastewater
5. Cascading of a discharged water with the better quality to other processes
6. Utilization of water with less quality

[28] Reported for closed water cooling.

[29] The lower consumption values are typical for the higher efficiency power plants for example the ultra-supercritical stations. Sub-critical plants have higher water pinch values.

[30] Based on data consolidation from public sources.

[31] Open Circulation Type

[32] Pei Liu, Water issues in the coal supply chain in China. Proceedings Wilson Center. July 2012.

These methods alone are generally associated with a negative impact on water quality, which can result in operational problems at the power station. Therefore, the acceptance of such water saving methods requires water treatment chemicals to address or control these operational problems.

3.1.1 Once-Through

In a typical water-use cycle for industrial applications, when water is abstracted and returned to a water body, it undergoes a thermal and chemical treatment. Historically, the application of chlorine or hypochlorite as antifouling treatment in once-through cooling seawater systems has been the universal method to combat micro and macro-fouling due to its proven effectiveness and relative low costs. More specifically, chlorination is still the best-known and widely applied antifouling method. Even in recent times the benefits of the chlorination process outshine its negative impacts.

Chlorination of a water intake system has two main objectives[33] as discussed below –

- To control the settlement and growth of biota in the cooling water system
- To avoid the blockage of heat-exchangers such as condensers and auxiliary heat-exchangers. This is accomplished through the detachment of shells or hard parts of these "biofouling[34]" on the condenser tubes and auxiliary heat exchangers.

This is paramount for keeping a maximum heat transfer capacity to ensure optimal operating performance.

Chlorination is often applied by bulk chlorination using a chemical mixture consisting of 13 - 17% sodium hypochlorite. For a cooling system located near seawater, the required chemicals for dosing are produced at the location from the sea water itself through the Electro-Chlorination process.

For seawater once-through cooling systems, often a continuous low-level chlorination system is applied in combination with a regular shock dosing. Also, intermittent dosing is applied if needed for some cases with a daily dosage of 1 hour. Discontinuous chlorination procedures can be effective for water, which has low amount of organic matter. A review by Jenner et al. (1998)[35] of the European experience in anti-fouling treatments applied to marine power stations has shown that a low-level continuous or semi-continuous chlorination procedure is effective against the macro-fouling. This procedure can in general control biofilm development as well. Low-level continuous chlorination consists of chlorinating the cooling water system while the macro-fouling species settle and grow. The settlement period of the different species such as mussels, oysters, barnacles, hydroids, tubeworms, etc. varies from several months to a year. In most European countries with temperate climate conditions, this typically corresponds to 6 to 9 months a year. In other regions situated nearer to the equator, settlement period of fouling species is all throughout the year.

A novel discontinuous low-level chlorination (or other oxidative biocide) treatment, developed and implemented by DNV GL is the Pulse-Chlorination® technology. This is considered Best Available Technology (BAT) by the European Union (EU), as well as the Regulatory and Supervisory Bureau (RSB) in Abu Dhabi. The technology has also been successfully implemented in APEC economies, such as Australia, Korea, and Singapore.

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[33] Particularly applicable for industrial water use applications.

[34] In addition to controlling the development of bacterial slime (biofilm).

[35] Jenner, H.A., Whitehouse, J.W., Taylor, C.J., & Khalanski, M. (1998). Cooling water management in European power stations Biology and control of fouling. Hydroécologie Appliquée, 10, I-225.

Pulse-Chlorination® (P-C) is based on the biological observation that bivalves (e.g. mussels and oysters) show a recovery period after exposure to a certain oxidative biocide period. Only after this period, they open their valves fully before restarting filtering seawater for oxygen and nutrients. This treatment enhances the cyclic mode of hypochlorite dosing (on/off dosing regimen), based on the behavioural responses of the mussel or oyster to chlorine, thereby taking advantage of this recovery period to delay the restart of Pulse-Chlorination®. During the time that bivalves are closed and show their recovery period, the dosing is off. As soon as the bivalves have returned to their 100% opening, the chlorine dosing is restarted, again resulting in the immediate closing of the bivalves.

The effect of Pulse-Chlorination® is based on the repetitive principle, i.e., too short recovery period for bivalves after exposure to short successive periods of chlorination. As mentioned above, during the dosing time of chlorination the mussels are closed and show a recovery period when dosing is off. P-C forces the bivalves to switch continuously between aerobic and anaerobic metabolism, leading to physiological exhaustion and death.

Pulse-Chlorination® is considered a proven technology and is increasingly being applied worldwide. In general, hypochlorite is added to the once-through cooling water at a dosage level of around 0.5 to 2.0 milligrams per litre (mg/l); depending on the demand to reach desired levels of Total Residual Oxygen (TRO) on all the sections of the cooling water system to be protected until the condenser outlet.

For a typical 540 MW_e coal-fired power plant in the Netherlands operating with a once-through cooling water flow of 18 cubic metres per second (m^3/s) and the necessity to effectively mitigate macro fouling settlement with a continuous sodium hypochlorite concentration of 0.30 mg/l of Total Residual Chlorine (TRC) at condenser during the fouling season of May until October, the annual use of hypochlorite (15%) will be 1,280 m^3. The resulting annual costs for bulk dosing are estimated at EUR 192,000.00 which through deployment of Pulse-Chlorination® can be reduced by 50%.

Legislation for sodium hypochlorite

The use of hypochlorite is limited by the discharge limits for cooling water from once-through systems which in most cases are country and even location specific.

The World Bank’s Pollution Prevention and Abatement Handbook published in 1998[36] replaced the "1988 Environmental Guidelines." The handbook is specifically designed to be used in the context of the World Bank's environmental policies, as set out in Operational Policy (OP) 4.01, "Environmental Assessment," and related documents. It promotes the concepts of sustainable development by focusing attention on the benefits of both environmental and economic for pollution prevention, including cleaner production and good management techniques. Part I contains a summary of key policy lessons in pollution management, derived from practical experience inside and outside the Bank Group over the past decade. Part II presents good-practice notes on implementation of policy objectives, based on experience with the Bank Group projects and on lessons from the policies and practices of other agencies and organizations in this field. Part III provides detailed guidelines to be applied in the preparation of the Bank Group projects. It represents state-of-the-art thinking on how to reduce pollution emissions from the production process.

Chlorination is only mentioned in the paragraph 'Thermal Power: Guidelines for New Plants'. It sets forth procedures for establishing maximum emissions levels for all fossil fuel-based thermal power plants.

[36] World Bank Group in collaboration with the United Nations Environment Program and the United Nations Industrial Development Organization.

Emission levels for the design and operation of each project must be established through the Environmental Assessment (EA) process based on country legislation and the Pollution Prevention and Abatement Handbook (1988), as applied to local conditions. The emissions levels selected must be justified in the EA and acceptable to the World Bank Group. The World Bank Group only makes decisions regarding the provision of the World Bank Group assistance for new fossil-fuel-fired thermal power plants when the maximum emissions levels are normally acceptable. Total Residual Chlorine (TRC) is mentioned under the liquid effluents. The maximum value is 0.2 mg/l. A specific note is made on shock dosing: '*chlorine shocking' may be preferable in certain circumstances. This involves using high chlorine levels for a few seconds rather than a continuous low-level release. The maximum value is 2 mg/l for up to 2 hours, not to be repeated more frequently than once in 24 hours, with a 24-hours limit of 0.2 mg/l. (The same limits would apply to bromine and fluorine)*'.

The permitting in Europe regarding fouling control and related to cooling water additives is subject to a variety of legislation, both on European and national level:

1. IPPC and the accompanying BREF Industrial Cooling Systems
2. Water Framework Directive (WFD) and the accompanying Daughter Directive on Priority Substances (PS) and Priority Hazardous Substances (PHS)
3. Biocidal Product Directive
4. National legislation in each Member State

In section 8.2, these four guidelines and directives are further explained. For discharge limits in Europe, Free Oxidant (FO) is generally used for freshwater with prescribed limits of 0.1 mg/l for Chlorine (Cl_2). For seawater, instead of FO, TRO limits are prescribed due to acute toxicity of mono-bromamines. TRO-limit is generally determined by the regulator on a case-by-case basis, for instance within the EU typically maximum TRO limits are defined in the range of 0.1 – 0.3 mg/l (as Cl_2) at the point of discharge. Also, water authorities pursue less hypochlorite discharge, i.e., as low as reasonable achievable (ALARA principle[37]). Outside Europe, discharging permits range from 0 (zero discharge) to about 0.5 mg/l, interpreted as either for Cl_2, TRO, Free Oxidant/Free Residual Chlorine (FO/FRC), depending on the geographical location and type of water. In many cases, permitting is managed by local water authorities, rather than just following national regulations.

Discharge permits hypochlorite use. To illustrate some European discharge limits for chlorine and Tri-Halo Methane (THM), those along the Mediterranean Sea (European coast) are presented in Exhibit 11.

Country	Parameter	Maximum marine discharge limit	
France		Maximum concentration over a period of 2 hours	Daily average concentration
	Total residual chlorine	0.3 mg/l	0.1 mg/l
	Halogenated organic (THMs)	10 ug/l	6 ug/l
Italy		Maximum discharge (marine / fresh water)	special protected areas (e.g., Venice lagoons)

[37] ALARA is an acronym used for the term "As Low as Reasonably Achievable".

Greece	Chlorine	0.2 mg/l	0.1 mg/l
		Maximum discharge for industrial installations	
	Free chlorine	0.7 mg/l	

Exhibit 11: Discharging Permits for Chlorine and THM's Mediterranean Sea

- **Spain:** General rules: Real Decreto 849/86 de 11 de abril 1986 (Royal Decree 849/86 of 11 April 1986). This decree is named: Reglamento del Dominio Público Hydráulico[38]. In the Anexo al titulo IV (4th annex) of this decree a table is included with emission limits, which depends upon the extent and efficiency of the applied wastewater treatment. The legislation concerning waste-water discharges into seawaters, either directly or via interior waters is laid down by the Real Decreto 258/1989 de 10 de marzo 1989[39]. According to this decree, the emission limits are fixed for each specific industrial plant and there are no general limits as such.
- **Greece:** The applicable regulations are prescribed through IPPC-FDM[40] under the purview of IPPC's Member States National Legislation and Standards. Additional information is provided by the Technical Working Group (TWG) of the "Food, Drink and Milk Industries" BREF. At the moment, new restrictions are coming in place for the discharge of Chloroform which will be limited to 2.5 µg/l. Bromoform will, however, stay at 12 µg/l.
- **Outside Europe:** Discharge permits range from 0 (zero discharge) to about 0.5 mg/l, which can be interpreted either for Cl_2, TRO, FO/FRC, etc. depending upon the geographical region and type of water. In many cases, permitting is arranged by local water authorities, rather than just following national regulations.
- **Middle East:** This region is another example where discharge limits have been introduced due to growing awareness. The discharge limits range between 0.05 to 1 mg/l for Cl_2, which is further elaborated in section 8.2.

In the **United States**, the Clean Water Act (CWA) governs the discharge of all wastewater into surface waters of the United States. The individual discharges are governed by specific Environmental Protection Agency (EPA) permits. Title 40 Part 423 of the Code of Federal Regulations that governs steam electric power generation, limits the maximum concentration of total residual chlorine at 0.20 mg/l (EPA, 1994b). Most of the states have been delegated water discharge permit authority by the EPA, and, in some cases, state limits on chlorine discharges are more stringent than federal regulations.

The toxicity of chlorine to freshwater and seawater aquatic life is usually expressed as the concentration of TRC and Chlorine-Produced Oxidants (CPO). The EPA states water quality criteria solely in these terms. The EPA criteria for protection of most aquatic species in all inland surface waters and enclosed bays and estuaries are presented in Exhibit 12.

[38] Regulations of the Hydraulic Public Domain.

[39] Royal Decree 258/1989 of 10 March 1989.

[40] IPPC-FDM: International Pollution Prevention Control – Food, Drink and Milk.

Parameter	1-hr average (µg/l)	4-day (96 h) average (µg/l)
TRC (freshwater)	19	11
CPO (saltwater)	13	7.5

Exhibit 12: USEPA Chlorine Residual Discharge Levels[41]

The key EPA (1986) procedures described in the Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms have been discussed below:

- Except possibly where a locally important species is very sensitive, freshwater aquatic organisms and their uses should not be affected unacceptably if the 4-day average concentration of total residual chlorine does not exceed 11 microns per litre (µ/l) more than once every 3 years on the average and if the 1-hour average concentration does not exceed 19 micron grams per litre (µg/l) more than once every 3 years on average.
- Except possibly where a locally important species is very sensitive, saltwater aquatic organisms and their uses should not be affected unacceptably if the 4-day average concentration of chlorine-produced oxidants does not exceed 7.5 µg/l more than once every 3 years on the average and if the 1-hour average concentration does not exceed 13 µg/l more than once every 3 years on average.
- The recommended exceeding frequency of 3 years is the Agency's best scientific judgment of the average amount of time that it will take an unstressed system to recover from a pollution event in which exposure to chlorine exceeds the criterion.

Most states in the U.S. use 19 and 11 µg/l as the acute and chronic criteria for TRC for receiving streams. Some states have adopted a toxicity-based criterion, as the water quality criterion for TRC. The state regulatory agencies require water utilities to abide by the receiving water quality criterion while discharging chlorinated waters. In addition, the regulatory agencies use Water Quality Criteria (WQC) to develop maximum allowable chlorine concentrations while issuing general/individual permits for discharge of chlorinated water into streams.

The permit processes used by state regulatory agencies to regulate chlorinated water discharge vary significantly from state to state. California, Oregon, Washington, Nevada, Maryland and West Virginia have stringent regulatory discharge limits for chlorinated waters. Chlorine discharge limits in all water releases into receiving streams must not exceed 0.1 mg/l (or a more stringent limit) in these states. Other states have more than one general permit to regulate various chlorinated water releases. However, these permits do not include all potable water discharges. Nebraska and Texas regulate hydro-testing waters through a general permit or an administrative rule. Utah has administrative guidelines for chlorinated water discharges. In many states, no general or individual permit program is in place for potable water releases. Although permits are not required, utilities in these states are required to meet the water quality criteria of receiving streams while discharging potable waters. Exhibit 13 highlights selected states based on the severity of permit processes for chlorinated water disposal.

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[41] California Environmental Protection Agency, State Water Resources Control Board, Division of Water Quality, Total Residual Chlorine and Chlorine-Produced Oxidants Policy of California (USA), June 2006.

Permit Requirement	States
States regulating all chlorinated water discharges through general permit, BMPs or individual permits	California, Oregon, Nevada, Washington, Maryland and West Virginia
States having multiple general permits	Colorado, Connecticut, Tennessee, Kentucky, South Carolina, Wisconsin and Wyoming
States regulating hydrostatic test waters only	Hawaii, Nebraska, North Dakota and Texas
States with no general permits that may or may not require individual permits for select discharges	Idaho, Iowa, Kansas, Illinois, Indiana, Michigan, Arkansas, Georgia, Louisiana, Maine, New Jersey, New Mexico, New York, South Dakota, Utah, Virginia and Vermont

Exhibit 13: Status of Permit Program for Chlorinated Water Release in the U.S.

In **China,** standards for discharge are summarized in the following points –

- The Environmental Protection Law of The People's Republic of China for implementation of Water Pollution Control Act and The People's Republic of China Sea.
- The Ocean Environmental Protection Law to protect rivers, lakes, canals to control water pollution and marine and other surface water channels, reservoirs and underground good water quality.
- These Laws are formulated with the underlying objective of protecting human health and safeguarding the ecological balance of the national economy and the development of urban and rural construction standards.

In the above-mentioned standards, the maximum allowable emissions of pollutants by industrial discharges are indicated. However this does not include chlorine and THM's.

To compare, in **India,** the standards for discharge are formulated in the following acts –

- The Environment (Protection) Act, 1986[42]
- The Environment (Protection) Rules, 1986 of the Ministry of Environment and Forests (Department of Environment, Forest and Wildlife).

General standards for discharge of effluents are mentioned as well as discharge limits for different industries. Chlorine discharge limits are presented in Exhibit 14.

Location	Parameter	Maximum marine discharge limit
China	Residual Chlorine	not mentioned
	Total Organic Halogen	not mentioned
India	Free Residual Chlorine (FRC)	0.05 mg Cl_2/l
	Free available chlorine	0.5 mg/l

[42] Section 29 of the 1986 Act talks about applicable discharge standards.

India	for thermal power plants General standards for discharge of effluents	1 mg/l

Exhibit 14: Chlorine Discharge Limits in People's Republic of China and India

The **Australian** legislation regarding the approval of antifouling products is very strict and comprehensive. Only chemical and biological products also referred to as biocidal products require registration with the Australian Pesticides and Veterinary Medicines Authority (APVMA[43]). Products which are acting as physical deterrents (biocide-free products) do not require registration. This includes fiber surfaces and non-stick coatings, basing *e.g.* on silicones.

The State government is responsible for controlling the use of these registered products. Twice a year, the APVMA meets with state government representatives to discuss areas of concern in a registration liaison committee. For Australia, the discharging permits for chlorine and THM's are presented in Exhibit 15.

	Location	Maximum marine discharge limit
Residual chlorine (FRC)	Sydney	0.2 – 0.5

Exhibit 15: Chlorine Residual Discharge levels for Australia[44]

Registered product information is also available through the Public Chemical Registration Information Systems Search (PUBCRIS) database. The PUBCRIS database can be searched for company name, product name, active constituents, or host and pest organisms. Information is available for each registered chemical product, active constituents, states registered, approved labels and packaging information.

3.1.2 Wet cooling tower operation

A method to reduce water consumption is to increase the cycling rate; however, this ultimately leads to conditions where the blow down of cooling tower can no longer be discharged. An example of such an event where drought occurred in Australia led to discharging the blow down on an ash dam is described in the article from Knights (2002)[45]. Once the rains returned, the polluted water on the ash dam threatened to overflow resulting in contaminated water and ash being discharged in natural waterways. Hence, even though it may sometimes seem to be a solution to increase cycling rate to help conserve water, it may lead to other issues which need to be addressed as well.

As mentioned, substituting once-through cooling for cooling tower systems and increasing cycles of concentration can save significant amounts of water in a coal-fired power plant.

The Cycles of Concentration (COC) in a cooling tower are mainly controlled by adjusting the blowdown water as the evaporation and windage losses don't vary much under normal operating conditions. A typical relationship between the cycles of concentration and make-up water quantity is shown in Exhibit 16. An increase in the cycles of concentration brings a reduction of blowdown water and a saving in make-up

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[43] APVMA was formally known as the National Registration Authority, http://www.apvma.gov.au

[44] *Protection of the Environmental Operations Act 1997.*

[45] D. Knights, Reducing the Volume of Water in Tarong Power Station's Ash Dam, Power Plant Chemistry 2002, 4 (7), pages 413 – 417.

water. As per Exhibit 16, make-up water is considerably decreased until cycles of concentration reaches 5, but not beyond 5. On the other hand, operation of cooling water systems at higher cycle of concentration may lead to a reduced cooling water quality. This in turn leads to various other problems related to poor operating efficiency which also has serious consequences to the structural integrity of the cooling water system. Moreover, water treatment chemicals have only a certain degree of effectiveness, so determining appropriate cycles of concentration and operating within the defined COC range is of paramount importance. Typically, cooling water systems operate with cycles of concentrations varying from 3 to 5.

Higher cycles of concentration promote scale deposition in cooling towers, since the dissolved solids become concentrated due to water evaporation. Since the thermal conductivities of these scale depositions are extremely low in comparison with those of tube materials, this can significantly reduce the thermal efficiencies of heat exchangers.

To overcome this, chemical water treatment and dosing of scale inhibitors is applied. Higher cycles of dissolved solids concentration require correspondingly higher scale inhibitors concentrations. Many factors influencing the effects of scale inhibitors such as the concentrations of scale-forming ions[46], pH[47] and water temperature, relate to scale formation. Various indices concerning the relationship between these factors and scale formation have been proposed and are deployed to predict scale formation.

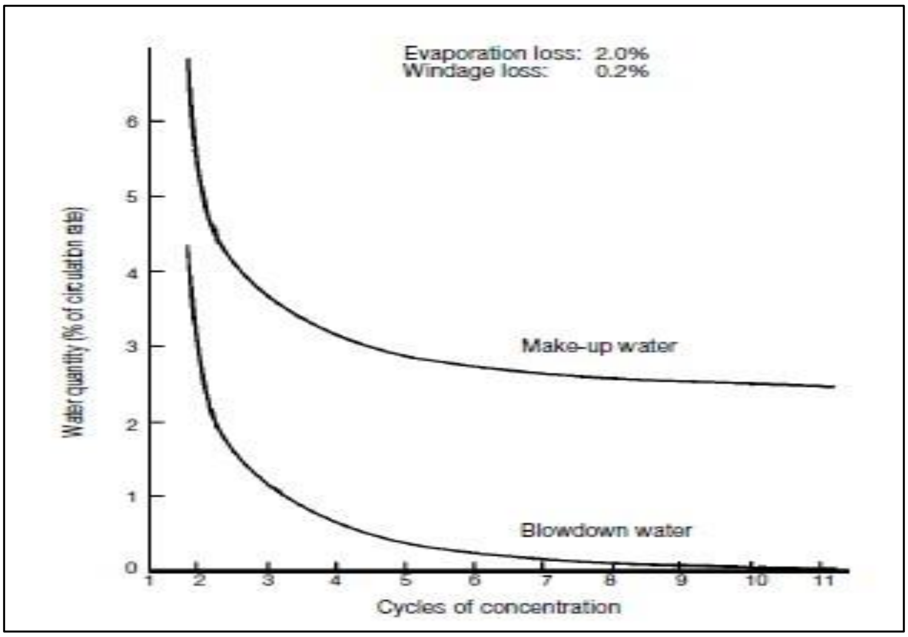

Exhibit 16: Relationship Between Make-up Water, Blowdown Water and C.O.C.[48]

Exhibit 17 shows a typical relationship between the critical deposition pH (pHc) of calcium phosphate, calcium hardness and dosage of a scale inhibitor (polymer). The increase of calcium hardness decreases the pH; however, the use of scale inhibitor raises this pH under specified water temperature and phosphate concentration.

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[46] Calcium ion, phosphate ion, etc.

[47] Chemical term used to specify the acidity or alkalinity of an aqueous solution, typically on a numerical scale from 0 to 14.

[48] Takahide, S., 1999. Kurita handbook of water treatment. Kurita Water Industries, Ltd., Tokyo.

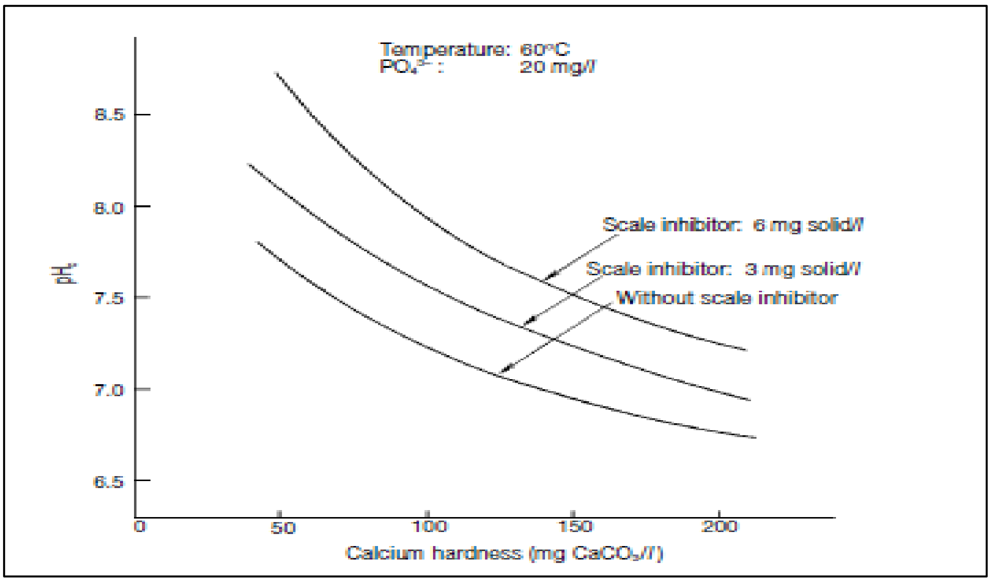

Exhibit 17: Relationship Between pHc and Dosage of Scale Inhibitor[48]

A suitable chemical treatment program for open recirculating systems is determined according to the make-up and cooling water qualities and operating conditions, such as cycles of concentration and water temperature. Especially the choice of corrosion and scale control methods to be deployed varies in accordance with the cooling water quality.

In the case of high calcium hardness[49], phosphate-based corrosion inhibitors easily form protective films on metal surfaces. Accordingly, the phosphates[50] of low concentration, such as 3 to 6 mg/l, demonstrate sufficient corrosion inhibitions in high hardness water. However, enough scale inhibitors (polymers) should be used to prevent scaling of calcium phosphate and calcium carbonate in heat exchangers operating with high hardness water. A water treatment program, which uses a low concentration of corrosion inhibitors with a relatively high concentration of scale inhibitors for high hardness, for high alkalinity and high pH water is called "alkaline treatment". The application results of an alkaline treatment process are indicated in Exhibit 18.

Operational conditions of system	Circulation rate (m^3/h):	20,000
	Holding water volume (m^3):	13,000
	Temperature difference (°C):	8
	Cycles of concentration:	2.5
Chemical treatment	Corrosion and scale inhibitor: (phosphonate-polymer) (mg/l):	40
	Chlorination (mg Cl_2/l):	0.5–1.0, 3 h/day
	Non-oxidizing biocide (mg/l):	50/month
Side stream filtration	3% against circulation rate	

[49] With concentrations more than 150 mg Calcium Carbonate (CaCO3)/l and pH more than 8

[50] Here, phosphates refers to PO^{3-}_4 an organic chemical and a salt of phosphorous acid.

		Make-up water	Cooling water
Water analysis	Turbidity (degree)	2	5
	pH	8.1	9.1
	Electrical conductivity	350	1,000
	(µS/cm)	170	430
	M-alkalinity (mg $CaCO_3$/l)	180	450
	Ca-hardness (mg $CaCO_3$/l)	20	63
	Chloride ion (mg/l)	31	79
	Sulfate ion (mg/l)	7	18
	Silica (mg SiO_2/l)		
Corrosion rate	Carbon steel	0.014–0.019 mm/year	

Exhibit 18: Example of Alkaline Water Treatment

Alkaline treatment is widely applied for high hardness cooling water in refineries, petrochemical plants, iron and steel works and electric power plants.

3.1.3 Dry cooling operation

The selection of dry cooling would have a significant impact on energy efficiency of a power plant. According to an USEPA study (2011)[51], the annual performance penalty is 6.9% when switching from wet cooling (once-through or wet cooling towers) to dry cooling.

Through deployment of ACC for dry cooling, there is a distinct advantage of no risks of contaminated water ingress. However, in the absence of cooling-water ingress, make-up water becomes the principle ingress route for most common dissolved/suspended contaminants other than carbon dioxide. The second major route is via the condensate polishing regeneration[52]. Galt, et al. (2009), representing Eskom based in South Africa, have the largest coal-fired power stations equipped with ACC. Galt et al. mention in their article about boiler make-up water specifications under operating conditions. Herein the target value of boiler feed water is 0.06 µS/cm[53] and there is a limit value of 0.07 µS/cm. The values set by Eskom are stricter than all other international guidelines, like those of VGB[54], Electric Power Research Institute (EPRI)[55] and KEMA[56]. The lowest theoretical conductivity value of water at 25°C is 0.055 µS/cm. When this value is achieved (mostly in a lab), there are no other compounds present except for water and its ionized cation and anion forms respectively Hydronium (H_3O^+) and Hydroxide (OH^-). In practice demineralization units and international guidelines provide specifications for make-up water between 0.10 to 0.20 µS/cm at 25 °C. This water can be made from demineralized units, which however depends on the raw water source. At this site there are two to three different sources of water, namely river and dam

[51] Environmental Protection Agency (EPA) 2011, Cooling water intake structures – CWA 316 (b), Basic information (Washington, DC: US EPA).

[52] K.J. Galt, M.M. Masenya, F. Fourie and S. Eksteen. Eskom's New generation Coal-fired power stations: reliability starts at the water Plant. Power Plant Chemistry, 2009 11 (10) pages 620-632.

[53] Water conductivity, provided in µS/cm, is a means to determine the amount of salt impurities. The higher the salt content the higher the conductivity, for example drinking water can have conductivities of 100 - 1000 µS/cm.

[54] VGB is the European technical association for power and heat generation.

[55] EPRI conducts research on issues related to the electric power industry in the United States.

[56] KEMA, established in 1927, was a global energy consultancy company headquartered in Arnhem, Netherlands and is now DNV GL

water. Exceptional effort in pre-treatment and polishing must be made to reach this stringent value[52]. Additionally, these power stations most also abide to the Zero Liquid Effluent Discharge (ZLED) policy of ESKOM and associated water use licenses. The only water leaving an Eskom plant is treated domestic sanitary effluent (treated sewage) and uncontaminated storm water. This implies that brine and waste-water streams produced at the water process plant (demineralization plant) warrant further treatment in the ZLED. In Sections 3.3 and 4.2, further elaborations on ZLED at Eskom and ZL (E) D technology are provided. Nevertheless, aside from the energy penalty associated with ACC[52], a sophisticated and complex water processing plant with multiple recycle/re-use streams is needed. DNV GL interprets this as a clear increase in OPEX and CAPEX of the water processing plant because of ACC and a slight increase in regenerate waste-water streams. For regions where water is scarce, generally the available raw water sources are more difficult to treat. In Section 4.5.1, DNV GL will elaborate more on this aspect based on the stakeholder consultation with Eskom.

The implementations of ACC also possess a higher risk of Flow Accelerated Corrosion (FAC) in the boiler. While the risk of cooling water ingress is reduced, ACC operation can affect water/steam chemistry conditions. These findings with power plant cases in Australia, China and the United States, were presented by Dooley during the American Petroleum Institute (API) conference in Australia in 2012[57]. A small increase in chemical demand (ammonia) can be expected to control FAC in the boiler of the water/steam cycle as the pH levels are slightly higher than the guidelines recommend.

3.2 Process Water Production

3.2.1 General

There are different technologies used to demineralize water of which the most popular are:

- Ion exchange (IX) technology
- Membrane technology such as Reverse Osmosis (RO)
- Thermal processes

Electro de-Ionization (EDI) is another technology used for water purification. The purpose of these water treatment technologies or combination of these treatment technologies are intended to demineralize water to “ultra-pure” water quality levels. This water is then suitable for use in water steam cycle and process water use. The choice of different water techniques depends foremost on the quality of raw water source such as:

- Drinking water
- Well water (fresh or brackish or saline)
- Industry water (grey water)
- Surface water
- Brackish and sea water

Between well water and surface water the composition of the Total Organic Chlorine (TOC) plays a key role in proper treatment. It is well documented fact that excessive TOC levels will break down in acidic

[57] B. Dooley, ACC corrosion / FAC. A perspective on Chemistry and corrosion. API PowerChem 2012 proceedings

degradation products[58] in the water/steam cycle. These products in turn cause acidic conditions in the water steam cycle and can potentially harm the reliability of the plant[59]. In certain cases, site-specific advantages for example deployment of available waste heat as an input energy source for thermal processes can also be looked into when considering possible technology options to be deployed. There are also regional preferences, for example, a lot of Ion Exchange (I-X) technology is used in Europe, with an upcoming use of RO and Mixed Bed (MB). While in the Middle East, thermal processes or reverse osmosis (RO) membrane technology are more widely deployed. In North America, EDI is used to polish the water[60]. The same technology is also deployed outside the United States, by Eskom for polishing purposes[52].

In the Asia Pacific region, a combination of these technologies can be expected, where a majority will typically utilize either IX-technology and/or RO membrane technology. For power stations located near or at the coast, typical once-through cooling systems are applied. In this case, an intake and outlet pipe are already in place making sea-water a possible raw water source. Here, sea-water reverse osmosis membranes can be applied to produce process water.

Various handbooks describe these techniques, such Basile *et al.* (2015)[61]. Below a brief description is given of the two most likely common process water production technologies to be applied in coal-fired power plants in Asia Pacific. This can also be found in the chapter written by DNV GL in Basile, et al. (2015).

A study carried out about 15 years ago of the Dutch power stations, which recycled as much water on the site as possible, indicates that the typical consumption of 350 – 500 MW_e power station was between 100 to 500 m^3 of demineralized water per day[62]. Nowadays, power stations are larger in size. A typical 650-MW_e coal-fired power station requires 37 m^3/hour to fulfill its process water needs[63]. Eskom applies a 2% maximum steaming rate plus 20% margin, and this would entail a 45 m^3/hr demin water rate for a 650-MWe coal-fired power station with an air cooled condenser but without an FGD unit[52]. Excluding the 20% Eskom margin the amount of process water[64] would be similar to the process water need used as a base case for the CapWa project studies[65].

3.2.2 IX-technology

The Ion Exchange (IX) technology is based on resins, which have a spherical form with a diameter of about 1 mm. The resins are based on polystyrene or polyacrylate and have active groups on the outside of the

58 Acidic degradation is defined as the breakdown of organic compounds (or contaminants) by hydrothermolysis (when subjected to heat and water pressure inside the boiler) leading to the formation of organic acid anions.

59 R. Heijboer, M.H. van Deelen-Bremer, L.M. Butter and A.G. L. Zeijseink. The Behavior of Organics in a Makeup Water Plant Power Plant Chemistry 2006, 8(4), pages 197–202.

60 G. Kamper-van der Koppel and R. Heijboer, Confidential Client, Literature study: international operational experience of make-up water production from surface water, 1998 KEMA Report 98-5076.

61 A. Basile, A. Cassano and N.K. Rastogi, Advances in Membrane Technology for water Treatment, chapter 20 page 605 – 624. Wood Head Publishing 2015.

62 E. van der Hoek, Possibilities and consequences of utilizing more cleaning water for E-bottom ash for 5 Dutch power stations, 1998, Confidential report, KEMA Report 98-5047.

63 L. Daal, H. Kamphuis, A. Stam, T. Konings, M. Huibers, S. van Rijen & J. de Ruijter. Evaluation of different water vapor capture technologies and energy modeling results for membrane technology. Proceedings of PowerGen India & Europe 2012.

64 About 36 m^3/hour.

65 Refer to Section 4.5.3 for more details regarding CapWa.

spheres. These active groups ensure an exchange of cation or anion compounds. In water, salts dissociate in positive (cation) and negative ions (anions). A cation resin only removes the positive ions, whilst the anion removes the negative ions. For example, table salt known as Sodium Chloride (NaCl), has the cation Na+ ion and Cl- as anion. For this reason, a demineralization line based on IX-Technology has both cation and anion filters. To ensure high water quality, a mixed bed (containing both anion and cation resins) is used to polish the water.

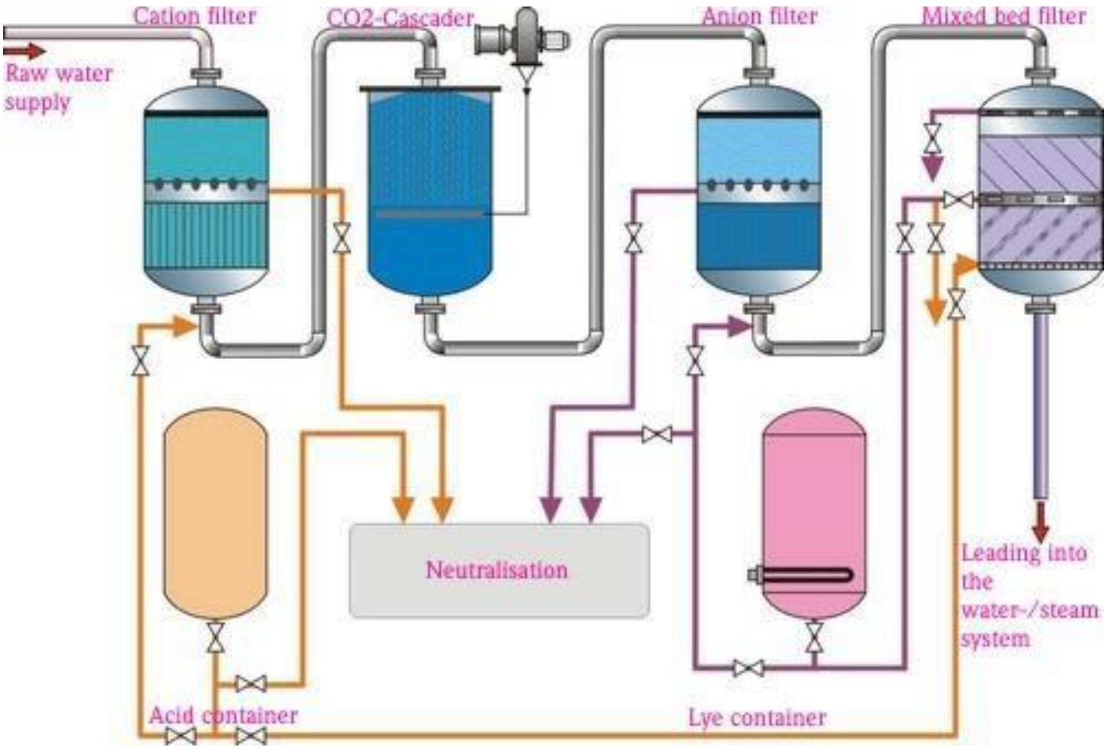

Exhibit 19: Demin Line Using Ion Exchange Technology[66]

Exhibit 19 shows a typical CO_2 cascader or tower, where CO_2 is removed. This is due to the acidic water coming from the cation filter and the hardness of water. Therefore, it will not be necessary to remove this hardness, which is present as carbonate and bicarbonate in the anion filter. This results in savings in amount of resin needed for anion filter.

Typical chemicals used for regenerating resins are 0.66 grams (g) of acidic and 0.54 g of alkaline chemicals per m^3 of water. Hydrogen Chloride (HCL) or Sulphuric Acid (H_2SO_4) are generally used for acidic chemicals, whereas Sodium Hydroxide (NaOH) are generally deployed for alkaline. The main operating features of this technology are summarized below -

- Typical cost of produced demin water varies from 0.40 to 0.50 EUR/m^3.
- Electrical consumption in the process varies from 0.31 to 0.5 kWh/m^3

[66] Basile et al., 2015. DNV GL Publication

- End quality of treated water as measured in terms of electrical conductivity should be less than 0.10 µS/cm

Investment costs are highly dependent on the raw water source. Also, the above costs assume a relatively clean raw water source like drinking water, fresh well water, surface water or industry water type[67]. Since the costs of various water sources vary per country, these have not been considered in the above estimates. However, with this inclusion, the total treatment cost would vary in the range of 0.4-2.0 EUR per m^3. Additional pre-treatment would be necessary when considering well water or surface water which is generally brackish and has high iron content[59]. The technology is not typically used for saline well water or seawater; wherein RO membrane technology is more cost-effective. Typical Pre-treatment in such cases would consist of flocculation, settling and sand filtration. For wastewater reuse, pH neutralization to 7 is a typical pre-treatment step[68]. Other pre-treatment steps can include active coal or membrane technology[69].

3.2.3 Membrane Technology

This technology deploys membranes which act as filters for purification of water. Depending on pore size of the membranes, different membrane technology types are further classified as[70]:

- Microfiltration (MF), with pore sizes of > 0.1 µm
- Ultrafiltration (UF), with pore sizes of 0.01 – 0.1 µm
- Nano-filtration (NF) with pore sizes roughly in between 0.01 and 0.001 µm
- Reverse Osmosis (RO) membranes: < 0.001µm

The actual pore sizes will differ from theoretical ones and in literature a wide variety of classifications for different membrane types can be found. Micro and ultrafiltration membranes are normally used for separation of particles. Nano-filtration and reverse osmosis technology changes the chemical or ionic composition of the water, as they remove small molecules and ions from the water[71]. In the following exhibit a membrane filtration spectrum is shown, giving an indication of the type of contaminants which can be removed through different membrane types.

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[67] Industry water type is also referred to as a raw water source in this context. Typically, in Europe (Netherlands, Germany, etc.) industrial users can procure pre-treated ground or surface water (which is non-potable) for general industrial use such as cooling. This source is referred to as industry water type.

[68] M.A.M. Beerlage and H.M. van Deelen-Bremer, Overview of treatment technologies for the demineralization of surface water or wastewater, 1998, Confidential client, KEMA Report, Nr. 98-5070

[69] H.M. van Deelen-Bremer and R. Heijboer, Guideline for make-up water preparation from different raw water sources, 1999, Confidential client, KEMA Report, Nr. 99-4407

[70] Refer to Exhibit 20 as well.

[71] http://www.primewater.com/technologie-en.html

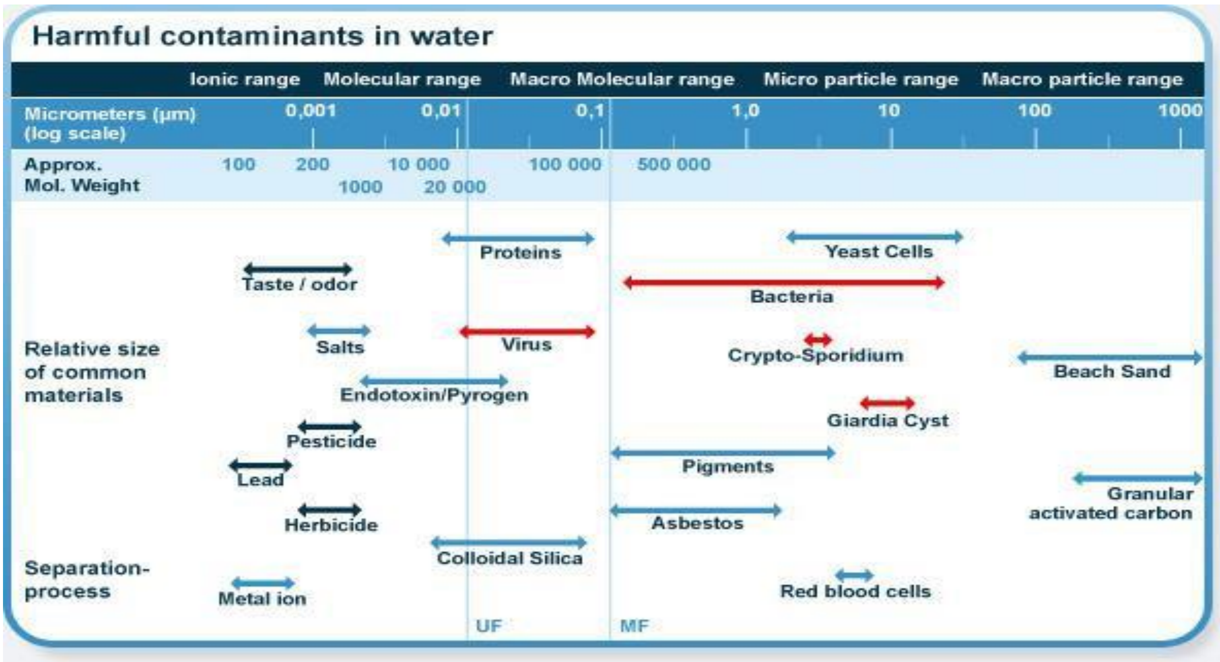


Exhibit 20: Membrane Filtration Spectrum[66]

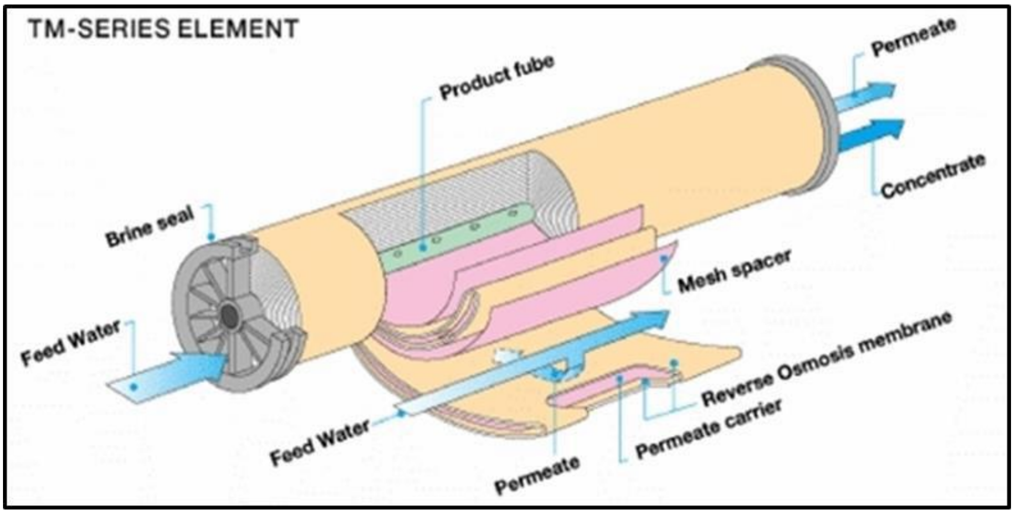


Exhibit 21: Spiral Wound Membrane from Toray[66]

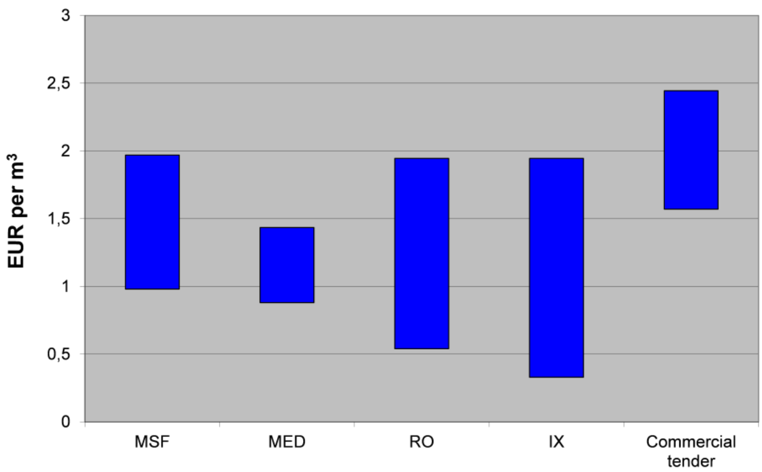
Most of the RO membranes are constructed in a spiral wound module. They are characterized by hollow fibre membrane modules and generally less deployed. The spiral wound module consists of the membrane, mesh paper (or spacer) and the permeate tube. The spacers are used to create flow channels within the module and ensure equal distribution of the flow. The membrane is glued on three sides and the open side is connected to a central permeate tube, around which the membranes sheets are rolled.

RO membranes are made of polymers, mostly Cellulose Acetate (CA) or composite polyamide type membranes. Key to proper membrane operation is fouling control. Fouling can be caused by organic, biological, colloidal and suspended solids fouling or scaling. To ensure proper operation, different pre-treatment steps and cleaning-in-place strategies are adopted[61]. An overall summary of this water treatment technology is discussed below.

- Typical chemicals used: Sodium bisulphite, Hypo Chlorite, Ferrous Chloride ($FeCl_3$), hardness stabilization chemicals or anti-scalant.
- Treatment cost per produced m^3: 0.55 – 2.00 EUR
- Electrical consumption: 2.5 – 7 kW/m^3 water produced
- Water quality with RO only: Achieved conductivity levels between 10 to 100 μS/cm. With polishing step mixed beds (MB), possible to achieve less than 0.10 μS/cm

The broad range of costs is linked to the raw water source. For example, drinking water as a raw source is easier to treat than sea water. Here, comparatively fewer chemicals are needed for pre-treatment and cleaning-in-place (CIP). Additional pre-treatment would be necessary when considering surface water mainly sea water or well water. Pre-treatment in such cases would consist of flocculation, settling and sand filtration. Typically, in such cases, an investigation with small pilots should ideally be done first followed with a thorough evaluation of results before constructing a full-scale treatment plant as properties of raw water may vary from source to source[72]. Here RO technology is as good as its pre-treatment[73]. The North Sea with its strong temperature change and brackish character in coastal zones due to river discharges requires special attention when controlling certain parameters, particularly macro-fouling. Nagel and Brinkmann (2010) provide a description of their challenges with micro-fouling in their article of 2010, with their pilot demineralization installation intended for recommendations for a 2 x 800-MW_e coal-fired plant[73] .

For waste-water reuse, a pH neutralization to pH 7 is a typical pre-treatment step.[68] Also, a polishing step with a mixed bed is typically used for the more difficult water streams. An overview of treatment cost per m^3 is provided in Exhibit 22, including the result of a commercial tender for a 400-MWe coal-fired power plant in the Netherlands. The commercial tender was for 3 different hybrid type demin plant configurations (UF+IX, RO+MB and RO+EDI). The total investment costs are between EUR 600,000 and EUR 1.2 million for 25-110 m^3/h demin supply or between EUR 11,000 and EUR 24,000 per m^3 of demineralized water.



The commercial tender is a demin plant in the Netherlands in 2010. All prices were from 2010 and have been corrected with inflation Source [Baron *et al*., 2010 & desal market data]. Capex figures EUR 11,000 and EUR 24,000 per m^3 demin water.

Exhibit 22: Variation in Demin Water Cost[74]

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[72] For example, seawater of the Persian Gulf is not similar to that of the North Sea.

[73] R. Nagel and J. Brinkmann, Brackish and seawater desalination for process and demineralised water production for large power plants in the North Sea Region. Power Plant Chemistry 2010, 12 (6) pages 316 – 324.

[74] Demin Water Cost (per m^3) for different technologies, MSF and MED are thermal treatment technologies, and RO and IX Condensate polishing, DNV GL.

Most modern plants with a sea-water once-through cooling system typically have a condensate polishing plant (CPP) installed in their water/steam cycle. This is usually a mixed bed installed downstream of the condenser prior to the de-aerator. This CPP ensures that water quality in the water/steam cycle meets boiler feed water guidelines. Boiler feed water is the sum of make-up water coming from a demineralization plant and condensate. CPP units require a minimal of demineralized water to regenerate and this regenerate is typically neutralized before being discharged as waste-water. This waste-water contains primarily ammonia (N-compound).

3.3 Coal and Ash Handling

As the amount of water used depends highly on local site conditions and coal type, the resulting amount of water consumed and recycled in this process is difficult to determine. In literature following items were found regarding this topic.

Ash dump as effluent waste-water sink – ZLED policy? In order to save on water usage Eskom has moved from wet ash dams such as ponds to dry ash dumps known as landfills. At Eskom, this landfill is typically an unlined facility, up to 60 meter high covering many hectares. Over an operational lifetime of a large coal-fired plant this can be as much as 700 hectare (1750 acres). Such a large area has the potential to absorb a large quantity of water (liquid), if this liquid does not leach out. The practice in some locations at Eskom and likely elsewhere in the world is to use the ash dumps as sinks for concentrated effluents such as regenerate, brines etc. This practice has allowed Eskom and some other power stations worldwide to "successfully" achieve ZLED on some plants with dry ash dumps. However here is a clear example of how policy changes influence the ZLED status. South African legislation classify fly ash as a dangerous substance and previous practical experience that ash dumps are not sustainable sinks for brine disposal, will result in lining of ash dumps and subsequent treatment leachate and ground water monitoring. Brine is typically used also to condition the ash dump, dust suppression and particularly[52]. According to this 2009 article, Eskom was in negotiation with the local authorities to not apply the US$ 150 million lining, but to agree on using the conventional ZLD approach (concentrators and evaporators) and not discharge brine on the ash dump.

Dry extraction of bottom ash. Magaldi Industri Srl offers a system for dry extraction, air cooling and mechanical handling of bottom ash from pulverized coal-fired boilers. According to their website, there are hundreds of installations worldwide since 1980. The Magaldi Ash Cooler (MAC) cools the ash with ambient air which is naturally drawn into the system by the furnace negative pressure. That air recovers a significant amount of energy in the form of ash sensible heat, ash chemical energy from unburned particles, and boiler radiation flux through the throat. According to the supplier the dry cooling process has been proven to have no negative effects on the main combustion. Advantages of the system are:

a. No water consumption

b. An increase in opportunities for reuse of bottom-ash for application

c. Reduction in OPEX and improved efficiency of the plant[75]

A power producer in Italy has adopted the technology. DNV GL will try and determine their operational experiences. Dutch power stations use a wet process and subsequently reuse the water for the FGD.

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[75] Magaldi solution for ash handling, from http://www.magaldi.com/en/magaldi_solutions_for/Ash-Handling-Mac

3.4 Boiler Cleaning

3.4.1 Water steam side

Boiler cleaning is both internal with respect to the water steam side, as well as external for the flue gas side. For internal this refers to chemical cleaning of internal boiler parts and auxiliary equipment. This is typically done at least once for any coal-fired power plant but can occasionally happen every 10 to 20 years. For example, during the commissioning phase, when debris, oil rags, etc. can be found in the boiler a boiler cleaning consisting of a boil out and chemical clean is done. The purpose of a chemical clean is to clean the surface of the boiler tube walls and to ensure passivation as discussed in the cleaning steps below:

1. Internal heating surfaces are washed with a solvent containing inhibitor to dissolve or disintegrate deposits
2. Clean water is used to flush out loose deposits, solvent, soluble iron salts, corrosive/explosive gases also (if formed)
3. Heating surfaces are then neutralized and rendered passive, as a very thin protective oxide film is formed on the freshly cleaned ferrous surfaces
4. The unit is washed with clean water to remove remaining loose deposits

Usually in this process, conditioned demineralized water is passed through the system and a protective oxide layer is further formed. If done correctly and the plant is maintained according to boiler water steam quality specifications, like the VGB, EPRI or KEMA guidelines, no further chemical cleaning would be anticipated for the plant. DNV GL is aware of power stations that have operated for over 25 years without a chemical clean. According to VGB guideline 513 (2006, page 35), the amount of effluent waste-water produced for a chemical clean is 4 to 14 boiler fillings. A typical 650-MWe natural circulation boiler has about 156 m^3 of water at ambient temperatures[76]; this would entail a waste-water volume of 624 to 2,184 m^3 for a chemical clean.

This wastewater must abide to stringent legislation and the most common chemicals used for treatment are:

1) Hydrochloric acid with ammonium biflouride
2) Hydroxyl acetic formic acid with ammonium biflouride and a corrosion inhibitor
3) Inhibited ammonium salts of ethylene-diaminetetra-acetic acid (EDTA)
4) Inhibited ammoniated citric acid[76]

These compounds can still be present in the wastewater together with iron corrosion products. Although chemical clean suppliers will not likely change their preferred chemicals, DNV GL does recommend operators to discuss with chemical clean supplier ways to limit wastewater and treatment costs[77]. The best

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[76] J.B. Kitto and S.C. Stultz. Steam - its generation and use 41st edition, Babcock & Wilcox, 2005.

[77] A. Smeets and R. Overhof. Guideline to reduce the amount of waste from chemical cleanings, KEMA Report 09-5515.

method is to limit the amount of chemical cleans a plant requires. Typically, the wastewater is treated onsite before discharge to save on wastewater discharge costs.

As mentioned, to save on chemical cleanings, the preference is not to have them done in the first place[78]. Demineralized water is typically clean for Northern Europe and United States as the raw source of water. In these regions, most of the power plants have access to experienced personnel or even third party water experts to address any related operational issues. In economies such as Australia and South Africa, a more rigorous chemical cleaning regime is needed, mainly due to the difficulty in maintaining demineralized water quality specifications for make-up water. This can be related to the fact that raw water sources can vary considerably due to water shortages, for example switching from surface water (river) to saline ground water or effluent from municipal waste-water treatment plants. As a result, chemical cleanings should ideally occur twice or thrice over a power plant's lifetime in regions with water shortages.

Other internal cleaning methods include shot blasting either with CO_2 media or with steel shot and steam blowing. Typically, a chemical clean is the preferred method as it ensures a new clean surface to commence the growth of a protective oxide layer. Shot blasting methods or steam blowing is meant to clear out debris.

3.4.2 Flue gas side

An inventory has been performed by DNV GL in 2007 to assess what approaches and techniques are available to reduce soot blowing costs. Presently soot blowing at the Dutch power stations is performed with steam blowers according to more or less fixed schedules or procedures. Soot blowing costs may be reduced by regulating the amount of steam or by completely avoiding its use. Furthermore, heat transfer surfaces will be cleaner by optimized soot blowing resulting in a better boiler and unit efficiency. Techniques to reduce or avoid steam consumption are water cannons, acoustic horns and shock wave cleaning. Another advantage of replacing steam blowers by different techniques is reduction in tube erosion and therefore possible savings on maintenance costs and reduction in forced outages of the boiler.

Techniques to optimize soot blowing schedules are "smart sensors" to measure heat fluxes, application of strain gauges to measure slagging on pendant super heaters or application of "intelligent soot blowing" by performing heat balance calculations. Depending on the current situation and depending whether claims provided given by suppliers are realistic, the economic benefits of applying advanced techniques can be substantial with a corresponding high return on investment[79].

An earlier study done by DNV GL in 1999 revealed the following findings pertaining to soot blowing practices in some Dutch coal-fired power stations:

- Water (steam) consumption varying between 50 to 240 ton per 12 hours
- Overall energy efficiency loss due to the use of high pressure steam was 0.15 to 0.2%.

Besides steam-based soot blowing technique, other techniques are available that use less water. One of the possibilities is acoustic cleaning, with which soot-blowers can be wholly or partially replaced depending on type of application.

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[78] The assumption here is that water quality in the boiler remains within desired specifications throughout the operating period.

[79] J. Witkamp, Recommendations on boiler cleaning, Confidential Client, KEMA Report 07-1960

Another water saving option is soot-blowing with water jets instead of using steam. The feasibility of this option depends on the particular boiler.

3.5 SO_x removal - Wet and Dry Flue Gas Desulphurization

The IPPC Document on Large combustion plants gives an overview of flue gas cleaning techniques. Also a report from Carpenter (2012) contains such an overview as well as new flue gas cleaning techniques[80]. A brief description of various flue gas cleaning technologies is discussed in appendix A. This section looks into the removal of SO_x, which is the main water consumer in an FGD system.

3.5.1 Wet Flue Gas Desulphurization

Wet Flue Gas Desulphurization (FGD) is mainly based on the use of limestone. The basic working principle is depicted in Exhibit 23.

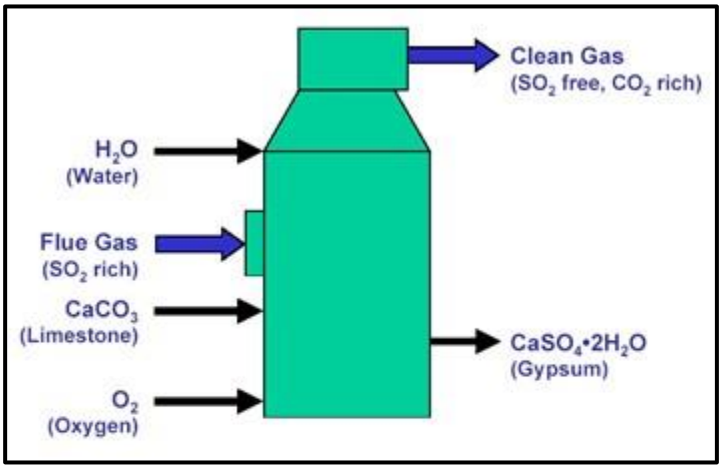

Exhibit 23: Example of Wet Flue Gas Desulphurization[81]

The sulphur dioxide rich flue gas enters the FGD unit and is cooled and saturated by spraying a solution of water, gypsum and limestone, thereby converting the resulting gas-liquid mixture into lime slurry. The sulphur reacts with the calcium in the slurry and forms gypsum which can be used as a by-product for the building industry. The removal percentage of sulphur is typically around 92-97%.

Even though a major portion of the water in this process is recycled, the wet FGD still consumes a significant amount of water, owing to evaporation losses. According to the Power Plant Water Usage and Loss Study by the U.S. Department of Energy[82], the water loss typically varies between 0.25 and 0.22 m^3/MWh for a subcritical and supercritical boiler, respectively. Thus, in case of a 500-MW supercritical power plant, the typical water consumption due to evaporation losses is about 110 m^3/hr. The main reason for this significant amount of water usage is the necessity to cool down flue gas. In a wet FGD process,

[80] Carpenter A.M. (November 2012), Low water FGD Technologies ISBN 978-92-9029-530-3, IEA Clean Coal Centre

[81] KEMA Proprietary

[82] Klett, Kuehn, Schoff, Vaysman and White, Power Plant Water Usage and Loss Study for the U.S. Department of Energy National Energy Technology Laboratory, August 2008, Revised May 2007.

the flue gas temperature is brought back adiabatically from approximately 120°C to about 55-80°C through evaporation of water.

According to the BREF, 80% of the FGD units used in coal-fired power plants are of the wet type. Most power plants located near the sea equipped with once-through cooling, also deploy sea-water as makeup for wet FGD.

FGD units require water to clean the demisters and together with lime create a suspension suitable for SO_X treatment. Much of this water is evaporated and exits the stack, while the remaining water is further treated in a waste-water treatment plant.

The requirements of water quality for the demisters are listed below:

a. The salt content should not exceed to that of sea water

b. Should be free of particles

c. The calcium content should not be too high to prevent scaling on the demisters.

The amount of water needed for the lime milk in the FGD is relatively lower - around 20 m^3/hr. At high chloride content[83], clotting can occur which leads to a reduction of calcium reactivity, resulting in poor gypsum quality[62]. Benchmark studies by DNV GL reveal that the amount of make-up water required varies per site and is subject to the quality of make-up water. To abide to water conservation policies, make-up water can be a mixture of other water sources like surface run-off water, seawater or fresh surface water[84]. However, the maximum amount of seawater that can be added is restricted by the allowable chloride content in gypsum.

Typically the flue gas water content prior to entering an FGD unit is about 7 to 9 volume (vol).% while after the FGD unit it is about 10 – 12 vol.%, with corresponding make-up requirements ranging between 0.080 to 0.265 m^3 per MW. These figures are based on Dutch power plants where some of them apply water saving steps such as utilizing surface water run-off[85].

3.5.2 Dry Flue Gas Desulphurization

The main characteristic of all types of dry flue gas desulphurization systems is that hydrated lime is injected into the flue gas stream in a circulating fluidized bed reactor. The difference between hydrated lime and lime slurry is that hydrated lime is drier and behaves more like dust rather than a fluid.

Hydrated lime is injected into a reactor. At a higher level in the reactor water is injected to reactivate the lime. The lime and water mixture reacts with the sulphur in the flue gas. The resulting dry material consisting of the reaction products and fly ash is collected in the dust filter (ESP or fabric filter). Part of the collected dry material is recycled back into the lime mixture, making use of the alkalinity in the ash.

The dry FGD processes use about 60% less water, but still significant water is consumed in this process. The dry processes typically deployed in this case are namely spray dry scrubbing (SDS), duct spray or circulating dry scrubbers (CDS). These processes have been mostly deployed in the USA and in Asia,

[83] About 8 mg/l.

[84] This is typically practices in the Netherlands (Vredenbregt and Visser, 2008).

[85] L. Vredenbregt and J. Visser. Inventory of N-compounds discharge at Dutch coal-fired plants. KEMA Report 08-1525

particularly China. The investment costs for a dry scrubber[80] are generally lower as compared to a wet scrubber; however, the cost increases with plant size. The capital cost for retrofitting a SDS system on the Big Stone Unit 1[86] was estimated to be $141,300,000[87] or a unit cost of $297/kW, compared to $171,800,000 or $362/kW for a wet scrubber. The SDS and CDS semi-dry systems have several advantages over wet limestone scrubbers[80] as discussed below:

- Consumption of ~60% less water;
- Production of no waste-water, as all the water added to the scrubber is evaporated. Thus, no waste-water treatment system is required;
- The waste products are dry and thus can be easily handled;
- The scrubbers can be constructed of unlined low carbon steel as opposed to more expensive lined carbon steel or alloys used for wet scrubbers;
- Smaller space requirement and thus more suited for retrofit applications;
- Lower auxiliary power consumption;
- More efficient capture of SO_3, HCl and other acid gases and mercury; and
- Lower investment cost for medium sized power plants with a capacity range of 300 – 450 MWe.

The main *dis*advantages of SDS and CDS systems when compared to wet scrubbers are also discussed below:

- Generally lower SO_2 removal efficiency, although modern CDS systems can remove over 98% of SO_2, approaching the levels reached by wet scrubbers;
- Multiple absorber vessels are typically required for units with a capacity higher than ~400 MW;
- No saleable by-product. The waste product has fewer uses than the saleable gypsum produced in wet scrubbing processes;
- Higher operating costs mainly due to their higher reagent costs; and
- Maintenance costs of fabric filters in CDS systems can be higher than those for wet FGD units due to their greater wear. Higher particulate loading in the fabric filter from the recycling of by-products in CDS systems means more frequent cleaning and thus greater wear.

DNV GL believes that the requirements on the water quality for dry FGD make-up will be stringent than those of a wet-FGD. Also, water re-use initiatives, as demonstrated in the Netherlands for wet FGD, can realize significant water reductions namely from 0.26 to 0.080 m^3 per MW. As there is no saleable by-product for dry FGD, the OPEX costs can be significantly higher, consequently most FGD units give preference to wet technology over the dry units.

3.6 Wastewater Treatment

3.6.1 General

The main wastewater streams produced at a power station that require treatment are as follows[88] -

- Blow down of the cooling tower
- Waste-water from the Flue Gas Desulphurization unit (FGD)

[86] With a net power generation capacity of 475 MW

[87] As per currency value of 2009.

[88] R. Hunik, Reuse of (waste)water streams, Confidential Client, KEMA Report 98-1098.

With regards to wastewater from the FGD unit, a dedicated physical chemical separation process is used. From the BREF of large combustion plants, the following description is provided for a wastewater treatment plant.

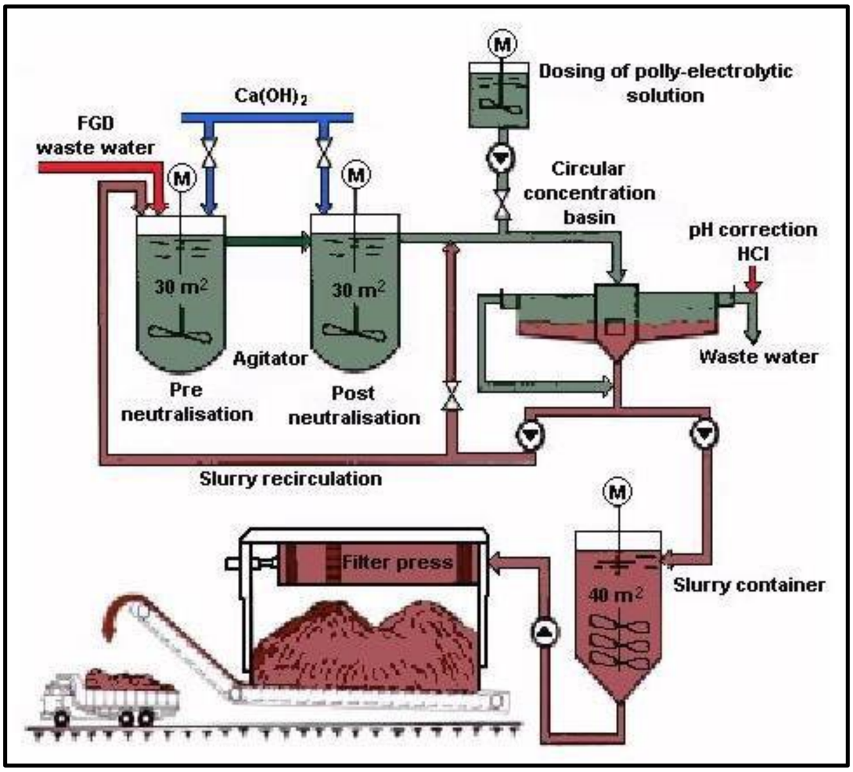

Exhibit 24: Example of FGD Wastewater Treatment Plant[89]

Exhibit 24 is an example of FGD wastewater treatment; it is pre-neutralised in an agitator with the aid of lime slurry. The pH is further increased by additional dosing of lime slurry in the second reactor. Initial flocculation and settling of heavy metal hydroxides occurs in the circular concentration reactor tank. Poly-electrolytic solution is fed into the supply line to the concentration reactor tank to avoid repulsion between hydroxide particles and to accelerate sedimentation. The treated water, with a pH of 6 to 9, may be transferred from the upper quiet zone of the circular concentration reactor tank to the main water inlet. If the pH is above 9, it is corrected with an acidic additive, for example hydrochloric acid. Part of the slurry withdrawn from the concentration tank is fed as contact slurry to support flocculation in the first agitator. This slurry acts as an accelerator for the precipitation of the hydroxides. Most of the slurry from the agitator is temporarily stored in a slurry container, dewatered in a filter press and finally stored in a bunker prior to disposal.

Several heavy metals like cadmium and mercury cannot always be properly removed in this manner. To help meet discharge limits, sulfides are dosed. Metal sulphides have a lower solubility than hydroxide metal compounds. In some cases, Ferrous Chloride ($FeCl_3$) is dosed to ensure extra removal of arsenic

[89] BREF LCP, 2006.

compounds. A typical manner to dispose of the formed clay from the filter press is feeding back in to the boiler to burn[90].

Operation of the waste-water treatment plant in flue gas desulphurisation plants is influenced by the composition as well as flow of influent. These variables are in turn influenced by some other parameters according to van den Broeke and Vredenbregt (2001):

- Fuel composition
- Lime(stone) composition
- Process-water composition
- Occasional water supplies from the power-plant site
- Quality of the oxidation step
- Gypsum separation
- Processes between boiler and flue-gas desulphurisation (E-filter, SCR)

Typical operational challenges occur when something in the process changes, as this affects the treatment efficiency of the wastewater treatment plant (WWTP) or can result in scaling in pipes or sensors.

While the use of seawater may seem attractive for FGD units, its usage (together with fresh water) is limited by the allowable chloride content in gypsum. Also, the resulting wastewater is more challenging to treat as it leads to precipitation problems because the density and viscosity of seawater/brackish water is higher than that of raw water sources having a lower salt content. This can ultimately lead to higher metal concentrations in the discharge of the WWTP. High chloride concentrations can affect the solubility of Cu, Ni and Cd, as well [Broeke and Vredenbregt, 2001].

According to Van den Broeke and Beerlage (1999)[91], it could be possible to further concentrate the lime suspension using nano-filtration as described in the Umsicht process (Hoffman et al., 1997)[92]. This was investigated by KEMA as an option to reuse permeates from this membrane filter technology to clean the demisters and FGD reactor. Alternatively, power stations can adopt special coatings to prevent scaling in this area. Nevertheless, this is a possible method to save water.

3.6.2 Discharge WWTP

The effluent flow of a (dedicated) wastewater treatment plant of a 650 MWe coal-fired power plant equipped with wet FGD is typically around 20 to 35 m^3/hour in the Netherlands. This effluent contains 7-50 mg/l chloride, 1.3-3.0 g/l sulphate and 0.04-0.7 mg/l Selenium[62]. Subsequent studies conducted 10 years later indicate a reduced effluent flow varying from 4 to 17 m^3/h, for a similar plant capacity[85].

3.6.3 Treatment of other wastewater streams

Other kinds of waste-water streams associated with a coal-fired power plant are listed below:

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[90] H.W. van den Broeke and L. Vredenbregt, Impact of FGD on waste water treatment plant, Confidential client, KEMA Report 01-1140

[91] W.F. van den Broeke and M.A.M. Beerlage, Production of cleaning water for FGD suspensions. Confidential Client 1999, KEMA report 99-4456.

[92] Hoffmann, A., Kümmel, R., Tsehernjaew, R.J. und Weinspaeh, P.-M, 1997. Erzeugung von Übersättigungen bei der Nanofiltration: Ermittlung der Auslegungsdaten fur ein neues Kristallisationsverfahren. Chemie Ingenieur Teehnik (69) 6197 S831-833.

- Boiler blow down
- Pump sealing water
- Waste-water from demin plant which can further be sub-categorized into the following:
    - Back-wash from filters
    - Regeneration water
    - Cleaning water
    - Waste-water from RO membrane technology – retentate stream
- Turbine sealing water for condenser (steam)
- Sampling rack (analysing water/steam cycle quality)
- Sanitary waste-water (toilets, showers etc.)
- Surface run-off water which has additional categories such as -
    - Risk-areas on the terrain (contaminated with oil and other solids)
    - Coal and fly-ash storage
- Bottom-ash cleaning
- Waste-water from flue gas re-heater cleaning
- Waste-water from air pre-heater cleaning

Not affecting WWTP. Most of the above streams are already led to the WWTP that treats the FGD blow down. Waste-water originating from cleaning activities within the FGD unit will not affect the operation of the WWTP as much, for example air pre-heater cleaning. Water from bottom-ash cleaning[93] has a high alkalinity and limited quantity of suspended solids. Since a WWTP operates at high pH, precautionary measures should be deployed to avoid any disruption during operation. Some typical measures deployed to ensure reliability of operation are gradually adding the wastewater streams and ensuring sufficient redundancy through additional storage tanks[94].

Boiler blowdown. Generally, boiler blowdown water is quite clean as it only contains a few conditioning chemicals. This wastewater stream can be reused for other applications in the plant such as for cleaning purposes, cooling tower use or for the FGD unit[88]. Removal of any ammonia present can be achieved by stripping with steam or air. Any solid alkalizer present in blowdown water should be neutralized in case of NaOH, however this is not needed in case of phosphates. It should be noted that not everywhere carcinogenic compounds like hydrazine[95] are prohibited for use in the water steam cycle. International guidelines do not promote the use of such compounds but they are still being deployed. In this context, it

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[93] Typically clean demineralized water is used in this case for cleaning.

[94] Broeke and Vredenbregt, 2001.

[95] A commonly deployed oxygen scavenger for industrial applications.

is important to consider treatment of the blow down[96] prior to reuse or discharge. Also the use of solid alkalizers in the boiler drum are not necessary to maintain proper chemical conditioning regime of the water steam cycle of high pressure boilers[97].

Sanitary wastewater. Most power stations have either one or two dedicated wastewater treatment plants. A treatment plant capable of treating household wastewater is typically designed to treat both sanitary wastewater produced on site as well as municipal wastewater from a neighbouring municipality. Additionally, on-site storm water or collected rain water can also be treated in this case. Effluent from this wastewater treatment plant is either reused on the plant as discussed subsequently or discharged to the environment or sewage system.

Demin lines & other streams. Small wastewater streams like the regenerate from demin lines is neutralized and discharged to the environment, for instance in case of once-through cooling water system. Sometimes this wastewater stream is collected along with other wastewater steams in a settling tank. For example, in some Dutch power stations wastewater from the different ash fields is being collected and reused in the FGD unit[62]. Additionally, storm water can also be collected on site and filtered before use in an FGD. This option was first investigated in the Netherlands during the 1990’s and is still being deployed by a few power stations[98]. In some cases, power stations also use treated surface run-off water for dust control on the coal storage fields (BREF LCP, 2006).

3.7 Water usage in carbon capture and storage

A CO_2 capture system in general requires additional water for cooling and make-up, increasing the existing requirements were a capture system not in place. It has been estimated that with the addition of a full-scale post-combustion capture system to a power generation plant, the increase in water consumption per megawatt of electrical output (MWh) can be as high as 90 per cent. However, water use estimates cannot be generalised, and are very dependent on the power plant type, the carbon capture technology and the cooling system used.

Processes associated with the capture system often require cooling of the flue gas, resulting in the condensation of water and the return of more water to the water source. Water consumption estimates can therefore be lower with a capture system than without such as for oxy-combustion systems, where the power production facility can become a net generator of water.

IGCC is the only major power production platform that shows an increase in consumption with addition of a capture system. This is because the water gas shift (WGS) reactor required for carbon capture operations in IGCC systems consumes steam to generate additional hydrogen and convert the carbon monoxide in syngas into CO2.

Macknick et al. (2012) provided figures on water consumption and withdrawal for IGCC and IGCC equipped with and without post-combustion carbon capture. It can be seen from the table below that both water

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[96] Since, blowdown water in most cases would possibly consist of oxygen scavenging chemicals like hydrazine

[97] Typically applicable for boilers operating at steam pressure more than 80 bar according to the international water/steam guidelines by VGB, EPRI and KEMA.

[98] T. de Vries, M. Boone, C. van der Westen, A. Snel, H. Thomas, A. van Vlerken, F. Schrotte and F. de Vos. Water management in power stations, Report written by entire Dutch Power Sector, Confidential, KEMA Report 08-9040

consumption and withdrawal numbers for a coal-fired power plant will increase when applying carbon capture.

Applying cooling tower	Coal-fired power plant	Coal-fired power plant with CCS	IGCC	IGCC with CCS
Withdrawal	2.3 – 3.8[99]	4.3 – 5	1.5	2.4
Consumption	1.9 – 2.6	3.2 – 3.5	1.4	2.0

Exhibit 25: Water Consumption and Withdrawal Comparison with Carbon Capture[100]

CO_2 storage and enhanced water recovery

There are several types of storage sites available that are well suited for CO_2 storage. The most important characteristic of a good geological storage site, is the presence of porous rock in which the CO_2 can be stored[101] and a layer of solid rock that CO_2 cannot travel through on top.

The best available techniques (BAT) reference document for large combustion plants (BREF LCP) makes mention of several possible locations/uses for storage of CO_2:

- Deep ocean
- Deep aquifers
- Exhausted gas and oil reservoirs.

In general, the exhausted oil and gas fields and deep aquifers have the most potential for application of CO_2 storage:

- Exhausted oil and gas fields that are no longer produced are excellent storage sites. These old reservoirs can hold oil or gas for millions of years without leakage, which means they are also capable of keeping CO_2 safely stored for millions of years to come. An added advantage is the fact that oil fields are very extensively surveyed while in use, so all the information needed about storage capacity, rock qualities and other factors in the storage process will be available. Existing wells that have previously been used to extract oil or gas may be used to inject CO_2. Care must be taken that all existing, unused wells are securely blocked, so that no CO_2 can escape through them.
- Deep, water-filled formations have a very large potential for CO_2 storage. As with oil and gas fields with some certainty, it can be said that such formations are capable of securely holding CO_2, as they have held water for a long time without leakage. Still, the formations must be extensively surveyed to make sure that are no cracks or weaknesses in the covering layer of dense rock that may allow CO_2 to escape to the surface. Very good methods for making such surveys have been developed by the oil and gas industry.

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[99] Range where indicated to be interpreted as sub-critical to super-critical

[100] The unit for water consumption figures indicated herein is m^3/MWh. Macknick et al., 2012.

[101] Much like water is held in a sponge

Enhanced water recovery has been studied by researchers as an alternative to the conventional approach of injecting CO_2 into water trapped deep saline aquifers. In enhanced water recovery, water is removed from the aquifer before CO_2 is injected. A study has found that this would substantially lower the risk of CO_2 leakage while providing a source of industrial water, assuming it can economically desalinated. GreenGen, a coal-fired power plant in Tianjin, China, which uses IGCC technology, is exploring the feasibility of injecting CO_2 into a deep aquifer 8 kilometers from the plant after extracting water for 6 months. Other sites in China have also been evaluated for enhanced water recovery. Xinjiang Province in Western China has been identified as an ideal region for a demonstration project due to its large coal reserves and lack of potable water supplies[102].

3.8 Water use in other coal Conversion Technologies

The coal to liquid (CTL) conversion process requires water for three main purposes:

1. Process cooling water which often uses wet evaporative cooling like conventional thermal power plants
2. Water consumption to produce hydrogen
3. Dust control, ash disposal, solids handling and other such control measures

There are varying estimates for water required in CTL facilities. This is because the consumption depends on several factors, including production technology, type of coal, and facility elevation.

One estimate for the U.S. state of Montana reported that water use for each barrel of final product could vary from 1 – 1.5 barrels at a zero-discharge air cooled plant to 5 – 7 barrels with water cooling and less use of waste heat for process heat or cogeneration. This was based not from an actual commercial operation, but from an energy balance exercise for a hypothetical CTL plant assuming each ton of sub-bituminous coal (9,000 Btu/lb) yielded 2 barrels of product.[103] The large difference between water use in air-cooled CTL vs water-cooled CTL clearly illustrates the fact that water use by the cooling technology is the biggest determinant of the overall water use in a CTL facility.

NETL studied the options to reduce the environmental impact of production of zero sulphur diesel fuel from coal[104]. The fuel synthesis is indirect based on coal gasification followed by Fischer–Tropsch (FT) synthesis. Three process cooling configurations were evaluated:

1. Wet cooling using mechanical draft evaporative cooling towers
2. Hybrid cooling in which a closed loop, air-cooled condenser is utilized to condense steam exiting the low-pressure turbine and the balance cooling needs make cooling towers as in (1)
3. Dry cooling in which air is blown through a dry-cooling tower to remove heat from a closed water loop.

The study modelled low temperature FT slurry phase reactor technology with iron based catalysts. In "once-through" cases, clean syngas is passed through the reactors only once with unconverted syngas and light hydrocarbons sent to gas turbines for power generation, creating a large quantity of power as a co-product. In "recycle" configurations, most of the unconverted syngas and light hydrocarbons is recycled

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[102] http://spectrum.ieee.org/energywise/green-tech/clean-coal/can-china-turn-carbon-capture-into-a-water-feature

[103] Nowakowski, S. (2007). Coal to Liquids Water Usage

[104] Tarka, T. J. (2011). Production of Zero Sulfur Diesel Fuel from Domestic Coal: Configurational Options to Reduce Environmental Impact.

back to the reactors (after CO_2 removal) to increase liquids production resulting in less co-produced power. The results of these cases using sub-bituminous coal as fuel are presented in Exhibit 26 below.

Cases	Recycle FT			Once-through FT		
Cooling Type	Wet	Dry	Hybrid	Wet	Dry	Hybrid
Efficiency, HHV (%)	53.0	51.3	52.2	50.6	50.1	50.5
Export Power (MW)	0.0	0.0	0.0	227.2	190.9	213.9
Water (bbl water/bbl FT product)	6.68	1.61	3.92	7.91	1.85	4.66
Required Selling Price ($/bbl FT diesel)	112.7	118.1	115.9	117.3	120.7	119.4

Exhibit 26: NETL modelling results for sub-bituminous CTL synthesis plant configurations

The NETL notes that this water for cooling processes can be optimized through different strategies for process cooling water management but similar reductions may not be possible in water consumed as a source of hydrogen and water use for solids and liquids handling.

Estimates of water use for CTL processes are also available from China's Shenhua Energy Company presented below.[105]

Item	Unit	Direct Liquefaction	Indirect Liquefaction		Methanol
			High Temp	Low Temp	
Efficiency	%	59.75	41.56	41.26	45.64
Water use	ton/ton	7.00	11.21	11.96	7.05
IRR	%	10.16	14.96	9.64	14.53

Exhibit 27: Shenhua comparison of coal conversion technologies

It is important to note here that although Direct CTL is a different process approach, the water demands use is for the same three reasons – process cooling, hydrogen demand and solids and liquid handling. Exhibit 27 shows that the water use in Direct CTL much lower than indirect processes. One of the reasons for this is because of the higher intrinsic efficiency of Direct CTL process. The company's environmental impact report indicates that the water use for the Direct CTL plant may be closer to 6 tons/ton of product. This is close to the 6.21 tons/ton figure reported by Sasol in 2013 for their South African Indirect CTL process plant.[106]

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[105] Zhang, Y. (2005). Shenhua coal conversion technology and industry development. In Proceedings of global climate and energy project international workshop on exploring the opportunities for research to integrate advanced coal technologies with CO2 capture and storage in China. Palo Alto: Stanford University.

[106] Sasol (2013) Sustainable Development Report

It is to be noted that later studies by NGOs suggest a much higher water consumption by Shenhua's CTL plant, approximately 10 tons/ton of product[107]. Because the project operates in the arid Inner Mongolia region, concerns have also been raised about declining groundwater levels and a decrease in the surface area of the Subeinaoer Lake, largest lake in the region.[108]

The NETL published its assessment of the performance of coal conversion systems, specifically to produce SNG and ammonia[109]. The modelling was done for a dry-feed entrained-flow gasifier and in configurations with and without carbon sequestration. The results are presented in Exhibit 28 below.

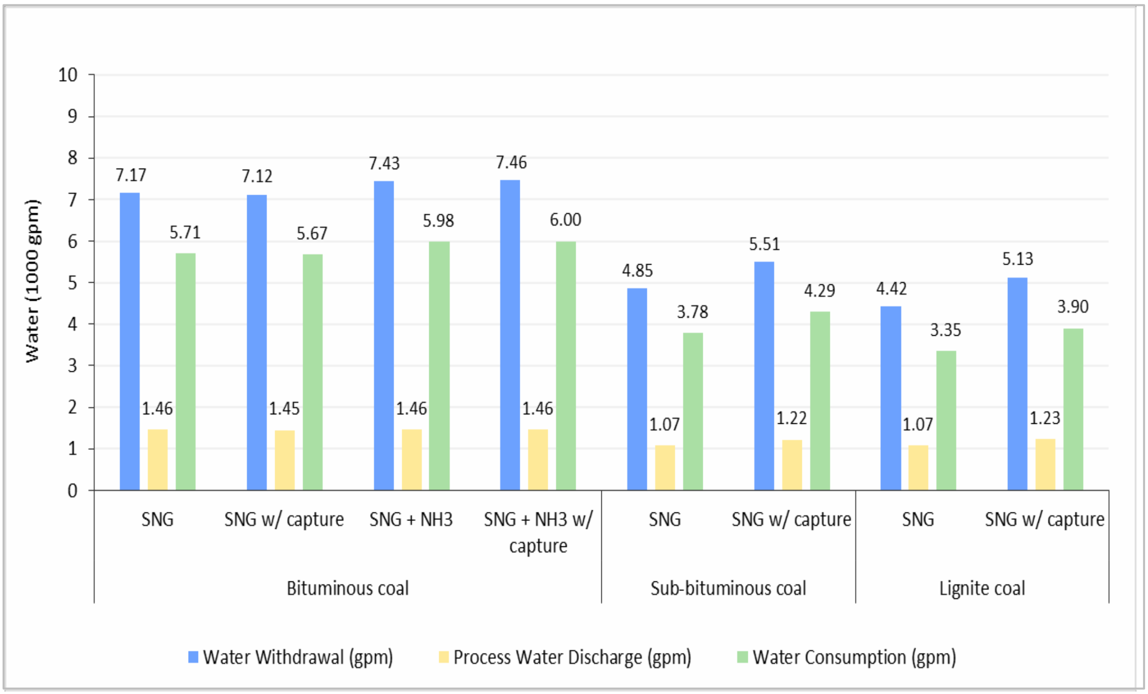

Exhibit 28: Raw water withdrawal and consumption for SNG and ammonia synthesis

The report noted that in all cases cooling tower makeup is the primary water consumer, ranging from 60 to 80 per cent of the total water withdrawal. The scenarios with coproduction of SNG and ammonia (third and fourth on graph) consume approximately 5% more water than the SNG only scenarios using bituminous coal. The reason for this increase is the excess shift steam required for hydrogen production to make ammonia. Finally, comparing the SNG only non-sequestration scenarios, the use of lignite is most water efficient followed by sub-bituminous coal. The same observation can be made when comparing the types of coal for SNG only sequestration scenarios as well.

107 Greenpeace (2012). Thirsty Coal 2

108 http://chinawaterrisk.org/opinions/coal-to-chemicals-shenhuas-water-grab/

109 U.S. DOE (2011). Cost and Performance Baseline for Fossil Energy Plants Volume 2: Coal to Synthetic Natural Gas and Ammonia

Yang and Jackson (2013)[110] calculate the water consumption of SNG production to be 6 – 12 litres per m^3 of SNG. On the other hand, shale gas needs roughly 0.1–0.2 litres of water per m^3 of methane produced, 50 to 100 times less than SNG. The nine approved SNG plants announced till 2012 were all in the arid regions of Xinjiang and Inner Mongolia. The study estimated that if these plants all operated at 90% of production capacity they would require 200 million tonnes of water annually thus worsening water shortages in areas already under significant water stress. The World Resources Institute[111] conducted a more extensive study by considering 18 approved large-scale SNG plants. They found that of 77% of this capacity will likely compete for water sources in areas with very high demand. Thus, 11 of the 18 facilities will likely face production cutbacks or outages during the dry season.

In 2015, China had suspended approvals for several coal conversion projects because of doubts about their economic viability and pollution risks. However, in May 2016 it was reported that three new Coal-to-Gas (CTG) plants have been approved in the coal-producing regions of Shanxi, Xinjiang, and Inner Mongolia. [112] Following this, local media reports that as of August 2016 China has more than 40 SNG plants under construction or planned.[113]

3.9 Integral Water Savings

Identifying opportunities to improve process operations is an activity that most power plant operators apply. In Byers (1995) a coal-fired power plant was considered a model for zero discharge for other industries to follow.[114] The water saving practices deployed in this instance were –

a. Replacing a once-through cooling system with cooling tower
b. Use of low quality water for FGD and ash quenching

These technologies even in present times are considered state-of-the-art, which illustrates the awareness of water conservation strategies adopted by some coal-fired power plants even 20 years ago.

In the Netherlands, DNV GL (then KEMA) conducted water pinch benchmark studies across several coal-fired power plants. Most these assets used once-through cooling with only one station having a cooling tower. A KEMA questionnaire in 1998 revealed that the water consumption was around 0.08 m^3 per MW_e, this however excluded water withdrawal. About 65% of this water consumption was dedicated for boiler water use[88]. During that period, combined cycle[115] power stations required 0.050 m^3 per MWe. A few plants in this case were also exporting steam to nearby industries, thus leading to higher water consumption when compared on the common scale of m^3/MW_e[116]. A similar benchmark study conducted in 2008 identified significantly different water pinch values between 0.013 to 0.166 m^3 per MWe[98]. This difference

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[110] Yang, C. J., & Jackson, R. B. (2013). China's synthetic natural gas revolution. *Nature climate change*, 3(10), 852-854.

[111] www.wri.org/blog/2013/10/china%E2%80%99s-response-air-pollution-poses-threat-water#fn:1

[112] www.reuters.com/article/us-china-coal-gas-idUSKCN0YB0UD

[113] www.scmp.com/tech/china-tech/article/1936048/china-heated-debate-turning-highly-polluting-coal-gas-fears

[114] B. Byers, Zero discharge: a systematic approach to water reuse. Chemical Engineering July 1995, pages 96 - 100

[115] In the context of gas and steam turbine.

[116] When compared on a similar scale of water consumption in m^3/Mwe some plants which supply steam to other industries would end up showing as more water consumption on this scale as compared to plants only generating steam for power consumption.

is not only attributed to power stations exporting steam to third parties but is also a function of the operating scenario and the frequency of cycling[117]. Cycling operation in the Netherlands is typically due to overcapacity, renewables and/or cheap electricity produced elsewhere.

In the 2008 benchmark study, the following integral (process) water savings were identified by the Dutch Power sector as discussed in the following points below:

1. Blow down of boilers:
    - **With a fixed alkalyzer**. This water has some concentration of salts but typically below 50 µS/cm. This is much lower than the permissible values for drinking water between 100 to 1000 µS/cm. This water can be reused as demin water by processing it over the demin street. This water would need to be cooled down to 30 °C in case of deploying IX-technology. A filtration step would also be needed to remove solid particles.
    - **With only ammonia**, again this stream is suitable for the demin line. Cooling is necessary prior to addition to the demin line. If necessary a filtration step can also be added for removing any suspended solids[118].
    - **With organic compounds**. Typically, different organic amines or organic oxygen scavengers are used. The blowdown stream containing these organic compounds can be led to a demineralization plant after cooling and even filtration if needed. However, it is known fact that amines require special attention as they may attach and form a film around the resins[119]. However, it is still not established whether this amine property has a similar impact on RO technology. It should be noted that organic amines or organic oxygen scavengers are not recommended for high pressure coal-fired power stations. Typically, they lead to formation of degradation products that result in acidic corrosive conditions in the early condensate and have a negative impact on the quantum of organic compounds entering the boiler through the demin plant[120].
2. **Steam.** All steam that comes free[121] in the plant can be reused for example from the deaerator[122] or turbine gland steam / sealing. Steam needs to be cooled or either directed to the condenser[123] wherein it is cooled. Thereafter, it can be led to the demineralization line.
3. **Sampling line**. This water is relatively clean with conductivity values lower than 10 µS/cm and comprises of condensate, boiler water, boiler feed water and steam[124]. This water can be led to the demineralization line for further processing.

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[117] A cycling operation with frequent start up and shut down cycle requires more water consumption per m^3/MWe produced as compared to continuous operation.

[118] Mainly, iron corrosion products.

[119] M. Lendi and P Wuhrmann, Impact of film forming amines on the reliability of online analytical instruments, API conference proceedings 2012.

[120] R. Heijboer, M.H. van Deelen-Bremer, L.M. Butter and A.G.L. Zeijseink, The Behavior of Organics in a Makeup Water Plant Power Plant Chemistry 2006, 8(4), pages 197–202.

[121] Here, free implies steam which is excess or is a by-product.

[122] B. Bramer, Developments in Spray Type deaerator applications, 2015 VGB Powertech Vol. 95, Issue 6, pages 73-79.

[123] Where feasible, provided the steam/water quality is maintained.

[124] After this water has passed through the cation filters.

4. Water from bottom ash dewatering installation. This water contains many kinds of salts, but is free from suspended solids and can be reused in the FGD unit.
5. Regenerate from the demineralization line or Condensate Polishing Unit. This water contains many salts and with deployment of a membrane technology can be reused as sealing water.
6. Air condensate, this water stream is produced when pure oxygen is made on site. The conductivity of this water is lower than10 µS/cm and can be further treated in the Demineralization line.

An article by Siemens written by Söllner, et al. (2011) proposes that (waste) water streams containing ammonia should preferably not be treated by RO systems (alone) and this water stream should be evaporated. DNV GL suggests a purge of nitrogen or steam to remove excess ammonia and/or treatment with a mixed bed.

As a result of Dutch policy, attempts have been made by Dutch power producers to monitor all water streams within the power station. These are monitored and benchmarked yearly to stimulate improvements. This is done in close corporation within different departments (chemistry and process) of the power station. Examples of parameters within power stations which can be monitored to improve efficiency are:

- Regeneration of demin line: Total demineralization production linked with amount of regenerate chemical used (HCl and NaOH)
- Combining the amount of start-ups and blowdown losses provides a value which can be used as a benchmark

These parameters together with all discharge information such as stream type, location, amount in m^3/year, temperature, CZV BOD value etc. are then provided to authorities on a yearly basis in a mandatory Dutch environmental report. Some examples are indicated below:

- Water from sampling lines which can be used as:
  - Make-up water for district heating
  - Break tank of the demin line
  - Fed into the condenser just prior to the Condensate Polishing Unit (CPU), or in the boiler feed water depending on cation conductivity of the captured water
  - For different water streams like sealing water or emergency firewater
- Surface runoff water from the roof (rain water) after filtration can be used for:
  - Break tank of the demin line
  - The sealing water tank
  - The emergency firewater tank
- Surface run-off water from the circulation field is used as dust control for the coal storage area
- Water extracted from the gypsum centrifuges returns to the FGD unit
- Water from the settling tanks goes to the FGD unit

Although the above was identified in the Dutch working group of water management representing the entire Dutch power sector, it was concluded that to achieve an efficient water management system the following steps are still needed:

- Ensure that all water streams are made visible in a clear overview and further monitoring of these streams, both in terms of quality and quantity
- Interpret trends from this information and implement improvements
- Benchmark findings with other plants

- Find different sources of water like surface run off water.

It is apparent that policy making and cost economics will play a key role in implementing water improvement practices at coal-fired power plants[98]. To limit the amount of ammonia (N-compound) wastewater produced from regenerate in a condensate polishing plant, several techniques were investigated by DNV GL[125]. Steam stripping and Ammonium Form Operation of the Mixed Bed[126] are applied on a small scale. Membrane distillation has the most possible advantages, but this technique still needs to be further proven.

To summarize, as far back as the early 2000s, articles were released, like those of Daniels in Power Magazine (2001)[19], showing the potential of reusing (waste) water streams for power generation use. Cooling tower blow down, brine of RO could be treated for make-up use using MF and UF membranes. Reject streams can be further treated using a crystallization process, while its distillate products can be reused in the power station. Additionally, RO effluents can also be used as make-up for ash water and FGD systems. Some other usage applications described here pertain to developments of effluent municipal wastewater for cooling tower use and other process water needs[127]. New power stations equipped with ZLD technologies would typically result in 98% water recovery, for instance, the Constellation Power Generation's High Desert Facility[128]. A common trend during that time was to move water treatment out of the power station domain and entrust it to dedicated water treatment service companies[19]. Another example of this trend of outsourcing is the Fairfield Recycled Water Treatment Plant[129] in Sydney, Australia. Here, secondary treated effluent produces high quality recycled water which is used by five of Sydney's largest industrial users. This includes a co-generation plant which utilizes this water as makeup for its cooling tower and as a raw source for its demineralization plant. The recycling plant was built by Veolia and can produce 20 Million Litres per Day (MLD) of treated water utilising the process of UF, RO, IX and degasification. In this plant IX regenerate (waste) water is recycled to the head of the plant and there is a close-coupling between RO, IX and degasser[130].

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[125] F. de Vos. Reducing en reuse of the ammonia rich regenerate of the CPP. KEMA Report 06-9505.

[126] Instead of the hydrogen form.

[127] An example location of deployment in this context is Oahu, Hawaii.

[128] S. J. Shulder and M. K. Mierzejewski, High Desert project takes new approach to zero liquid discharge. Power Jan/Feb 2002, pages 47 – 50.

[129] Part of the Rosehill-Camellia Recycled Water Scheme.

[130] M. Nunn, Fairfield Recycled Water Treatment Plant: a case study in water recycling, paper & presentation API PowerChem conference 2012 and Fairfield Recycled Water Plant Rosehill Recycled Water Scheme

4 EMERGING TECHNOLOGIES FOR REDUCTION OF WATER USE

This section builds on the basics of water use in coal-fired power plants outlined in section 2 by exploring emerging technologies that aim to reduce overall water consumption by modifying different stages of the generation process.

4.1 Water Vapour Capture from Exhaust Flue Gas

In a typical 650-MW_e coal-fired power plant equipped with wet FGD, there are about 190 tonnes of water exiting the stack every hour. Capturing just 20% of this would fulfil process water needs like boiler make-up water for which the mentioned plant capacity would roughly be 37 m^3/hour. This would, however, not provide sufficient make-up water requirements for FGD or cooling. DNV GL led an international consortium of 13 partners in developing a membrane technology for water vapour capture from flue gases. In this project a benchmark with all known existing water vapour capture technologies was made and presented at PowerGen conferences in India and Europe[63]. Various parameters evaluated in this case were the maturity of the technologies, performance, economic evaluation, water purity, operational aspects, health and safety. The evaluation of different technologies included cryogenic separation, cooling with condensation, liquid and solid sorption. An initial screening revealed that liquid sorption and cooling with condensation where the most mature and promising technologies.

4.1.1 Liquid Sorption

Liquid sorption or desiccant based water capture has been researched through several studies funded by the US Department of Energy (DOE) during 2003-2006. Various articles were published on this topic including the one by Folkedahl *et al*. (2006)[131]. DNV GL in one of their published reports from Daal *et al*. (2012) evaluated this technology and for more detailed information one can refer to this article. The key characteristics and operating features of Liquid Sorption technology have been summarized in the subsequent points:

Maintenance and durability: Two points are of main interest with respect to maintenance and durability, namely corrosion and crystallization. It was mentioned by Folkedahl *et al*. (2006) that corrosion is a major design stumbling block in the proposed design. Most of the salt-based desiccants (such as calcium chloride) are highly corrosive to steel and most other common metals. Corrosion inhibitors will not be very helpful since oxygen is present in the flue gas. Coating with or use of complete polymer components may be the only solution.

Investment costs: US$ 5.8 million for a turnkey installation as estimated by Folkedahl *et al*. (2006). This includes equipment cost of US$ 4.7 million and installation cost of US$ 1.1 million. The prices are based on vendor data. Assuming an interest rate of 4%, this typically results in a capital cost of US$ 200,000 per year.

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[131] Folkedahl, B., Weber, G.F., Collings, M.E. Water extraction from coal-fired power plant flue gas. Final report DOE Cooperative Agreement No. DE-FC26-03NT41907. December 2006.

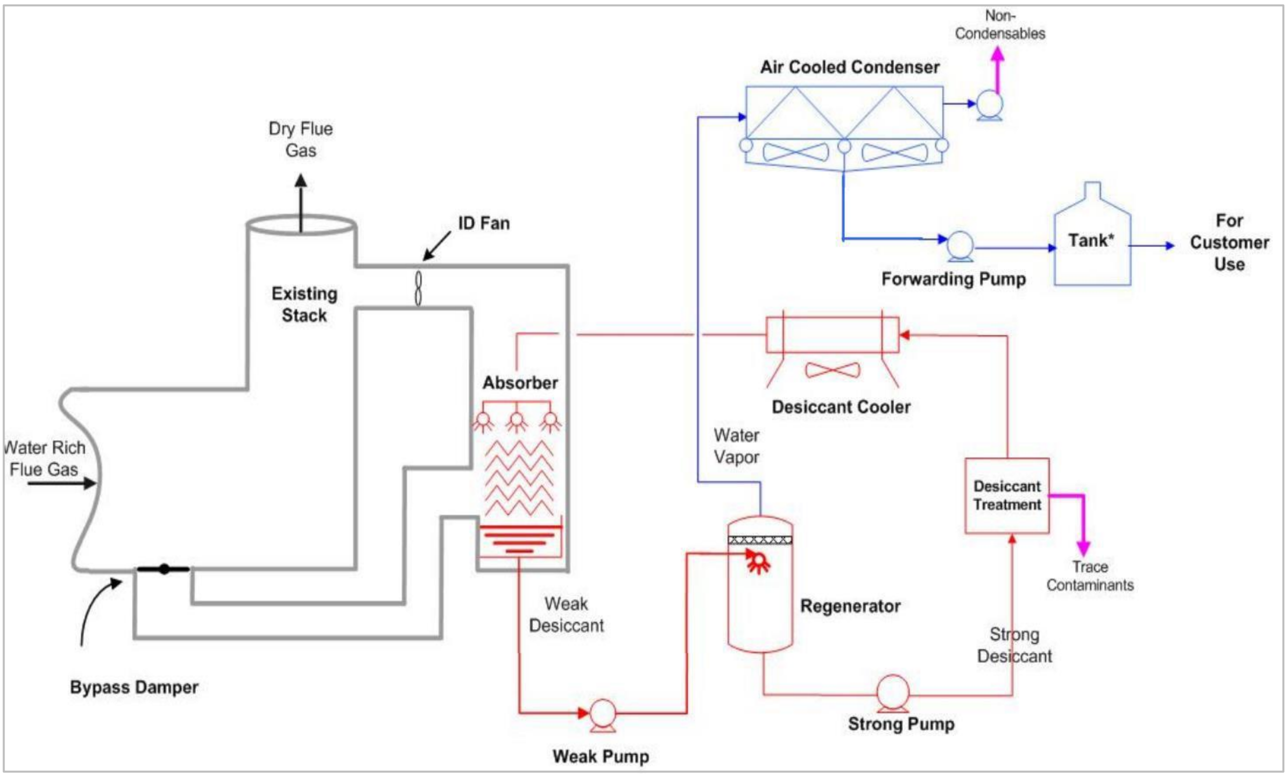

Exhibit 29: Schematic of a Liquid Desiccant Based Water Capture Plant[132]

Energy costs / benefits: The power use for a 250 MW_e coal-fired power plant was estimated to be about 1,150 kW which is the sum of the desiccant pump power (400 kW), air fans of condenser and desiccant cooling (500 kW) and the vacuum pump (250 kW). At a price of US$ 0.01 per kWh and 24 hours per day operation, this results in an operating energy cost of US$ 100,000 per year.

Cost of auxiliary materials and operation: Whether desiccant degrades or not is not explicitly mentioned by Folkedahl *et al*. (2006). The operational costs include desiccant costs estimated for a 250 MW_e coal-fired plant to be in the range of US$ 200,000 per year.

Economic viability: The total annual costs were estimated to be about US$ 500,000, resulting in a price of US$ 0.02 per gallon of pure water (US$ 4.40 per m^3). Whether this is economically viable or not depends very much on the location of the plant; in areas where water is scarce this may be the case. The 250 MWe coal plant would yield about 0.123 million m^3 of water per year.

4.1.2 Heat-exchangers

When flue gas is brought below the water dew point, the entrained water vapour will condense. This straightforward physical phenomenon can be used to remove water from flue gas by installing heat exchangers in the flue gas ducts.

[132] Copen, J.H., Sullivan, T.B. and Folkedahl, B.C., 2005, December. Principles of flue gas water recovery system. In Proceedings of the power-gen international conference; Las Vagas NV.

Maintenance and durability: A significant section of the flue gas coolers operates below the acid dew point[133] temperature. For instance, sulfuric acid condenses on heat exchanger surfaces, forming a thin layer of diluted sulfuric acid that attracts fly ash and forms deposits. The deposits, forming on vertical heat transfer tubes, should be washed away using a pre-installed washing system. When these deposits are not removed, they may lead to corrosion.

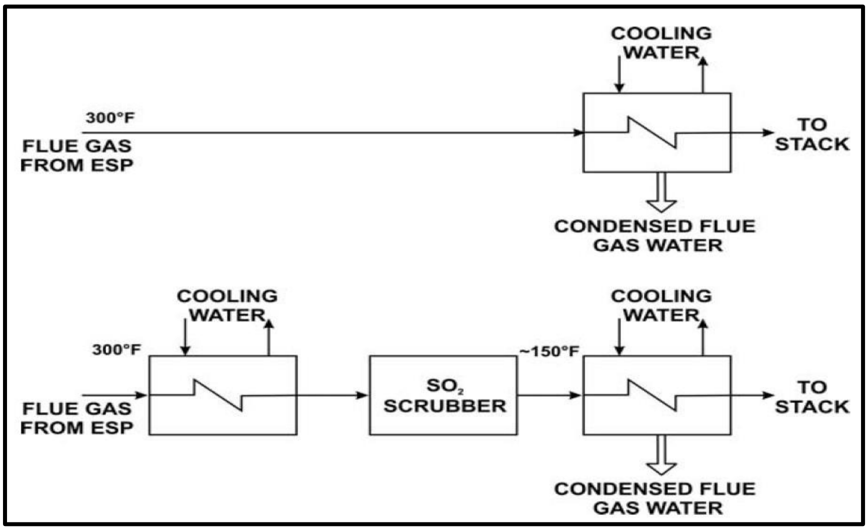

Exhibit 30: Flow sheet of Condensing Heat Exchangers in Flue Gas Duct134

Investment costs: The turn-key project cost for a 30 MW_{th} fluoroplastic heat exchanger that replaces a steam air preheater was reported to be in the range of EUR 4.7 million (2004 prices)[135]. However, this project is a special case as the deployment of the low-quality coal necessitates the steam air preheater to be operational at least 90 percent of the time. The overall efficiency increase in this case was 0.37 % for a 750 MW lignite fired power plant.

KEMA also studied the use of plastic heat exchangers for heat recovery from flue gas[136]. Several options were studied for a 652 MW_e net bituminous coal-fired power station. Exhibit 31 shows the electric efficiency improvement and the associated capital investment costs[137].

[133] Acids referred to in this case are namely H_2SO_4, HCl, Nitric Acid (HNO_3) and Hydrogen Fluoride (HF).

[134] Levy, E., Bilirgen, H. and DuPont, J., 2011. Recovery of water from boiler flue gas using condensing heat exchangers. Final Project Report DOE/NETL Project DE-NT0005648. The upper half of the exhibit illustrates flue gas stream without FGD, whereas the lower half indicates a flow stream with FGD.

[135] B. Michels, F. Adamczyk, and J. Koch. Retrofit of a flue gas heat recovery system at the Mehrum power plant. An example of power plant lifetime evaluation in practice. VGB PowerTech, Nr. 10, 2004.

[136] D. Van Vlist and P.H.M. van Wichern. Plastic heat exchangers for efficiency improvement of coal-fired power plants. Confidential client. KEMA Report no. 95101-KPG/PEN 97-2758.

[137] Reference Costs from the base year as indicated in the respective articles have been corrected to take into account the subsequent inflation effect.

Case	Efficiency improvement (percent point)	Capital investment cost (million EUR, 2011)		
		Minimum	Maximum	Average
A	0.75	15.24	20.79	18.02
B	0.85	16.63	22.87	19.75
C	1.10	26.33	36.73	31.53

Exhibit 31: Heat Recovery from Flue Gas, Electric Efficiency Improvement and CapEx

Based on these capital cost estimates, a payback period ranging from 9.5 to 19 years has been calculated. Only energy savings have been considered in this evaluation. Water recovery has not been considered since the minimum temperature considered was still above the water dew point.

Energy costs/benefits: Energy is not consumed but gained in this process. Theoretical analyses using Aspen Plus process simulation software on four different types of US coals resulted in an increase of net power output of 1.25 to 1.77%. The resulting heat rate and water capture efficiency improvement increases further with higher moisture concentration levels of inlet flue gas, better heat exchanger efficiency and decreasing temperature of inlet combustion air.

There have been several initiatives in other industrial processes to capture the remaining latent heat of the flue gas through heat exchangers. Teppler[138] describes a waste-to-energy plant which uses the Radscan Intervex process to capture about 90% of the present water in the flue gas for boiler make-up water needs. The water content is substantially higher than that of a coal-fired plant, namely 30 to 50 vol.% versus 12-14 vol.% water content. The process is based on the use of scrubbers, heat-exchangers, UF and RO membranes, membrane degasification and EDI polishing. It produces 20 to 25 m^3/h and has an investment of EUR 10 million. The water quality fulfils international boiler make-up guidelines. Typical standalone Waste to Energy (WtE) plants has efficiency of around 60%, while those coupled with district heating are between 60-70%. By utilizing the Radscan process, efficiencies can reach up to 90%[138]. After two years of normal operation[139], the unit has paid back its investment. DNV GL designed the world's first high pressure WtE plant in Amsterdam, which however has not reached efficiency levels discussed here. Nevertheless, it is expected that better efficiencies can possibly be achieved by bringing down the flue gas exit temperature to 40 °C as compared to the normally observed operating levels of 60 – 70 °C.

4.1.3 Membrane water vapour capture – CapWa

Several articles report the findings of the CapWa project which was aimed at upscaling the promising membrane technology to a pre-industrial scale (see section 4.5.3 for more details). Aside from the benchmark study [Daal *et al.*, 2012], the energy calculations were also published in Daal *et al.*, 2013[140].

[138] M. Teppler, J. Wood and P. Buzzell, Flue gas Condensate and Energy recovery. PowerPlant Chemistry 2009, 11(2), pages 115-121

[139] With annual operating hours varying from 5000 to 6000.

[140] L. Daal, H. Kamphuis, F. de Vos, M. Huibers, S. van Rijen and J. de Ruijter. A new source of water that saves energy. VGB Powertech 2013 (8), pages 78 – 83.

More importantly, the study results formed the basis of a pilot project, wherein industrially constructed membrane modules were deployed in a coal-fired power plant in Israel[141].

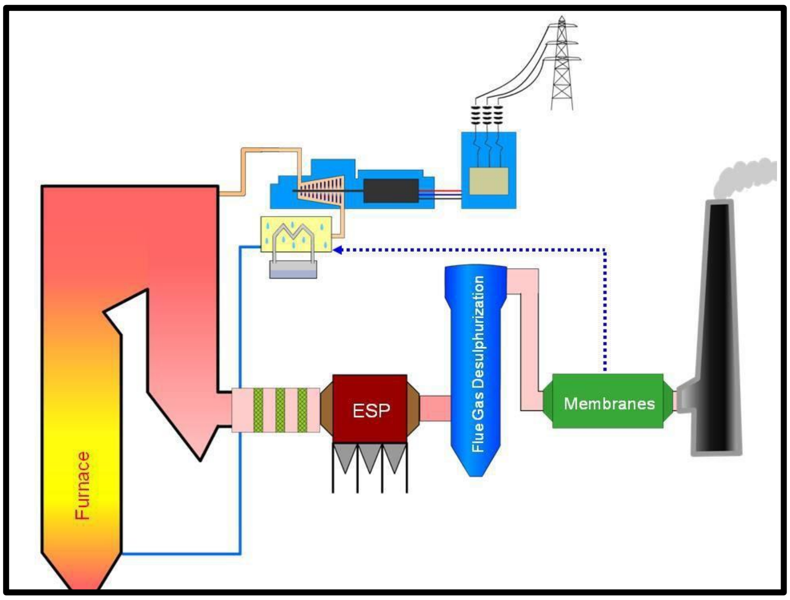

Exhibit 32: Schematic of Water Vapour Capture*[142]*

The evaporated water can be removed by using selective membranes. The captured water is in a single step, close to demineralized water quality levels. The advantage of selectively removing water over condensing the entire flue gas stream is that less cooling energy demand is needed and the removed water is non-corrosive[143]. A schematic of how gas separation technology could be implemented in a coal-fired power plant is shown in Exhibit 32. In this schematic, a coal-fired power plant operating with FGD is illustrated. The membrane modules are placed downstream of the FGD, and the membrane unit either replaces the flue gas re-heater system[144] or can be integrated within the FGD unit itself for reducing footprint. The recovered water vapour (permeate) is transported directly to the existing condenser system, where condensation takes place. From this schematic, it is clear that the recovered water vapour should not contain any non-condensables to prevent any negative impact on the operation of vacuum condenser. Hence very selective membranes for water vapour are needed. The driving force is the partial pressure difference of water vapour between the flue gas side (outside of a fibre) and the vacuum side (inside of the membrane fibre). The selected membranes have excellent properties and the recorded water quality[145]

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141 F. de Vos, P. van Daele, J. Gabster, D. Sherban, R. Mehr, D. Yitzhak, I. Bettermann, S.Weuster,W. Ansorge, H. Teunis, Z. Borneman, and L. Daal. Pilot Test to Capture Water from the Flue Gas of a Coal-Fired Power Station. PowerPlant Chemistry 2014, 16(2), pages 126–142

142 DNV GL. The membrane modules are placed inside a flue gas stream of a coal fired power plant and the captured water vapour is send to the condenser.

143 When condensing flue gas, the resulting condensed water has corrosive properties.

144 The re-heater system is intended to protect the stack from corrosion by maintaining the flue gas temperature to more than the acid dew point.

145 Less than 20 µS/cm

is analogous to that achieved in a demineralization process. Additionally, the recovered water is free from any bacteria and viruses.

Alternative membranes for water vapour capture. In 2008-2011, a research project was conducted in the United States by Gas Technology Institute (GTI), Media and Process Technology, Inc. and RMT Inc. /Alliant Energy under supervision of the U.S. Department of Energy (DOE), which focused on the development of a membrane separation technology to recover water vapour from power plant flue gas based on modifications to GTI's Transport Membrane Condenser (TMC). The intention of the research project was to develop a modified TMC based system to recover water from power plants.

It is expected that with enough (cold) cooling water available, up to 90% of water vapour in the flue gas can be cost-effectively recovered, especially in case of high moisture content coals. Although it seems promising, no results have been presented to date. DNV GL, UTwente and Ecole Nationale d'Ingénieurs de Tunis (ENIT) within the CapWa consortium evaluated the technology and realized that pores of ceramic filters[146] are exposed to a very small portion of the present dust particles (0.01%). However, due to large quantity of flue gas passing through the membranes, the consortium anticipated that it will likely clog and is still unclear as to what methods GTI intends to adopt for cleaning of the pores. Also, unclear is whether acidic compounds can be allowed to pass through the membrane, or a cleaning step is necessary to remove the same. TMC technology is currently applied commercially in small gas fired applications.

4.1.4 Benchmark water vapour capture

In Daal, et al. 2012, benchmark water vapour capture values from the pilot tests were provided. The same have been summarized in Exhibit 33.

Parameter	Liquid dehydration	Condensation cooling	Membranes
Water quality	++	-	+
Energy consumption / savings	-	++	+
CapEx	-	-	±
OPEX	-	+	±
Technology maturity	TRL 6-7	TRL 8-9	TRL 6

Exhibit 33: Qualitative Benchmark of Technologies for Water Recovery from Flue Gas

4.2 Re-use of Water and ZLD technology

4.2.1 Effluent municipal wastewater as make-up

Boiler make-up water. There are several public articles/proceedings on operations of the Eraring Power plant in Australia. The example of the Eraring plant is taken here in-depth to illustrate the many difficulties in assessing re-use of effluent municipal wastewater for boiler make-up use, in spite of the extensive information available.

[146] Which, in this case, are of nanometre size.

Eraring is a coal-fired power station with 4 units of 660 MW_e each. It has a closed cooling water circuit where water is extracted from a nearby lake. The plant is known for its effluent wastewater use where it is tertiary treated on site using Micro-Filtration and reverse osmosis. The effluent and site surface water run-off would first enter the site storage tank. Thereafter $FeCl_3$ is dosed, a pre-filter is applied and subsequently a dual MF unit. The reject stream will be directed to the sewage treatment plant, wherein the clear liquor is removed and transferred back to the storage tank to be reprocessed. The product of the MF unit is dosed with hypochlorite to prevent biofouling and sulphuric acid for conditioning of the RO units. This stream then goes to a two train RO unit. Prior entering the RO unit an anti-scalent is dosed and a 5 µm cartridge filter is used. The permeate (clean water) then goes to a degasser tower to remove CO_2. The RO brine is treated with $FeCl_3$ to precipitate phosphorous and this is then deposed of in the ash dam. The proceedings from 1998 further describe the Cleaning in Place practices and the operational experience after 3 years. Also, operational chemical cost per activity is supplied and the total chemical cost is AU$ 0.09 per m^3 of reclaimed water. With fixed effluent cost of AU$ 0.01 per m^3, service costs[147] at AU$ 0.15 per m^3 and electrical costs of about $ 0.20 per m^3, the reclaimed water would have a total cost of around AU$ 0.25 to AU$ 0.50 per m^3 (as per 1998 prices)[148].

In 1998, about half of the 4 Million Litres/day (MLD)[149] of water used by this power plant, was replaced by treated effluent wastewater (2.2 MLD). The site was originally designed to treat up to 3.8 MLD of wastewater. According to Eraring the cost savings for reduced chemical usage for the demineralization plant coupled with reduction in potable water use, amounted to AU$ 1.5 Million per year. Based on this information and the assumption that reclaimed water would cost around AU$ 0.25 to AU $0.50 per m^3, Eraring claims returns of investment to be in the range of 6 to 7 years. This return on investment as per Eraring in 1998, is considered acceptable for a power station lifetime of 40 years. Although no quality data have been provided herein, other proceedings show that the water quality is not suitable for direct boiler make-up water use. DNV GL believes the figures are not entirely accurate. For example, the saved chemical cost on the demineralization line is not clear. In fact, it is likely that this would increase compared to potable water[150]. The proceedings from Juratowitch and Harvey during the API conference in 2012 show a complete IX demin line[151]. While this article does claim that potable water has higher conductivities, it does not analyse critical aspects such as difference in composition of potable water vis-a-vis reclaimed water. Higher conductivity is more difficult to treat for an IX, thus RO pre-treatment can possibly be more effective here. The set-up at Eraring uses the reclaimed water, post tertiary treatment over a complete IX line[152] as compared to a simple polishing step, for instance through a mixed bed. Additionally, DNV GL and EPRI members noted that the make-up water quality of 25 µS/cm specification was being deployed by

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[147] This will typically include analytical and spares/consumables costs for items such as acid cleans, autopsy, spare MFP modules, valves, etc.

[148] G. Craig. Water recovery plant – the first three years: a case study. Proceedings Power Station Chemistry Conference Australia, March 1998

[149] 167 m^3/hr or 63 litres per MWe

[150] Treatment of potable water would be less complex as compared to the reclaimed water having complex chemicals and additives like hypochlorite.

[151] T. Juratowitch and P. Harvey. Performance of demineralization plant ion exchange resins when contaminated with high chlorinated feed water. Proceedings API PowerChem Australia, 2012

[152] Which typically consists of a cation, anion and a mixed bed.

Eraring. On some occasions, quality levels below 10 μS/cm were achieved, which are well above KEMA, EPRI and VGB guidelines. These proceedings also illustrated the typical challenges faced on the upstream side of the reclaimed water processing plant. For instance, (over) dosing hypochlorite resulted in make-up water quality specifications not being achieved. This led to an extensive investigation exercise for root cause determination.

Another factor overlooked in the above discussed case studies is the cost for RO membrane replacement, which will most likely come under consideration 7 years after commencement of operations. However, the MF replacement cost when clubbed with other costs[153] amount to a total treatment cost of AU$ 0.02 per m^3. This number is too low as compared to costs incurred for similar applications under a normal operating scenario. Additional factors such as specialized labour costs should also be considered to monitor both the tertiary treatment and the demineralization plant.

In several proceedings of the American Petroleum Institute (API) in 2012[154], the effects of tertiary treatment plant on the operations of the demineralization plant and the steam boiler were discussed. The maintenance aspects of the boiler are greatly impacted by improper cycle chemistry of the plant. However, the boiler make-up water also plays a key role here and it is unclear if the demineralization line can adhere to prescribed international limits of 0.10 – 0.20 μS/cm, for ensuring reliability of operation. Hence, DNV GL believes the return of investment (ROI) is not entirely accurate and that this would be more in the region of 10 to 15 years or even higher.

An interesting note is that the staff at Eraring was concerned for their safety when treating effluent wastewater. This needs to be addressed by every power station when dealing with similar wastewater streams.[155]

Cooling tower Discharge water from wet cooling towers contains high inorganic loads[156] along with a concentration of water treatment chemicals, which typically includes corrosion and scale inhibitors. As the water volume in the tower is reduced due to evaporation and drift, the concentration of these chemicals and their byproducts increases. Cooling towers also pick-up contaminants from ambient air. To maintain chemical and contaminant concentrations at a prudent level, water is periodically removed from the system through a process called as "blowdown" or "bleed off". The blowdown water and the water lost through evaporation and drift are replaced with fresh "make-up" water[157]. Blow-down water must subsequently be discharged to a local wastewater treatment facility or discharged onsite to the environment. The blowdown water typically contains little organic material and the local wastewater treatment facility will generally charge extra sewage fees for accepting this water. These additional costs can be quite significant as compared to the overall costs of operating a Cooling Tower (CT). Discharge of the blowdown water to the environment onsite is also coming under increasing challenges due to stricter regulation of contaminants typically found in blow-down water. To use discharge water from the CT, thus requires other corrosion and anti-scale water treatment.

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[153] The additional costs considered herein were labour costs associated with Clean-in-Place activities and other consumables, such as wale spare, etc.

[154] M. Wyburn, Copper transportation at Eraring Power station. Proceedings API PowerChem, Australia, 2012

[155] Craig, G. (1999). The Eraring experience: four years on. IQPC Conference on Water Recycling and Effluent Re-use

[156] Comprising of calcium phosphate, calcium carbonate etc.

[157] This make-up water will also contain minerals and other impurities.

The use of ozone for CT maintenance has good prospects for improving operational performance and reducing maintenance costs. A small amount of ozone acts as a powerful biocide that decreases or nearly eliminates the need to remove quantities of water from the cooling tower to decrease the concentration of organic and mineral solids in the system. Ozone dissipates quickly and will not be found in the blow down water. This reduces the overall chemical load typically associated with the discharged water, making it easier to comply with stringent regulations.

There is also a belief within the industry that under certain conditions ozone acts as a descaling agent, and therefore can act as a 'stand-alone cooling water treatment program". The point of contention here is that ozone oxidizes the biofilm that serves as a binding agent adhering scale to heat exchange surfaces.

Energy consumed by ozone generators and auxiliaries is typically 9 kilowatt hours (kWh) to 14 kWh per pound of ozone generated. Costs for a typical ozone system capable of treating a 1,000 ton (3,500-kW) cooling tower are estimated to range from US$ 25,000 to 70,000, depending upon manufacturer and actual system size. An assumption of US$ 36/ton of cooling may be used to provide a rough cost estimate for an ozone system. The ozone systems are sized according to need and typically range from 10 gram/hour to 3,700 gram/hour with a corresponding price range of US$ 10,000 to 300,000. The wide variation in cost is a result of the fact that the size, and subsequently the cost, of the system depends heavily upon the operating temperature and environment of the tower. An EPRI case study focused on the Digital Equipment Corporation offices in Littleton, Massachusetts, a 500,000 square-foot complex[158]. The ozonation system was commissioned in 1989. Digital engineers found ozonation to be economically and environmentally superior to previous chemical treatments. In addition to the biocidal effect, ozonation reduced blow down and eliminated the need for employees to handle chemicals. Tests over a period of two and half years showed no scale formation; corrosion rates within industry standards and adherence to equipment manufacturer recommendations. Annual operating costs were reduced by almost $90,000 with a resulting payback period for capital investment of about 2 years.

A case study examines a system of four ceramic-filled concrete cooling towers with a capacity of 2,500 tons (8,750 kW) each[158]. The towers reject heat from the air-conditioning system that provided temperature and humidity control for Space Shuttle processing in the Vehicle Assembly Building (VAB) at NASA's Kennedy Space Center (KSC), Florida. The cooling towers that provide service to the VAB are in the Utility Annex (central plant) at KSC. The make-up water is purchased from a Privately-Owned Treatment Works (POTW) at a cost of US$ 1.18/1,000 gallons (US$ 0.31 per m^3) and blow down was discharged to local surface waters. Chemical treatment for the cooling tower was US$ 10.18/ton per year (US$ 2.91/kW) and consisted of two-phase scale and corrosion inhibitors and alternating biocide application. In 1990, the Florida Administrative Code (FAC) 17-302, Surface Water Quality Standards, introduced stricter environmental regulations that made the blow down water unable to meet regulatory criteria for discharge to the local surface waters. Hence, ozone treatment was installed in February 1994 to reduce the amount of blow down being discharged.

The four cooling towers have a total capacity of 10,000 tons (35,000 kW) and contain a total of 204,000 gallons (or 772 m^3) of cooling water. The towers had an average volumetric rate for make-up water at 146,000 gallons/day. Average blow down quantity was around 67,200 gallons/day, while the rest was attributed to a combination of drift and evaporation losses. The towers generally operated with a

158 www.spartanwatertreatment.com/articles/Ozone-Treatment-for-Cooling-Towers-Federal-Technology-Alert.pdf

concentration ratio of 4 to 7. Cooling water is circulated at 7,500 gal/min (28.4 m^3/minute) through each tower. The observed tower water temperature drop was from 110°F (43.3°C) to 90°F (32.2°C).

The average installed cost of an ozone system as discussed is typically in the range of US$ 10/kW or US$ 36/ton, for smaller systems. As the ozone generators get larger, the cost per ton subsequently reduces. An average chemical treatment program cost is $10/ton per year while an average ozone treatment will cost around US$ 2/ton[159] per year**.** The cost of make-up water and disposal of blow down varies widely and ideally should be obtained for the particular cooling tower application under consideration. In addition, local energy costs should be used for the ozone energy consumption. The estimated costs and savings for the Utility Annex cooling tower system are listed in Exhibit 34.

Parameter	Existing system	Ozone System	Difference
Operating cost (US$/year)	164,680	40,215	124,465
Ozone equipment cost (US$)	Not Applicable	320,500	(320,500)
Annual water use (gal)	59, 130,000	30, 894,200	28, 235,800

Exhibit 34 : Estimated Cooling Tower System Operating Information

The estimates from the above calculations are to use 690 grams per hour (gr/hr) ozone generator. Annual savings are estimated to be in the range of US$ 124,465. Using the Building Life-Cycle Cost software[160] available from the National Institute of Standards and Technology (NIST), the total life-cycle cost for the ozone technology is US$ 663,850 compared to a life-cycle cost of US$ 1,463,555 for the conventional chemical treatment program. A life cycle of 10 years was used in this analysis. The resulting net present value (NPV) is determined to be US$ 799,705 and the savings-to-investment ratio (SIR) is 3.5.

The ozone system installed at the Utility Annex has a generation capacity of 600 gr/hr. For comparative purposes, the actual costs and savings reported by Tierney and Mott[161] are identified in Exhibit 35. The water consumptions savings here are 33%. The overall savings were determined to be US$ 100,012/year. Experience at the Utility Annex cooling towers has shown that ozone treatment is indeed a viable water treatment method for cooling towers. The idea that zero blowdown can be practiced is not feasible, since the calcium levels will eventually get too high and scale will start forming. At 60 to 80 cycles, the cooling towers were 60% plugged with scale in 8 months. In addition, the ozone injection circuit was plagued by the same problem and was difficult to keep on line. This forced the operators to reduce the concentration cycles to be between 10 and 20. Research indicated that they could further increase the concentration cycles to be between 30 and 40, which is the present state of operations.

[159] Operating Cost

[160] BLCC Version 4.2, 1995.

[161] Tierney, D.J., R.A. Mott. Ozone V. Chemical Treatment of Cooling Towers at Kennedy Space Center: A Progress Report. Tierney 407-867-1190.

Parameter	Existing system	Ozone system
Operating Cost (US$)	161,484/yr	61,472/yr
Ozone Equipment Cost (US$)	Not Applicable	330,000
Annual Water Use (gal)	53,290,000	35,690,000
(a) Reported from telephone interview with site personnel.		

Exhibit 35: Reported Cooling Tower Operating Information

Overall, the results are good. The reduction in blow down, make-up water and chemical costs usually will provide a simple payback time of less than 6 years.

Cooling tower make-up & ZL(E)D. The reuse of effluent wastewater from municipalities as make-up for cooling tower use has been applied for many decades. In proceedings of the Power Station Chemistry conference in Australia 1998, it was mentioned that already over 20 power stations were reusing effluent for CT make-up. Some power stations in this regard were Las Vegas by Nevada Power, Palo Verde Nuclear Power Station from Arizona Public Service Electric Company (APS) in Phoenix (both 30 years to date)[162] and six stations from Federal Electric in Mexico[163]. Effluent water[164] varies in quality which in turn depends upon its original application as listed below in the following examples:

a. Silica as a result of detergent use
b. Phosphate as a result of domestic sewage, detergents and industrial chemicals
c. Nitrogen compounds, such as ammonia, nitrate, and nitrite, due to domestic sewage impact
d. Chloride due to domestic and industrial discharges.

Due to quality variation in these compounds[165], cycling in CT becomes challenging. These compounds can result in scaling, biofouling and corrosion. Also, due to the large amount of water needed for the CT, pre-treatment should be kept to a minimal to make it economically feasible. In most cases, it is circulating water that determines the water specifications and not the make-up water specifications. Limiting concentrations of impurities is determined by key CT system operations like water treatment options, metallurgy, temperature, water velocity and heat flux of critical heat exchangers, and sub-optimum design of heat exchangers[166]. Once the limiting concentration has been established, measures must be taken to ensure that these limits are not exceeded as discussed below:

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[162] Largest US reuse of effluent by a single power station. Station 4030 MWe with 90 Million Gallon per day ZLD station, extracted from: http://www.azenergy.gov/doclib/6-20-14_AMC-PVNGS_B.Lotts.pdf

[163] P. Puckorius. Water reuse practices in USA utility power plants. Power station chemistry conference, Australia. March 1998

[164] In context of industries and municipalities.

[165] Silicon (Si), Calcium (Ca), Suspended Solids (SS), Ammonia Based Compounds (N- Compounds), nutrients, such as phosphates and organics, etc.

[166] For example, vertical heat exchanger with shell side cooling water

- Cold lime softening to reduce concentration of Ca, Si, SS, phosphates and some organic materials. This can be applied to both make-up or a side stream of the circulating water
- Chlorination of make-up or circulating water to control microorganisms, ammonia, nitrite and nitrate.
- Filtration to remove Suspended Solids (SS). This can be done to make-up water, side stream or both.
- Activated carbon filter for removal of both organic compounds and particulate matter.
- RO membrane technology or sodium cycle ion exchange are occasionally applied to make-up or side-stream.
- Nitrification to remove ammonia or apply pH increase and strip with air for example with a splash fill cooling tower.

According to Puckorius[163], treated municipal wastewater can successfully replace freshwater for cooling tower makeup. Success depends on knowledge of the problems related to the contaminants and how they should be controlled. It also requires matching the entire cooling water system characteristics and operation with the water treatment chemical, to enable continuous efficient operation. The use of treated municipal water can either increase or decrease costs. Increasing costs are (chemical) pre-treatment to control (bio) fouling, scaling and corrosion, and the additional labour costs to monitor water quality and (chemical) pre-treatment process. Also, there is a potential increase in CT maintenance due to fouling scaling and corrosion. On the benefit side, this enables water conservation and is a potentially viable water source in water stressed regions.

In Florida, for instance, a 380-MWe coal-fired cogeneration plant equipped with a spray drier to tackle SO_x in the flue gas and exporting steam to a third party is applying ZLD technology. The plant receives three different sources of water with varying quality for its cooling tower. The cooling tower is responsible for almost 90% of the plant's water consumption and is cycled more than four times to help conserve water. The three sources of water are namely surface water (river), highly saline ground water and treated municipal solid wastewater. The latter is typically combined with well water during droughts or surface water when it is available. This gives highly varying make-up water quality for the cooling tower. According to Maurer, et al. (2014) this water is filtered, but more detailed description of the treatment was not provided in the article[167]. The blowdown of the cooling tower at 150 m^3/hr passes over the ZLD scheme to produce make-up water for the spray driers in the flue gas and boiler feed water (make-up). The original set-up was to apply two brine evaporative concentrators (BEC). However, these proved to be costly replacement on account of high maintenance costs due to extensive stainless steel corrosion. According to the article, these maintenance costs were in the range of millions of US$. Also, each BEC unit consumed 700 kW to operate further adding a significant amount to the operating cost. DNV GL calculates that this would translate to about 4.6 kW per m^3 or a 0.4% plant efficiency loss, the article however claims an annual energy loss of US$ 397,000. The BEC units were replaced with MF and two RO-pass steps to treat CT blow down. The permeate undergoes a Mixed Bed polishing step to become suitable for boiler make-up water. The brine of the RO and MF reject would be sent to the spray drier or as lime slaking. The system was installed in 2011 and has been in operation for 2 years, and according to Maurer et al. (2014) the return on investment on this technology is 2 to 3 years. While attractive, this figure could be higher as

[167] C. Maurer, B. Doll, M. Drake, R. Venkatadri. Significant cost savings obtained using advanced membrane systems for cooling tower water treatment and in zero liquid discharge plants. VGB Powertech 2014, 3, pages 44 to 47

membrane replacement costs are most likely not considered. Unfortunately, the authors have also not provided the achieved make-up water quality specifications. As there are three different raw water sources for the CT it would be very difficult to maintain consistent level of specifications throughout the year without dedicated operational support. Assuming an additional cost of US$ 67,000 per year on membrane replacement (7-year replacement) and operational support, the ROI of 3 to 4 years should still be achievable as summarized below:

- CAPEX US$ 2,254,000[168] for a 140 m^3/h unit
- OPEX of US$ 203,000 with what DNV GL believes an additional US$ 167,000 (1 operational support staff of US$ 100,000 and US$ 67,000 for membrane replacement)

Bartholomew *et al*. (2003)[169] described a case of a 225-MWe coal-fired power plant located near Lake Superior. Due to ZLED policy, this site was obliged to treat all its process water for:

- Ash wetting
- Offsite disposal at a wastewater treatment plant which in this case was around 160 kilometres (km) away
- As dust control at the barge loading area

When there is no coal barge, the wastewater would be treated offsite. This was an expensive approach at US$ 0.055 per gallon in 2003 (>US$ 200 per m^3) and thus an alternative approach was adopted. Cooling tower blowdown and boiler blowdown were combined with Lake Superior water. The target water quality purity levels were the EPRI guidelines (0.10 or 0.15 µS/cm). After carefully studying the different wastewater streams on site, a selection was made for good quality water and having the same pre-treated with a filter[170] through application of a mobile IX-technology unit. While this plant would typically cost US$ 0.02 per gallon when treating Lake Superior water, by applying a re-use approach this cost was reduced to US$ 0.005 per gallon[171]. The resulting purification cost at US$ 18.50 per m^3 (in 2003) was still very high and unacceptable for most power operators.

The use of multiple raw water sources intended for cooling tower and subsequently treating the blow down for make-up water use has been deployed at few power stations over the years. For example, the Shand Power station from SaskPower, a 305 MW coal (lignite) fired power plant in Canada employed with ZLD technology since 1992 has used effluent wastewater[172], surface water and surface run-off water & drainage of the site as cooling water. A simplified overview is shown in Exhibit 36. The make-up water of this site is made from cooling tower blow down after passing through an evaporator, RO treatment and granulated activated carbon (GAC) treatment. DNV GL believes the use of GAC is an expensive approach. There are operational challenges just after the vapour compressor evaporators (VCE's), wherein slime formation has

[168] Typically, 40% of the total CAPEX is attributed to membranes which need replacement every 5 to 7 years.

[169] R. D. Bartholomew, D.A. Cline and G.H. Roberts, Renovation or replacement of existing make-up water treatment plants. Power plant Chemistry 2003, 5(2), pages 96 – 104.

[170] After passing an heat-exchanger to cool the water down.

[171] Bartholomew, et al., 2003.

[172] After passage over a constructed wetland.

been found in the distillate forwarding tank and the carbon filter. This slime forming is prevalent and affects the water treatment plant when organics break through the carbon filters and contaminate the mixed beds. This would lead to increased regenerations and resin replacement as the organics will clog the resin exchange[173]. In two separate articles from Quagraine[174], multiple approaches are investigated to tackle these biological issues.

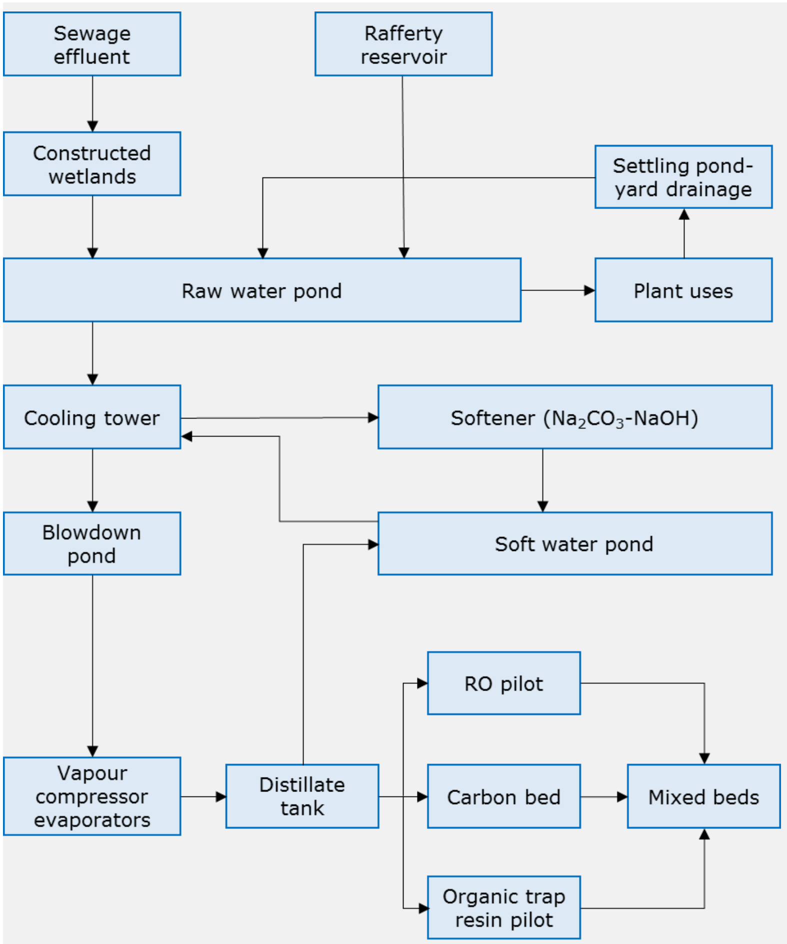

Exhibit 36: Schematic of Water Streams at Shand Power station (ZLD plant)[173]

While the articles are well written, DNV GL has some reservations of the ZLD approach at this facility for the following reasons:

- No cost figures have been provided in these articles. The application of granulated activated carbon (GAC) and VCE's for the entire blowdown stream are typically costly approaches. It is unclear why they were selected.
- Arguments were provided for not using oxidizing biocides prior to the GAC, to protect its operation and that of the RO and mixed bed. Yet no alternative (pre)-treatment technology was investigated to

[173] E.K. Quagraine, K. D. Hill and F. Omorogbe. Evaluation of organics removal options: a case study from a zero liquid discharge power plant, Power Plant Chemistry 2010, 12 (1), pages 22 -39

[174] E.K. Quagraine, S. Hood, T. McNabb, T. Weiss and B. Janzen. BAC & GAC in Tandem for removing organics in boiler make-up water: performance evaluation from a ZLD facility. Power Plant Chemistry 2013, 15(3).

replace the GAC altogether with alternative technologies. Furthermore, no explanation has been provided on the effectiveness of the pre-chlorination of cooling water make-up and whether or not any film formation was identified in the cooling tower.

- Although the plant is satisfied with its ZLED technology where the brine of the RO unit goes is unclear.

From the critical review of various technical articles and case studies on ZLD technologies, it is evident that each operator has a different interpretation regarding ZLED and the choice of technologies adopted for achieving zero liquid discharge status of coal-fired power plants.

ZLED. Fleming and Al-Samadi (2008)[175] are among few authors that present in their article economic figures on ZLD based on adoption of various processes, such as:

a. A typical RO membrane technology

b. A customized and patented high-recovery RO technology

In their case study, the blow down of a cooling tower and some other wastewater streams comprising of RO membrane reject water (brine) and sand filter back-wash at a coal-fired power station warrant further ZLD treatment. Together with the CT blow down the wastewater would be neutralized if necessary, followed by aeration and filtration. After a pre-treatment step using a scale inhibitor the wastewater is treated in a 1st stage low pressure RO train, followed by a high pressure 2nd stage. The further treatment steps can possibly be a precipitation stage or IX polishing / softening step, depending upon the intended use. For example, the produced water can either be deployed as make-up for the cooling tower or as raw source for the demineralization line to be further used as make-up water for boiler. The precipitation consists of a softening step, wherein through NaOH, pH levels are raised and chemicals such as Ca, Mg and Silica are precipitated. This slurry wastewater is further led into a clarifier, where it is filtered, recycled and blended with the feed of the 2nd stage RO to increase water recovery and mitigate scaling. A 98% water recovery is achieved and the resulting reject stream can be treated in an existing "solar" pond for a disposal rate of up to 2.2 m^3/hr. The 98% recovered water is suitable for CT make-up or could be sent as raw water source for the demin line.

The same article made a computed estimation of a typical RO technology as well as their patented RO technology. The treatment costs are provided in the following exhibit. The wastewater here is of similar quality to the previous Power station example. DNV GL has some reservations with this comparison of these two cases as the raw water quality in both cases are different. Nevertheless, a price indication can still be achieved with this approach.

Description – costs have ±30% accuracy	Case I RO1 + RO2 + Precipitation	Case II RO1 + RO2 + IX Softening
Raw water flow rate (m^3/hr)	315	157
Reject stream in m^3/hr (brine to be evaporated)	6.3	14
Capital cost (US$)	2,950,000	1,550,000

175 H. Fleming and R. Al-Samadi. Membrane process offers improved water recovery. Ultra-Pure water April 2008, pages 18-28.

Description – costs have ±30% accuracy	Case I RO1 + RO2 + Precipitation	Case II RO1 + RO2 + IX Softening
Installed cost in an existing building (US$)	5,000,000	2,650,000
Installed cost (green site) (US$)	8,850,000	4,650,000
Installed cost existing building (US$ per m^3/h)[176]	16,197	18,531
OPEX (annual cost)[177] (US$)	1,110,000	440,000
Product water cost (US$/$m^3$)	0.65	0.55

Exhibit 37: Variation in Water Treatment Cost[178]

The same article also made a similar estimation of the RO technology and their patented RO technology versus evaporators[179] with water recoveries ranging from 70% to 99%. Here the authors assumed the treatment of 1,000 gpm water or wastewater for potable or industrial use. DNV GL finds this a difficult comparison for RO technology as it implies a substantial difference in operational costs depending upon the particular quality of raw water source referred to in this case, which has not been clearly stated. The authors do provide a ±30% margin; however, they recommend a 50% margin should ideally be ±50%. This combination of the patented RO technology with mechanical vapour compression (MVC) units for achieving ZLD status and maximum water recovery of 99%, would entail an annual cost (OPEX) of US$ 1,100,000[180] while that of MVC's alone would be US$ 3,500,000 corresponding to 1.93 – 2.75 per m^3.

Recycling FGD wastewater – ZLD technology. Ogiermann *et al*. (2012)[181] provided an overview of several ways to treat wastewater from the FGD unit. This includes the MetCLEAN process which reduces heavy metals in the wastewater, ZLD and ZLD Cold systems. The MetClean process does not offer a reduction in water discharge or increase in water reuse. The ZLD systems apply a pre-treatment by adding an acid to neutralize the pH and remove calcium carbonate. The further steps involve CO_2 removal for corrosion prevention and a falling-film evaporator concluding with a crystallizer. The ZLD is capable of recycling 98% of the water, which can be used for cooling water or other processes. The resulting sludge salts can be disposed of at landfills. When there is a higher salt content in the wastewater (above 5 wt.%) than removal of the last 25% of the water in the evaporator will be difficult to achieve. Here Cold ZLD systems can be considered as an alternative option where evaporation takes place under lower temperatures and vacuum pressure. Some advantages of this process are:

- No chemical pre-treatment

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[176] Process flow rate minus reject stream is the total capacity of the unit. Using the total cost divided by the total capacity provides a better comparison on CAPEX cost.

[177] Annual costs include depreciation (10% straight line), labour, chemicals, power and membrane replacement.

[178] H. Fleming and R. Al-Samadi. Membrane process offers improved water recovery. Ultra-Pure water April 2008, pages 18-28. The wastewater quality in consideration for these two cases is equivalent to that of CT blowdown for two different polishing approaches, in order to achieve ZLD status.

[179] Mechanical Vapour Compression or MVC

[180] US$ 0.60 per m^3 based on 8,000 operating hours.

[181] K. Ogiermann, K. Hagen, T. Hagen, T. Meyerhoff, J.L. Basabe and M. Vendrup. Treatment of wastewater from the FGD unit. VGB Powertech 2012, 9 pages 125-129.

- Higher operational reliability
- Lower investment costs
- Lower energy costs due to reduced operating temperatures
- Less sludge waste due to chemical addition
- A strong leach-free end product which poses no leaching risk for landfill applications

The article mentions a ZLD site installed in Italy in 2009 with a treatment capacity of 7 m^3/hr. However, DNV GL has some reservations with the benefits claimed. For instance, maintaining vacuum conditions requires a significant amount of energy and since no CAPEX or OPEX figures are provided in this context, it is hard to comment on the accuracy levels of these benefits.

The Italian-based power generation company, Ente Nazionale per l'Energia Elettrica (Enel), investigated several water reuse technologies before deciding on a ZLD approach. This is described in two articles from Mosti and Cenci (2012)[182, 183]. After Enel equipped its coal-fired power stations in the late 90's with state-of-the-art flue gas cleaning technologies, they faced various issues related to water shortages and stringent waste disposal legislation. Different approaches using chemical-physical treatment[184] could not provide confidence in lowering concentrations of some chemical compounds critical for discharge. Enel decided to apply the ZLD approach called Softening Evaporation and Crystallisation (SEC) and equipped some of its remaining power stations with FGD. The thermal treatment approach ensured salt removal, and targeted primarily the wastewater from FGD units. Enel conducted a literature search as well and found at that time a limited amount of power stations applying thermal treatment of wastewater (ZLD). This was likely due to the difficulty of setting up a dynamic process to treat the wide variation in input characteristics[185]. The ZLD approaches that Enel used focussed primarily on water savings and were applied to wastewater streams with low and more stable dissolved solids like CT blowdown or RO brine.

Exhibit 38 provides the list of stations found in the above context. It is worthwhile to note that many of these are no longer in service now. Enel's focus was on mitigating discharge and not water savings. DNV GL assumes that the raw water sources (or FGD or CT make-up) for these processes were well water, drinking water or relatively constant seawater.

Utility	Power unit(s)	Location	Supplier	First operation	Process	State of operation
Enel	2,640 MW	Brindisi, Italy	Aquatech	2009	Chemical Treatment + BC (Brine Connector) + CRY (Crystallizer)	Running
Enel	960 MW	Fusina, Italy	Aquatech	2009	Chemical Treatment + BC + CRY	Lay-up

[182] Mosti, C., & Cenci, V. (2012). ZLD systems applied to ENEL coal-fired power plants. VGB powertech, (1-2)

[183] Mosti, C., & Cenci, V. (2012). Wastewater Treatment-Chemistry in Zero Liquid Discharge Systems. Power Plant Chemistry, 14(2), 84.

[184] Acidification or oxidation, additives dosing and other R&D solutions.

[185] For instance, large variation in coal quality to be burned affects the FGD wastewater.

Enel	1,980 MW	Torrenord, Italy	Aquatech	2009	Chemical Treatment + BC + CRY	Running
Enel	600 MW	La Spezia, Italy	Aquatech	2008	Chemical Treatment + BC + CRY	Running
Enel	240 MW	Sulcis, Italy	Aquatech	2009	Chemical Treatment + BC + CRY	Running[1861]
A2A	336 MW	Monfalcone, Italy	Veolia - HDD	2008	Chemical Treatment + BC + CRY	Running
Kansas City	850 MW	Iatan, USA	Aquatech	2009	BC+AS (Fly Ash Stabilizer)	Running
Vattenfall	410 MW	Vodskov, Denmark	Anhydro A/S	2005	SD (Spray Dryer)	Running
DoE	Pilot[1872]	USA	GE-RCC	1995	BC	Out of Service
Springfield City	440 MW	Dallman, USA	Aquatech	2007	BC+SD	Out of Service
Transalta	1,376 MW	Washington, USA	Swenson	NA	Chemical Treatment + CRY	Out of Service
Matsushima	1,000 MW	West coast Japan	GE-RCC	1996	BC	Out of Service

Exhibit 38: Overview of ZLED Systems with Wet FGD[182]

Enel commissioned the thermal approach based ZLD in five power stations during 2008 -2009. DNV GL notes that aside from WET FGD blow down, power stations can also have their CT blow down led to a storage tank. Also, make-up for the CT can be provided from this storage tank.

The process starts with a pre-treatment step to adjust water hardness. A part of the water stream returns to the storage tank and is mixed with Softening Evaporation Crystallization (SEC) distillate to save treatment costs (both CAPEX and OPEX). Lime and sulphide addition and precipitation are carried out in the first clarifier and soda ash softening is performed in the 2nd clarifier. In both these clarifiers suspended solids and metals are also removed. This allows clean $CaCO_3$ sludge from the soda ash softening clarifier back to the FGD scrubber. The wastewater is then led into the brine concentrators (BC's) and then to the Force Circulation Crystallization (FCC) and a belt press. The operation of the BC's is in the "seeded mode", allowing crystals to be formed in a falling film thereby limiting corrosion or scaling of the exchanging surface. Exhibit 39 depicts a schematic of Enel's ZLD approach.

[186] Intermittent operation

[187] 1 TPH Demonstration Pilot

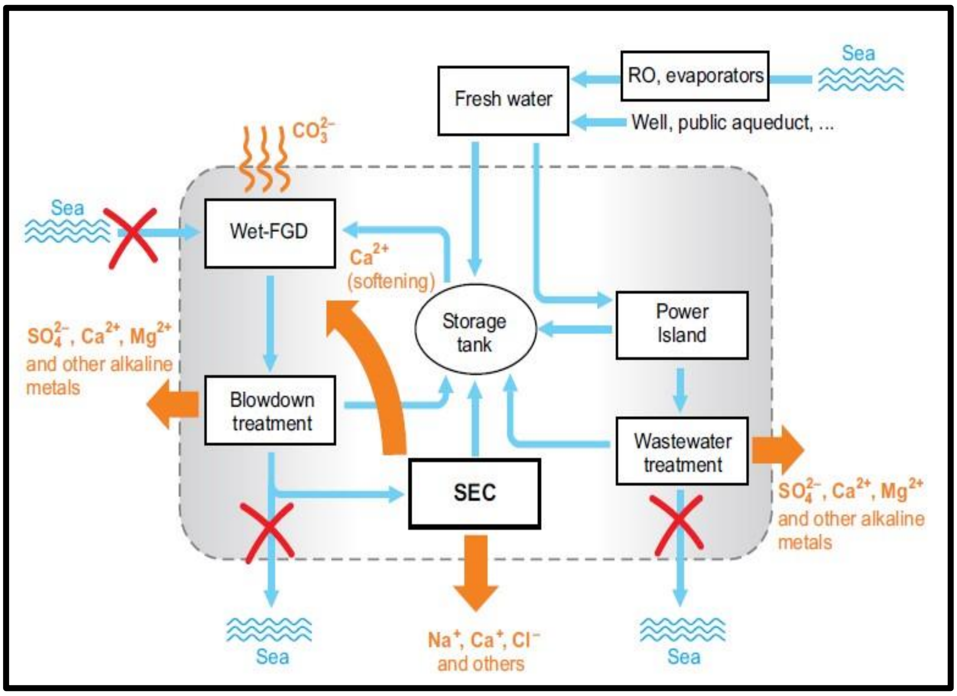

Exhibit 39: Schematic of Enel's ZLD Approach[182]

An overview of the various Enel sites adopting ZLED along with their specific needs is further discussed below:

- Brindisi is a seawater FGD unit that helps limit discharge of metals and SS to the sea. The 140 m^3/h pre-treatment of the blow down takes place in two clarifiers with the addition of $FeCl_3$. Half of the feed, i.e., 70 m^3/hr is rerouted back to the FGD and the rest through SEC. About 10 m^3/h will be treated in the FCC unit which has a 2-ton/h belt press. Remaining effluent water is treated with hydrogen hydroxide before discharge to the sea.
- Fusina has a similar set-up as discussed above with half the size.
- At La Spezia, metals and magnesium reduction is required. The design capacity for wastewater treatment is 30 m^3/h. The steam heading towards the softening and BCs would be typically half of this flow.
- Sulcis has a similar system designed for 45 m^3/h of wastewater treatment capacity.
- Torrevaldaliga is designed for a wastewater flow rate of 50 m^3/h, while the BC's are designed for 35 m^3/h.

The distillate from the FCC and BC's has a conductivity of 20 to 100 μS/cm and a pH of 7.5 to 9.0. Enel uses the distillate both for the CT and as make-up water for FGD. Enel is also investigating the suitability of using this distillate for boiler make-up. DNV GL believes a polishing step like IX or EDI would be required to meet international boiler make-up water guidelines.

The articles and the case studies discussed in this section analyze the operational experience of SEC technology both in terms of the quality of by-products[188] as well as the resulting scaling in BC units. Enel had a dedicated task force monitoring the performance of the ZLD approach to optimize and learn from

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[188] For instance, the leach ability of the produced cakes.

the process. Several solutions were implemented like back-up approach in case of malfunction, spare-parts, monitoring of scaling potential of waters through scaling indexes. Other opportunities identified were to limit the amount of wastewater going to the BC by concentrating the FGD blow down using RO technology; reuse as boiler make-up water; SEC salt processing for chemicals recovery to be re-used in wastewater treatment[182].

4.2.2 Industrial third party wastewater

The Cedar Bay Generation plant (Jacksonville Florida) is a 250-MW coal-fired fluidized bed cogeneration plant commissioned in January 1994, and provides steam to a nearby linerboard mill as well as electricity to the state. The site applies a ZLD policy where cooling tower blow down and onsite wastewater are processed at the ZLD facility. During the construction period, it was decided to utilize secondary effluent from the paper mill. Together with site run-off and process wastewater, these streams were gathered, pre-treated[189] and applied as make-up for the cooling tower or other internal uses. An article by Goodrich and Lewis (1996) describes this approach, as well as the ZLD treatment of the CT blow down. The ZLD treatment comprises of the following processes:

a) Flocculation
b) Clarifier
c) Sand filter
d) An RO unit from where the permeate is redirected as make-up for CT
e) Brine Concentrators (BC)
f) Crystallizers

Operational challenges were faced with the strong variation in organic loading of the secondary effluent from the paper mill. This disrupted the normal operation of the pre-treatment process, the RO unit, the BCs as well as the crystallizers. Even two years after commissioning, the process needed further improvements, which called for additional investment and the need for having specialized operational staff to ensure consistent operation and optimized chemical usage. The site did prove the fact that it is possible to recycle paper mill effluent as a make-up water source for a cooling tower[190]. Unfortunately, the article did not provide any CAPEX or OPEX figures. DNV GL assumes that these would be higher than typical values.

The Polk Power Station in Florida, USA, uses a variation of this approach. In 2015, this 260-MW IGCC plant started using treated wastewater from an existing nearby facility for its makeup water supply. Water was transported 15 miles from the Lakeland Wetland Treatment System and then treated further onsite using a three-stage process – high-rate settling and clarification, gravity flow filtration and finally reverse osmosis. This upgrade has minimized future groundwater withdrawals by the power plant and reduced the discharge by the existing wastewater treatment facilities.[191]

Another industrial wastewater stream sometimes used is mine water from a neighbouring (coal) mine. The Verve Energy's Muja and Collie Power Stations are 854-MWe and 300-MWe coal-fired power stations,

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[189] In a clarifier or softener.

[190] W. G. Goodrich and K.G. Lewis, The future is upon us – zero discharge. NACE international CORROSION 96 proceedings, 24-29 March, Denver, Colorado, Paper no. 572.

[191] Overton, T. W. (2015). Tampa Electric Co.'s Polk Power Station Reclaimed Water Project. Power, 159(8), 44-47.

respectively. The power stations and the mine relied on ground water for their water supply, particularly for their cooling needs. As the groundwater levels in the Collie Basin are depressed because of a century of coal mining, the mine dewatering operations can be used as make-up for the cooling towers[192]. This mine water has a quality of about 1,000 mg/l total dissolved solids and through filtration and RO technology this could be reduced to about 45-65 mg/l[193]. This enabled the continued operation of the power stations whilst minimising groundwater abstraction.

In the Australian context, Walker and Lloyd[194] described other different sources suitable for industry (and agriculture). New technologies coupled with the right raw source of water and matching with end use can lead to effective water conversation strategies. Further improvement in these technologies will lead to cost reductions and enhancing adoption rates. Some examples and cases discussed that reuse ground water, recycle municipal wastewater; mine-water reuse and desalination are indeed welcome trends.

In Israel, the Israeli Electric Corporation (IEC) investigated the use of boronic water, which is a reject stream from a nearby desalination plant for FGD make-up water[195]. IEC started investigating this choice as other available water sources like potable or municipal treated wastewater in Israel are primarily made available for agricultural use. Israel is a world leader in water saving as currently it is re-using about 70-80% of water, followed by Spain wherein less than 15% of water being re-used. The current Orot Rabin Power station consisting of 4 units of 360 MWe and 2 units of 575 MWe consume a total of 1 million m^3 of water per year. Equipped with wet FGD this station would have otherwise consumed about 5 million m^3 per year. Assuming 8000 operational hours this results in a water pinch of 0.048 m^3 per MWe. If these stations are equipped with an FGD unit, the consumption would increase between 0.160 – 0.195 m^3 per MWe[196]. The nearby desalination plant is the largest of its kind producing 100 million m^3 per year of fresh water. The boronic water is low-salinity water reject from the seawater RO units. High boron concentrations in potable water represent reproductive dangers and boron is also suspected to have teratogenic properties. The desalination plant produces about 800,000 m^3 per year of boronic water. The tests done by Marcu, et al. (2012) were in a lab and in a test facility mimicking flue gas conditions. Here also the liquor of the FGD unit from another Israeli power station was used. The test results prove that boronic water is technically and economically feasible. The Original Equipment Manufacturer (OEM) approved its use and the national water supply has agreed to be the standby source[197]. It was learned through an email exchange with the IEC that the plant has just commenced commissioning in 2016.

4.2.3 From coal to gas fired power plants in dry regions

Many articles were found referring to ZLD and reuse concepts with gas-fired power plants. In section 8.1 several examples are included for further reading. ZL (E) D technology seems to be more extensive or mature in combined cycle gas fired applications rather than coal fired [Nagel *et al.*, 2008]. Over the last

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192 K. McNaughthon and K. Schackleton, Muja Power Station Water Supply, Paper & presentation API PowerChem 2012

193 Tackling increasing water salinity, extracted from: http://www.osmoflo.com/en/markets/power/tackling-increasing-water-salinity/

194 T. Walker and L. Lloyd, Alternative water sources for industry, PowerPlant Chemistry 2006, 8(7), pages 415-420

195 V. Marcu, Y. Shechtman, S. Moskovich, E. Gal and M. Mengel. A study of possible sources of water for the FGD project at the Orot Rabin Power station. PowerPlant Chemistry 2012, 14(4), pages 234 - 240

196 The comparable number for Dutch Power Stations in this context is 0.08 – 0.16 m^3/MWe.

197 An email exchange with IEC has learned that the plant has just commenced commissioning in 2016.

few years, new gas-fired power plants with a steam turbine are optimized to use a minimum of process water; for example, a 380-MWe combined cycle power plant can consume 1 m^3/hr[140]. Also, Siemens provide their gas fired power plants with a ZLD concept as described in an article written by Söllner, et al. in 2011[198]. In this article, RO technology was not preferred to reduce the wastewater stream but to apply immediate evaporation. DNV GL believes other (pre-)treatment technologies apart from evaporation are also suitable in this case. It is clear that Siemens and other suppliers recognize the need to supply power in dry regions. Coal-fired stations typically require large sums of water as compared to gas-fired applications. Also in gas fired stations there is excess heat available which can be applied for thermal ZLD concepts. It should also be noted while coal-fired power plants are typically suited for baseloads, combined cycle plants operate often during peak mode and hence capitalize on the spot market with higher energy prices. In dry and hot regions, consumers typically require energy for air-conditioning units. Here combined cycle plants can operate in a profitable manner. This enables these assets to be more willing to invest in higher water treatment cost (savings or discharge) as compared to coal-fired power plants. To illustrate this trend further, power plant executives, like NV Energy, plan to retire their coal-fired generation units and apply gas-fired units with ZLD and dry cooling to help the company reduce its water usage even more[199]. This is an important trend that should not be overlooked by APEC power plant operators.

4.3 Tackling cooling water use

4.3.1 Operational cooling use improvements

Cooling towers have the highest water consumption rate, and exploring different sources of water to replace high quality[200] water can be a suitable method to save water. In the previous paragraph, examples of treated effluent from municipal wastewater treatment plants with its associated drawbacks on application were discussed. Alternatively, studying the quality of different water sources does allow an operator to choose a raw water source that has a higher cycling rate capacity which in turn reduces water consumption and improves power plant efficiency[98]. Maintaining optimal condenser operation ensures a more efficient power station which in turn leads to higher energy output along with reduction in the water pinch (m^3/MWe). Also, other factors influencing cooling water use and its operations are financial incentives. For example, in 2006 & 2007, the Loy Yang Power station in Australia, a 2x500MWe coal-fired power plant with natural draught CT, required expensive water to replace its cooling water demand caused by a drought. A total of 5.5 billion litres was purchased for about AU$ 1 million. To purchase that much amount of water in recent times would have cost in excess of AU$ 8 million[201]. For reducing operational costs, the power station implemented a water saving strategy which involved improving its cycling rate of the CT and implementing a site drainage system to recover surface water run-off. For the drainage system a deep drainage pit was constructed together with a weir arrangement wherein rainfall was captured and brought back to the CT to offset makeup requirements. After four years of operation the conclusion was that the

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[198] A. Söllner, W. Glück, H. Fahrnbauer and O. Rappich, Zero Liquid discharge for combined cycle power plants by using closed loop recycling methods an important step for the environment. VGB Powertech 2011, 4, pages 44 - 48

[199] J. Martino, NV Energy: planning for a New Energy Frontier. Power Engineering October 2013

[200] Here, high-quality water is referred to in context of drinking water as well.

[201] Water prices have surged from 0.08 Australian dollars per m3, to Australian $ 0.25 per m3 in 2007 and to Australian $ 1.50 per m3 in 2012.

return on investment on the drainage system was 3 to 4 years and it saved up to 600 Million litres per year. Together with optimizing the cycling rate, the total discharges of the site have been reduced from 4 billion litres per annum to 0.1 billion and salt discharges from 2,000 tonnes to about 300 tonnes. This meant the site water savings were in the range of 4 billion litres per year[202].

Aside from a different water source other means to increase power plant efficiency with similar water footprint are:

- Cooling ponds
- Anti-fouling and fouling-release coatings & sintered new materials
- Cold storage

An often overlooked option is the use of cooling ponds to help increase power plant efficiency. This is already applied in the United States[20]. In the IPPC document on cooling, an example is provided from a KEMA study[203]. The CAPEX and OPEX figures of cooling ponds are surprisingly equal or slightly better than cooling towers. However, cooling ponds require a large footprint and this is the determining factor on CAPEX investment (land price). Also, there is a "not in my backyard" (NIMBY) effect with respect to the use of other water sources like effluent from a municipal wastewater treatment plant for this application. There is concern on bacteria/viruses being spread through this manner as water is sprayed. The energy saving of a cooling pond is equivalent to 6.5 kW_e per MW_{th} of cooling which is equivalent to a decrease of CO_2-emissions of about 38 tons per MW_{th} per year.

Anti-fouling and fouling release. The application of coatings in cooling water conduits and other surfaces is well known and many coatings are specifically developed for this purpose. Application of coatings in condenser tubes and in heat exchangers is however less common. Typically, this will enhance fouling control and increase the lifetime of the condenser. Therefore, such coatings can be very cost effective. Reducing the amount of fouling in conduits also ensures a better heat transfer of the heat-exchanger with a corresponding reduction of hydraulic head-loss for the water pumps. This ultimately increases power plant efficiency and reduces the water pinch (m^3/MWe). In the EU funded Advanced Nanostructured Surfaces for the Control of Biofouling (AMBIO) project, approximately 500 different nanostructured coatings, representing 64 generic coating chemistries, were prepared at laboratory-scale and evaluated for their antifouling and fouling-release performance. Of these, 15 were selected for testing in a range of field and representative end-user tests. Several coatings showed promise in these trials, and have either been commercialized, or have the potential to be so after further development[204]. Exhibit 40 depicts test results conducted by DNV GL.

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[202] A. Tyler, Cooling water management & resource conservation, paper & presentation. API PowerChem 2012. Cooling Water Management & Resource Conservation.

[203] See BREF document IPPC cooling, pages 272 – 273. Its source is a feasibility study for large power generation assets based on the DOW chemicals plant in Terneuzen, the Netherlands. KEMA Report 99-4439.

[204] Callow, J. (2010). Advanced nanostructured surfaces for the control of biofouling. The publishable final activity report of the AMBIO Integrated Project. Project Nº NMP4-CT-2005-011827.

Exhibit 40: Depiction of Test Results[205]

DNV GL was actively involved in the AMBIO project and some recommendations[206] with respect to applying coatings are discussed below:

- It is not possible to solely depend on coatings for an effective fouling control in cooling water systems, since specific conditions may allow growth and monitoring coating effectiveness thus becomes difficult.
- When combined, foul release coatings provide extra protection to surfaces in cooling water systems that are not efficiently treated by chemical (oxidants) and heat treatment
- Foul release coatings will reduce the effort and cost of manual removal of fouling species
- Foul release coatings can be very cost-beneficial when applied before commercial commissioning of a power station (dry surfaces for application) or during an Operation and Maintenance (O&M) period. During this period the power station is off-line, hence no production loss and/or penalties are caused by applying the foul release coating. These production loss and/or penalties costs are approximately 90% of the total costs.

Cold storage. Cold storage is the use of underground water storage to help cool closed re-circulating cooling water systems. A description is provided in the IPPC BREF cooling document (page 273). Also the MATChING EU project will also investigate the feasibility of underground cold storage. It should be noted that this application is typically for smaller applications and not large power plants.

4.3.2 District heating

While not previously addressed, there are many power plants that provide district heating or heat for other industrial processes. The export of heat or combined heat and power configuration has a profound effect on the heat discharge of these plants[207]. This can also translate to less cooling water use. This waste heat is put to productive use and often has attractive pay-back periods, if the infrastructure is available or can be installed economically.

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[205] DNV GL. The red coating is a Fouling Release coating and outperformed other coatings. Exposure period: (left to right) July 9th (start); July 23rd; August 27th and and October 16th. Bruijs & Venhuis, 2010. The pictures depict the impact on exposing test panels to seawater at Massvlakte power station in the Netherlands.

[206] M. Bruijs and L.P. Venhuis. Application of coatings in cooling water systems: a comparison of coatings with other fouling mitigation technologies in the power industry. Confidential client, 2010. KEMA Report 10-4067

[207] Ecofys, TNO and Deltares. Pilot project on availability, use and sustainability of water production of nuclear and fossil energy – Geo-localised inventory of water use in cooling processes, assessment of vulnerability and of water use management measures. ENV.D1/SER/2013/0004.

4.4 Membrane technologies

4.4.1 Forward osmosis

In contrast to reverse osmosis, where water is pushed through a semi-permeable membrane, forward osmosis hardly needs any pressure to have the water flow to the other side of the membrane. The difference between both techniques is that in the case of forward osmosis the water crosses the membrane from the lower osmotic pressure side to the higher osmotic pressure. This process requires little energy as it is a natural process (compared to reverse osmosis which uses a lot of energy to pressurize the water to overcome the osmotic pressure, as the water needs to cross the membrane from the higher osmotic pressure side to the lower osmotic pressure side). A schematic of the typical cooling water make-up process using forward osmosis and an osmotic agent is illustrated in Exhibit 41.

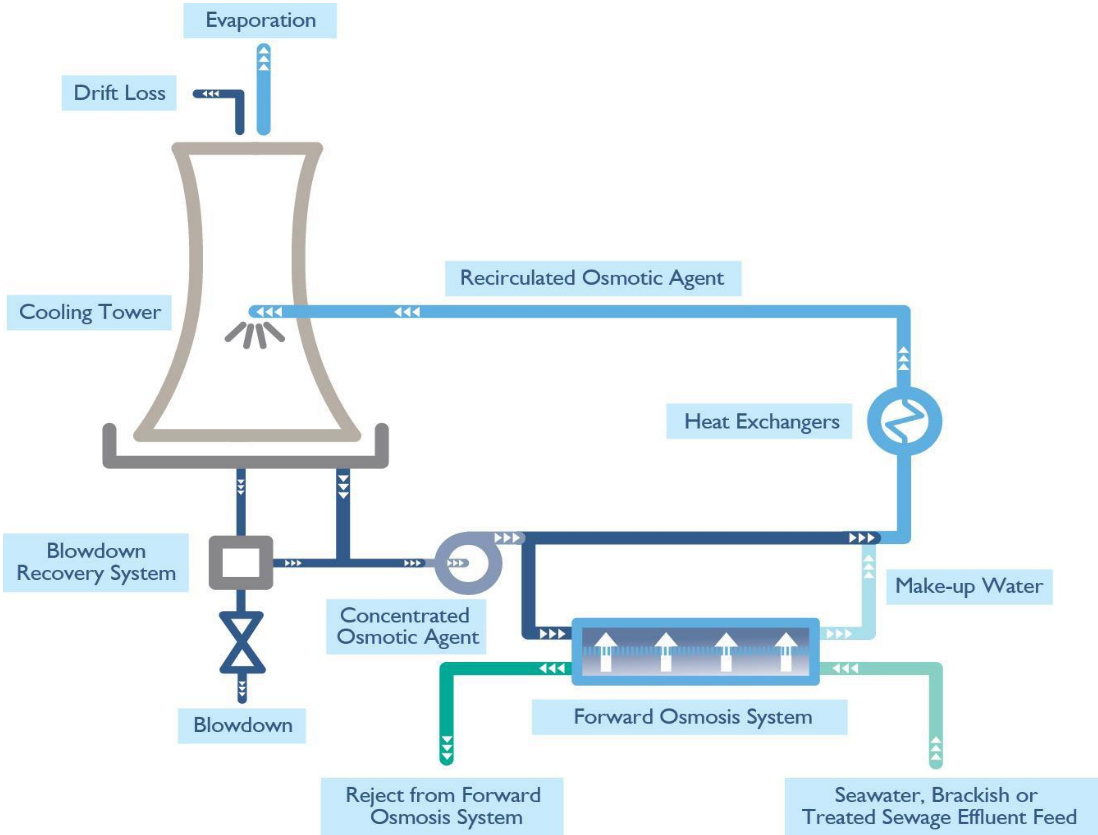

Exhibit 41: Schematic of Cooling Tower Make-up Water using Forward Osmosis and Osmotic Agent[208]

Nicoll *et al*. (2012)[209] describe a method where sea-water is used on one side of the forward osmosis membrane and the relatively clean cooling tower water with its conditioning chemicals and the osmotic agent on the other side. According to the authors this process produces make-up water at a fraction of the OPEX, about 15%. Chemical additives to the cooling water such as the osmotic agent are retained in the process, which also reduces its consumption. Also, the chemistry of the cooling water does not support

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[208] Modern Water and the image is being used with their permission. Copyright of this image is held by Modern Water.

[209] P. Nicoll, N. Thompson and V. Gray. Forward osmosis applied to evaporative cooling make-up water. Proceedings Cooling technology institute Conference 2012.

the growth of Legionella.[210] The outcome of the corrosion testing coupons with different materials show limited to no corrosion.

Membrane Distillation Membrane distillation combines membrane separation and distillation through hydrophobic membranes and differences in vapour pressure. The technology is driven by low-grade heat (70-90°C). It is ideal in combination with waste heat from industrial processes or renewable sources. The technology is provided by Memstil, Singapore and Aquaver, Netherlands. Currently, Aquaver provides units up to 24 m^3/h as these are modular in construction larger sizes can be effectively used. Typical distillate quality is less than 20 µS/cm and a mixed bed technology would be further needed to reach boiler make-up water quality.

Both suppliers utilize a vacuum Multi Effect Membrane Distillation configuration which adds the advantages of low-temperature operation and multi-effects to the membrane distillation characteristics.[211]

While these technologies are attractive, DNV GL believes that pre-treatment, fouling control and re-use of brine discharge still need to be further addressed.

ZLD by FGD water treatment using FO membrane. The 1.3GW ultra-supercritical Changxing coal-fired power plant in China implemented the first commercial application of FO-based brine concentration and water reuse process to treat FGD wastewater for ZLD. The plant also collects and sells the salt byproduct from the osmosis process in the form of mixed salt crystals. The company claims to be now transforming 630m^3/day of FGD wastewater with a system energy requirement of 90 kWh_t/m^3 of processed wastewater[212]. DNV GL is unable to comment on the long-term socio-economic evaluation of this technology because it was only commissioned in 2015.

Other Membrane Technologies for CT Blow Down. Several articles deal with treating the cooling tower blowdown for process water use. Here membrane technologies such as UF and RO are generally used. Wied and Haake (2009) describe such a process[213]. Their process includes a (course) filter of 150 µm, dosing and mixing of flocculent metal salts, a flocculation reactor followed by UF and RO treatment. The provided water quality specification of 40 µS/cm would entail a further polishing step to meet make-up water specifications, which in this article was proposed to be EDI.

4.5 Case Studies

4.5.1 Coal Fired Power Plants with Access to Cooling Water

Based on the critical analysis of several articles and information in the public domain, it is evident that quite often the information was either incomplete or not sufficient to make conclusive statements. As an additional step to the desktop research and analysis conducted by the project team, several power plant operators were contacted in water-stressed areas to retrieve direct feedback on operational issues and challenges faced with respect to adoption of latest water saving technologies in coal-fired power plants. In this context, utilities such as Enel, IEC and Eskom were contacted based on the articles they have published.

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[210] The genus Legionella is a pathogenic group of Gram-negative bacteria that includes the species L pneumophila causing Legionellosis, a respiratory disease.

[211] Aquaver, extracted from http://www.aquaver.com/technology-membrane-distillation/ and http://www.memsys.eu

[212] Patel, S. (2016). Huaneng Power's Changxing Station ZLD Project, China. Power, 160(8), 35-37.

[213] A. Wied and A. Haake, Recovery of process water from cooling tower blow down. VGB Powertech 2009, 3, Page 50 - 53

A majority of the coal-fired assets of IEC and Enel are located near the sea and have access to cooling water. While Eskom has some assets near the sea the majority are inland with little to no access to (cooling) water.

The following feedback from IEC and Enel provides information on coal-fired power plants with Wet FGD and cooling water access, either for once-through or wet cooling tower application.

IEC. At the time of this report the use of boronic wastewater as make-up for the FGD units was under commissioning at the power station, thus no information on operational experience could be provided. The boronic wastewater originates from the nearby desalination plant. Israel is well known for its water re-use policy, and is ranked highest in the world[214]. Yet, the use of FGD for ZLD was not considered. Large sums of money were invested in applying ZLD for cooling tower blow down which had (treated) sanitary (municipal) wastewater. For the IEC power station that adopted the ZLD approach, it was found through published reports that it its operation was not economically feasible and was subsequently abandoned. DNV GL also shares a similar opinion on these findings. Treated sanitary (municipal) wastewater as make-up water for either FGD or cooling tower is a challenging raw water source. Further ZLD treatment of any blow down would prove to be even more challenging.

Enel. Contrary to many power stations who have adopted ZL(E)D technologies after policy changes, Enel management decided to voluntarily adopt ZLED solutions. This was done with the aim to avoid compliance risks that could derive from variability in the composition of wastewaters originating from the FGD unit. Another goal was to maximize wastewater reuse after treatment. Enel in their published articles clearly investigated the different ZLED options carefully before implementing their own.

After operating the ZLED units at their five (5) generation sites, they concluded that ZLED systems need intensive tuning and optimization after installation. The softening evaporation crystallization systems (SEC) require dutiful chemical monitoring and control by skilled personnel. The most challenging was to achieve stable operation of the ZLD system as a whole. This is in line with the findings of DNV GL in this report. Enel managed to overcome these challenges with a dedicated task-force of chemical engineers and skilled plant personnel. Aside from chemical tuning and plant upgrading, installation of additional storage capacities was needed. The latter is also in line with what others have recommended when operating with ZLED systems. According to Enel by managing the ZLED operation, the chemical variability in the wastewater composition was controlled. The re-used water streams intended as make-up for the FGD units had no effect on its availability. The by-products from ZLED operation are high in calcium carbonate ($CaCO_3$) sludge from the softening stage and solid salt from evaporation. The $CaCO_3$ could be used as reactant in the FGD and the salts are disposed of underground.

Enel recommends ZLED as an option to address both discharge limits and water conservation. ZLED has turned to be very effective for water reuse. In Enel's case the entire seawater need was replaced with a smaller amount of fresh water make-up.

To summarize Enel recommends that each technology should be evaluated based on site-specific situations and resulting CAPEX and overall OPEX figures. For example while the Magaldi bottom ash dry extraction is attractive and has been applied to several Enel generation assets, however one 660 MW unit did not change the wet extraction system because the Internal Rate of Return (IRR) was not attractive enough.

[214] Refer to Section 4.2.2 for more details

Based on the above (operational experience) cases and the findings of this report DNV GL shares the above findings of Enel adopting ZL(E)D technologies provided that:

- Make-up water used in the process is of good water quality (and not tertiary or from effluent wastewater treatment)
- Dedicated and skilled staff is made available to operate and optimize the ZLED facility
- Sufficient funds are made available for optimizing the ZLED after installation.
- Sufficient storage (redundancy) is adopted in the facility
- The facility is aware of the by-products formed (outlet, market influence, landfill)

From the above it is clear that ZL(E)D technologies are both costly and require dedicated operating attention (time) but they do offer ways to limit discharges and promote water conservation.

4.5.2 Coal Fired Power Plants with Access to Little or No Water

One of the world's leading operators in dry regions is South Africa's Eskom. Eskom's power stations are generally located near coal mines and are typically large stations consisting of multiple identical units. A handful of operating units have wet FGD and wet cooling tower, while others have dry cooling and no FGD treatment as there is little water available for cooling and/or wet FGD.

Eskom is operating the world's largest air cooled condensers (ACC's) at the Matimba power station (3990 MW – 6x 665 MW). Also the nearby Medupi station and Kusile station apply dry cooling. There was little choice as such for adopting dry cooling in these water scarce locations. ACC has a negative impact on plant efficiency as the condenser temperature can be too high which results in back-pressure issues for the turbine. Learning from the Matimba power station, commissioned in 1989 and 1993, an optimised ACC design was adopted for the Medupi power station, allowing the ACC to operate at lower condensate temperatures and thus be more energy efficient. According to the design, energy penalties of about 5.5% for Medupi and about 3.5% for the Kusile station can be expected when high ambient temperatures are reached. For the two sites these are about 40 °C and 33 °C respectively. According to Eskom the Medupi ACC unit is operating according to design parameters.

Eskom recommends the use of ACC if the aim is to save water in water-scarce areas. From a chemistry perspective, special attention is required to mitigate Flow Accelerated Corrosion (FAC) in the water/steam cycle. Eskom's plants apply an elevated pH level of oxygenated treatment (Alkaline OT) to condition their water/steam cycle. Also, high make-up water is required. Eskom's operational experience is that these values are easily met with no additional operational cost other than expected. These costs are higher when adopting less stringent water quality requirements. Eskom is able to realize the make-up requirements (conductivity target $\leq$0.6 µS/cm) as the demineralization plant has been specifically designed to cope with this requirement. The water treatment plant (WTP) is equipped with several continuous electro-deionisation polishing units (CEDI), Reverse Osmosis (RO) and Ultra-Filtration (UF) separation steps capable of processing river water (and stored water) as a raw water source. Eskom applies, and highly recommends, a full flow condensate polishing plant to ensure water quality requirements within the water/steam cycle are met.

Eskom also applies a ZL(E)D policy driven by the company management since mid-1990. Being in a water-scarce area, water as a resource needs to be available for the human population and for agriculture use. For Eskom, this implies that brine (from RO units or polishing units) is discharged on ash dump sites. The ash content of the coal can reach as high as 45%. On the ash dump sites water is needed for dust suppression, irrigation for rehabilitation plant life and for stabilization of the dump. Thus, degraded water is used for this purpose instead of fresh water. As a result of legislation, it is anticipated that as of 2021, co-disposal of regeneration brine will be prohibited. Eskom would need to investigate brine concentrators and crystallisation.

Kusile and Medupi power plants will be back-fitted with FGD once the secondary water supply becomes available in 2021. Until then there is insufficient water available to supply operation of six units with FGD. For all units, wet FGD was preferred over dry FGD, due to removal capacity and having a saleable by-product i.e. gypsum. This preference was also partly in recognition of the fact that a dry FGD has a size limitation. Eskom does note that Medupi and Kusile plants alone will produce more gypsum than the South African market can sustain. So, there will be a gradual roll out of this and other (NOx) air quality abatement measures.

DNV GL believes that by adopting the next generation of high efficient boilers (clean coal technologies), the high efficiency will offset the energy penalty associated with operating ACC. Eskom through its recent published case studies has demonstrated that further optimization of the ACC is possible. DNV GL has also observed that operators (see sections 4.5.1 and 4.5.2) have their own interpretation of ZL(E)D.

4.5.3 Sensitivity analysis on an Innovative Technology (CapWA)

The previous section describes examples that are currently deployed by operators in dry areas in the world. This section describes an innovative technology that could be applied in APEC economies, such as China. The discussion here is application of an innovative water savings technology, for example water vapour capture from flue gases using membranes. This technology known as CapWa has been developed by DNV GL and the technology was discussed in section 4.1.3.

Within the CapWa project, the membrane and modules have been manufacturing in a pre-industrial environment, however the pilot test results in real flue gas conditions proved that the upscaling was indeed a success. The next step is to demonstrate the technology at a pre-commercial scale followed by subsequent widespread deployment[215]. During the CapWa project, DNV GL had discussions with potential buyers of the technology. These included large system integrators in Europe, China, and the United States. For these discussions, the Net Present Value (NPV) after 10 years was determined and a sensitivity analysis was performed. To determine the NPV, DNV GL collected various related parameters in the CapWa project. Exhibit 44 presents the input parameters for the NPV calculation of a coal-fired power plant of 600 MW in Europe. The total investment costs for a CapWa unit for a plant with access to cooling water would be 5.8 million EUR, while that in a dry region utilizing air-cooled condensers would be slightly higher 6.2 million EUR because of lower membrane performance[216].

From the cost benefit estimates in Exhibit 42, it is evident that the financial savings depend significantly on local site factors. For example, a total amount of 0.5% is achievable.[217] The base case here assumes prevention of reheating and condensate preheating which amounts to 850,000 EUR[218] or 0.5%. Carbon credits have NOT been added here in this equation as this is very speculative for different parts of the

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[215] The initial patent owner of this technology was KEMA, and KEMA was taken over by DNV which subsequently became DNV GL. DNV GL as an independent service provider, does not provide technological solutions.

[216] Due to the associated energy penalty with dry cooling and thus more membrane area would be needed to compensate for it.

[217] In some cases even higher values, i.e., up to 1.2 % are possible.

[218] To be interpreted as x 1000 Euros for all similar subsequent references in the report. In this case it implies an amount of 850 x 1000 Euros.

world. There is also a corrosion saving for the plant this is a yearly value of 40,000 EUR when the capture rate is above 30%. If the plant captures more than 20% of the water vapour then 10% can be sold for the raw water price (assumed 1 EUR per m^3). At 30% capture rate this amounts to 147,000 EUR.

Parameter	Value – base case	Description	Additional value
Membrane price	EUR 80 per m^2	Maintenance	3%
		Replacement	5 years
Condensor	1,043 kEUR	Maintenance	1%
		Depreciation	25 years
Pipework	1,667 EUR	Maintenance	1%
		Depreciation	25 years
Vacuum pump	225,000 EUR	Maintenance	1%
		Depreciation	25 years
Energy consumption	8 kWe/m^3 water	For water cooling @ 30% capture rate	
	40 kWe/m^3 water	For air cooling @ 30% capture rate	
Financials for NPV	10%	WACC	
	2%	Growth	
Demin water savings	1.00 EUR per m3	Raw water source (drinking water)	
	1.50 EUR per m3	Treatment to reach demin water	
Corrosion savings	40,000 EUR per year	When capture rate is above 30%	
Energy savings	850,000 EUR per year	When capture rate is above 30%	

Exhibit 42: Financial Parameters of CapWa Technology for 30% Capture Rate

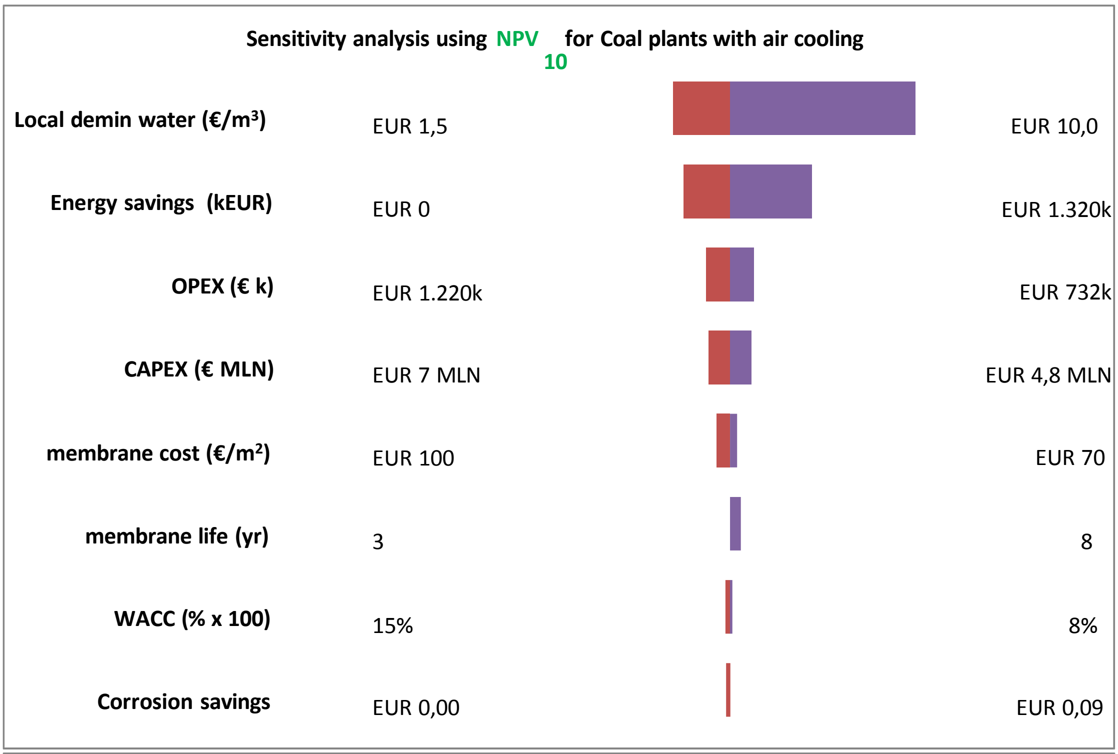
Description	Cooling water available			
	Lower value	Upper value	Lower value	Upper value
Energy saving	EUR 0	EUR 1.690k	EUR 0	EUR 1.320k
Total [219] water price per m^3	EUR 1,50	EUR 3,50	EUR 1,50	EUR 10,00
Membrane price per m^3	EUR 70	EUR 100	EUR 70	EI R 100
Membrane life	3 yrs	8 yrs	3 yrs	8 yrs
CAPEX[220] or OPEX	-25%	+25%	-25%	+25%
WACC	8%	15%	8%	15%
Corrosion savings	0	Base case	0	Base case

Exhibit 43: Parameters for Sensitivity Analysis of NPV Calculations

219 Here the total price includes demin and raw water price

220 With the exception of the membranes in CAPEX

Once the NPV has been determined, a sensitivity analysis was performed and the results presented below in tornado diagrams. The changing parameters for sensitivity analysis and the resulting Tornado diagrams have been illustrated in the following exhibits.



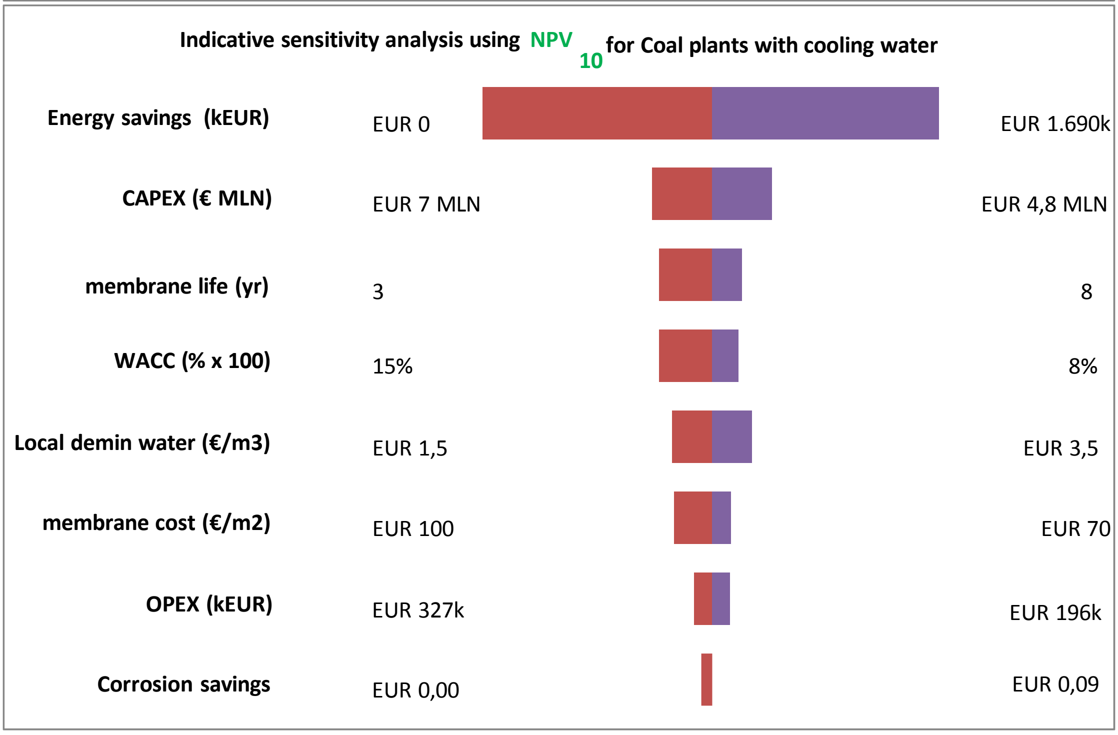


Exhibit 44: Sensitivity Analysis of a Coal-fired Power Station Applying CapWa

The ROI for the power plant with access to cooling water is 3 to 12 years. Here, the main driver of the return is the possibility to integrate the energy saving, as illustrated in the tornado diagram in Exhibit 44. The latent heat of the water vapour can be used elsewhere in the power station. Surprisingly, demineralized water price including raw water cost of 1.5 EUR to 3.50 EUR per m^3 as well as membrane lifetime have little effect to the returns of this particular type of power station.

For plants with dry cooling, like those in North West China[221], the return can be 3 years in case water prices are EUR 10.00 per m^3, or no return at all. The tornado diagram shows that water price influences the returns. The OPEX cost when dry cooling is applied is about EUR 1.80 per m^3, excluding raw water source savings. Typically, the raw water source in dry regions can range from EUR 0.10 to EUR 3.00 per m^3 and this needs to be subtracted from the OPEX cost. These costs are of comparable level with the costs for demin water production with IX or RO technology utilizing effluent waste water (0.40 to 2.00 EUR per m^3). These techniques consume water and produce a waste water stream. The CapWa technology harnesses a new source of water not used before and does so without the use of chemicals or production of waste water stream.

The (business) driver behind CapWa is not the water but the energy saving in areas where sufficient cooling water is available. It should be noted that DNV GL has not been able to find a suitable buyer for CapWA. For European system integrators and power sector, the "EnergieWende" resulted in a complete turnaround of the market, and many thermal fired power plants are threatened to be potentially mothballed. In China, there is reluctance to adopt a new technology that is not market ready. Also, even in China, the signals of system integrators suspect more renewables to be introduced in the future.

[221] It should be noted while CAPEX and OPEX costs for a CAPWA unit would be significantly lower than in European economies, the returns on energy saving and water price are similarly low. The Tornado diagram would be of similar nature, just the NPV value would be different (base case)

5 MEMBER ECONOMIES' STATUS AND POLICY REVIEW

This section briefly discusses the status of coal generation and water use in member economies' with particular focus on the regulatory regimen and policies implemented.

5.1 Australia

Coal-based power generation has over the years dominated the Australian electricity sector. However, the last decade has seen a steady decline in power generation from coal. There has been a progressive increase in electricity generation from renewable sources. The government is also emphasizing the adoption of cleaner generation technologies in its power mix. However, it is noticeable that Australia has seen an unprecedented reduction in electrical demand. Declining demand, extended generation from aged generation assets and the steady legislated increase in renewable energy generation has led to a surplus of generation capacity. Most of the policies in the recent past have been to encourage the use of renewable sources with practically little effort in regulating water utilization of existing coal power plants. Australian government funded R&D are mostly directed towards lower emission technologies and CCS in coal power industry[222]. Regulatory emphasis has been on carbon emissions from the coal power plants. Also, the National Water Initiative (NWI) regulates the allocation of water resources to each of the sectors including power plants, as discussed in subsequent paragraphs.

The policies and regulation standards pertaining to coal-fired power plants in Australia are handled by a variety of statutory authorities. The National Environment Protection Council (NEPC) has established two National Environment Protection Standards (NEPM), namely the Ambient Air Quality Measure and the National Pollutant Inventory. The NEPMs represent the minimum form of point source regulation on coal-fired power plants. In 2010, the Government established an Interdepartmental Task Group (ITG) 223 for the 'Cleaner future for Power Stations' election commitment which stipulated best practice emission standards for new coal-fired power stations and Carbon Capture and Storage (CCS) ready standards. However, the policy was replaced by the Carbon Pricing Policy in July 2012, also referred to as the Carbon Tax. This policy required purchase of emission permits for power plants emitting 25,000 tonnes of CO_2 per year. On July 2014, the Carbon Tax was repealed for a series of reasons, one of which was to reduce the $90 million per annum compliance cost.

To meet its 2020 target of 5% reduction in emission by 2020 based on 2000 levels, the Clean Energy Regulator administered the Emission Reduction Fund in December 2014 with a government funding of $2.55 billion. The plan was finalised by 2015 and will come into full effect from July 2016.

Emissions Reduction Fund

The Emission Reduction Fund provides strong incentives for companies to reduce their carbon emissions at the lowest cost possible. The emission reduction fund has 3 elements:

1. Crediting

The emission reduction assurance committee has legislated more streamlined estimating methods for emission reduction. Companies will work with the committee to report, verify and get credited Australian

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[222] Carpenter, A. M. (2014). R&D programmes for clean coal technologies.

[223] Australia Department of Resources, Energy and Tourism (2010). A Cleaner Future for Power Stations: Interdepartmental Task Group Discussion Paper

Carbon Credit Units. The units could be sold back to the government or other buyers in the voluntary market.

2. Purchasing

Emission reduction project contracts will be auctioned to companies. The bidder with the lowest cost will be awarded the contract and must deliver emission reduction as per the contract agreement, or make up for the shortage by purchasing Australian Carbon Credit Units in the secondary market.

3. Safeguarding

The safeguarding mechanism requires facilities with more than 100,000 tonnes of $C0_2$ emissions per year to baseline their emission on business as usual standards. This ensures that the emission reduction purchased by the Clean Energy Regulator is not offset by an increase in emission in other parts of the economy.

Water Policies Pertaining to Coal Power

To improve the efficiency of water use, Australia has implemented water markets and water trading. The economy is also implementing state-specific water caps, wherein each state is mandated to submit an implementation plan that adheres to the state government's water policy and the National Water Initiative (NWI).

The NWI was introduced to increase the efficiency of water use and reduce the over-allocation of water resources. It represents the shared commitment by the governments across Australia to formulate a policy framework for reform such that a there is a more consistent strategy in managing, measuring, planning, pricing and trading water. Coal-fired power plants are covered under the water extraction law of the industrial sector in general. The ACT government has partnered with the 2004 COAG in this initiative. Under the ACT Water Resources Act 2007[224], the water planning processes have already covered many of the action stipulated under the NWI. One of the more significant milestones is the statutory water plan within this Act, which aids in finding the balance between environmental and human consumption needs.

Environmental Flow Guidelines (2013) [225]

The guidelines serve as an instrument of the Water Resource Act 2007, which includes the requirements for environment flow regulation so that the aquatic ecosystem could be maintained. The ACT environmental flows are provided in either

I. Release or spills from dams
II. Restriction on volume of water that can abstracted from a water management area

These regulations are issued before the volume of water available for abstraction is released.

Impact of Water Reform for Coal-fired Power Plants

Progress with the policy reform of the NWI is largely relevant to coal-fired power generation. The NWI determines the planning framework for water management which includes creating water access entitlements.

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[224] ACT Parliamentary Council. Retrieved from http://www.legislation.act.gov.au/a/2007-19/current/pdf/2007-19.pdf

[225] Water Resource Environmental Flow Guidelines. Retrieved from http://www.legislation.act.gov.au/di/2013-44/current/pdf/2013-44.pdf

The basic elements of the framework would be:

I. Water entitlement
II. Water markets and trading
III. Best practice water pricing

These water allocation plans have been adopted at different rates among the Australian states and practically did not affect the current water access arrangements for power generators. This could be attributed to the high water security needs of power plants which deem the changing of existing licences and contracts to be a risky move. Moreover, there exists an inconsistency between the contracts for the different jurisdictions. These inconsistencies seem to limit efficient water use in the power plants. For example, some of the contract terms restrict the trading of surplus water by the power plants which makes it difficult for power generator to manage supply risk. It also creates a disincentive to implement water efficiency measures, as any water saved through adopting water saving technologies cannot be traded in the market for profit.

During drought periods, the government would directly intervene to restrict power plant water extraction. Some power plants do purchase water from the market as a strategy for managing water risk supply security, but the water market constraints do not allow for the extension of such strategies. Moving forward, once the water reform has matured enough, policy makers should consider adopting a consistent water policy for all the states in the interest of more efficient water use in power generation.

Water Allocation

Some of the environmental regulations in Australia consist of zero discharge policies[226]. This would necessitate recycling some of the treated effluent, in other words, gain some savings in the quantity of water extracted from the consumptive pool. However, there is no clear law on how the company could benefit from these savings as there is no trading regulation for water entitlement.

Murray–Darling Basin Plan

The plan takes care of issues such as over-allocation of water, drought, climate change and climate variability which would affect the amount of water which could be abstracted from the basin. The limits the plan enforces on quantity and quality would certainly affect water allocation to coal-fired plants. The Plan includes aims for efficient allocation through water trading regimes.

Economy Summary

Australia has over the years undertaken a variety of measures, both direct and indirect, for reducing its water consumption in the coal sector. Energy policies should typically lead to innovation and adoption of technologies aimed at reducing water demand for the coal-fired power sector. Measures such as adoption of the supercritical steam cycle with dry cooling along utilizing recycled wastewater are being promoted in Australia. Such a coal-fired power plant would typically consume 90% less water as compared to a conventional plant. Additional actions such as steam turbine upgrades, coal drying and in-plant water recycling are also being explored. More cost-intensive measures such as retrofitting existing units with dry bottom ash handling are also being evaluated. For water supply Australia is increasing turning towards sea

[226] Australian Government Department of the Environment. Retrieved from https://www.environment.gov.au/system/files/resources/718680e6-6857-4dd3-bb00-fa958f770b77/files/tanning-related-industries-paper19.pdf

water desalination. To offset the typically high energy intensity of the desalination process, Australia is exploring renewable as well as waste heat based desalination. The National Centre of Excellence in Desalination (NCEDA) and the Australian Water Recycling Centre of Excellence are two research centres created by the Australian government as part of the NWI's efforts to increase the economy's water resilience.

5.2 Canada

Historically, Canada's main source of electricity generation has been from hydro power plants. Exhibit 45 provides an overview of the electricity generation mix over the last few years for Canada.

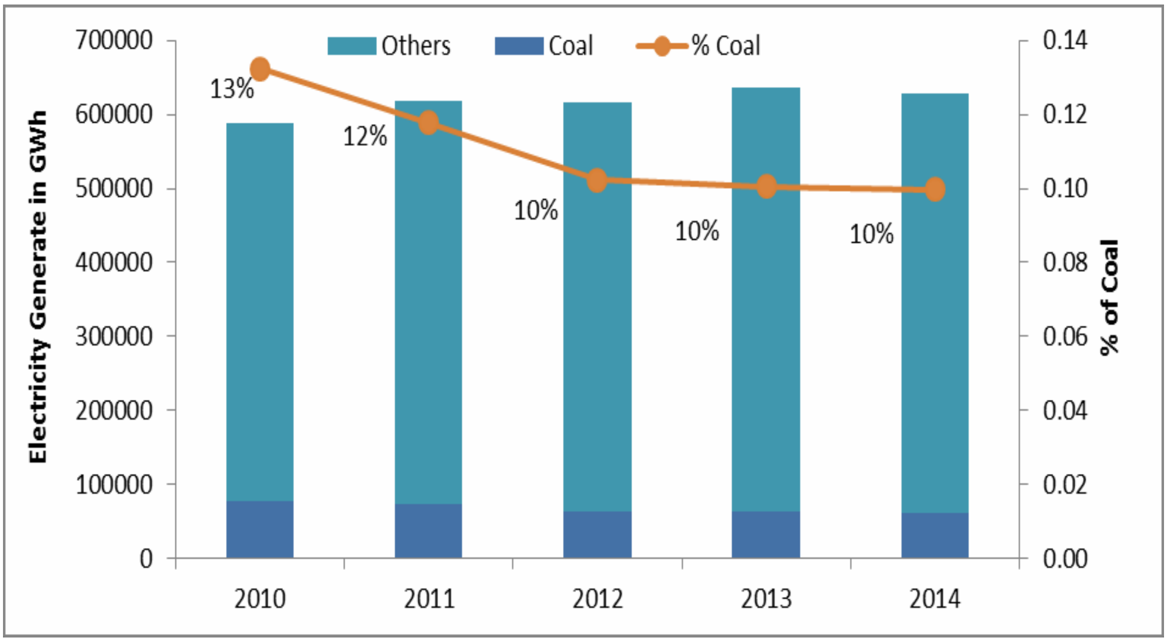

Exhibit 45: Canada's Electricity Generation Mix[227]

As per 2014 statistics coal accounted for only 10% of electricity generation in Canada. The Canadian Federal Government has recognized the importance of phasing out unabated coal[228]. Ontario is a leading example in this regard as it has successfully implemented its policy of phasing out coal by 2014. In September 2012, the Government of Canada published final regulations for reducing GHG emissions from coal based electricity generation. These performance standards came into effect on 1 July 2015 and establish a limit of 420 tonnes of CO_2 per gigawatt hour (t/GWh) of electricity generation for new coal-fired power plants[229] and units that have reached their end of life. Incentives for the use of CCS have also been prescribed as any new power plant can only adhere to these norms through deployment of CCS. For

[227] Generated from data from The Shift Project Energy and Climate Data Portal, http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart

[228] Unabated Coal is a coal burning without CCS.

[229] New coal power plants have been defined as those commissioned after 1 July, 2015.

old units, which have reached their end of life but continue to produce electricity, these regulations are applicable as well. These regulations therefore address two essential elements of a coal phase-out strategy.

Canadian Environmental Protection Act (CEPA)

The regulations brought out under CEPA in 1999 mandates the performance standards of new coal-fired electricity generation units, and units that have reached the end of their useful life. The regulations came into force from July 1st 2015. The regulation concentrates more on the emissions side of the coal power plant than on the water usage, by mandating the use of carbon capture and storage systems for both new as well as end-of-life units[230].

Water Conservation Efficiency and Productivity (CEP), Alberta, Canada[231]

The water conservation, efficiency and productivity (CEP) is a part of the Government of Alberta Water for Life Strategy proposed in 2003. The Council also established a sector planning CEP project team as a forum for the seven major sectors, including the electric power generating sector, for the collaboration of water conserving efforts and share of knowledge and ideas. The participation is on a voluntary basis, where each sector will develop and execute water efficiency plans as per the recommendation and targets of the Council and generate progress reports which would be reviewed regularly. Some of the water savings already realized was achieved through methods such as optimizing boiler blowdown and utilization of cooling ponds. The latest update of the CEP plan for the power sector was in Oct 2015 where the progress was reviewed. Some of the CEP targets discussed were the water productivity improvement of 31% by 2015 and 50% by 2029 from 2005 base year levels.

Canadian Clean Power Coalition (CCPC)

In 2000, CCPC was established as an association of responsible Canadian and the United States electricity generators with the aim of conducting R&D to develop and advance clean coal technologies. One of the coalition members, SaskPower, is developing one of the largest CCS projects in the Boundary Dam Power Station, Esteven, Saskatchewan. It is a CAD 1.24 billion government-industry partnership. The demonstration involves a rebuilt plant integrated with CCS technologies and link to enhanced oil recovery. Being the largest commercial-scale, coal-fired CCS facility, it is anticipated to reduce CO_2 emission by up to 90% and provide an unprecedented opportunity to amass comprehensive knowledge for future clean coal-fired power plants worldwide.

Economy Summary

Canada's coal consumption has shown a rapid decrease over the last decade or so due to reduced electricity generation from coal power plants. With respect to the coal-fired power plants in Canada, the most significant development of recent years has been the Ontario coal phase-out program where more than 6 GW of coal-fired capacity were retired. The new Federal Emission Performance Standards as discussed previously impose stringent CO_2 emission limits for both new coal power plants, as well as plants that have come to their end of useful service life. Because of these new regulations coal-fired power plant capacity is expected to reduce further but possibly at a slower rate than already achieved in Ontario. This will lead to the retirement of more than half of Canada's remaining coal capacity by 2030.

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230 www.ec.gc.ca/cc/default.asp?lang=En&n=C94FABDA-1

231 esrd.alberta.ca/water/programs-and-services/water-for-life/water-conservation/efficiency-and-productivity.aspx

5.3 Chile

The electricity sector in Chile has undergone extensive reforms leading to establishment of competitive conditions in the generation and sale of electricity. Private investment in generation, transmission and distribution has been instrumental in catering to the growing domestic demand. As of 2015, the total installed generation capacity in Chile was 20,375 MW. The power grid is separated into the following systems:

a. The far north of Chile, mostly part of the Atacama Desert, holds the Sistema Interconectado del Norte Grande SING system, primarily feeding the mining industry and holds 77.7% of the total installed generation capacity.
b. In central Chile, a large portion of the economy's population uses the Central Interconnected System (CIC) comprising 21.5% of the total installed generation capacity.
c. Chile has other smaller electricity grids called "Sistemas Medianos" in the Aysen, Magallanes, Los Lagos, Cochamo, Hornopiren and Eastern Island.

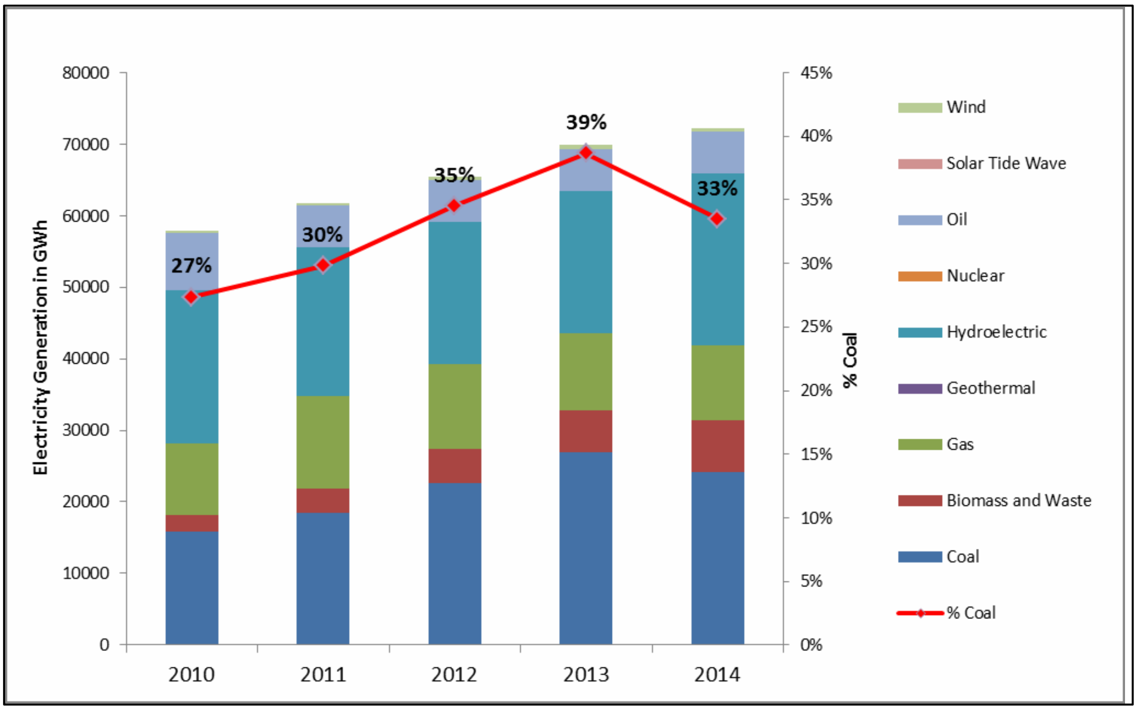

Exhibit 46: Electricity Generation Mix of Chile[232]

Exhibit 46 shows the electricity generation mix for Chile for five years from 2010. Approximately 50% of the generation is from thermoelectric plants, of which coal-fired plants are the primary component. Hydroelectric power has been the other major source of power generation for Chile. Solar, wind, biomass and small hydro generation capacity has grown significantly in Chile in recent years. As of June 2016, the

[232] Generated from data from The Shift Project Energy and Climate Data Portal, http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart

installed renewable capacity was reported to be 2,550 MW, i.e. 12.65% of the total installed generation capacity[233].

As part of the Energy Agenda published in May 2014, the Ministry of Energy committed to support the sustainable development of Chile's thermoelectric generation base together with the Ministry of Environment. One specific initiative mentioned is the generation of background information to regulate the intake and discharge of cooling waters by thermoelectric plants

Since 2011, Chile has made important progress to reduce the emissions from thermoelectric facilities. Emission standards for power plants were revised in 2011 to ensure they were in line with international limits. Additionally, a carbon tax for thermal power generators in Chile with a thermal input equal to or more than 50 MW was introduced as part of the 2014 tax reform. The carbon tax was set to 5 US$/ton of CO_2. This carbon tax will incentivize thermal power plants to invest in clean technology options. It is meant to force power producers to gradually move to cleaner sources and help achieve Chile meet its voluntary target of cutting 2007 GHG emission levels by 20% by 2020[234].

Since 2014 Chile has also made important progress in solving some of the challenges associated with water use at thermoelectric facilities. In Chile, the availability and use of water for thermoelectric generation systems is becoming one of the most important factors influencing the development and operations of thermoelectric facilities. During the period 2014-2015, the Sustainable Development Division of the Ministry of Energy commissioned studies on different alternatives and good practices for cooling systems for thermoelectric plants. These studies concluded that, for Chile, where thermoelectric plants are located along the coast, the most appropriate mechanism in terms of achieving an efficient and abundant cooling medium is the use of seawater for the operation of a once-through cooling system, using protection devices for marine organisms. In addition, cooling towers or other closed-loop cooling systems tend to be the most appropriate where the water intake elevation exceeds the elevation at which it is environmentally sustainable and economically efficient to pump the water volume required by a once-through cooling system. Dry-cooling systems should only be used when water usage concerns do not permit the use of a once-through cooling system or cooling towers. While dry-cooling systems decrease water use, they increase atmospheric emissions per unit of net-energy produced. The foregoing is aligned not only with the sustainable development objectives of thermoelectric generation projects that provide safe and economic energy to the country, but also with energy efficiency objectives as a State Policy, as defined by the Ministry of Energy in the Energy Agenda and in the Energy Policy of Chile, Energy 2050.

Based on the above studies, in 2016 the Sustainable Development Division of the Ministry of Energy published the Guide: "Good Practices in the use of water for cooling of thermoelectric power plants" and submitted a proposal for environmental regulation to the Secretary of Fisheries and Aquaculture, with the objective of regulating the environmental impacts produced by industries, including thermoelectric plants, from the withdrawal of water from water bodies. Both the regulatory proposal and the guide aligned with the Energy Agenda and Pillar No. 3 of the 2050 Energy Policy 2050 developed by the Ministry of Energy.

[233] CIFES Report: Renewable Energy in the Chilean Market July 2016. http://cifes.gob.cl/en/documentos/reportes-cifes/reporte-cifes-julio-2016/

[234] http://uk.reuters.com/article/carbon-chile-tax-idUKL6N0RR4V720140927

5.4 People's Republic of China

Increasing population and economic growth continue to drive China's demand for energy and water resources. Electrical generation capacity of China has grown by leaps and bounds in the last decade. The total installed capacity has increased from 718.22 GW in 2007 to 1257.68 GW in 2013[235]. An overview of the electricity generation mix, based on different types of fuels for the last 5 years, is illustrated in Exhibit 47. China's electricity generation has been heavily dominated by coal over the last few years. Based on the 2014 numbers, 72% of electricity was generated from coal, which is the highest compared to other APEC economies. After many years of rapid increase and dependence on coal for meeting electricity needs, the Chinese government is now taking steps to reduce coal consumption. In September 2013, following rising concerns about growing air pollution levels, the government issued the Air Pollution Prevention and Control Action plan, aiming for reducing coal consumption to 65% of total primary energy by 2017.

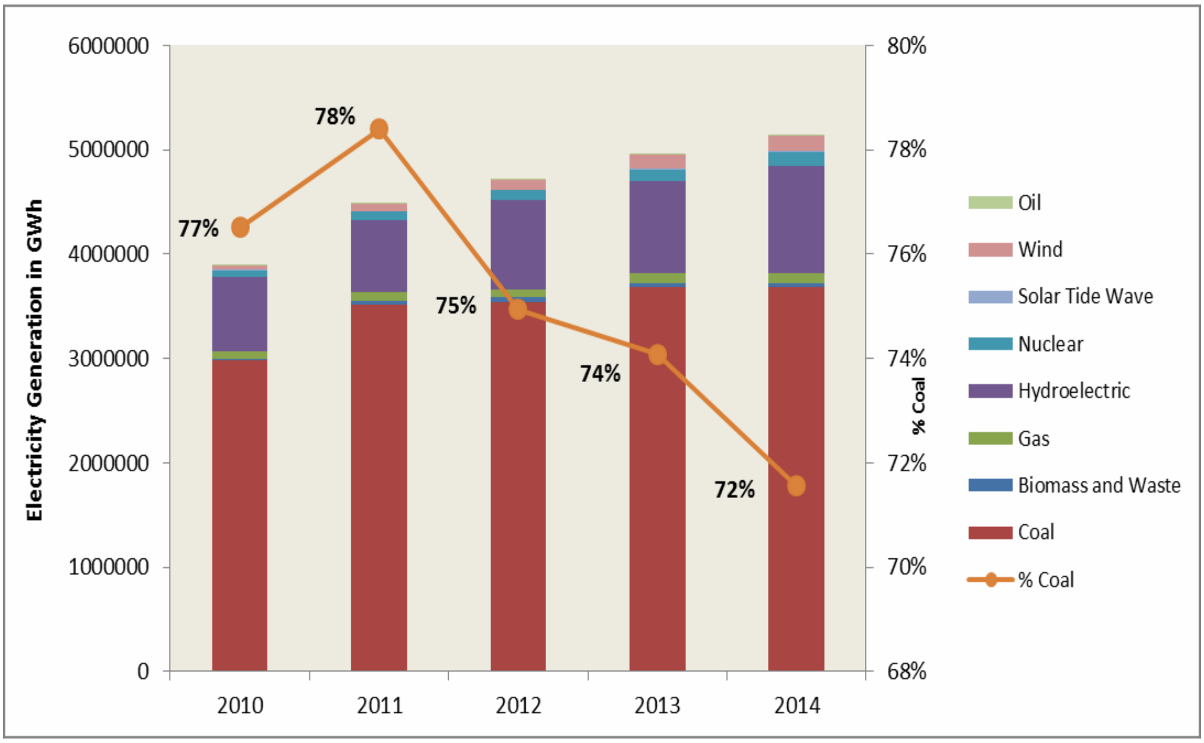

Exhibit 47: China's Electricity Generation Mix Based on Fuel[236]

The energy growth profile (dominated by coal) has translated to a rapid increase in water demand. The energy water nexus is further intensified in China because the majority of the coal reserves are found in the economy's driest regions. In recognition of the importance of water to the economy's socio-economic development, the Chinese government announced a stringent water management plan in 2011, known as the 3 Red Lines Water Policies. These policies were fully implemented in 2012 with specified targets on total water use, water use efficiency for industrial and agricultural use, and water quality improvements on regional and national scale.

[235] Extracted from http://english.cec.org.cn/No.117.index.htm

[236] Generated from data from The Shift Project Energy and Climate Data Portal, http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart

The future development of China's energy landscape has global implications and receives great attention. To meet growing energy needs and the pressure for reducing greenhouse gas emissions, China's future energy plans include an increase in the proportion of natural gas, nuclear and renewables in the energy mix, along with encouraging energy efficiency improvements. However, coal is still expected to play a significant future role in the energy mix. With due recognition to the water energy nexus for coal power generation, the Chinese government added the Water for Coal Plan to the 3 Red Lines Water Policies in 2013, requiring future large scale coal powered utilities to be developed in partnership with local water authorities. Coal-fired power generation represents the largest potential for water saving.

China's Five Year Plans have also been instrumental in the development of the energy sector. The 12th Five Year Plan Development Plan for Energy released in 2013 focussed on the development of energy supply in China, with the underlying objective of having a secure and environment-friendly energy supply situation. Many new industrial policies to support clean energy industries and related technologies were also included. This plan intends to reduce energy intensity by another 16% as compared to the 11th Five Year Plan[237]. The plan also targets increasing non-fossil energy sources to 11.4 % (up from 8.3 % in 2010). While not officially mandated, the 12th Five Year Plan had an underlying cap on total energy consumption at 4 billion tonnes of coal equivalent in 2015[238] as an endeavour for transitioning to a less intensive energy economy.

China's Coal and Water Conundrum

China's share of coal for power generation is likely to increase in the future, coal being the vanguard of China's energy mix due to its huge amount of coal reserves. In other words, China's power generation is dominated by coal and any problems regarding coal supply will inevitably affect energy security and power generation. Most of the coal reserves are geographically located in water-scarce regions, being susceptible to water risks. Availability of water dictates the coal production and consequently coal-based industries such as power generation, chemical production and mining which are water intensive. Ultimately, water scarcity places China's coal based power in jeopardy.

Water supply solutions undertaken by the government include desalination and water diversion to help ease the stress in water-scarce regions. China has invested in mega water diversion projects[239] to physically move water from the south to the north. The central route of the water diversion project has been operational since December 2014 and the western route is yet to be completed. However, these supply solutions have come under scrutiny as they are extremely power-intensive thus conflict with the energy conservation efforts to curb carbon emissions.

Water trading between agriculture and industry has been another solution for the water scarcity the government has been experimenting with. However, the potential success of using market-based mechanisms is yet to be realised.

Two market mechanisms have been implemented as discussed further:

a. Wastewater discharge permits – To control total amount of wastewater discharged
b. Water use permits – To regulate total water consumption

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[237] Key Targets of China's 12 Five Year Plan, Xinhua, March 5, 2011.

[238] http://www.gov.cn/english/2011-03/05/content_1816947.htm

[239] $62 billion South-North Water Transfer Project (SNWTP)

The schemes encourage water saving and cleaner methods of operation through reward (by selling excess permits) and penalty (as companies must buy permits to cover shortage and inefficiency). The effectiveness of such policies is yet to be reviewed and still in the pilot stage.

There is no easy direct solution to satisfy both interests in energy and water security if coal remains the dominant source of power. Meanwhile, a balance must be sought through water and energy savings and improving efficiency through better technologies to avoid environmental pollution.

<u>China's Policy Direction for Water Energy Nexus</u>

The power sector is the 2nd largest consumer of water in China and the largest industrial water consumer. Coal based power is especially water intensive compared to other sources of fuel. China's plan to expand the power sector in the next few decades amidst the limited water resource calls to question the sustainability of the power sector. One of the approaches to ensure so will be to control the water use in coal-based power generation through the use of more water-efficient technologies.

China's water resource management framework can be described by the three red lines approach:

I. Control water use
II. Improve water use efficiencies
III. Prevent and control pollution
IV.

Each part of the three-pronged approach to water management would affect coal based power generation significantly. All water policies and regulation will thereby follow the principles of the three red lines to tackle water scarcity and pollution.

<u>Control Water Use</u>

Controlling water use, in other words, water conservation appears to be the only direct solution for tackling water, energy and climate problems all at once.

<u>Five Year Plans</u>

The Five-Year Plan is the fundamental policy planning system which guides the economy's economic growth and environmental protection. It can be thought of as the economy's over-arching plan for the near future dealing with a wide array of issues including the water energy nexus. Targets are set, for example, on water quality standards and caps are fixed for energy & water consumption. The 13th five year plan[240] aims to reduce water consumption by 23% from 2015 levels by 2020. Water quality target has been set at 2% reduction in chemical oxygen demand (COD) and ammonia nitrogen emission. The five year plans serve as guideline for existing policies, regional plans, and strategic initiatives.

<u>Water for Coal Plan (Ministry of Water Resources, 2013)</u>

This is one of the key policies addressing the water energy nexus. The plan brought attention to the availability of water for the coal based power development in the future. This was a huge step in the coupling of water and energy and redefined the policy making to place more emphasis on water security instead of energy security. It made construction of coal power plants and related industrial sectors

[240] The National People's Congress. Retrieved from http://www.npc.gov.cn/englishnpc/Speeches/2016-03/23/content_1985905_2.htm

compulsorily take into account water feasibility in order to obtain approval from the relevant authorities. The effort to manage the strain on water resources was augmented by the Ministry of Environmental Protection (MEP) in 2014, when it issued a notice calling for water capacity assessments based on water resource demand and allocation among all the main industries in coal-fired energy sector.

It is apparent that targeting water use in coal-based power generation will bring about huge water saving. Targeting the entire coal chain, from mining to processing to power generation would yield slightly more water savings and would be a more sustainable approach, which is reflected in the water for coal plan.

The water for coal plan recommends several water saving options along the coal chain such as

a. Quotas for provinces
b. Coordinating water use between coal mines and coal-fired power plants
c. Adopt dry cooling to bring down the water consumption in arid regions
d. Stricter control for the use of surface water
e. New power plants must give water saving priority by implementing necessary measures and submitting compulsory water feasibility studies for approval

Power Sector Coal Consumption Cap Plan and Policy

Limiting coal consumption in coal based power generation will subsequently reduce water consumption. The coal cap will complement the water conservation efforts, without which the water utilization for coal based energy will exceed the currently set red line (74.7 billion cubic meters). In October 2013, the Natural Resource Defense Council (NRDC) launched a Coal Consumption Cap Project[241]. The objective was for a collaboration of stakeholders (government bodies, research institutes and industry associations), to develop comprehensive policies and plans to cap China's peak coal consumption by 2020. The coal cap integrates three methodologies[242]:

I. Top-down National Coal Cap – Accounts for the macroeconomic, national and international policies and targets
II. Bottom-Up Regional Coal Cap – incorporates environmental and ecological red lines (air, water public health, CO_2 etc.)
III. Sectoral Coal Cap – takes into account sector development

This approach allowed for several targets, such for water and carbon emissions, to be met simultaneously. The coal caps are allocated at national, regional, provincial and city levels to suit the economic, technical, financial and natural conditions in each area. For details on the specific targets set refer to the NRDC China Coal Consumption Cap Plan and Policy Research Project website.[243]

[241] NRDC. Retrieved from https://www.nrdc.org/sites/default/files/china-coal-consumption-cap.pdf

[242] NRDC, China Coal Consumption Cap Plan and Research Report: Recommendations for the 13th five-year plan, Oct 2015.

[243] For more information, visit www.nrdc.cn/coalcap/index.php/English/index

Improve Efficiency for Energy & Water

Energy efficiency is the most effective strategy when considering carbon and water. Energy saving was also the main strategy for emission reduction in the 2012 five year plan (FYP). Using less energy would reduce water consumption in the water-intensive coal based power generation. Over the past decades China focused on getting coal based energy efficiency to levels almost on par with the U.S.

The Action Plan (2014 – 2020)

In 2014, the Coal Power Energy Conservation and Emission Reduction (2014-2020), also known as the Action Plan[244], was formulated jointly by the National Energy Administration (NEA), MEP and the NDRC, to address the coal-based power efficiency and environmental protection. Rigorous measures were taken to transform and upgrade China's coal-based power fleet as summarized below:

- Decrease proportion of coal in primary energy consumption to be less than 62% by 2020 and electrical coal consumption to less than 60%
- Efficiency of existing coal-fired generating units to be improved to be less than 310g/kWh
- Newly built/retrofitted plants with more than 600MW capacity to have higher efficiency of < 300g/kWh.
- Essentially all coal-based generating units to reach gas turbine emission standards
- Phase out more than 10 million kW of outmoded power units by 2020
- All newly built coal-fired generating units to be equipped with advanced desulphurization, denitration and de-dusting facilities
- Strict conformation to energy efficiency and environmental access standards
- No new coal-fired power plants to be approved except for cogeneration
- Ban on importing inferior coal for power generation

Currently, the best technology adopted is in Jiangsu Taizhou Plant[245] equipped with the world's first secondary reheat technology, which achieved 258 g/kWh coal consumption. The national average is 318 g/kWh[246].

Two-pronged Approach for the Efficient Management of Water Use

The Chinese government's two-pronged strategy for efficient water management is to

I. Consolidate and centralize
II. Efficiently manage water resource

The first strategy refers to the consolidation/centralization of coal mines. Smaller ones are to be shut down and/or integrated to larger coal bases. The same is applicable for coal-fired power plants as well. This will pave way for the execution of the second strategy, which is to efficiently manage water resources. From the centralized location, water use can be better managed between coal-fired power plants, and regulatory measures such as stricter water use and pollution control standards can be easily implemented and

[244] NEA. Retrieved from http://www.nea.gov.cn/2014-12/03/c_133830458.htm

[245] DRC. Retrieved from http://en.drc.gov.cn/ChenFeihu.pdf

[246] China Electricity Council (CEC). Retrieved from http://www.cec.org.cn/yaowenkuaidi/2015-03-10/134972.html

monitored. Water efficiency measures also include encouraging water reuse and implementation of water-efficient technologies.

Prevent & Control Pollution

China's policies are transitioning from economy vs. environment to a more holistic economy & environment approach. The policy framework for water resource management i.e., the Environmental Protection Law (EPL) has been substantially amended in 2014 and came into effect in 2015. Apart from giving the MEP greater power to control over pollution sources, it established the policy direction of coordinating economic development together with environmental protection. Regarding power plants, the greater regulatory control of the government is enforced through stricter effluent discharge standards, more stringent discharge permits and higher discharge fees. The law was put into action through the Water Pollution Prevention & Control Action Plan[247]. This plan was meant to be an amalgamation of plans targeting water consumption in a wide range of sectors. One of the actions undertaken under the plan was by the National Development & Reform Commission (NDRC), MEP and Ministry of Industry and Information Technology (MIIT), called the cleaner production evaluation index system for thermal power[248].

Water Energy Trade-offs

The energy sector in China has been facing water scarcity constraints on account of development of large-scale coal-fired power plants in the extremely arid north-western region. In response to water scarcity there has been a gradual increase in the uptake of air-cooled coal-fired power plants over the last 10 years. According to China's latest regulations for regulating water use for the coal power sector, air cooling technology has become a mandatory requirement for new coal-fired thermal power plants in water scarce regions[249]. However, there is a trade-off in operating efficiency with air-cooled coal power plants. This trade-off is poised to be more significant with the growth air-cooled units following the 2013 regulation.

Development of Coal Bed Methane, SNG

Unconventional gases such as Coal Bed Methane are still in the early stages of development. Coal-based SNG is also emerging as a more promising unconventional gas supply source. As of August 2013, the central government had approved 4 SNG projects (two of which got commissioned in 2013) with a total planned capacity of 15.1 bcm/year in line with the 12th Five Year Plan target. Fourteen additional projects have been given permission to proceed with early stage studies. Coal-to-gas conversion projects typically consume large amounts of water and have a larger environmental footprint. These factors will thus pose a constraint in large-scale development of SNG projects. The water energy nexus needs to be given due consideration when developing a road map for further coal-based SNG development.

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[247] China State Council. Retrieved from http://www.gov.cn/zhengce/content/2015-04/16/content_9613.htm

[248] Cleaner Production Evaluation Index System for Thermal Power Industry (Chinese only) Retrieved from http://www.sdpc.gov.cn/

[249] Regulations on implementing water resources evaluation for development plan of large coal power bases; Ministry of Water Resources (MWR), Beijing, 2013 http://www.mwr.gov.cn/zwzc/tzgg/tzgs/201312/t20131217_520799.html

Environmental Regulations

China's latest National Air Pollution Standards for Thermal Power Plants come into effect in 2012 (Ministry of Environmental Protection). The prescribed standards are much more stringent compared to previous norms and in line with international regulations in the U.S. and EU. They also include provisions for imposing tighter emission limits in highly polluted areas. New power plants needed to comply with these standards from 1 July 2012, while compliance of existing plants began from 1 July 2014. Compliance for a prescribed mercury emission limit is applicable to all plants from 1 July 2015. To comply with these standards, electric utilities need to commit significant investment to install or upgrade pollution control equipment in addition to escalation of Operation & Maintenance (O&M) Costs. Typically these costs[250] will be higher for conventional coal-fired power plants and thus the new regulations would make coal a less preferred choice.

Another key environmental regulation is the State's Council Action Plan for Air Pollution Prevention released on 10 September 2013[251]. This particular plan is in response to the ever-worsening air pollution of inhalable particulates associated with coal power generation ($PM_{2.5}$ and PM_{10}). This prohibits building new coal-fired power plants in the Beijing-Tianjin-Hebei region, the Yangtze River Delta and the Pearl River Delta. It also requires replacing coal with natural gas in coal-fired boilers, captive[252]power plants and industrial kilns in these three regions by 2017.

Emerging Carbon Cost in China

China's climate change related goals for 2020 under the Copenhagen Accord include reduction of CO_2 per unit of GDP by 40-45% relative to 2005 along with increasing the share of non-fossil fuels in primary energy consumption by 15 %. Pilot Emission Trading Schemes (ETS) were launched in a few select cities and provinces in 2013 and 2014. The seven pilot schemes in progress are expected to be as the first steps by China in developing a national carbon market. The emerging carbon costs would further put the carbon-intensive coal sector at a disadvantage. However, this also very much depends on whether any incremental carbon cost imposed in the near future will be passed on to end users of electricity.

China's Policies and Actions on Climate Change 2014

The National Development and Reform Commission, the Ministry of Environmental Protection and the National Energy Administration formulated the "Action Plan on Upgrading and Transforming the Energy Conservation and Emission Reduction of Coal-Fired Power (2014-2020)". The plan proposes the following actions:

- More stringent standards of energy efficiency to protect the environment
- Faster upgrading and transformation of coal-fired power plants
- Reduced dependence on coal for electricity supply

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[250] O&M costs would increase significantly due to the associated trade-offs (efficiency drop) with the adoption of emission control technologies on conventional coal power plants.

[251] State Council, 2013

[252] The word 'captive' in this context implies that the new regulations are applicable not only to power plants but also to captive power plants, i.e., industrial facilities having in-house power generation part of which is consumed in-house and can also export to the grid.

- Reduced pollutant discharge
- Reduced share of coal in the power generation mix
- Improving the standards of technology equipment

Initiatives to promote efficient and clean use of coal would include a project involving four coal-fired power plants to demonstrate the application of the above actions. There has also been a series of other policies and regulations for Carbon Capture Utilization and Storage (CCUS) such as the "Policy on Coal Bed Gas Industry" and "Notice on Regulating the Scientific and Orderly Development of Coal-to-Liquids Industry and Coal-to-Gas Industry." The latter recommends five principles to regulate coal-to-oil and coal-to-gas projects:

1) Acting within the water capacity
2) Clean and efficient conversion
3) Starting with demonstration
4) Scientific and reasonable layout
5) Independent innovation

Furthermore, the Notice stipulates entry-level energy conversion efficiency, energy consumption, water consumption, carbon dioxide emission and pollution discharge.

Notice of National Development and Reform Commission (NDRC) on Promoting CCUS Pilot and Demonstration

The notice addresses Development and Reform Commissions (DRCs), the relevant government bodies, state-owned key enterprises and industry associations.

It details the associated tasks and working arrangements as required by the 12th Five Year Greenhouse Gas (GHG) Control Plan. The 12th Five Year GHG Plan announced by the State Council[253] states the need for the promotion of Carbon Capture, Utilization and Storage (CCUS) while simultaneously building up human resource, financial security and policy support.

The CCUS technology is heralded as a means to achieve large-scale reduction in GHG emissions, becoming a key strategy to achieving China's medium to long-term climate change commitments. The initial stages of CCUS development are envisioned to be the establishment of pilot and demonstration CCUS technologies, which would pave the way for large-scale application and commercialization.

Economy Summary

Water is a constraint on coal-fired power generation in inland China and as already discussed in the previous paragraphs, a string of measures such as Dry Cooling and Water for Coal Plan have been implemented by the Government to reduce the growing water demand for the coal-fired power sector. It is important to reiterate the facts that dry cooling typically results in drop in thermal efficiency by 3-10% in addition to significant retrofit costs in the range of US$ 200 million per 1000 MWe of coal-fired power plant capacity. Close to 100 GWe of coal-fired power plant capacity in Northern China (about 12% of the entire coal power fleet) uses dry cooling and the demand for dry cooling is expected to increase to around 175 GWe in the near future[254]. The water conservation benefit of air-cooling technology has obviously

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[253] (SC 2011, No. 4 document)

[254] http://www.world-nuclear.org/information-library/current-and-future-generation/cooling-power-plants.aspx

received much more attention than its associated energy penalty from both energy planners and power suppliers since its recent introduction in China. Going forward there is a need for more careful evaluation of water resources carrying capacity and the availability of alternative non-conventional water sources for power plant cooling in arid regions, before outlining ambitious long-term energy plans and huge capital investments in the coal-fired power plant sector. A thorough identification of the magnitude of the water energy nexus embedded in current technology choices should be an underlying basis for defining the roadmap for achieving the growing power demand. Application of CCS technology on new coal-fired power plants should also be explored as policy options for triggering more technological advancements in this field.

5.5 Hong Kong, China

Hong Kong, China has very few domestic energy resources and is thus by and large dependent on fuel imports for meeting its energy and power generation needs. Due to the implementing of energy efficiency measures over the past few years and the concerted efforts of the community in conserving energy, the growth in electricity consumption has slowed to some extent.[255]

The deficit between the local generation and the actual consumption is met through electricity imports from the Mainland[256]. Coal has dominated the electricity mix for Hong Kong for many years. In 2011 coal accounted for 53% of the total electricity generation. Most the existing coal-fired power plants came online back in the 1980s and are scheduled for retirement in 2017[255]. However, subject to actual operation conditions some of these existing units could possibly be extended beyond their current book lives of 35 years. In 2014, the government published the public consultation document for the 'Future Fuel Mix for Electricity Generation'[257] detailing its two fuel mix options for power generation, namely grid purchase from mainland China and local generation with natural gas as the predominant fuel. Policy targets for 2020 reduce coal's share to 25%, natural gas around 50% and nuclear power will cover the remaining mix.

Emission Standards

Air quality comes under the purview of the Environmental Protection Department. The latest publication of environmental standards related to coal-fired power plants was in January 2014. The construction of new coal-fired power plants has been banned since 1997, under the scheme of control agreements (SCAs) signed with the only two power companies in operation[258]. This move was to favour the switch of power generation fuel sources from coal to the less carbon-intensive natural gas. For existing power plants the Air Pollution Control Ordinance (Cap.311) (APCO) has stipulated emission caps in Technical Memorandum (TM). Two technical memoranda were issued in 2008 and 2010, respectively. The emission allowances in the second TM (effective from 1 January 2015) were determined with due regard to maximizing the use

[255] Public Consultation Documents extracted from http://www.gov.hk/en/residents/government/publication/consultation/docs/2014/FuelMix.pdf

[256] Electricity is also exported to the Mainland.

[257] Public Consultation Future Development Electricity Market extracted from http://www.enb.gov.hk/en/resources_publications/policy_consultation/public_consultation_future_development_electricity_market.html

[258] http://www.epd.gov.hk/epd/english/climate_change/elec_gen.html

of existing gas-fired generation units and prioritizing the use of coal-fired generation units equipped with advanced emission control devices[259].

5.6 Indonesia

As one of the largest economies in Southeast Asia, Indonesia is one the largest energy consumers in the region. Formerly a net oil exporter in the Organization of Petroleum Exporting Countries (OPEC) for several decades, Indonesia now struggles to attract sufficient investment to meet growing domestic energy consumption, due to lack of proper infrastructure and a complex regulatory environment. Indonesia comprises more than 17,000 islands presenting geographical challenges in matching energy supply in the eastern provinces with demand centres in Java and Sumatra. In general, the rise in energy demands in other parts of the economy has outpaced the energy infrastructure development.

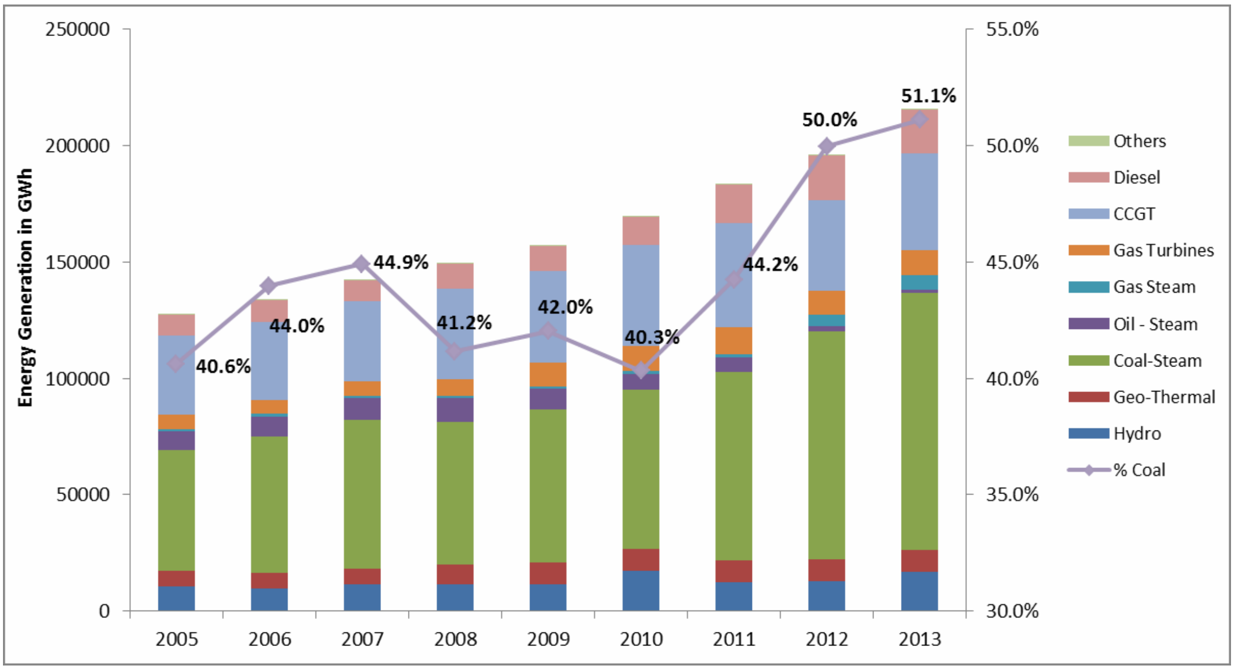

Exhibit 48: Energy Generation Mix of Indonesia (2005-2013)[260]

Indonesia's electricity fuel mix is dominated by fossil fuels. In 2013, coal accounted for almost 51.1% of the total electricity generation. In aggregate terms coal-based generation has increased from 51,825 GWh in 2005 to 110,452 GWh in 2013, in percentage terms it implies a corresponding increment from 40.6% to 51.1% when compared with the total electricity generation for the period. The total electricity generation has increased from 127,554 GWh to 216,139 GWh during this period. Notably Indonesia is one of the largest producers of geothermal energy, after the United States and the Philippines. Growth in power generation from coal is linked to completion of two Fast Track Programmes. The first was launched in 2006 to meet growing electricity demand and to switch from oil to coal-based generation, and was scheduled to

[259] Review of the Second TM for Allocation of Emission Allowances for Power Plants

[260] Generated from data from The Shift Project Energy and Climate Data Portal, http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart

be completed by 2009. Fast Track Programme 2 was launched in 2014 to develop a further 10 GW of capacity, dominated by coal. Indonesia is also considering high-efficiency coal combustion technologies such as supercritical in its coal power mix.

Coal is expected to play a major role in the near future in Indonesian's electricity mix. As per Perusahaan Listrik Negara (PLN), a state-owned firm dominating the electricity generation and distribution market in Indonesia, electricity generation from coal is expected to increase to 66% by 2022 [261]. Domestic coal consumption has grown considerably in Indonesia over the last 10 years. The electricity sector is one of the largest coal consumers and is expanding because of addition of coal-fired power generation capacity. The Indonesian government encourages increased use of coal in the power sector because of its relatively abundant domestic supply of lignite and the need to reduce the use of expensive diesel and fuel oil for power generation. To guarantee sufficient domestic supply, the Indonesian government introduced a Domestic Market Obligation Scheme in 2010, which required nominated coal producers to sell a minimum percentage of their coal output to the domestic market. In line with its strong reliance on coal for power, Indonesia is also one of the top 5 consumers of water in coal production with a total consumption of 225.51 million m^3 of water per year for coal production. With proposed addition of 45.4 GW of coal-fired power plants to the existing fleet of 19.4 GW as of 2013, the total water consumption by coal-fired power plants in Indonesia is expected to be about 310.66 million m^3 of water per year.

Regulatory Framework for Emission Control

The emission standards applicable for thermal power plants were issued in December 2008 and replaced the earlier 1995 standards. The new regulations impose more stringent limits for critical pollutants such as SO_2, NOx and PM for existing, in-development and new power plants. However, the prescribed limits in the new regulations are still very lenient as compared to developed APEC economies and latest international standards. Old power plants and those that commenced development before the announcement of this revision still need to comply with the archaic emission standards of 1995. New power plants and those in development needed to comply with these standards by 1 January 2015. The revised pollutant levels applicable for new coal-fired power plants in Indonesia are very lax compared to applicable standards in developed APEC economies. For instance, the proposed SO_2 limit for new power plants is set at 750 mg/m3 which is very high compared to equivalent standards in China of 100 mg/m3. These revisions thus do not promote the use of best available technologies for emission reduction to prevent the harmful impacts of coal-fired power plants to the environment.

Deployment of Clean Coal Technologies

Reliance on coal will challenge Indonesia's commitments to reducing its carbon footprint as declared and achieving the targets sets in the energy mix for 2025. It is crucial that new coal-fired power plants should focus on super critical or ultra-supercritical technologies to minimize emissions per kWh and enhance efficiency of electricity generation. The Indonesian government together with the state-owned utility PLN has considered investments in clean coal technologies such as coal drying, coal blending, gasification, coal slurry, SynGas etc. PLN has constructed a coal-drying facility at the Labuan power plant and has expressed interest in building more such facilities[262]. This is because Indonesia has ample reserves of low rank coal, which is high in moisture content, thus limiting its effective utilization. Plans for a coal blending facility and gasification plants are also either in feasibility study or development phases. IHI has built a twin gasifier

[261] PLN Long term Electricity Plan (2013-2022)

[262] Tharakan, P. (2015). Summary of Indonesia's Energy Sector Assessment.

demonstration plant in Pupuk Kujang Industrial estate based on circulating fluidised bed reactor technology, that produces syngas from lignite coal. A recent regional study of CCS potential in four economies, including Indonesia, found that Indonesia's gas- and coal-fired power plants will offer opportunities to develop commercial-scale CCS in the future. The 660-MW Cirebon steam power plant is the first super-critical power plant in Indonesia. In 2011, a 2000 MW super-critical coal-fired power plant was proposed to be built in Pemalang in Central Java in a joint venture with Japanese firms. Originally, the plan was for the first 1000-MW unit to be operational by 2016, followed by a second unit in 2017. However, he plan has been delayed for various reasons and construction is yet to begin.

Law on Water Resources

Following the economic crisis of the 1990's, the government realized the need for further reforms in the water sector through effective policies, better regulation and strengthening the institutional structure. The proposed Water Law in 2004, along with suggesting radical changes in the water sector at a national level, also aimed at developing favourable conditions for private investment in infrastructure growth. Law 7/2004 on water resources aimed for a sustainable and integrated water resource management along with clarifying the roles and responsibilities of the national and sub-national government. The provincial government was assigned the task for allocating resources to industries including coal power plants. However, the 2004 Act was successfully challenged in 2015 at the Constitutional Court, as encouraging commercialisation of water resources at the expense of public interests.,. The court ruling reinstated the archaic 1974 Water Law to protect water resource availability to the public. This new ruling emphasises the role of the state in water management with the government acting as the policymaker, enforcer and manager of water affairs. This is enabled through the issuance and revoke of concessions and permits for use of water by the government. The impact of this ruling will have far reaching consequences not only to coal-fired power plants but to the overall industrial sector in Indonesia[263].

With the passage of the Regional Autonomy Law No. 32/2004, the various provinces and regions within Indonesia were exclusively accorded autonomy over certain taxing powers. One such regional tax arrangement is the taxation on collection and utilisation of underground and surface water at a maximum tariff rate of 10% of the purchase value of water. This could also affect the use of water in the power generation industry[264].

263 www.amcham.or.id/fe/4919-water-law-crisis-opens-floodgates

264 www.pwc.com/id/en/publications/assets/eumpublications/utilities/power-guide-2015.pdf

5.7 Japan

As one of the world's leading industrialized nations and a major importer of fuels, the choice of future energy paths by Japan will have a significant impact on the energy sector both globally and in the region. In 2014, coal accounted for 30% of annual electricity generation in Japan. The share of coal in electricity generation has seen a sharp increase since the Fukushima accident, which prompted Japan to shutter most of its nuclear power plants, as indicated in Exhibit 49.

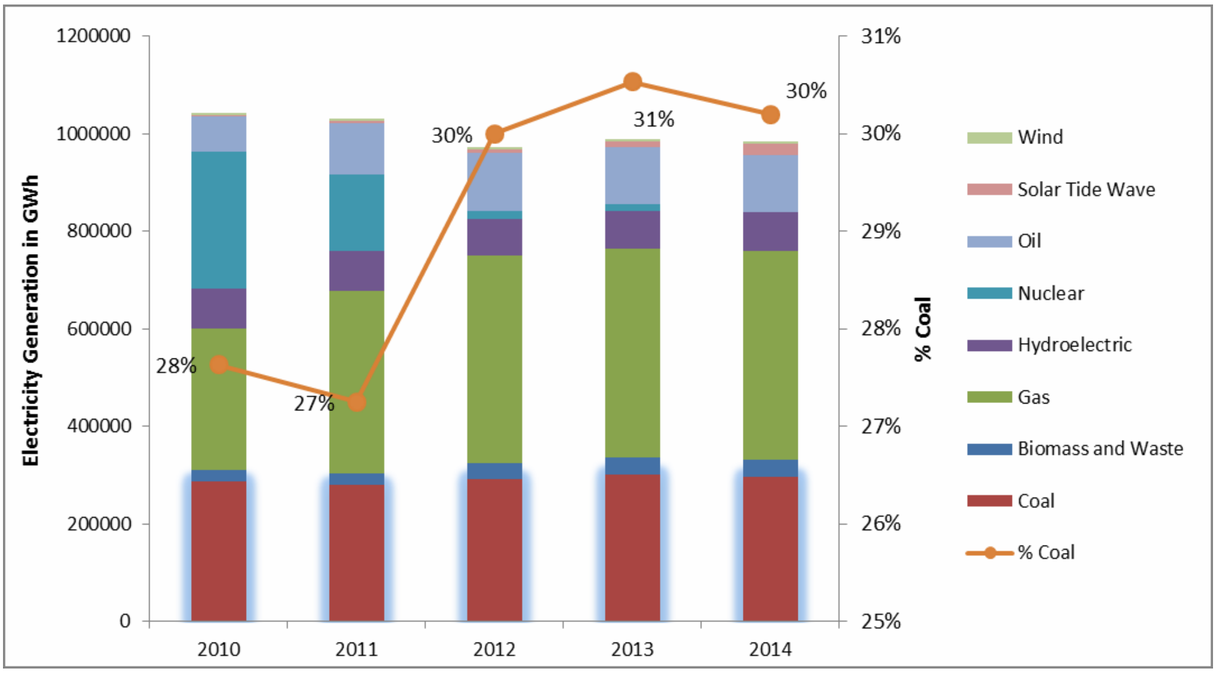

Exhibit 49 : Electricity Generation Mix of Japan[265]

From the regulatory perspective, the Ministry of Environment (MOE) is the governing body for coal-fired power plants. MOE was formed in 2001, from the sub-cabinet level Environment Agency established in 1971. In 1968, the Air Pollution Control Law was enacted providing the basis for air pollution legislation in Japan. This Law has been amended over the years, the latest amendment being in 1998. Emission standards for soot, dust and NOx are specified under two categories - general and special. Typically, general standards are national standards applicable to all existing plants. Special standards apply to new plants in defined areas.

In 2014, Japan issued its latest energy policy that emphasizes energy security, economic efficiency and emissions reduction. The plan would serve as the basis for Japan's energy policy direction, taking into consideration the changes in both the domestic and international environment. The plan also incorporated the impact of the Great East Japan Earthquake and the TEPCO's Fukushima Daiichi Nuclear Power Station Disaster. The plan is based on four key principles, namely, 'safety', 'energy security', 'improving economic efficiency' and 'environment suitability'. Japan acknowledges that increased dependency on fossil fuel to compensate for the cessation of nuclear power plant operations can be problematic. The Strategic Energy Plan declares Japan's stance on coal as an energy resource and summarizes the direction current and future policies will take to reconcile the power supply stability and environmental responsibility. Based on

[265] Generated from data from The Shift Project Energy and Climate Data Portal, http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart

this plan, the economy intends to develop the most advanced generation technologies using fossil fuels, strengthen the share of renewables and alternative energy sources, and reduce its dependence on oil in the transportation sector.

Energy efficiency has been projected as one of the major tools for achieving significant reductions in fossil fuel consumption[266]. Electricity generation from coal is expected to decline going forward. As per 2014 numbers, 30% of electricity in Japan was coal-based. Electricity generation from coal is expected to further shrink to around 25% in 2030 per this scenario. Apart from using the most advanced coal technology, the Government of Japan (GOJ) encourages the electricity industry to create a framework for voluntary efforts while the GOJ formulates policies and plans for emission reduction targets. Moreover, the environmental assessments are to be conducted more regularly - on an annual basis rather than once every 3 years.

The other part of the strategy is to promote the use of high efficiency coal-fired power plants such as IGCC, and CCS to further reduce emissions. A study will be conducted together with research and development geared towards practical implementation by 2020. Japan is also exploring the option of exporting its technology to other economies with coal as a substantial fuel in their power mix. In November 2015, the GOJ published the Long-term Energy Supply and Demand Outlook, in which it forecasts the power generation mix in 2030 if the plan goes as intended.

A lot of initiatives are currently underway in Japan for promoting adoption of Clean Coal Technologies (CCT). At the centre stage of these initiatives is Japan Coal Energy Centre (JCOAL). JCOAL has organized the Technology Development Committee for setting agendas that contribute to early establishment, demonstration and commercialization of key clean coal technologies. JCOAL has also prepared a CCT Roadmap and has been instrumental in development of pilot projects for various clean coal technologies.

Water Policy

In 2000, the National Comprehensive Water Resources Plan (Water Plan, 2000) was implemented as a guide for the development and rational use of water resources. Under the basic goal of achieving a sustainable water use system, measures addressing water resources and energy consumption were stated but there was no explicit mention of any measures specifically targeted to address the water energy nexus for coal-fired power plants. The plan also promotes research and technical development activities. The stipulated target year for this plan to be implemented was from 2010 to 2015; however, there is no publicly available record detailing its implementation status and the success achieved.

There are restrictions on the consumptive use of water, which is linked to the Basic Plan for Water Resources Development. Water rights for surface and ground water are managed separately. For surface water, publicly owned utilities for industrial uses are allocated river water rights. These entitlements define factors, such as the purpose of use, the maximum volume used for a nominal period, and the applicable abstraction charges. For ground water, an Industrial Water Law[267] stating the mandatory requirement of permits from local governments before groundwater withdrawal, is applicable in areas where water resources are scarce. Moreover, water trading is prohibited by the River Law[268] and is only allowed for

[266] Long Term Energy Supply and Demand Outlook, July 2015, Ministry of Economy Trade and Industry, Japan.

[267] http://law.e-gov.go.jp/htmldata/S31/S31HO146.html

[268] Network of Asian River Basin Organizations www.narbo.jp/narbo/event/materials/twwa03/tw03_09_01-2.pdf.

special cases like land improvement districts. The River Law also defines environmental flow requirements, including the preservation and enhancement of aquatic life.

The roles of relevant government bodies in Japan's water policy are listed below:

I. Ministry of Economy, Trade, & Industry – Responsible for water supply for industrial use (industrial water law)
II. Ministry of Environment – Water Quality & Environmental Preservation (the basic environmental law/plan, water resources development law/plan)
III. River Bureau – River water utilization (The River Law)
IV. Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Water Resources Department – Overall Coordination, water supply and demand planning
V. Japan Water Agency[269] – This Agency ensures the reliable supply of water, including water supply for power generation through the JWA Act.

Improving Water Efficiency

As discussed in previous sections of the report, the amount of water withdrawal and consumptive use in a coal-fired power plant is dependent on the thermal efficiency and combustion technology. In this aspect, development of high efficiency coal-fired power plants as proposed in the 4th Strategic Plan would provide additional benefits of reduced water consumption. Japan is also deeply involved in various R&D activities pertaining to IGCC; integrated fuel cell combined cycle power generation (IGFC) and advanced supercritical pressure coal-fired power generation (A-USC). An additional action for reducing water use would be adoption of efficient cooling methods. However, the current regulations have no explicit mention on the type of cooling methods to be used, or for promoting adoption of dry cooling technologies and/or technical feasibility of dry cooling with USC and A-USC.

Economy Summary

Japan's latest energy policy while focusing on energy security and GHG emission, doesn't explicitly address the likely impact of the planned energy policies on water resources or vice versa. The water use statistics show that the industrial water (including power generation) accounts for around 15% of the total water intake[270]. Although availability of water resources is dependent on climate change (which impacts the water cycle), some mitigation measures (such as carbon capture technologies) inadvertently increase water intake in power generation. Thus, integration between energy and water is essential for future policies to ensure consistency and balance.

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[269] Japan Water Agency. Retrieved from www.water.go.jp/honsya/honsya/english/02.html

[270] MLIT. Retrieved from www.mlit.go.jp/tochimizushigen/mizsei/water_resources/contents/current_state2.html

5.8 Korea

The power sector in Korea is dominated by Korean Electric Power Company (KEPCO). The government is one of the major shareholders. Coal-fired power generation has been the backbone of the power sector over the years (Exhibit 50). Nuclear power comes second, but the growth of this sector over the last 10 years has been relatively stagnant. Natural gas-based generation has shown a significant increase in the electricity mix of Korea. Since the economy only has proven reserves of anthracite, it must rely on imports for meeting demand of steam coal for power generation. Coal consumption in Korea has increased significantly over the last 10 years, driven primarily by the growing demand from the electric power sector. the government has plans to further augment its nuclear capacity in the coming years.

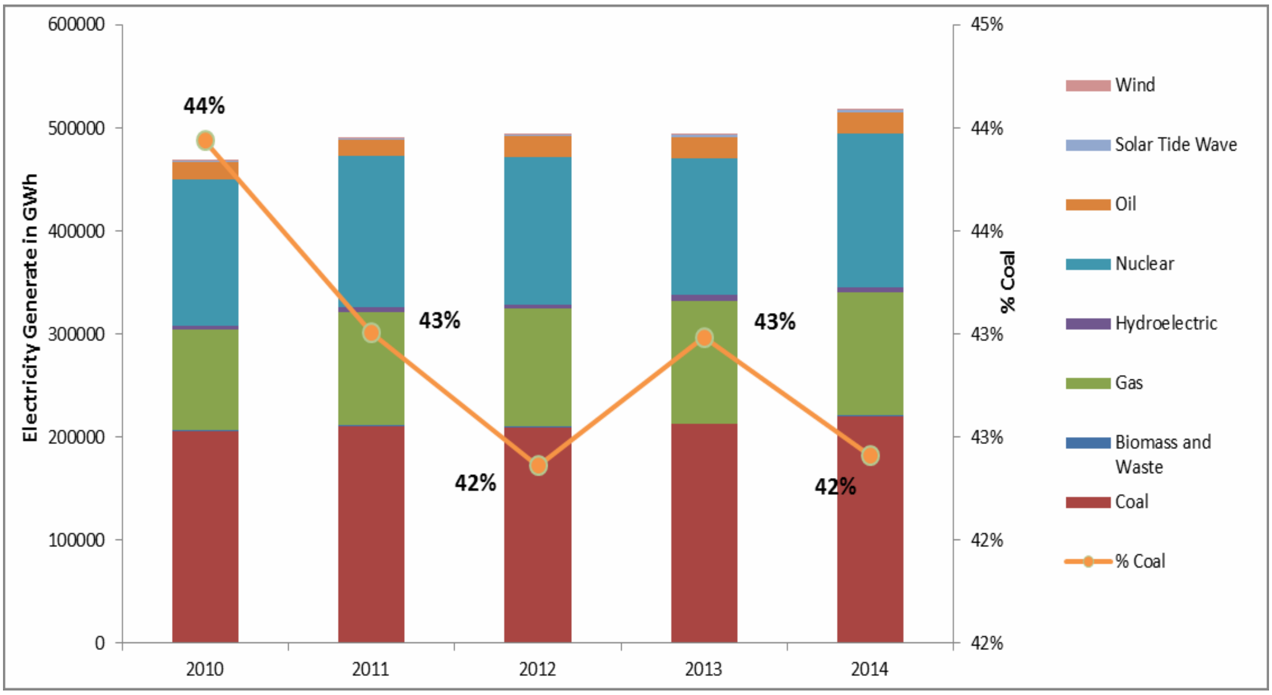

Exhibit 50: Electricity Generation Mix for Korea[271]

Korea announced the Road Map to Achieve Greenhouse Gas Reduction Goals in January 2014. The power sector is expected to contribute a major portion of GHG reductions, specified at 26.7 %. To ensure that reduction goals are achieved in an effective manner without burdening the power sector (or other specified sectors such as buildings, transport etc.) the government is looking at a market-friendly reduction system. There is a focus on core technology development and demonstration in the fields of CCS and non-CO_2 reduction technologies. Energy efficiency improvement and demand reduction for the industrial sectors (heavy consumers) will also be one of the key focus areas of the government. The Energy Master Plan launched in January 2014 also calls for applying advanced GHG reduction technologies to new power plants.

In 2015, Korea also launched its national Emission Trading Scheme (KETS), a nation-wide Cap and Trade Program. The KETS covers some of the largest emitters including the power sector. KETS is designed in three phases commencing in 2015 and is projected to conclude in 2025.

[271] Generated from data from The Shift Project Energy and Climate Data Portal, http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart

Emission Standards

Korea has been very proactive in this area and prescribed emission standards for power boilers back in 1979. These were followed by standards on other critical pollutants such as NO_x and SO_X. Currently, legally binding emission standards are actively enforced in industrial areas in general and are applicable to coal-fired power plants as well. The revisions in 2004 defined a PM limit between 20 to 40 mg/m^3 for all new coal-fired power plants coming into operation post 1 January 2005. The prescribed limits are in line with relevant PM limits prescribed in advanced APEC economies like China and USA. Similarly, stringent limits are defined for SO_X and NO_x which are in line with international regulations and call for the adoption of Best Available Technologies.

Framework Act on Low Carbon, Green Growth[272]

The Framework Act on Low-Carbon, Green Growth (2010) mentions national adaptation plans for six sectors including water. A proposed approach in water management for coping with climate change was demand control strategies. It can be expected that coal-fired power plant may be indirectly affected through the effects of climate change on water.

The high uncertainty of how climate change would affect water resources and the fragmented institution of water management makes it difficult for an interdisciplinary study of the water-energy nexus.

Water Quality Policy and Implications on Coal Power

Korea's current policy on water shows much focus on pollution regulations and industrial wastewater management. The "Master Plan for Water Environment Management"[273] outlines this policy stance and focus, which would guide subsequent government legislation and action.

Korea's Master Plan affects coal-fired power generation mainly through the effluent discharge standards for industrial wastewater. Water quality conservation is promoted under the "Support for Environmental Technology and Environmental Industry Act"[274].

Policy Promoting Water Conservation

The "Act on the Promotion of the Conversion into Environment-Friendly Industrial Structure" (latest amendment Aug 2011) [275] contains the promotion of water conservation in Article 3, under the establishment of a comprehensive policy. The comprehensive policy contains goal setting every five years for aspects such as level of environmental friendliness, degree of energy consumption and degree of industrial water-use and recycling rate of resources. This comprehensive policy seems to give some scope for the water-energy nexus but the application to the power sector and measures taken are not yet available.

Regulation on Water Use

[272] Ministry of Government Legislation. http://www.moleg.go.kr/english/korLawEng?pstSeq=54792

[273] Ministry of Environment. http://eng.me.go.kr/eng/web/index.do?menuId=262

[274] Ministry of Government Legislation. http://www.moleg.go.kr/english/korLawEng?pstSeq=57725

[275] Ministry of Government Legislation. http://www.moleg.go.kr/english/korLawEng?pstSeq=57709&brdSeq=33

Water use for power generation is regulated under the River Act[276] 2010. Permits must be obtained from the Ministry of Land, Transport and Maritime Affairs. The government may exercise its rights not to grant the permits, or restrict quantity withdrawn, should they find the water use a hindrance to the proper maintenance of the river, such as when ensuring the base flow conditions of the river. Moreover, the quantity used (and discharged) must be measured and verified by the authorities. After the amendment of the Promotion of Water Reuse Act[277] in 2013, all power generation plants are required to install rainwater-using facilities. It also specifies the reuse of thermal discharge from power generation plants.

Industry developments

The power generation sector in Korea is becoming proactive in recognizing the critical nature of the water-energy nexus as evident from the statements of Daesung Group Chairman Younghoon David Kim[278]. In 2016, the economy hosted the 7th World Water Forum and the World Clean Coal Conference. Korea has built the 2000-MW Samcheok Green Power Project using CFBC technology. This will offer significantly low emissions of SOx and NOx, fuel flexibility, and will deliver water savings because it avoids the conventional FGD technology for emission control. The Korea Southern Power Company (KOSPO) claims[279] that specific emphasis was placed on water supply and disposal methods during the design phase. Water for the power plant will be secured using several methods: the bank filtrated water, collected rainfall purification systems and seawater desalination systems. It will also recycle all outflow by establishing an integrated water and wastewater treatment system.

Economy Summary

Korea does not seem to have a single coherent policy addressing the water energy nexus for coal-fired power generation. The government has recently announced building 19 new coal-fired power plants by 2020 and shutting down 10 old coal power plants by 2025. State-run utilities will spend US$ 8.68bn on closures and upgrading existing plants by 2030 to lower emissions, partly to meet COP21 commitments[280]. However, some policies targeting the industrial use of water are also applicable in a broader sense for coal-fired power plants. The water legislation seldom distinguishes water used for coal-fired power plants, which may indicate that the water-energy nexus has yet to become a priority when considering future coal based capacity addition. In February 2016, the Korea Water Resources Corporation (K-Water) signed a memorandum of understanding (MOU) for technological cooperation with Asian Development Bank (ADB), to introduce its world-renowned smart water management technology in South East Asia.

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276 Ministry of Government Legislation. http://www.moleg.go.kr/english/korLawEng?pstSeq=52772

277 APEC-VC-Korea. www.apecvc.or.kr/?p_name=database&sort=program&sort2=EP1&gotopage=2&keyfield=1&skey=water&query=view&unique_num=1985

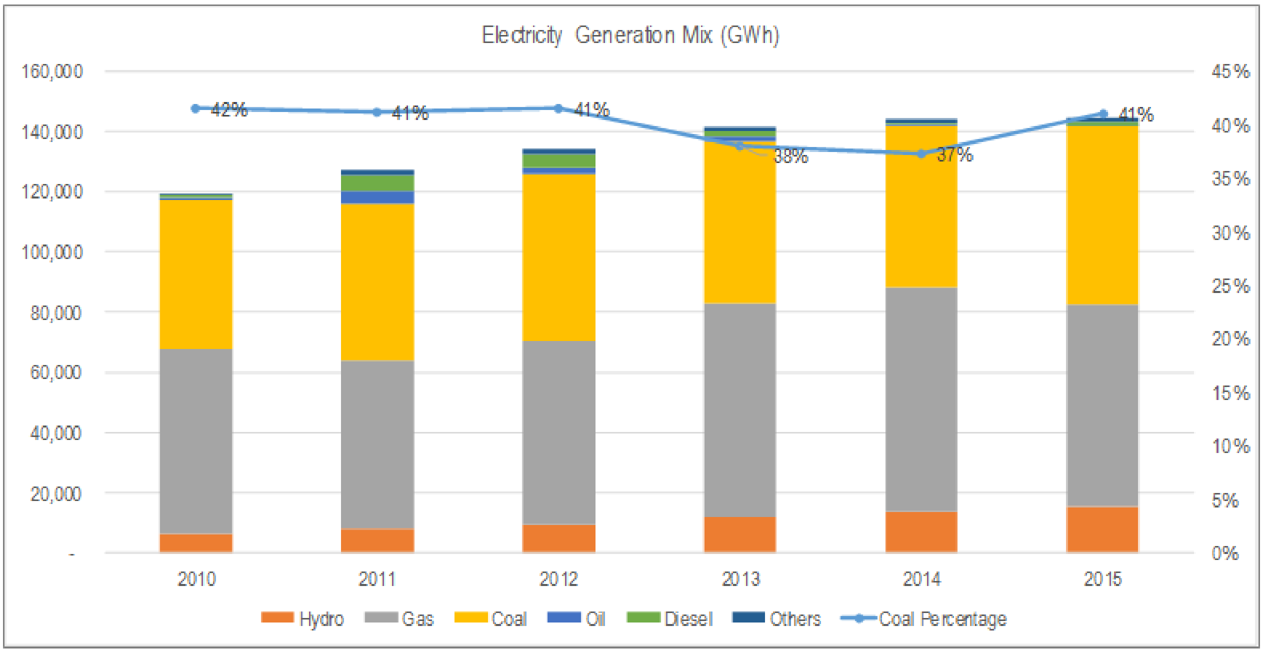
278 Korea Joongang Daily. (2015, April 21). Daesung chairman talks 'interlink' of water, energy. koreajoongangdaily.joins.com/news/article/article.aspx?aid=3003317

279 www.modernpowersystems.com/features/featuresamcheok-leads-way-in-advanced-ultrasupercritical-cfb-4927714/

280 www.powerengineeringint.com/articles/2016/07/south-korea-plans-to-shut-ageing-coal-plants.html

5.9 Malaysia

Malaysia's economic development and population growth resulted in the rapid growth of electricity demand. As displayed in Exhibit 51, fossil fuels, primarily coal and natural gas, have dominated the power mix in Malaysia in the past.



Source: Malaysia Energy Statistics Handbook 2016

Exhibit 51: Electricity Generation Mix for Malaysia (2010-2014)[281]

Natural gas had been the most important fuel for power generation historically, but coal has taken an increasing share since 2000. As of 2013, Malaysia had about 7 GW of coal-fired power plants installed capacity. With its hydro potential nearly fully developed, Peninsular Malaysia is increasingly looking towards diversifying the fuel mix to meet its base load power. 2020 forecasts see coal dominating Malaysia's power generation mix at about 50% with gas natural gas playing a minor role (~ 30%)[282].

Regulatory Framework

Emission standards applicable for coal-fired power plants first came into effect in 1978 and covered existing and new facilities. These standards contained emission limits for only particulate matter and were applicable to new facilities. The existing plants were given a time frame of 3 years to comply with these regulations.

These archaic regulations were finally revised through the Environmental Quality (Clean Air) Regulations in 2014. More stringent regulations are prescribed for new coal-fired power plants or plants in development (provided they begin operation within a year of these regulations) for critical pollutants such as SO_X, NOx

[281] As received from Aswita Sazmin Ismail, Ministry of Energy, Green Technology and Water (MEGTW), Malaysia

[282] http://www.powermag.com/malaysia-commissions-1-gw-ultrasupercritical-coal-plant/

and Mercury. Per this regulation, the revised SO_X and NO_x emission limits do call for the use of Best Available Technologies for emission reduction. However, the prescribed limits are not so stringent as those in developed APEC economies, as well as international norms such as those in the EU[283]. However, the proposed limits for Hg emissions are in line with those in some advanced APEC economies. New facilities are also required to install Continuous Emission Monitoring Systems. The revised regulations certainly indicate Malaysia's focus on regulating emissions.

Deployment of Clean Coal Technologies

Coal is expected to play a major role for meeting Malaysia's growing electricity demand. Notably, Malaysia has already started considering new capacity addition based on high efficiency clean coal technologies. Construction contracts for the economy's first supercritical coal-fired power plants have already been signed, adding 3 GW of capacity by 2017. One example is the 1-GW ultra-supercritical coal plant in Tanjung Bin built by Malakoff Corporation, which entered commercial operation on March 2016. Another 2 GW of coal-fired power plant are expected to come online by 2019.

For coal-fired power generation, the major issue needing to be addressed by Malaysia is the diversification of supplies. Historically, Malaysia has been reliant on Indonesia for meeting its coal demand owing to the geographical proximity and resulting lower price. However, there is a potential risk of price rises and shortages of supply as Indonesia is set to consume more coal for meeting its growing electrical demand. Diversification of coal imports will lead to more volatile and comparatively higher coal prices.

Water Regulations

Annual freshwater withdrawal for industry accounts for some 42.8% of the total withdrawal[284], making it a very significant portion of water demand. Malaysia has no dedicated authority responsible for overall coordination of planning and integrated management of its water resources. This responsibility is shared by the various government agencies. The Ministry of Energy, Green Technology and Water (KeTTHA) is responsible for management of water use in programs related to power generation. In Feb 2012, the National Water Resources Policy (NWRP)[285] was released as a framework for the integrated approach to water management, involving the various sectors in the economy, including energy. KeTTHA is one of the key government bodies of the NWRP which implemented the Green Technology Master Plan (GTMP). This policy aims to integrate green technology in four key sectors, namely, energy, building, water and transport.

Economy Summary

In April 2016, Malaysia reported the water crisis it may be potentially facing as it braced itself for the full impact of the El Nino. One of the most affected would be the industrial water consumers, including thermal power plants, when the water rationing measures start getting kicked in. Thermal power plants could adapt to such water shortages through efficient use of water in their cooling processes and possibly reuse wastewater to reduce dependence on natural water resources.

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[283] The revised 2014 regulations impose a SO_X limit of 500 mg/m3 for all new plants (more than 10 MW capacities). The comparable number prescribed in China for this is 100 mg/m3. In EU this is between 150 to 200 mg/m^3.

[284] World Bank (2014) http://databank.worldbank.org/data/reports.aspx?source=2&country=MYS&series=&period=

[285] Ministry of Natural Resources and Environment (NRE). Retrieved from www.nre.gov.my/msmy/PustakaMedia/Penerbitan/Dasar%20Sumber%20Air%20Negara.pdf

Since agriculture in Malaysia causes a greater strain on the water resources, much of the needed emphasis on the water energy nexus has been diverted to the water food nexus. Moreover, even in the efficiency perspective, there is no clear integration between water and energy policies although the over-arching policy agenda is to incorporate green technology across several industrial sectors including the coal fired sector. Even for energy efficiency, demand-side efficiency management is accorded much greater emphasis than supply-side efficiency. However, there are isolated supply-side initiatives such as that undertaken by the main power utility, Tenaga Nasional Berhad (TNB), called the "Research on Water Utilization & Treatment Technology towards Zero Water Discharge at TNB Thermal Water Power Plants". The research aims to shed light on the water footprint of power plants at TNB and identify processes that could potentially reduce water usage. TNB also strives towards zero water discharge through the adoption of appropriate water recycling technology.

5.10 Mexico

According to SENER (Secretaria de Energia), Mexico had 54.4 GW of installed electric generation capacity in 2014. The economy generated an estimated 258 billion kWh of electric power in 2014. Fossil fuels - coal, gas and oil - accounted for around 78% of electricity generation. The most dominant fuel in the power mix was gas, accounting for about 48% of the power generation, followed by oil at 18% and coal at 11%. The balance of generation was met through hydropower, geothermal and other renewable sources such as solar and wind. The National Energy Strategy outlined by SENER has set a target to generate 35% of electricity from non-fossil fuel sources by 2024. Non-fossil fuels accounted for about 22% of the generated electricity in 2014.

The state-owned Comision Federal de Electricidad (CFE) is the dominant player in the generation sector controlling a major chunk of the economy's installed generation capacity. The recent reforms in the electricity sector in 2014 will further strengthen the competitiveness in the generation of power and is expected to drive the leverage of natural gas for power generation through the expansion and reinforcement of the gas pipeline network. It will also contribute to attaining the objectives of enhancing non-fossil fuels in the electricity mix. The Law on Energy Transition was published in December 2015 in the Federal Official Gazette. The main purpose of this Law is to regulate the use of sustainable energy in Mexico, as well as the obligations regarding clean energies and reduction of pollutants by the power sector.

Mexico does not appear to have a legislative or regulatory framework to address the water-energy nexus. In the mid-2000s there were plans to develop Coal Mine Methane (CMM) and Coal Bed Methane (CBM) projects to tap the high gas content of coal deposits in Mexico. However, a methane explosion in February 2006 led to the closure of the proposed projects at the Pasta de Conchos mine 286. In June 2015 the Global Methane Initiative (GMI) International identified two active CMM recovery projects and three proposed CMM recovery projects in Mexico[287]. However, they contribute only marginally to the overall energy supply of the economy and no data are available on water use.

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286 http://www.economia.unam.mx/publicaciones/econinforma/pdfs/359/brucelish.pdf

287 https://www.globalmethane.org/documents/toolsres_coal_overview_ch21.pdf

5.11 New Zealand

New Zealand has been relatively rich in natural resources such as hydropower, geothermal and wind, which have dominated the electricity generation mix over the last many years. The economy has relatively high rainfall and is generally mountainous which is best suited for the development of hydro power stations.

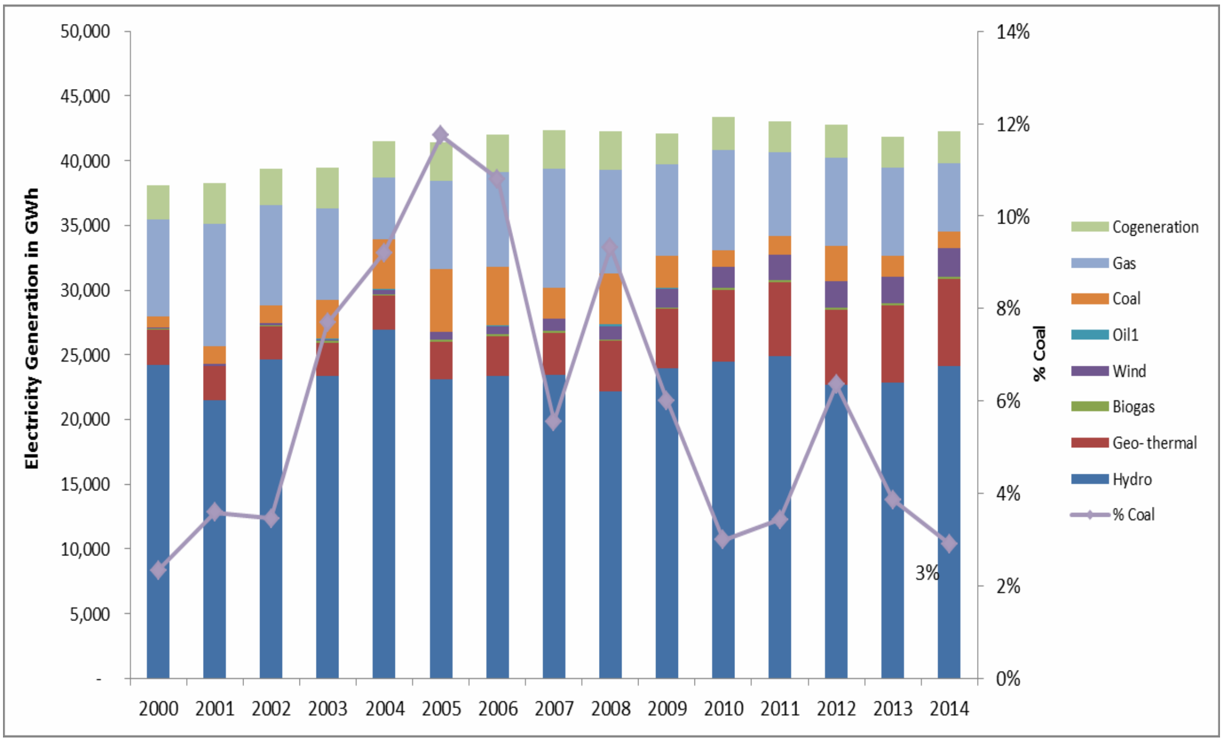

Exhibit 52: Electricity Generation Mix New Zealand[288]

As indicated in Exhibit 52, hydro power has dominated the electricity generation mix in 2014, contributing to about 61% of the power generation (excluding co-generation). This was followed by geothermal at 17% and gas at 13%. Coal accounted for a meagre 3% in the electricity generation mix. Electricity demand has been stable for many years. Even though the power sector is heavily dominated by renewables it is a part of New Zealand's Emission Trading Scheme (ETS). This scheme was launched by the NZ government in 2010 under its commitments for reducing greenhouse gas emissions.

As per New Zealand's Energy Strategy 2011-2021, the government aims to increase the share of electricity generation from renewable sources to 90% by 2025. Fossil fuels will only cater to a limited portion of electricity generation going forward. Emphasis has been given to energy efficiency improvement at all levels of supply, infrastructure and demand.

[288] Generated from data from The Shift Project Energy and Climate Data Portal, http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart

5.12 Philippines

The electricity generation sector in the Philippines has been dominated by fossil fuels such as coal and oil.

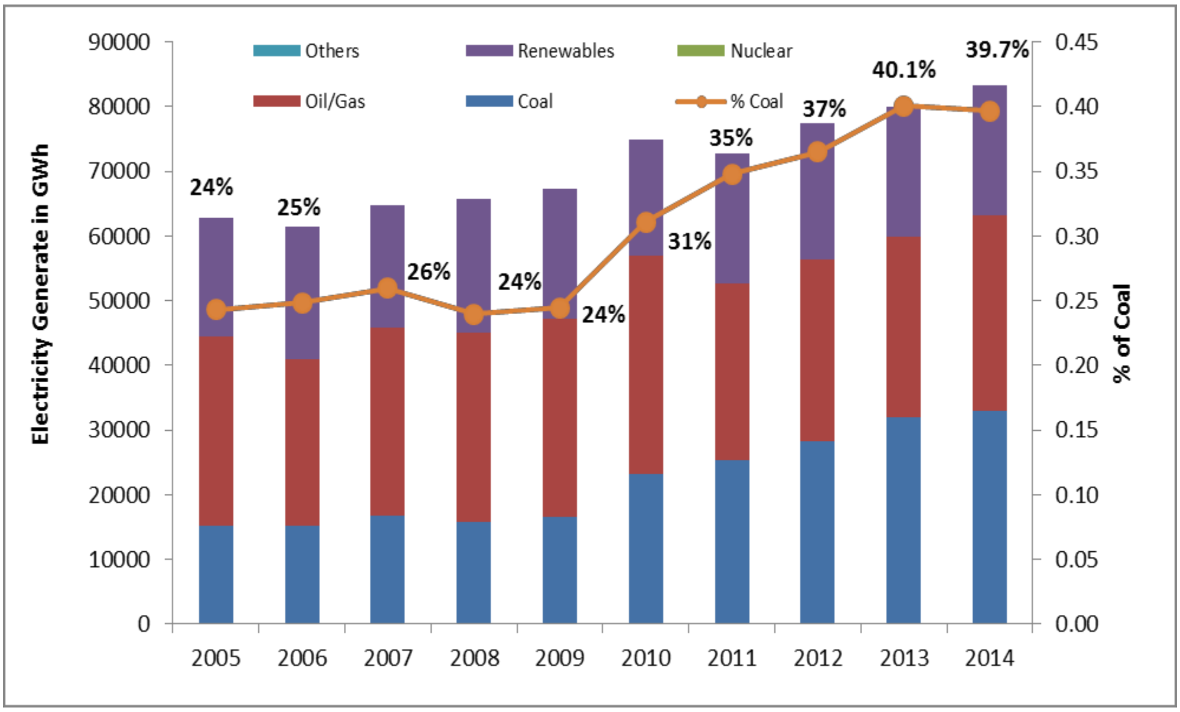

Exhibit 53: Electricity Generation in the Philippines[289]

As per published recent figures (see Exhibit 53), there has been an upward trend in the coal share of the power mix from 2009, tapering off at about 40% for 2013 and 2014. The Philippines Energy Plan (PEP) enacted in 2012, will be the overarching policy document guiding the economy's future development of the electricity sector. According to the government's power development plan (PDP) analysis[290], for the period of 2009-2030, around 17 GW of new capacity will be needed to meet the power demand and reserve requirements.

Philippines Energy Plan (PEP) (2012-2030)

The Philippines Energy Plan[291] (PEP) is a policy framework consistent with the Energy Reform Agenda (ERA) such as the three key pillars of the energy sectors namely energy security, optimal energy pricing and sustainable energy plan. It estimates that the economy will need about 13.2 GW of new generation capacity to meet domestic power demand. It also incorporates long-term international policy frameworks such as the UN Sustainable Energy for All Initiative and APEC's Green Growth Goals. Moreover, the PEP subcategories include the Indigenous Energy Development Plan, which even though it places much emphasis on increasing coal supply, also talks of promoting clean technologies, such as coal liquefaction

[289] Extracted from http://www.doe.gov.ph/electric-power-statistics/philippine-power-statistics

[290] Power Development Plan extracted from http://www.doe.gov.ph/power-and-electrification/development-plans/321-power-development-plan

[291] 2012-2030 PEP Executive Summary Revised extracted from http://www.doe.gov.ph/doe_files/pdf/01_Energy_Situationer/2012-2030-PEP-Executive-Summary_revised.pdf

and gasification. However, the resulting impact on water demand with adoption of clean coal technologies has not been thoroughly addressed in the PEP.

Regulatory Framework

Policies and regulations related to the generation of power come under the purview of the Republic of Philippines Department of Energy (DOE). Under the Department of Energy Act (1992) Rule 5, compliance to regulations is to be handled by the Energy Regulation Council (ERC), covering the aspects of technical, financial and environmental standards. Power generation companies are obliged to obtain the certificate of compliance (COC) from the ERC[292]. The COC prerequisites include the Environmental Compliance Certificate (ECC) approved by the Department of Environment and Natural Resources (DENR), and alignment with the Power Development Program.

Emission Standards

A comprehensive air quality policy was enacted via the Philippines Clean Air Act of 1999 (Republic Act No. 8749) and the Implementing Rules and Regulations of the Philippine Clean Air Act of 1999[293]. The prescribed emission limits for particulate matter, SO_X and NO_X are lax compared to those of developed APEC economies both for existing and new plants[294]. However, these revisions imply adoption of emission control technologies such as FGD and ESP. FGD is a typically water-intensive technology and would lead to generation of wastewater streams. These factors have not been thoroughly addressed in the revisions as well as in the PEP.

Water Code of the Philippines

The National Water Resources Board (NWRB) is the authority for water resource management and development. The Board also deals with the integration of relevant government agencies for the undertaking of water resource programmes and projects. Rules and regulation for water utilization are promulgated in the Water Code of the Philippines[295]. Section 1(d) of the code declared the need for permit application for water used for power generation.

This permit procedure is applicable only for new coal-fired power plants. It appears to be a one-time administrative procedure wherein a fixed amount of water quantity is allocated prior to commencement of operations. The allocation does not consider the type of cooling technology deployed, efficiency of generation and water consumption per unit of electricity generated when in operation. Only a brief description of the project stating how water will be used, amount of water needed, power to be generated etc. is needed to be submitted to the relevant authorities[296]. However, penalties are proposed if a coal-fired power plant does exceed its allocated water consumption. Fines are imposed based on severity of the offence. A failure of appropriator[297] to keep a record of water withdrawal for submission to the authorities

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292 http://www.erc.gov.ph/SectorPage/Generation

293 http://119.92.161.2/embgovph/air/Home/ThePhilippineCleanAirAct.aspx

294 These standards prescribe emission limit of SO_X at 1500 and 700 mg/m3 for existing and new plants, respectively. This is much less stringent as compared to comparable regulations, e.g., in China which imposes limits of 200 and 100 mg/m3 for similar categories of coal power plants.

295 http://www.nwrb.gov.ph/images/laws/pd1067_amended.pdf

296 http://www.nwrb.gov.ph/images/laws/pd1067_amended.pdf

297 In this context, an appropriator implies a new coal-fired power plant.

on a quarterly basis is a "light offence" which carries a fine of not more than five hundred pesos. Failure to install a regulating and measuring device for the control and measure of volume of water withdrawn is considered a “less grave offence” and has a fine of up to one thousand pesos.

The water allocation system in the Philippines for the general industrial sector including coal-fired power plants is also guided by water policies formulated by NWRB through Board Resolutions, which aim to integrate current issues and new challenges into the water allocation system. One of the major challenges with respect to the allocation system is its linking to the water basin development plans. This requires key policy changes in the water allocation system, to account for immediate to medium term competing water requirements within the basin as well as the various industrial and domestic sectors. It also requires periodic review of sector allocation policies and priorities in recognition of the changing environment.

Clean Water Act

The Philippines Clean Water Act in 2004 provides the rules and regulations to protect water bodies from pollution by point sources, including industrial establishments such as power plants. The Act describes the framework, including details on compliance with permits and charges, for the effective engagement of the relevant agencies to implement the regulation. However, the Act does not place stringent limits on use of water by power generation facilities.

5.13 Russia

Russia is one of the top producers and consumers of electric power across APEC. As per published statistics of 2014, the total power generation was about 986,089 GWh.

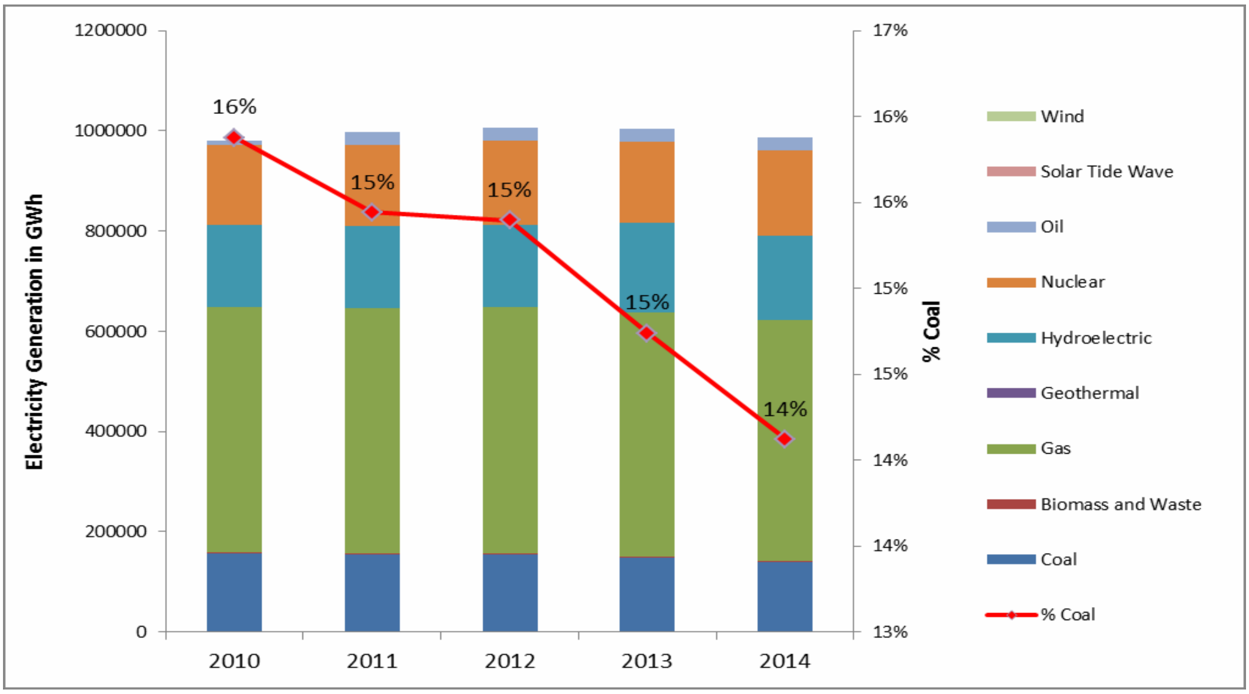

Exhibit 54: Electricity Generation Mix of Russia[298]

Exhibit 54 depicts the trend of electricity generation of Russia over the last 5 years along with the fuel mix. Fossil fuels namely gas, coal and oil have dominated the electricity generation at roughly 65% in 2014 with natural gas being the dominant fuel.

The Energy Strategy of Russia is the overarching document that will guide the development of the coal-fired power industry to 2030. It recognizes that reducing wastewater discharge from the energy sector is an important consideration for future development. This strategy emphasizes reducing dependence on gas-based generation, which will be complemented by coal and renewable energy sources. New coal-based capacity addition should adopt clean coal technologies. The strategy document specifies environmentally friendly coal-based units deploying ultra-supercritical technology, with unit size between 660 and 800 MW and target efficiencies in the range of 43-46%.

The government also aims to come up with policies supporting projects in deep treatment and enrichment of coal, as well as production of synthetic liquid fuels from energy sources such as coal and biomass etc. The current system doesn't have any provisions for an emission quota system and thus offers no economic incentives for utilities to reduce their environmental footprint during operation[299].

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[298] Generated from data from The Shift Project Energy and Climate Data Portal, http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart

[299] Sustainable Modernization of the Russian Power Industry (http://www.mdpi.com/2071-1050/7/9/11378)

Overall, it appears that Russian legislation and regulatory regime do not directly address the importance of water efficiency in coal fired power generation. Although, it is broadly recognized in the 2030 Energy Strategy, no further detailed policy framework is available.

5.14 Chinese Taipei

Chinese Taipei has very limited domestic energy resources and is generally dependent on fuel imports for meeting its growing energy needs. Chinese Taipei's electricity generation is mostly dependent on fossil fuels and has grown from 218 TWh in 2004 to more than 260 TWh in 2012.

The New Energy Policy of Chinese Taipei has set ambitious targets for energy saving and reducing carbon intensity in electricity generation. The policy aims to diversify electricity generation mix by promoting all forms of renewable energy and enhancing the share of electricity generation from renewable sources in 2025 by about 8%. The policy also calls for development of a low carbon high efficiency electric power system. Emphasis is given to accelerated replacement of existing power generation units. Introduction of Clean Coal and CCS technology will also be promoted for reducing CO_2 emissions of the power sector. The plan has an underlying target for reducing carbon intensity by more than 30% by 2025.

Emission Controls

In Chinese Taipei, the Air Pollution Control Act was first promulgated in 1975. Emission standards for power plants were prescribed by the Environmental Protection Administration and came into force in 1994. The standards were subsequently revised in 1999 and 2003. Limits have been prescribed for critical pollutants, such as PM, SO_X and NO_x as applicable to steam boilers. PM limit of high capacity steam boilers (based on the exhaust gas flow rate) are prescribed at 50 mg/m3 for existing units and 25 mg/m^3 for new units. These are generally in line with similar standards in China and the United States. The standards for SO_X and NO_x are slightly lower than those of the China and the United States.

CCS Strategic Alliance[300]

The alliance was established on March 2011 to accelerate the development of emission reduction technologies through the cooperation of the government, industry, research institutions and academia. Some of the recent R&D activities and project are:

Carbon Capture and Storage in ITRI

Since being commissioned by the Bureau of Energy, Ministry of Economic Affairs (MOEABOE) in 2007, the Industrial Technology Research Institute (ITRI) has been undertaking research in carbon capture technologies. The top two technologies in focus were Calcium Looping Capture Technology and the Mesoporous Silica Particles (MSP) carbon dioxide capture technologies.

Carbon Capture and Storage in TPC

Recent projects by Taiwan Power Company (TPC) are listed below.

a. Investigation, Pilot Planning and Research of Preferred Test Site for Carbon Dioxide Geo-Sequestration (2009)
b. Setup Two-phase Flow Test Facility with Functional Validation (2009)

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[300] Environmental Protection Agency, Taiwan, Carbon Capture and Storage http://ccs.gov2.tw/

c. Characterization on Pilot Site and Study of Validation Methods for Carbon Geo-Sequestration Application (2011-2013)
d. Planned construction of deep wells for precise geological modelling and examination of CO_2 injectivity in reservoir (2014-2017)

There are also similar research efforts by the China Steel Company and the China Petroleum Corporation.

Water Scarcity

Governments worldwide are struggling to deal with water scarcity and Chinese Taipei is no exception. In May 2015, Chinese Taipei faced the worst drought in 10 years, which coincided with the worst power shortage. One of the measures taken was water rationing for industrial users. The Drought Central Emergency Operations Centre decided to impose a water supply reduction of 10% on industrial users that consume at least 1000 cubic meters of water each month[301]. One of the worst hit sectors was petrochemicals. Whether this had any significant impact on coal-fired power plants as well is not very clear, but much of the power shortage that happened during the same period could be attributed to the shutting down of the nuclear power plants for maintenance and the stopping of hydraulic power.

It is conceivable how drought conditions impact coal-fired power plant operations, and government policies should address the water supply and demand issues with regard to the energy sector. Chinese Taipei passed the Reclaimed Water Resources Development Act[302] on December 2015 to ease industrial water shortages. The Act calls for 10 per cent of the total supply to be generated from recycled water by 2031. Another measure is capturing rainwater during seasons of high rainfall levels, which Chinese Taipei did not capitalize on in the past. Desalination facilities will also be developed for industrial customers. Chinese Taipei has also decided to build six wastewater reuse plants between 2016 and 2021[302].

In May 2016, Legislative Yuan passed amendments to Water Act with the objective of effectively managing "precious water resources and water use efficiency without compromising on quality and operation of everyday life"[303]. It is still too early to assess the effective legislature support following these amendments. Nevertheless, the policy direction will inevitably affect the way coal-fired power plants operate in the future. For example, as stated by the Water Resources Agency, "better water resources management and the pricing mechanism serve as significant enticement for more water conservation and more efficient water usage and multiple water sources"[303].

Water Quality

Another policy aspect which might affect coal-fired power plants is the water quality regulation on industrial effluent discharge, governed by the Water Pollution Control Act Enforcement Rules[304] and the Water Pollution Control Measures and Test Reporting Management Regulation[304]. These were both recently

[301] Central Emergency Operation Centre http://eoc.nfa.gov.tw/eoc/Uploads/2015/0225%E6%97%B1%E7%81%BD/1T/%E6%9C%83%E8%AD%B0%E8%A8%98%E9%8C%84%E7%99%BC%E6%96%87%E7%89%88%20ok%20revised.pdf

[302] Ministry of Economic Affairs https://www.moea.gov.tw/MNS/english/news/News.aspx?kind=6&menu_id=176&news_id=49769

[303] Ministry of Economic Affairs https://www.moea.gov.tw/MNS/english/news/News.aspx?kind=6&menu_id=176&news_id=52790

[304] Laws & Regulation Database. http://law.moj.gov.tw/ENG/lawClass/lawContent.aspx?pcode=O0040002

amended in November 2015. By the water pollution enforcement rules, the following are to be monitored quarterly.

1. Water temperature
2. Hydrogen ion concentration index
3. Dissolved oxygen
4. Heavy metals
5. Other items designated by the central competent authority based on water body characteristics

There are no general limits set on temperature by the Environmental Protection Administration, the authority for water quality control, while it is mentioned in the regulations that "central competent authority shall delineate water zones and determine water body classifications and water quality standards based on the special characteristics and on-site conditions of water bodies". Moreover, the regulation allows the authority to set extra stringent standards should they deem these fit for the protection of the water body. Hence, coal-fired power plants may be significantly affected depending on their location and the strictness of effluent standards.

Economy Summary

The average water consumption for industrial needs, under which coal-fired power generation is categorized, accounts for 9 per cent of total water consumption[305] on average.

Chinese Taipei's geological conditions are such that it is very susceptible to floods and droughts, it is crucial that Chinese Taipei implements effective policies to ensure its water security for the water-intensive industrial sectors including coal-fired power plants. However, the current policy framework for water still seems to be isolated from the energy sector.

[305] Water Resources Agency. http://eng.wra.gov.tw/ct.asp?xItem=48254&CtNode=7679. The statistics on how much water coal-fired power plants consume is not available in the public domain.

5.15 Thailand

The power generation sector in Thailand has diversified in terms of its ownership. The Thai government awards generation licenses for promoting competition and attracting more investment in advanced technology for fossil fuel plants.

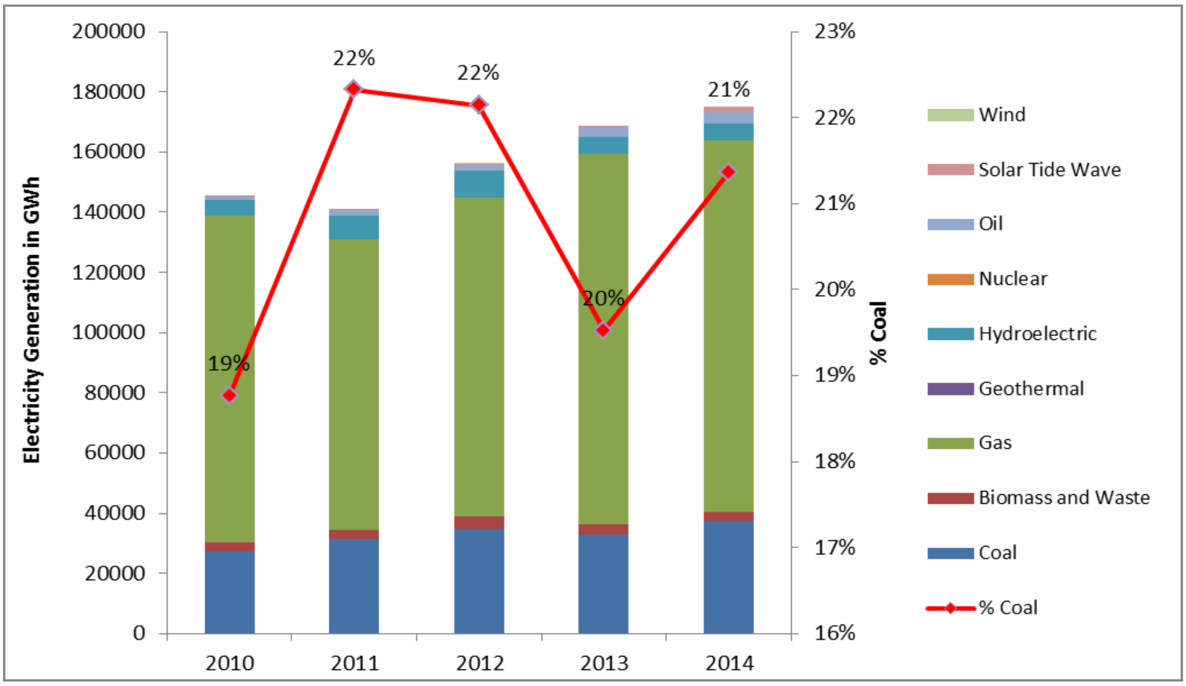

Exhibit 55: Electricity Generation Based on Source for Thailand (2010-2014)[306]

The electricity generation has generally shown an increasing trend over the last 5 years, except for 2011 due to a heavy flood (Exhibit 55). Natural gas has been the dominant fuel in the electricity mix of Thailand and along with coal has been used to replace the more expensive oil-based generation since the late 1990s. Coal accounts for only a fifth of the annual electricity generation. Thailand has only proven lignite resources and, thus, has been importing coal over the last decade. The demand for imported coal has increased recently since the 660-MW GHECO plant came online in 2012.

Emission Standards

Emission standards for new coal-fired power plants were revised in 2010, replacing the previous standards issued on 30 January 1996. The revised emission standards are applicable for all new coal-fired power plants which come into operation post 15 January 2010. These standards are prescribed for critical pollutants such as SO_X, NO_x and PM. The prescribed limits are much more stringent and are generally comparable to those set in developed APEC economies and internationally[307]. The prescribed standards in general call for the adoption of newer emission control technologies if not the best.

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[306] Generated from data from The Shift Project Energy and Climate Data Portal, http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart

[307] The proposed SO_X limit for new coal power plants varies between 180 mg/m^3 (for 50 MW and above) and 360 mg/m^3 (less than 50 MW). These are comparable to regulations in developed APEC economies, such as China, which are prescribed at 100 mg/m^3 for all new plants. Even for PM, the proposed emission limit of 80 mg/m^3 by Thailand is very close to similar regulations in China which prescribe 30 mg/m^3 for a similar category.

Policy Framework

The latest revision of the Power Development Plan PDP (2015-2036) indicates that the Thai government is aiming for fuel diversification. The Plan's main objectives are achieving energy security, economic stability of the energy sector, and reduction of the environmental footprint, while satisfying the growing power needs of the nation. The Plan considers coal-fired power development as a necessity in an appropriate proportion for meeting Thailand’s future energy needs. According to the plan, coal is expected to account for 20-25% of electricity generation from 2026 to 2036. Clean coal technologies, particularly for reduction of CO_2 emissions, have been recommended in the Plan, along with a focus on enhancing generation efficiency and reducing air pollutant emissions. Enhancing energy efficiency of the industrial sector is also one of the key measures which the government will focus on in the PDP.

Water Resource Management

The existing institutional framework for water resource management is highly fragmented with about 30 departments and bureaus overseeing water management issues in about 8 ministries. Policies, codes and laws have been formulated within these contexts which in general indicate a lack of a holistic approach. Initiatives for Integrated Water Resource Management (IWRM) started as early as the 1990’s but as yet the translation of initiatives into concrete policies has been slow. As of 2015, no specific policies addressing reduction of water use for the coal power sector are in place. Considerations of the water energy nexus have also not been explicitly stated in the PDP and other relevant policies.

Due to rapid economic development in the past decade, water demand continues to grow and two of the four regions, namely the Northeast and the Central Plain, experience frequent droughts and flooding. The agriculture sector has accounted for an average of more than 70% of the water use, followed by the industrial and other sectors. However, recent years have witnessed a growing trend of reduced water usage by the agriculture sector with a corresponding increase for industrial and domestic water usage.

Several studies (e.g., United Nations Economic and Social Commission for Asia and the Pacific, Stockholm Environment Institute, Asian Institute of Technology) have been conducted and conferences held to address the water-food-energy nexus in Thailand. However, they have not had coal power generation as the focus. Instead, the main focus was on the change in Mekong river flows and its interactions with food production and hydropower.

Economy Summary

Thailand’s PDP is the governing document of power capacity expansion in the economy, as it contains detailed information about new power plants and load forecasts until 2030. Even though the PDP talks about adoption of clean coal technologies, no specific technologies are promoted for adoption. New capacity addition is not restricted to high efficiency supercritical or ultra-supercritical technologies. However, Thailand has been progressive in adopting supercritical technology. A new lignite-based supercritical 600 MW power plant is under development in the Mae Moh province. Moreover, coal-based capacity expansion projects have faced stiff opposition from local public and environmental groups because of their environmental impacts. In this context, CCS and clean coal technologies such as IGCC could offset some of these negative externalities. However, the resulting impact on water withdrawal and consumption with deployment of clean coal technologies also needs to be given due consideration. No specific policies are in place targeting reduction in water withdrawal and consumptive use in coal-fired power plants.

5.16 United States

An overview of the U.S. electricity generation mix over the last 10 years is shown below.

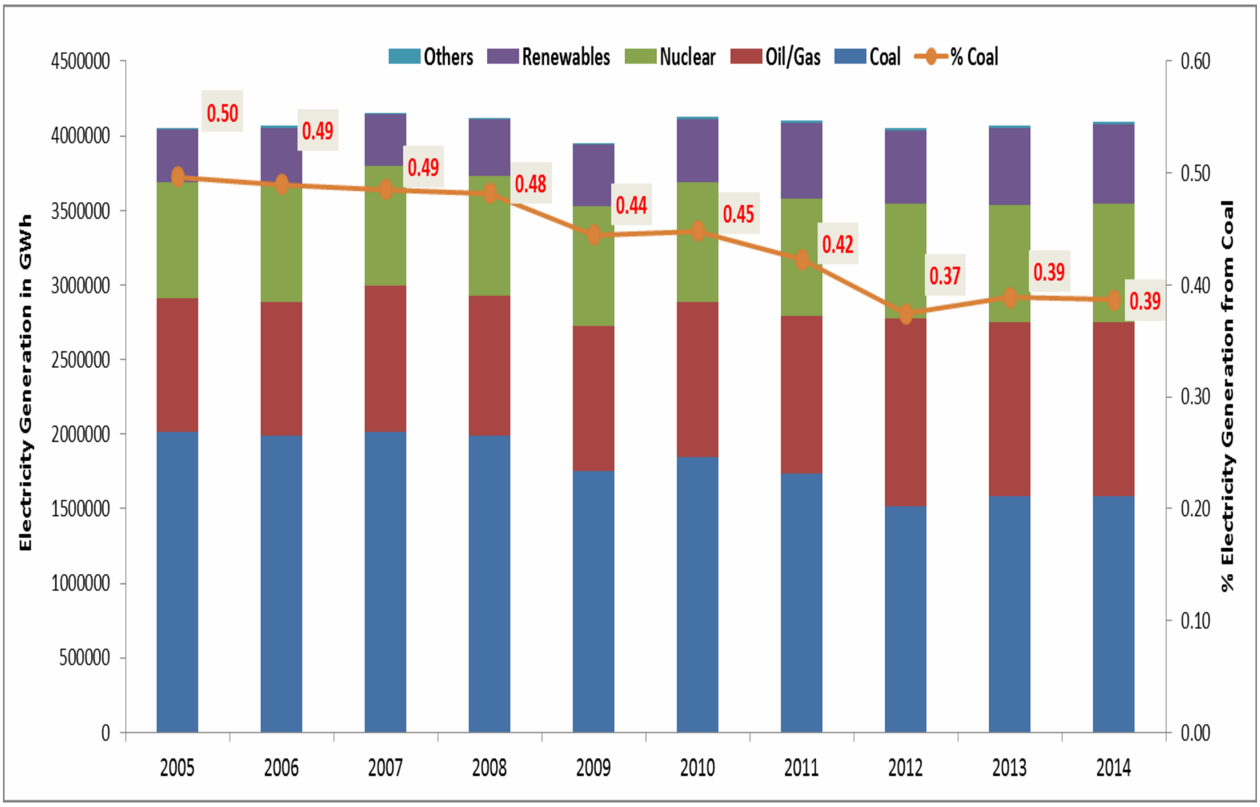

Exhibit 56: Electricity Generation Mix for US Based on Fuel Type[308]

The share of electricity generation from coal has been steadily decreasing since 2005. Coal fired power plants have been under significant economic pressure in the recent years due to low natural gas prices and a slow electrical demand growth. The installed capacity of coal as a percentage of the total installed capacity from all other sources is on a decreasing trend, as indicated above. Stringent upcoming regulations in 2016 such as Mercury and Air Toxic Standards (MATS) which require significant reduction in mercury and other toxic emissions, are expected to accelerate the planned retirement of some coal-fired power plants. These projections, however, do not consider the impact of the proposed Clean Power Plan.

In the United States, the EPA governs the major regulations and standards on environmental protection. Through the Clean Air Act (CAA) and the Clear Skies Act (CSA), EPA regulates pollutant emission to the air, while the Clear Water Act (CWA) regulates the pollutant emission to water. The New Source Performance Standards (NSPS), also issued by the EPA and referred to in the CAA and CWA, are intended to promote the use of best combustion control technologies. Under the CAA there is an NSPS with emission limits for new stationary sources of combustion, such as boilers for steam generation. Under the CWA, there is an NSPS which sets allowable limits for wastewater from new coal mines. A brief overview of the various regulations pertaining to coal-fired power plants in the United States is discussed in the following paragraphs.

[308] U.S. Energy Information Administration website extracted from http://www.eia.gov/electricity/annual/

Clean Air Act and New Source Performance Standards

The CAA of 1963 and its 1970 amendments form the basis for air pollution control legislation in the United States, authorising the development of federal and state regulations to limit emissions from industrial sources and transportation. Subsequently, the CAA went through a series of amendments to incorporate additional regulations as summarized in Exhibit 57.

Amendment	Description
The Acid Rain Program	Aimed at specifically reducing SO_2 and NO_X emissions from existing coal based power plants. A Cap and Trade System was proposed through this amendment enacted in 1990.
Inter State Emissions	In 2005, a variant on the cap-and-trade system was introduced to respond to the fact that emissions can also contribute to NAAQS violations in states downwind of the emitting source. After facing a number of legal challenges, the latest US Court of Appeals for the D.C. Circuit decision (July 2015) has kept the CSAPR in place.
Mercury and air toxics emissions	In 2011, the Mercury and Air Toxics Standard (MATS) was introduced to reduce emissions of mercury, other heavy metals, and the acid gases HCl and HF, from new and existing power plants over 25 MW. The regulation however became effective in 2015[309].
Clear Skies Act 2003	The Clear Skies Act of 2003 which introduced a cap and trade program for the pollutants SO_2, NO_X and mercury. The goal was to reduce emissions from these pollutants by approximately 70 % by 2018 as compared to the reference year of 2000.

Exhibit 57: Amendments in the Clean Air Act[310]

Clean Water Act

The CWA of 1972 introduced a permit system for regulating point sources, including among others coal mining. Unless otherwise stated in the Act, the permit system prevents industrial sources and publicly owned treatment works discharging pollutants into navigable waters without a permit. A permit can be issued upon condition that the discharge meets applicable requirement outlined in the Act. The objective of the Act was to ensure necessary improvements to conserve waters for public water supplies, propagation of fish and aquatic life, recreational purposes, agricultural and industrial uses. The CWA includes stringent requirements for thermal discharge when necessary, although owners and operators may propose less stringent limits if they can assure the protection of a balanced, indigenous population of shellfish, fish and wildlife. Water quality standards must require that the location, design, construction and capacity of cooling water intake structures reflect the best technology available for minimising adverse environmental impact.

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309 Final mercury and air toxic standards for power plants, Environmental Protection Agency, extracted from http://www3.epa.gov/mats/actions.html.

310 Summary of the Clean Air Act, Environmental Protection Agency, extracted from: https://www.epa.gov/laws-regulations/summary-clean-air-act

Clean Power Plan

The Clean Power Plan (CPP) was first proposed in June 2014 and later finalized on August 2015 by the Environmental Protection Agency (EPA). The plan has established national standards to limit carbon pollution from power plants. Aimed at the power sector, the goals of the plan include reduction of carbon dioxide emission by 32 per cent and increase of renewable energy generation by 30 per cent by 2030, using 2005 as the baseline. The plan is expected to have significant climate and social health benefits and is designed to accelerate the transition towards cleaner and low-polluting American energy. In the development phase of CPP, EPA has taken into consideration perspectives of diverse range of stakeholders and federal agencies[311]. This has resulted in development of a comprehensive and robust plan with some degree of flexibility as well. The final CPP is dependent upon federal-state partnership to achieve the carbon pollution targets. States have the flexibility to develop, submit and implement their own plans in consultation with the EPA. The main features of the CPP are shown below in Exhibit 58.

Exhibit 58: Main Features of Clean Power Plan[312]

The source-specific CO_2 emission performance rates depend on proven technologies. The Best System of Emission Reduction (BSER) is expressed differently for various fuels such as coal/oil and natural gas. The standards apply regardless of location. Fairness and cost-efficiency are also ensured by making higher-emitting plants reduce their emissions more and at a lower cost than the lower-emitting plants. The plants also can use the interconnectivity of the electric grid to do emission trading to reduce their carbon intensity of power generation. Two types of emission performance rates, rate-based and mass-based, are used for each state, to better represent a mix of power plants specifically for the state. Three building blocks have been used as summarized in Exhibit 59.

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[311] Federal Energy Regulatory Commission (FERC) and the U.S Department of Energy (DOE)

[312] Clean Power Plan, U.S. Environmental Protection Agency https://www.epa.gov/cleanpowerplan/clean-power-plan-key-topics

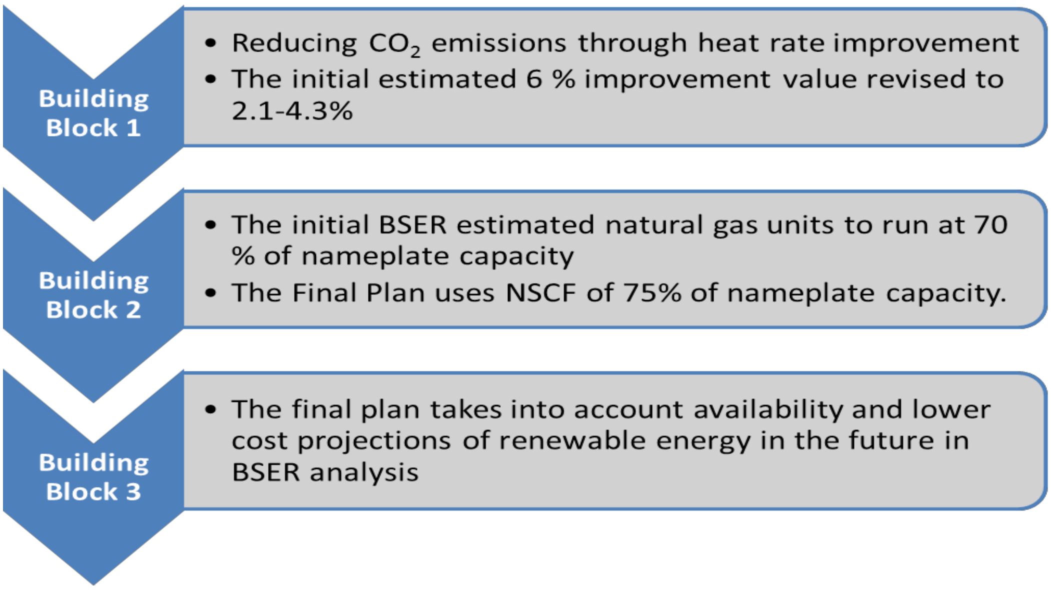

Exhibit 59: Building Blocks of the Clean Power Plan[313]

Essentially, steps have been taken to start moving towards clean power early, before the mandatory reductions begin in 2022. This allows for a gradual transition termed 'glide paths' when reducing the carbon pollution per MW-hr. The transition is also structured in phases and interim goals which are achievable. It has been made necessary for the state to address reliability considerations through consultations with competent agencies. There is also an additional reliability safety feature in place to deal with any emergency. The final plan removed the requirement to have up-front agreements between states on trading programs to facilitate easier transactions of emission credits. The EPA will work with states to provide a tracking system for transactions. The Clean Energy Incentive Program is in place to encourage early investment in renewable energy and demand-side energy efficiency projects. The overall goal is to produce carbon-free electricity in addition to reduction in energy demand during 2020 and 2021. EPA also intends to create Emission Rate Credits (ERC) or allowances through this program.

A. Final Standards for Cooling Water Intake Structures (CWIS)

On May 2014, the EPA released a final ruling for cooling water intake structures under Section 316(b) of the Clean Water Act (CWA) which seeks to minimize the environmental impact. The main features of these regulations in the context of this study are summarized below:

- Existing facilities withdrawing more than two million gallons of water per day (MGD) from U.S. water, of which at least 25% is exclusively for cooling, are required to reduce fish impingement. To ensure flexibility in compliance, the existing facility can chose any one option out of the prescribed seven options for meeting best technology available (BTA) requirements. Closed-cycle cooling circulation system has also been mentioned as one of the compliance options, if technically and economically feasible.

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[313] Clean power plan final rule – regulatory impact analysis, Environmental Protection Agency, extracted from: https://www.epa.gov/cleanpowerplan/clean-power-plan-final-rule-regulatory-impact-analysis

- New units that add electrical generation capacity at an existing facility are required to add technology that achieves one of the two alternatives prescribed under national BTA standards for entrainment. One of the alternatives is reducing annual intake flow (AIF) commensurate with a closed-cycle cooling system while second pertains to reduction in entrainment mortality for marine life.

The forecasted impact of the Clean Power Plan[313] (CPP) is summarized as follows:

- **Heat Rate Improvements (HRI)**

The EPA Analysis has stated that the operating efficiency of existing coal power generators can be improved through the HRI. The HRI allows the energy generating units to use less fuel, hence emit less CO_2 (lbs/MWh). Most existing power plants are to improve their power generation efficiency following the CPP.

- **Generation Shifting**

Generation shifting implies moving from a more to a less CO_2 intensive generation. Comparing coal steam energy generation units to natural gas combined cycle units, the latter is less carbon-intensive although the capacity factor is lower than the best system of emission reduction (BSER) level of 75%.

- **Deployment of Cleaner Generating Technologies**

The projected power generation mix under the CPP compared to the baseline scenario shows a greater decline in coal-fired generation, shown in Exhibit 60. Electricity generation from natural gas and renewable sources are expected to increase at a more rapid rate compared to a Business as Usual (BAU) scenario.

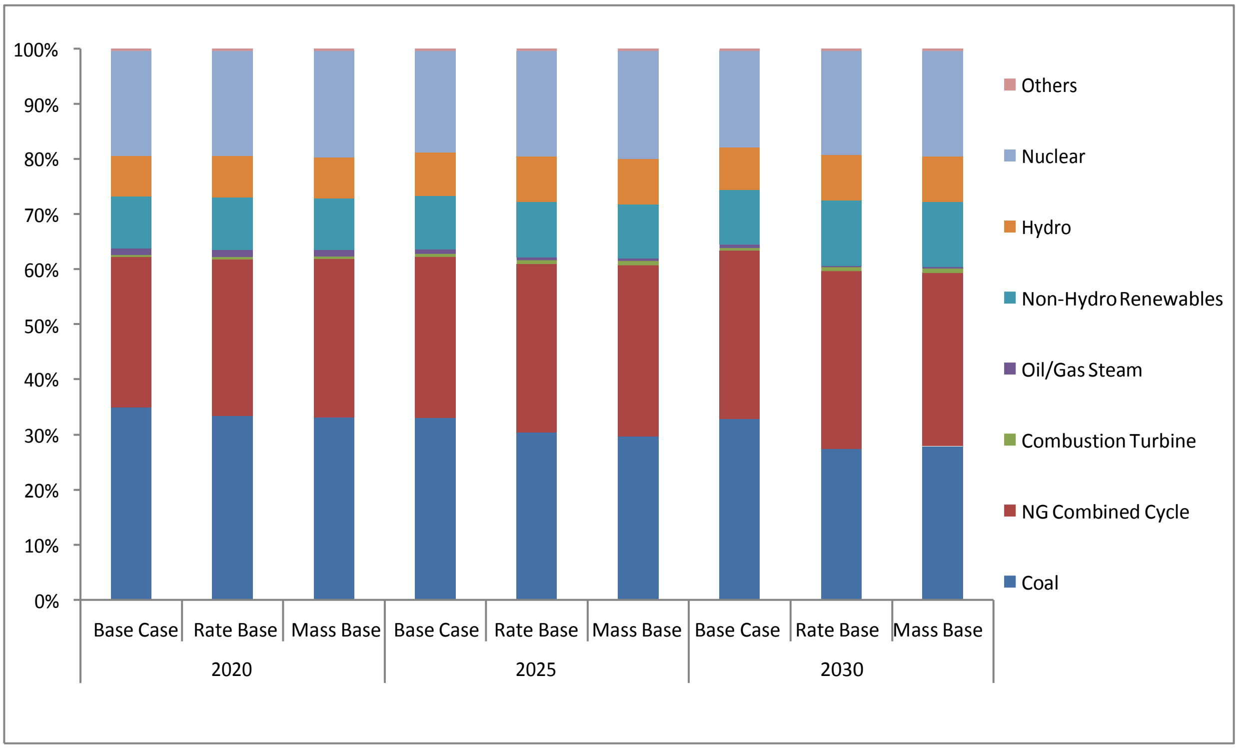

Exhibit 60 : Projected Impact of Clean Power Plan on Electricity Generation Mix[313]

Carbon Capture and Storage (CCS)

CCS technologies allow CO_2 to be captured from stationary sources such as coal-fired power plants and sequestered underground for long-term storage. The final rule clarified that the CO_2 injected underground via the UIC Class VI wells will be excluded under the EPA's hazardous waste regulations. EPA has confirmed that the CO_2 streams do not present substantial risk to human health or environment and comply with the Safe Drinking Water Act regulations. An overview of the various CCS-related regulations is provided in Exhibit 61.

Exhibit 61: Summary of CCS Regulations in US

Regulation	Description
American Clean Energy and Security Act[314]	On May 21, 2009, the American Clean Energy and Security Act of 2009 was passed by the House Energy and Commerce Committee to establish an economy wide cap & trade program and creates other incentives and standards for increasing energy efficiency and low carbon energy consumption.
Carbon Capture and Storage Early Deployment Act (Boucher Bill)[315]	Introduced in March 2009, to accelerate the development and early deployment of carbon capture and storage technologies by raising distribution funds to CCS technologies.
American Clean Energy Leadership Act[316]	Introduced on July 2009 to establish a framework for funding for CCS programmes.
Carbon Storage Stewardship Trust Fund	Introduce on July 2009 to establish long-term stewardship of a carbon dioxide storage facility under the regulation of the EPA.
EPA Proposal	On July 2008, the EPA proposed regulations for geologic sequestration of carbon dioxide.
Interstate Oil and Gas Compact Commission Guidelines	Published on September 2007 to detail regulation on acid gas injection and natural gas storage based on enhanced oil recovery (EOR).

The Office of Fossil Energy undertakes several high-priority initiatives including the 10-year Clean Coal Power Initiative. Some of the key initiatives are listed below in Exhibit 62.

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[314] 111 Congress House Bill, 2454 extracted from extracted from https://www.congress.gov/bill/111th-congress/house-bill/2454

[315] H.R. 6258 (ih) - Carbon Capture and Storage Early Deployment Act extracted from https://www.gpo.gov/fdsys/pkg/BILLS-110hr6258ih/content-detail.html

[316] S. 1462 American Clean Energy Leadership Act of 2009 extracted from https://www.congress.gov/bill/111th-congress/senate-bill/1462

Initiative	Description
Regional Carbon Sequestration Partnerships	Network of federal, state and private sector partnerships to determine most suitable technologies, regulation and infrastructure for CCS.
Industrial Carbon Capture & Storage	The DOE has allocated American Recovery and Reinvestment Act (Recovery Act) funds to CCS for large-scale industrial sources.
Recovery Act Projects	Implemented by the President in 2009, where $3.4 billion will go into CCS development for coal-fired power plants.
Interagency Task Force on Carbon Capture and Storage	put into effect by the President in 2010, the task force aims to circumvent barriers to the widespread and cost-effective deployment of the CCS technologies within 10 years.
The Carbon Sequestration Leadership Forum	International ministerial level forum which convenes regularly to discuss progress of RD&D of CCS on a global scale.
Carbon Capture, Utilization and Storage Core Program	DOE's program which aims to develop technologies to capture and permanently store greenhouse gases.

Exhibit 62: Overview of CCS Initiatives in USA

Carbon Capture Utilization and Storage (CCUS)[317]

As a pioneer of CCUS technology, the United States has developed cutting edge technology through various R&D and demonstration projects. DOE administers a Clean Coal and Carbon Management Program to encourage and support public/private partnerships to research, develop and demonstrate clean coal technologies, particularly CCUS, with the objective of accelerating large-scale commercial deployment.

Advanced Coal Gasification Technology with CCUS

Integrated Gasification Combined Cycle (IGCC) power generation is a new technology which is to some extent commercialized only in the US. The DOE's Clean Coal Demonstration Project helped construct 3 IGCC plants during the period 1990 to 1998. However, these plants faced technical difficulties during the initial years of operation. One of the plants (Wabash River Generating Station) polluted river water by discharging higher than permitted levels of arsenic, selenium and cyanide from 1998 – 2001[318]. The Pinon Pine project sought to demonstrate gasified coal system technology but was eventually shut down because the facility never operated successfully[319].

The Texas Clean Energy Project (TCEP) when fully operational will be first of its kind commercial clean power plant having IGCC coupled with CCUS. TCEP will be a 400 MW power/poly-gen project that will also produce urea for the US fertilizer market and capture 90% of its CO_2 emissions to be used for enhanced oil recovery (EOR) in the West Texas Permian Basin.

[317] More details on various bi-lateral CCS and CCUS activities across APEC have been provided in Section 9.1

[318] http://www.osti.gov/scitech/servlets/purl/787567

[319] http://www.osti.gov/scitech/servlets/purl/805670

Economy Summary

In regions affected by water scarcity, electricity generation competes for water with other uses like drinking water and agricultural irrigation. For instance, in 2011 Texas experienced the worst single-year drought in its history, which also affected regional energy sources, raising concern among grid operators. Water and energy needs in the US will be dependent on population growth and migration patterns, as well as changes in fuels used and energy technologies deployed. This in turn will also be greatly impacted by government policies and programmes such as the Clean Power Plan and Cooling Water Intake Regulations. According to EIA data, planned retirements and addition of cooling systems will likely decrease water withdrawals, increase water consumption, and increase the diversity of water sources used. While more than 90% of the capacity set to retire requires cooling, only 45% of the planned capacity addition requires cooling[320]. Most existing coal-fired power plants in the US use fresh water for cooling operations (more than 70%). However, a much smaller proportion of proposed systems (less than 20%) are planning to draw fresh water, and instead intend to utilize reclaimed water or dry cooling technologies.

In addition to decisions on generation and cooling technologies, deployment of CCS will also have a significant impact on water consumption. Widespread use of CCS can possibly intensify water stress in some areas. As per EIA's 2040 baseline projections, only 930 MW of CCS based generation capacity is expected to come online by 2040 (EIA 2013a). Even with technological advances for CCS in reducing capital costs, the water and energy intensities of operating these systems pose a potential barrier for widespread deployment.

While many of the factors affecting the water energy nexus for the coal-fired power sector are beyond the federal government's direct control, the future of the nexus is however dependent to a certain extent on several factors that are within the DOE's scope of influence and control. Such factors include the choice of technology options, location of energy activities, and the overall energy mix and its corresponding impact to the coal-fired power sector.

[320] EIA Form 860 (EIA 2013a). The planned capacity addition refers to the time period 2013-2022. Most of the capacity retired pertains to cooling required coal power plants. The cooling free capacity addition for the above-mentioned time period will be mainly catered by gas combustion turbines in new combined cycle units.

5.17 Viet Nam

Fossils fuels have been increasingly dominant in the electricity generation mix of Viet Nam. Historically power generation in Viet Nam was dominated by gas and hydropower plants. Hydropower at 43% accounted for the largest share in power generation in 2013, followed by gas at 32% and coal by 20%, as displayed in Exhibit 63. Over the past five years there have been investments made in bio-fuel and the wind sector, but to date the generation through these technologies in absolute terms is very minimal. The electricity demand in Viet Nam is expected to grow rapidly owing to the expansion of the industrial and manufacturing sector.

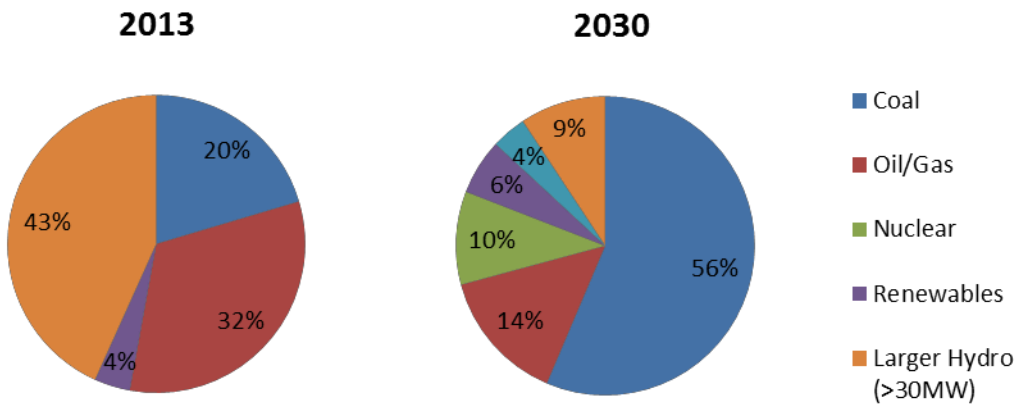

Exhibit 63: Comparison of Electricity Generation Mix in GWh[321]

Projections indicate that generation from coal will increase significantly from 20% in 2013 to 56% in 2030. To meet the growing electricity demand, the 7th National Power Development Master Plan was promulgated by the Ministry of Industry and Trade of Viet Nam in 2011. Despite the plan to increase the share of coal in the generation mix, Viet Nam's Prime Minister released a statement[322] indicating that the government intends to stop building new coal-fired power plants and to gradually replace the current ones with gas-fired plants. He justified this based on the need for sustainable development and environmental protection. This contradiction with the Master Plan will be resolved by a revision of the plan to be made by the Ministry of Industry and Trade[322].

Regulatory Framework

Viet Nam's Emission Standards are covered under the National Technical Regulation on Emission of Thermal Power industry, QCVN 22: 2009/BTNMT. The regulation stipulates the maximum allowable concentration of pollution components of NOX, SO_2 and dust in waste gas of the thermal power plants.

Water Regulation

Water regulation related to industrial plants is covered under the National Technical Regulation on industrial wastewater. Cooling water is classified under wastewater for thermal power plants[323] and the

[321] National Master Plan for Power Development for the 2011-2020 period with the vision to 2030 extracted from http://nangluongvietnam.vn/news/en/policy-planning/national-master-plan-for-power-development-for-the-2011-2020-period-with-the-vision-to-2030.html

[322] http://news.chinhphu.vn/Home/Plans-on-developing-power-coal-sectors-adjusted/20161/26495.vgp

[323] Viet Nam's regulation on industrial effluent, QCVN 40:2011/BTNMT

temperature limit for effluent discharge has been set at 40°C No specific mention of any technology (open loop or closed loop) has been indicated with respect to compliance.

The law of environmental protection (No. 55/2014/QH13) released in Jun 2014, has outlined the scope of environmental regulation including the policy on water resources. One of the basic requirements stated is the protection for river water in extraction and utilization as well as waste discharge into the rivers. Any power plant utilizing water resources requires permits by law and the owner will bear responsibility in ensuring effluent discharge standards are met. The Ministry of Natural Resources and Environment (MONRE) will be the authority monitoring the environment and enforcing the laws and regulations on any facility at risk of imposing effects on the environment, which includes coal-fired power plants.

The Law on Water Resources

The Law on Water Resources (LWR, No. 17/2012/QH13) was the update of the very first law on water resources of the same name issued in 1999 with the objective of the sustainable exploitation and utilization of water resources. Since then over 300 regulations have been issued (and amended when necessary) for the implementation of the LWR. The LWR stipulates under chapter IV section 1: Water Conservation, that any business or work which has the potential of causing pollution, degradation or depletion of water sources must have a plan for preventing this. Some of the key measures listed in the LWR (article 39) are:

a) Adopting plans to replace and gradually remove obsolete water-intensive means and equipment
b) Applying advanced techniques, technologies and equipment in water exploitation and use and increasing the use of recycled water and water reuse
c) The MONRE to develop, popularize and disseminate water conservation models, technology and equipment
d) Relevant ministries and agencies to formulate technical regulations on water use to encourage and drive water conservation

The Detailing Decree

Some articles of the LWR were further detailed in the Decree No: 201/2013 / ND-CP[324]. In this decree the responsibility of the various ministries for the investigation of the current state of exploitation and use of water resources and the waste-water discharge in water sources was emphasized. It also covers the general conditions for the licencing and permitting of water utilization and effluent discharge.

Water Resources Planning & Investigation

According to the National Centre for Water Resources Planning and Investigation (NAWAPI), Viet Nam is presently in the process of completing and synchronizing its LWR and assigning responsibilities to the relevant government agencies. Moreover, policy making is still hindered by the lack and quality of information on the water resources including the utilization by coal-fired power generation. The government is currently working on establishing an intelligent and integrated water management system. Only then could policies concerning water intake for coal-based power generation and other related industrial sectors emerge.

The primary tasks and solutions for these challenges are (as listed by the NAWAPI):

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[324] General Headquarters of fisheries. Retrieved from http://www.fistenet.gov.vn/b-van-ban-phap-luat/nghi-111inh-so-201-2013-n111-cp-ngay-27-thang-11-nam-2013-cua-chinh-phu-ve-huong-dan-luat-tai-nguyen-nuoc/

a) Improving the understanding of the Water Resources Act 2012 and the circulars, decrees and guidelines under Water Resources Act;
b) Early finalization of the assigned implementation plan for water resources investigation and planning
c) Constructing highly qualified and capable staff, which employ professional knowledge and new technologies to the implementation and completion of the required tasks
d) Expanding, promoting international cooperation for integration of new technologies and techniques to meet the requirements for accuracy, prompt and advanced collection, aggregation and processing of information
e) Promoting the dissemination and transfer of the results of water resources investigation and planning to water-users, increasing the state management level on water resources

Raising the Efficiency

Decision No. 182/QD-TTg[325] was the legislation approving the National Action Plan (NAP) to increase the efficiency of management, protection and general use of water resources for the period 2014-2020. NAP was to refine the system of sub-law documents, putting into effect a consistent policy framework for water resource management. The action plan consists of completing a general inventory of national water resources, completing the mapping of water resources nationwide with a scale of 1:100000. The database system would include online automatic monitoring and surveying system of large and important reservoirs and rivers. Through this the government aims to control pollution and mitigate water depletion. The list of programs and projects undertaken under this plan is summarized below in Exhibit 64.

No.	List of program and project	Responsible organs	Time for approval
1	Project to overall inventory national water resources by 2015 and 2020.	Ministry of Natural Resources and Environment	2015
2	Surveying, evaluating and making a map of water resources in the watersheds, water-scare areas, water shortage areas and key areas.	Ministry of Natural Resources and Environment	2015
3	Project of water resource planning	Ministry of Natural Resources and Environment and localities	2014
4	Project to develop the system of information, database of water resources and monitoring system of water resources on watersheds.	Ministry of Natural Resources and Environment	2016

325 ASEMCONNECT. Retrieved from http://asemconnectvietnam.gov.vn/law.aspx?ZID1=10&ID1=2&MaVB_id=2218

5	Project to establish water conservation corridor; improve and restore several rivers, river sections and reservoirs in seriously polluted and depleted cities.	People's Committees of provinces and centrally-affiliated cities	2016
6	Project of statistics and inventory of present condition of exploitation and use of water resources and discharge of wastewater into water sources.	People's Committees of provinces and centrally-affiliated cities	2015
7	Research program and establishment of scientific basis, application and development of technology for building, proposing the mechanisms, policies, measures and technical tools to raise the effect and effectiveness of management, protection and general use of water resources.	Ministry of Science and Technology, Ministry of Natural Resources and Environment	2015

Exhibit 64: List of Projects under the National Action Plan

Economy Summary

Most of the existing coal-fired power plant capacity in Viet Nam is based on sub-critical. However, the government is deliberating the adoption of ultra-super critical coal-fired power plants going forward. Long Phu 1 is one of the first supercritical power plants developed in Viet Nam. The plant is expected to be operational in 2018. The Power Development Master Plan does not explicitly mandate adoption of super or ultra-supercritical technologies for new capacity additions. Impact on water demand with adoption of emission control technologies (like FGD's etc.) has also not been considered. No specific policies exist to date pertaining to adoption of the type of cooling technology, water withdrawal and use specifically for coal power plants.

5.18 Other APEC Economies

The remaining APEC economies to be discussed briefly below are those with a negligible share of coal in their present power generation mix. Those economies are Singapore, Brunei Darussalam, Peru and Papua New Guinea. These economies are focussing on diversifying their fuel mix with enhanced generation from renewable energy sources.

Singapore's first Biomass and Clean Coal (BMCC) cogeneration plant commenced operation in Feb 2013. It employs state-of-art fluidized bed technology for high efficiency and low carbon emission. About 66% per cent of its capacity is fired by low-ash, low-sulphur coal, 16% per cent by palm kernel shells and wood chips, and the rest by natural gas. The plant's pollutant emission levels, according to the National Environment Agency standards[326] have been met. Singapore's generation mix is largely dependent on natural gas and the share of coal is close to zero percent.

Brunei Darussalam's power generation is entirely dependent on natural gas. Nevertheless, there have been some efforts on diversification of the generation mix with renewables such as solar[327].

Peru's electricity generation is dominated by hydro and natural gas. In the National Energy Plan[328] 2014-2025 announced in 2013, the government plans to use renewables to fuel 60 percent of its electricity mix by 2025 and reduce dependence on oil and gas.

Papua New Guinea's generation mix is largely dependent on geothermal. The rest of the mix includes oil, gas and hydroelectric.

326 http://www.nea.gov.sg/anti-pollution-radiation-protection/air-pollution-control/air-quality-and-targets

327 According to the economy's energy white paper in 2013, about 99.95% of power was generated by gas power plants and 0.05% by the Tenaga Suria Brunei solar power plant.

328 PERÚ Ministerio de Energía, Plan Energético Nacional 2014-2025

6 APEC INITIATIVES

This section briefly describes the various clean coal, water energy nexus and CCS initiatives presently undertaken by APEC economies.

U.S. – China Clean Energy Research Center (CERC)

The Protocol establishing the U.S.-China Clean Energy Research Center (CERC) was signed in 2009. The CERC has five research consortia and the Advanced Coal Technology Consortium (ACTC) has the aim of advancing coal technology in CCUS in both the economies. The bilateral diplomatic initiative also aims to advance clean energy technologies for electricity, liquids and syngas.

In 2011, a 5-year Joint Working Plan (JWP) for the ACTC was signed by both countries to outline the collaborative areas of research. Each consortium is supported by more than US$ 50 million of public and private funding, for a total project support of more than US$ 250 million.

Joint Work Plan Research Areas:

- Advanced Power Generation
- Coal Conversion Technology
- Pre-Combustion Technology
- Post-Combustion CCUS
- Oxy-Combustion R&D
- CO_2 Algae biofixation and use
- Integrated Industrial Process Modelling
- Communication and Integration

In 2015 the protocol was amended to add CERC's Energy Water Track, and in 2016 a JWP was signed. The CERC-WET (Water Energy Technologies) consortium aims to develop new approaches to reduce water consumption and CO_2 emissions from thermoelectric plants. This is to be achieved by technological breakthroughs in the areas of dry cooling, non-conventional power conversion, dry carbon-capture methods, and reduced fuel consumption[329]. The following are the ongoing research projects, as indicated on the center's website.

Research Topic	Context	Objective
Dry CO_2 capture based on nanoscale framework materials	Post-combustion CO_2 capture process requires large amounts of energy and water. By replacing traditional aqueous amine absorbent capture technology with solid adsorbents, savings in both energy and water resources can be realized.	Identify the diamine-appended metal-organic framework best suited to minimize this energy and water consumption. Develop strategies and partnerships to advance technology readiness of the chosen adsorbent through scale-up, process modelling and slipstream testing.

[329] http://cercwet.berkeley.edu/research/water-uNationalse-reduction

Research Topic	Context	Objective
Reheat air combined cycles (RACC)	Molten salts can transport and store heat at temperatures useful for combined cycle power conversion, enabling coupling to non-fossil energy sources including nuclear reactors and concentrating solar power towers.	Evaluate RACC system performance with computer simulation and experiments, with specialized models for heat exchange, duct, and thermal storage systems. Collaborate with Chinese partners to develop a roadmap to achieve the major outcomes projected by 2020.
Integrated gasification and natural gas hybrid fuel cell power plants	Integrated solid oxide fuel cell (SOFC) gas turbine hybrid power plants can contribute to achieving air quality and climate goals. Higher efficiency of hybrids reduces heat rejection and makeup water to wet cooling towers typically used.	Develop integration schemes to fully realize the potential of hybrid SOFC/gas turbine power plants in small to large scale applications with fossil and renewable bio fuels.
Dry cooling for steam condensation	Approximately 1% of thermoelectric power plants utilize air-cooled condensers due to much lower thermal efficiency compared with water-cooled condensers.	Develop enhanced modular air-cooled condensers (EMACC) to increase the air-side heat transfer coefficient.
Synthesis of flexible, low-temperature thermoelectrics and heat exchangers	Custom hybrid materials provide water-free cooling and enable waste heat recovery for co-generation. The aim is to eliminate high water consumption on spray cooled condensers.	Prepare nanostructured phase-change "tapes" that do water-free cooling, providing passive thermal management. Also, our materials perform energy co-generation via direct thermal to electrical energy conversion, thus reducing water use and enhancing energy generations.
Nanostructured surface enhancement of spray cooling water vaporization processes	Inadequate heat transfer and high water consumption for water spray cooling of power plant air cooled condensers.	Develop scalable methods to create nanostructured super-hydrophilic surface coatings on aluminium, and experimentally assess coating durability and effectiveness to enhance heat transfer and reduce water consumption for water spray cooling of power plant air cooled condensers.

Exhibit 65: Ongoing CERC-WET research projects for water use reduction at thermoelectric plants

U.S. Government R&D Initiatives

The United States has a well-established research programme through EPRI. According to Bushart and Shi (2014)[330], the EPRI programme on advanced cooling technology (main water consumer in coal power generation) had the following projects running in 2014:

- Hybrid dry/wet cooling to enhance air cooled condensers with University of Stellenbosch in South Africa
- Thermosyphon Cooler Technology (Johnson Controls)
- Advanced M-Cycle Dew Point Cooling Tower Fill (Gas Technology Institute)
- Heat Absorption Nanoparticles in Coolant (Argonne National Laboratory)

Projects running in 2014 on membrane technology:

- Reverse Osmosis Membrane Self Adaptive Cleaning by Flow Reversal (UCLA)
- Membrane distillation aided by degraded water source (A3E and Sandia National Lab)
- Carbon Nanotube Immobilized Membrane Distillation (NJIT)

Projects that received funding in 2014:

- Indirect Dry Cooling Tower with Phase-Change Materials as Intermediate Coolants (Drexel University)
- Novel Heat-driven Micro-emulsion-based Adsorption Green Chillers for Steam Condensation (UMD)
- Auto Flutter Enhanced Air Cooled Condensers (GA Tech/ Johns Hopkins)
- Advanced Air Cooled Condensers with Vortex-Generator Arrays between Fins (University of Illinois)
- Nanostructure Enhanced Air-Cooled Steam Condensers (MIT and HTRI)
- Exploratory Project: Porous Structures with 3D Manifold for Ultra-Compact Air Side Dry Cooling (Stanford)

In 2010, together, with Georgia Power, EPRI set the Water Research Centre was set up at Plant Bowen. The activities at this demonstration site include among others: moisture recovery (flue gas, cooling tower or scrubbing activities), CT and advanced cooling, Zero Liquid discharge, carbon technology water issues, water modelling & best practices and reuse of various sources within the plant (CT blowdown, FGD discharge, storm water runoff). While some aspects may have been demonstrated elsewhere as discussed in this report, other water saving initiatives are either investigated with novel technologies or existing ones not applied in a power plant context[331].

[330] Bushart and J. Shi. EPRI Innovation Programme overview, Proceedings EPRI Advanced Cooling Technology and Power Plant Water Mgt Workshop in Madrid, 2014.

[331] Electric Power Research Institute, extracted from http://www.epri.com/Pages/Water-Research-Center-Makes-World-Premier.aspx

Other U.S. government R&D Initiatives

The federal government has provided funding for various demonstration projects through the National Energy Technology Laboratory (NETL). The two schemes relevant to this study are the Clean Coal Technology Demonstration Program (CCTDP) launched in 1986 and the Clean Coal Power Initiative (CCPI) initiated in 2002.

The CCPI provides co-funding for new coal technologies which looks at reducing sulphur, nitrogen and mercury pollutants from power plants[332] while CCTDP's primary goal is to develop and demonstrate, at a commercial scale, a family of clean coal technologies [333].

The status of projects funded by these schemes, as of 2016, is shown below.

Status	CCPI	CCTDP
Complete	4	33
Active	4	0
Withdrawn/Discontinued	10	24
Total Projects	**18**	**57**

Exhibit 66: Status of CCPI and CCTDP projects

One of the projects funded by DOE under these schemes is to develop a novel dry cooling technology for thermal power plants. The funding of US$ 3 million was awarded to EPRI[334].

The NETL also runs the Water-Energy Program which collaborates with industry, academia and other government and non-government stakeholders to conduct research on four topics:

- Non-traditional sources of process and cooling water
- Innovative water use and recovery
- Advanced cooling technology
- Advanced water treatment and detection technology

Note that these research activities under the Water-Energy Program are not restricted to coal generation alone but also cover other power plant types.

The US DOE also supports research into the energy-water nexus under various research Funding Opportunity Announcements (FOAs)[335]. In 2013, the Water Power Program funded 15 projects associated with the water-energy nexus from three FOAs with cumulative funding of US$ 15.7 million.

332 energy.gov/fe/science-innovation/clean-coal-research/major-demonstrations/clean-coal-power-initiative

333 www.netl.doe.gov/research/coal/major-demonstrations/clean-coal-technology-demonstration-program

334 www.power-eng.com/articles/2015/06/epri-awarded-3mn-to-research-power-plant-dry-cooling-technologies.html

335 http://energy.gov/under-secretary-science-and-energy/recently-funded-projects-related-water-energy

7 CONCLUSION

This report aimed to compile and objectively analyze the current policy framework and technology scenario pertaining to adoption of clean coal and water saving technologies in coal-fired power plants across APEC.

Cooling water use and in particular cooling towers consume the largest amounts of water, followed by wet FGD and boiler make-up water. Cooling water consumption depends on a variety of factors such as the type of plant, choice of combustion technology and operating efficiency, configuration of the cooling system, mode of operation and the site location itself. From the review of the various technical articles, it is clear that the right water quality needs to be matched to the desired quality requirements in an effort to reduce treatment costs: this in most cases is challenging. For example, treatment and reuse of wastewater (such as municipal waste) as boiler feed water will need to comply with the stringent water quality requirements and incur significant treatment costs. While reuse of municipal wastewater for make-up may seem attractive from a water conservation approach, DNV GL has some reservations based on the cases described in this report[336]. In many of the articles reviewed the quality of the make-up water achieved has not been described in sufficient depth. Seasonal variations affect municipal WWTPs and the quality of effluent. This, in turn, affects the performance of the (tertiary) treatment technology at the power station resulting in variation of make-up water quality. The quality of the produced make-up water is critical for operational reliability of different units, such as FGD, CT and the steam boiler itself. Also, very few articles if at all discuss the impact of the make-up water on the cycling rate of a cooling tower. If the cycling rate decreases because of poorer make-up water quality, the CT will typically consume more water to compensate.

Elcock and Kuiper (2010) identified existing coal-fired power stations vulnerable due to water shortages in the United States. In their study, they utilized among others GIS mapping tools to identify other sources of water including saline aquifers, coal bed methane (CBM) fields, mine pools (after a mine has ceased), oil and gas fields and shale gas plays. For APEC economies experiencing water shortages it is recommend to investigate among others the proximity and availability of similar alternative sources of water.

With respect to ZLD technology, some research papers conclude that it can be used to realize water savings. This argument is valid when using more stable water quality sources such as CT blow down or RO brine as raw water. This however might not hold true in case of FGD wastewater due to the large variety in coal quality. DNV GL assumes that the raw water sources of CT and RO unit (demin) referred in this case were also relatively clean and not having effluent wastewater as source for raw water. A correspondence by DNV GL with a power plant operator utilizing effluent wastewater for a cooling tower designed for ZLD revealed the following "it was too expensive and economically not worth treating this stream, thus we did not utilize the ZLD plant[337]. The cases with ZLD discussed in Chapter 4 pertain to power stations that have been confronted with a changing discharge policy. In most of these cases, discharge is either too expensive or not permitted; thus alternatives were searched.

It should be noted that few articles mention high water[338] price as a driver to adopt water conservation

[336] Reservations on use of municipal wastewater are also shared by some power plant operators and other authors. For example "prolonged use of treated wastewater for power plant operation such as raw source for cooling tower or demin line, needs further investigation according to Macknick et al. 2012".

[337] Email correspondence with chief chemist of a power plant asset in a dry region, 2016

[338] Here, the quality of water referred to is potable water.

technologies. Looking back articles published 2 to 3 decades ago, these would claim that water prices would double or more in time, which in general is not the present scenario apart from some exceptions, such as Israel and Australia. For the latter, two cases were discussed namely the Eraring plant and Loy Yang Power station, which purchased water when a drought occurred[202]. Even countries that tried to implement water price increases for industrial use were faced with stiff opposition. For example, in 2013/2014 the Dutch government attempted to raise water prices for industries that utilize tap water which implied that a large industrial site would roughly pay around EUR 1 million additional taxes per year[339]. This led to fierce opposition from the industry. It was contrary to the general perception of an environmental friendly water policy in a water-friendly economy being easily accepted. While the advantage of raising taxes would be to enable novel technologies like water vapour capture to become more attractive, gaining industry acceptance would be challenging. In general, energy efficiency or renewable policies are more likely to be accepted as they are linked to mitigating climate change. A similar approach needs to be adopted for water accountability which should translate into realistic targets for reducing water pinch (m^3 per MWe) of the coal-fired power sector going forward.

Availability of water consumption and withdrawal statistics for the coal-fired power plant sector across APEC are very limited. Accurate estimates of water use in power plants at both individual and regional levels are required to identify current consumption levels for the variety of cooling systems and combustion technologies presently deployed. Proper estimation of the current water consumption levels of the sector is critical to estimate the future water needs and decide on equitable water allocation amongst competing sectors in the future. The responsible government agencies across APEC need to significantly improve their methodologies for collecting and analyzing water consumption data.

Most of the developed APEC economies, such as Australia; China; Hong Kong, China; New Zealand; and the United States plan to diversify their power generation mix in the near future and significantly reduce dependence on coal. For economies in which future capacity addition will still be dominated by coal (such as Japan; Malaysia; Russia; and Viet Nam), the importance of adopting clean coal and environmentally friendly technologies has been strongly emphasized in their respective planning documents. This transition to clean coal technologies will further stress the water demand for the coal-fired power plants[340]. This projected water demand can be offset through adoption of dry cooling technologies or deploying non-fresh water sources for cooling. The resulting trade-off in efficiency can be mitigated to a certain extent through high combustion efficiency technologies. Other water-saving approaches like matching appropriate water quality to the desired end use will also reduce water pinch, for example surface run-off water for reuse in emission control technologies, such as FGD.

Alternatives, such as combined cycle gas-fired power plants equipped with ZLD and dry cooling especially for dry or arid regions, should also be considered as an alternative to coal-fired power plants. Typically, combined cycle gas power plants are less water intensive and recent technological advancements indicate a higher maturity level for ZLD technologies compared to coal-fired power plants.

[339] Dutch government taxes website

[340] If a transition from conventional coal technology (sub-critical) to high combustion efficiency technologies for future capacity addition doesn't takes place. Albeit even some of the clean coal technologies are more or less on the same scale of water consumption as compared to conventional technologies. Only a shift to high combustion efficiency coal power plants coupled with dry cooling, alternative sources of raw water, ZLD, etc. would significantly offset the water demand of the sector.

8 APPENDICES

8.1 Appendix A - Summary of articles of gas-fired power plants applying ZLD

Shulder and Mierzejewski (2002) describe the High Desert project with its ZLD plant in the following scheme[128]. The power station restores water into the aquifer. The supply of the water to this project is through the Mojave Water Agency from the California Aquaduct. DNV GL's opinion of this approach is that while the ZLD plant on the back end is what one would expect to reduce water consumption, a considerable amount of water is still lost. As this is surface water (Aquaduct originating from Sierra Nevada Mountains), one could consider using raw water source like effluent from a municipal waste-water plant. Also it is unclear why Granulated Activated Carbon GAC is needed in this scheme. According to the authorities steps are needed to reduce the amount of waste-water going to the evaporators / crystallizers to help reduce operational cost. The article does not provide any water quality results or associated costs.

Nagel et al. (2008) describes a ZLED plant as follows[341]:

- Precipitation & Flocculation using chemicals $FeCl_3$, Lime and granulated activated carbon; in this pre-treatment stage liquid sludge is produced
- Ultrafiltration
- Activated carbon filter (to help reduce DOC, & protect RO from chlorine and oil)
- Two RO passes
- Mixed bed polishing

This setup (in Madrid) was designed after analysis of the effluent waste-water quality and a pilot was done. The results presented in Nagel, et al. 2008, show that boiler feed water quality could be met as the 2nd RO unit is just slightly above conductivity values and other key parameters are below the quality specification. The polishing step can easily remove the remaining impurities to reach make-up water requirements. For a similar site in Italy the same setup was utilized, however this site did not allow any waste-water discharge. This resulted in the use of a dry cooling tower, brine concentrators and evaporator for all waste-waters containing solids. Backwash water from the Ultra Filtration (UF[342]) step, concentrate from the UF process and press-water are brought back to the pre-treatment stage and the liquid sludge is further pressed. This liquid sludge leaves the brine regenerate with a need for further chemical treatment. The core of the process is that the evaporator[343] together with the circulation pump and the steam-heated heat exchanger is subjected to forced circulation of the crystal suspension. The key here is to control proper seeding of the high crystal density in the evaporators; if this is not controlled properly the heat exchanger will require

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[341] R. Nagel, K. Ogiermann and M. Graulich, The use of wastewater as boiler feed water and zero discharge in power stations, VGB Powertech 2008, 6, pages 94-104.

[342] Ultra filtration is a type of membrane filtration wherein the application of hydraulic pressure or concentration gradients leads to a separation through a semi-permeable membrane. Suspended solids and solutes of high molecular weight are retained in the so called retentate, while water and low molecular weight solutes pass through the membrane in the permeate.

[343] Which in this case functions as a crystallizer.

additional maintenance (deposits to be cleaned). Mechanical vapour compression is applied to help reduce steam requirement. About 0.75 kg of live steam is needed for each kg of concentrate; this can be reduced in larger plants with multiple-effect systems.

The Redhawk Power station from Arizona Public Service near Phoenix, Arizona (USA) is a ZLD plant, using effluent municipal waste-water for both cooling tower (CT) and make-up water, is a combined cycle gas fired power plant of 2 x 540 MWe. The plant consumes about 1 billion gallons of reclaimed waste-water each year[344]. The effluent waste-water is treated three times (how and what is not described), the conductivity of this water is 1,400-1,800 µS/cm, with TDS values of 900 mg/l. The plant also has a backup water reclamation system on standby in case there is limited effluent water. This effluent water is directed as make-up water for the CT. Although it seems from the schematic in the figure that the effluent stream is not (chemically) treated, the CT is. A continuous chlorine residual of 0.2 – 1.0 ppm is maintained, the pH is maintained with sulphuric acid at 6.9 – 7.5, dispersing agents are fed to 10 – 20 ppm and a de-foaming agent is injected as well. The cycling of CT can be up to 20,000 mg TDS per litre.

The demin line set-up utilizes first a pre-treatment of filters (multimedia and cartridge) and then two passes over a three-train RO system. Upstream and downstream of the multimedia filter a value of 0.4-0.8 ppm is maintained to control biofouling. The resulting water quality after the RO's is 1 – 4 µS/cm at a 50 gpm (11 m^3/hr). A mixed bed battery of 12 bottles is then used to meet international make-up guidelines. The bottles are setup 6 in parallel with two in series, where the first MB bottles are primary and the 2nd the polisher. The units have conductivity monitors at the outlet of the primary MB bottle, with a target limit of 0.08 µS/cm, followed by a polisher where even lower levels are met. The outlet manifold contains additional Si monitor set at 10 ppb.

The ZLD system is processing a large waste-water stream such as blow-down of cooling tower. This stream is first treated to remove calcium carbonate through acidification[345], pre-heating and de-aeration (CO_2 removal). This stream is then treated in the brine evaporation system, and concentrated further in a crystallizer. Here solids are removed using a centrifuge and landfilled. Evaporated water/distillate is reused in the plant.

Yarbrough (2006) provides ten lessons learned after operating the ZLD plant for 4 years. These are for example a better mesh, foaming affecting monitors, purge system, optimize centrifuge, solid testing unit, add a hydro-cyclone, add storage (brine concentrator surge pond), evaporator & crystallizer maintenance, and outage planning for a ZLD is just as serious as a power block. Also water quality can change over time, algae growth in the storage ponds may lead to changing TOC. Nitrates vary seasonally and can increase boiling points in the evaporators/crystallizers. While no water treatment costs or OPEX figures are provided, DNV GL carefully concludes that this article clearly illustrates that the ZLD system is a unit that requires dedicated staff.

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[344] M. Yarbrough, Recycling, reuse define future plant designs. Power May 2006, pages 26-34.

[345] Addition of sulphuric acid to convert (bi) carbonate to CO_2

Also, K. Bourdreux et al. (2014) clearly describe the challenges of operating brine concentrators (BCs) and crystallizers, in particular foam forming. Operation of a ZLED plant remains a sophisticated process and it requires (specialized) operator attention.[346]

Sampson (2013)[347] describes the challenges associated when applying ZLED technology at a 720 MW CC power plant. Here well water is sent to a cooling tower and the blow-down is treated. First a softening step is applied followed by media filters, RO, brine concentrators and a final crystallization step. After the first 3 years of operation following commissioning, bottlenecks have restricted the operation of the ZLED unit and resulted in expensive waste-water discharge. The article describes an approach on how to tackle ZLED processes. Interestingly the author points out that ZLED technology is a complex process involving multiple steps, and the reliability of the total system will be reduced. For example if each step had a reliability of 90% then the total system of 6 steps, is 54% reliable. Also operators would need to build in sufficient capacity or redundancy to ensure reliable operation throughout the year. For example the actual capacity was for some process steps higher in a certain time frame (April-September) which hampered operations later in the system. A simple solution is to construct storage tanks to tackle redundancy. A clear understanding of the process, actual situation, and the options to improve and ensure reliable operation[438]. DNV GL fully agrees with the analysis provided in the article.

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[346] K. Boudreaux, S. Biggar and E. Palomo; Troubleshooting and Antifoam application minimizes ZLD Plant operation costs and downtime, Power plant Chemistry 2014, 16 (1), pages 25-37

[347] D. Sampson, No easy answers: ZLD improvement options for a 720 MW Power Generation Facility. PowerPlant Chemistry 2013 15(1), pages 14-24.

8.2 Appendix B - Directives on cooling water discharge in non-APEC economies

This Appendix provides a brief overview of cooling water discharge directives in European and Middle Eastern countries.

1. Integrated Pollution Prevention and Control Guideline (IPPC)

The IPPC reference document on the application of best available techniques (BAT) to Industrial Cooling Systems (IPPC, 2000) draws the conclusion that 'industrial cooling processes are very site- and process-specific'. So, site-specific conditions determine the actual practices applied. Both chlorine and hypochlorite are included as recommended techniques in the BAT document.

The IPPC is replaced by the Industrial Emissions Directive (IED, 2010/75/EU). The IED states that the BREFs are applied as reference for setting permit conditions and those competent authorities may set stricter permit conditions than those achievable using BAT.

2. Water Framework Directive (WFD)

With the adaptation of permits to the IPPC-guideline, based on article 22 paragraph 6 of the WFD, the priority (hazardous) substances (PS/PHS) from the WFD must be considered. Annex III of the IPPC-guideline contains an indicative list of substances that are to be address during permitting. Article 22 paragraphs 6 of the WFD determines that the priority (hazardous) substances that are not on the indicative list, must be added. Based on article 9 of the IPPC-guideline a permit must contain emission limit values for all these substances, when these substances are released from the IPPC-installation in significant quantities. Also, where possible these substances must be tested against the applying water quality standards. For this, an integrated approach, as determined in the 'emission-evaluation', must be applied.

Priority substances are subject to reduction. Priority hazardous substances are subject to cessation or phasing out of discharges, emissions and losses within an appropriate timetable. In practice, all these substances environmental quality standards are available, on which further measures can be demanded. Important questions are the extent of reduction of emissions of priority substances, within which time frame priority hazardous substances must be phased-out, and whether this can be achieved. On the priority substances list several chlorination by-products (CBPs) are listed:

- 1,2 Dichlorethane
- Dichloromethane
- Hexa-chlorobenzene
- Pentachlorophenol
- Tri-chlorobenzene
- Tri-chloromethane
- C10-C13 alkanes

Not all these substances are necessarily formed during chlorination and present in the discharged cooling water; this depends on the dosed hypochlorite concentration and the presence of necessary precursors. When the hypochlorite is pre-diluted prior to dosing, the formation of Chlorination By-Products (CBPs) (and the concentration in which they are formed) will be reduced.

3. Biocidal Product Directive

The Biocidal Product Directive (BPD) of the European Union describes biocides as: 'products used to control the growth and settlement of biofouling organisms (microbes and higher forms of plant or animal species) on vessels, aquaculture equipment or other structures used in water' (EU, 1998). The scope of the Directive is very wide, covering 23 different product types. These include disinfectants used in different areas, chemicals used for preservation of products and materials, non-agricultural pesticides and anti-fouling products used on hulls of vessels. The Directive does not apply to certain product types already covered by other Community legislation, such as plant protection products, medicines, and cosmetics.

The basic principles of the Directive are:

- Active substances have to be assessed and the decision on their inclusion into Annex I of the Directive shall be taken at Community level.
- Comparative assessment will be made at the Community level when an active substance, although in principle acceptable, still causes concern. Inclusion to Annex I may be denied if there are less harmful, suitable substitutes available for the same purpose.
- Member states shall authorize the biocidal products in accordance with the rules and procedures set in Annex VI of the Directive. They can only authorize products which contain active substances included in Appendix I.
- The producers and formulators responsible for the placing on the market of the biocidal products and their active substances must apply for authorization and submit all necessary studies and other information needed for the assessments and the decision making;
- A Biocidal product authorized in one Member State shall be authorized upon application also in other Member States unless there are specific grounds to derogate from this principle of mutual recognition.

The biocides work area provides Technical and Scientific support to Member States' Competent Authorities and the Commission with respect to the implementation of the Biocidal Products Directive (BPD) 98/8/EC on the placing on the market of biocidal products, which entered into force on 14 May 2000.

The Directive defines biocidal products and sets out a frame for their evaluation in a two-step procedure where the first step is the entry of the active substances onto Annex I (or IA or IB) and the second step is the authorization of the products in which the active substances are used. Active substances are divided into:

- New active substances that cannot be placed on the market for biocidal purposes unless they are included onto Annex I.
- Existing active substances evaluated in the Review Programme, according to Article 16 of the BPD. The Review Program was established via several Regulations. The latest Regulation is Regulation (EC) No 1451/2007, which repeals Regulation (EC) No 2032/2003, and entered into force on 31 December 2007.

4. Mixing Zone Guidance[348]

In the future, the Mixing Zone Guidance (MZ) and the Industrial Emissions Directive (IED) will play an increasingly important role, not only for the application of chlorine as antifouling additive, moreover with respect to the discharge of chemicals (discharge limits and monitoring). There may be direct issues related to the MZ for some plant on PS/PHS, e.g., chloroform, possibly some emissions from sea water process

[348] EU Common Implementation Strategy document "Guidelines for the identification of Mixing Zones under the EQS Directive (2008/105/EC).

and potentially indirect issues for cooling water discharges if the MZ is applied to heat or other substances (e.g., temperature, TRO).

Discharge limits for the Middle East

In the Middle East region, there is an increasing attention to environmental regulation, especially with the very fast growth of industrial activities. For seawater to be efficiently and reliably utilized for cooling a biocide must be added to prevent marine growth. For desalination, other chemicals are also needed and there is a discharge of brine. Typical industry practice along coastlines worldwide includes continuous chlorination of the seawater with occasional shock dosing. This practice is not based upon eco-toxicological data of targeted species but rather either a post-hoc observation of antifouling efficiency or an attempt to meet regulated discharge to sea residual biocide concentrations. Shock dosing is applied in the erroneous notion that it stops fouling species from adapting to continuous chlorination. These practices have been identified as major contributors to land-based pollution of the sea, especially within the Arabian Gulf (UNEP 2000; Khan *et al*., 2002; Abuzinada *et al*., 2008). Therefore, opportunities exist for science-based decisions to optimize both site-specific biocide regimes and regulatory discharge limits within this marine environment that has more than 50% of the world's desalination plants and significant quantities of cooling water for the power and hydrocarbon facilities along the shoreline. For the Middle-east countries, the discharging permits for chlorine are shown below.

Country	Parameter	Maximum marine discharge limit
UAE	Residual chlorine	1 mg Cl_2/l[349]
State of Qatar	Free Residual Chlorine (FRC)	0.05 mg Cl_2/l
Bahrain	Residual chlorine (FRC)	0.2 mg Cl_2/l [350]
Sultanate of Oman	Total chlorine	0.4 mg Cl_2/l [351]

[349] EAD, 2008, "Standards and Limits for Pollution to Air and Marine Environments, Occupational Exposure, Pesticides and Chemical Use," Technical Guidance Document TG-0003R, Environment Agency - Abu Dhabi (EAD), United Arab Emirates.

[350] Monthly average value. Government regulation of free residual chlorine (FRC) discharge to the sea is capped at 0.5 mg/l FRC with a monthly average of 0.2 mg/l, with a maximum allowed peak concentration of 2 mg/l.

[351] Sultanate of Oman: Council for Conservation of Environment and Prevention of Pollution (by OLNG).