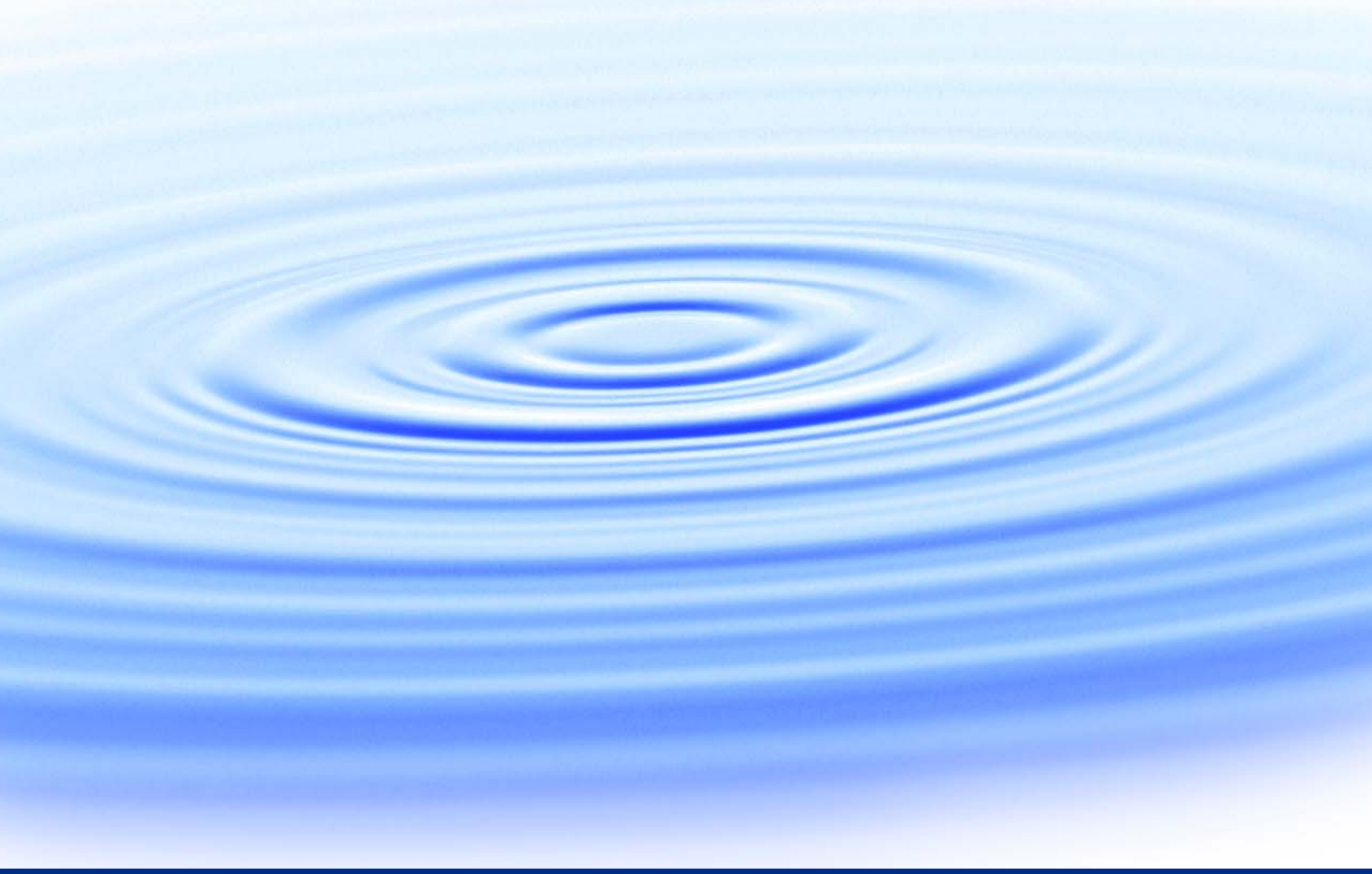
WATEREUSE

Drivers, Successes, Challenges, and Opportunities of On-Site Industrial Water Reuse

A Path Forward for Collaboration and Growth



WateReuse Research Foundation

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About the WateReuse Research Foundation

The WateReuse Research Foundation builds support for water reuse through research and education. The Foundation’s research advances the science of water reuse and supports communities across the United States and abroad in their efforts to create new sources of high quality water for various uses through reclamation, recycling, reuse, and desalination while protecting public health and the environment.

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, reduction of energy requirements, concentrate management and desalination, public perception and acceptance, economics, and marketing. The Foundation’s research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of providing a reliable, safe product for its intended use.

The Foundation’s funding partners include the supporters of the California Direct Potable Reuse Initiative, Water Services Association of Australia, Pentair Foundation, and Bureau of Reclamation. Funding is also provided by the Foundation’s members, water and wastewater agencies, and other interested organizations.

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WATEREUSE

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Acronyms and Abbreviations

AMD	acid mine drainage
ANZSIC	Australian and New Zealand Standard Industrial Classification
AOP	advanced oxidation process
AOX	assimilable organic halogen
ASME	American Society of Mechanical Engineers
BOD	biochemical oxygen demand
CEC	California Energy Commission
COC	cycles of concentration
COD	chemical oxygen demand
CWA	Clean Water Act
CWSRF	Clean Water State Revolving Fund
EPRI	Electric Power Research Institute
FGD	fluidized gas desulfurization
FOG	fats, oils, and grease
GEMI	Global Environmental Management Initiative
GICS	Global Industry Classification Standard
GVA	gross value added
IPIECA	International Petroleum Industry Environmental Conservation Association
ISIC	International Standard Industrial Classification
KPI	key performance indicator
LEED	Leadership in Energy and Environmental Design
LWT	Local Water Tool
MBR	membrane bioreactor
MF	microfiltration
MLSS	mixed-liquor suspended solids
NACE	Nomenclature of Economic Activities
NAICS	North American Industry Classification System
O&G	oil and gas
PTA	purified terephthalic acid
RO	reverse osmosis
ROI	return on investment
SAGD	steam-assisted gravity drainage
SIC	Standard Industrial Classification
TDS	total dissolved solids
TMAH	tetramethyl ammonium hydroxide
TOC	total organic carbon

TSS	total suspended solids
U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UF	ultrafiltration
UV	ultraviolet
WBCSD	World Business Council for Sustainable Development
WCTI	Water Conservation Technology International
WEFTEC	Water Environment Federation Technology Conference
WWF	World Wildlife Fund for Nature
ZLD	zero liquid discharge

Foreword

The WateReuse Research Foundation, a nonprofit corporation, sponsors research that advances the science of water reclamation, recycling, reuse, and desalination. The Foundation funds projects that meet the water reuse and desalination research needs of water and wastewater agencies and the public. The goal of the Foundation's research is to ensure that water reuse and desalination projects provide sustainable sources of high quality water, protect public health, and improve the environment.

An Operating Plan guides the Foundation's research program. Under the plan, a research agenda of high priority topics is maintained. The agenda is developed in cooperation with the water reuse and desalination communities, including water professionals, academics, and Foundation subscribers. The Foundation's research focuses on a broad range of water reuse and desalination research topics including:

- Defining and addressing emerging contaminants, including chemicals and pathogens
- Determining effective and efficient treatment technologies to create "fit for purpose" water
- Understanding public perceptions and increasing acceptance of water reuse
- Enhancing management practices related to direct and indirect potable reuse
- Managing concentrate resulting from desalination and potable reuse operations
- Demonstrating the feasibility and safety of direct potable reuse

The Operating Plan outlines the role of the Foundation's Research Advisory Committee (RAC), Project Advisory Committees (PACs), and Foundation staff. The RAC sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. PACs are convened for each project to provide technical review and oversight. The Foundation's RAC and PACs consist of experts in their fields and provide the Foundation with an independent review, which ensures the credibility of the Foundation's research results. The Foundation's Project Managers facilitate the efforts of the RAC and PACs and provide overall management of projects.

The objective of this study was to further understanding of the application potential of reusing/recycling industrial waste streams (i.e., retention of water within a facility that has already served a useful purpose and putting that same water to use again for a beneficial purpose within the same facility). A review of the literature, an industry survey, and industry participant workshops were performed to aggregate information and clarify industry reuse/recycling opportunities and challenges. In terms of generic water use categories that cut across industrial sectors, the easiest and most readily applied water reuse/recycling applications appear to be irrigation, process-related cleaning/rinsing, and makeup water for cooling towers. The most difficult application is utilization directly in product production, whereas cogeneration is perceived to be an untapped application with a lot of future potential.

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The authors are deeply grateful to the WateReuse Research Foundation for funding this project and providing the technical expertise of the Project Advisory Committee (PAC). This report would not have been possible without the technical input, guidance, and firsthand knowledge obtained from the participating industries and vendors. Their understanding of key project issues greatly enhanced the success of the project. Gratitude is also extended to the Technical Advisory Committee (TAC) for their input and review of project deliverables and to Maria Chau (MWH) for technical production.

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Boeing

Coca-Cola

Duke Energy

Dow

GE Water

Gold Fields

Jackson Family Wines

Kellogg

Newmont Mining Corporation

Perrigo

Veolia

Executive Summary

The business case for the sustainable use of water is continually increasing because of greater competition for this finite resource that has heightened water's strategic role in risk mitigation. Prudent industrial use of water is driven by water and energy-related costs, customer/shareholder expectations for environmentally sound corporate decision making, and maintaining a "license to operate" by adequately addressing the sustainability impacts of an industry's operations (GEMI, 2002). One strategy industries can consider to minimize global water and energy risks is optimization of on-site water reuse and water recycling opportunities.

Water reuse and recycling investments tend to be driven in the short term by regional water scarcity concerns or wastewater discharge limitations that create beneficial economics for water reuse/recycling. To further drive large-scale, corporate-level water reuse/recycling implementation, a culture embracing effective incentive structures at the government level in various policy areas should provide additional motivating factors. On-site water reuse/recycling is less clearly delineated for the industrial sector than it is for the municipal sector. This is due to the diversity of industrial facility processes, the proprietary nature of industrial corporations, the wide and more exotic variety of constituents that can be present in industrial process–generated wastewaters, and the greater need for a rapid return on capital investments or subsidized economic incentives. Therefore, the goal of this project is to obtain a greater understanding of the drivers, successes, challenges, and opportunities for implementing and further developing on-site industrial water reuse and recycling practices.

Industries were classified according to the first two digits of the North American Industry Classification Standard, with emphasis on Sectors 21, 22, and 31 through 33 (i.e., mining, oil and gas extraction, power, and manufacturing). They were evaluated for on-site industrial water reuse/recycling opportunities through performance of a peer and gray literature review, an industry survey, vendor outreach activities, and workshops attended by project industry participants. The industrial survey included 29 questions categorized under five subject topics, and responses were received from 10 industries representing 17 discrete facilities. Collectively, the two workshops were attended by 10 individuals representing nine companies from the industrial sectors of mining (n=2), food and beverage (n=3), chemical manufacturing (n=1), metal manufacturing (n=2), and power (n=1). The two workshops included breakout session discussions tasked with identifying: (1) similarities and differences between industries for on-site water reuse/recycling; (2) opportunities and drivers for implementing on-site water reuse/recycling; (3) challenges and obstacles to on-site water reuse/recycling; and (4) potential solutions for overcoming cited challenges.

In California industry represents approximately 7% of urban water use. Although water withdrawal is slowing down in the industrial sector of many Western countries as a result of increased conservation and reclamation, it remains one of the heaviest sources of pollution, and further implementation of recycling and reuse would benefit the environment. Industrial water use reporting at the government level is predominantly restricted to industry as a single entity without breakout by sector classifications, and corporate-level reporting tends to be inconsistent within and between sector classifications. One exception was a 2003 study performed in Norway (Statistics Norway, 2006).

Water requirements are highest for the electric power industry, but usage is highly variable and influenced primarily by the type of plant, fuel, and choice of cooling system and additionally by local climate, water source, environmental regulations to which the plant must comply, and the water management system employed. Thermoelectric power plant water requirements are large because many plants utilize steam turbines as the prime mover to generate electricity, and the cooling system used to recondense the steam relies on wet rather than dry cooling. The cooling water is withdrawn for once-through wet cooling and consumed for recirculating closed-cycle, wet-cooling systems. Most new power plants in the United States use recirculating cooling water systems and, to a lesser extent, dry cooling systems, but presently 43% of all U.S. plants do not recirculate water. One way to reduce the amount of water used in a recirculating cooling tower is achieved by using higher cycles of concentration (COC), which are dependent on the mineral content of the water.

The mining industry is the second largest industrial user of water in the world, and the U.S. mining industry accounts for approximately 1% of total water withdrawals in the United States. Some of the largest mining operations exist within regions of North America, South America, Australia, and Africa that are classified as being at moderate to high risk of water scarcity.

The food production industry accounts for more than two-thirds of all freshwater use worldwide (Ait Hsine et al., 2005), but a much smaller amount is used for processing, and water of high quality may be required for individual phases of production. A 2006 publication of the California Energy Commission (CEC) found that total food processing water in California accounted for approximately 37 billion gallons per year (exclusive of water needed to grow crops) (State of California Department of Water Resources, 2013). This is approximately 0.6% of the water withdrawals reported in 2005 for the industrial sector by the United States Geological Survey. The amount of water used and the way it is used vary by food product

There are many water needs within a manufacturing facility, and on a global basis, about twice as much water was used by industry than was used for domestic purposes (on average 665 billion m^3 per year) between 1987 and 2003. Top industrial water users were countries in Eastern Europe (Bulgaria, Serbia and Montenegro, Slovenia, Republic of Moldova, Romania), North America (Canada and United States), and Europe (France and Germany). In the United States, industrial withdrawals in 2005 were estimated to be 18,200 Mgal/d, representing 4% of the nation's total withdrawals. Nearly all of these withdrawals were freshwater, with 83% coming from surface water and 17% from groundwater. Industrial water withdrawal in Asia has been reported as 10% of total water withdrawal, and demand in China nearly tripled between 1980 and 2007.

Common water uses across multiple industries occur in the following eight generic categories: (1) cooling and boilers; (2) cogeneration and energy recovery; (3) process; (4) in-plant conveyance; (5) cleaning; (6) environmental controls; (7) sanitation; and (8) landscape irrigation. The three dominant water uses are for heat dissipation, power generation, and processing; 50% or more of the water intake to a plant is often used just for process cooling. The amount of water that is consumed and unavailable for reclamation can vary widely among these generic use categories. This will impact on-site water reuse/recycling opportunities by (1) reducing available effluent volumes and (2) impacting effluent stream qualities through concentration of background minerals and salts and added process chemicals. Water is tremendously undervalued as a commodity, which has historically contributed to the impairment of water quality and a concern of surpassing peak ecological water—the point of human water use that causes serious or irreversible ecological damage to a watershed. As freshwater becomes scarcer, water prices are expected to increase as subsidies are phased out. Ten of the seventeen survey respondents consider their water supplies to be strained, but surveys and water supply costs reported in the literature demonstrate that wastewater discharge costs are often a larger driver of water reclamation than water supply costs.

Industrial wastewater production stream qualities and flows vary by industrial sector, sector products, facility production processes and levels, sustainability practices, and regional discharge requirements. The industrial facility process locations that were cited by the survey participants for generating waste streams are summarized in Table ES.1. Cooling towers are common to all these industries except for mining, and production processes are common to all the participating industries.

Table ES.1. Industrial Process Locations Generating Wastewater Streams

Chemical Manufacturing	Food & Beverage	Metal Manufacturing	Power and Mining
• production processes • clean in place • cooling towers • boilers • purified water system	• sanitation • production processes (cooking, coating, cleaning, crushing, pressing, harvesting equipment) • environmental controls • cooling towers	• paint rinsing • anodizing quench • product washing • product treatment • material rinsing • product testing • cooling towers	• air pollution control equipment • domestic wastewater • process waste streams • stormwater runoff • laboratory • cooling towers for certain power facilities

A key driver of on-site reuse/recycling implementation in regions with adequate and inexpensive source water occurs when there is a narrowing of the gap between the treatment needs to adhere to wastewater discharge requirements and those to reuse or recycle the water. When this gap sufficiently narrows to demonstrate at least a 2- to 3-year return on investment (ROI), reuse/recycling opportunities convert to project implementation. Water reuse adaptation varies widely across industrial sectors and is highly dependent on site-specific situations. Readily implementable reuse opportunities requiring lower capital investment are usually installed first (e.g., cooling tower makeup water), and studies for additional reuse opportunities are delayed or not implemented at full scale until the cost of treatment modifications will provide a reasonable ROI.

Cooling is the most common industrial reuse option because of its high water demand, relatively low water quality required, ease with which the practice may be applied to different types of industries, and simplicity of implementation. There is little or no evidence of applications for direct use of reclaimed water within products, as this typically requires the greatest amount of treatment in order to alleviate product manufacturing risks or carries unacceptable public health and safety concerns. Water reclamation is, however, applied in product processing steps such as cleaning and rinsing. Drivers of water reuse for individual industrial sectors are provided in the report; additional examples are in the sector-specific literature reviews in Appendices E through J.

The percent distribution of the overall reclaimed water volume among the generic use categories on a facility-specific basis according to the survey is shown in Figure ES.1. These data demonstrate that the greatest utilization of reclaimed water by volume for this group of respondents, as previously found in the literature, is for product processing or cooling and boilers. The respondents clarified that product processing water was not actually utilized in any of the products but only represented the water utilized during processing steps such as diluting or rinsing.

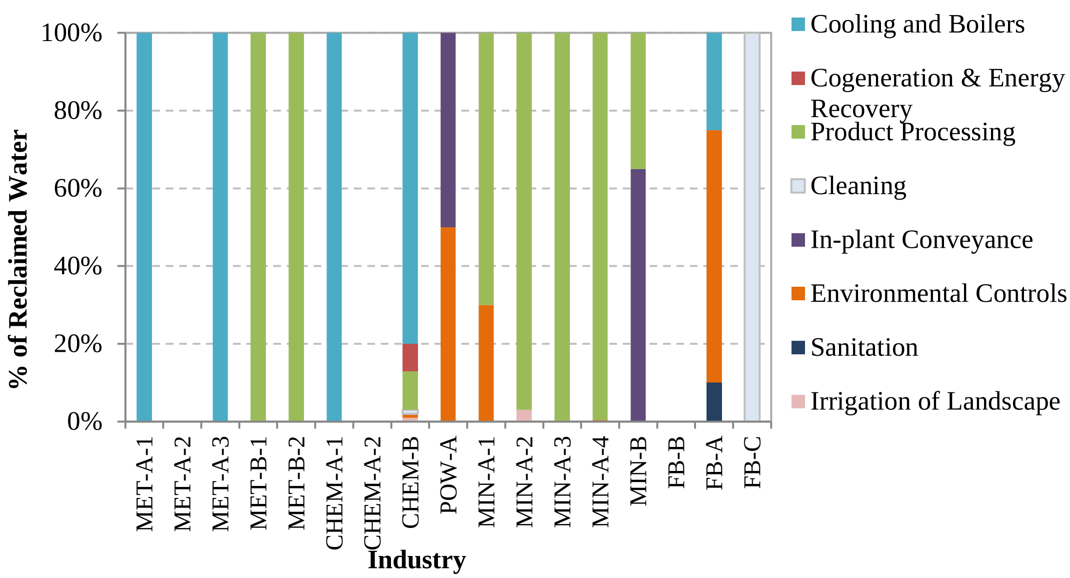

Figure ES.1. Percentage distribution of overall reclaimed water volume among the generic use categories by the 17 reporting facilities.

Despite the broad utilization of water reuse/recycling across generic water-use categories, the percentage of total annual water usage consisting of reused/recycled water for the survey respondents was less than 20, with the exception of mining industry facilities and a winery in a drought-stricken region, as shown in Figure ES.2. For these respondents, reuse/recycling percentages are high and frequently approach 100%.

Many factors must be considered during the decision process for implementation of on-site water reuse/recycling at an industrial facility. Each of these factors can be grouped under one of the following four categories: (1) sustainable, (2) technological, (3) regulatory, and (4) economic. Table ES.2 provides a summary of these factors and their classification category. Depending on the disposition of these factors relative to the facility’s geographical setting, management culture, facility infrastructure, local governance policies, and water quality treatment needs, they will function as either a driver or a challenge for developing on-site water reuse/recycling capabilities.

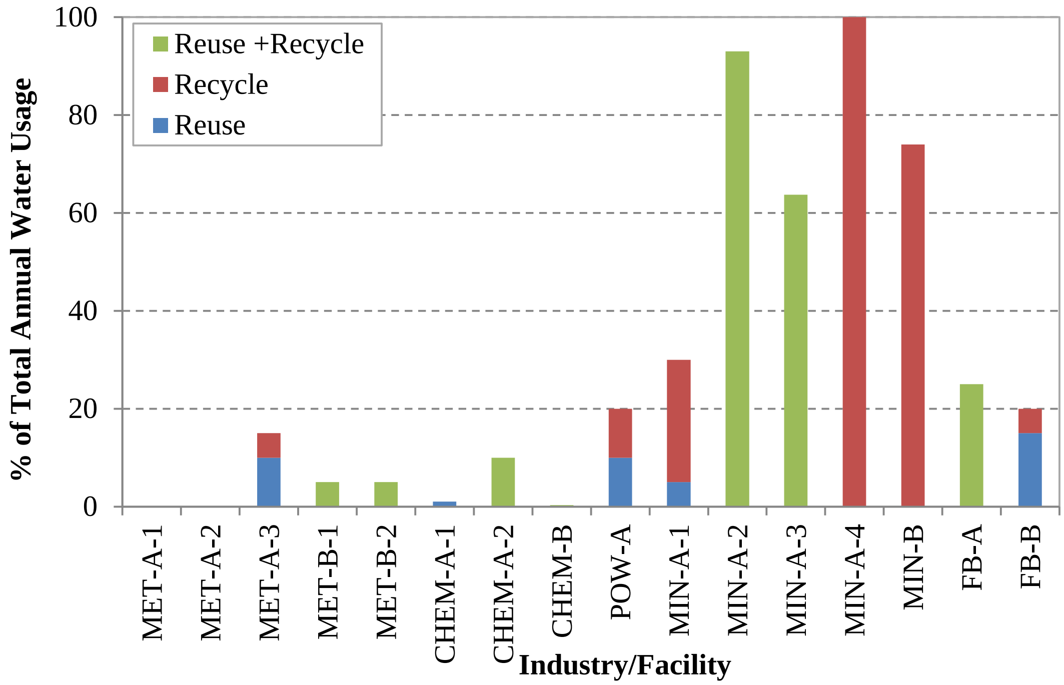

Figure ES.2. Percentage of total annual water use that is reuse/recycle water reported by the 17 surveyed facilities.

Table ES.2. Categorical Factors that Translate to Site-Specific Drivers and Challenges When Considering On-Site Industrial Water Reuse/Recycling Projects

Sustainable	Technological	Regulatory	Economic
• KPI metrics for water • Water scarcity and facility location(s) and expansion plans • Water reclamation volume/quality recovery relative to water needs • Ease of wastewater discharge permitting and discharge limits • Social license to operate issues	• Reuse vs. discharge technology parity (e.g., ability to handle matrix and pre or post-treatment requirements) • Demonstrated performance (case studies) of reuse technology options • Ease of reuse technology for site-specific application	• Locational regulations impacting wastewater discharge options (e.g., EPA Toxics Release Inventory) • Guidelines for regulatory permitting of water reclamation projects • Pending regulatory programs anticipated to impact future discharge for industry sector	• Production risks associated with reuse • Availability of incentives • ROI timeline • Availability of economically viable sink for captured pollutants • Knowledge of true cost of water and its utilization in alternatives assessment

Notes: EPA=Environmental Protection Agency; KPI=key performance indicators; ROI=return on investment.

Once the decision to implement an on-site industrial water reuse/recycling project has been made, a project's success is dependent upon additional factors that can be categorized under the same categories of (1) sustainable, (2) technological, (3) regulatory, and (4) economic. Table ES.3 provides a summary of these factors and their categorical classification. The likelihood of project success is closely linked to having a high percentage of these factors addressed or readily implementable during the preliminary planning and design stages of the water reuse/recycling system.

The biggest overall drivers of on-site industrial water reuse/recycling are wastewater discharge regulations and water supply restrictions that are largely regionally and locally driven. Regional water scarcity can lead to corporate margin erosion and in severe cases can result in a loss of license to operate. The sector most impacted by these issues is the mining industry because water is needed for a broad range of mining activities, and operations are often constrained to water-scarce locations. In 2011 the mining industry used approximately 2.1 trillion gallons of water per year (second only to the power industry), with a capital expenditure on managing this water at approximately $8 billion. Fracking operations, a subsector of the mining industry for oil and gas (O&G), have also generated concerns related to wastewater disposal practices. The ability to implement water reuse/recycling strategies resulting in zero liquid discharge (ZLD) in this industry sector may mitigate concerns over loss of water from the hydrological cycle from deep well injection of wastewater or the possible spread of contaminants from wastewater disposal practices that can only be avoided by using costly treatment options.

Table ES.3. Categorical Factors Linked to Site-Specific Success of On-Site Industrial Water Reuse/Recycling Project Implementation

Sustainable	Technological	Regulatory	Infrastructure Cost
• Water auditing capabilities relative to water quality, water quantity, energy usage, and GHG emissions • Resource recovery goals and strategies • Tools for true cost of water assessments	• Proven solution for site-specific application or ability to tailor applicability through piloting efforts • Acceptable risk mitigation design-build strategies • Suitable real-time monitoring strategies for risk mitigation during operations • Suitable contingencies to prevent production impacts	• Strength of stakeholder partnerships • Successful outreach efforts toward relevant organizations • Detailed understanding of permitting process requirements	• Ability to segregate facility waste streams as required for successful design approach • Flexibility of pipeline routing and suitability of existing pipeline materials • Feasibility of process treatment train or ZLD options at site • Volume matching of recycled streams

Notes: GHG=greenhouse gases; ZLD=zero liquid discharge.

The predominant use of water in the power industry is in the cooling towers utilized to cool the steam circuit. Reclaimed water usage at power plant cooling towers is primarily from an off-site supply of reclaimed wastewater effluent or other off-site marginal water because sources of recycled water within a power facility are inadequate for the cooling requirements. Only a 5 to 20% overall reduction in water consumption can be collectively achieved for a wet tower-cooled facility through implementation of on-site water reuse/recycling of blowdown and process water and elimination of water for fluidized gas desulfurization (FGD) and ash handling. Other options to reduce water consumption by a factor of two or more are limited to utilization of a more thermally efficient generation technology, implementation of topping-cycle cogeneration, use of a different cooling system, or implementation of recycled water offsets from a recycled water producer.

Water reuse/recycling opportunities in the food and beverage industry are principally in the cleaning and rinsing of raw product, processing equipment, and packaging materials, as well as thermodynamic processes (e.g., cooling towers and boilers) and irrigation of the agricultural raw product if it is grown on-site. Health and safety regulations and public risk perceptions prevent the use of reclaimed water directly on the finished food products. Water reuse implementation appears to be highly influenced by regional location and does not have the same corporate visibility as water conservation.

Water needs in manufacturing industries are quite variable, with highest water use cited in the literature for paper, textile, iron and steel, tannery, and chemical manufacturing industries. Many of these higher water use industries are located in Asia, although there has been a slowing of industry relocation options to developing countries. Water reuse/recycling opportunities first target easier applications such as thermodynamic processes (e.g., cooling towers and boilers), process cleaning, and rinsing applications. Difficulties in process wastewater treatment are greatest for industries that utilize or manufacture recalcitrant organic compounds (e.g., textile dyeing, semiconductor, paper production, chemicals).

Membrane treatment is a foundation for many water reuse processes that must handle high salts or recalcitrant organics. Pretreatment requirements are driven by the need to prevent unacceptable membrane fouling, and post-treatment is utilized to remove additional contaminants that persist within the process permeate (e.g., silica, boron, ammonia, small organics). The biggest deterrent to on-site water reuse/recycling implementation is demonstrating adequate ROI (2–3 years) because of the undervaluation of source water supplies and treatment residual disposal issues.

In terms of the generic water use categories that cut across industrial sectors, the easiest and most readily applied water reuse/recycling applications appear to be for irrigation, process-related cleaning and rinsing, and makeup water for cooling towers. The most difficult application is utilization directly in product production, whereas cogeneration is perceived to be an untapped application with a lot of future potential. Closing the loop on energy recovery when water is the carrier medium across the facility will yield water reuse opportunities.

Promotion and expansion of on-site water reuse/recycling capabilities within industries will see benefits from additional research efforts designed to address existing knowledge gaps and implementation challenges. The major research topics identified during this project are summarized in Table ES.4 under different topical categories. The finance, technology, and communication topical categories will best drive on-site water reuse/recycling efforts when they occur simultaneously and positively reinforce one another in driving the overall process for on-site industrial water reuse/recycling implementation. Guidance on topics related to planning, predesign, design, and implementation of reuse/recycling projects specific to industrial facilities also needs to be developed.

Table ES.4. Major Research Topics Identified for Promoting and Expanding Industry Use of On-Site Water Reuse/Recycling

Finance

- Develop ROI calculator based on the true cost of water.
- Identify and seek means to further develop subsidies and public–private partnership opportunities that promote on-site water reuse/recycling.

Technology

- Identify and further develop treatment technologies for critical industrial sector needs (e.g., salt-handling capabilities with an economical sink, recalcitrant organics).
- Compile the latest technology developments, their benefits over traditional alternatives, and areas of demonstrated applicability.
- Develop cost-effective ZLD applications.
- Identify and develop technological criteria for standardization of treatment skids to address specific reuse/recycle applications as identified by a cross-industry working group.

Communication

- Develop strategies and tools to promote a circular economy corporate culture that will drive water reuse/recycling implementation.
- Create knowledge-sharing platforms between different industrial groups with similar needs where industries can learn from one another regarding water management.
- Compile and continually update case study information relative to water management through a cross-industry working group.

Guidance

- Document design criteria for new facilities that promote utilization of marginal waters.
- Document auditing procedures for existing facilities that promote water reuse/recycling practices.
- Document treatment and residuals criteria and model treatment schemes for different industrial sectors.
- Document validation protocols for process train solutions.
- Document water reuse/recycling criteria for generic water usage categories that cut across industrial sectors (e.g., thermodynamic, conveyance, environmental controls, facility sanitation, process, irrigation).
- Integrate water reuse/recycling options within existing water footprint/scarcity tools.

Notes: ROI=return on investment; ZLD=zero liquid discharge.

Chapter 1

Introduction

1.1 Background

The business case for the sustainable use of water is continually increasing as a result of greater competition for this finite resource that has heightened water's strategic role in risk mitigation (Global Environmental Management Initiative [GEMI], 2002a). Water-related risk can be categorized as physical, regulatory, or reputational (World Wide Fund for Nature [WWF], 2011; CEO Water Mandate, 2013). Physical risk occurs when regional water supplies are not always available at the quantities or qualities needed to adequately support the myriad community needs (Hejazi et al., 2014; WWF, 2011). Regulatory risk relates to restrictions that are placed on water use by federal, state, and local government agencies regarding pricing of water supply and wastewater discharge, licenses to operate, water rights, and water quality standards (WWF, 2011). Reputational risk relates to a company's brand or image that can be tarnished by business decisions that are seen to negatively impact aquatic ecosystems or a community's access to clean water (WWF, 2011).

1.1.1 Water Risk

Water risk can become particularly prevalent because of the critical interdependency of water and energy use, wherein a change in the supply or demand of one has an impact on the other (Electric Power Research Institute [EPRI], 2003; U.S. Department of Energy [U.S. DOE], 2014). Heavy water usage in the industrial sector arises not just from direct freshwater withdrawals and utilization of public water utility services, but also from the water used to create the energy needed for water treatment, pumping, and on-site heating, cooling, and additional pumping (EPRI, 2003 American Society of Mechanical Engineers [ASME], 2010; U.S. DOE, 2014). Therefore, prudent industrial use of water is driven by water- and energy-related costs, customer/shareholder expectations for environmentally sound corporate decision making, and maintaining a license to operate by adequately addressing the sustainability impacts of an industry's operations (GEMI, 2002b). One strategy industries can consider to minimize global water and energy risks is optimization of on-site water reuse and recycling opportunities.

Regional water availability for industrial use is impacted by numerous factors. These include location of existing freshwater resources, historical water management, competing interests, development-related pollution and climate change (UNEP, 2008; U.S. DOE, 2014). The United Nations Environmental Programme has numerous maps that project global changes in water availability resulting from different factors. Figure 1.1 shows the projected change in water availability caused by climate change. Worldmapper is a collection of world maps; territories are resized on each map according to a subject of interest, and the industrial water use map for the 10 highest and lowest industrial global water users is available on the site.

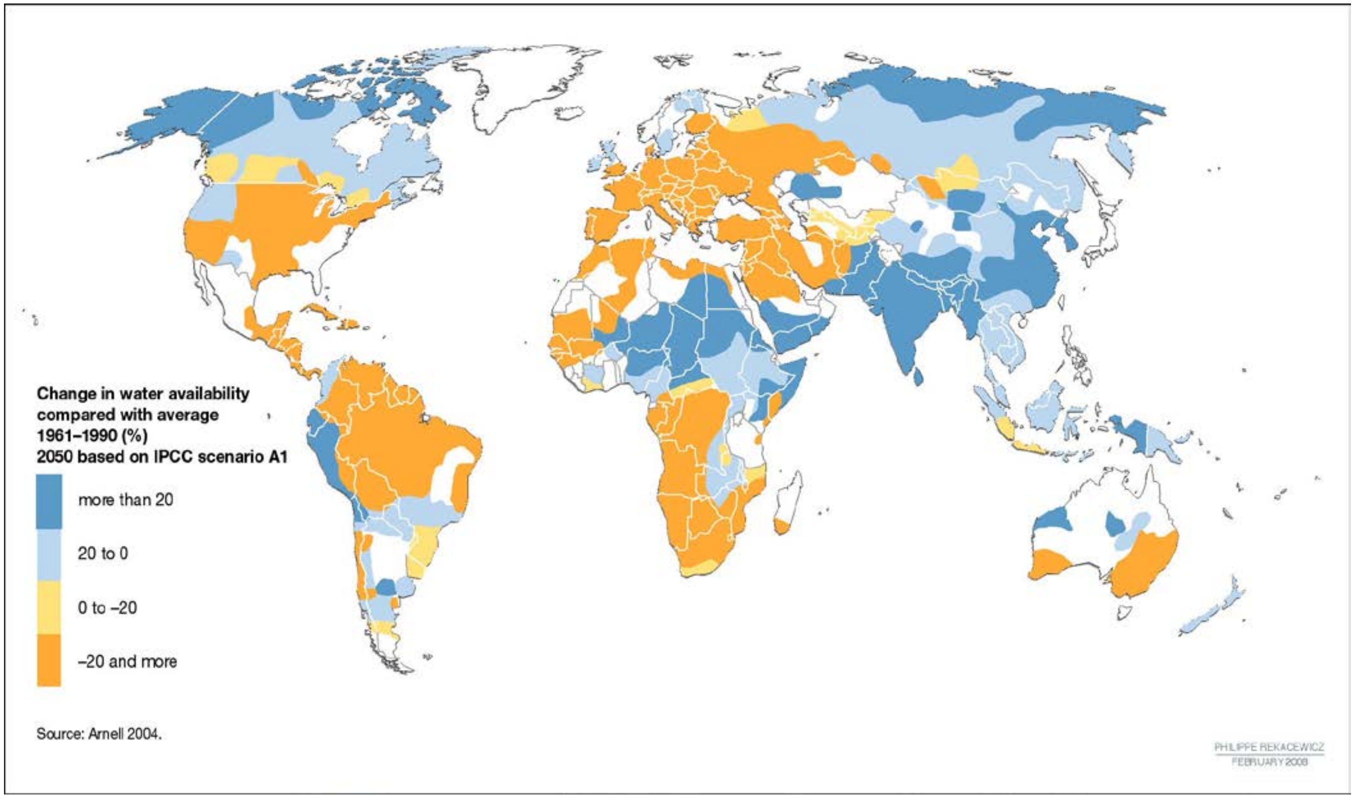

Figure 1.1. Projected change in water availability caused by climate change.

Source: http://www.unep.org/dewa/vitalwater/jpg/0407-runoff-scenario-EN.jpg

A manufacturing water use model demonstrated that manufacturing water withdrawal increased by a factor of 3.6, and water consumption increased by a factor of 7 between 1950 and 2010 through simulations made utilizing the manufacturing gross value added (GVA) economic metric as the demand driver of past and current manufacturing water use (Flörke et al., 2013). Flörke et al. (2013) stated that manufacturing water use leveled off between 1980 and 2000 despite rising GVA because of enhanced recirculation of process and cooling water, but shifts in global manufacturing from American and European economies toward the Chinese and Southeast Asian economies over the last decade have resulted in increasing industrial water use in the manufacturing sector in these regions.

Summaries of existing tools for assessing water risk for different target groups (i.e., investors, facilities, companies, academics, regional groups) indicate that they differ in granularity, ease of use, and ability to quantify risks (WWF, 2011). GEMI has a corporate-level water sustainability tool for the design of a company water strategy and a facility-level operational guidance for a situational water resources assessment. The corporate-level water sustainability tool consists of five modules that assist the user in assessing: (1) key water uses, impacts, and sources; (2) prioritization of business risks linked to water uses; (3) existing opportunities for addressing water-related risks; (4) business case for pursuing a water sustainability strategy; and (5) strategy development and implementation (GEMI, 2002b).

The facility-level operational guidance contains three modules that include: (1) facility water use data needed for input into a water–chemical mass balance program; (2) water management risk questionnaire; and (3) reference program for identification of case studies and reference links (GEMI, 2007). The link to the GEMI Local Water Too (LWT) and the GEMI® LWT Oil and Gas can be found online. Other corporate-level water sustainability tools include the World Business Council for Sustainable Development (WBCSD) Global Water Tool that allows companies to map their water use and assess risks relative to their global operations and supply chains (http://www.wbcsd.org/work-program/sector-projects/water/global-water-tool.aspx). This tool is regularly updated with improved data sets and functionalities, has been customized to various industrial sectors (oil and gas, power utilities), and is being adapted to specific geographies (India, China under development, Europe under development). Specific industries (e.g., oil and gas) have also begun to issue guidance documents to provide companies within their industrial sector with comparative information on the potential applicability of currently available water-risk tools relative to their business needs (e.g., International Petroleum Industry Environmental Conservation Association [IPIECA], 2014).

1.1.2 Water Use Sustainability and Efficiency

Industries track the ongoing success of their operations in achieving corporate sustainability goals through use of key performance indicators (KPIs). Seven water-related indicators cited by the Global Reporting Initiative (GRI) to provide consistent and harmonized approaches to indicator measurement for sustainability reporting are: (1) total water use, tracked as withdrawal and consumption; (2) significant discharges to water as point or nonpoint sources; (3) water source withdrawal impacts on related ecosystems/habitats; (4) annual withdrawals of local source water as percent of annual renewable quantity of water available from that source; (5) total recycling and reuse of water as a measure of water use efficiency; (6) impacts to water sources and related ecosystems/habitats from discharges of water and runoff; and (7) ratios of water use and pollutant loads to amount of product produced (GRI, 2003). The GRI, which offers detailed guidelines for measuring and documenting these indicator parameters, demonstrates how water reuse/recycling is just one of many water KPIs that are tracked.

Conducting a water inventory and auditing process is the foundation for determining cost-effective water efficiency measures. A water audit consists of three key actions: (1) gathering current and documented information relevant to water use within the facility; (2) performing a water–chemistry mass balance by surveying the facility relative to water volume and quality needs and losses; and (3) determining the true cost of water use (California Department of Water Resources, 1994). A water audit also helps an industry to understand which suite of best management practices will be most effective (State of California, 2013).

Industries typically first address regional water limitations through implementation of water conservation practices because these provide the most economical option. More costly water reuse/recycling programs are initiated in order to bridge remaining supply gaps or minimize wastewater discharges that cannot be cost-effectively treated to meet receiving water body quality standards or maintain a license to operate. These industrial water reuse/recycling efforts can utilize off-site treated wastewater supplies (e.g., municipal effluent, degraded sources) or implement on-site treatment of wastewater streams. In California, 22 agencies collectively provided 50,416 acre-feet per year of treated wastewater to industries (California State Water Resources Control Board, 2009). On-site treatment of wastewater streams usually offers the following benefits over the use of off-site recycled water: (1) less conveyance infrastructure and associated conveyance energy utilization;
(2) lower water utilization; and (3) decreased discharged water volumes.

1.1.3 On-Site Water Reuse and Recycling

The terminology utilized in the literature for on-site water reclamation is often unclear. The best definition of the three types of on-site water reclamation are shown in Figure 1.2 (adapted from Klemeš, 2012), in which utilization of wastewater from Operation 2 as input to a lower quality Operation 1 without the need for treatment is referred to as "reuse"; utilization of wastewater from Operation 2 back around as input to Operation 2 following suitable treatment regeneration is referred to as "regeneration-recycling"; and utilization of wastewater from Operation 2 to a different Operation 3 that occurs following treatment is referred to a "regeneration-reuse."

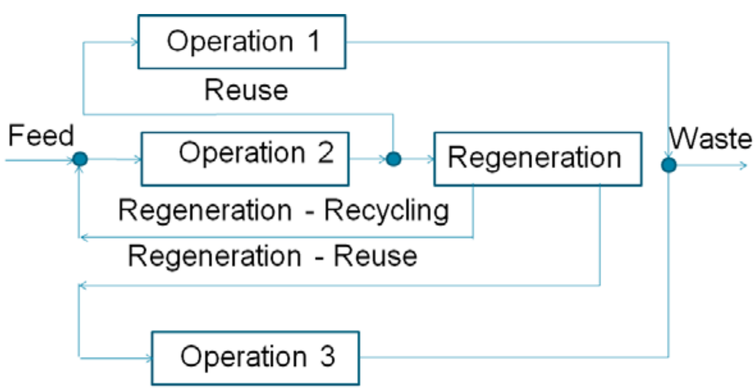

Figure 1.2. Definitions of on-site industrial water reclamation practices.

Source: Klemeš, 2012.

The ultimate goal of efficient water use within a process industry is the achievement of zero liquid discharge (ZLD) or a system of closed loops, which can be approached by modeling the following problem statement:

> Given a set of water-using/water-disposing processes and a set of treatment processes, it is desired to determine a network of interconnection of water streams between the processes, and between the processes and the treatment units, so that the overall freshwater consumption is minimized or completely eliminated, while each of the processes receives water of adequate quality. (Koppol et al., 2003).

Extensive literature exists on utilizing process integration analysis (i.e., “pinch” analysis) as a methodology for achieving a target resource usage rate for a single process or defined boundary of processes by optimizing the arrangement of the mass exchange networks to minimize resource consumption within a manufacturing process (Byers et al., 2003).

The fundamentals of pinch analysis, originally developed for energy applications at the University of Leeds in the late 1970s, have been applied to water resource applications (Wang and Smith, 1994) and provide the foundation for many water use optimization analyses performed by industry in recent years (Agana et al., 2013) for wastewater regeneration reuse, wastewater reuse, and wastewater regeneration recycle loops (Mehrdadi et al., 2009). Koppol et al. (2003) evaluated ZLD solutions for case studies with single and multiple contaminants using different solution procedures for these contaminant systems. The case studies showed that ZLD is not always possible because of a lack of adequate treatment strategies, and that the cost feasibility of demonstrated ZLD or partial liquid discharge cycles was determined from the relationship between the regeneration and freshwater supply costs as well as the discharge concentration of the treatment.

1.1.4 Water Reuse and Recycling Incentive Programs and Research Partnerships

Water reuse and recycling investments tend to be driven in the short term by regional water scarcity concerns or wastewater discharge limitations that create beneficial economics for water reuse/recycling. To further drive large-scale, corporate-level water reuse/recycling implementation, a culture embracing effective incentive structures at the government level in various policy areas should provide additional motivating factors. Such water policy areas include (1) water pricing that reflects scarcity or external environmental costs through adjusted increasing block tariffs or provision of rebates and rate reductions for water reuse; (2) water quality trading programs that encourage water reuse and recycling investments by offering incentives for reductions below discharge limits; (3) production tax credits or investment tax credits for water reclamation/reuse implementation; and (4) public–private partnerships such as tax-exempt private activity bonds that are issued by or on behalf of local governments, with the proceeds of their sale used to finance private projects (General Electric [GE], 2011). Guidance on how industries can utilize collective action to achieve responsible business engagement in establishing effective water policy is provided in the 2013 CEO Water Mandate website (http://ceowatermandate.org).

Financial incentives to industrial water users in the United States have recently been offered through the 2014 Water Resources Reform and Development Act, which allows private-sector companies to obtain Clean Water State Revolving Fund (CWSRF) loans to construct on-site industrial water reuse facilities, effective October 1, 2014 (https://watereuse.org/wp-content/uploads/2015/01/Industrial-Reuse-CWSRF-WP.pdf). The CWSRF program is administered through state programs that operate as infrastructure banks to provide eligible borrowers access to much lower interest rates than those available from the bond market or bank loans. These lower interest rates for capital costs incurred for construction of new facilities or the rehabilitation of existing facilities have the potential to help drive on-site water reuse or recycling projects. The flexible repayment options can also provide greater financial stability and decrease risk associated with implementation of new technologies, provided that program requirements related to environmental review, exclusive use of U.S. manufactured iron and steel products, and Davis–Bacon Act wage rates can be met for the construction assisted by the CWSRF program funds. The likelihood of a successful funding request is dependent upon the project's fit with the state's project priority system, summarized in each state's annually released Intended Use Plan.

Research incentives to industrial water users in Europe have occurred through the Seventh Framework Programme of the European Commission's AquaFit4Use project focused on "water fit for use" for the four industrial categories of chemical, paper, textile, and food. This project focused on the six issues of (1) water quality, definition, and control; (2) modeling and monitoring; (3) water treatment technologies; (4) sustainable water management; (5) pilot cases in the four target industries; and (6) knowledge transfer and dissemination, with a website providing information relative to project findings (http://www.aquafit4use.eu).

1.1.5 Water Reuse and Recycling Best Management Practices

Several recent documents on industrial water best management practices consider water reuse and recycling options in addition to water efficiency practices. A brief summary of these documents is provided in Table 1.1 and the rest of this subsection.

Table 1.1. Agencies Producing Best Management Practices for Industrial Water Reuse/Recycling

Lead Agency/Citation	Background Rationale	Document Title	Key Needs
American Society of Mechanical Engineers (ASME, 2010)	ASME seeks to be a key resource in the development and integration of water management technology solutions that enable the sustainable use and reuse of water.	"Best Management Practices and Innovations for the Process Industries, Final Report, June 2010," developed from a by-invitation-only workshop on industrial water use for the process industries, held on May 13–14, 2009, in Washington DC.	• Determine 10 action items for ASME's role in promoting industrial water treatment and reuse. • Identify nine barriers and challenges. • Identify nine needs and opportunities.
State of California Report to the Legislature by Commercial, Institutional, and Industrial Task Force Members (State of California CII Task Force, 2013)	Report required by California Senate Bill SB X7-7 that directed the Department of Water Resources, in coordination with the California Urban Water Conservation Council, to convene a task force to develop best management practices for the commercial, industrial, and institutional water sector of California.	Commercial, Institutional, and Industrial Task Force Water Use Best Management Practices Report to the Legislature, October 2013	• Improve regulations to promote recycled water use. • Encourage financial and technical assistance to increase recycled and alternative water use. • California Energy Commission should consider allowing offsets for use of recycled water at power plants.

ASME Document

The ASME document (2010) summarized the findings of a by-invitation-only workshop in Washington, DC in 2010. The workshop focused on defining ASME's role in promoting industrial water treatment and reuse practices, identifying barriers and challenges to water treatment and reuse, and identifying the needs and opportunities for water treatment and reuse.

The following action items were identified in defining ASME's role in promoting industrial water treatment and reuse practices:

1. Establish a community engagement platform on industrial water reuse management technology
2. Give ASME awards/recognition for outstanding water reuse projects, equipment, and activities
3. Develop industry-specific workshops to promote and capture best management practices
4. Produce industry case study resource guide
5. Create water efficiency codes and standards within areas of expertise
6. Use thermal pinch experience to promote water pinch
7. Develop an online tool analogous to the Produce Water Management Information System
8. Define "10 Great Challenges" for industrial water reuse
9. Identify industries best suited for water reuse
10. Establish benchmarking through case studies

The following barriers and challenges to water treatment and reuse were identified:

1. Technology feasibility
2. Regulatory compliance
3. Management
4. Economics
5. Public perception and health
6. Lack of training
7. Lack of information
8. Contaminants and residuals management
9. Water rights

The following needs and opportunities for water treatment and reuse were identified:

1. Research to fill in the knowledge gaps
2. Increasing public awareness of the benefit of water reuse
3. Correlation of energy and carbon dioxide (CO_2) impacts with water savings through water reuse
4. Technology transfer and education
5. Testing facility for new water management technologies to reduce risk for industries
6. Improvements in instrumentation and controls
7. Complete solution offerings—entities that design, build, and operate systems

8. Increased interaction between U.S. Environmental Protection Agency (EPA) Office of Research and Development and industry to promote research
9. Development of an online tool analogous to the Produced Water Management Information System to help identify technology solutions for water treatment and reuse in industrial plants

State of California CII Document

The CII document (State of California CII Task Force, 2013) fulfilled a legislated requirement to report on best management practices for the CII water sector of California. The document defines eight generic categories of water usage that can potentially occur within industrial facilities.

These eight categories are listed with estimates of their range of consumptive water provided in parentheses:

1. Cooling (60–85%) and boiler (65–97%)
2. Cogeneration and energy recovery (not reported)
3. Processes (5–90%)
4. In-plant conveyance (not reported)
5. Cleaning (10–50%)
6. Environmental controls (not reported)
7. Sanitation, including food services (2–8%)
8. Irrigation of landscapes (97–100%)

Categories with lower consumptive use caused by evaporation or higher volume, lower concentration streams offer the best opportunities for water reuse/recycling strategies, provided that existing minerals, salts, and any added chemicals can be effectively utilized in another process requiring lower water quality (reuse or regeneration/reuse) or suitably treated before being used again in the same process (regeneration/recycling).

The document also provides an assessment of water use activities commonly found in specific manufacturing sectors, and a simplified derivative summary is provided in Table 1.2. Several sources of on-site, nonpotable water were cited that could be captured and used at CII facilities in place of potable water. These on-site sources include rainwater harvesting, stormwater harvesting, air conditioner condensate, cooling tower blowdown, reverse osmosis (RO) and nanofiltration (NF) reject water, graywater, on-site treated wastewater, foundation drain water, and boiler blowdown.

There is generic discussion of common treatment technologies and the types of wastewater contaminants they remove, although the type of treatment required in specific applications is stated to be dependent on the application and the required water purity for the intended use. Many industrial processes require a level of water quality that must be higher than potable water. This is particularly true for certain thermodynamic processes, such as low-pressure boiler feed, in which hardness must be removed; high-pressure boiler feed, in which other salts must be removed; and industries that require ultrapure water (e.g., microelectronics manufacturing, pharmaceutical). Some industries (e.g., food and beverage, pharmaceutical) also have regulations that prevent the use of reclaimed water directly in their products for health and safety perceptions.

Table 1.2. Water Use Activities Commonly Performed in Specific Manufacturing Sectors

	Aero-space[1]	Plating, Printed Circuit Boards, and Metal Finishing	Food and Beverage[2]	Petroleum Refining and Petro-chemical	Pharmaceuticals and Biotech[2]	Power
Molding, casting, milling, and cutting	X					
Welding and quenching	X					
Parts and cleaning	X	X	X	X	X	
Air scrubbers	X	X	X	X[4]	X	X[4]
Painting	X					
Irrigation	X	X			X	
Cooling towers	X	X	X	X	X	X
Boilers	X	X	X	X	X	X
Refrigeration			X			
Energy recovery and cogeneration			X	X		
Sanitation	X	X	X	X	X	
Food service	X	X	X			
Fluming			X			
Process water	X[3]	X	X	X	X	
Chemical solutions makeup		X		X		
Water treatment	X[3]	X	X			
Laboratory	X[3]		X			

Notes: [1] Includes NAICS 336411, 336412, 336413, 336414, 336415; excludes support industries 332510, 332710, 332721, 332722, 332912. [2] Excludes water used in product, as regulations prohibit uses of reclaimed water for this application. [3] Not denoted in CII document, but water use known to occur in aerospace industrial sector. [4] Not denoted in CII document, but water use known to occur for air scrubbers in these other industries.

1.2 Project Goal

The WateReuse Research Foundation began providing water reuse/recycling research support to industrial water users in 2012 by funding an initial project titled "Analysis of Technical and Organizational Issues in the Development and Implementation of Industrial Reuse Projects (WRRF-12-03). The focus of this first project was to develop a better understanding of the application potential of off-site treated wastewater as a supply of reuse water for industrial facilities. This project (WRRF-13-04) is exclusively focused on the potential of reusing/recycling on-site industrial waste streams (i.e., retention of water within a given facility that has already served a useful purpose and then putting the same water to use again for a beneficial purpose within the same facility; EPRI, 2008). In compliance with this definition, this report will not include consideration of on-site water sources that have not already served a useful purpose. Such sources include harvested stormwater and foundation drain water.

On-site water reuse/recycling is less clearly delineated for the industrial sector than it is for the municipal sector. This is due to the diversity of industrial facility processes, the proprietary nature of industrial corporations, the wide and more exotic variety of constituents that can be present in industrial process–generated wastewaters, and the greater need for a rapid return on capital investments or subsidized economic incentives. Therefore, the goal of this project is to obtain a greater understanding of the drivers, successes, challenges, and opportunities for implementing and further developing on-site industrial water reuse and recycling practices.

Chapter 2

Project Approach

The project approach consisted of performing several tasks in order to better understand the drivers, successes, challenges, and opportunities for development of on-site industrial water reuse/recycling practices. These tasks included:

- *Industrial Sector Classification*—selection of a classification standard for the organization of companies and corporations into different industrial sectors
- *Peer and Gray Literature Review*—consolidation of the widely dispersed information available on this topic in peer-reviewed and gray literature and webpages
- *Industry Survey*—creation of survey questions and compilation of the survey responses obtained from the project industry participants in order to understand water reuse/recycling practices within the context of process water needs
- *Vendor Outreach*—review of major vendor products available for industrial reuse and recycling practices and process design
- *Workshops*—organization of workshops attended by participating industries and technology vendors focused on developing a research road map to enhance implementation of on-site industrial water reuse/recycling practices

2.1 Industrial Sector Classification

There are several industrial classification standards that organize companies into sectors based on similar production processes, products, or behavior in financial markets. These taxonomies are sponsored by different organizations and differ in geographical scope, as summarized in Table 2.1. The North American Industry Classification System (NAICS) utilizes a six-digit code, with the first two digits designating the largest business sector, the third digit designating the subsector, the fourth digit designating the industry group, the fifth digit designating the NAICS industries, and the sixth digit designating the national industries. For this report, the first two digits of the NAICS are utilized for classifying industrial sectors, as shown in Table 2.2, and only Sectors 21, 22, and 31–33 (i.e., mining, oil and gas extraction, power, and manufacturing) were evaluated for on-site industrial water reuse/recycling efforts.

Table 2.1. Industrial Sector Classification Systems

Abbreviation	Full Name	Sponsor	Comments
ISIC	International Standard Industrial Classification of All Economic Activities	United Nations	
NAICS	North American Industry Classification System	United States, Canada, and Mexico	
NACE	Statistical Classification of Economic Activities in the European Community	European Community	
ANZSIC	Australian and New Zealand Standard Industrial Classification	Australia and New Zealand	
SIC	Standard Industrial Classification	United States	Superseded by NAICS, but still utilized by U.S. Securities and Exchange Commission
ICB	Industry Classification Benchmark	FTSE International Ltd.	British provider of stock market indices, wholly owned by London Stock Exchange
GICS	Global Industry Classification Standard	Standard & Poor's, Morgan Stanley Capital International	American financial services companies
UKSIC	United Kingdom Standard Industrial Classification of Economic Activities	United Kingdom	
TRBC	Thomas Reuters Business Classification	Thomas Reuters	Multinational mass media and information firm
SNI	Swedish Standard Industrial Classification		

Source: Adapted from Wikipedia.

Table 2.2. North American Industry Classification System

Sector	Description
11	Agriculture, forestry, fishing, and hunting
21	Mining, quarrying, and oil and gas extraction
22	Utilities
23	Construction
31	Food and beverage, textiles, apparel manufacturing
32	Wood product, paper, printing, petroleum, chemical, plastics/rubber, nonmetallic mineral manufacturing
33	Metal manufacturing (includes electronics, semiconductor, motor vehicle, aerospace, furniture)
42	Wholesale trade
44–45	Retail trade
48–49	Transportation and warehousing
51	Information
52	Finance and insurance
53	Real estate
54	Professional, scientific, and technical services
55	Management of companies and enterprises
56	Administrative and waste management
61	Educational services
62	Health care and social assistance
71	Arts, entertainment, and recreation
72	Accommodation and food services
81	Other services (except public administration)
92	Public administration

Note: Only Sectors 21, 22, and 31–33 are considered in this report for on-site water reuse/recycling efforts.
Source: Adapted from the U.S. Census Bureau (http://www.census.gov/cgi-bin/sssd/naics/naicsrch?chart=2012)

2.2 Literature Review

The literature review was performed by searching appropriate keywords using Elsevier's Scopus bibliographic database. Scopus provides access to more than 15,000 peer-reviewed titles from more than 4000 publishers, including more than 12,850 academic journals, 28 million abstract records, 13 million patent records, and 250 million scientific webpages, with the physical sciences most heavily covered and represented by 5500 source titles (Sullo, 2007). Scopus provides the same citation searching option that is available in Web of Science and may be more useful for recent literature because of its limited citation coverage of references prior to 1996 (Sullo, 2007). Suitable articles were obtained via links through the Johns Hopkins University library. Additional gray literature was obtained through review of

2010 through 2013 Water Environment Federation Technology Conference proceedings papers and Google and Google Scholar Internet searches.

Key words utilized during the searches included: "industrial water reuse/recycling," "cooling towers," "semiconductor water reuse/recycling," "food and beverage water reuse/recycling," "pharmaceutical water reuse/recycling," "power industry water reuse/recycling," "manufacturing water reuse/recycling," "water pinch," "industrial ZLD," "mining water reuse/recycling," and "oil and gas water reuse/recycling." The majority of the captured publications were published in 2010 or later, unless they were considered to be a seminal work or a topic lacking activity in recent years.

There is a tremendous amount of disparate information related to the topic of industrial water use and a large number of publications on treatment issues related to meeting industrial-process discharge requirements, particularly in China and Southeast Asian locations for "dirtier" industries such as textile dyeing and pulp and paper manufacturing. Although these publications contain information on the performance of various treatment technologies that could prove useful in regenerative reuse and recycling opportunities, these papers were not considered if they did not specifically attempt to treat the wastewater for the end objective of water reuse or recycling.

2.3 Industry Survey

A survey was distributed to the 21 industries in order to collect firsthand information on sector-specific water management and on-site water reuse/recycling practices. The survey consisted of 29 questions that were categorized into five subject topics, as summarized in Table 2.3. A copy of the full survey questionnaire is provided in Appendix A. Responses were received from 10 participants representing 17 discrete facilities, summarized in Table 2.4.

Table 2.3. Categorization of Distributed Survey Questions among Subject Topics

Subject Topic	Number of Questions
Water management	9
Water auditing	5
Water reuse/recycling drivers and strategies	9
Water reuse/recycling technologies	2
Water reuse challenges	4
TOTAL	29

Table 2.4. Characterization of Survey Responses by Industrial Sector

Industry Sector	NAIC	Corporations	Number of Facilities
Metal manufacturing	33	2	5
Food and beverage	31	3	3
Power	22	1	1
Mining	11	2	5
Chemical manufacturing	32	2	3
TOTAL		10	17

Note: NAIC=North American Industry Classification.

The submitted data were transferred to an Excel file in order to produce summary statistics and plots of the collected information. Analysis of the data for commonalities and differences in practice could then be compared with findings from the literature review.

2.4 Vendor Outreach

Vendor outreach consisted of generating summaries of commercial treatment products available for targeted contaminants and industries. This was achieved by collecting information from selected vendor websites and discussions with participating project vendors in order to augment information gathered during the literature review. The objective of this outreach was to create a preliminary relational database of vendor treatment product options for removal of industrial wastewater pollutant groups sorted by industrial sectors in order to achieve various end uses of the water.

2.5 Workshops

The goal for the project workshops was development of a research road map for evaluating implementation of on-site industrial water reuse/recycling practices. Prior to the workshop, participants were given a preliminary workshop agenda and participation guidance, as provided in Appendix B. The participation guidance was presented as a series of questions in order to get the workshop participants thinking about the types of drivers and impediments and sequence of steps needed to implement on-site industrial water reuse.

A total of three workshops were scheduled, with each to occur at a distinct geographic location (West Coast, Midwest, and East Coast). Only two workshops were completed because of unforeseen scheduling conflicts that could not be resolved for the East Coast workshop within the timeframe of the project. The two workshops were attended by a total of 10 individuals representing nine companies from the industrial sectors of mining (n=2), food and beverage (n=3), chemical manufacturing (n=1), metal manufacturing (n=2), and power (n=1)). The format of the two workshops was identical and began by allowing the industry participants to introduce themselves and describe their organization and any examples they had of water reuse and recycling projects. A brief presentation then provided some of the survey data findings within the context of relevant literature, and the goals and objectives were established for the subsequent breakout sessions. The purpose of the breakout sessions was to establish smaller groups of individuals for discussions on a series of road map–specific topics. The entire group was then reassembled, and each breakout group reported on its findings.

Each breakout group was tasked with completing four forms that focused on the following topic areas:

1. Similarities and differences between industries for on-site water reuse/recycling
2. Opportunities and drivers for implementing on-site water reuse/recycling
3. Challenges and obstacles to on-site water reuse/recycling
4. Potential solutions for overcoming cited challenges

MWH facilitators also captured comments and additional discussions that occurred as these forms were being completed. Each participant was asked to provide the following information prior to leaving the workshop:

1. Relative ranking of the ease of utilizing reclaimed water for the generic water-use categories
2. Potential for increasing use of reclaimed water for each generic water-reuse category
3. Identification of regulations and trade organizations impacting reuse implementation and ranking the importance of water reuse/recycling relative to other sustainability indicators

Chapter 3

Findings from Literature Review, Survey, and Vendor Technology Assessment

This section provides a compilation of the findings from the literature review, industrial project participant survey responses, and vendor technology assessment relative to the following suite of topics that are critical to understanding the drivers, successes, challenges, and opportunities for implementing on-site industrial water reuse/recycling efforts:

- Water Supply
  - Industrial sector needs
  - Generic water usage categorical needs
  - Water costs
  - Auditing practices
- Water Reuse and Recycling
  - Industrial wastewater streams
  - Drivers and opportunities
  - Technologies
  - Implementation advantages and challenges
  - Industry-specific case studies

3.1 Water Supply

It is important to distinguish between withdrawal and consumption when considering water supply requirements. Withdrawal refers to a volume of water that is removed from its source for an inconsequential period of time, whereas consumption refers to water that is removed from a source and not returned for one of the following reasons: (1) evapotranspiration; (2) product incorporation; (3) return to a different water body; or (4) return to the same water body after a significant time in on-site storage (Hoekstra et al., 2002). The term water use often denotes both withdrawal and consumption in the power industry because the use of water can occur as withdrawal for once-through wet-cooling or as consumption for closed-cycle wet cooling during the power production process (Strzepek et al., 2012). Both withdrawal and consumption can cause undesirable environmental consequences through the displacement of water from the local watershed or alteration of the quality of the returned water.

On a global scale, food production accounts for the highest percentage of human water consumption (70%), the industry and energy sectors collectively account for 20% of water consumption, and the remaining 10% is consumed in households (WWF, 2011). The power sector accounts for approximately half of industrial water withdrawals in the AQUASTAT database (AQUASTAT, 2012), with the remainder primarily used for manufacturing and a small portion used for mining and production of primary energy fuels (Hejazi et al., 2014). In California, industry represents approximately 7% of urban water use (State of California, 2013). Although water abstraction is slowing down in the industrial sector of many Western countries as a result of increased conservation and reclamation, it remains one of the heaviest sources of return flow pollution (Asano and Visvanathan, 2001), and further implementation of recycling and reuse would benefit the environment. The United States Geological Survey (USGS) estimates of water withdrawals by water-use category for the year 2005, as summarized in Table 3.1, demonstrate the dominance of the power industry compared with other sectors.

Table 3.1. Water Withdrawals by Water Use Category, 2005

	Freshwater Withdrawals		Saline Withdrawals	
Category	**(Mgal/d)**	**% of total)[1]**	**(Mgal/d)**	**(% of total)**
Thermoelectric power	143,000	41	58,100	95
Mining	2310	0.66	1710	2.8
Industrial	17,000	4.9	1190	2.0
Public supply	44,200	13		
Domestic	3830	1.1		
Irrigation	128,000	37		
Livestock	2140	0.61		
Aquaculture	8780	2.5		

Note: [1] Does not equal 100% because of independent rounding.
Source: Adapted from United States Geological Survey, 2005.

Industrial water use reporting at the government level tends to be restricted to industry as a single entity without breakout by industrial sector classifications, and corporate-level reporting tends to be inconsistent within and between sector classifications (Harling, 2009). Therefore, industrial sector-specific water use is most readily available in the literature on a sector-specific basis. Subsequent comparative assessment of water use can then be made from these individual assessments and the information obtained from the industrial survey participants of this project.

3.1.1 Industrial Sector Needs

3.1.1.1 Power Industry Sector (NAICS 22)

The largest industrial user of water in the United States is the power industry; 90% of the electricity is produced by thermoelectric power plants (Union of Concerned Scientists, 2012). Thermoelectric power plant water requirements are large because many plants utilize steam turbines as the prime mover to generate electricity (Veil, 2007; Ayert et al., 2011; U.S. EPA, 2013a), and the cooling system used to recondense the steam relies on wet rather than dry cooling. The cooling water is withdrawn for once-through wet cooling and consumed for recirculating closed-cycle, wet-cooling systems (Strzepek et al., 2012). Dry-cooled systems rely on air blown across steam-carrying pipes for cooling and therefore utilize almost no water, but they are inefficient when ambient air temperatures are high, and they are utilized at only a small fraction of newer power facilities. To comply with environmental standards promulgated in the early 1970s (U.S. DOE, 2006), most new power plants in the United States use recirculating cooling water systems and, to a lesser extent, dry cooling systems, but presently 43% of all U.S. plants, as shown in Figure 3.1 do not recirculate water (Tweed, 2014). Power generation accounted for 39% (136 Bgal/ day) of all freshwater withdrawals in the United States in 2000 (Feeley et al., 2008), 143 Bgal/day in 2005, and 4% of the total Texas water consumption in 2010 (Scanlon, 2013).

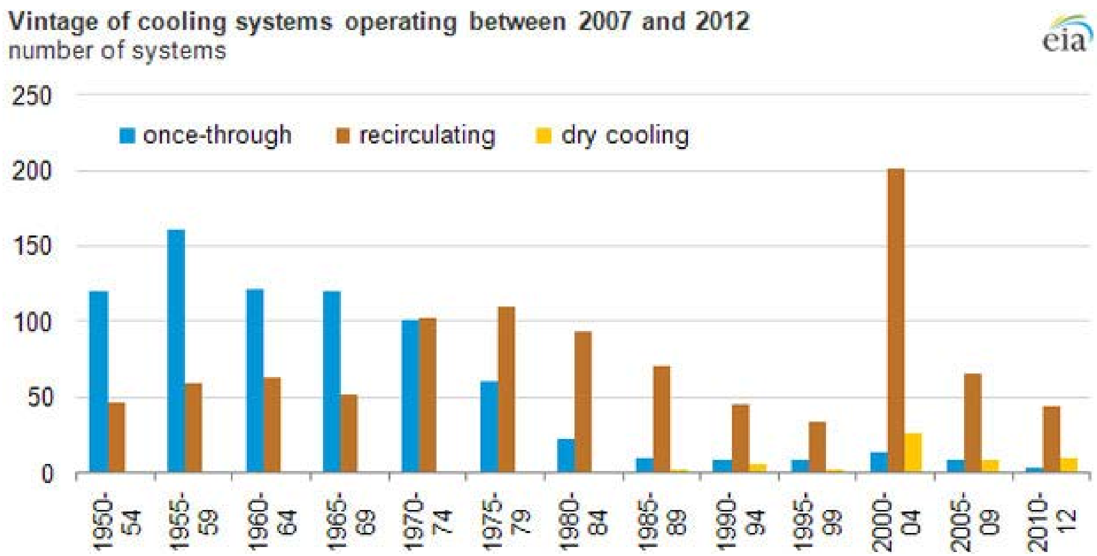

Figure 3.1. Evolution of U.S. power plant cooling systems.

Source: Tweed, 2014.

Water requirements for electric power generation are highly variable and influenced primarily by type of plant, fuel, and choice of cooling system and further by local climate, water source, environmental regulations to which the plant must comply, and the water management system employed (EPRI, 2008). A summary of national average water withdrawal and consumption factors for thermoelectric plants utilizing wet cooling towers is provided in Table 3.2 (Feeley et al., 2008). One way to reduce the amount of water used in a recirculating cooling tower is to increase the cycles of concentration (COC), which are dependent on the mineral content of the water. In China, 80% of coal-fired power units operate their water cooling systems with a COC of less than three. Water consumption can be improved when the COC in the cooling system is in the range of four to five (Pan et al., 2012). A plant with a 1000 to 1300 MW capacity would normally require around 60 to 80 million L/day of water for a COC of five to six (Power Engineering International, 2012), which translates to a consumption factor range of 0.51 to 0.88 gal/kWh.

Table 3.2. Summary of National Average Water Withdrawal and Consumption Factors for Thermoelectric Plants Utilizing Wet Cooling Tower, 2005

Generation Type	Withdrawal Factor (gal/kWh)	Consumption Factor (gal/kWh)
Pulverized coal	0.463–0.669*	0.394–0.518*
Nuclear	1.101	0.624
Oil and natural gas	0.25	0.16
Natural gas combined cycle	0.15	0.13
Integrated gasification combined cycle	0.226	0.173

Note: *Range is due to differences in boiler (subcritical or supercritical) and type of flue gas desulfurization (wet, dry, or none).
Source: Adapted from Feeley et al., 2008.

3.1.1.2 Mining and Upstream Oil and Gas Industry Sector (NAICS 21)

The mining industry is probably the second largest industrial user of water in the world after the power generation industry (Global Water Intelligence, 2011). Although the U.S. mining industry accounts for approximately 1% of total water withdrawals, it relies on a higher percentage of total water use from saline sources than the power industry does (U.S. Geological Survey, 2009). Water is used by the mining industry for multiple activities, including (1) transporting ore and waste in slurries and suspensions; (2) separating materials through chemical or physical processes; (3) cooling systems needed for power generation; (4) suppression of dust arising from processing, conveyors, and roads; (5) washing equipment; and (6) potable water to support mining staff in remote areas.

Unlike other industrial sectors, mining operations are fully reliant on the location of the ore, and a sustainable water management plan is critical to ensure that sufficient water is available for mining operations. This is particularly important because some of the largest mining operations exist within water-scares regions of North America, South America, Australia, and Africa, as shown in Figure 3.2 (Moody’s Investor Service, 2013).

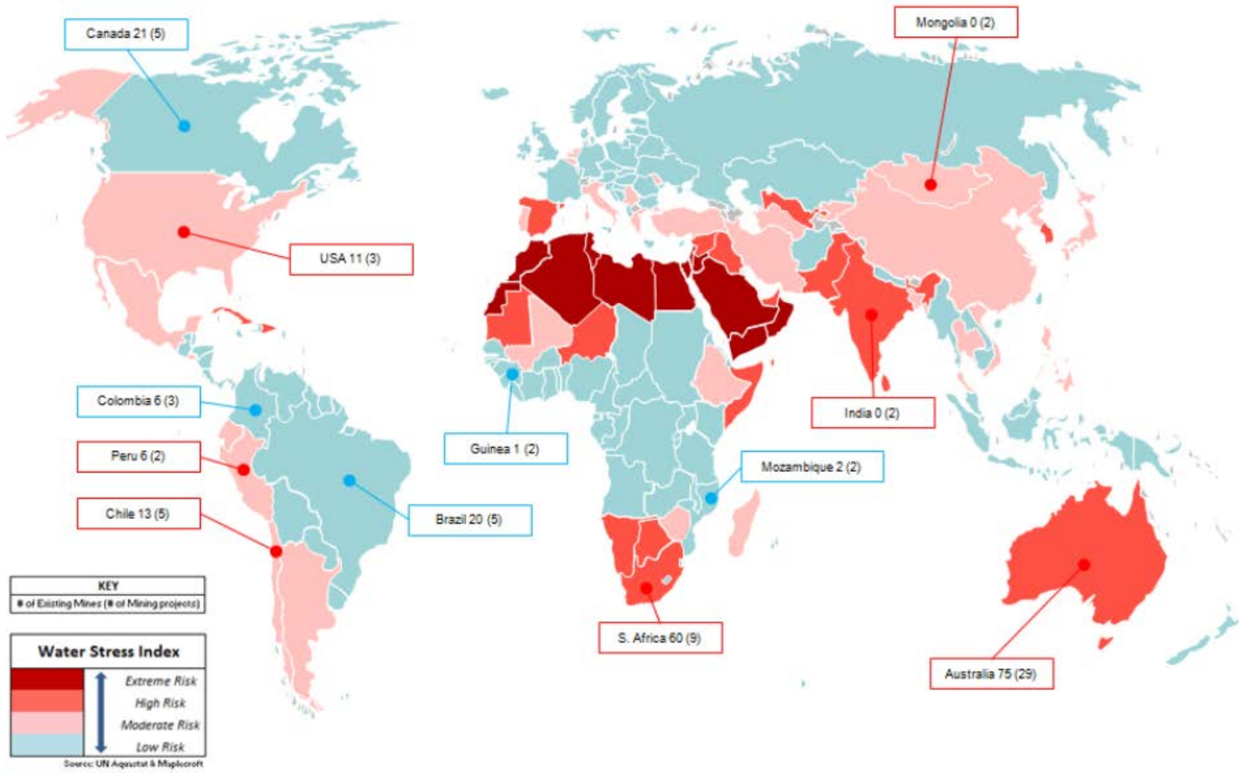

Figure 3.2. Water stress conditions in mining countries.

Source: Moody's Investor Service, 2013.

3.1.1.3 Food and Beverage Industry Sector (NAICS 31)

The food production industry accounts for more than two-thirds of all freshwater use worldwide and may require water of high quality for individual phases of production (Ait Hsine et al., 2005). Food processing refers to the activities that convert raw food materials to final consumable products, and beverage manufacturing includes the production of bottled and packaged fluids such as distilled spirits, beer and wine, soft drinks, bottled water, and ancillary products related to the processing industry, such as product and bottle manufacturing and storage (State of California, 2013). The food and beverage industry in California produces 89% of U.S. wine and more than $13 billion of processed fruits and vegetables a year, which is $1 billion more than the next two states combined (State of California, 2013). A 2006 study conducted by the California Energy Commission (CEC) found that total food processing water use accounted for approximately 37 billion gallons of water per year (exclusive of water needed to grow crops), as summarized in Table 3.3 (CEC, 2006, as reported in State of California, 2013). This is approximately 0.6% of the industrial water withdrawals reported in 2005 for the industrial sector by the USGS (Table 3.3).

Table 3.3. Water Use by Major Food Processing Industries in California

Food Processing Sector	Water Use (Mgal/Yr)
Fruits and vegetables	30,000
Cheese	600
Milk powder/butter	360
Beef	1200
Poultry	2000
Wine	2900

Sources: CEC, 2006; California Food Processing Technology Road Map, as reported in State of California, 2013.

The amount of water used and the way it is used vary by food product, but common uses include (1) thermodynamic processes (cooling towers, boilers, refrigeration, air conditioning, energy recovery, cogeneration, humidification); (2) environmental controls (air pollution, dust control, wastewater treatment); (3) process water use (inclusion in product, transport, washing, cooking, autoclaving, preparation, processing, canning and bottling, container cooling/warming, conveyor lubrication, pump seal water, and other uses), cleaning (clean in/out of place systems, can/bottle/package cleaning, transport vehicle cleaning, crate and pallet washing, other cleaning); (4) laboratory uses; (5) water treatment; (6) equipment cleaning; and (7) domestic uses (sanitation, irrigation; State of California, 2013).

Water use for most food products produced in Australia falls within 0.07 and 0.32 gallon per pound of product produced, with meat and meat products using considerably more water (>2 gal/lb of product) than other food processing industries (Australian Food and Grocery Council Sustainability Report, 2008–2009, as reported in State of California, 2013). For the North American bottled water industry, a water use ratio of 1.39 L/L was reported in 2011, which was a higher level of performance when compared to the 2011 global average for bottled water facilities, 1.47 L/L; this is still lower than the ratios for other beverage sectors such as carbonated soft drink bottling and beer production because of other water utilizing processes unique to these beverages, such as flavor mixing, blending, carbonation, and fermentation, that drive their water use ratio to approximately 2 L/L (IBWA, 2013).

Almost all food and beverage companies are now monitoring water consumption and have strategies and goals for minimizing usage in consideration of scarcity issues and rising costs (Williams, 2011). Although the beverage sector has been proactive in managing water issues compared to many other sectors, a lot of challenges remain regarding identification and evaluation of water risks and opportunities and a better understanding of the water dynamics of the production processes (BIER, 2012).

3.1.1.4 Manufacturing Industry Sector (NAICS 32–33)

Industrial water is defined as the water needed within a manufacturing facility for fabricating, processing, washing, diluting, cooling, or transporting a product; incorporating water into a product, or for sanitation needs within the facility (U.S. Geological Survey, 2004) . On a global basis, about twice as much water was used by industries than for domestic purposes (on average 665 billion m^3/year) between 1987 and 2003. Top industrial water users were countries in Eastern Europe (Bulgaria, Serbia and Montenegro, Slovenia, Republic of Moldova, Romania), North America (Canada and the United States), and Europe (France and Germany); (SASI Group and Newman, 2006). In Europe water use in the manufacturing sector has been compiled by country, year, and public versus self-supply, but there are numerous data gaps in this compilation (Eurostat, nd).

In the United States, industrial withdrawals in 2005 were estimated to be 18,200 Mgal/d, representing 4% of total withdrawals (see http://water.usgs.gov/edu/wuin.html). Nearly all of these withdrawals were freshwater, with 83% coming from surface water and 17% from groundwater. Louisiana, Indiana, and Texas accounted for 40% of the total industrial withdrawals. U.S. industrial withdrawals are probably lower than what has been reported on a global basis because of past offshoring of water-intensive industries and the non-overlapping timeframes of these data.

Industrial demand in China has nearly tripled between 1980 and 2007, and the industrial sector represents about a quarter of the country's water consumption (Hu and Cheng, 2013). Water consumption is also usually higher in developing countries, as demonstrated by the water consumption in the steel industry in India (25–60 m^3 water/ton of steel), which is 8 to 10 times higher than that in developed countries (Ranade and Bhandari, 2014).

Although statistics and models on regional water withdrawal by industry as a collective group are available, it is much more difficult to find or generate statistics on water use broken down by individual industrial manufacturing sector. Models, such as WaterGAP3, can be used to estimate current and future withdrawals and consumption in the manufacturing sector (Flörke et al., 2013), A Norwegian project funded in part by EUROSTAT attempted to develop a methodology based on statistical analyses of a sample survey to provide data for water abstraction and use for individual industrial NACE Codes 10 through 37 for the base year 2003. The Norwegian study results for 2003 are provided in Table 3.4; it was anticipated that the industry-specific coefficients for water use in the different categories would be further refined after collection of future data sets. Norwegian industries exhibiting high total water use included upstream oil and gas, metal mining, food and beverage manufacturing, pulp and paper manufacturing, coke and petroleum refining and manufacturing, chemical manufacturing, and metal manufacturing. Within the manufacturing sectors, the majority of the water was used for processing or cooling.

Table 3.4. Water Use in Norway by Industry, 2003

Industry	NACE Code	NAICS Code	Percent of Total
Mining	10–14	21	18.96
Food and beverage	15	31	3.71
Tobacco, textiles, apparel, leather			0.07
Manufacturing (wood, paper, chemical, nonmetallic)	20–26	32	57.39
Manufacturing (metals, machinery, equipment, furniture)	27–36	33	19.66
Recycling		37	0.21
TOTAL			100

Source: Adapted from Statistics Norway, 2006.

Water demand in a crude oil refinery was reported as approximately 0.7 m^3 water/m^3 processed oil, with 60% of the water consumed for the cooling tower system (Torres et al., 2008). The textile industry was cited as a higher consuming industrial manufacturing sector (i.e., >100 L/kg of processed fabric), with an estimated annual consumption of freshwater in European textile companies of 600 million m^3, with 90% of the input water on average needing end-of-pipe treatment prior to discharge (Vajnhandl et al., 2014). Textile industry wastewater discharge in China was approximately 7.5% of the total discharge of Chinese industrial wastewater in 2003. The automotive sector was cited as a less water- and energy-intensive branch of industry, but die casting, mechanical processing, paint finishing, and hardening are areas with a high potential for process water reuse and heat recovery (Enderle, 2012). Water use for different industries reported for India is summarized in Table 3.5.

Table 3.5. Water Use Reported for Industries in India

Industrial Category	Water Use (gal/lb)
Normal paper	~ 40
High quality paper	≤132
Petroleum	1.3–40
Chemical fertilizer	36
Automotive	4

Source: Adapted from Ranade and Bhandari, 2014.

3.1.1.5 Comparative Assessment of Water Needs by Industrial Sectors

Industries stated to use significant amounts of water include pulp and paper, iron and steel, tanning, food processing, textiles, refineries, electronics, and chemical production (Reardon, 2010), but it is difficult to assess water quantity requirements on a unit-production basis for multiple industries. This information often remains sequestered within corporations or trade associations. Published data on unit-production and survey-derived, facility/corporate annual needs obtained from participating industries are summarized in Table 3.6. What is immediately apparent is that industrial facility water use can range to three orders of magnitude, and only corporate-level, rather than facility-level, water needs approach those of the urban municipal water sector. Nonetheless, increasing global water strain has exposed the industrial sector to water-related production risks that will need to be addressed through increasing water conservation and reuse and recycling measures.

Table 3.6. Unit or Annual Basis Industrial Water Use

Industry	Vol/unit produced (from literature)	Mgal/Yr (Facility) (from project survey)	Bgal/Yr (Corporate) (from project survey)
Mining (NAICS 11)	5–54 gal/lb Cu [1]	212–4980	8–82
Power (NAICS 22)	0.1–1.1 gal/kWh [2] 8 gal/kWh [3]	118	-
Food and beverage (NAICS 31)	0.07–2 gal/lb [4] 1.39 L/L [5] 2 L/L [6] 1 gal/lb[7] 0.06 gal/klb[8]	85–318	3.5–66
Manufacturing (NAICS 32)	2–12 gal/lb[9]	-	732
Manufacturing (NAICS 33)		12–70	-

Sources: [1] Singh (2010). [2] Feeley et al. (2008) for thermoelectric power plants. [3] Torcellini et al. (2003) for hydroelectric power plants. [4] State of California, 2013. [5] IBWA (2013) for bottled water. [6] IBWA, 2013, for carbonated soft drinks. [7] BIER (2011) for water consumption for aluminum can body and lid. [8] BIER (2011) for glass container and steel cap. [9] Rupp (201l) for textile dyeing. Compiled from literature and survey.

Survey data from the project participants revealed, as shown in Figure 3.3, that average annual water use in the past 5 years did not exhibit any dominant trends, and the facilities where water use continually decreased attributed this behavior to implementation of conservation strategies and reuse/recycling or other factors such as site size reduction or changes to product lines or production volumes. Six of the seven respondents citing implementation of water reuse or recycling also reported constant or decreasing water use in the past 5 years, and they represent the food and beverage, mining, metal manufacturing, and chemical manufacturing industries. The only industry reporting highly variable water use from year to year was mining.

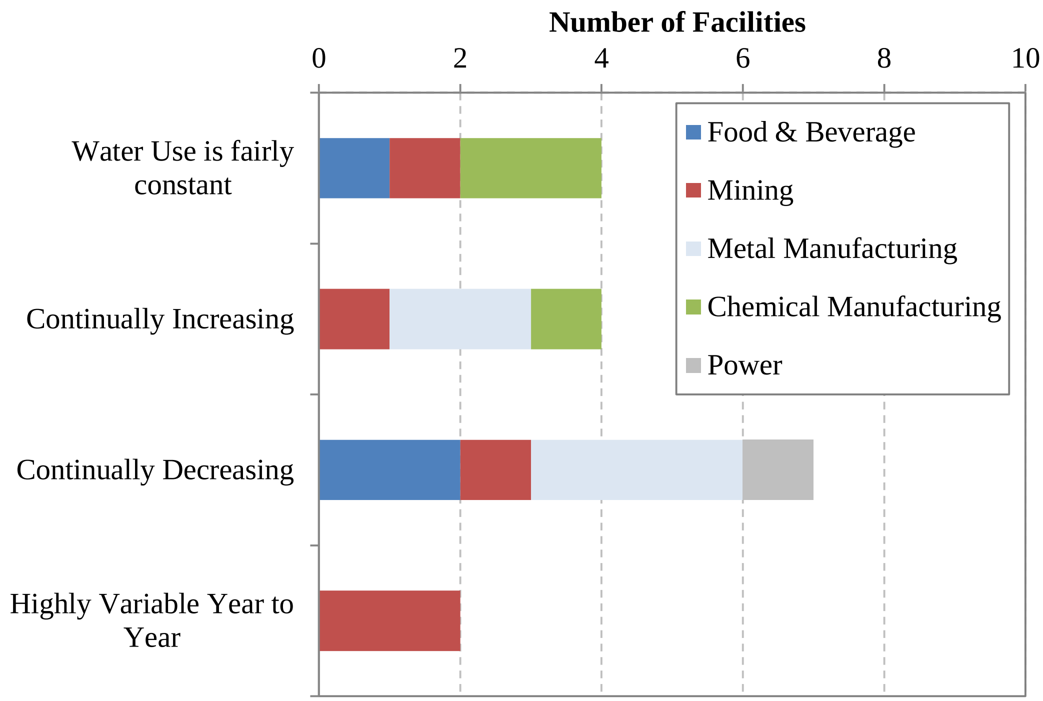

Figure 3.3. Participating industry survey responses on water use trend over the past 5 years.

3.1.2 Generic Categories of Water Use that Occur across Industrial Sectors

Industrial water is used in the following eight basic ways: (1) cooling and boilers; (2) cogeneration and energy recovery; (3) process; (4) in-plant conveyance; (5) cleaning; (6) environmental controls; (7) sanitation; and (8) irrigation of landscape (State of California, 2013). The three major uses of water within industry are for heat dissipation, power generation, and processing; 50% or more of the water intake to a plant is often used just for process cooling (Asano and Visvanathan, 2001). As shown in Table 3.7, the amount of water that is consumed and unavailable for reclamation can vary widely among these generic use categories. This will impact water reuse/recycling opportunities by (1) reducing the effluent volume and (2) impacting the effluent quality by a concentration of background minerals or salts and added process chemicals.

Data from the Norwegian study of water use by industry (Table 3.4) were further broken down in this study to show water usage across generic categories within each industrial sector. These data, adapted to show the generic category water use for each industry on a percentage basis, are provided in Table 3.8 and show that the highest percentage uses are for cooling water, processing water, and sanitary water.

Table 3.7. Percentage of Water Typically Consumed in Industrial Generic Use Categories

Generic Process Category	Percentage of Water Consumed in Process
Cooling tower	60–85
Boiler	65–95
Process	5–90
Process cleaning	10–50
Sanitation	2–7
Irrigation	>95

Source: Adapted from State of California, 2013.

Table 3.8. Literature-Reported Percentage of Water Consumed by Industrial Generic Use Categories

NACE Code	Total Annual (Mgal)	Sanitary (%)	Processing (%)	Cooling (%)	Water in Products (%)	Leakage and Evaporation (%)	Other (%)	Total (%)
10	51	76	24	-	-	0.06	-	100
11	86,097	0.17	0.0021	22	0.0015	0.0015	69	91
13	10,534	0.11	99	0.28	0.049	-	0.00077	100
14	2372	2.4	46	4.1	1.2	-	46	100
15	19,382	2.8	40	49	2.8	0.85	4.5	100
16	10	15	13	7.7	0.34	64	-	100
17	305	13	61	11	13	0.026	1.3	100
18	19	49	48		0.024	0.17	16	113
19	46	2.9	58	39				100
20	756	9.5	17	18	0.83	1.3	53	100
21	45,937	0.40	40	57	0.52	1.6	0.045	100
22	168	71	8.7	15	0.029	0.19	1.6	97
23	81,175	0.13	17	82	0.00006		0.86	100
24	166,641	0.50	8.6	90	0.37	0.24	0.097	100
25	505	19	22	51	0.14	0.21	7.9	100
26	4580	1.7	55	38	1.5	2.2	1.8	100
27	99,834	0.55	33	54	0.00079	2.0	10	100
28	701	14	5.9	78	0.29	0.058	1.1	100
29	286	62	7.4	8.8	0.37	2.8		81
30	1.7	55		44		1.6		100
31	224	29	1.1	69		0.016	0.36	100
32	50	66	30	0.79	0.34	0.079	2.7	100
33	61	91	2.3	1.9			5.1	100
34	1048	9.8	4.9	81		4.5	0.23	100
35	377	53	12	3.1	10	1.4	21	100
36	82	55	31	6.6	0.18	4.2	2.7	100

Notes: NACE=Nomenclature of Economic Activities; NAICS=North American Industry Classification System.
Source: Adapted from EUROSTAT, 2006. NACE code descriptions and cross-referencing with NAICS provided in Appendix C.

The average and maximum percentages of annual water use by category, as reported by the project survey participants collectively representing multiple industries, is provided in Figure 3.4, and it agrees fairly well with the Norwegian study findings. The highest average and maximum use were observed for product processing and cooling/boilers, with additional high uses also observed for process cleaning, environmental controls, and sanitation. Seasonal variations of higher water use in the summer were reported for cooling towers, boilers, and irrigation. A chemical manufacturer also reported a water use variation arising from a change in product demand that impacted inlet water quality. A food and beverage facility cited daily variations in water use from scheduled process or product cleaning schedules. Variations in water use for mining were strictly due to changes in tonnage throughput.

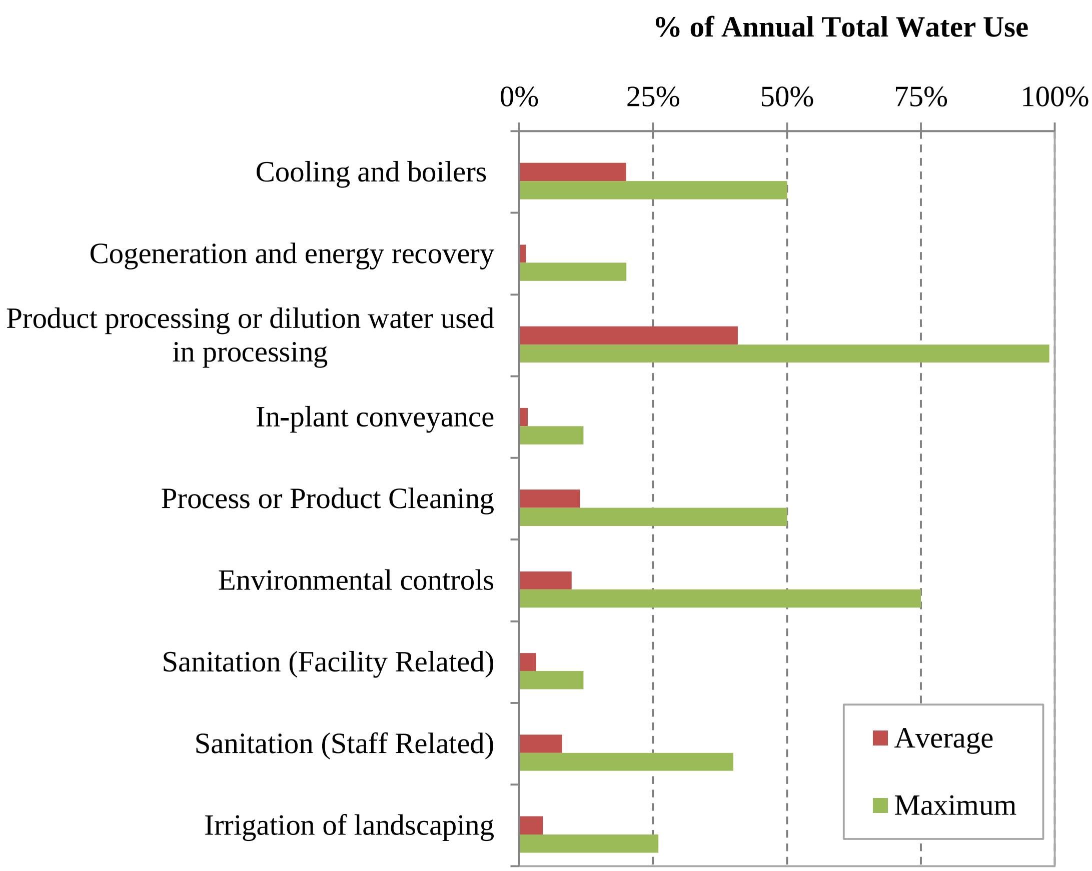

Figure 3.4. Survey-reported percentage of water consumed by industrial generic use categories.

3.1.3 Water Scarcity and Cost

Water is tremendously undervalued as a commodity and has traditionally been considered a free good, with charges affixed primarily to cover treatment and distribution (Mitchell, 1984). This undervaluation historically contributed to the impairment of water quality in developed areas (Jakimchuk, 1987) and a concern of surpassing peak ecological water, representing the point of human water use that causes serious or irreversible ecological damage to a watershed (Palaniappan and Gleick, 2013). As freshwater becomes scarcer, water prices are expected to increase as subsidies are phased out (Lambooy, 2011).

Ten of the 17 project survey respondents consider their water supplies to be strained, Their assessments were made through a variety of mechanisms that include (1) government agency assessments; (2) local municipality assessments; (3) water management district assessments; (4) use of water balance models, predominantly within the mining industry; (5) hydrogeological assessment and testing; and (6) use of World Business Council for Sustainable Development (WBCSD) Global Water and World Research Institute Aqueduct tools.

Water costs summarized in Table 3.9 (UN Educational, Scientific and Cultural Organization, UN Water, 2014) demonstrate that many countries subsidize water for agricultural purposes, whereas parity of costs exists for industrial and domestic water in many countries. In the Netherlands, France, and the United States, household water costs are substantially higher than industrial costs, whereas Hungary and Canada exhibit household water costs substantially lower than industrial costs.

Table 3.9. Cost of Water by OECD Nation

OECD Nation	Household Supply ($U.S./1000 gal)	Industrial and Commercial ($U.S./1000 gal)	Irrigation and Agriculture ($U.S./1000 gal)
Australia	6.2	6.2	0.076
Austria	4.0	4.0	3.8
Canada	2.6	6.0	0.038
France	12	3.6	0.30
Greece	4.3	4.3	0.19
Hungary	1.7	5.8	0.011
Netherlands	12	4.1	5.4
Portugal	3.8	4.8	0.076
Spain	4.0	4.1	0.19
Turkey	5.7	6.4	0.038
UK	8.6	6.4	0.076
USA	4.7	1.9	0.19

Note: OECD=Organisation for Economic Cooperation and Development (a multidisciplinary international body made up of 30 member countries).

Source: UN Educational, Scientific and Cultural Organization, UN Water, 2014

Reported water costs obtained from the survey participants, summarized in Table 3.10, correspond well with the literature values. One participant also reported a wastewater discharge cost of $3/1000 gal, compared with a cost of $1.90/1000 gal for city potable water. Therefore, avoidance of wastewater discharge costs is often a larger driver of water reclamation than avoidance of water supply costs.

Table 3.10. Cost of Water Reported by Survey Participants

Statistic (n=14)	Cost ($/1000 gal)
Range	0–11.00[1]
Mean	2.88
Mean	2.66

3.1.4 Water Auditing Practices

Governments have introduced new legislation and established tougher compliance strategies in order to regulate industrial operations and reduce the discharge of their process wastewaters to the environment. Water pinch offers a systematic technique for analyzing water networks and identifying projects that increase the efficient use of water in industrial processes; although simple savings in freshwater and wastewater are not likely to justify the cost of a water pinch study for retrofit alternatives, it should be part of new process design and incorporated into normal design procedures (Natural Resources Canada, 2003). In order to apply a water pinch analysis, purity profiles need to be developed for each contaminant, and a common piping network that performs well for all components needs to be identified using mathematical programming that optimizes trade-offs and minimizes system cost via water reuse subject to quality and quantity constraints (Natural Resources Canada, 2003).

The typical phases of a water pinch study for introduction of water reclamation opportunities to reduce wastewater treatment system cost consist of (1) a water–chemistry mass balance; (2) a water pinch analysis; and (3) a project identification and investment strategy road map (Natural Resources Canada, 2003). The key objective of the water pinch analysis is to identify the minimum freshwater targets and combinations of reuse and recycling alternatives and distributed wastewater effluent treatment options (i.e., stream segregation) that will be most cost effective (Natural Resources Canada, 2003). None of the project survey respondents utilize water pinch analysis, but a majority of the survey respondents perform water audits to evaluate facility water usage and compliance with regulatory discharge requirements, as shown in Figure 3.5.

The mining facility survey participants audit at least once per year; other industrial sector participants audit less frequently. One mining facility also reported use of GoldSim, a mine system modeling software solution. Findings from these audits drive water reuse efforts at the mining facilities. At the other industrial sector facilities, the findings drive water conservation and sometimes water reuse efforts. Water audit inputs consist of the items depicted in Figure 3.6. The details of the other specified inputs are provided in Table 3.11.

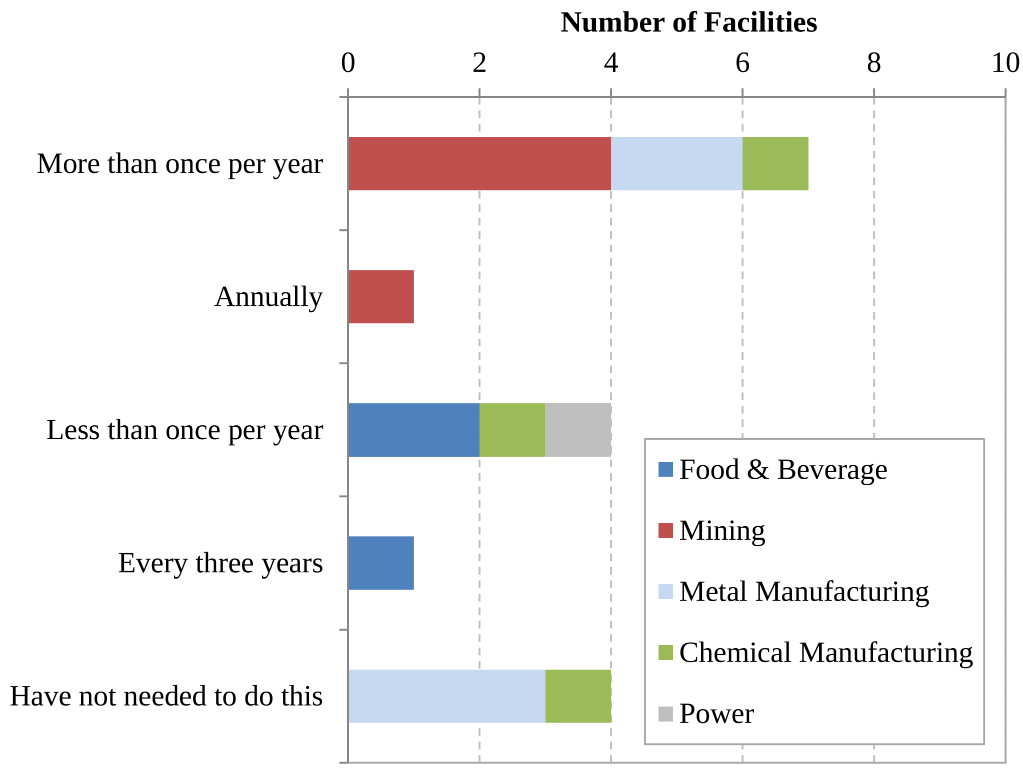

Figure 3.5. Water auditing frequencies reported by survey participants.

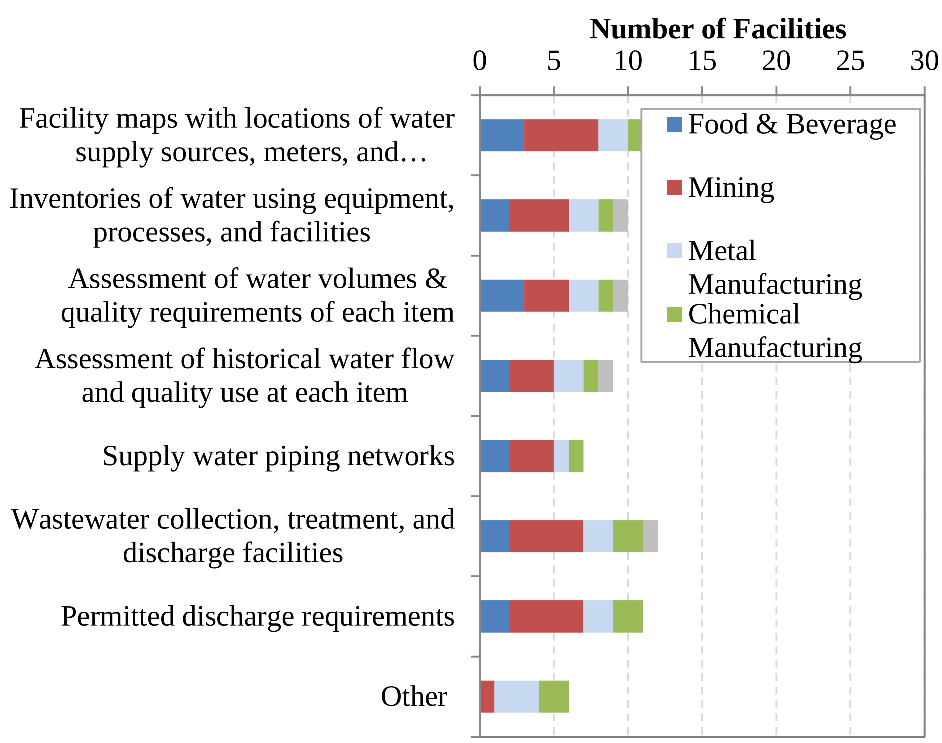

Figure 3.6. Water audit inputs utilized by industrial sector survey participants.

Table 3.11. Description of Other Water Audit Inputs

Industrial Sector	Other Inputs Utilized for Water Audits
Chemical manufacturing	Water supply risk assessment
Metal manufacturing	Bills by meter and type for total consumption data that can be analyzed and compared to sewage outfall data for discovery of leaks and metering issues
Mining	Water use licenses/authorizations; water discharge permit; discharge point location maps; register of water consumption; monitoring reports

Note: Water audit outputs consist of the items depicted in Figure 3.7. The details of the other outputs are provided in Table 3.12.

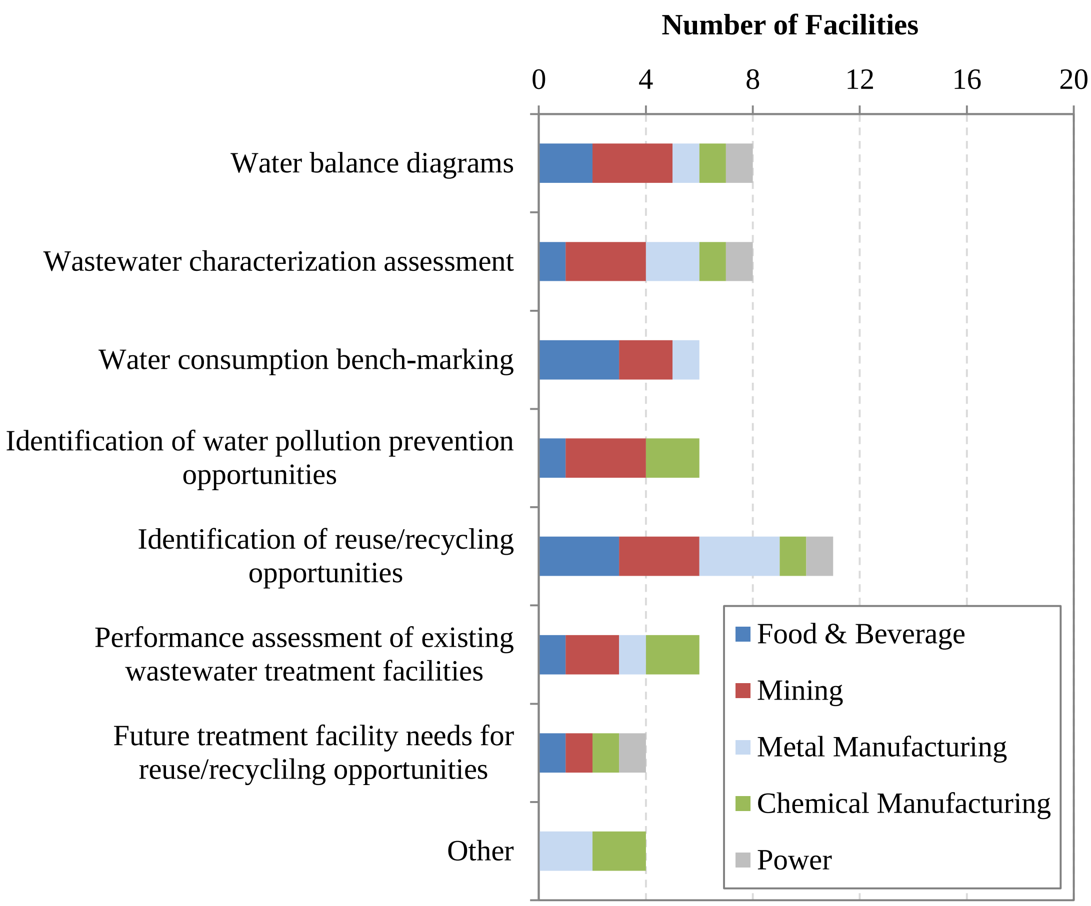

Figure 3.7. Water audit outputs utilized by industrial sector survey participants.

The literature reveals that when a corporate or government water conservation policy is lacking, then cultural attitudes that support minimizing water use and effluent discharge may fail to occur (Barrington et al., 2013), and such attitudes are important in driving adaptation of water reuse/recycling efforts.

Table 3.12. Description of Other Water Audit Outputs

Industrial Sector	Other Outputs of Water Audits
Chemical manufacturing	Future regulatory risk overview for identification of high-risk areas for change or need of improvement; provide Pareto diagram of opportunities by cost.
Metal manufacturing	Two facilities do not utilize any of these water audit outputs.

3.2 Water Reuse and Recycling Opportunities

ASME cited great potential for on-site water reuse in food processing, pulp and paper, textile, silicon chip manufacturing, and metal finishing through capture of rinse/wash water and moisture from flue gas or dryer exhaust streams and improved sludge dewatering of on-site treatment processes (2010). EPRI cited these same industries with good opportunities for on-site reuse because of their extensive use of rinsing processes (2008). Ultimately, the scope of water recycling and reuse varies by industry because of differences in process requirements, type of wastewater produced, and the treatment technology needed for recycling (Asano and Visvanathan, 2001).

The potential for water reclamation with or without initial treatment depends upon the characteristics and volumes of the wastewater and the ability to segregate waste streams according to their volumes and profiles. Large-volume wastewaters with low pollutant content tend to be suitable for on-site reuse to other processes requiring a lower quality water, whereas low-volume wastewaters with high pollutant content are better suited for recycling to the same process after appropriate treatment (Visvanathan and Asano, 2009. Many industries can utilize boiler blowdown as on-site reuse water for cooling tower makeup water, industrial combustion-based processes for flue gas moisture capture, and product dryer exhaust streams with high moisture content for capture and reuse (EPRI, 2008). Most industries engage with representative trade organizations in order to maintain a current understanding of industry sector-specific requirements. A compilation of trade organizations organized by industrial sector that have published documents specifically related to water reuse/recycling is provided in Appendix D.

3.2.1 Industrial Wastewater Streams

The U.S. EPA cited that industrial operations released or disposed of approximately 470 million pounds of toxic chemicals as surface water discharges or injections into on-site underground wells in 2006, but tighter federal and state pretreatment standards for municipal water systems are driving expansion of on-site industrial wastewater treatment systems (ASME, 2010). Approximately 144,000 Class II wells are in operation in the United States, injecting over 2 BGD of brine (http://water.epa.gov/type/groundwater/uic/class2/). Most industries continue to produce some liquid waste, although recent trends in the developed world have been to minimize wastewater production or reuse the wastewater within the production process (Kukade, 2010). This is supported by the 55% reduction in industrial toxic chemical releases to water reported in 2012 compared with 2006 (U.S. EPA, 2014).

Industrial wastewater production stream qualities and flows vary by industrial sector, sector products, facility production processes, facility production levels, sustainability practices, and regional discharge requirements. Table 3.13 demonstrates the variability observed in wastewater effluent volumes produced by different food and beverage sector products (200–20,000 L/ton of product).

Table 3.13. Wastewater Effluent Flows Produced from Various Food and Beverage Sector Products

Industry	Wastewater Effluent of Product	References
Food Processing Industry		
Dairy	200–10,000 L/ton of milk	Vourch et al., 2005
Seafood	11,000 L/ton	Afonso and Borquez, 2002
Meat	3000–10,000 L/ton HSCW	Sampson et al., 2005
Fruits and vegetables	1.2–5 L/ton	Muro et al., 2012
Sugar	1.5 L/ton	Chavez-Rodriguez et al., 2013
Animal and vegetable fat	0.25–1.24 L/ton olives	Valta et al., 2014
Beverage Processing Industry		
Beer	3000–10,000 L/ton beer	Simate et al., 2011
Wine	3000–5000 L/ton grapes	Mosse et al., 2013
Alcohol distilleries	10,000–20,000 L/ton alcohol	Saha et al., 2005

Note: HSCW=hot standard carcass weight.

Table 3.14 demonstrates the variability observed in typical wastewater effluent contaminants produced by different industrial sectors.

Table 3.14. Typical Contaminants Found in Different Industrial Sector Wastewaters

Industrial Sector	Typical Contaminants	Reference
Food and beverage	BOD/COD, TDS/TSS, FOG, strong odors/colors	Saha et al., 2005
Power	TSS, TDS (e.g., Ca, Mg, alkalinity, SO_4, Cl, SiO_2, PO_4, pH), NH_3, metals, organic compounds, oils	U.S. EPA, 2013b; EPRI, 2003
Mining	iron, SO_4, and pH most prevalent, along with other metals, TDS, TSS, turbidity, conductivity, ammonia, hardness, and free acid	Zinck and Griffith, 2013
Automotive and metal treatment	COD, O&G, surfactants, borates, silicates, alkalis, phosphates, complexing agents, metals, TSS	Enderle et al., 2012; http://www.ecologixsystems.com/industry-automotive.php; http://www.ovivowater.com/content/files/data/Ovivo_Industry_MetalTreatment_023471ac3f3246838fe9a89160d57c95.pdf
Chemical	degradable and refractory TOC, AOX, nitrogen species, phosphate, copper, chromium, bromide, chloride, sulfate	Industrial Water World, nd
Petroleum refining	O&G, BOD, COD, NH_3, turbidity, sulfides, TSS, phenols, chloride, mercaptans, cyanide, 1,4-dioxane	Torres et al., 2008; El-Naas et al., 2014; Ranade and Bhandari, 2014
Pharmaceutical	O&G, pH, TSS, BOD and COD from strong organic effluent, residual pharmaceuticals, and inorganic mineral content (i.e., TKN, ammonia)	Industrial Water World, nd; Gadipelly et al., 2014
Pulp and paper	TSS, AOX, high COD, low BOD_5/COD ratio, colored compounds, dissolved salts, toxic pollutants, chlorine dioxide, chlorine, sulfides, metals	O'Connor et al., 2014; Kamali and Khodaparast, 2014; Pokhrel and Viraraghavan, 2004; Ranade and Bhandari, 2014; Galil and Levinsky, 2007; Pizzichini et al., 2005
Semiconductor	recalcitrant organics; degradable organics such as isopropanol, acetone, ethylene glycol; recalcitrant nitrogen compounds such as TMAH, degradable nitrogen compounds; turbidity; conductivity; trace metals	Watson, M., personal communication MWH Confidential client, 2014; McCandless, 2012
Dyes and textiles	BOD, COD, TSS, color, pH, toxicity, dye molecules, copper, zinc, lead, chromium, cobalt, PAHs, salts	Pang and Abdullah, 2013; Ranade and Bhandari, 2014
Oilfields	O&G, cations, anions, heavy metals, radionuclides bromides, sulfides, solids, dissolved gas, additives, biocides	Ahmadun et al., 2009; Tidwell et al., 2015

Notes: AOX=assimilable organic halogen; BOD=biochemical oxygen demand; COD=chemical oxygen demand; FOG=fats, oils, and grease; O&G=oil and gas; PAH=polyaromatic hydrocarbons; TDS=total dissolved solids; TKN=total kjheldahl nitrogen; TMAH=tetramethylammonium hydroxide; TOC=total organic carbon; TSS=total suspended solids; U.S. EPA=United States Environmental Protection Agency.

Table 3.15. Industrial Process Locations Generating Wastewater Streams

Chemical Manufacturing	Food and Beverage	Metal Manufacturing	Power and Mining
• production processes • clean in place • cooling towers • boilers • purified water system	• sanitation • production processes (cooking, coating, cleaning, crushing, pressing, harvesting equipment) • environmental controls • cooling towers	• paint rinsing • anodizing quench • product washing • product treatment • material rinsing • product testing • cooling towers	• air pollution control equipment • domestic wastewater • process waste streams • stormwater runoff • laboratory • cooling towers for certain power facilities

The industrial facility process locations that were cited by the project survey participants for generating waste streams are summarized in Table 3.15. Cooling towers are common to all these industries except for mining, and production processes are common to all the participating industries.

As shown in Figure 3.8, the 17 participating survey facilities collectively discharge 18 wastewater streams to sewers or surface waters with a permit or without requirement for treatment. Six facilities report reuse of wastewater streams after treatment, seven facilities report recycling of wastewater streams after treatment, and seven facilities report other wastewater stream management approaches. These seven alternatives consisted of discharge to locations other than sewers or surface waters (n=2), reclaiming the water without treatment (n=4), or utilizing the water after treatment for irrigation of agricultural commodity used in product (n=1). The majority of the 17 surveyed facilities are using several wastewater stream handling alternatives, and 13 of the 36 reported wastewater streams are handled by reuse/recycling.

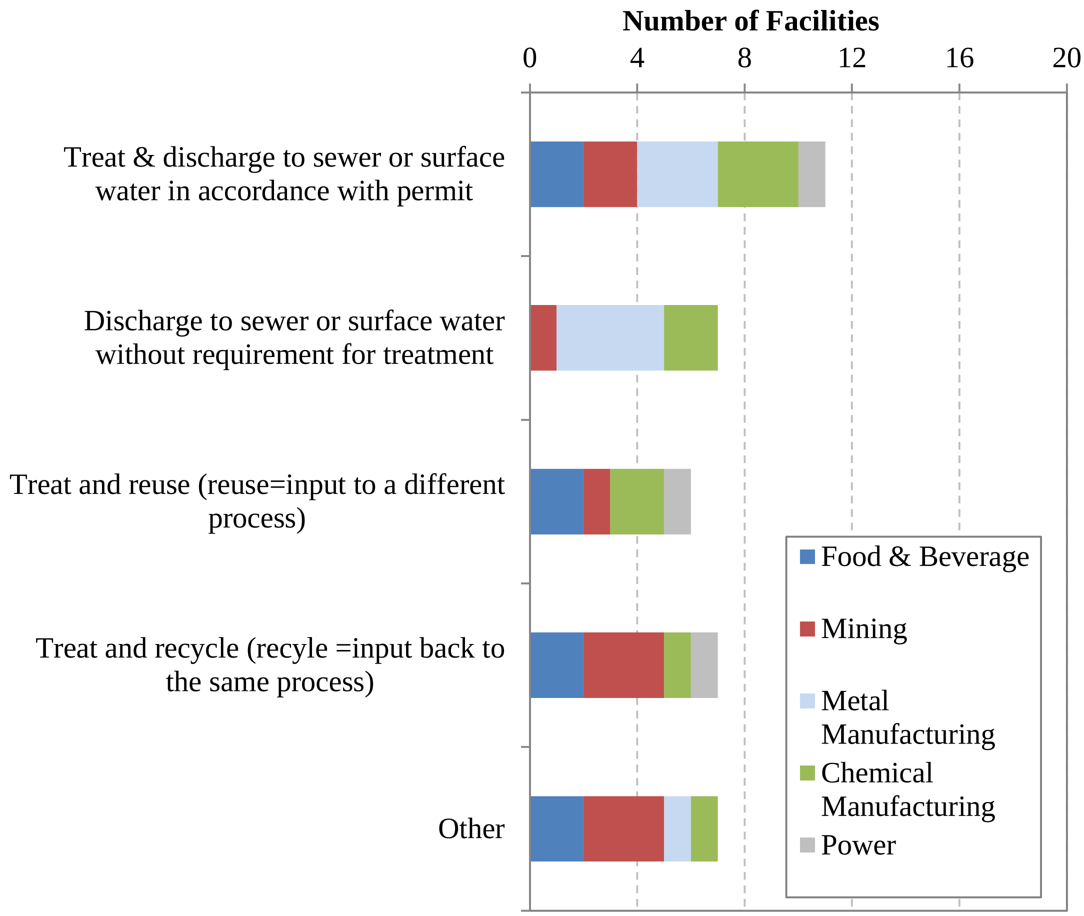

Figure 3.8. Wastewater stream handling alternatives utilized by the 17 surveyed facilities.

3.2.2 Reuse/Recycling Drivers and Opportunities

A key driver of on-site reuse/recycling implementation in regions with adequate and inexpensive source water occurs when there is a narrowing of the gap between the treatment needs to adhere to wastewater discharge requirements and those to reuse or recycle the water. When this gap sufficiently narrows to demonstrate at least a 2- to 3-year return on investment (ROI), reuse/recycling opportunities convert to project implementation. Water reuse adaptation varies widely among industrial sectors and is highly dependent on site-specific situations (Vajnhandl and Valh, 2014). Readily implementable reuse opportunities requiring lower capital investment are usually installed first (e.g., cooling tower makeup water), and studies for additional reuse opportunities are delayed or not implemented at full-scale until the cost of treatment modifications will provides a reasonable return on investment (Lawler, nd)

Cooling is the most common industrial reuse option because of its high water demand, the relatively low water quality required, and the ease with which the practice may be applied to different types of industries and simplicity of implementation (Jiménez and Asano, 2008). There is little or no evidence of applications for direct use of reclaimed water within products, as this typically requires the greatest amount of treatment in order to alleviate product manufacturing risks or carries unacceptable public health and safety concerns. Water reclamation is, however, applied in product processing steps such as cleaning and rinsing.

Successful reuse of water within industrial applications is dependent upon a comprehensive understanding of process design, water chemistry, membrane systems, and other treatment technologies, chemical treatment, instrumentation, and control (Christophersen, 2008). Brief descriptions of water reuse drivers for individual industrial sectors are provided in the following paragraphs; additional examples are provided in the sector-specific literature reviews in Appendices E through J.

3.2.2.1 Textile Industry

The textile industry has shown less implementation of water reuse despite being a high water consumer because of the complex and highly variable characteristics of the wastewater, coupled with smaller overseas enterprises that lack the resources for acquiring closed water loops (Vajnhandl and Valh, 2014). Concern for the environmental pollution caused by the high water use of this industry, in the range of 100 to 250 times the weight of fabric processed (Sala and Gutierrez-Bouzan, 2014; Vajnhandl and Valh, 2014), coupled with its toxic and difficult-to-treat organic residues (Abid et al., 2012), is driving laboratory and pilot-scale studies on dye decolorization that will permit water reuse (Vajnhandl and Valh, 2014; Sala and Gutierrez-Bouzan, 2014; Jadhav and Singhal, 2013; Masmoudi et al., 2014; He et al., 2013).

With appropriate pretreatment, nanofiltration (NF) and RO membranes have been successfully used for process recycling (Ranganathan et al., 2007). Within the apparel industry, Levi Strauss and Co. developed a standard in 2013 for water recycling and reuse that it has applied to its finishing facilities that are in compliance with the global effluent requirements to recycle or reuse effluent water as full or partial replacement of freshwater at an individual facility, considering on- and off-site recycled water for laundry, landscape irrigation, facility cooling tower makeup, and on-site sanitary toilet flushing (LS&Co. Water Reycle/Reuse Standard, nd).

3.2.2.2 Petroleum Refining Industry

Petroleum refiners have unique characteristics because of the type of crude that is refined and the products that are desired, and some refineries can be large consumers of water relative to other industries (IPIECA, 2010). Reuse at petroleum refineries is sometimes driven by water source sustainability issues (Pugh et al., 2010). Water is used in many processes, and the water that has not been in direct contact with hydrocarbons or only has minimal contamination can be a source for reuse (IPIECA, 2010). Table 3.16 matches application areas that can receive reuse water with potential sources of reuse water.

Table 3.16. Applications and Sources of Reuse Water within a Refinery

Applications	Sources
Desalter makeup process water	stripped sour water vacuum tower overhead crude tower overhead
Coker quench process water	stripped sour water
Coke cutting process water	stripped sour water
Boiler feed water makeup	treated and upgraded refinery wastewater
Cooling tower makeup	treated and upgraded refinery wastewater

Source: Adapted from IPIECA, 2010.

Concerns over water source sustainability at a Midwestern petroleum refinery resulted in a commissioned design study for a water reclamation system to utilize effluent from an existing refinery wastewater treatment system with low quality, on-site well water to provide boiler feed water. In addition, higher quality, on-site refinery well water was treated to provide cooling tower makeup water. Two different treatment trains were needed to achieve the water quality objectives for each application, but the trains were designed to have some common processes (Pugh, 2010). A Brazilian crude oil refinery needing to move from permitted wastewater discharge to industrial reuse explored advanced treatment of existing primary and secondary wastewater treatment (gravimetric oil and water separator, flocculation and aerated lagoon, rotating biological contactor, and lagoon for solids deposition) to achieve the water quality needed for the cooling tower system or steam generation through pilot testing membrane bioreactor (MBR) systems fed with primary effluent treated to control O&G to less than 20 mg/L (Torres et al., 2008).

3.2.2.3 Semiconductor Industry

The semiconductor industry must continually manufacture denser microprocessors and smaller microchip devices, requiring large quantities of ultrapure water, which promotes facility wastewater recycling efforts to produce feed water for the high purity water production process (Equova, nd). The need for almost distilled quality for washing circuit boards and other electronic compounds indicates that the reuse of electronic wastewater is seriously complicated, particularly because of the presence of toxic and slow -biodegrading compounds (Lee et al., 2008).

Inorganic wastewater generated from chemical mechanical planarization and lithography processes still contains volatile, low molecular weight compounds after treatment that preclude its use for ultrapure water production; organic wastewater generated from etching, stripping, and cleaning can be treated with biological processes and RO, but residual acetone, isopropyl alcohol, acetaldehyde, methanol, acetonitrile, and other small organic molecules must still be removed with an advanced oxidation process (AOP). Studies of a solid-phase AOP appear to be promising in this application (Choi and Chung, 2014). Biological treatment can be complicated by the presence of other constituents such as tetramethyl ammonium hydroxide (TMAH), utilized in etching the surface of the silicone chip (Lee et al., 2008), and triazole corrosion inhibitors (Watson, M., personal communication, MWH Confidential client, 2014). The complex compositions of semiconductor wastewater streams may also lead to RO membrane fouling. A pilot study of MBR–RO technology for treatment of three semiconductor wastewater streams showed the process to be feasible if appropriate cleaning and antiscaling strategies are utilized (Xiao et al., 2014), but the type of water reclamation and reuse was not specified.

3.2.2.4 Pharmaceutical Industry

The pharmaceutical industry produces highly variable dilute wastewater streams that are mainly treated by biological and oxidation processes, membrane techniques, and AOP. A review of the efficacy of the various treatment technologies is presented by Gadipelly et al. (2014), with a recommendation for more emphasis on recovery and reuse of pharmaceutical wastewaters. Direct reuse in the pharmaceutical industry remains fairly restricted by contamination risks to the consumer; however, recycling from nonmanufacturing point sources for reuse in irrigation or boiler system cooling water is commonplace in many pharmaceutical manufacturing facilities (Industrial WaterWorld, nd).

3.2.2.5 Food and Beverage Industry

The food and beverage industry has restrictions on direct reuse in products but engages in other on-site reuse opportunities related to cleaning, washing, rinsing, transportation, firefighting, and thermodynamic processes (State of California, 2013).

3.2.2.6 Upstream Oil and Gas Industry

Water reused for hydraulic fracturing is typically treated first, either on- or off-site, and then mixed with freshwater if salt concentrations remain high. Although no national estimate of producers' use of this practice is available, a 2009 study on shale gas development reported that interest in this type of reuse for produced water was high. However, the study also noted that certain water treatment challenges needed to be overcome to make this type of reuse more widespread (U.S. Government Accountability Office [GAO], 2012). Water is also used on-site in operations such as dust control, vehicle washing, and fire control (Ahmadun et al., 2009). Successful internal reuse can reduce the freshwater demands for subsequent hydraulic fracturing operations as well as produced water disposal costs. Internal reuse has expanded as shale gas producers have experimented with reusing produced water that has not been desalinated.

For internal reuse, produced water is often blended with freshwater to reduce the high dissolved solids concentration and mitigate its effects on fluid viscosity. Internal reuse of produced water with elevated concentrations of dissolved solids must also consider factors such as corrosion of well materials, scaling that impedes gas flow to the well, and the effects of varying salinity on clay swelling within the formation. Direct beneficial reuse of produced water in the United States is limited by the Clean Water Act to livestock watering or agricultural uses west of the 98th meridian (Shaffer et al., 2013). The suitability of water for irrigation depends on a number of factors, including the type of crops grown, the soil type, irrigation methods, and the types and quantity of salts dissolved in the water. In addition, the reliability of the produced water supply over time, proximity to the irrigation site, and costs also present challenges. Organizations such as Canada's Oil Sands Innovation Alliance (COSIA), an alliance of 13 companies that collectively represent almost 90% of the oil sands production in Canada, have set aggressive goals to reduce water use and increase water recycling in oil sands facilities (http://www.cosia.ca/).

3.2.2.7 Mining Industry

The mining industry continually seeks water reuse and recycling opportunities; bodies of ore are frequently located in water-stressed regions, and the stringency of effluent discharge limits sometimes approach receiving water background levels. Mining is a great example of reuse/recycle. Typically, solid–liquid separation occurs in the tailings pond. Water is reclaimed, treated, and reused in the process. Water balances are critical in both arid and wet climates. They dictate how much water to store to sustain operations or how much to treat or release to prevent a buildup of excess water.

Reuse and recycling treatment technologies must overcome certain challenges that are prevalent in this industry. These include climatic conditions that can freeze water transport lines or generate excessive runoff from permafrost, the propensity toward scaling of mine drainage water during treatment, and difficulties in solid–liquid separations in low strength waters that are resistant to coagulation. According to Watson and Umble (2014), the reuse and recycling opportunities in the mining industry include:

- Process makeup water
- Dust suppression (haul roads)
- Restricted agricultural irrigation
- Reforestation/pastureland irrigation
- Aquaculture
- Boiler makeup water
- Environmental flow management
- Material washing
- Aquifer recharge
- Municipal water supply augmentation
- Cooling water

3.2.2.8 Power Industry

Power plant process operations tend to concentrate waste stream contaminants into low volumes that are becoming difficult to discharge in conformance with water quality and quantity requirements. These waste streams (e.g., wastewaters from cooling tower blowdown, filter backwash, boiler blowdown, roof and floor drains, and sump discharges) often require further volume reduction prior to discharge or need to become part of a ZLD configuration; this can be achieved using an evaporator/crystallizer or proper pretreatment to remove problematic constituents ahead of RO, which then potentially converts 75% of the waste stream into clean makeup water for the plant while further minimizing the volume of wastewater (Buecker and Clarke, 2011).

Reclaimed water for power plant cooling towers is primarily from an off-site supply of either reclaimed wastewater effluent or another impaired water because potential sources of recycled water within a power facility have an inadequate volume for the cooling requirements. Although tuning a wet tower-cooled plant for efficiency, implementing blowdown and process water recycling schemes, and using dry fluidized gas desulfurization (FGD) and ash handling all result in reduced water consumption, these steps collectively still only represents a 5 to 20% reduction in overall water consumption. To achieve a water consumption reduction factor of two or more, there are only a few feasible options: (1) switch to a more thermally efficient generation technology; (2) implement topping-cycle cogeneration; (3) use an innovative alternative cooling system; (4) implement the use of degraded water from off-site sources; or (5) implement recycled water offsets from a recycled water producer. Most new power installations utilize combined-cycle gas turbines (CCGT), which provide the benefits of (1) and (2) listed previously; numerous research projects have focused on furthering the evaluation, development, and implementation of (3) and (4).

3.2.2.9 Project Survey Reuse/Recycling Implementation

Survey results obtained from the project participants regarding water reuse/recycling implementation are presented in Figure 3.9. These results demonstrate that water reuse/recycling practices have been implemented across all the generic water use categories, with most of the industries exhibiting a wide range of applications.

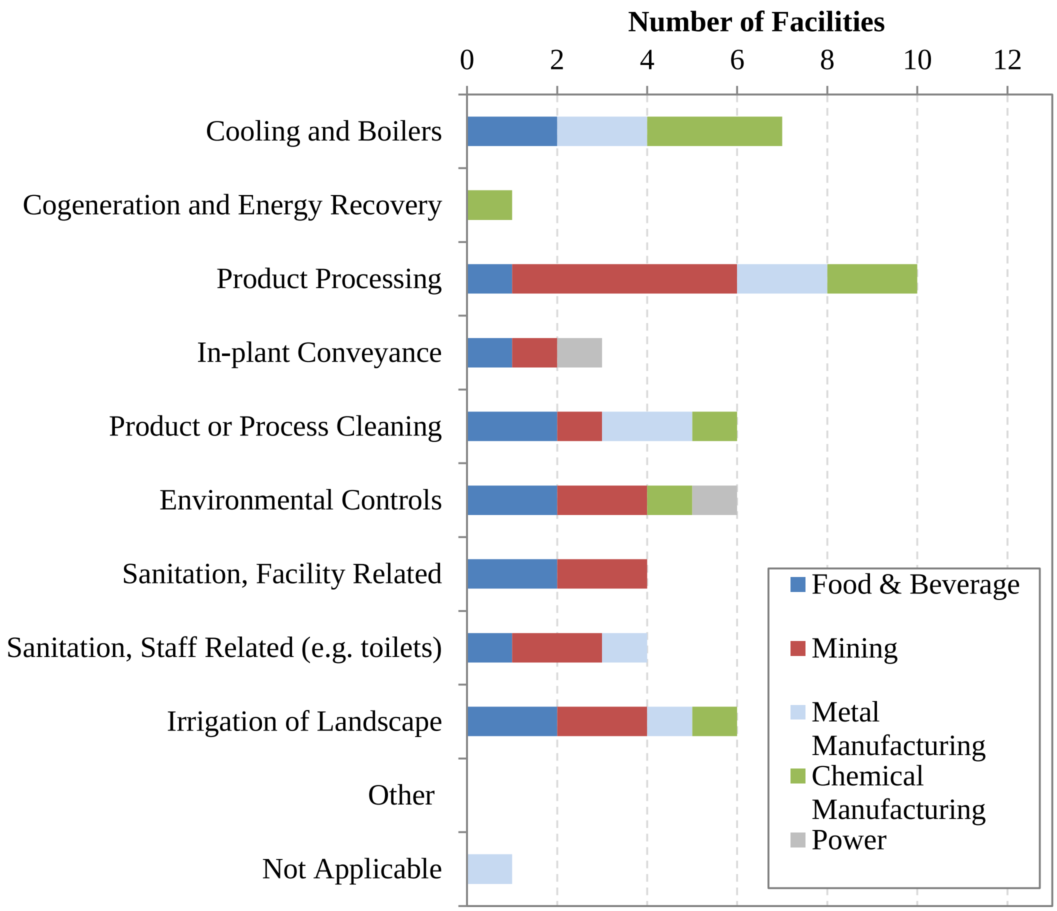

Figure 3.9. Distribution of water reuse/recycling among the generic water use categories reported by the 17 surveyed facilities.

The percent distribution of the overall reclaimed water volume among the generic use categories on a facility-specific basis is shown in Figure 3.10. These data demonstrate that the greatest utilization of reclaimed water by volume for this group of respondents is for product processing or cooling and boilers. The respondents clarified that product processing water was not actually utilized in any of the products but only represented the water utilized during processing steps such as diluting or rinsing.

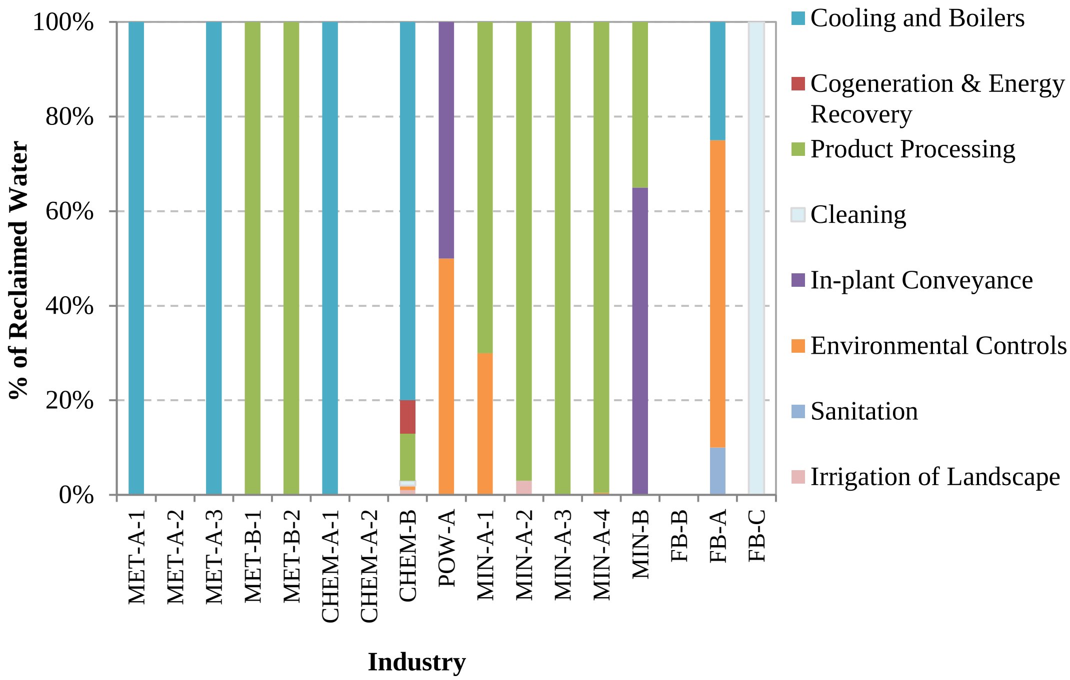

Figure 3.10. Percentage distribution of overall reclaimed water volume among the generic use categories by the 17 reporting facilities.

Despite the broad utilization of water reuse/recycling across generic water use categories, the percentage of total annual water usage consisting of reused/recycled water for the survey respondents was below 20, with the exception of mining industry facilities and a winery in a drought- stricken region, as shown in Figure 3.11. For these respondents, reuse/recycling percentages are high and frequently approach 100%. Survey responses as to what drivers result in implementation of water reuse/recycling included:

1. Cost mitigation
   a. Decreased reliance on water supplies affected by rising costs
   b. Reduction of wastewater streams subject to increasing discharge costs
   c. Enhanced chemical product recovery
   d. Minimization of expansion threats from water scarcity issues
2. Preservation of brand
   a. Supporting stewardship or consumer advocacy marketing strategies
   b. Avoiding discharge permits or other regulations with high risk of attainment
3. Water supply threats
   a. Eroding community acceptance
   b. Eroding supply quality
   c. Required shift to seawater

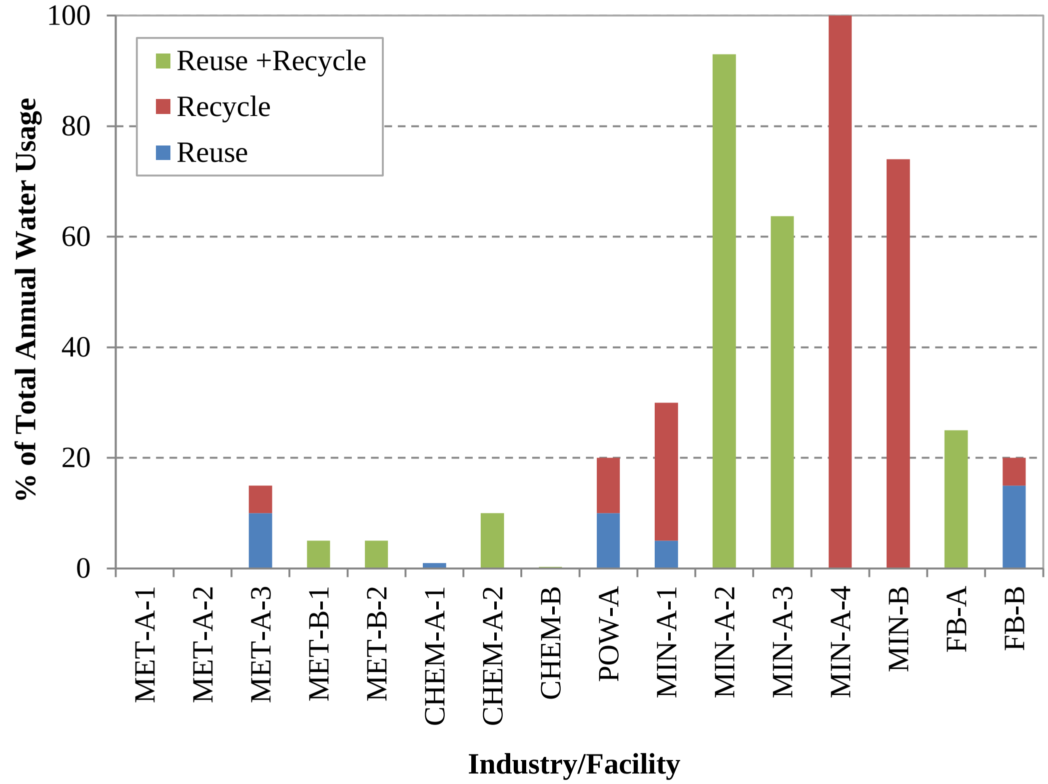

Figure 3.11. Percentage of total annual water use that is reuse/recycle water reported by the 17 surveyed facilities.

3.2.3 Reuse/Recycling Technologies

Treatment technologies selected for water reuse/recycling applications depend upon the constituents that need to be removed, the percentage removal required for each constituent, pretreatment needed to ensure adequate and cost-effective operations of each selected process, avoidance of hazardous/toxic waste stream byproducts, and optimized sequencing when multiple processes are needed to achieve reuse/recycling goals. The easiest reuse/recycling applications are those that have similar input quality requirements independent of industry (i.e., thermodynamic processes such as cooling towers and boilers), those with less stringent input quality requirements (i.e., cooling towers), or those that can readily segregate waste streams to match unit process treatment capabilities.

Categorization of treatment processes needed for reuse and recycling applications on an industry-specific basis is presently not available. This is probably due to the fact that industrial wastes differ from municipal wastes in both their composition and variability from one facility to another. For these reasons, more emphasis must be placed on fully delineating an industrial facility’s waste characteristics, and less reliance can be placed, as it is for municipal facilities, on utilizing the performance characteristics demonstrated by installed technologies at multiple locations (Woodard and Curran, 2006). Instead, consideration of processes known to be appropriate for removal of certain constituents are usually first evaluated through bench testing and process train pilot testing in order to adequately address unique matrix constituents, mitigate production risks, and ensure performance economics. This subsection summarizes the array of technologies that are utilized for removal of specific constituents, provides examples of vendor products for these technologies, and discusses some of the key issues involved in process train selection.

A preliminary compilation, derived from the literature and the project survey results, of commercially available treatment processes for different constituents and associated industries requiring removal for discharge compliance or reuse/recycling applications is provided in Table 3.17. Examples of vendor-specific products covering most of these treatment processes are provided in Tables 3.18 through 3.21. Table 3.18 summarizes industrial versions of the conventional primary solids separation processes, secondary biological processes, and tertiary filtration process categories used at municipal wastewater treatment facilities. |

Table 3.19 summarizes other physical/chemical processes (e.g., activated carbon, ion exchange), Table 3.20 summarizes membrane processes, and Table 3.21 captures other additional processes (e.g., ZLD, AOP). An analysis of the trends in the application of different wastewater treatment processes, based upon the number of publications in the past 40 years, demonstrates the dominance of biological processes, followed by physicochemical methods such as adsorption, oxidation, membrane separation, coagulation, and ion exchange, with much less activity for extraction and cavitation processes (Ranade and Bhandari, 2014).

Most industrial systems that produce a biologically degradable wastewater utilize activated sludge systems similar to municipal systems, although additional up- and downstream treatment components are usually necessary (Cunningham, 2013). Variable manufacturing production schedules also frequently necessitate the need for an equalization or neutralization holding tank ahead of the designed treatment process (Cunningham, 2013). Membrane biological processes (i.e., MBRs) have been installed at industrial facilities since the 1990s, but insufficient guidance is available on their effective utilization within different industrial facilities.

Key differences in the nature of industrial and municipal water limit the application of municipal wastewater MBR design concepts and effective operational envelopes to industrial applications (Judd, 2011). Industries without the ability to adequately segregate waste streams may have a reduced ability to apply biological treatment processes because of low biomass body strength, and those with biochemical oxygen demand (BOD_5)/chemical oxygen demand (COD) ratios of less than 0.5 (e.g., tannery, textile, dyeing) will require physical or chemical pretreatment (Mutamin et al., 2013). With high strength industrial wastewater (COD>1000 mg/L and low BOD_5/COD ratio), the high mixed-liquor suspended solids (MLSS) of an MBR is preferable to a lower MLSS for a conventional activated sludge system, but the increased loading can result in difficulties with membrane fouling, the need for greater aeration, and alternative cleaning protocols (Mutamin et al., 2013; Judd, 2011). Mutamin (2013) presents differences in MBR operational parameters for high industrial strength industries (i.e., textiles) versus lower industrial strength industries (i.e., food) and details fouling mitigation measures. Further details on novel applications of membrane processes for industrial wastewater treatment can be found in Pellegrin et al. (2013). Demonstrations of effective treatment train processes are presented in the subsequent subsection on “Reuse/Recycling Implementation Advantages and Challenges” under “Industry-Specific Case Studies.”

Table 3.17. Commercially Available Treatment Processes by Constituent and Industry

Constituent	Processes	Industries
Oil and grease	• API separators • dissolved air flotation • granular activated carbon • organo-clay adsorbents • walnut shell filtration • hydrocyclones/centrifuges	oil and gas metal manufacturing food and beverage refinery pharmaceutical
Diesel- and gasoline-range organics	• dissolved/induced gas flotation • dissolved air flotation • granular activated carbon • walnut shell filtration • stream stripping	oil and gas
Bacteria	• membrane bioreactor • microfiltration/ultrafiltration • chemical oxidation • ultraviolet	food and beverage power cooling towers
Ammonia and other nutrients	• air stripper • reverse osmosis • forward osmosis • membrane distillation • ion exchange • activated sludge	oil and gas mining metal manufacturing chemical refinery pharmaceutical semiconductor
Hardness	• chemical precipitation/softening • ion exchange • reverse osmosis • forward osmosis • membrane distillation • evaporation • electrocoagulation	mining
Alkalinity	• acidification/degasifiers • reverse osmosis • forward osmosis • membrane distillation • evaporation	mining power
Metals	• chemical precipitation/softening • electrocoagulation • nanofiltration/reverse osmosis	mining power metal manufacturing chemical pulp and paper semiconductor dyes and textiles
Total dissolved solids	• ion exchange • reverse osmosis • forward osmosis • membrane distillation • evaporation	oil and gas mining power metal manufacturing food and beverage chemical

Constituent	Processes	Industries
		refinery pulp and paper semiconductor dyes and textiles cooling towers
Total suspended solids	• organo-clay adsorbents • walnut shell filtration • hydrocyclones/centrifuges • clarifiers/settling ponds • multimedia filtration • microfiltration/ultrafiltration • membrane bioreactor • cartridge filters	oil and gas mining power metal manufacturing food and beverage refinery pharmaceutical pulp and paper semiconductor
Biochemical oxygen demand Chemical oxygen demand Total organic carbon	• microfiltration/ultrafiltration • membrane bioreactor • activated sludge • chemical oxidation	oil and gas power metals manufacturing food and beverage chemical refinery pharmaceutical pulp and paper semiconductor dyes and textiles

Table 3.18. Examples of Commercially Available Products for Conventional Treatment Processes

Conventional Processes	GE	Dow	Veolia	Infilco Degremont	Evoqua	Pentair
Primary treatment (solids removal)			• Filtraflo • Multiflo • Actiflo	• Accelerator • Aquadaf • Densadeg		
Secondary treatment (biological processes)			• Biostyr • Azenit • Bio-denitro • Bio-denipho • Triple Ditch • UASB/SBR	• Ferazur-Magnazur-Nitrazur • Biofor • Denifor • Hybacs • Ibio • Meteor Ultragreen • Cyclor • Cleargreen	• Captivator • Orbal • Verticel • Biosphere MBBR/IFAS • Omniflo Interchange Sequencing Batch Reactor • diffusers • mechanical aerators	
Filtration				• ABW • Superpulsator		

Table 3.19. Examples of Commercially Available Products for Other Physicochemical Treatment Processes

Other Processes	GE	Dow	Veolia	Infilco Degremont	Evoqua	Pentair
Activated carbon					• Vantage CT Series towers • Heat-optimized technology for towers • PV Series • HP Series • LP Series • PG Series • Aqua-scrub • FB • RB • Vent-scrub • AquaCarb • Bevcarb • Ultracarb • VOCarb • Midas OCM odor control • VOCarb impregnated media	
Ion exchange resins		• Amberlite • XAD • Dowex • Optipore • Duolite			• CDI • CEDI • resins	
Specialty	ABMET			IBIO	• Copper Select • Continuous precipitation system	Porous media (particle/liquid separators)
Fine-particle filtration		Tequatic Plus				

Table 3.20. Examples of Commercially Available Products for Membrane Treatment Processes

Membrane Processes	GE	Dow	Veolia	Infilco Degremont	Evoqua	Pentair
Membrane bioreactor	• LEAPmbr • AnMBR		Biosep		MemPulse	
Membrane housings						Codeline
Low-pressure membranes (micro- and ultrafiltration)	• ZeeWeed 1000 • ZeeWeed 1500 • ZeeWeed 500	• Integraflo • IntegraPac • SFD modules • SFP modules		• Ecoskid • Skid • Ultrasource • Smartrack	• MemPulse • Memtak • Xpress • Forty-X	X-Flow (capillary ultrafiltration) (tubular microfiltration)
High-pressure membrane systems (nanofiltration, reverse osmosis)	• BEV Series • E Series • Hero • Pro • Pro E • Propak • Repak			• Mobilpro • NF Skids • RO Skids	Vantage	X-Flow (tubular)
Electrodialysis	• EDI • ED • BPED • EDR	EDI-310				

Table 3.21. Examples of Commercially Available Products for Other Processes

Other Processes	GE	Dow	Veolia	Infilco Degremont	Evoqua	Pentair
Catalysts		Amberlyst				
Advanced oxidation process				Ozonia	Vanox	
Thermal and zero liquid discharge	• Aquasel-NTBC • brine concentrator • brine crystallizer • SAGD water evaporators • wastewater evaporators			S.M.A.R.T. Zone Modules		

Note: SAGD=steam-assisted gravity drainage.

3.2.4 Reuse/Recycling Implementation Advantages and Challenges

Project survey participants were asked to indicate what advantages and challenges were involved with actual or anticipated retrofits of wastewater treatment facilities to provide on-site reuse/recycling. The responses received are summarized in Table 3.22.

Difficulties in demonstrating sufficient ROI for installation of water reuse/recycling capabilities are therefore principally related to:

- the undervaluation of available water supplies
- infrastructure costs for segregating, capturing, and storing waste streams as required
- treatment design, operational challenges, and byproducts handling
- perceived public health issues (food and beverage products, cooling tower emissions, critical performance of industrial products linked to national security or consumer safety)

Table 3.22. Project Survey Responses for Advantages and Challenges Associated with Retrofitting Treatment Facilities To Provide On-Site Water Reuse/Recycling Capabilities

Advantages	Challenges
• Reduction in surface water discharge • Reduction in city water demand • Smaller footprint of reuse technology, freeing up valuable land needed for agricultural product • Treatment requirements often similar to those needed to meet stringent discharge requirements	• Disposition of treatment byproducts • Infrastructure, pipes, and pumps • ROI demonstration because displaced water is available and essentially free • Waste stream segregation and capture • Facility operational capability • Oil–water separation • Equipment reliability in harsh conditions (mining industry) • Limited storage capabilities • Product safety concerns even when reuse water not used directly in product (food industry) • Formation of gypsum in process piping (mining industry) • Legionella in cooling towers • Capital justification for infrastructure replumbing or purchase of treatment equipment

Note: ROI=return on investment.

3.2.5 Industry-Specific Case Studies

Industries are increasingly implementing water reuse and recycling strategies in order to reduce water usage and minimize wastewater discharge issues. Although the detailed optimal treatment strategies are site specific, certain key contaminants and treatment issues are relevant to different industrial sectors. Selected examples of industry-specific case studies are cited in the following sections.

3.2.5.1 Mining

Many mines are driven to ZLD as a result of the high salt and metal content of their wastewater and the aridness and ecological fragility of the surrounding areas. A common strategy is to sufficiently remove particles, inorganic salts, dissolved metals, and organic constituents so that the water can be reused for process needs or environmental controls. Two examples are provided below; additional case study examples are available in Appendix H.

The Buchanan coal mine (owned by CONSOL Energy) is the largest producer of high British thermal unit (Btu) bituminous coal in the United States. It installed a 1600 gpm plant to treat and reuse water (GE, 2014; Bowen, 2014). The treatment processes include GE's advanced filtration membranes and thermal water treatment technology and are expected to heat and recover about 99% of the water for reuse in other mining operations throughout the Oakwood, VA plant. The system incorporates ZeeWeed ultrafiltration (UF) technology, which employs hollow-fiber membranes to separate particulates from water, and RO technology, which removes dissolved impurities from water through the use of a semipermeable membrane. The concentrated brine is then treated by thermal evaporation, crystallization, and drying technologies, achieving ZLD. The remaining solids are further purified into a saleable road salt. The benefits and resource savings from the new system significantly reduced the volume of mine water requiring management and the company's freshwater demand.

Treatment of conventional acid mine drainage (AMD) traditionally relies upon a combination of neutralization and precipitation (mainly by lime softening), followed by settling of the precipitate in a pond or clarifier. A research project in South Brazil tested an innovative flocs–liquid separation process using flotation with microbubbles or lamellar settling. The AMD-treated water was characterized by its quality for recycling in terms of inorganic or organic elements and suspended or dissolved solids. Flocculation of precipitates was carried out in a special proprietary flocculator, FGR. The main characteristics and advantages of this in-line mixing reactor over agitated tanks are no moving parts, plug flow (fewer short circuits and dead zones) operation, low volume/retention times, and low footprint (Rubio and Carissimi, 2005). Two types of flocs were formed: aerated and nonaerated. Aerated flocs (formed within seconds) entered into a rapid solid–liquid separation by flotation (high rate). The nonaerated flocs settled in a lamella settler. Both AMD treatment techniques showed similar efficiencies (>90% removal of ions) but the separation by lamella settling has advantages because less reagent is required. The quality of the treated water is fairly good: nearly free of heavy metal ions, low BOD and total organic content (TOC), low solids content, and may be readily reused for irrigation, industrial processes, and as wash water (streets, vehicles, dust control).

3.2.5.2 Food and Beverage

The majority of water reuse/recycling applications in the food and beverage industry occurs in nonfood contact environments because of existing health regulations and public perception issues. One notable exception is the water recycling facility at the PepsiCo Frito-Lay snack manufacturing facility in Casa Grande, AZ. This is the only food and beverage manufacturing facility treating wastewater with a MBR for advanced biological nutrient removal in tandem with an advanced drinking water treatment technology that consists of granular activated carbon, ultraviolet (UV) light disinfection, and RO technologies. This plant recycles up to 75% of the facility's process water, producing effluent that meets U.S. EPA primary and secondary drinking water standards for food contact direct reuse (e.g., cooking corn, washing potatoes), cleaning and sanitizing production equipment, and other in-plant cleaning and production needs (U.S. EPA, 2012).

Coca-Cola has developed a scientifically rigorous water recovery and reuse conceptual approach that is implementable by any of its 900 bottling plants in 206 countries. The system treats beverage process wastewater to high water quality standards using a combination of physicochemical and biological processes that are selected from a set of secondary biological treatment, membrane processes, and disinfection. Depending upon the treatment processes selected, the water can be utilized for lower quality applications such as truck and floor washing, irrigation, or cooling tower makeup or treated to higher levels for production process reuse or recycling (International Life Sciences Institute (ILSI) 2013). Similar strategies are also being implemented in use at breweries and juice processing facilities. Additional case study examples for this industry are available in Appendix E.

3.2.5.3 Oil and Gas

Produced water (i.e., the water that returns to the surface with hydrocarbon) is the largest wastewater stream generated in oil and gas extraction processes. It consists of water injected during the fracture process or stream flooding as well as the natural formation water. The quality of this water can vary tremendously, which then greatly impacts the type of treatment process required for reclaimed water applications. Often, the combination of physicochemical treatment with biological processes is not sufficient, and desalting processes (e.g., RO, thermal distillation, evaporation, and crystallization) are needed to produce a sufficient effluent quality. De-oiling and evaporation and crystallization for ZLD have been employed.

The Tempa Rossa oil field in southern Italy plans to implement GE's advanced evaporator and ZLD technology to recycle up to 98% of the produced water and meet new national environmental regulations governing wastewater discharge. Multiple-effect steam-driven units will be used for concentration and crystallization, and the evaporation process vapors will be condensed to produce demineralized water for firefighting use. Installation is anticipated by the third quarter of 2015. Developers of oil sand resources are also increasingly turning to evaporative and ZLD technologies in order to produce a sufficient quality of water for recycling to steam generators. Grizzly Oil Sands' Algar Lake project near Fort McMurray, Alberta, in Canada plans to utilize evaporative and ZLD technologies to achieve recycling water of adequate quality for boiler feed water. Additional case study examples for this industry are available in Appendix I.

3.2.5.4 Manufacturing

The simpler water reuse and recycling opportunities tend to be exploited first. These include utilization of off-site water reuse applications when municipal wastewater is accessible as an alternative supply, on-site water reuse opportunities afforded through internal water cascade operations, dilution of wastewater streams with source waters prior to consideration of reuse applications, or use of wastewater streams as cooling tower makeup water. Many different industries use evaporative cooling towers that require large volumes of makeup water with clearly understood water quality requirements, so this is often the first type of water reuse application actually put into practice. Major contaminants and the typical treatment technologies utilized for wastewaters generated by different industries have been characterized, but often the presence of additional proprietary chemicals or the inability to segregate process streams prior to treatment creates water reuse and recycling challenges that have generated a tremendous need to capture findings from recent case studies describing successful water reuse and recycling installations.

Treatment of chemical industry wastewater from petroleum refineries for cooling tower makeup is typically reported to consist of oil removal, activated sludge, chlorination, granular media filtration, and activated carbon. Treatment for boiler feed requires the addition of softening, UF, and RO to produce a suitable quality effluent. Similar processes are utilized in other manufacturing industries (e.g., semiconductor, chemical, pharmaceutical, textile, tannery, automotive), with additional reported utilization of other processes such as ion exchange mixed-bed filters, chemical oxidation, and UV light disinfection.

A reclamation plant for Indian Oil Corporation Ltd., Panipat (Lahnsteiner et al., 2007), consists of clarification (including silica adsorption on magnesium hydroxide), pressure sand filtration, UF, RO, and mixed-bed ion exchange filter polishing. The effluent is used mainly as boiler makeup and process water for the production of purified terephthalic acid (PTA), which is used in the textile industry. The manufacture of PTA requires high quality water with zero colloidal silica, low TOC, and practically absolute softened water. Subsequent installation of evaporation and crystallization results in ZLD. Operating costs were reported as EUR 0.46 /1000 L of reclaimed water, with approximately 24% of this cost for energy, 24% for chemical consumption, 16% for labor, and 36% for maintenance and material replacement. Total investment costs were approximately EUR 10 million, amortized to EUR 0.18/1000 L, assuming 10% interest and a 20 year depreciation period, for a total operating cost of EUR 0.64/1000 L. A schematic of this process, along with other case study examples for this industry, are available in Appendix J.

Chapter 4

Workshop Discussions and Road Map Development

Two on-site workshops collectively attended by 10 individuals representing nine companies (food and beverage=3; mining=2; metal manufacturing=2; chemical manufacturing=1; power=1) provided an opportunity for industrial-sector representatives to discuss some of the issues associated with on-site water reuse/recycling from the unique perspectives of their different sector facilities.

4.1 Similarities and Differences in the Factors that Influence On-Site Industrial Water Reuse/Recycling Implementation

A summary of the similarities and differences in factors that influence implementation of on-site industrial water reuse/recycling among various industrial sectors is provided in Table 4.1. These factors have been categorically grouped. There is a fairly even split in the number of similarities and differences expressed by the workshop attendees for each category, with the exception of the regulatory category, which is dominated by differences.

Table 4.1. Similarities and Differences in the Factors that Influence On-Site Industrial Water Reuse/Recycling Implementation

Similarities	Differences
Corporate • Reuse implementation is highly dependent upon economics and risk mitigation. • Conservation measures are usually considered ahead of reuse/recycling efforts. • Investment is allocated to meet regulatory restrictions, but there is little investment overlap with production budgeting. • There has been greater focus to date on energy over water conservation. • Use of cost instead of quantity requirements can impact KPI and erode comparative use of the metric.	*Corporate* • Corporate cultural differences • Tolerance toward and ability to manage risks (risk increases as treatment monitoring requirements increase) • Utilization of green chemistry that focuses on water reduction as well as energy reduction and minimization of residuals is not equally prominent across industries.
Technology • Energy-intensive membrane or thermal processes are needed to address salt removal. • Reasonably accurate flow and impurities-mass balance are needed to assess feasibility of treatment design alternatives. • Blending of wastewater and incoming water is often considered as a way to expand reuse/recycling opportunities. • Must adequately remove risks from residual impurities	*Technology* • Different degree of exploitation of cogeneration opportunities (i.e., largely untapped potential) • Water–mass balance measurements differ among industrial sectors (metering needs improvement in some industries to better assess flows, and more contaminant monitoring may define where reuse applications will be cost-effective or viable). • Definitions of suitable water quality are industry specific; overlying site-specific risk mitigation needs and scales of operation affect treatment.
Infrastructure Replumbing and water storage requirements frequently	*Infrastructure* Storage needed for reuse of condenser water.

Similarities	**Differences**
impede reuse alternatives,	
Discharge Irrigation exceeding 10% of discharge volume is considered land application, with much stricter permitting requirements that could impede water reuse for this application.	*Discharge* Discharge water quality and quantity is site specific.
Regulatory None cited.	*Regulatory* • Industry-specific regulatory constraints (e.g., food and beverage cannot utilize reuse water directly in products) • Environmental controls (e.g., waste incineration combined with other processes) can evoke RCRA regulations, making it difficult to reuse water. • Water management standards differ by industry. • Permitting restrictions (local, state, federal regulations) and type of discharge (e.g., surface water, ocean) can also drive the type of treatment selected for recycling.
Reuse/Recycling Application Areas • Floor cleaning, general equipment washing, process wash water/rinsing, and environmental controls (e.g., wet scrubber in incinerators or for cereal dust, dust suppression in mining) are common applications. • Landscape irrigation, noncontact cooling water, and boiler feed water are easiest to implement, although boiler feed must be treated to a higher quality. The exception is once-through steam generators, which tolerate a much lower quality water. • Boiler and cooling tower blowdown treatment costs are high and usually don't offer effective opportunity for reuse. • Running evaporative cooling to higher cycles of concentration is restricted by capital outlay and salt limitation challenges. • Reuse water for boiler feed will be avoided if the steam is used in the process because many contaminants will transfer to the steam.	*Reuse/Recycling Application Areas* • Reuse for irrigation purposes is location driven and dependent on whether crop is utilized in product. • Power plants focus on air pollution regulatory impacts, which influence their use of water. • Food safety requirements discourage implementation of water reuse/recycling in the food and beverage industry (not in final rinse or as product ingredient). • The potential to concentrate undesirable compounds is sometimes too high for the chemical industry. • Process limitations caused by certain product technical specifications forbid reuse water applications (e.g., satellite plating, food ingredients).

Notes: KPI=key performance indicators; RCRA=Resource Conservation and Recovery Act.

4.2 Opportunities and Drivers Identified for On-Site Water Reuse/Recycling

Drivers and opportunities that promote on-site water reuse/recycling projects were identified by the workshop attendees. Drivers refer to activity-driven behaviors, and opportunities refer to circumstances that allow these activities to occur. Table 4.2 summarizes these drivers and opportunities under categorical subheadings. The majority of the drivers are perceived to occur at the industrial corporate level, through regional public–private partnerships initiated in response to drought referendums or by imposition of regulatory restrictions arising from source water limitations or discharge restrictions. Opportunities were cited at the industrial corporate level via public–private partnerships, technology innovations, facility practices, and financial instruments.

Table 4.2. Workshop Attendee–Identified Water Reuse/Recycling Drivers and Opportunities

Drivers	Opportunities
Corporate • Social responsibility (social license to operate) • Water supply risk reduction (however, ISO water foot printing is not on corporate radar) • Supply-chain risk reduction • Assigning true cost of water • Accounting systems capable of distributing true cost of water within a department • Corporate systems that promote water efficiency • Water minimization studies that drive incentives • Strategic location requirements • Slowing of industry relocation options to developing countries is due to restricted water availability.	*Corporate* • Enterprise-level sustainability goals that incorporate reuse goals, not just conservation goals • Improved metering capabilities that relate to water reuse options, not just conservation • Corporate environmental stewardship considerations, such as LEED concept
Public–Private Partnerships Drought referendums, such as the one in Texas to fund water projects, with resultant public–private partnerships creating marketing opportunities for water reuse/recycling	*Public–Private Partnerships* • Utilize application of life-cycle basis of project to thwart opposition from shareholders to public–private partnerships. that might not succeed strictly on economics • Discourage water utilities from raising their charges for industries that have achieved water savings through reuse or conservation. This is a regional issue that has occurred in different parts of the United States.
Regulatory • Fixed water allocations coupled with facility expansion needs • More stringent discharge requirements • Increased water reuse requirements	*Regulatory* None cited

Drivers	**Opportunities**
Technology None cited.	*Technology* • Reusing condensate with a ZLD process • Recovery of cooling tower water lost to evaporation • Innovative solutions for resource recovery • Continued development of technologies that target restricted discharge constituents
Facility None cited.	*Facility* • Clean-in-place opportunities • Product rinsing • Overcome barrier to capture discharge water in tankage for investigation of water quality and treatment feasibility studies. • Recapture conveyance push water (e.g., wineries). • More flow meters and quality monitoring by which to generate water reuse decisions sometimes avoided through regulatory reporting requirements • Reuse potential of streams that don't currently count as discharge (e.g., filter backwash) • Cost avoidance by reuse water efficiency gains that mitigate new treatment system requirements • Cooperation among industrial facility finance and operations groups
Financial None cited.	*Financial* • Water utility incentives/rebates, particularly for cooling towers, irrigation, or staff-related sanitation • Financing options • Evaluation models of capital investments that incorporate true cost of water considerations

Notes: LEED=Leadership in Energy and Environmental Design; ZLD=zero liquid discharge.

Workshop attendees were also asked to specifically identify tipping factors that promote installation of on-site water reuse/recycling practices. The primary responses were (1) public perception and marketing needs; (2) high flow rates; (3) availability of water flow metering and quality sensing at process level that facilitate system design; and (4) utilization of water for energy production (cogeneration). Cost was not cited as a key tipping factor because of the frequent undervaluation of supply water and the equivalent or greater degree of treatment need for water reclamation compared with wastewater discharge requirements. This situation may change for locations within newly constructed industrial parks with more stringent discharge requirements or when feasibility studies consider the true cost rather than just the supply cost of water.

4.3 Identification of Challenges that Forestall On-Site Water Reuse/Recycling Practices and Suggested Recommendations to Overcome these Challenges

Specific challenges to the practice of on-site water reuse/recycling implementation at industrial facilities and suggested recommendations to overcome these challenges were identified by the workshop attendees. These challenges and recommendations are summarized in Table 4.3 under categorical subheadings. Within the corporate category, there is a strong need to develop a program to calculate the true cost of water in a manner that delineates the potential role of on-site water reuse/recycling in mitigating present and future costs and production risks. Within the public–private partnership category, there is the need for government and nongovernment organizations to assist industries with promotion of water reuse/recycling efforts through updated dissemination of successful case studies and establishment of accreditation programs that provide incentives for water reuse/recycling implementation. Within the technology category, a strong need exists for cost-effective residuals handling, disseminating information on the latest treatment developments with the boundary conditions for their application, and development of cost-effective online monitoring of constituents. Within the financial category, there is a need for identifying the most cost-effective reuse solutions or outside funding assistance.

Table 4.3. Workshop Attendee–Identified Water Reuse/Recycling Implementation Challenges and Recommendations to Overcome these Challenges

Challenges Impeding On-Site Water Reuse/Recycling	Recommendations To Overcome Challenges
Corporate • Lack of education or awareness within the organization • Perceived public health or safety concerns • Negative public perception • Production control practices that focus on product quality without much consideration of minimizing water use • Poor translation of corporate initiatives into practice • Need to revisit and reset quality metrics • Quality control and quality assurance (i.e., acceptability for use in process) supersede consideration of environmental impacts. • Corporate governance of water consumption lacks focus on water reuse/recycling. • Need for a more meaningful corporate model that incorporates the benefits of reuse/recycling • Understanding the true cost of water so that energy and gas concerns don't always come first.	*Corporate* • Educate corporate management about true cost of water to eliminate institutional barriers to water reuse/recycling implementation (i.e., promote circular economy philosophy). • Make public and corporate aware of water reuse/recycling benefits.
Public–Private Partnerships • Lack of neutral third-party assessment of water reuse expertise (i.e., verification program) • Lack of water reuse presentations at more standard sustainability conferences attended by industries	*Public–Private Partnerships* • Establish accreditation program for industrial water reuse similar to LEED for buildings. • Promote federal agency equivalent to Federal Energy Regulatory Commission to minimize undervaluation of water. • Create database of case study projects with detailed information on clients, vendors, and experts involved. • Seek ways to expand benchmarking presentations at conferences. • Involve government affairs offices and improve community relations. • Create mechanisms to capture ongoing research. • Support independent third-party listing of industrial water reuse best practices.

Challenges Impeding On-Site Water Reuse/Recycling	Recommendations To Overcome Challenges
	• Third-party listing should go beyond benchmarking by incorporating beneficial practices for common processes in order to provide an à la carte approach; need is for factual rather than anecdotal information that captures methodology, conditions, investment, and return on investment. • Need for calculator of true cost of water to be developed by neutral third party
Regulatory • Regulations that are too restrictive, lacking, overly politicized, or difficult to extrapolate to the future • Conflicts between reclamation options and permit requirements (e.g., creates mass loading violations, generates hazardous waste residual)	*Regulatory* • Creation of guidance manual for industry interaction with local regulators and municipalities • Creation of guidance on reuse practices for food and beverage industries, particularly regarding contact with reuse water
Technology • Cost-effective pollutant sinks and sludge management • Performance guarantees (i.e., acceptability for use in process) • Neutral third-party provision of latest technology products • Need for enhanced online low-level monitoring of trace pollutants and cost-effective removal sinks • Overcoming or limiting buildup of salinity and other constituents of concern during reuse/recycling and developing more cost-effective alternatives to salinity sinks than zero liquid discharge.	*Technology* • Fouling- and heat-resistant membranes are needed. • Biological catalysts may alleviate pretreatment and sidestream treatment for recalcitrant compounds. • The Water Conservation Technology International closed-loop system can dramatically reduce cooling tower blow down. • Develop tools to evaluate fate and transport of chemicals. • Integrate available modeling tools. • Process models are better tools than water pinch analysis; the pinch concept is too complicated for water because of multiple contaminants and sources and dispersed discharges.
Facility • Footprint challenges • Need for more accurate site mass and water balance programs (e.g., models, tools) • Insufficient process metering within unit/work cells of process (e.g., different cereal lines, component and modular production differences)	*Facility* • Identify locations with higher total dissolved solids production, which will drive reuse/recycling options. • Obtain sufficient granularity of process flows and water quality to identify problem nodes. • Environmental engineering needs to more fully integrate with plant engineers and other groups. • Utilize gamification to drive goals developed inside the fence line.

Challenges Impeding On-Site Water Reuse/Recycling	Recommendations To Overcome Challenges
Financial • Negative cost perception of on-site reuse/recycling is due to high cost for some municipal reuse water. • Insufficient return on investment or internal rate of return • Capital expenditure funding availability • Perceived production risk impacts • Influence of vendor supply risks can negatively impact internal reuse drivers. • Environmental impact assessment of capital projects tends to focus on regulatory compliance and risk reduction for the lifespan of the project rather than considering long-term ecological risks.	*Financial* Maintain dedicated budget for water that captures true value of water (e.g., better balance between sustainability and productivity budget so funding is earmarked for flow meter installation).

Note: LEED=Leadership in Energy and Environmental Design.

4.4 Most Implementable Water Reuse/Recycling by Industrial Sector for Generic Water Use Categories

Workshop attendees were asked to rank the ease of implementation of water reuse/recycling for the eight generic use categories. Six total attendees responded, representing mining (n=2), food and beverage (n=2), power (n=1), and metal manufacturing (n=1). For these respondents, the easiest application cited was landscape irrigation, and the hardest applications cited were cogeneration/energy recovery and product processing. The remaining categories had much greater variability in responses even between facilities within the same sector. The highest growth potential in the next 5 years was thought to be cogeneration for the mining industry, cooling and boilers for the food and beverage industry, and product processing for metal manufacturing. It should be noted that these results come from a small number of respondents and should not be considered as representative of these sectors. The importance of water reuse/recycling relative to other sustainability indicators was also discussed. In many cases, water was not ranked as high as other sustainability indicators related to energy production or use. For water considerations, conservation is still the prevailing KPI, with little emphasis specifically on water reuse/recycling.

Chapter 5

Research Road Map for On-Site Industrial Water Reuse/Recycling

The key findings from the peer-reviewed and gray literature, the survey responses provided by the participating industries, and the workshop attendee discussions are synthesized here, to provide a better understanding of factors with the greatest influence on successful implementation of on-site industrial water reuse/recycling, where opportunities for implementation of on-site water reuse/recycling are most likely to occur, and what research efforts are needed to assist in maximizing these installations.

5.1 Factors that Influence Implementation of On-Site Industrial Water Reuse/Recycling

Many factors must be considered during the decision process for implementation of on-site water reuse/recycling at an industrial facility. Each of these factors can be grouped under one of the following four categories: (1) sustainable; (2) technological; (3) regulatory; and (4) economic. Table 5.1 provides a summary of these factors and their classification category. Depending on the disposition of these factors relative to the facility's geographical setting, management culture, facility infrastructure, local governance policies, and water quality treatment needs, they will function as either drivers or challenges for developing on-site water reuse/recycling capabilities.

Table 5.1. Categorical Factors that Translate to Site-Specific Drivers and Challenges When Considering On-Site Industrial Water Reuse/Recycling Projects

Sustainability	Technology	Regulatory	Economic
• KPI metrics for water • Water scarcity, facility locations, and expansion plans • Water reclamation volume and quality recovery relative to needs • Ease of wastewater discharge permitting and limits • License to operate	• Reuse vs. discharge technology parity (ability to handle matrix and pre- or post-treatment requirements) • Demonstrated performance (case studies) of reuse technology options • Ease of reuse technology for site-specific application	• Locational regulations impacting wastewater discharge options (e.g., EPA Toxics Release Inventory) • Guidelines for regulatory permitting of water reclamation projects • Pending regulation anticipated to impact future discharge for industry sector	• Production risks associated with reuse • Availability of incentives • ROI timeline • Availability of economically viable sink for captured pollutants • Knowledge of true cost of water and its utilization in alternatives assessment

Notes: EPA=United States Environmental Protection Agency; KPI=key performance indicators; ROI=return on investment.

Once the decision to implement an on-site industrial water reuse/recycling project has been made, a project's success is dependent upon additional factors that can be categorized under the same categories of (1) sustainable; (2) technological; (3) regulatory; and (4) economic.

Table 5.2 provides a summary of these factors and their categorical classification. The likelihood of project success is closely linked to having a high percentage of these factors addressed or readily implementable during the preliminary planning and design stages of the water reuse/recycling system.

Table 5.2. Categorical Factors Linked to Site-Specific Success of On-Site Industrial Water Reuse/Recycling Project Implementation

Sustainable	Technological	Regulatory	Infrastructure Cost
• Water auditing capabilities relative to water quality, quantity, energy usage, GHG emissions. • Resource recovery goals and strategies • Tools for true cost of water assessments	• Proven solution for site-specific application or ability to tailor applicability through piloting efforts • Acceptable risk-mitigation design-build strategies • Suitable real-time monitoring strategies for risk mitigation during operations • Suitable contingencies to prevent production impacts	• Strength of stakeholder partnerships • Successful outreach efforts toward relevant organizations • Detailed understanding of permitting process requirements	• Ability to segregate facility waste streams as required for successful design approach • Flexibility of pipeline routing and suitability of existing pipeline materials • Feasibility of process treatment train or zero liquid discharge options at site • Volume-matching capabilities of recycled streams

Note: GHG=greenhouse gas.

5.2 Best Opportunities for On-Site Industrial Water Reuse/Recycling

The biggest overall drivers of on-site industrial water reuse/recycling are wastewater discharge regulations (and disposal well availability) and water supply restrictions, which are largely regional. Local water scarcity can lead to corporate margin erosion and in severe cases can result in a loss of license to operate. The sector most impacted by these issues is the mining industry because water is needed for a broad range of activities, and operations are often constrained to water-scarce locations. In 2011, the mining industry used approximately 2.1 trillion gallons of water per year (second only to the power industry), with a capital expenditure on managing this water at approximately $8 billion (Global Water Intelligence, 2011). The ability to implement water reuse/recycling strategies resulting in ZLD in this industry sector mitigates concerns over loss of water from the hydrological cycle caused by deep-well injection of wastewater or the possible spread of contaminants from wastewater disposal practices that can only be avoided by using costly treatment options.

The predominant use of water in the power industry is in the towers utilized to cool the steam circuit. Reclaimed water at power plant cooling towers is primarily from an off-site supply of reclaimed wastewater effluent or other marginal water because sources of recycled water within a power facility are inadequate for the cooling requirements. Only a 5 to 20% overall reduction in water consumption can be collectively achieved for a wet tower-cooled facility through implementation of on-site water reuse/recycling of blowdown and process water and elimination of water for FGD and ash handling. Other options to reduce water consumption by a factor of two or more are limited to utilization of a more thermally efficient generation technology, topping-cycle cogeneration, a different cooling system, or offsets from a recycled water producer.

Water reuse/recycling opportunities in the food and beverage industry are principally in the cleaning and rinsing of raw product, processing equipment, and packaging materials as well as thermodynamic processes (e.g., cooling towers and boilers) and irrigation of the agricultural raw product if it is grown on-site. Health and safety regulations and public risk perceptions prevent the use of reclaimed water directly on the finished food products. Water reuse implementation appears to be highly influenced by location and does not have the same corporate visibility as water conservation.

Water needs in manufacturing industries are quite variable, with the highest use cited in the literature for paper, textile, iron and steel, tannery, and chemical manufacturing industries. Many of these industries are located in Asia, although there has been a slowing of industry relocation to developing countries. Water reuse/recycling opportunities first target easier applications such as thermodynamic processes (e.g., cooling towers and boilers) and process cleaning and rinsing applications. Difficulties in process wastewater treatment are greatest for industries that utilize or manufacture recalcitrant organic compounds (e.g., textile dyeing, semiconductor, paper production, chemicals). Membrane treatment is foundational to many water reuse processes that must handle high levels of salts or recalcitrant organics. Pretreatment requirements are driven by the need to prevent unacceptable membrane fouling, and post-treatment is utilized to remove additional contaminants that persist within the process permeate (e.g., silica, boron, ammonia, small organics). The biggest deterrent to on-site water reuse/recycling implementation is demonstrating adequate ROI (2-3 years) because of the undervaluation of source water supplies and treatment residual disposal issues.

In terms of the generic water use categories that cut across industrial sectors, the easiest and most readily applied water reuse/recycling applications appear to be for irrigation, process-related cleaning and rinsing, and makeup water for cooling towers. The most difficult application is utilization directly in product production, whereas cogeneration is perceived to be an untapped application with a lot of future potential. Closing the loop on energy recovery when water is the carrier medium across the facility will yield water reuse opportunities.

5.3 Research Needed To Further Promote On-Site Industrial Water Reuse/Recycling

Promotion and expansion of on-site water reuse/recycling capabilities within industries will benefit from additional research efforts designed to address existing knowledge gaps and implementation challenges. The major research topics identified during this project are summarized in Table 5.3 under different topical categories. The finance, technology, and communication categories will best drive on-site water reuse/recycling efforts when they occur simultaneously and positively reinforce one another in driving the overall process for on-site industrial water reuse/recycling implementation. Guidance on topics related to planning, predesign, design, and implementation of reuse/recycling projects specific to industrial facilities also needs to be developed.

Table 5.3. Major Research Topics Identified for Promoting and Expanding Industry Use of On-Site Water Reuse/Recycling

Finance

- Develop ROI calculator based on the true cost of water.
- Identify and seek means to further develop subsidies or public–private partnership opportunities that promote on-site water reuse/recycling and overall water use optimization.

Technology

- Identify and further develop treatment technologies for critical industrial sector needs (e.g., salt-handling capabilities with an economical sink, recalcitrant organics)
- Compile the latest technology developments, their benefits over traditional alternatives, and areas of demonstrated applicability.
- Develop cost-effective ZLD applications.
- Identify and develop technological criteria for standardization of treatment skids to address specific reuse/recycle applications.

Communication

- Develop strategies and tools to promote a circular economy corporate culture that will drive water reuse/recycling implementation.
- Create knowledge-sharing platforms (or industrial water management working groups) between different industrial sectors with similar needs.
- Compile and continually update case study information in a publicly accessible format.

Guidance

- Document design criteria for new facilities that promote utilization of marginal waters.
- Document auditing procedures for existing facilities that promote water reuse/recycling practices.
- Document treatment and residuals criteria and model treatment schemes for different industrial sectors.
- Document validation protocols for process train solutions.
- Document water reuse/recycling criteria for generic water usage categories that cut across industrial sectors (e.g., thermodynamic, conveyance, environmental controls, facility sanitation, process, irrigation).
- Integrate water reuse/recycling options within existing water footprint/scarcity tools.

Notes: ROI=return on investment; ZLD=zero liquid discharge.

References

Abid, M. F.; Zablouk, M. A.; Abid-Alameer, A. M. Experimental study of dye removal from industrial wastewater by membrane technologies of reverse osmosis and nanofiltration. *Iran. J. Environ. Health Sci. Eng.* **2012,** *9*, 17.

Afonso, M. D.; Borquez, R. Review of the treatment of seafood processing wastewaters and recovery of proteins therein by membrane separation processes—prospects of the ultrafiltration of wastewaters from the fish meal industry. *Desalination* **2002,** *142*, 29–45.

Agana, B. A.; Reeve, D.; Orbell, J. D. An approach to industrial water conservation—a case study involving two large manufacturing companies based in Australia. *J. Environ. Manage.*

alh, J. V. The status of water reuse in European textile sector. *J. Environ. Manage.* **2014,** *141*, 29–35.

Ahmadun, F.-R.; Pendashteh, A.; Abdullah, L. C.; Biak, D. R. A.; Madaeni, S. S.; Abidin, Z. Z. Review of technologies for oil and gas produced water treatment. *J. Hazard. Mater*. **2009,** *170*, 530–551.

Ait Hsine, E.; Benhammou, A.; Pons, M. N. Water Resources management in soft drink industry water use and wastewater generation. *Environ. Technol.* **2005,** *26,* 1309–1316.

American Society of Mechanical Engineers (ASME). Water Management Technology Best Management Practices and Innovations for the Process Industries, June 2010. http://files.asme.org/Committees/K&C/TCOB/CRTD/30028.pdf (accessed June 2015).

AQUASTAT. Database, FAO’s Global Information System on Water and Agriculture, 2012.

Asano, T.; Visvanathan, C. Industries and water recycling and reuse. Presented at Founders’ Seminar, August 15, 2001, Stockholm City Conference Center, Norra Latin, Sweden. http://faculty.ait.ac.th/visu/Prof%20Visu%27s%20CV/chapters%20in%20Books/16/Founders%20Seminar%20Asano.%20Final.pdf (accessed June 2015).

Ayert, K.; Fisher, J.; Huber-Lee, A.; Lewis, A.; Machnick, J.; Madden, N.; Rogers, J.; Tellinghuisen, S. Freshwater use by U.S. power plants: Electricity’s thirst for a precious resource. A report of the Energy and Water in a Warming World Initiative. Cambridge, MA: Union of Concerned Scientists, November 2011.

Barrington, D. J.; Prior, A.; Ho, G. The role of water auditing in achieving water conservation in the process industry. *J. Cleaner Prod.* **2013,** *52,* 356–361.

Beverage Industry Environmental Roundtable (BIER). A Practical Perspective on Water Accounting in the Beverage Sector, December 2011, Version 1.0 Report. http://www.waterfootprint.org/Reports/BIER-2011-WaterAccounting SectorPerspective.pdf (accessed June 2015).

BIER. Managing Water-Related Business Risks & Opportunities in the Beverage Sector. Practical Perspective, November 2012. Report.

Bowen Engineering. Buchanan Mine WTP, 2014. http://www.bowenengineering.com/portfolio/buchanan-mine-wtp/ (accessed June 2015).

Buecker, B.; Clarke, B. Controlling water usage and wastewater discharge. *Power Engineering*, September 1, 2011. http://www.power-eng.com/articles/print/volume-115/issue-9/features/controlling-water-usage-and-wastewater-discharge.html

Byers, W.; Lindgren, G.; Noling, C.; Peters, D. *Industrial Water Management, A Systems Approach*, 2nd ed.; American Institute of Chemical Engineers: New York, 2003.

California Department of Water Resources. Water Efficiency Guide for Business Managers and Facility Engineers, 1994.

California Energy Commission. Technology Roadmap Energy Efficiency in California's Food Industry; Report CEC-500-2006-073, July 2006. http://www.energy.ca.gov/2006publications/CEC-500-2006-073/CEC-500-2006-073.pdf

California State Water Resources Control Board. Municipal Wastewater Recycling Survey, 2009. http://www.waterboards.ca.gov/water_issues/programs/grants_loans/water_recycling/docs/munirecsrvy/Table1.pdf (accessed June 2015).

CEO Water Mandate. Guide to Water-Related Collective Action, September 2013. http://ceowatermandate.org/wp-content/uploads/2013/09/guide-to-water-related-ca-web-091213.pdf (accessed June 2015).

Chavez-Rodriguez, M. F.; Mosqueira-Salazar, K. J.; Ensinas, A. V.; Nebra, S. A. Water reuse and recycling according to stream qualities in sugar–ethanol plants. *Energ. Sustain. Dev*. **2013,** *17*, 546–554.

Choi, J.; Chung, J. Reuse of semiconductor wastewater using reverse osmosis and metal-immobilized catalyst-based advanced oxidation process. *Ind. Eng. Chem. Res*. **2014,** *53*, 11167–11175.

Christophersen, D. Water Reuse Strategies: Steel Industry Case Studies, 2008. http://www.veoliawaterstna.com/crownsolutions/ressources/documents/2/21820,NACE-Steel_Mill_Water_Reuse_2008_r.pdf (accessed June 2015).

Cunningham, J. Comparing municipal to industrial wastewater treatment. *Clear Waters,* Spring **2013,** 13–16. https://nywea.org/clearwaters/13-1-spring/6.pdf (accessed June 2015).

Electric Power Research Institute (EPRI). 2003. Gasifipedia. http://www.netl.doe.gov/File%20Library/Research/Coal/energy%20systems/gasification/gasifipedia/index.html (accessed June 2015).

EPRI. *Program on Technology Innovation: Technology Research Opportunities for Efficient Water Treatment and Use*, 1016460, EPRI: Palo Alto, CA, 2008.

El-Naas, M. H.; Al-Zuhair, S.; Abu Alhaija, M. Evaluation of a three-step process for the treatment of petroleum refinery wastewater. *J. Environ. Chem. Eng.* **2014,** *2,* 56–62.

Enderle, P.; Nowalk, O.; Kvas, J. Potential alternative for water and energy savings in the automotive industry: case study for an Austrian automotive supplier. *J. Cleaner Prod.* **2012,** *34*, 146–152.

Equova. Critical ultrapure water applications for the semiconductor industry, n.d. http://www.evoqua.com/en/semiconductor-solar/semiconductor/Pages/upw-apps-semiconductor-industry.aspx (accessed June 2015).

Eurostat, nd. http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Water_statistics

Feeley, T. J. III; Skone, T. J.; Stiegel, G. J. Jr.; McNemar, A.; Nemeth, M.; Schimmoler, B.; Murphy, J. T.; Manfredo, L. Water: A critical resource in the thermoelectric power industry. *Energy* **2008,** *33,* 1–11.

Flörke, M.; Kynast, E.; Bärlund, I.; Eisner, S.; Wimmer, F.; Alcamo, J. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Global Environ. Change* **2013,** *23,* 144–156.

Gadipelly, C.; Pérez-González, A.; Yadav, G. D.; Ortiz, I.; Ibáñez, R.; Rathod, V. K.; Marathe, K. V. Pharmaceutical industry wastewater: Review of the technologies for water treatment and reuse. *Ind. Eng. Chem. Res.* **2014,** *53,* 11571–11592.

Galil, N. I.; Levinsky, Y. Sustainable reclamation and reuse of industrial wastewater including membrane bioreactor technologies: case studies. *Desalination* **2007,** *202,* 411–417.

General Electric Company (GE). Creating Effective Incentives for Water Reuse and Recycling, March 2011. http://www.sustainableplant.com/assets/GE-White-Paper-Creating-Effective-Incentives-White-Paper.pdf (accessed June 2015).

GE. Water treatment solutions for the mining industry, 2014.

Global Environmental Management Initiative (GEMI), 2002a. http://www.gemi.org/water/indexhtm.

Global Environmental Management Initiative (GEMI). Connecting the Drops Toward Creative Water Strategies. A Water Sustainability Tool, 2002b. http://www.gemi.org/resources/connectingtheDrops.pdf (accessed June 2015).

Global Water Intelligence. Don't waste a drop. *Mining Magazine*, October 2011 (http://www.globalwaterintel.com/dont-waste-drop-water-mining/).

GEMI. Collecting the Drops: A Water Sustainability Planner, 2007. http://www.gemi.org/waterplanner/Documents/CollectingDrops.pdf (accessed June 2015).

Global Reporting Initiative (GRI). Water Protocol. For use with the GRI 2002 Sustainability Reporting Guidelines, February 2003. https://center.sustainability.duke.edu/sites/default/files/documents/gri_waterprotocol.pdf (accessed June 2015).

Harling, A. Memorandum from OECD Competitive Intelligence Research Service to Humboldt Bay Municipal Water District. What Industries/Products are the most water-intensive within the United States? 2009. http://www.hbmwd.com/site_documents/HSU%2010-28-09%20Research%20water%20intensive%20industries.pdf (accessed June 2015).

He, Y.; Wang, X.; Xu, J.; Yan, J.; Ge, Q.; Gu, X.; Jian, L. Application of integrated ozone biological aerated filters and membrane filtration in water reuse of textile effluents. *Bioresour. Technol.* **2013,** *133,* 150–157.

Hejazi, M.; Edmonds, J.; Clarke, L.; Kyle, P.; Davies, E.; Chaturvedi, V.; Wise, M.; Patel, P.; Eom, J.; Calvin, K.; Moss, R.; Kim, S. Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technol. Forecast. Soc.* **2014,** *81,* 205–226.

Hoekstra, A. Y.; Hung, P. Q. *Virtual Water Trade. A Quantification of Virtual Water Flows Between Nations in Relation to International Crop Trade,* Value of Water Research

Report Series, No. 11, UESCO-IHE: Delft, The Netherlands, 2002. http://www.waterfootprint.org/Reports/Report11.pdf (accessed June 2015).

Hu, Y.; Cheng, H. Water pollution during China's industrial transition. *Environ. Dev.* **2013,** *8*, 57–73.

Industrial Water World. Water Treatment: Chemical and Pharmaceutical Industries. nd. http://www.waterworld.com/articles/iww/print/volume-12/issue-05/feature-editorial/water-treatment-chemical-and-pharmaceutical-industries.htm

International Bottled Water Association (IBWA). Water Use Benchmarking Study: Executive Summary, October 21, 2013. http://www.bottledwater.org/files/IBWA%20Water%20Use%20Benchmarking%20Report%20-%20Exec%20Summary%20FINAL%20102113.pdf (accessed June 2015).

International Life Sciences Institute (ILSI). Water Recovery and Reuse: Guidelines for Safe Application of Water Conservation Methods in Beverage Production and Food Processing. ILSI: Washington, DC, 2013.

International Life Sciences Institute (ILSI). Considering Water Quality for Use in the Food Industry. Report, 2008. http://www.ilsi.org/Europe/Publications/R2008CON_H2O.pdf (accessed June 2015).

International Petroleum Industry Environmental Conservation Association (IPIECA). Review of Water Risk Tools. Guidance Document for the Oil and Gas Industry, 2014. http://www.ipieca.org/publication/review-water-risk-tools-guidance-document-oil-and-gas-industry (accessed June 2015).

Jadhav, S. B.; Singhal, R. S. Polysaccharide conjugated laccase for the dye decolorization and reusability of effluent in textile industry. *Int. Biodeter. Biodegr.* **2013,** *85*, 271–277.

Jakimchuk, R. D. The Role of Environmental Assessment in Support of Sustainable Development. In *Sustainable Development and Environmental Assessment: Perspectives on Planning for a Common Future*; Jacobs, P.; Sadler, B., Eds.; A Background Paper Prepared for the Canadian Environmental Assessment Research Council, 1987.

Jiménez, B.; Asano, T. Water Reuse: An International Survey of current practice, issues and needs. Water Intelligence Online: IWA Publishing: London, UK, 2008. http://www.iwaponline.com/wio/2008/05/wio200805RF1843390892.htm (accessed June 2015).

Judd, S. *The MBR Book, Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment*, 2nd ed. Elsevier Ltd.: Oxford, UK, 2011, pp 278–280.

Jupp, R. Dyeing Printing & Finishing, *Textile World*, March/April 2011. http://www.textileworld.com/Issues/2011/March-April/Dyeing_Printing_and_Finishing/Sustainable_Dyeing_And_Finishing (accessed June 2015).

Kamali, M.; Khodaparast, Z. Review on recent developments on pulp and paper mill wastewater treatment. *Ecotox. Environ. Safe.* **2014,** *114*, 326–342.

Klemeš, J. J. Industrial water recycle/reuse. *Curr. Opin. Chem. Eng.* **2012,** *1*, 238–245.

Koppol, A.; Bagajewicz, M.; Dericks, B.; Savelski, M. On zero water discharge solutions in the process industry. *Adv. Environ. Res.* **2003,** *8*, 151–171.

Kukade, S. Reuse of effluent to solve problem of water scarcity. *Chem. Eng. World* **2010,** 45 , 6, *66*-68.

Levi Strauss & Co. (LS&Co). Water Recycle/Reuse Standard, nd. http://levistrauss.com/wp-content/uploads/2014/02/LSCo-Water-Recycle-Reuse-Standard.pdf

Lambooy, T. Corporate social responsibility: sustainable water use. *J. Cleaner Prod.* **2011,** *19,* 852–866.

Lahnsteiner, J.; Klegraf, F.; Mittal, R.; Andrade, P. Reclamation of wastewater for industrial purposes—advanced treatment of secondary effluents for reuse as boiler and cooling make-up water. Paper presented at the Sixth IWA Specialist Conference on Wastewater Reclamation and Reuse for Sustainability, October 9–12, 2007, Antwerp, Belgium.

Lawler, D. Final Report: Simultaneous water conservation/recycling/reuse and waste reduction in semiconductor manufacturing. n.d. http:/cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.publications/abstract/5878 (accessed June 2015).

Lee, S. J.; Lee, Y.-W.; Chung, J.; Lee, J. K.; Lee, J. Y.; Jahng, D.; Cha, Y.; Yu, Y. Reuse of low concentrated electronic wastewater using selected microbe immobilized cell system. *Water Sci. Technol.* **2008,** *57* (8), 1191–1197.

Masmoudi, G.; Trabelsi, R.; Ellouze, E.; Amar, R. B. New treatment at source approach using combination of microfiltration and nanofiltration for dyeing effluents reuse. *Int. J. Environ. Sci. Technol.* **2014,** *11* (4), 1007–1016.

McCandless, R. Overview of membrane technology applications in industrial reuse. Proceedings of 85th Annual Water Environment Federation Technical Exposition & Conference [CD-ROM]; New Orleans, LA, September 29–October 3. Water Environment Federation: Alexandria, VA, pp 8578–8589.

Mehrdadi, N.; Bidhendi, G. N.; Mohammadnejad, S. An overview on different water pinch methods for industrial water and wastewater minimization. *Environ. Sci.* **2009,** *6* (4), 29–42.

Mitchell, B. The value of water as a commodity. *Can. Water Res. J.* **1984,** *9* (2), 30–37. http://www.tandfonline.com/doi/pdf/10.4296/cwrj0902030 (accessed June 2015).

Moody's Investor Service. Global mining industry, 2013. https://www.moodys.com/research/Moodys-Water-scarcity-could-increase-rating-pressure-on-global-mining--PR_266225 (accessed June 2015).

Mosse, K. P. M.; Lee, J.; Leachman, B. T.; Parikh, S. J.; Cavagnaro, T. R.; Patti, A. F.; Steenwerth, K. L. Irrigation of an established vineyard with winery cleaning agent solution (simulated winery wastewater): Vine growth, berry quality, and soil chemistry. *Agr. Water Manage.* **2013,** *123,* 93–102.

Muro, C.; Riera, F.; del Carmen Díaz, M. Membrane Separation Process in Wastewater Treatment of Food Industry. In Valdez, B., Ed.; *Food Industrial Processes—Methods and Equipment;* InTech, Feburary 22, 2012.

Mutamin, N. S. A.; Noor, Z. Z.; Hassan, A.; Ariffin, M.; Yuniarto, A.; Olsson, G. Membrane bioreactor: applications and limitations in treating high strength industrial wastewater. *Chem. Eng. J.* **2013,** *225,* 109–119.

Natural Resources Canada. Pinch Analysis: For the Efficient Use of Energy, Water & Hydrogen, 2003.

O'Connor, M.; Garnier, G.; Batchelor, W. Life cycle assessment comparison of industrial effluent management strategies. *J. Cleaner Prod.* **2014,** *79,* 168–181.

Palaniappan, M.; Gleick, P. H. “Peak Water.” In Gleick, P.H.; Cohen, M. J.; Palaniappan, M.; Morikawa, M.; Morrison, J.; Cooley, H.; *The World’s Water 2008–2009: The Biennial Report on Freshwater Resources;* Island Press, 2013. http://worldwater.org/wp-content/uploads/sites/22/2013/07/ch01.pdf (accessed June 2015).

Pan, L.; Liu, P.; Ma, L.; Li, Z. A supply chain based assessment of water issues in the coal industry in China. *Energ. Policy* **2012,** *48,* 93–102.

Pang, Y. L.; Abdullah, A. Z. Current status of textile industry wastewater management and research progress in Malaysia: A review. *Clean Soil, Air, Water* **2013,** *41*, 751–764.

Pellegrin, M.-L.; Aguinaldo, J.; Arabi, S.; Sadler, M. E.; Min, K.; Liu, M.; Salamon, C.; Greiner, A. D.; Diamond, J.; McCandless, R.; Owerdieck, C.; Wert, J.; Padhye, L. P. Membrane processes. *Water Environ. Res.* **2013,** *85* (10), 1092–1175.

Pizzichini, M.; Russo, C.; Di Meo, C. Purification of pulp and paper wastewater, with membrane technology, for water reuse in a closed loop. *Desalination* **2005,** *178,* 351–359.

Pokhrel, D.; Viraraghavan, T. Treatment of pulp and paper mill wastewater—a review. *Sci. Total Environ.* **2004,** *333,* 37–58.

Power Engineering International. Rethinking coal fired power plants’ water reuse. Print publication, January 5, 2012. http://www.powerengineeringint.com/articles/print/volume-20/issue-5/features/rethinking-coal-fired-power-plants-water-reuse.html (accessed June 2015).

Pugh, L.; Burghart, A.; Finlay, C. Wastewater reuse considerations at a petroleum refinery. Proceedings Paper, WEFTEC,Oct 2-6, 2010, October 2-6, 2010, New Orleans, LA.

Ranade, V. V.; Bhandari, V. M. *Industrial Wastewater Treatment, Recycling, and Reuse;* Elsevier: Oxford, UK, 2014.

Ranganathan, K.; Karunagaran, K.; Sharma, D. C. Recycling of wastewaters of textile dyeing industries using advanced treatment technology and cost analysis—Case studies. *Resour. Conserv. Recy.* **2007,** *50,* 306–318.

Reardon, R. *The Guidebook to Membrane Technology for Wastewater Reclamation*; Wilf, M., Ed. and Coauthor; Balaban Desalination Publications: Hopkinton, MA, 2010, p 32.

Rubio, J.; Carissimi, E. The flocs generator reactor—FGR: a new basis for flocculation and solid–liquid separation. *Int. J. Miner. Process.* **2005,** *75* (3–4), 237–247.

Rupp, J. Sustainable Dyeing and Finishing. March/April 2011. http://www.textileworld.com/Issues/2011/March-April/Dyeing_Printing_and_Finishing/Sustainable_Dyeing_And_Finishing

SASI Group and Newman, M. Industrial Water Use. 2006 (http://www.worldmapper.org/posters/worldmapper_map325_ver5.pdf).

Saha, N. K.; Balakrishnan, M.; Batra, V. S. Improving industrial water use: case study for an Indian distillery. *Resour. Conserv. Recy.* **2005,** *43,* 163–174.

Sala, M.; Gutierrez-Bouzan, C. Electrochemical treatment of industrial wastewater and effluent reuse at laboratory and semi-industrial scale. *J. Cleaner Prod.* **2014,** *65,* 458–464.

Sampson, B.; Hilless, K.; Laganistra, M. Wastewater Environmental Best Practice Manual, The Australian Meat Processor Corporation Report, 2005. http://www.ampc.com.au/site/assets/media/reports/Resources/Wastewater-enviromental-best-practice-manual.pdf (accessed June 2015).

Scanlon, B. R.; Reedy, R. C.; Duncan, I.; Mullican, W. F.; Young, M. Controls on water use for thermoelectric generation: Case study Texas, U.S.. *Environ. Sci. Technol.* **2013,** *47,* 11326–11334.

Shaffer, D. L.; Arias Chavez, L. H.; Ben-Sasson, M.; Romero-Vargas Castrillón, S.; Yip, N. Y.; Elimelech, M. Desalination and reuse of high-salinity shale gas produced water: drivers, technologies, and future directions. *Environ. Sci. Technol.* **2013,** *47* (17), 9569–9583.

Simate, G. S.; Cluett, J.; Lyuke, S. E.; Musapatika, E. T.; Ndlovu, S.; Walubita, L. F.; Alvarez, A. E. The treatment of brewery wastewater for reuse: State of the art. *Desalination* **2011,** *273,* 235–247.

Singh, M. Water Consumption at Copper Mines in Arizona, State of Arizona Department of Mines & Mineral Resources, Special Report 29, December 2010. http://www.admmr.state.az.us/Publications/sr29WaterConsumptionCopperMines.pdf (accessed June 2015).

State of California Department of Water Resources, 2013. Commercial, Industrial, and Institutional Task Force Best Management Practices Report to the Legislature, Volume I, October 21, 2013. http://www.water.ca.gov/legislation/docs/CII%20Volume%20II%20july%202014.pdf (accessed June 2015).

Statistics Norway. Statistics on Environmental Accounts: Water Use by Industries, 2006. Final Report to EUROSTAT, May 31, 2006 https://www.google.com/url?sa=t&rct=j&q=&esrc=s&frm=1&source=web&cd=7&cad=rja&uact=8&ved=0CFAQFjAG&url=https%3A%2F%2Fcircabc.europa.eu%2Fsd%2Fd%2F76f5298e-a1b0-4863-83e5-a8024b033aa0%2FWater%2520accounts%2520Norway.pdf&ei=46b7U667NMurogSdw4GoAg&usg=AFQjCNGGd_nCXg11jjhb6A1m7QE7Y_eknw&bvm=bv.73612305,d.cGU.

Strzepek, K.; Baker, J.; Farmer, W.; Schlosser, C. A. Modeling water withdrawal and consumption for electricity generation in the United States, June 2012, Report No. 222, http://globalchange.mit.edu/files/publication/MITJPSPGC_Rpt221.pdf (accessed June 2015). MIT Joint Program on the Science and Policy of global Change.

Sullo, E. Scopus. *J. Med. Libr. Assoc.* **2007,** *95* (3), 367–368.

Tidwell, T. J.; De Paula, R.; Smadi, M. Y.; Keasler, V. V. Flow cytometry as a tool for oilfield biocide efficacy testing and monitoring. *Int. Biodeter. Biodegr.* **2015,** *98,* 26–34.

Torcellini, P.; Long, N.; Judkoff, R. Consumptive Water Use for U.S. Power Production National Renewable Energy Laboratory (NREL/TP-550-33905), December 2003. http://www.nrel.gov/docs/fy04osti/33905.pdf (accessed June 2015).

Torres, A. P.; Santiago, V. M. J.; Borges, C. P. Performance evaluation of submerged Membrane bioreactor pilot units for refinery wastewater treatment. *Environ. Prog.* **2008,** *27* (2), 189–194.

Tweed, K. Nearly Half of U.S. Power Plants Don't Reuse Water. *IEEE Spectrum*, 2014. http://spectrum.ieee.org/energywise/energy/fossil-fuels/nearly-half-of-us-power-plants-dont-reuse-water (accessed June 2015).

Union of Concerned Scientists. How it Works: Water for Power Plant Cooling, 2012. http://www.ucsusa.org/clean_energy/our-energy-choices/energy-and-water-use/water-energy-electricity-cooling-power-plant.html#.VGKMzbHTnIU (accessed June 2015).

UN Educational, Scientific and Cultural Organization, UN Water. The United Nations World Water Development Report 2014: Water and Energy. March 21, 2014. http://reliefweb.int/report/world/united-nations-world-water-development-report-2014-water-and-energy (accessed June 2015).

UNEP (2008) Vital Water Graphics, Retrieved from http://www.unep.org/dewa/vitalwater/article186.html

U.S. Department of Energy (DOE). Energy Demands on Water Resources. Report to Congress on the Interdependency of Energy and Water. December 2006. http://www.circleofblue.org/waternews/wp-content/uploads/2010/09/121-RptToCongress-EWwEIAcomments-FINAL2.pdf

U.S. DOE. The Water–Energy Nexus: Challenges and Opportunities, June 2014. http://www.energy.gov/sites/prod/files/2014/07/f17/Water%20Energy%20Nexus%20Full%20Report%20July%202014.pdf (accessed June 2015).

U.S. Environmental Protection Agency (U.S. EPA). Guidelines for water reuse. EPA/600/R-12/618. September 2012. http://nepis.epa.gov/Adobe/PDF/P100FS7K.pdf (accessed June 2015).

U.S. EPA. Technical Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category. EPA-821-R-13-002, April 2013a. http://water.epa.gov/scitech/wastetech/guide/steam-electric/upload/Steam-Electric_TDD_Proposed-rule_2013.pdf (accessed June 2015).

U.S. EPA. Environmental Assessment for the Proposed Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category. EPA-821-R-13-003, April 2013b. http://water.epa.gov/scitech/wastetech/guide/steam-electric/upload/Steam-Electric_EA_Proposed-rule_2013.pdf (accessed June 2015).

U.S. EPA. 2012 Toxics Release Inventory National Analysis Overview, February 2014, p 2. http://www2.epa.gov/sites/production/files/2014-01/documents/complete_2012_tri_na_overview_document.pdf (accessed June 2015).

U.S. Geological Survey (USGS) Estimated Use of Water in the United States in 2005. Circular 1344, U.S. Geological Survey, Reston, Virginia: 2009. http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf

U.S. Geological Survey (USGS) Estimated Use of Water in the Unnited States in 2000. Circular 1268, U.S. Geological Survey, Reston, Virginia: released March 2004, revised April 2004, May 2004, February 2005. (http://pubs.usgs.gov/circ/2004/circ1268/htdocs/text-in.html).

U.S. Government Accountability Office (U.S. GAO). Energy–Water Nexus: Information on the Quantity, Quality, and Management of Water Produced during Oil and Gas

Production. A Report to the Ranking Member, Committee on Science, Space, and Technology, House of Representatives, January 2012.

Vajnhandl, S.; V rd, UK, 2006.

Vajnhandl, S.; Valh, J. V. The status of water reuse in European textile sector. *J. Environ. Manage.* **2014,** *141*, 29–35

Visvanathan, C., Asano, T. The Potential for Industrial Wastewater Reuse. Report, 2009. www.worldwewant2015.org/file/303908/download/329870 (accessed June 2015).

World Wildlife Federation. Assessing Water Risk. A Practical Approach for Financial Institutions, 2011. http://awsassets.panda.org/downloads/deg_wwf_water_risk_final.pdf (accessed June 2015).

Xiao, Y.; Chen, T.; Hu, Y.; Wang, D.; Han, Y.; Lin, Y.; Wang, X. Advanced treatment of semiconductor wastewater by combined MBR-RO technology. *Desalination* **2014,** *336,*168–178.

Zinck, J.; Griffith, W. Review of mine drainage treatment and sludge management operations. A report submitted to Mining Association of Canada, Project Number: 603054, 2013.

Appendix A

Final Survey Questions

Background

As water and energy scarcity continue to impact the planet, pressures to find energy-efficient opportunities to recycle and reuse water in the industrial sector will continue to increase. Water reuse by industrial sector facilities can be accomplished in two different ways: (1) through purchase of reclaimed municipal water or (2) by direct reuse/recycling of facility wastewater. This study focuses only on opportunities and practices related to direct reuse/recycling of facility water. The objectives of the study are to:

- Understand current industrial direct reuse/recycling practices.
- Assess the opportunities for future expansion of direct reuse/ recycling practices.
- Explore potential roadblocks or impediments that could restrict or slow the growth of direct reuse/recycling practices.
- Summarize gaps in the knowledge, tools, and technologies needed to support direct reuse/recycling practices.
- Identify the benefits of additional drivers that could be achieved through economic incentive programs, regulatory guidance, technological process breakthroughs, and planning tools.

The purpose of this questionnaire is to collect firsthand information on sector-specific water management and direct water reuse/recycling practices.

Instructions

Please return the completed questionnaire to Ms. Joan Oppenheimer (joan.oppenheimer@mwhglobal.com) by **March 21, 2014**.

QUESTIONNAIRE

SECTION 1 - WATER MANAGEMENT	
Q1	Has your average annual water use (gallons per year) changed in the past 5 years? *(<u>Please underline the one that applies.</u>)* a. Water usage is fairly constant. b. Water usage is continually increasing. c. Water usage is continually decreasing. d. Water usage is highly variable from year to year with no trend.
Q2	What can the change in water use be attributed to? *(<u>Please underline or highlight all that apply.</u>)* a. Increasing or decreasing production volumes b. Changes to product lines c. Changes to manufacturing process technologies d. Initiation of water conservation strategies e. Implementation of water reuse or water recycling f. Other, please specify:
Q3	Can you provide the total annual average water use (gallons per year) for overall corporate or the specific facility or operation where you are located? Please note whether the facility data are provided by your corporate office or assessed locally at your facility. *(<u>Please respond below.</u>)*
Q4	For your facility or operation, please indicate the approximate percentage of your annual total water use that goes to each of the following generic categories (only include underground extraction of water if that water is utilized within your operations or facility and not solely discharged to the environment as wastewater): a. Cooling and boilers <u>%</u> b. Cogeneration and energy recovery <u>%</u>

SECTION 1 - WATER MANAGEMENT	
	c. Product processing or dilution water used in processing % d. In-plant conveyance (i.e., water used to transport materials/products on plant site) % e. Process or product cleaning % f. Environmental controls (e.g., dust suppression) % g. Sanitation (facility related; e.g., laundry, cleaning of structures) % h. Sanitation (staff related; e.g., kitchens and bathrooms supplied by potable water) % i. Irrigation of landscaping %
Q5	Do you experience wide variances in water use for any of these generic water use categories within your facility? If so, are these swings seasonal, monthly, daily, hourly? (*Please respond below.)*
Q6	Does your facility/corporation utilize a water volume per unit production measure metric, and if so, can you tell us what you use? (*Please respond below.)*
Q7	Do you have facilities or operations in locations where water supplies are considered strained/scarce (now or in the near future) relative to your water needs? (*Please respond below.)*
Q8	Do you know how the assessment of strained/scarce water supplies was made? If not, is there an individual we can talk to, to find out? (*Please respond below.)*
Q9	Does your facility pay for water usage? If so, how much (per gallon)? (*Please respond below.)*

SECTION 2 - WATER AUDITING	
Q1	How frequently do you perform water audits focused on water usage and compliance with regulatory mass load environmental discharge requirements at your facility/operation? *(Please underline the one that applies.)* a. Annually b. More than once per year c. Less than once per year d. Have not needed to do this
Q2	Have the results of these audit-driven implementation of water reuse at your facility or just water conservation measures? (*Please respond below.*)
Q3	Which of the following inputs are collected for the water audits? *(Please underline or highlight all that apply.)* a. Facility maps with locations of water supply sources, meters, and submeters b. Inventories of water-using equipment, processes, and facilities c. Assessment of water volumes and quality requirements of each item in (b) above d. Assessment of historical water flow and quality use at each item in (b) above e. Supply-water piping networks f. Wastewater collection, treatment, and discharge facilities g. Permitted discharge requirements h. Other, please specify:
Q4	What are the outputs from the water audit, and how are they utilized? *(Please underline or highlight all that apply.)* a. Water balance diagrams b. Wastewater characterization assessment c. Water consumption benchmarking

SECTION 2 - WATER AUDITING	
	d. Identification of water pollution prevention opportunities e. Identification of reuse/recycling opportunities f. Performance assessment of existing wastewater treatment facilities g. Future treatment facility needs for reuse/recycling opportunities h. Other, please specify below:
<u>Q5</u>	If water audits have been conducted, did you subsequently use additional algorithms or models to conduct a water pinch analysis (i.e., a water minimization technique adapted from analysis and optimization of heat exchanger networks that identifies the configuration of a water network that minimizes freshwater use while respecting process constraints) or any other evaluation to reduce water use and promote wastewater regeneration within your existing facility? (*<u>Please respond below.</u>)*

SECTION 3 - WATER REUSE/RECYCLING DRIVERS AND STRATEGIES *(In this section, water reuse and water recycling are not used interchangeably. Water recycling denotes process wastewater that is treated and input back to the same process, whereas water reuse denotes process wastewater that is treated and input back to a DIFFERENT process within the facility or operations.)*	
Q1	In which locations of your production processes are wastewater streams being generated? (*Please respond below.*)
Q2	How do you currently manage your wastewater streams? *(Please underline or highlight all that apply.)* a. Treat and discharge to sewer or surface water in accordance with permit. b. Discharge to sewer or surface water without requirement for treatment. c. Treat and reuse (input to a different process). d. Treat and recycle (input back to the same process). e. Other *(Please provide example below.)*
Q3	If you have water reuse/recycling at your facility, which of these generic water use categories are in use at the specific facility where you are employed? Please specify if the reuse/recycle water is generated on-site (direct) or purchased from an outside supplier. If an outside supplier is used, please specify which one. *(Please underline or highlight all that apply.)* a. Cooling and boilers (on-site/outside) __________ b. Cogeneration and energy recovery (on-site/outside) __________ c. Product processing (on-site/outside) __________ d. In-plant conveyance (on-site/outside) __________ e. Product or process cleaning (on-site/outside) __________ f. Environmental controls (on-site/outside) __________ g. Sanitation, facility related (on-site/outside) __________

SECTION 3 - WATER REUSE/RECYCLING DRIVERS AND STRATEGIES *(In this section, water reuse and water recycling are not used interchangeably. Water recycling denotes process wastewater that is treated and input back to the same process, whereas water reuse denotes process wastewater that is treated and input back to a DIFFERENT process within the facility or operations.)*	
	h. Sanitation, staff related (e.g., toilets; on-site/outside) __________ i. Irrigation of landscape (on-site/outside) __________ j. Other; please provide example: (on-site/outside) __________
Q4	If you rely upon water reuse/recycle at your facility, what is the approximate percentage of your total annual water usage that is reuse/recycle water, and can you further break down the percentage that is reuse water and the percentage that is recycle water? (*Please respond below.*)
Q5	What is the percent distribution of the overall water reuse/recycle volume that you utilize among the generic use categories, and can you further break down the percentage that is reuse water and the percentage that is recycle water? Overall % *(Provide breakdown in parentheses.)*: a. Cooling and boilers __________ b. Cogeneration and energy recovery __________ c. Product processing __________ d. In-plant conveyance __________ e. Cleaning __________ f. Environmental controls __________ g. Sanitation __________ h. Irrigation of landscape __________ i. Other *(Please provide example.)* __________

SECTION 3 - WATER REUSE/RECYCLING DRIVERS AND STRATEGIES *(In this section, water reuse and water recycling are not used interchangeably. Water recycling denotes process wastewater that is treated and input back to the same process, whereas water reuse denotes process wastewater that is treated and input back to a DIFFERENT process within the facility or operations.)*	
Q6	If there is no water reuse at your facility, is there water reuse at other facilities within your corporation? If so, what was the reason that reuse was implemented at these other locations? Is this reuse water generated on-site or purchased from an outside source? (*Please respond below.*)
Q7	Which water categories rely on reuse water produced on-site in other corporate facilities of your organization? *(Please underline or highlight all that apply.)* a. Cooling and boilers b. Cogeneration and energy recovery c. Product processing d. In-plant conveyance e. Cleaning f. Environmental controls g. Sanitation h. Irrigation of landscape i. Other *(Please provide example.)*
Q8	Which of the following drivers made you implement or seriously consider implementing water reuse/recycling at your facility? (Please rank in order of importance from 1=most important to 8=least important.) *(Please underline or highlight all that apply and rank them.)* a. Cost reduction measure for rising supply water costs ______ b. Cost reduction measure for rising discharge water permit compliance costs ______ c. Cost reduction for chemical product recovery opportunities ______

SECTION 3 - WATER REUSE/RECYCLING DRIVERS AND STRATEGIES *(In this section, water reuse and water recycling are not used interchangeably. Water recycling denotes process wastewater that is treated and input back to the same process, whereas water reuse denotes process wastewater that is treated and input back to a DIFFERENT process within the facility or operations.)*	
	d. Water scarcity issues threatening production expansion capabilities ______ e. Water scarcity issues threatening community acceptance ______ f. Water scarcity issues related to lack of acceptable freshwater quality ______ g. Water scarcity forcing use of seawater instead of freshwater ______ h. Environmental stewardship or consumer advocacy marketing strategies ______ i. Regulations mandating discharge requirements that will be difficult to attain ______ j. Other regulations not related to meeting discharge requirements ______
Q9	Do you utilize stormwater runoff capture as an alternative source of water? If so, has this enabled you to avoid or delay implementation of on-site water reuse/recycling? (*Please respond below.)*

SECTION 4 - WATER REUSE/RECYCLING TECHNOLOGIES	
Q1	What are the most common water quality (WQ) constituents in your wastewater stream(s) that need to be treated prior to reusing/recycling? If possible, please list the major WQ parameters, typical concentration range, and whether you have single or commingled streams. (*Please respond below.)*
Q2	Do you currently have any wastewater treatment facilities that could be retrofitted or have been retrofitted to produce reuse water? *(If yes, please respond to the following questions:)* a. What treatment technologies are/were used to meet your discharge treatment goals? b. Are you able to provide a conceptual schematic of the process train treating your wastewater for discharge? c. Do you know how capital and operations and maintenance (O&M) costs of the treatment plant were/would be impacted when/if modified for reuse or recycling? d. Do you use any proprietary treatment technology for treating your wastewater? If you do, can you share the name of the vendor? e. What are the major treatment challenges you have to deal with for discharge? f. How would these challenges have changed upon treatment modification for reuse or recycling? g. What advantages have or could come from a retrofit to produce reuse water? h. What challenges have come with consideration of a retrofit to produce reuse water? *(If no, please respond to the following questions:)* a. Can you explain why your equipment shouldn't be retrofitted for water reuse/recycling? b. Are you looking for any opportunity to further treat your wastewater?

SECTION 5 - WATER REUSE CHALLENGES *(Only for those currently practicing on-site reuse/recycling)*	
Q1	What types of operational issues do you have regarding your treatment system in meeting your reuse/recycle performance specifications? (*Please respond below.)*
Q2	How do you handle the residuals (e.g., sludge, concentration) generated from the treatment processes? Do you have to have zero liquid discharge operation of your wastewater treatment plant? (*Please respond below.)*
Q3	Do you have any of the following water quality problems during recycling/reusing of treated wastewater? *(Please underline or highlight all that apply.)* a. Scaling b. Corrosion c. Biological growth d. Fouling e. Foaming f. Pathogenic organisms g. Others *(Please describe.)*
Q4	Which of the following have been problematic to implementation of water recycling/reusing at your facility? Please elaborate further on any problems that you indicate (e.g., if you indicate that "Stringent regulations" are a problem, which specific regulations, and how do they hinder implementation of water reuse?). *(Please underline or highlight all that apply and provide a more detailed discussion below.)* a. Effectiveness of currently available treatment technologies b. Cost of currently available treatment technologies c. Stringent regulations d. Cost of operational modifications required for internal reuse/recycling e. Lack of technical information f. Cost of distribution infrastructure

SECTION 5 - WATER REUSE CHALLENGES *(Only for those currently practicing on-site reuse/recycling)*	
	g. Water quality reliability h. Public/customer acceptance i. Institutional coordination j. Variable mass loading of contaminants k. Fluctuation in flow rate l. Poorly characterized effluent water quality m. Others *(Please describe)*:

This concludes the Questionnaire. We greatly appreciate your time in answering these questions.

Appendix B

Workshop Agenda

Workshop Objective

Development of a road map for on-site industrial water reuse/recycling

Participation Guidance

Participants are at different points in water reuse/recycling implementation and work in different industrial sectors. To obtain a level playing field for workshop discussions, each industry participant may want to think about the series of questions posed below prior to the workshop.

Example answers are provided in parentheses below each question.

- What are key drivers that promote serious consideration of reuse/recycling?

  (Lack of adequate supply in critical production/processing location)

  (Treatment cost for discharge approaching treatment cost for reuse/recycling)

  (Ability to apply for subsidized funding)

- What are key impediments that delay or dismiss reuse/recycling application(s) from further consideration?

  (Poor return on investment because of low cost of water supply and waste discharge)

  (Lack of knowledge on how to effectively treat to quality needed for reuse)

- What is the proper sequence of steps that needs to occur in evaluating water reuse/recycling requirements and implementing water reuse/recycling capabilities?

- What type of knowledge is still needed to assist with evaluating water reuse requirements and solutions?

TENTATIVE AGENDA

(1) Welcome: (9:00–9:20)

Breakfast and coffee will be provided.

(2) Overview of Project Workshop Objective: (9:20–9:30)

Background material for subsequent breakout sessions will be provided.

(3) Attendee Introductions: (9:30–10:15)

Your name and position

Brief description of your company and location of facilities

If possible, an example of a reuse/recycling project your company has considered or implemented

(4) Preliminary Survey Findings: (10:15–10:45)

We will provide a brief summary of preliminary survey findings (no individual data will be revealed to the group) that frame our breakout session questions.

(5) Breakout Sessions: (11:00–1:30)

Lunch will be provided.

You will be assigned to a smaller group of individuals for the breakout sessions and asked to discuss the series of topics listed below. Each group will be assigned a leader, a scribe, and a reporter. The leader will ensure that the topics are covered and summarized within the allotted timeframe, the scribe will capture what is discussed, and the reporter will summarize the major points and present back to the entire group. We anticipate having three breakout groups per workshop.

TOPIC ONE: Reuse/Recycling Drivers and Opportunities

Objective: To understand how opportunities for reuse/recycling of waste streams are identified, ranked, and developed for the nine generic water use categories (listed below)

1. Cooling and Boilers
2. Cogeneration and Energy Recovery
3. Product Processing
4. In-plant Conveyance
5. Product or Process Cleaning
6. Environmental Controls
7. Sanitation, Facility Related
8. Sanitation, Staff Related
9. Irrigation of Landscape

We are particularly interested in understanding the drivers or tipping factors that result in serious consideration or implementation of water reuse/recycling practices and which drivers or factors are most prevalent.

TOPIC TWO: Reuse/Recycling Measures of Success and Challenges

Objective: To understand the successes and challenges involved in implementation and operation of water reuse and recycling facilities. Which water reuse/recycling applications are relatively easy, and which ones are more challenging? What are the issues encountered during planning, design, construction, or operation of these facilities? Is there sufficient industry-specific guidance and expertise available from trade organizations, vendors, and consultants? If not, what is lacking?

TOPIC THREE: Future Direction and Research Needs

The WateReuse Research Foundation is interested in expanding applications of on-site industrial water reuse/recycling efforts by supporting relevant research needs through foundation-sponsored projects. We are looking for your input in characterizing where these efforts are needed. Please provide and rank a list of pertinent research needs. A few suggestions are cited below:

- Benchmarking data on industrial water use and reuse/recycling efforts
- Evaluation of risk/alternatives assessment strategies for water security
- Compendium of best practices for water auditing
- Compilation of on-site industrial water reuse/recycling case studies
- Guidelines for water reuse/recycling process optioneering
- Needs assessment strategies for process performance guarantees
- Other (please specify):

(6) Breakout Session Presentations (1:30–2:30)

Each breakout group will present its findings to all workshop attendees.

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(7) Summary of Breakout Sessions (2:30–3:45)

Commonalities and differences among the reporting groups will be noted, and a brief discussion will assess on-site water reuse/recycling research opportunities of most benefit to industries.

(8) Wrap-up of Workshop (3:45–4:00)

Appendix C

NACE and NAICS Cross-Referencing

Industry	**NACE Code**	**NAICS Code***
Mining of coal and lignite; extraction and peat	10	212
Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction, excluding surveying	11	211
Mining of uranium and thorium	12	212291
Mining of metal ores	13	2122
Other mining and quarrying	14	2123
Manufacture of food products and beverages	15	311 and 312
Manufacture of tobacco products	16	3122
Manufacture of textiles	17	313 and 314
Manufacture of wearing apparel; dressing and dyeing of fur	18	315
Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness, and footwear	19	316
Manufacture of wood and products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	20	321
Manufacture of pulp, paper, and paperboard	21	322
Publishing, printing, and reproduction of recorded media	22	323
Manufacture of coke, refined petroleum products, and nuclear fuel	23	324
Manufacture of chemicals and chemical products	24	325
Manufacture of rubber and plastic products	25	326
Manufacture of other nonmetallic mineral products	26	327
Manufacture of basic metals	27	331
Manufacture of fabricated metal products, except machinery and equipment	28	332
Manufacture of machinery and equipment	29	333
Manufacture of office machinery and computers	30	334
Manufacture of electrical machinery and apparatus	31	333
Manufacture of radio, television, and communication equipment and apparatus	32	334
Manufacture of medical, precision, and optical instruments; watches; and clocks	33	339
Manufacture of motor vehicles, trailers, and semi-trailers	34	336
Manufacture of other transport equipment	35	336
Manufacture of furniture, other manufacturing	36	337
Recycling	37	-

Appendix D

Trade Organizations

Sector	Trade Organization		General Info	Reuse/Recycle Activities
Mining	ICMM	International Council on Mining & Metals	Founded in 2001 to improve sustainable development in mining and metals, it brings together 21 companies as well as 35 national and regional mining associations and global commodity associations to address core sustainable development challenges.	http://www.icmm.com/www.icmm.com/water-case-studies
	NMA	National Mining Association	NMA has a membership of more than 300 corporations and organizations involved in various aspects of mining.	http://www.cochilco.cl/descargas/english/research/research/best_practices_and_the_efficient_use_of_water.pdf
Semiconductors	SIA	Semiconductor Industry Association	Industry trade association representing >70 U.S. companies	http://www.theguardian.com/sustainable-business/water-management-solutions-industry-efficiency-intel
	SEMI	Semiconductor Equipment and Materials International	International trade association for the semiconductor industry SEMI F98-0305: Guide for Treatment of Reuse Water in Semiconductor Processing	http://www.semi.org/en/Press/P034608
Technology	CTSI	Clean Technology and Sustainable Industries Organization	Nonprofit trade organization focused on speeding development, commercialization, and adoption of clean technologies	http://www.ct-si.org/publications/proceedings/keywords/W/40
Oil & Gas	API	American Petroleum Institute	Only national trade association that represents all aspects of U.S. oil and natural gas industry	http://www.api.org/environment-health-and-safety/clean-water/water-conservation
	AEPC	American Exploration and Production Council	National trade association representing 32 U.S. premier independent natural gas and oil exploration and production companies	No information specifically on water reuse/recycling

Sector	Trade Organization		General Info	Reuse/Recycle Activities
	IPAA	Independent Petroleum Association of America	A national trade association representing thousands of independent crude oil and natural gas explorers/producers in the United States	http://www.eenews.net/special_reports/drought_2012/stories/1059969536/print
	COGA	Colorado Oil and Gas Association	A nationally recognized trade association that aggressively promotes expansion of Rocky Mountain natural gas markets supply and transportation infrastructure through its growing and diverse membership	http://www.coga.org/pdf_Basics/Basics_ColoradoWaterSupply.pdf
	TWRA	Texas Water Recycling Association	The voice of the Texas water recycling industry, providing coordinated and focused outreach to the public, media, and stakeholder groups through timely publications, reports, news releases, website, and planned events	http://www.txwra.org/membership.html
	IPIECA	International Petroleum Industry Environmental Conservation Association	Brings together the collective expertise of the oil and gas industry; membership represents >60% of the world's current oil production.	http://www.ipieca.org/focus-area/water
	CAPP	Canadian Association of Petroleum Producers	The voice of Canada's upstream oil, oil sands, and natural gas industry	http://www.capp.ca/environmentCommunity/water/Pages/UsingWater.aspx
Power	EPRI	Electric Power Research Institute	A nonprofit organization funded by the electric utility industry, EPRI conducts research on issues related to the electric power industry in the United States.	http://www.epri.com/search/Pages/results.aspx?k=water recycling&r=mptabresults%3aARABUmVzZWFyY2ggUmVzdWx0cwxtcHRhYnJlc3VsdHMBAl4iAiIk,mplevel3name%3aAR8CV2F0ZXIgQXZhaWxhYmlsaXR5IGFuZCBSZXNvdXJjZSBSaXNrIE1hbmFnZW1lbnQMbXBsZXZlbDNuYW1lAQJeIgIiJA
Food and Beverage	FIVS		A worldwide federation serving the wine, beer, and spirit sectors since 1951; encourages exchange of information among its members	https://fivs.org/wm/strategicInitiatives/fivsForesee.htm

Sector	Trade Organization		General Info	Reuse/Recycle Activities
	WI	Wine Institute	Represents >1000 wineries and affiliated business from wine regions throughout California	http://www.wineinstitute.org/winerywaterguide
	BIER	Beverage Industry Environmental Roundtable	A technical coalition of leading global beverage companies working together to advance environmental sustainability within the beverage sector	http://www.bieroundtable.com/#!water/c21at
	ILSI	International Life Sciences Institute	A nonprofit, worldwide organization with a mission to provide science that improves human health and well-being and safeguards the environment	http://www.ilsi.org/ResearchFoundation/Publications/Guideline%20for%20Water%20ReUse%20in%20Beverage%20Production%20and%20Food%20Processing.pdf
All Sectors	CTI	Cooling Technology Institute	A nonprofit, self-governing, technical association dedicated to improvement in technology, design, performance, and maintenance of cooling towers	http://www.cti.org/tech_papers.php
	GRI	Global Reporting Initiative	A leading organization in the sustainability field that promotes the use of sustainability reporting as a way for organizations to become more sustainable and contribute to sustainable development	https://www.globalreporting.org/information/news-and-press-center/Pages/ON-THE-WATER-FRONT.aspx

Appendix E

Water Reuse in the Food and Beverage Industry

Water minimization and wastewater reuse are priority issues of industrial wastewater management, especially in industries that are consuming high amounts of water (El-Salam and El-Naggar, 2010). The food processing and beverage industry account for more than two-thirds of all freshwater abstraction worldwide and may require water of high quality for individual phases of production (Ait Hsine et al., 2005). Food processing refers to the activities that convert raw food materials to final consumable products; beverage manufacturing includes the production of bottled and packaged fluids such as distilled spirits, beer and wine, soft drinks, bottled water, and related products processing, which includes both product and bottle manufacture and storage (State of California, 2013).

The food and beverage sector is very broad and varies from country to country in various aspects, from the raw materials used to the demand and the different treatment technologies applied. The scale of food and beverage processing operations and the characteristics and generation rates of resulting wastewater are highly variable and may require specific recycling options. Examples of common food and beverage processing industries and related wastewater volumes are presented in Table E.1.

Table E.1. Example of Common Food and Beverage Processing Industries and Related Volumes of Water Consumption

Industry	Wastewater Effluent of Product	References
Food Processing Industry		
Dairy	0.2–10 m^3/ ton milk	Vourch et al., 2005
Seafood	11 m^3/ton	Afonso and Borquez, 2002
Meat	3–10 m^3/ton HSCW[1]	Sampson et al., 2005
Fruits and vegetables	1.2–5 m^3/ton	Muro et al., 2012
Sugar	1.5 m^3/ton	Chavez-Rodriguez et al., 2013
Animal and vegetable fat	0.25–1.24 m^3/ton olives	Valta et al., 2014
Beverage Processing Industry		
Beer	3–10 m^3/ton beer	Simate et al., 2011
Wine	3–5 m^3/ton grapes	Mosse et al., 2013a
Alcohol distilleries	10–20 L m^3/ton alcohol	Saha et al., 2005

Note: HSCW=hot standard carcass weight

Drivers for Water Reuse

The main factors driving water efficiency in the food industry can be categorized as economic, environmental, and technological. Although the beverage sector has been recognized as proactive on managing water issues compared to many other sectors, a lot of challenges still need to be overcome, particularly in identifying and evaluating water risks and opportunities and understanding the water dynamics in production processes (BIER, 2012).

Almost all food and beverage companies are now monitoring water consumption and have strategies and goals for minimizing usage in consideration of scarcity issues and rising costs (Williams, 2011). In addition, enforcement of wastewater discharge regulations from municipal and regional sewer authorities and escalating sewage surcharges and disposal costs have forced the food and beverage processing industry to look for cost-effective technologies to provide pretreatment or complete treatment of its wastewater, particularly for the reduction of organics (biochemical oxygen demand [BOD] and chemical oxygen demand [COD]) and total solids loading into the sewers.

Food processors located within or adjacent to municipalities historically have relied on local. publicly owned treatment works (POTW) for wastewater treatment and disposal. However, the discharge of wastewater from these industries into municipal wastewater treatment plants is not always acceptable because of the high levels of associated contamination (Vasanthi and Viramuthu, 2008). Thus, the food processing industry is seeking cost-effective reduction technologies and water reclamation opportunities that include both source reduction options (technologies to reduce the amount of water used) and treatment options (technologies to reduce the amount or contamination level of wastewaters requiring discharge; Food Manufacturing Coalition, 1997).

Typical Contaminants

Wastewater derived from food production has attributes that are very distinct from other industrial activities. In particular, food processing wastewater generally contains very low to negligible amounts of toxic materials, such as those listed under the U.S. Environmental Protection Agency (U.S. EPA) Toxic Release Inventory (with a few exceptions, such as phenolics from the processing of some plant materials). However, food processing wastewaters can be subject to bacterial contamination, which represents a special issue for wastewater reuse (Food Manufacturing Coalition, 1997).

The characteristics and generation rates of wastewater derived from food and beverage production are highly variable, depending on the specific types of processing operations (e.g., fruit and vegetable, oils, dairy, meat, soft drinks) and the particular site activity (Muro et al., 2012). For example, animal processors and rendering plants will generate effluents with different characteristics to those from fruit and vegetable washers and edible oil refiners (suspended/colloidal and dissolved solids, organic pollution and oil and greases as well as microbial contamination).Wastewaters that derive from the food and beverage processing industries are typically characterized by the following (Saha et al., 2005):

- High BOD and COD
- Total dissolved solids (TDS) and total suspended solids (TSS)
- Fats, oils, and grease (FOG)
- Strong odors and colors

General characteristics of wastewaters arising from contact with spoiled raw materials or finished products, rinsing or washing, transport, processing, cooling, spills, and cleaning of equipment are shown in Table E.2 (Visvanathan and Asano, 2009). Industrial dairy process waters, which are mixtures of water and milk products without chemicals, are variable in composition of fat content and whey–milk ratio (Vourch et al., 2005). Winery wastewater contains key compound classes (fatty acids, phenols, polyphenols, and sugars) with potential for environmental harm from the presence of considerable quantities of phytotoxic, recalcitrant, phenolic compounds with proven resistance to aerobic degradation (Mosse et al., 2013b). A typical raw winery wastewater presents a pH between 3 and 4, high COD and BOD values, soluble sugars, alcohols, and high molecular weight compounds, such as tannins and lignins (Souza et al., 2013). Waste sugar is often the largest contributor to the BOD discharge from a typical soft drink manufacturing facility during spillage and washing procedures in canning, bottling, and blending sequences (Ait Hsine et al., 2005).

Table E.2. Pollutants and Their Origins in Agroindustries

Industries Producing Wastes	Origin of Major Wastes	Major Characteristics
Canned goods	trimming, culling, juicing, and blanching fruits and vegetables	high in suspended solids and colloidal and dissolved organic matter
Dairy products	dilutions of whole milk, separated milk, buttermilk, and whey	high in dissolved organic matter, mainly protein, fat, and lactose
Brewed and distilled beverages	steeping and pressing grain, residue from distillation of alcohol, condensate from stillage evaporation	high in dissolved organic solids, containing nitrogen and fermented starches or their products
Meat and poultry products	Stockyards, slaughtering animals, rendering bones and fats, residues in condensates, grease, and wash water	high in dissolved and suspended organic matter, blood, and other proteins and fats
Beet sugar	transfer, screening, and juicing water, draining from lime sludge, condensates after evaporator, juice, and extracted sugar	high in dissolved and suspended organic matter, containing sugar and protein
Soft drinks	bottle washing, floor and equipment cleaning, syrup storage tank drains	high pH, suspended solids, and biochemical oxygen demand

Source: Visvanathan and Asano, 2009.

Current Technologies for Water Treatment and Treatment Issues in the Food and Beverage Sector

Food and beverage processors are employing various levels of treatment and technologies as conditions merit. The traditional aims of wastewater treatment for reuse in these industries are COD and BOD removal, reduction of TDS and TSS, and destruction of pathogenic microorganisms. In addition to these goals, other treatment requirements are considered necessary in specific industries and under specific regulations, such as removal of nutrients (N and P), heavy metals, and other industry-specific contaminants.

The selection of the right recycling technology depends on the nature and constituents of the wastewater as well as the purity required for its final utilization (Vasanthi and Viramuthu, 2008). Some wastewaters only need basic physical treatment (water used for washing floors or equipment); others may require a higher treatment degree (water used in the preparation of food material). Water for cooling accounts for nearly half the total amount of water usage in food processing plants: this water needs to be treated to remove suspended solids, and pH, hardness, and alkalinity must be adjusted to avoid scaling or corrosion. Thus, advanced treatment, such as reverse osmosis (RO) or activated carbon, is necessary to obtain water of consumable quality, whereas for nonpotable uses, simple physical or biological treatment would be sufficient (Vasanthi and Viramuthu, 2008). Water for nonpotable uses (cleaning, washing, rinsing, firefighting, and transportation) may be of low, medium, or high quality, depending on the end use.

When designing a recycle stream, it is important to segregate streams according to their volumes and contaminant concentrations. Treating wastewater streams separately may prove more economical than mixing them all into one treatment unit; some wastewaters may have low levels of contaminants and only require simple physical treatments, whereas others may require more complex treatment steps. A wastewater treatment design should not involve too many operating units, which would increase operational and maintenance costs. However, it should be effective in removing constituents and low in cost and environmental impact and require minimal supervision (Vasanthi and Viramuthu, 2008). In addition, important variations in wastewater volume and quality should be taken into consideration when dealing with recycling opportunities from these industries.

The selection of treatment technologies must also be made on a case by-case basis that considers the cost effectiveness of current and emerging reduction technologies. Certain technologies and operating strategies can provide an easy return on investment regardless of the scale of operation. In addition, certain technologies will only be applicable to small operations (e.g., because of the inherent flexibility of the production process), whereas others will generally only apply to larger operations (e.g., because of high capitalization costs; Food Manufacturing Coalition, 1997). Typical wastewater treatment processes that have been tested at the lab-scale level to treat water for reuse in the food and beverage industry are presented in Table E.3.

Several works dedicated to the treatment of food industry streams show the use of membrane operations for producing purified water for reuse (Vourch et al., 2005). Nanofiltration (NF), for example, has the potential for use in a wide range of industries, such as vegetable oil processing and the beverage, dairy, and sugar industries. N has greater separation efficiency and carries distinctive properties such as pore radius and surface, which influence the separation of various solutes (Salehi, 2013). Advanced treatment processes using filtration systems have been combined in single or multistage units (e.g., UF+RO, NF+NF, RO+RO) depending on the wastewater characteristics. For example, in the dairy industry, high levels of COD in the feed solution require two-stage membrane treatments (e.g., NF+RO and RO+RO) because crossflow filtration alone does not produce a permeate stream that complies with the standard of drinking water quality (total organic carbon [TOC]<2 mg/L) in a single membrane stage (Vourch et al., 2005).

Fouling is a major issue for membrane systems and results from material buildup that blocks fluid flow across the membrane. RO is particularly susceptible to blockage. Temperature, solute–solute, and solute–membrane interactions all affect the fouling process. One common means of addressing fouling is to provide high cross-flow velocities to reduce the thickness of the buildup and control pressure and permeate recovery (Food Manufacturing Coalition, 1997). FOG, for example, can have negative impacts on wastewater treatment systems. Industrial dairy process waters must be treated within a few hours before degradation of milk components occurs because membrane operations afford moderate quality permeates (Vourch et al., 2005).

The use of biological treatment may not be the best technology for industries that have seasonal production of wastewaters with high loading of solids and soluble organic contaminants, such as wine production and bottling (Tanzi and Mazzei, 2009; Ioannou et al., 2013). Activated sludge systems for such industries must be designed with larger oxidation tanks and an oversized aeration (pure oxygen) system to deal with peak loads. This variable load and the random presence of sugars also cause bulking problems, with difficulties in sludge settling and resulting turbid effluent. In consideration of these disadvantages associated with the use of activated sludge, membrane bioreactors can be considered an effective approach to treating wastewater from wineries (Tanzi and Mazzei, 2009), and RO may also overcome the challenges associated with biotreatment.

Table E.4 shows examples of water recycle and reuse in full-scale food and beverage industries, with related environmental and financial savings.

Table E.3. Examples of Wastewater Treatment Processes that Have Been Tested at the Lab Scale to Treat Water for Reuse in the Food and Beverage Industry

Process	Technology	Examples of Application	Scale	Reference
Primary treatment	screening/settling	fruits and vegetables	lab	Kern et al., 2006
	coagulation/flocculation	beverages	lab	Hussain et al., 2013
	sedimentation/flotation	fruits and vegetables	lab	Mundi, 2013
	filtration	pasta manufacturing	lab	El-Salam and El-Naggar, 2010
Secondary treatment	biological treatment (activated sludge, MBR)	mineral oil	lab	Bienati et al., 2008
Advanced treatment	membranes (MF, UF, NF, RO)	dairy	lab	Vourch et al., 2005
		seafood	lab	Afonso and Borquez, 2002
		beer	lab	Madaeni and Mansourpanah, 2006
	activated carbon/ion exchange	food	lab	Roy, 1994
	ozone	fruits and vegetables	lab	Martinez et al., 2013

Notes: MBR=membrane bioreactor; MF=microfiltration; NF=nanofiltration; RO=reverse osmosis; UF=ultrafiltration.

Table E.4. Examples of Water Recycle and Reuse Full-Scale Application in the Food and Beverage Industry

Sector	Industry	Issue/Solution	Environmental Benefit	Cost Saving	Source
Dairy processing	Bonlac Food (Australia)	Reduced effluent by 30% by diverting wastewater to Bonlac-owned farm irrigation.	Reduced the amount of wastewater and hydraulic loading of wastewater to local waterway.	Reduced treatment costs; grew millet grass on irrigated farmlands, later sold as fodder for cattle.	www.p2pays.org/ref/04/03342.htm
Dairy processing	Dairy Farmers (Booval)	Reusing tank rinse water for cleaning in less critical areas. Reusing pasteurizer cleaning waters for the first rinse on tanks.	Reduced water consumption by 30% (95,000 kL).	Annual savings of $73,000.	www.geosp.uq.edu.au/emc/cp/
Dairy and fruit juice processing	Parmalat (Canada)	During milk processing, steam was condensed and removed from the product with excess water. The discharged steam and resulting water are now reused and replace some municipal water for case washing.	Reduced use of 19,488 L/day.	Cost savings (rebate) of $6300, a savings of $8926 per year.	www.peelregion.ca/watersmartpeel/business/capacitybuyback.htm
		Hydraulic oil used by certain equipment is cooled with once-through cooling using municipal water. Municipal water was also used to prevent steam from washing during equipment sterilization. The steam was cooled with once-through cooling. Piped discharged cooling water is sent to a water recovery tank for case washing.	Reduced use of 27,643 L/day.	Cost savings (rebate) of $6817, a savings of $12,663 per year.	
Cheese processing	Pine River Cheese (Ontario)	Only 50% of condensate from the steam boiler was being returned to the boiler feed water from the pasteurizer. Recovered more condensate and heat from the flash steam of this condensate and heat from boiler blowdown.	Reduced propane, chemical, and water consumption.	Annual savings of $3000 from propane and $1500 from water and chemicals.	www.omafra.gov.on.ca/english/food/investment/ficb_pdf/pine.htm

Sector	Industry	Issue/Solution	Environmental Benefit	Cost Saving	Source
		The plant was already very efficient in water usage, but there were still opportunities for reuse. Collected startup water in the CIP rinse tank for reuse as the CIP first rinse washer.	Reduced water consumption.	Cost effective, but did not meet the company's payback criteria.	
Egg processing	Burnbrae Farms (Canada)	Reused rinse water from egg breaking for cleaning in the Inedible Department. Proposed to recycle egg peeler water and water used to continuously wash breaker machines.	Estimated reduction of 28 m^3 of water per day.	Potential annual savings of $130,000.	www.oceta.on.ca/documents/burnbrea_fnl.pdf
		All wastewater was collected and transported to a facility for treatment and disposal. Proposed to install membrane bioreactor to reuse treated water.	Potentially reduce environmental impact related to the treatment of facility wastewater.	Potential annual savings of $400,000.	
Brewing	Brick Brewery (Ontario)	Wasted water in chiller usage and overflows from bottle washer and hot water tank. Install a holding tank to capture overflows and reuse water within the plant. Install a cooling tower to recycle water from chiller and compressor. Recycling CIP water in the bottle shop to wash the caustic tank. Recycling final rinse water to CIP makeup and floor washing.	Potentially improve the water to beer ratios to between 7:1 and 5:1.	Potentially ensure a long-term, reliable, and high quality water supply from groundwater wells.	www.oceta.on.ca/documents/brick_fnl.pdf
Brewing	Sleeman's Brewery (Guelph, Ontario)	Installed automatic shut-off valves on all high-pressure hoses used in floor washing; diverted water from the pasteurizer overflow and final rinse water from the bottle washer for reuse in external keg and floor washing.	Significant water use reduction.	Estimated annual savings of $37,500 and a payback of 2 years.	www.oceta.on.ca/documents/sleeman_fnl.pdf

Sector	Industry	Issue/Solution	Environmental Benefit	Cost Saving	Source
Brewing	South Australia Brewing Company (Adelaide)	Bottle and can pasteurization disposed of water after a single use. Upgraded water reclamation system on bottle and can pasteurizer (excess holding capacity enables recycled water to be used in place of freshwater).	Less wastewater discharged to sewer. Less freshwater used. Energy savings.	Water related cost-savings of $60,000 per year. Payback of 10 months.	www.epa.sa.gov.au/cp_brewing.html
Poultry processing	ACA Cooperative Ltd. (Kentville, Canada)	High level of water used for scalding and cleaning. Proposed to recirculate water in scalding and crate washer and improve cleaning procedures.	Potential annual water savings of 7500 m^3.	Potential annual savings of nearly $5000 from water conservation.	www.dal.ca/eco-efficiency
Tuna processing	Port Lincoln Tuna Processors (South Australia)	RO and vacuum pump installed to treat wastewater used for washdown. Washdown hoses fitted with flow trigger nozzles.	Washdown achieved using 85% recycled treated water.	Not quantified.	www.epa.sa.gov.au/cp_tuna.html
Snack foods	Humpty Dumpty (Brampton, Ontario)	Wash and rinse water was not recycled. Evaluated water quality needs and flow rates. Determined how best to recycle rinse water.	60% reduction in total water usage.	Expected savings of $100,000 per year.	www.omafra.gov.on.ca/english/food/investment/ficb_pdf/humpty.htm
Bottling plant	Dr. Pepper Snapple (Victorville, CA)	Need sustainable, reliable, cost-effective solution that meets stringent ingredient water specifications. System including RO and backwash recovery will be used to make purified bottled water and soft drinks.	Recover >90 % of water.	Not reported.	http://www.evoqua.com/SiteCollectionDocuments/Industries/Food_and_Beverage/BeverageWorld_1109.pdf
Seaweed processing	Acadian Seaplants, Ltd (Nova Scotia, Canada).	Wasting evaporator water. Capturing and recycling of evaporator water.	Potential water savings of 7724 m^3 per year.	Potential savings of $5700 per year in wastewater expenses.	www.dal.ca/eco-efficiency
		Producing excess waste water by not recycling. Providing storage capacity for recycled water.	Potential water savings of 7724 m^3 per year.		

Note: CIP=clean in place; RO=reverse osmosis.

Source: Adapted from Ontario Centre for Environmental Technology Advancement (OCETA), 2013.

Typical Reuse Applications

The potential for water recycling and reuse in the food and beverage sector depends on the water requirements of the plant, treatment technologies available, company policies, and potential of waste material recovery and reutilization from a wastewater stream (Vasanthi and Viramuthu, 2008). Before determining a water reuse or recycling scheme within a plant, detailed feasibility studies need to be carried out. Typical water uses and recycling opportunities in the food and beverage industry are summarized in Table E.5. Today, with some exceptions, the reuse of treated wastewater occurs in environments of no food contact because of existing regulations and public perception of the cleanliness and safety of treated process wastewater in direct contact with a food product (Williams, 2011).

According to the Draft Guidelines for the Hygienic Reuse of Processing Water in Food Plants (Codex Alimentarius Commission, 1999), reuse water should be safe for its intended use and not jeopardize the safety of the product through the introduction of chemical, microbiological, or physical contaminants in amounts that represent a health risk to the consumer. The reuse water should be reconditioned to obtain a microbiological level that meets the specifications for drinking water (Martinez et al., 2013), and the best purity standards to follow are different depending on the recycled water end use.

There is no generalized industrial water quality standard, and a number of regulatory bodies such as U.S. EPA, American Water Works Association (AWWA), American Society of Mechanical Engineers (ASME), Food and Agriculture Organization (FAO), and World Health Organization (WHO) have established water quality standards for different industrial scopes. These regulations are evolving continuously based on each industry's needs in emerging water shortages. (e.g., ASME and U.S. EPA for cooling waters, ASME for boilers, WHO on drinking water quality, or U.S. for food processing) (Jami et al., 2013; Vasanthi and Viramuthu, 2008; ASME, 2015; U.S. EPA, 2008; WHO, 2008).

Water quality requirements are a function of the type of food, processing conditions, and methods of final preparation (e.g., cooked or uncooked). They are also dictated by the use of the water within a particular process or process stream; thus, if the water is potable, then it is probably acceptable for all food contact uses (ILSI, 2008). However, not all uses require water to be of this standard, and where it is possible to reuse water, the quality requirements will need to be tailored appropriately to avoid using water of unnecessarily high quality or unnecessary treatment of the water, while allowing more efficient use of water resources (ILSI, 2008).

Matching water quality requirements with the type of water use requires an analysis of the possible routes and potential for contamination of the food products concerned and identification of the critical control points for preventing contamination (ILSI, 2008). For example, using water of lower quality might be appropriate for washing the factory floor but could pose a health risk if used for washing surfaces that come into contact with the food product. Control measures would include introducing fail-safe methods of water use or adjusting the water quality to control the contaminants of concern (e.g., high microbiological quality, but a lower chemical quality; ILSI, 2008). Water for washing should not contain excess organic matter because this may provide an energy source for the growth of microorganisms. Such water may also have a high pH (11–12) to limit biological growth. Water used in cooling devices should be low in mineral content, particularly with regard to suspended solids, pH, alkalinity, and hardness to prevent scaling. The pH should range from neutral to slightly alkaline. Chloride concentrations should be sufficiently low to prevent corrosion. Water used in heating systems should be low in hardness, bicarbonates, dissolved solids, silica, and alumina.

In the French dairy industry, the targeted microbiological and chemical quality of the treated water must at least approach the characteristics of water for human consumption (e.g., TOC<2 mg/L) to ensure larger reuse possibilities for applications where unexpected contact with the milk product may occur (e.g., cooling water for pump seal or plate heat exchangers; Vourch et al., 2005). In beverage industries, with a few exceptions, all products have the same basic water uses and opportunities for water savings that are typical of the food processing industry, such as cleaning, bottling, and the common uses of boilers, cooling towers, domestic use, irrigation, and related uses (State of California, 2013).

The law does not always allow a facility to entirely clean the bottles with recycled water, requiring the last cleaning to be performed using drinking water (Ait Hsine et al., 2005). Thus, industries in the food and beverage sector reuse water only in nonproduct applications for bottling plant activities, such as irrigation of landscaping, truck washing, cooling towers, warehouse floor washing, and specific processes after treating it for safety but never using the collected water for product water. As an example, to reduce the use of external water sources, approximately 86 production facilities across the Coca-Cola Company (39% of overall facilities) reuse water before or after treatment or use collected rainwater. The water used during system operations is recycled through treatment and cleansing processes and sometimes within the production plants for utility purposes in boilers, evaporators, and chillers and outside for landscape irrigation and dust control.

Table E.5. Typical Water Uses and Recycling Opportunities in the Food and Beverage Processing Industry

Typical Water Use	Examples of Water Use and Recycling Opportunities
Process water	inclusion in products fluming/transport product washing cooking/autoclaving, blanching/precook peeling and preparation sterilization water, ice water canning and bottling, can/bottle cooling/warming conveyor lubrication product storage
Environmental control	air pollution, air cleaning/dust control wastewater treatment and reuse water treatment laboratory operations
Cleaning	clean in/out of place system can/bottle/package cleaning transport vehicle cleaning equipment cleaning floor cleaning
Rinsing	rinse bottles and packaging materials rinse food
Domestic uses	sanitation irrigation potable uses in canteens or offices
Thermodynamic processes	cooling towers boilers refrigeration cogeneration and thermal recovery air conditioning, humidification
Emergency	firefighting

Source: Adapted from State of California, 2013

Case Studies

Case Study 1: Water recycling at a soft drink factory in Japan

A water recycling system utilizing floating media filtration and NF was implemented for the reuse of water at a soft drink factory that produces both carbonated and noncarbonated soft drinks (Miyaki et al., 2000).

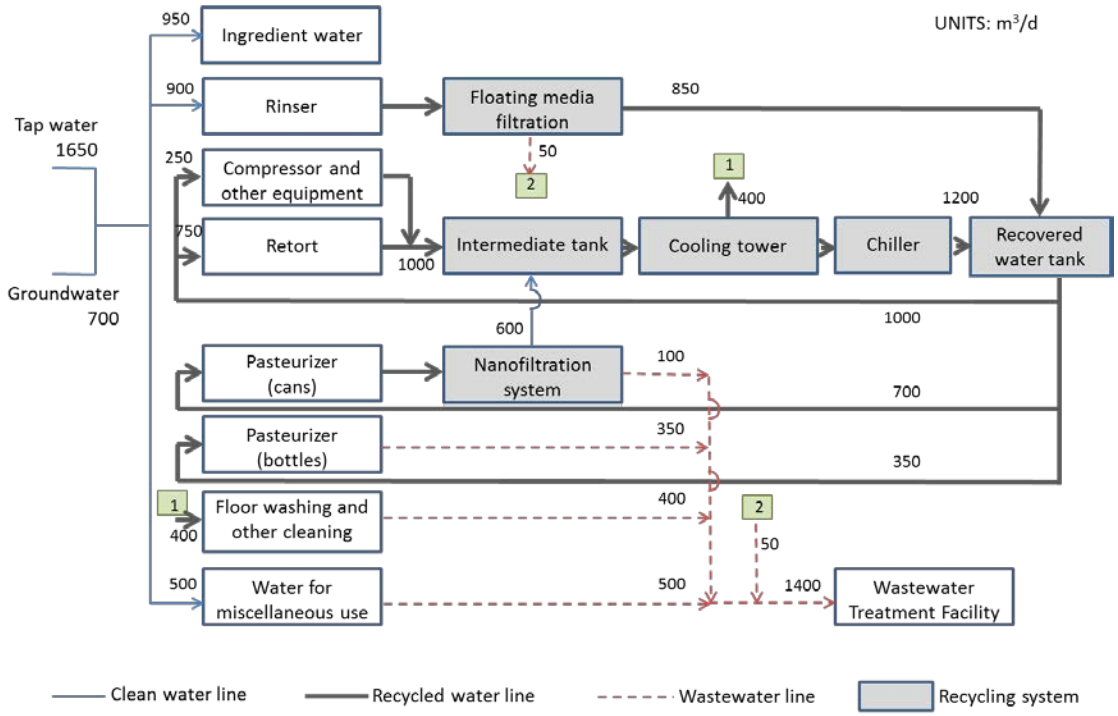

Figure E.1. Flow chart of water use after installation of the water recycling system at a soft drink factory in Japan.

Source: Adapted from Miyaki et al., 2000.

Use of the present water recycling system featuring NF enabled a savings in water usage and a minimization in wastewater almost 55% less than prior system installation (Table E,6). Not only was there a savings in tap water usage but also a minimization of water resource usage and wastewater generation. The present system has been in operation since 1994.

Table E.6. Comparison of Data Before and After Use of the Water Recycling System

	Before Reuse	After Reuse
Tap water (m^3/d)	3600	1650
Wastewater (m^3/d)	3350	1400
Recovered water (m^3/d)	640	2450

Source: Adapted from Miyaki et al., 2000.

Case Study 2: Water recycling at a PepsiCo Frito-Lay's snack manufacturing facility in Casa Grande, AZ

Frito-Lay's manufacturing plant in Casa Grande produces corn and potato products and snacks (Lay's, Ruffles, Doritos, Tostitos, Fritos, and SunChips) almost entirely on renewable energy and reclaimed water while producing nearly zero waste (near net zero; U.S. EPA, 2012). The PepsiCo Frito-Lay's snack manufacturing facility is currently the only facility treating wastewater with membrane bioreactors for advanced biological nutrient removal in tandem with an advanced drinking water treatment technology that includes granular activated carbon, ultraviolet light disinfection, and RO technologies. The 650,000 gpd process water recovery treatment plant recycles up to 75% of the plant's process water, allowing the company to lower water use by 100 million gallons annually, according to published reports. Frito-Lay treats water to EPA primary and secondary drinking water standards for food contact direct reuse in cooking corn, washing potatoes, cleaning/sanitation of production equipment, and for other in-plant cleaning and production needs (U.S. EPA, 2012). The reclaimed water from the process water recovery treatment plant has higher quality than the local potable water supply in terms of alkalinity, arsenic, and silica (U.S. EPA, 2012). A schematic of the treatment process is shown in Figure E.2.

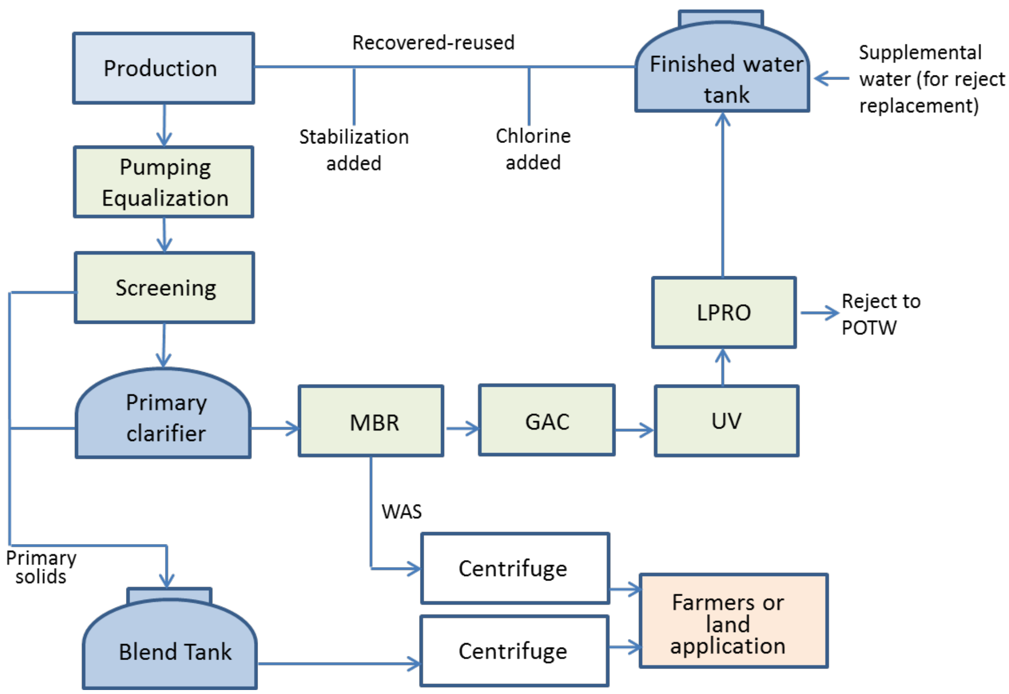

Figure E.2. Process flow diagram of the process water recovery treatment plant at the PepsiCo Frito-Lay's snack manufacturing facility in Casa Grande, AZ.

Source: U.S. EPA, 2012.

Case Study 3: Conceptual water recovery and reuse scheme at a Coca-Cola bottling plant

Coca-Cola developed a scientifically rigorous water recovery and reuse conceptual approach that virtually could be used by any of its 900 bottling plants in 206 countries. The system treats beverage process wastewater to high water quality standards using a combination of physicochemical and biological processes (Figure E.3). The selection of treatment technologies includes:

- Secondary biological treatment
- Membrane bioreactor combining UF with biological treatment
- Ultrafiltration (UF) using a pressure-driven barrier to remove suspended solids and pathogens
- RO
- Disinfection with ozonation, medium-pressure ultraviolet treatment, and chlorination

The treated water will be reused in nonproduct applications, such as floor washing and landscape irrigation, and it is reusable for a higher degree of purpose, such as indirect potable reuse.

A 6 month pilot trial was successful in reliably and consistently recovering and treating process wastewater to highest quality standards that meet the physical, chemical, and microbial specifications of WHO, European Union, U.S. EPA, and Coca-Cola Company, as well as local regulatory requirements for each plant location. Internal and third-party laboratory analyses were conducted for 126 parameters that include inorganics, synthetic organics, semi- and volatile organics, disinfection byproducts (e.g., trihalomethanes), pesticides, and microbial components (e.g., *Escherichia coli*).

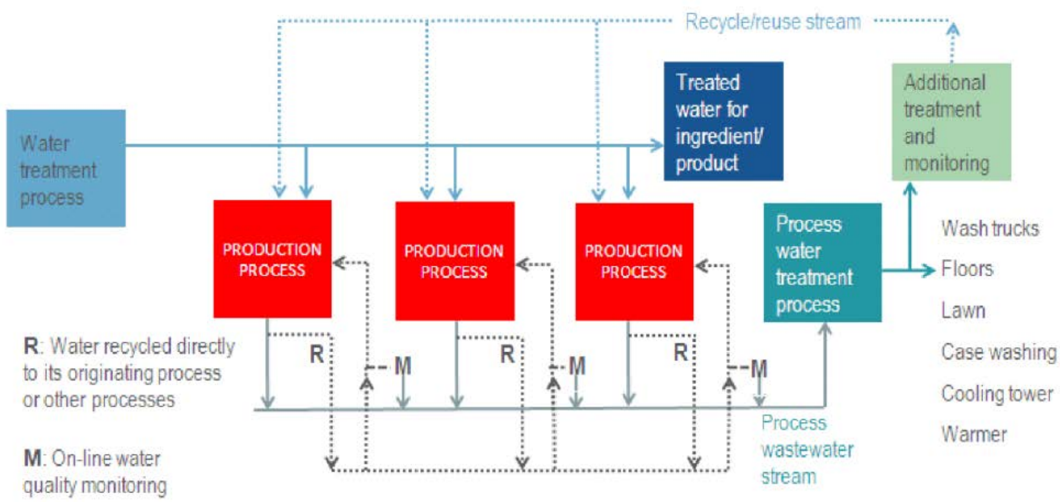

Figure E.3. Conceptual water reuse and recovery at Coca-Cola Company.
Source: ILSI, 2013.

Case Study 4: On-site industrial water recycling at Carlton United Breweries Yatala Brewery (Australia)

The brewery process located at the Carlton United Breweries (CUB) Yatala location south of Brisbane produces 3.4 to 4.3 ML/d liquid trade waste, of which approximately 65% is treated and reused as process water. CUB started treating its own industrial effluent on-site and decided to invest in a water recycling plant in order to avoid the charges for the expansion of the local treatment plant because of its additional discharges and escalating water and trade waste discharge fees imposed to cope with drought conditions.

The multibarrier treatment system includes an upflow anaerobic sludge blanket (UASB) system, which allows recovery of approximately 90% of the energy contained in the wastewater, and RO to remove salts. Most of the solid streams are dewatered and disposed to landfill, and the RO concentrate, some backwash water, and other solid streams are discharged to the sewer line. In detail, wastewater is subject to:

- Prescreening
- Clarification and acidification
- Anaerobic treatment with UASB
- Dissolved air flotation
- Moving bed bioreactor
- Microfiltration and RO
- Advanced oxidation (ultraviolet light–titanium dioxide) and chlorination

All types of wastewater produced in the brewery, with the exception of RO brine discharge and sanitary effluent, are treated and recycled. End uses include cooling towers, boiler feed, clean-in-place systems, pasteurization, precleaning of vessels and pipes (not final rinses), floor washing, toilet flushing, and irrigation. The benefits include water savings of 1.3 to 1.5 mL/d, wastewater discharges reduced to 0.8 L/L of beer, and greatly reduced discharges of COD and suspended solids. Water use was reduced from 3.5 to 2.2 L/L of beer.

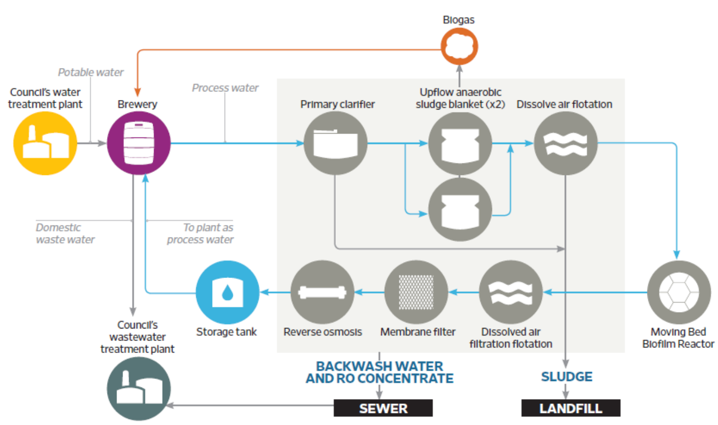

Figure E.4. Conceptual water reuse and recovery at CUB Yatala Brewery.

Source: Institute for Sustainable Future, 2013.

Case Study 5: On-site industrial water recycling at Algoma Orchard Juice Processing facility

Algoma is a recognized top-40 apple and juice supplier worldwide. Its facility in Clarington, located in a rural area, needs to identify options to manage wastewater and deal with the risk of supply uncertainty, as juice production is considerably water intensive. The expected freshwater requirement for the facility is 45 kL/day.

Algoma considered that ultrahigh water efficiency/zero discharge concepts, combined with a minimal water-taking strategy, had to be implemented to resolve the water supply and treatment issues. The solution, proposed by ALTECH, was a proprietary, closed-loop process able to treat 40 kL per day of apple sizing, flume, and juice processing wastewater to meet all the process water needs for the plant. The system has been in operation since 2009.

The closed-loop system includes a high efficiency System Hydrokleen membrane bioreactor. The system, as shown in Figure E.5, includes an anaerobic–anoxic chamber, followed by a UF membrane. Concentrates from the UF and the un-degraded organics from the activated sludge are recirculated to the aeration tank for further processing. The UF permeate is then treated through RO and further chlorine disinfection to produce clean water at potable standards for the clean-in-place process equipment and other sanitation activities.

The initial investment for the project was $1.17 million, with a total of $6 million annual revenue by 2011. This represented a 27% return on investment for Algoma.

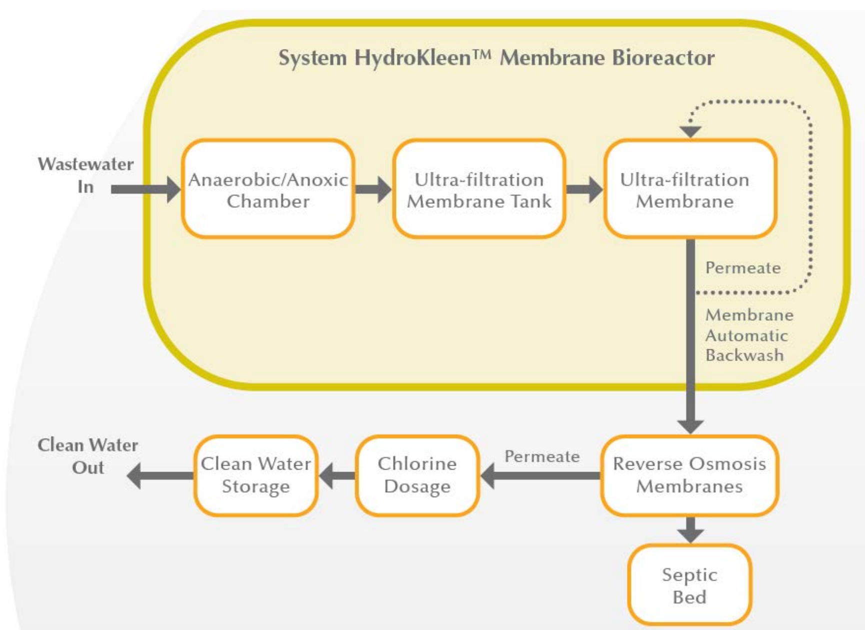

Figure E.5. System Hydrokleen water recycling scheme at Algoma Orchard Juice Processing Facility.

Source: Bloom Center for Sustainability, 2013.

Conclusions

This literature review summarizes the drivers, success, challenges, and opportunities for on-site water reuse in the food and beverage sector. A growing number of these industries, such as dairies, juice processors, soft drink manufacturers, bottling plants, and food manufacturers, have recently focused attention on water recycle and reuse opportunities, mostly driven by the enforcement of wastewater discharge regulations and water supply restrictions in local areas. To justify and enable recycle/reuse scheme implementation, almost all food and beverage companies are now monitoring water consumption and have strategies and goals for minimizing water usage. In many areas, however, where the cost of water is low compared to other resources such as gas or electricity, the reuse driver based on return on investment analysis might not provide justification for the integration of reuse processes at these industries.

One opportunity that may drive more industries in the food and beverage sector toward water reuse/recycling is utilization of the true cost of water, which incorporates a range of costs from heating to treatment to pumping, moving, and disposing of water instead of utilizing the nominal purchase price of water during sustainability alternative evaluations. This true cost of water should also monetize the risk from inadequate water quality or quantity and account for the total loss of operating license, when considering capital expenditures for water reuse/recycling alternatives. By understanding the full cost of water, a company views water as a valuable resource and strategic asset, which then elevates the role of water reuse and recycling as a sustainability measure.

The challenges observed during the implementation of reuse/recycling processes were facility specific. Common challenges encountered were the insufficiency of flow metering systems and water quality control instrumentation that would enable better water balance accounting and identification of beneficial recycle and reuse opportunities within the production process. A full understanding of the water cycles within a production process is imperative to appropriate planning decisions and can be enhanced by improving or maintaining accurate monitoring and tracking systems.

Many of the examples presented in this literature review were financially, economically, and environmentally successful in implementing recycling or reuse schemes and improving operational and technological performance. For these industries, the implementation of water recycling/reuse systems resulted in economic growth without negatively affecting water availability, while reducing polluted discharges to the environment. These green strategies improved product quality and process efficiency while enhancing the reputation of the industry.

References

Afonso, M. D.; Borquez, R. Review of the treatment of seafood processing wastewaters and recovery of proteins therein by membrane separation processes—prospects of the ultrafiltration of wastewaters from the fish meal industry. *Desalination* **2002,** *142,* 29–45.

Ait Hsine, E.; Benhammou, A.; Pons, M. N. Water Resources management in soft drink industry—water use and wastewater generation. *Environ. Technol.* **2005,** *26,* 1309–1316.

ASME, American Society of Mechanical Engineers. Website: www.asme.org (accessed June 2014).

Beverage Industry Environmental Roundtable (BIER). Managing Water-Related Business Risks & Opportunities in the Beverage Sector. *Practical Perspective,* November 2012.

Bienati, B.; Bottino, A.; Capannelli, G.; Comite, A. Characterization and performance of different types of hollow fibre membranes in a laboratory-scale MBR for the treatment of industrial wastewater. *Desalination* **2008,** *231,* 133–140.

Bloom Center for Sustainability. Driving adoption of innovative solutions. Water reuse enables business growth at Algoma Orchards. Report, 2013. http://bloomcentre.com/wp-content/uploads/BLOOM_CaseStudy_Algoma_CI.pdf (accessed June 2015).

Chavez-Rodriguez, M. F.; Mosqueira-Salazar, K. J.; Ensinas, A. V.; Nebra, S. A. Water reuse and recycling according to stream qualities in sugar–ethanol plants. *Energ. Sustain. Dev.* **2013,** *17,* 546–554.

Codex Alimentarius Commission. Discussion Paper on Proposed Draft Guidelines for the Hygienic Reuse of Processing Water in Food Plants. *Joint FAO/WHO Food Standards Programme Codex Committee on Food Hygiene*. Thirty-second Session, **1999**. Washington, D.C., USA, November 29 – December 4.

El-Salam, M. M. A.; El-Naggar, H. M. In-plant control for water minimization and wastewater reuse: a case study in pasta plants of Alexandria Flour Mills and Bakeries Company, Egypt. *J. Cleaner Prod.* **2010,** *18,* 1403–1412.

Food Manufacturing Coalition. State-of-the-Art Report: Food Manufacturing Coalition for Innovation and Technology Transfer. Report, 1997. http://www.ciprocess.co.uk/pdfs/article-wastewater.pdf (accessed June 2015).

Hussain, R.; Sattar, S.; Khan, M. H.; Nafees, M. Low Cost Wastewater Treatment at Beverage Industry, Hattar Industrial Estate, Pakistan—A Case Study. *Int. J. Environ. Prot.* **2013,** *3* (11), 23–28.

Institute for Sustainable Future. Yatala Case Study: On-site industrial recycling improves water efficiency in beverage manufacturing. [Report] 2013. http://waterrecyclinginvestment.com/wp-ontent/uploads/2013/11/ISF019_AWRC_D7_Yatala_4-2.pdf (accessed June 2015).

International Bottled Water Association (IBWA). Water Use Benchmarking Study: Executive Summary, October 21, 2013. http://www.bottledwater.org/files/IBWA%20Water%20Use%20Benchmarking%20Report%20-%20Exec%20Summary%20FINAL%20102113.pdf (accessed June 2015).

International Life Sciences Institute (ILSI). Considering Water Quality for Use in the Food Industry. Report, 2008. http://www.ilsi.org/Europe/Publications/R2008Con_H2O.pdf. Accessed June 2015.

Ioannou, L. A.; Michael, C.; Vakondios, N.; Drosou, K.; Xekoukoulotakis, N. P.; Diamadopoulos, E.; Fatta-Kassinos, D. Winery wastewater purification by reverse osmosis and oxidation of the concentrate by solar photo-Fenton. *Sep. Purif. Technol.* **2013,** *118*, 659–669.

Jami, M. S.; Amosa, M. K.; Alkhatib, M. F. R.; Jimat, D. N.; Muyibi, S. A. Boiler-Feed and Process Water Reclamation from Biotreated Palm Oil Mill Effluent (BPOME): A Developmental Review. *Chem. Biochem. Eng. Q.* **2013,** *27*(4), 477–489.

Kern, J.; Reimann, W.; Schluter, O. Treatment of Recycled Carrot Washing Water. *Environ. Technol.* **2006,** *27,* 459–466.

Madaeni, S. S.; Mansourpanah, Y. Screening membranes for COD removal from dilute wastewater. *Desalination* **2006,** *197* (1–3), 23–32.

Martinez, K.; Le, V.; Choudhury, G.; Lathrop, A. Ozone Treatment of Defrost Water for In-Plant Reuse. *Ozone-Sci. Eng.* **2013,** *35*, 273–282.

Miyaki, H.; Adachib, S.; Suds, K.; Kojima, Y. Water recycling by floating media filtration and nanofiltration at a soft drink factory. *Desalination* **2000,** *131*, 47–53.

Mosse, K. P. M.; Lee, J.; Leachman, B. T.; Parikh, S. J.; Cavagnaro, T. R.; Patti, A. F.; Steenwerth, K. L. Irrigation of an established vineyard with winery cleaning agent solution (simulated winery wastewater): Vine growth, berry quality, and soil chemistry. *Agr. Water Manage.* **2013a,** *123*, 93–102.

Mosse, K. P. M.; Verheyen, T. V.; Cruickshank, A. J.; Patti, A. F.; Cavagnaro, T. R. Soluble organic components of winery wastewater and implications for reuse. *Agr. Water Manage.* **2013b,** *120,* 5–10.

Mundi, G. Assessment of Effective Solids Removal Technologies To Determine Potential for Vegetable Washwater Reuse. Master's Thesis. University of Guelph. Ontario, Canada, 2013.

Muro, C.; Riera, F.; del Carmen Díaz, M. Membrane Separation Process in Wastewater Treatment of Food Industry. In Valdez, B., Ed.; *Food Industrial Processes—Methods and Equipment*; InTech, Feburary 22, 2012.

Ontario Centre for Environmental Technology Advancement (OCETA). Innovations in Minimizing Waste and Wastewater Effluent from Food and Beverage Processing Operations: Case Studies. Report, 2013. http://provisioncoalition.com/Assets/5.%20case-studies.pdf (accessed June 2015).

Roy, Glenn M. Activated carbon applications in the food and pharmaceutical industries. CRC Press: Boca Raton, FL, 1994.

Saha, N. K.; Balakrishnan, M.; Batra, V. S. Improving industrial water use: case study for an Indian distillery. *Resour. Conserv. Recy.* **2005,** *43,* 163–174.

Salehi, F. Current and future applications for nanofiltration technology in the food processing. *Food Bioprod. Process.* **2013,** *92* (2), 161–177.

Sampson, B.; Hilless, K.; Laganistra, M. Wastewater environmental best practice manual. The Australian Meat Processor Corporation. Report, 2005. http://www.ampc.com.au/site/assets/media/reports/Resources/Wastewater-enviromental-best-practice-manual.pdf (accessed June 2015).

Simate, G. S.; Cluett, J.; Lyuke, S. E.; Musapatika, E. T.; Ndlovu, S.; Walubita, L. F.; Alvarez, A. E. The treatment of brewery wastewater for reuse: State of the art. *Desalination* **2011,** *273,* 235–247.

Souza, B. S.; Moreira, F. C.; Dezotti, M. W. C.; Vilar Boaventura, V. J. P. Application of biological oxidation and solar driven advanced processes to remediation of winery wastewater. *Catal. Today* **2013,** *209,* 201–208.

State of California Department of Water Resources, 2013. Commercial, Industrial, and Institutional Task Force Best Management Practices Report to the Legislature, Volume I, October 21, 2013. http://www.water.ca.gov/legislation/docs/CII%20Volume%20II%20july%202014.pdf (accessed June 2015).

Tanzi, G.; Mazzei, A. Combination of advanced aeration system and membrane bioreactor for winery waste water treatment. **2009**. http://mazzei.net/wp-content/uploads/Combination%20of%20Advanced%20Aeration%20System%20%26%20Membrane%20Bioreactor%20for%20Winery%20Waste%20Water%20Treatment_2009-04-02_Winery%202009-Environmental%20Sustainability_ITALY.pdf

U.S. Environmental Protection Agency (U.S. EPA). Drinking Water Standards. **2008**, U.S. Environmental Protection Agency: Washington, DC. http://www.epa.gov/safewater

U.S. Environmental Protection Agency (U.S. EPA). Guidelines for water reuse. EPA/600/R-12/618. September 2012. http://nepis.epa.gov/Adobe/PDF/P100FS7K.pdf (accessed June 2015).

Valta, K.; Kosanovic, T.; Malamis, D.; Moustakas, K.; Loizidou, M. Water consumption and wastewater generation and treatment in the Food and Beverage Industry. *Desal. Water Treat.* **2014,** *53* (12), 1–13.

Vasanthi, S.; Viramuthu, V. A. Water recycling in the food industry. In *Handbook of Water and Energy Management in Food Processing;* J. Klemes, R. Smith and J-Kim, Eds. CRC Press: Boca Raton, FL, 2008.

Visvanathan, C., Asano, T. The Potential For Industrial Wastewater Reuse. Report, 2009. www.worldwewant2015.org/file/303908/download/329870 (accessed June 2015).

Vourch, M.; Balannec, B.; Chaufer, B.; Dorange, G. Nanofiltration and reverse osmosis of model process waters from the dairy industry to produce water for reuse. *Desalination* **2005,** *172,* 245–256.

World Health Organization (WHO). Drinking Water Quality. World Health Organization: Geneva, Switzerland, **2008**. http://who.int/water_sanitation_health/dwq

Williams, L. K. Challenges, Opportunities for Water Reuse in the Food & Beverage Industry. Industrial WaterWorld 2011. Fact Sheet. http://www.waterworld.com/articles/iww/print/volume-12/issue-04/feature-editorial/challenges-opportunities-for-water-reuse-in-the-food-beverage-industry.html (accessed June 2015).

Appendix F

Water Recycling/Reuse in Cooling Towers

Wet or fluid cooling towers are widely utilized in many industrial sectors. Cooling towers are usually one of the first processes targeted for water recycling applications because of the significant volumes of makeup water required for systems using evaporative cooling mechanisms. The U.S. Department of Energy (U.S. DOE)'s National Energy Technology Laboratory funded several studies on the use of alternative water sources for power plant cooling using mine pool water, coal bed methane–produced water, and reclaimed municipal water (Veil, 2007). Water intensity at thermoelectric power plants is particularly high regardless of fuel type, as shown in Table F.1 (U.S. Department of Energy (DOE), 2006), and the Electric Power Research Institute (EPRI) is focused on expanding the electric industry's water resources through minimization of water loss and waste and the expansion of current water sources for cooling (EPRI, 2012). Recirculating cooling systems avoid the large water withdrawal volumes of once-through systems, but they consume more water through utilization of an evaporative process to condense the steam, whereas dry-cooled systems that utilize almost no water are much less efficient in regions with high ambient air temperatures. Further details on freshwater use by U.S. power plants as a function of geographic location and fuel type can be found in Averyt et al. (2011).

Table F.1. Water Intensity at Thermoelectric Power Plants for Closed-Cycle Cooling Tower

Plant Type	Water Intensity (gal/MWh)	
	Withdrawal	Consumption
Fossil/biomass/waste	300–600	300–480
]Nuclear	500–1100	400–720
Geothermal steam	~2000	~1400
Natural gas, combined cycle	~230	~180
Coal, integrated gasification combined cycle	~250	~200

Drivers for Water Recycling or Water Reuse

Water evaporation is both the driver and limiting factor for water recycling opportunities in cooling towers because dissolved minerals that build up in the recirculating water may precipitate after exceeding their solubility products. This buildup is typically measured through the cycles of concentration (COC) parameter. The maximum COC is defined in Equation (1) as the concentration limit for minerals in the recirculating water divided by the concentration of minerals in the makeup water and in Equation (2) for ion pair limits (EPRI, 2012). Computer modeling with ion association model predictions of scale formation can assist in optimizing flows, maximizing cycles, and minimizing impacts to the environment (Ferguson and Ferguson, 2010). To prevent precipitation of the dissolved minerals, a portion of the recirculating water (i.e., blowdown) is typically removed and replaced with fresh makeup water.

$$COC = \frac{C_{Limit,i}}{C_{MU,i}} \tag{1}$$

Where: COC=cycles of concentration

$C_{Limit,i}$=water quality limit for constituent i

$C_{MU,I}$=concentration of constituent i in the makeup water

$$COC=\sqrt{\frac{C_{Limit,ij}}{C_{MU,i}C_{MU,j}}} \tag{2}$$

Where: $C_{Limit,ij}$=water quality limit for constituent i

$C_{MU,i}$=concentration of constituent i in the source water

$C_{MU,j}$=concentration of constituent j in the source water

The following cooling tower water balance equations (Puckorius, 2013) can be used to calculate evaporation rate, blowdown, makeup requirements, and overall system water balance:

$$E=Rx\Delta T_F/1000 \tag{3}$$

$$B=E/(COC-1) \tag{4}$$

$$M=(ExCOC)/(COC-1) \tag{5}$$

$$M=E+W+B+L \tag{6}$$

Where: E=evaporation rate (gpm)

R=recirculation rate (gpm)

ΔT_F=temperature difference (^oF)

B=blowdown (gpm)

COC=cycles of concentration

M=makeup (gpm)

W=windage or drift loss (gpm)

L=leakage (gpm)

As a general rule of thumb, for each 10°F of water cooling, 1% of the cooling water is evaporated (San Diego County Water Authority, 2009). The associated water savings from increasing the COC can be calculated using Equation (7) (U.S. EPA and U.S. DOE, 2005).

$$Vsaved=M1*(CR_2-CR_1)/CR_1(CR_2-1) \quad (7)$$

Where: $M1$=initial makeup water volume

CR_2=desired or final concentration ratio of dissolved solids

CR_1=initial concentration ratio of dissolved solids

CR=ratio of dissolved solids concentration in blowdown and makeup waters

Balancing Water Minimization and Water Quality Treatment Costs

Increasing the COC is a common water conservation measure that can also reduce the treatment chemical costs for cooling towers. Assessing the optimum number of COC is a balancing act between savings in water, sewer, and chemical costs and the increased risk of scale, plugging, and film fill failure that can occur if the dissolved solids content is too high (San Diego County Water Authority, 2009). Conversion from potable to recycled water for cooling tower makeup can therefore require changes to COC or additional pretreatment because the solids content of the recycled water is typically higher than that of the potable water. An example of the water quality differences is provided in Table F.2.

The key to successful water recycling applications lies in generating a water quality for the blended makeup and recirculating water that is compatible with the cooling system equipment. The metallurgy of the equipment in the entire cooling system, operating parameters of that equipment, identity of any potential contaminants in the process fluids that could migrate into the cooling water, and identification of potential stagnant periods of operation are all critical components of the water quality needs assessment. The study by Puckorius (2013) discussed the limitations of ammonia concentrations for copper and copper alloy equipment and the impact of chloride to stainless steel equipment and copper to mild steel equipment. In addition, the role of phosphate, calcium, and pH scale formation prevention, particularly with high bulk water temperatures, and the limitation of organics to prohibit microbiological deposits or mediated corrosion are discussed. Additional water quality impacts on cooling system materials are discussed in another study conducted by San Diego County Water Authority (2009). EPRI has developed a list of standard water quality parameters for cooling tower applications, summarized in Table F.3.

Table F.2. Comparison of Potable and Recycled Water Quality at Same Cycles of Concentration

Constituent	5X Potable	5X Recycled
Calcium as $CaCO_3$ (mg/L)	312	625
Chlorides (mg/L)	80	550
Conductivity (µS/cm)	1155	4700
Nitrate as NO_3 (mg/L)	2	310
Orthophosphate as PO_4 (mg/L)	0.6	4.5
pH (units)	8.3	9
Puckorius Scaling Index at 90° F	6.0 (no scale)	4.5 (scaling)
Sulfate (mg/L)	210	750
Total alkalinity (mg/L)	208	380
Total chlorine (mg/L)	0.79	1.5

Source: Holmquist et al., 2012.

Table F.3. Cooling Tower Water Quality Parameter Standards

Parameter	**Units**	**Current EPRI Standards (1998)**
Ca	mg/l_{CaCO3}	No value given—EPRI's SEQUIL RS predicts case-specific limits.
Ca x SO_4	$(mg/l)^2$	50,000—conservative value; EPRI's SEQUIL RS predicts case-specific limits.
Mg x SiO_2	mg/l_{CaCO3} x mg/l_{SiO2}	35,000—conservative value; EPRI's SEQUIL RS predicts case-specific limits.
Alkalinity	mg/l_{CaCO3}	No value given—EPRI's SEQUIL RS predicts case-specific limits.
SO_4	mg/l	No value given—EPRI's SEQUIL RS predicts case-specific limits.
SiO_2	mg/l	150
PO_4	mg/l	No value given—EPRI's SEQUIL RS predicts case-specific limits.
Fe (total)	mg/l	<0.5
Mn	mg/l	<0.5
Cu	mg/l	<0.1
Al	mg/l	<1
S	mg/l	5
NH_3	mg/l	<2 (if copper bearing alloys present; does not apply to 70:30 or 90:10 copper–nickel)
pH		No value given—EPRI's SEQUIL RS predicts case-specific limits.
TDS	mg/l	—
TSS	mg/l	<100 with film fill and <300 with open fill
BOD	mg/l	—
COD	mg/l	—
Langlier Saturation Index		<0
Ryznar Saturation Index		>6
Puckorius Saturation Index		>6

Notes: BOD=biochemical oxygen demand; COD=chemical oxygen demand; EPRI=Electric Power Research Institute; TDS=total dissolved solids; TSS=total suspended solids.

Current Technologies for Treatment

To alleviate operational concerns arising from high COC or use of marginal source water, conventional treatment of cooling tower water is achieved using chemical processes. Chemical treatment consists of inhibitors for corrosion control, deposition control to prevent scale formation, or microbiological growth control to prevent corrosion and fouling. Corrosion control can be achieved by adding phosphates, zinc salts, molybdates, and polysilicates for mild steel and organic nitrogen azole compounds for copper alloys.

Deposition control is achieved through use of solubilizing agents that prevent scale precipitation, crystal modifiers that alter a precipitate's ability to adhere to surfaces, dispersants and surfactants that adsorb suspended solids and cause mutual repulsion, or mineral scale inhibitors such as acid, phosphonates, and water-soluble polymers. Microbiological growth control is achieved by addition of disinfectants such as chlorine, bromine, hydrogen peroxide, or hydroxyl radicals. Some regulatory agencies (e.g., California Department of Public Health) still require biocide addition to recycled water used in cooling towers.

Some guidelines on recommended maximum concentrations can be found in San Diego County Water Authority (2009).There are also physical alternatives to traditional chemical treatment that advertise operation at much higher COC and the ability to recycle blowdown:

- Physical electromagnetic treatment systems
- A patented corrosion and scale inhibition technology licensed by Water Conservation Technology International (WCTI) to U.S. and international water treatment companies

The electromagnetic treatment systems consist of a high frequency electromagnetic wave generator and an inductor coil unit that induces a high frequency, time-varying electromagnetic field into the circulating water as it is transmitted from the cooling tower basin through the inductor coil by means of a submersible pump (Bhd, 2004–2005). These pulsed power systems create active colloidal nucleation sites in the bulk solution that generate an amorphous precipitate that does not adhere to the pipe wall but instead remains with the bulk solution and can be removed via blowdown, sidestream filtration, or both. These systems therefore rely upon colloidal chemistry instead of inorganic chemistry to control scaling (San Diego County Water Authority, 2009).

In the event that calcium carbonate scale does form, it is in the higher state of aragonite, a much softer scale than the low energy calcium carbonate calcite that would normally form (Bhd, 2004–2005). This system, in combination with copper–silver ionization, provides a continuous stream of copper and silver ions that control the growth of bacteria, but the biostatic properties of the system do not meet requirements for a biocide such as those specified by California.

A BacComber ultra-low frequency (ULF) patented system has been installed at numerous industrial facilities and is marketed by Ecospec Global Technology Pte. Ltd. (http://www.ecospec.com/upload/brochure_pdf/79_r5bynu7vvh725vxc0z3l61dlxhn1fcuw.pdf), a Singapore-based research and development technology company offering environmental solutions. This patented system eliminates scaling potential by removing hardness with ion exchange pretreatment (softening) and modification of silica to nonscaling form with a silica chemistry control process. The silica corrosion inhibition mechanism is highly effective, and extremely high COC can be achieved. The technology is considered "green chemistry" because use and discharge of environmentally restricted organic, phosphate, and heavy metal containing chemicals used in traditional water treatment are eliminated. Another physical removal option for salt control is use of low- and high-pressure membrane systems.

Water Recycling Implementation Steps

A prescribed series of steps is recommended for evaluation and possible utilization of degraded water sources for cooling tower makeup water, as presented in Table F.4. Cooling tower operational issues that need to be minimized through proper water quality criteria for makeup include mineral scaling and biological fouling of heat transfer surfaces, corrosion of heat transfer and structural metal, and fouling loads on cooling tower fill (EPRI, 2012). Common treatment technologies for waste reduction (post-treatment), environmental concerns (pretreatment), and operational concerns (pretreatment and sidestream treatment) are summarized in Table F.5.

Table F.4. Steps for Consideration of Degraded Water Sources for Cooling Tower Makeup Water

Steps	Description
Step 1: Identify and characterize source water.	• Obtain analysis of constituents of concern. • Obtain flow profiles for each water. • Assess feasibility of using water source(s).
Step 2: Evaluate constituents of concern.	• Verify compliance with operational quality criteria and environmental regulations. • Calculate maximum cycles of concentration for each constituent or constituent pair, and find the limiting parameter.
Step 3: Identify cooling tower design and operating impacts.	Use limiting parameters to identify potential design or retrofits, operation requirements, and associated capital and operating costs.
Step 4: Determine the need for treatment.	Assess short list of treatment scenarios based on cycles of concentration for constituents, source water quality, situational limitations, and regulatory limitations.
Step 5: Evaluate treatment requirements.	Develop necessary pre-, side- and post-treatment needed to support source water quality, and select best options.
Step 6: Evaluate disposal issues.	Evaluate disposal issues for cooling tower blowdown and makeup water treatment waste streams.

Source: Adapted from EPRI, 2012.

Table F.5. Common Treatment Technologies for Cooling Towers to Address Waste Reduction, Environmental Concerns, and Operational Concerns

Waste Reduction (Post-treatment)	**Environmental Concerns (Pretreatment)**	**Operational Concerns (Pre- and Sidestream Treatment)**
Evaporative brine concentrators are an energy-intensive process to minimize waste volume and produce highly concentrated brine. The brine undergoes further drying in an evaporation pond or evaporative crystallizer.	air stripping followed by vapor-phase granular activated carbon for removal of volatile organic compounds, THMs, and some pesticides	makeup softening for removal of hardness, carbonate alkalinity, and incidental removal of silica
Evaporative crystallizers further treat brine from evaporators to form a dry salt cake.	air stripping followed by vapor-phase thermal oxidation for removal of volatile organic compounds, THMs, and some pesticides	sidestream filtration and softening for removal of hardness, carbonate alkalinity. and incidental removal of silica
Reverse osmosis utilizes high-pressure pumps to force water through membranes while retaining salts in a brine solution. Softening and prior filtration are frequently required to prevent fouling of membranes.	liquid-phase granular activated carbon for removal of volatile and nonvolatile organic compounds and pesticides; incidental removal of some BOD, COD	
Evaporation ponds are appropriate for use in warmer climates and sites with available land.	aerobic biological treatment for removal of organic compounds, ammonia, and incidental removal of BOD and COD	
Spray dryers are useful to treat smaller volumes.	anaerobic biological treatment for removal of organic compounds, arsenate, chromate, selenite, selenite, perchlorate, and incidental removal of BOD, COD, and possibly nitrate	
	strong base anion–ion exchange for removal of arsenate, chromate, selenite, selenite, perchlorate, and incidental removal of phosphate, nitrate, and fluoride	
	Chelating ion exchange for removal of transition metals (Cu, Ni, Cd, Cr^{+3})	
	Precipitation	

Notes: BOD=biochemical oxygen demand; COD=chemical oxygen demand; THM=trihalomethanes.
Source: Adapted from EPRI (2012).

Case Studies

Numerous case studies have been published on reusing water for cooling tower applications. Examples of reuse water for cooling tower makeup water and reuse of cooling tower blowdown as boiler feed are provided in Tables F.6 and F.7, respectively.

Table F.6. Case Studies of Reclaimed Makeup Water for Cooling Tower Applications

Application/Treatment Issues	Citation	Recommended Treatment Solutions
Cooling tower makeup water for corn-refining facility using a blend of pond-treated process effluent (30–100 ppm COD and 10 ppm suspended solids) and potable water had unacceptable levels of biofouling despite mixed oxidant treatment of pond effluent and additional bleach added during process leaks. Unacceptable levels of chloride were also generated, resulting in equipment corrosion and a 3 COC limit. Additional stainless steel pitting was due to manganese contributed from supplemental well water blended with the makeup water.	Elliot and Geiger (2009)	Implementation of hollow-fiber UF membranes sized for partial treatment of pond makeup water reduced suspended solids, COD, and oxidant demand of makeup water, which diminished biological fouling. Chloride-induced pitting remained a problem, addressed by changing the chlorine dioxide generation method to lower the chloride concentration. A chemical treatment program was also designed to address high corrosion potential of the makeup water by setting operational limits for calcium hardness, pH, chloride, conductivity, orthophosphate, and Langlier Saturation Index, adding alum ahead of the UF and dosing with orthophosphate to control phosphate levels and create a passive oxide film on the carbon steel.
Develop a silica removal technology to be used in concert with commercial electrodialysis reversal technology to provide a cost-effective treatment of impaired water as cooling tower makeup water in coal-fired power plants to provide a 50% savings of freshwater use. A 90% reduction in silica was needed.	Colborn (2012)	A molybdenum-modified alumina that outperformed existing adsorbents was developed and tested with a bench-scale model column. A 98% removal of silica was achieved using simulated impaired water with 100 ppm of silica. The pretreatment allowed COC to increase from 2.5 to 10 on the basis of silica and from 2.5 to 6 on the basis of hardness and verified with a controlled evaporation research tower that simulates a cooling tower. This increase in COC provides a 28% water savings.

Notes: COC=cycles of concentration; COD=chemical oxygen demand; UF=ultrafiltration.

Table F.7. Case Studies of Cooling Tower Blowdown Reuse

Application/Treatment Issues	Citation	Recommended Treatment Solutions
Treatment of cooling tower blowdown for feed to 8 boilers in Beijing's Gaojing power plant: source of cooling tower makeup was changed from surface water to secondary effluent from Gaobeidian Municipal Wastewater Treatment Plant. The waste stream had high hardness (10.25–16.1 mg/L), total alkalinity (4.86–7.2 mmol/L), sulfate (186–408 mg/L), and silica (11.8–33.4 mg/L).	Case History: Dow Filmtec Membranes BW30-365FR and BW30-400 and Dow Ultrafiltration SFP 2660 Cooling Tower Blowdown Reuse in Gaojing Power Plant	Blowdown water was pumped into a multimedia filter to reduce turbidity from 20 to 4–8 NTU, and a subsequent UF unit further decreased the turbidity to <0.4 NTU and protected the RO unit from colloids, TSS, bacteria, and large molecular weight organics. Reducing agents, antiscalant, and acid were dosed ahead of the first-pass RO system. The permeate water from the first-pass RO was degasified and the pH increased to 9.5 with NaOH dosing before entering the second-pass RO. ED was installed for final demineralization to meet the requirement for boiler makeup water. Dual-membrane technology with proper pretreatment and chemical dosing resulted in 70% reuse of cooling tower blowdown.
Brine concentrators of cooling tower blowdown derived from 3 sources of makeup water (surface water, highly saline groundwater, and treated municipal wastewater) provided high purity boiler feed water at Indiantown Cogeneration Plant, FL. The varying mix of makeup water caused brine concentrators to suffer stainless steel skin corrosion issues. Alternative membrane treatment system was sought to replace the brine concentrators.	Drake et al. (2012)	Integrated MF/RO unit designed at full scale consisting of 2 RO trains with 8:4 and 4:2 array, average flux <14 GFD and recovery of 45–75%. Biocide (DBNPA at 100 ppm) was needed in the blowdown feed to the MF to prevent RO biological fouling. pH adjustment was needed to prevent second-stage RO fouling caused by aluminum when surface water was used in the makeup water to the cooling tower. ROI for implementation of MF/RO system replacement to brine concentrators was calculated at 2.4 years.
Comparative bench study of mild desalination of cooling tower blowdown water with ED and MCDI based on energy requirements, current efficiencies, and membrane performance.	Heidekamp (2013)	Limiting current density was a key parameter influencing desalination of blowdown water by ED, and it increased linearly with increasing salt concentration and flow rate. Current efficiencies were 80% or higher. Two stacks with different membrane types were tested in the MCDI experiment, but only low feed water flows could be accommodated because of the maximum supply of 20 amperes. Because of this limitation, current efficiencies were only 60%. Most important, energy consumption was five times higher for MCDI than desalination with ED (2.1 kWh/m^3 vs. 0.4 kWh/m^3). MCDI is more energy competitive with ED when the salt concentration is lower. An ED pilot design was made consisting of prefiltration with cartridge filters and 4 ED stacks, and further pilot testing was recommended.

Notes: ED=electrodialysis; MCDI=membrane-capacitive deionization; MF=microfiltration; RO=reverse osmosis; TSS=total suspended solids; UF=ultrafiltration.

References

Averyt, K.; Fisher, J.; Huber-Lee, A.; Lewis, A.; Machnick, J.; Madden, N.; Rogers, J.; Tellinghuisen, S. Freshwater use by U.S. power plants: Electricity's thirst for a precious resource. A report of the Energy and Water in a Warming World Initiative. Union of Concerned Scientists: Cambridge, MA, November 2011.

Bhd, I. A. S. Keeping water in cooling tower clean without the aid of chemicals. *Ingenieur* December **2004**–February **2005,** 60**–**64. http://www.bem.org.my/publication/dec04feb05/F(CoolingT)60-64.pdf (accessed June 2014)

Colburn, R. Technology to facilitate the use of impaired waters in cooling towers. Department of Energy Report, July 31, 2012. http://www.alrc.doe.gov/technologies/coalpower/ewr/water/pdfs/Final%20Report%2005961.pdf (accessed April 2014)

Drake, M.; Wise, S.; Venkatadri, R. Treatment of cooling tower blowdown water with membranes in a zero liquid discharge power plant, IWC 12-15. Pall Corporation: Port Washington, NY, 2012. http://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR962.pdf (accessed June 2014).

Duke, D.; Kubis, J.; Reed, J. Zero Liquid Discharge (ZLD) cooling tower treatment at CSI. *Iron Steel Technol.* April **2008.** http://water-cti.com/pdf/AIST_2008_Pub_April08_Draft.pdf (accessed July 9, 2014)

Electric Power Research Institute (EPRI). Water treatment for power plant cooling towers: a supplement to the EPRI 2012 RFI for those unfamiliar with the power industry. EPRI: Palo Alto, CA, 2012. http://mydocs.epri.com/docs/PublicMeetingMaterials/0712/watertreatment_RFI_Final.pdf (accessed June 2014)

Elliott, P.; Geiger, G. An integrated approach to water reuse. Paper presented at the Cooling Technology Institute Annual Conference, San Antonio, TX, 2009. http://www.cti.org/cgi-bin/eshop.pl?add (accessed April 2014).

Ferguson, R. J.; Ferguson, B. R. Computer modeling of blended streams for water reuse and discharge. Paper presented at the Cooling Technology Institute Annual Conference, Houston, TX, February 7–11, 2010. http://www.frenchcreeksoftware.com_cti2010_cti-2010_paper-22.pdf (accessed June 2014)

Heidekamp, M. Mild desalination of cooling tower blowdown water with electrodialysis and membrane capacitive deionization: a comparative study. Master of Science Thesis, Delft University of Technology, Delft, The Netherlands, June 2013.

Holmquist,A., Puckorus, P.R., Tiangco, J. M. An evaluation of cooling tower conversions from potable water to recycled water. 27th Annual WateReuse Symposium, September 9-12, 2012, Hollywood, FL.

Puckorius, P. R. Consider recycled water for your cooling tower makeup. *Chem. Eng. Prog.* **2013** *109* (2), 24–29.

San Diego County Water Authority. Technical information for cooling towers using recycled water. San Diego County Water Authority: San Diego, CA, July 2009.

U.S. Department of Energy (DOE). Energy Demands on Water Resources. Report to Congress on the Interdependency of Energy and Water, December 2006. http://www.circleofblue.org/waternews/wp-content/uploads/2010/09/121-RptToCongress-EWwEIAcomments-FINAL2.pdf

U.S. Environmental Protection Agency (U.S. EPA) and U.S. Department of Energy (U.S. DOE). Laboratories for the 21st century: best practices, May 2005. http://www.i2sl.org/documents/toolkit/bp_rightsizing_508.pdf (accessed April 2014).

Veil, J. A. Use of Reclaimed Water for Power Plant Cooling. Report for the U.S. DOE National Energy Technology Laboratory, August 2007. http://www.veilenvironmental.com/publications/pp/ANL-EVS-R07-3_reclaimedwater.pdf (accessed April 2014).

Appendix G

Water Recycling/Reuse in Manufacturing Industries

Industrial water use is tracked in most countries in terms of total quantity withdrawn and then further broken down into regional and source percentage utilization. Industrial water is the water needed within a manufacturing facility for fabricating, processing, washing, diluting, cooling, or transporting a product, incorporating water into a product, or sanitation needs within the facility (http://pubs.usgs.gov/circ/2004/circ1268/htdocs/text-in.html). Percentage water withdrawals by regional sectors for agriculture, domestic, and industry show industrial water usage is approximately 50% in Europe and North America and 20% or less for the rest of the world (http://www.fao.org/nr/water/aquastat/globalmaps/AquastatWorldDataEng_20121214_Withdrawal.pdf).

In the United States, industrial withdrawals in 2005 were estimated to be 18,200 Mgal/d, representing 4% of the nation's total withdrawals and about 9% of total withdrawals for all categories, excluding thermoelectric power for self-supplied water (http://water.usgs.gov/edu/wuin.html). Nearly all these withdrawals were freshwater, with 83% coming from surface water and 17% from groundwater. Louisiana, Indiana, and Texas accounted for 40% of total industrial withdrawals. In Europe, water use in the manufacturing sector has been compiled by country, year, and public versus self-supply, but there are numerous data gaps in this compilation (http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Water_statistics). On a global basis, about twice as much water was used by industries than was used for domestic purposes (on average 665 billion m^3 per year) between 1987 and 2003. Top industrial water users were countries in Eastern Europe (Bulgaria, Serbia and Montenegro, Slovenia, Republic of Moldova, Romania), North America (Canada and the United States), and Europe (France and Germany; http://www.worldmapper.org/posters/worldmapper_map325_ver5.pdf).

Industrial water withdrawal in Asia has been reported as 10% of total water withdrawal (http://www.fao.org/nr/water/aquastat/countries_regions/asia/index4.stm). However, industrial water demand in China has nearly tripled between 1980 and 2007, and the industrial sector represents about a quarter of the country's water consumption (Hu and Cheng, 2013). Water consumption is also usually higher in developing countries, as demonstrated by the water consumption in the steel industry in India: 25 to 60 m^3 water/ton of steel, which is 8 to 10 times higher than that in developed countries (Ranade and Bhandari, 2014).

Statistics and models on regional water withdrawal by industry as a collective group are available, but it is much more difficult to find or generate statistics on water use broken down by individual industrial category. Models, such as WaterGAP3, can be used to estimate current and future water withdrawals and consumption on the manufacturing sector (Flörke et al., 2013). A Norwegian project funded in part by EUROSTAT attempted to develop a methodology based on statistical analyses of a sample survey to provide data for water abstraction and use for individual industrial NACE Codes 10 through 37 for the base year 2003. A cross-referencing of European NACE codes with North American NAIC codes is provided in Table G.1. The Norwegian study results for 2003 are provided in Table G.2.

The industry-specific coefficients for water use in the different categories will be further refined after collection of future data sets. Norwegian industries exhibiting high total water use included upstream oil and gas, metal mining, food and beverage manufacturing, pulp and paper manufacturing, coke and petroleum refining and manufacturing, chemical manufacturing, and metal manufacturing; within the manufacturing sectors, the majority of the water was used for processing or cooling.

Water demand in a crude oil refinery was reported as approximately 0.7 m^3 water/m^3 processed oil, with 60% of water consumption for the cooling tower system (Torres et al., 2008). The textile industry was cited as one of the more water- consuming industrial manufacturing sectors (i.e.; more than 100 L/kg of processed fabric), with an estimated annual consumption of freshwater in European textile companies of 600 million m^3; 90% of the input water, on average, needed end-of-pipe treatment prior to discharge (Vajnhandl et al., 2014). Textile industry wastewater discharge in China was approximately 7.5% of the total discharge of Chinese industrial wastewater in 2003. The automotive sector was cited as a less water- and energy-intensive branch of industry, but areas of die casting, mechanical processing, paint finishing, and hardening have a high potential for process water reuse and heat recovery (Enderle, 2012). Water use for different industries in India is summarized in Table G.3.

Table G.1. Comparison of European (NACE) and North American (NAICS) Industrial Codes

Industry	NACE Code*	NAICS Code*
Mining of coal and lignite; extraction and peat	10	212
Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction, excluding surveying	11	211
Mining of uranium and thorium	12	212291
Mining of metal ores	13	2122
Other mining and quarrying	14	2123
Manufacture of food products and beverages	15	311 and 312
Manufacture of tobacco products	16	3122
Manufacture of textiles	17	314
Manufacture of wearing apparel; dressing and dyeing of fur	18	315
Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness, and footwear	19	316
Manufacture of wood and products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	20	321
Manufacture of pulp, paper, and paperboard	21	322
Publishing, printing, and reproduction of recorded media	22	323
Manufacture of coke, refined petroleum products, and nuclear fuel	23	324
Manufacture of chemicals and chemical products	24	325
Manufacture of rubber and plastic products	25	326
Manufacture of other nonmetallic mineral products	26	327
Manufacture of basic metals	27	331

Manufacture of fabricated metal products, except machinery and equipment	28	332
Manufacture of machinery and equipment	29	333
Manufacture of office machinery and computers	30	334
Manufacture of electrical machinery and apparatus	31	333
Manufacture of radio, television, and communication equipment and apparatus	32	334
Manufacture of medical, precision, and optical instruments and watches and clocks	33	339
Manufacture of motor vehicles, trailers, and semi-trailers	34	336
Manufacture of other transport equipment	35	336
Manufacture of furniture and related product manufacturing	36	337
Recycling	37	-

Notes: *=Industry statistics are reported using different regional reporting codes. NACE is for Eurostat reporting, NAICS is for U.S., Canada, and Mexico, and ANZSIC is for Australia and New Zealand. The codes have detailed differences but all derive from United Nations ISIC standard. ANZSIC=Australian and New Zealand Standard Industrial Classification; ISIC=International Standard Industrial Classification; NACE=Nomenclature of Economic Activities; NAICS=North American Industry Classification System.

Table G.2. Water Use by Industry and Purpose, 2003

NACE	Total (m^3)	Sanitary (m^3)	Processing (m^3)	Cooling (m^3)	In Products (m^3)	Leakage and Evaporation (m^3)	Other (m^3)
10	192,861	146,211	46,530	-	-	120	-
11	325,874,464	563,908	6836	70,001,369	4855	4836	225,292,661
13	39,874,537	46,914	39,568,568	110,190	19,560	-	305
14	8,979,812	215,273	4,179,617	365,935	111,887	-	4,107,101
15	73,367,162	1,996,888	29,409,201	35,973,422	2,078,783	624,804	3,284,064
16	39,135	6000	5000	3000	135	25,000	-
17	1,153,411	154,160	707,623	125,938	150,000	300	15,390
18	73,320	36,220	35,194	-	-	147	1833
19	173,811	5,056	101,255	67,500	-	-	-
20	2,861,641	271,397	477,657	527,512	23,678	36,465	1,524,932
21	173,891,330	690,687	69,621,469	99,739,253	913,677	2,847,866	78,380
22	636,523	453,351	55,541	97,919	18,497	1200	10,015
23	307,281,347	411,162	51,240,000	253,000,000	185	-	2,630,000
24	630,806,616	3,148,937	54,206,143	568,95 866	2,350,970	1,529,758	611,943
25	1,911,857	359,521	416,168	978,174	2668	4094	151,232
26	17,335,974	300,632	9,503,960	6,569,467	263,078	378.947	319.890
27	377,911,606	2,071,432	124,236,713	205,861,663	3000	7,608,540	38,130,257
28	2,653,649	374,370	155,917	2,084,274	7592	1529	29,967
29	1,084,362	671,771	79,873	95,744	4035	30,220	-

30	6402	3502	-	2800	-	100	-
31	847,266	249,835	9483	584,768	-	134	3046
32	190,462	126,261	56,776	1500	640	150	5135
33	230,177	208,710	5360	4425	-	-	11,682
34	3,968,243	386,977	196,109	3,198,013	-	178,057	9087
35	1,427,929	754,96	165,859	44,563	148,340	20,094	294,109
36	310,051	170,214	97,428	20,464	571	12,986	8388
37	4,138,662	3957	3,510,883	618,958	-	-	4863

Note: Totals might be slightly off due to rounding errors.

Table G.3. Water Use Reported for Industries in India

Industrial Category	Water Use (m3/per ton of product)
Normal paper	~ 300
High quality paper	≤1000
Petroleum	10–300
Chemical fertilizer	270
Automobile	30

Source: Adapted from Ranade and Bhandari, 2014.

Drivers for Water Recycling or Water Reuse in Manufacturing Industries

Manufacturing industries historically utilized abundant freshwater sources and applied minimal treatments to meet surface water discharge standards for generated wastewater. Increasing water scarcity from drought and expanded population are driving a water-saving culture, particularly in high-density urban regions. This is increasing implementation of industrial water reuse strategies that utilize cost-effective treatments that enable formerly discharged wastewater to be reused within a single facility. Another option is development of industrial water reuse synergies that can engage traditionally separate industries into a collective cooperative approach of industrial symbiosis (Chertow, 2000).

Literature often cites industries' need or desire to minimize permitted wastewater discharge or further reduce water intake through implementation of water reuse practices (Torres et al., 2008; Lawler, nd; Levi Strauss & Co., nd; Xu, 2014). Water reuse strategies and processes vary widely between industrial sectors and are highly dependent on site-specific situations (Vajnhandl et al., 2014). Readily implementable reuse opportunities requiring low capital investment are usually installed first (e.g., cooling towers), and studies for additional reuse opportunities are delayed or not implemented at full scale until the cost of treatment modifications can provide a reasonable return on investment (Lawler, n.d.). Cooling is the most common industrial reuse option because of its high water demand, comparatively low water quality required, ease with which the practice may be applied to different types of industries, and simplicity of implementation (Jiménez and Asano, 2008).

The ability to implement on-site industrial water reuse in the manufacturing sector is contingent upon meeting local requirements that are often derived in consideration of a host of ancillary regulations. One exception is San Jose, CA, which has issued guidelines for planning and implementing an on-site industrial wastewater reuse system from the conceptual planning phase to the post-construction phase in compliance with the city's requirements, permitting, and approval process (http://www.sanjoseca.gov/archives/164/GuidelinesForIndustrialWastewaterReuse.pdf; http://www.sanjoseca.gov/ArchiveCenter/ViewFile/Item/1442).

A study attempting to better understand the wide variations observed in water recirculation practices among Canadian facilities (a low of 0.42 to a high of 4.51 for primary metal, fabricated metal, transportation equipment, and chemical subsectors for the reporting period of 1986–1996) using an econometric model based on a cross-sectional survey of facilities determined that the driver to recirculate is influenced by long-run factors, such as the chosen technology of product and plant location, whereas the size of the plant and the marginal costs of water intake, recirculation, and discharge influence the optimal volume of water recirculation once the decision to recirculate has been made (Bruneau et al., 2010). A model of water demands in the Taiwanese integrated circuit industry (Chao-Hsein et al., 2006) demonstrated from simulation results that plants' optimal water recirculation rates depend on the price of water intake and the form of technologies needed for water recirculation versus water discharge regulations.

Typical Contaminants

Contaminants in wastewater from manufacturing industries are highly variable and often contain additional constituents that are not readily treatable by more conventional processes utilized for domestic wastewaters. Often, in order to move from permitted wastewater discharge to industrial water reuse, additional treatment has to be added to the existing primary and secondary treatment used to remove free oils and solids and biodegradable organics and nutrients, respectively (Torres et al., 2008; U.S. DOE, 2013). The nature of these additional contaminants is highly dependent upon the type of manufacturing industry; a compiled overview is provided in Table G.4.

Contaminants can also vary widely within a particular industry depending upon the particular product being produced. An example is the pulp and paper industry, where the type of process, starting materials, process technology applied, management practices, internal recirculation of the effluent for recovery, and the amount of water used in a particular process have a large impact on the characteristics of the generated wastewater (Pokhrel and Viraraghavan, 2004).

Table G.4. Contaminants and Treatment Requirements of Industrial Wastewaters in the Manufacturing Sector

Industry Wastewater	**Major Contaminants**	**Typical Treatment**
Automotive and metal treatment	COD, O&G, surfactants, borates, silicates, alkalis, phosphates, complexing agents, metals, suspended solids	physicochemical, clarification, multimedia filtration, pH adjustment, metal recovery processes such as ion exchange and electrolysis
Chemical	degradable and refractory TOC, AOX, nitrogen species, phosphate, copper, chromium, bromide, chloride, sulfate	The complex and unique nature of these industries creates wastewaters with considerable variation in quality, leading to a unique chain of treatment solutions tailored to a specific situation, typically including biological treatment, which may be preceded by defatting, neutralization, and clarification/sedimentation processes and adsorption of toxic compounds by polysaccharide-based materials.
Petroleum refining	O&G, BOD, COD, NH_3, turbidity, sulfides, TSS, phenols, chloride, mercaptans, cyanide, 1,4-dioxane	physiochemical, mechanical methods, biological treatment with advanced techniques to remove non-biodegradable, high concentrations of organic substances
Pharmaceutical	O&G, pH, TSS, BOD, and COD from high strength, organic effluent, residual pharmaceuticals, and inorganic mineral content (i.e., TKN, ammonia)	membrane separation techniques such as extractive membrane bioreactor or UF/RO
Pulp and paper	TSS, AOX, high COD, low BOD_5/COD ratio, colored compounds, dissolved salts, toxic pollutants, chlorine dioxide, chlorine, sulfides, metals	flotation, clarification, biological processes, membrane treatment, adsorption, oxidation

Semiconductors	recalcitrant organics, degradable organics such as isopropanol, acetone, ethylene glycol, and recalcitrant nitrogen compounds such as tetramethylammonium hydroxide, degradable nitrogen compounds, turbidity, conductivity, trace metals	RO membranes with appropriate pretreatment (i.e., coagulation, sedimentation, biological degradation, and filtration). Post-treatment may be needed (e.g., ion exchange for boron) as well as additional treatment (i.e., ozone, advanced oxidation process) to handle process interferents.
Dyes and textiles	BOD, COD, TSS, color, pH, toxicity, dye molecules, copper, zinc, lead, chromium, cobalt, PAHs, salts	adsorption, ion exchange, membrane filtration, biological processes, coagulation and flocculation, chemical oxidation

Notes: AOX=assimilable organic halogen; BOD=biochemical oxygen demand; COD=chemical oxygen demand; O&G=oil and grease; PAH polyaromatic hydrocarbons=; RO=reverse osmosis; TSS=total suspended solids; UF=ultrafiltration.

Sources: Automotive: Enderle et al., 2012; http://www.ovivowater.com/content/files/data/Ovivo_Industry_MetalTreatment_023471ac3f3246838fe9a89160d57c95.pdf).

Chemical manufacturing: http://www.waterworld.com/articles/iww/print/volume-12/issue-05/feature-editorial/water-treatment-chemical-and-pharmaceutical-industries.html.

Petroleum refining: Torres et al., 2008; El-Naas et al., 2014; Ranade and Bhandari, 2014.

Pharmaceutical: http://www.waterworld.com/articles/iww/print/volume-12/issue-05/feature-editorial/water-treatment-chemical-and-pharmaceutical-industries.htm; Gadipelly et al., 2014.

Pulp and paper manufacturing: O'Connor et al., 2014; Kamali and Khodaparast, 2015; Pokhrel and Viraraghavan, 2004; Ranade and Bhandari, 2014; Galil and Levinsky, 2007, Pizzichini and Meo, 2005

Semiconductor manufacturing: Watson, M., personal communication, MWH Confidential client, 2013- 2014; McCandless, 2012.

Textile manufacturing: Pang and Abdullah, 2013; Ranade and Bhandari, 2014.

Assessment of the contribution to pollution of wastewater flows, COD, ammonium nitrogen, heavy metals, and petroleum hydrocarbons from industrial sources in China determined that this industry contributes at least 50% of the pollution in each category, with several industries responsible for the pollutant discharges within a particular pollutant category, as shown in Table G.5 (Hu and Cheng, 2013).

Table G.5. The Top Pollutant Discharges and Their Industrial Sources in China in 2011

Flow	**Flow**	**COD**	**Ammonium – N**	**Heavy Metals**	**Petroleum**
Chemical material and processing	x	x	x		x
Coal mining and washing					x
Ferrous metal manufacturing					x
Food/agriculture		x	x		
Leather, fur, feather product manufacturing				x	
Metal product manufacturing				x	
Nonferrous metal manufacturing				x	
Nonferrous metal ore mining				x	
Petroleum, coke, nuclear fuel processing					x
Power	x				
Paper	x	x	x		
Textile	x	x	x		

Source: Hu and Cheng, 2013.

Current Technologies for Treatment of Wastewater

Within a single facility, water reduction is generally implemented ahead of water reuse or recycling in order to conserve the resource without the need for additional treatment (Barrington et al., 2013). Within an industrial symbiosis setting (i.e., shared resource industrial park), often there is tension reconciling trade-offs between water efficiency options and water recycling options because use of less water at one facility will lead to an increasing concentration in wastewater discharges, usually resulting in greater treatment costs for the collective group of industries (Giurco et al., 2010).

An integrated water management strategy is needed for manufacturing facilities seeking to implement reuse or conservation practices. An initial water audit, resulting in a water flow diagram, and subsequent holistic process integration approaches are typically needed to select new process technologies or retrofit the existing process plants (e.g., water pinch analysis).

The water flow diagram differentiates mass transfer based (MTB) and non-mass transfer based (NMTB) processes, where MTB processes utilize water as a mass separating agent (e.g., product cleaning), and NMTB processes utilize water as a cooling or heating medium (e.g., cooling towers, boilers; Manan and Alwi, 2007). Commercially available software packages have been developed to analyze water networks as steady-state processes and work within the boundaries of sources and sinks. For example, the United Kingdom firm KBC Advanced Technologies has developed WaterTarget, a suite of software tools consisting of WaterTracker for generating reconciled water and contaminant balances and WaterPinch for the design of optimized water networks and wastewater treatment strategies (http://www.kbcat.com/energy-utilities-software/water-target).

Critical to the success of the water flow diagram is the inclusion of water quality characteristics for each represented flow. Applications for water pinch analysis as a tool to identify water reuse/recycling opportunities in industrial applications are numerous (Ataei et al., 2009; Mohammadnejad et al., 2010), but these studies are restricted to a small number of pollutants, which is often not representative of a real-world situation. Some published works have tried to simplify multicontaminant water networks through development of a “key component” strategy, an approach for solving a multi contaminant waste allocation problem with only one objective of either freshwater consumption or a cost-objective function. But because the key contaminant may change as a function of the freshwater flow rate used in the network, the strategy is valid only for finding the minimum freshwater target and not for designing an optimal water network fulfilling several objectives (Boix et al., 2011). Furthermore, the solutions obtained from these modeling efforts are often not implementable because of the limitations of existing physical infrastructure (e.g., piping limitations, physical barriers between processes; personal communication, Tim Findley, Dow Corporation, 2014).

Water pinch application is therefore most appropriate to construction of a new facility. In this case, purity profiles need to be developed for each contaminant, leading to development of a unique ideal design for each pollutant that meets the specific flow-range target. These multiple design requirements then have to be merged into a common piping network that performs well for all the components. This is achieved by utilizing mathematical programming formulations to optimize trade-offs and provide a single piping network design that minimizes system cost via water reuse, subject to quality and quantity constraints (Natural Resources Canada, 2003).

Following water audits and pinch analysis approaches, final consideration of potential advanced water treatment technologies should be made (Agana et al., 2013). In terms of water reuse and recycle treatment technologies, membranes are widely and successfully employed to achieve the reuse strategies of a wide range of industries for the removal of molecules, colloids, suspended particles, and salts. Removal of these contaminants will make the water suitable for a variety of reuse applications, such as cooling tower makeup, boiler feed, or process streams (U.S. DOE, 2013) in many industrial fields (Richard, 2004; U.S. DOE, 2012) such as pulp and paper manufacturing effluent (Sheldon et al., 2012; Kamali and Khodaparast, 2015), industrial park wastewater treatment plant effluent (Juang et al., 2007), textiles (Pang and Abdullah, 2013; Vajnhandl et al., 2014; Lu et al., 2009), refinery wastewater (Torres et al., 2008; Jin et al., 2013), pharmaceuticals (Lopez-Fernandez et al., 2012; Cleary, 2006; Sallach et al., 1997).

Membrane technologies, including membrane bioreactors (MBR), microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), can provide consistent high quality water for reuse in an industrial setting provided that the wastewater contaminants that are incompatible with membranes are effectively removed using pretreatment processes or appropriate equalization and waste segregation strategies are implemented ahead of the membrane technologies (McCandless, 2012). Pretreatment must also remove particles larger than 500 microns and maintain a pH within the operating range of the membrane selected (typically 4–10) for MF and UF, screen materials down to 1 to 3 mm, and limit fats, oils and grease (FOG) to less than 100 mg/l. avoid presence of fouling agents such as oxidizing agents, solvents, or other chemicals and completely remove suspended solids as demonstrated by a silt density index less than or equal to 3 for NF and RO systems (McCandless, 2012). A 2012 annual review of membrane processes (Pellegrin et al., 2013) revealed that textiles was the dominant sector testing membrane applications for treatment to meet discharge standards or produce reuse-quality water (Ellouze et al., 2012).

Biological processes are frequently combined with UF, NF, and RO in industries with refractory and inhibitory contaminants in their wastewater that cannot be addressed just by using anaerobic, anoxic, and oxic processes (A_2O) either by employing an MBR or through a sequential process with membranes. This approach was evaluated by a coking facility in China, where regulations issued in 2008 required newly built coking plants to achieve zero discharge (Jin et al., 2013). The high sensitivity of the bioprocess and impediment of solids separation from certain industrial chemicals (e.g., phenolics and other aromatic compounds) have also resulted in numerous studies of MBR applications to industrial wastewater utilizing conventional activated sludge treatment (Galil and Levinsky, 2007; Hoinkis et al., 2012). MBR applications to high strength industrial wastewater have also been reviewed, and a tailored operations approach is needed to achieve optimal treatment (Mutamin et al., 2012).

Comparison of membrane filtration systems ahead of RO for pulp and paper wastewater demonstrated superior performance of a tubular ceramic membrane over spiral-wound polymeric MF and UF membranes based on higher productivities and lower fouling resulting from higher Reynolds numbers and cross-flow velocity (Pizzichini et al., 2005). Use of Fenton oxidation ahead of an MBR was tested on textile dyeing effluent and achieved compliance with China's reuse criteria for urban recycling water quality for miscellaneous water consumption (i.e., GBT 18920-2002; Feng et al., 2010). A full-scale RO as pretreatment to an activated sludge process at a Swedish industrial park was a successful application for the removal of major contaminants (e.g., polyalcohols, formic acid, methanol, and formaldehyde) and alleviated severe fouling problems during the first year of operation. In the same process, part of the permeate is used as makeup water in the cooling towers of one of the plants (Into et al., 2004).

A compilation of major technologies applicable to water reclamation for industrial water facilities (Byers et al., 2003) is shown in Table G.6. Ultimately, the lack of uniformity among facilities of a particular industrial sector and the singularity of contaminated stream water quality require bench or pilot testing of the site-specific technology process train alternatives in order to verify acceptable and cost-effective performance.

Table G.6. Wastewater Technologies by Application

Technology	Contaminant Applicability
Bio-oxidation and biotreatment	NO^-, PO, CN^-, HS, BOD, COD, VOCs, SVOCs, biosolids
Carbon treatment (sorption or adsorption)	some heavy metals, aromatics, chlorinated organics, high molecular weight hydrocarbons, VOCs, COD, hydrophobics
Centrifuge (non-gravity separation)	noncolloidal solids, unless polymer used
Chemical oxidation (ozone, wet air, peroxide supercritical, other)	NH_3, CN^-, sulfides, mercaptans, phenols, hydrocarbons, BOD, COD, TOC, pathogens, bacteria, viruses
Crystallization	TDS, inorganic salts, organics except VOCs
Electrodialysis	ionic species, metals, TDS
Evaporation (mechanical, ponds, distillation)	salts and heavy metals, organics except VOCs, TDS
Filtration (granular bed, vacuum drum, press, belt filter, other)	insoluble precipitates, COD, BOD, bacteria, algae
Flotation	heavy metals, oil and grease, BOD, COD
Gravity separation or settling (coagulation, flocculation, or clarification)	heavy metals, grit, silt
Ion exchange	most anions and cations, TOC, COD, metals
Membrane separation (reverse osmosis, ultrafiltration)	heavy metals, anions, oils, medium to high molecular weight organics, TDS, conductivity, colloidal TSS, most bacteria and viruses
Precipitation	heavy metals, CN, F, PO_4^{3-}, COD, alkalinity, hardness
Solidification or stabilization	most heavy metals, organics, except VOCs
Solvent extraction	actinide chemicals, metals, organics except VOCs or azeotropes
Stripping (steam, air, other)	H_2S, NH_3, CO_2, HCN, VOCs, light hydrocarbons, TOC
Thermal treatment (drying, incineration, spray drying, other)	toxic organics, recalcitrant organics

Notes: BOD=biochemical oxygen demand; COD=chemical oxygen demand; SVOC=semivolatile organic compounds; TDS=total dissolved solids; TOC=total organic carbon; TSS=total suspended solids; VOC=volatile organic compounds.

Sources: Byers et al., 2003; Ranade and Bhandari, 2014.

Typical Reuse Applications

The potential for water recycling and reuse in the manufacturing sector is largely dependent upon the contaminants present in the process wastewater and the ability of available technology to treat this water to acceptable quality for reuse within other areas of the facility (e.g., cooling towers, boilers, ultrapure water systems, cleaning, process) at an acceptable return on investment and operational cost. Successful reuse of water within industrial applications is dependent upon a comprehensive understanding of process design, water chemistry, membrane systems, chemical treatment, instrumentation, and control (Christophersen, 2008). One of the most common reuse applications is treatment of process water for subsequent use in cooling towers and boilers, with less evidence of direct process recycling applications, as this typically requires the greatest amount of treatment in order to alleviate product manufacturing risks.

Despite being a high water consumer, the textile industry has shown less implementation of water reuse because of the complex and highly variable characteristics of the wastewater, coupled with smaller overseas enterprises that lack the resources for acquiring closed water loops (Vajnhandl and Valh, 2014). Concerns for the environmental pollution caused by the high water use of this industry, in the range of 100 to 250 times the weight of fabric processed (Sala and Gutiérrez-Bouzán, 2014; Vajnhandl and Valh, 2014), coupled with the toxic and difficult treatment of organic residues (Abid et al., 2012), are driving laboratory- and pilot-scale studies on dye decolorization that will permit water reuse (Vajnhandl and Valh, 2014; Sala and Gutiérrez-Bouzán, 2014; Jadhav and Singhal, 2013; Masmoudi et al., 2014; He et al., 2013). With appropriate pretreatment, NF and RO membranes have been successfully used for process recycling (Ranganathan et al., 2007).

Within the apparel industry, Levi Strauss and Co. developed a standard in 2013 for water recycling and reuse that it has applied to its finishing facilities that are in compliance with the global effluent requirement to recycle or reuse effluent water as full or partial replacement for freshwater. At an individual facility, there are opportunities for on- and off-site recycling in laundry, landscape irrigation, facility cooling tower makeup water, and on-site sanitary toilet flushing (Levi Strauss & Co.Water Recycle/Reuse Standard, ND

Petroleum refineries can be large consumers of water relative to other industries (IPIECA, 2010). Refiners have unique characteristics because of the type of crude refined and the products desired. Reuse at petroleum refineries is sometimes driven by water source sustainability issues (Pugh et al., 2010). Water is used in many processes, and the water that has not been in direct contact with hydrocarbons or only has minimal contamination can be a source for reuse (IPIECA, 2010). Table G.7 matches application areas that can receive reuse water with their potential water sources.

Table G.7. Applications and Sources of Reuse Water within a Refinery

Applications	Sources
Desalter makeup process water	• stripped sour water • vacuum tower overhead • crude tower overhead
Coker quench process water	• stripped sour water
Coke cutting process water	• stripped sour water
Boiler feed water makeup	• treated and upgraded refinery
Cooling tower makeup	• treated and upgraded refinery wastewater

Source: IPIECA, 2010.

Concerns over water source sustainability at a midwestern petroleum refinery resulted in a commissioned design study for a water reclamation system that could utilize effluent from an existing refinery wastewater treatment system and low quality, on-site well water to provide boiler feed water. Treatment of higher quality, on-site refinery well water was performed to provide cooling tower makeup water. Two different treatment trains were needed to achieve water quality objectives for each application, but the treatment trains would have some common processes (Pugh et al., 2010). Another crude oil refinery in Brazil needing to move from permitted wastewater discharge to industrial reuse explored the implementation of advanced treatment beyond the existing primary/secondary wastewater treatment (gravimetric oil/water separator, flocculation/aerated lagoon, rotating biological contactor, and lagoon for solids deposition) to achieve the water quality needed for the cooling tower system or steam generation. The MBR solution was selected and pilot tested to treat the primary effluent and control O&G to levels less than 20 mg/L (Torres et al., 2008).

The semiconductor industry must continually manufacture denser microprocessors and smaller microchip devices, requiring large quantities of ultrapure water, which promotes wastewater recycling efforts to produce feed water for the high purity water production process (Equova, n.d.). The need for almost distilled quality for washing circuit boards and other electronic compounds indicates that the reuse of electronic wastewater is complicated (Lee et al., 2008). Inorganic wastewater generated from chemical, mechanical planarization, and lithography processes still contains volatile low molecular weight compounds after treatment that preclude its use for ultrapure water production. Organic wastewater generated from etching, stripping, and cleaning processes can be treated with biological processes and RO, but residual acetone, isopropyl alcohol, acetaldehyde, methanol, acetonitrile, and other small organic molecules must still be removed with promising advanced oxidation (Choi and Chung, 2014).

Biological treatment can be complicated by the presence of other constituents such as tetramethyl ammonium hydroxide (TMAH), utilized in etching the surface of the silicone chip (Lee et al., 2008), and triazole corrosion inhibitors (Watson, M., personal communication, MWH, 2014). The complex compositions of semiconductor wastewater streams may also lead to RO membrane fouling. A pilot study of MBR–RO technology for treatment of three semiconductor wastewater streams showed the process to be feasible if appropriate cleaning and antiscaling strategies are utilized (Xiao et al., 2014), but the type of water reclamation and reuse was not specified.

The pharmaceutical industry produces highly variable dilute wastewater streams that are mainly treated by biological processes as well as oxidation processes, membrane techniques, and advanced oxidation processes. A review of the efficacy of the various treatment technologies is presented by Gadipelly et al. (2014), with a recommendation for more emphasis on recovery and reuse of pharmaceutical wastewater. Direct reuse in the pharmaceutical industry remains fairly restricted because of contamination risks to the consumer; however, recycling from nonmanufacturing point sources for reuse in irrigation or boiler system cooling water is commonplace in many pharmaceutical manufacturing facilities (http://www.waterworld.com/articles/iww/print/volume-12/issue-05/feature-editorial/water-treatment-chemical-and-pharmaceutical-industries.html).

Examples of additional water recycle/reuse applications at bench-, pilot-, and full-scale applications in the manufacturing industry are presented in Table G.8.

Table G.8. Examples of Water Recycling and Reuse at Bench-, Pilot-, and Full-Scale Applications in the Manufacturing Industry

Sector	Industry	Issue/Solution	Cost Saving	Source
Semiconductor	Intel (Chandler, AZ)	Pilot-scale comparisons of coagulation/settling processes and fiber ball filtration system pretreatment ahead of UF and RO treatment of manufacturing facility wastewater in order to demonstrate product water quality suitable for reintroduction to the high purity water treatment system.	not reported	McCandless, 2012
Semiconductor	Industrial Park (southern Taiwan)	Pilot-scale study of a three-stage system consisting of fiber ball filtration followed by UF/RO dual-phase units for treatment of wastewater from an industrial park mainly composed of semiconductor factories.	not reported	Huang et al., 2011
Semiconductor	Representative Semiconductor Facility (Taiwan)	Operation of a pilot-scale process-to-process recycling system for direct reclamation of high purity water from backgrinding and sawing process wastewater.	Cost of this low-grade, high purity water for the IC assembly process is only U.S.$0.85/m^3 as compared with semiconductor-grade HPW cost of U.S.$2.38–5.28/m^3, which reduces the ROI period.	Wu et al., 2004
Petrochemical	Reliance Petroleum Limited (Jamnagar, India)	Wastewater is treated in three separate trains, one of which has high TDS. The treated low TDS stream is reused as makeup in the freshwater cooling tower, as fire water makeup, and for local green belt development and irrigation. The treated high TDS stream is reused as partial makeup in the seawater cooling tower. Treatment consists of API separator and dissolved air flotation for oil removal, biological treatment, dual-media filtration, and polishing with granular activated carbon.	Investment costs for the reclamation plant were approximately €12.5 million, with operating costs of €0.32/m^3 being more economic than seawater desalination.	Lahnsteiner and Klegraf, 2005

Sector	Industry	Issue/Solution	Cost Saving	Source
Petroleum refining	Pemex Refinery One (Mexico)	Process and cooling tower makeup water are supplied from treatment of refinery wastewater. Boiler feed water is supplied by treating local municipal wastewater. Refinery wastewater treatment consists of oil removal, activated sludge, chlorination, granular media filtration, and activated carbon. In addition, blowdown waste from the cooling towers and boilers is used for the boiler feed water following warm lime softening, recarbonation, chlorination, granular media filtration, activated carbon, and RO. ZLD is achieved using evaporator/ crystallizer on RO concentrate.	not reported.	Pugh et al., 2010
Petroleum Refining	Pemex Refinery Two (Mexico)	Cooling tower makeup and boiler feed water are supplied from treatment of refinery wastewater. Treatment consists of dissolved air flotation, activated sludge, cold lime softening, recarbonation, chlorination, granular media filtration, activated carbon, and RO.	not reported	Pugh et al., 2010
Petroleum refining	Pemex Refinery Three (Mexico)	Cooling tower makeup water is supplied from treatment of refinery wastewater. Treatment consists of dissolved air flotation, activated sludge, cold lime softening, recarbonation, chlorination, and granular media filtration. Cooling tower blowdown is also treated through the wastewater reclamation system.	not reported	Pugh et al., 2010
Petroleum refining	Pemex Refinery Four (Mexico)	Boiler feed water is supplied from treatment of process wastewater. Treatment consists of dissolved air flotation, activated sludge, chlorination, UF, and RO. UF reject water is reprocessed through the activated sludge system. Following chlorination, a portion of the treated process wastewater undergoes granular media filtration and is used to supply cooling tower makeup water.	Ten years of full-scale performance have proven that the UF membrane system is reliable and superior to granular media filtration.	Pugh et al., 2010
Chemical	DuPont (Hamm-Uentrop, Germany)	Biologically pretreated chemical wastewater (including nitrogen and phosphorus removal) is reclaimed and used primarily as process water for production and boiler feed water. The reclamation plant consists of tertiary filtration with UF (NORIT), activated carbon adsorption, UV disinfection, RO, and ion exchange in mixed-bed filters.	Economic feasibility derives from reduction in wastewater discharge by 90%.	Lahnsteiner and Klegraf, 2005 http://www.wabag.com/wp-content/uploads/2012/04/Industrial- Water-Reuse.pdf

Sector	Industry	Issue/Solution	Cost Saving	Source
Chemical	Sasol coal to liquids facility (Secunda, South Africa)	Pilot study and subsequent full-scale installation of MBBR as pretreatment to powdered activated carbon activated sludge system to produce cooling water makeup for plant use. The wastewater is treated for removal of oils with API separation and dissolved air flotation ahead of the MBBR. The powdered activated carbon sludge effluent is further treated by clarification, sand filtration, and ozone or hydrogen peroxide chemical oxidation.	not reported	Ratcliffe et al., 2006
Paper	Palm-Eltmann (Germany)	Effluent from the biological treatment plant was further purified using dual-media filtration and NF (initial spiral-wound membranes from Koch were subsequently replaced by Microdyn-Nadir membranes) in order to reuse the effluent as process water. The NF recovery rate was 90%, and permeate is reused at sensitive points of the paper machine.	not reported	Lahnsteiner and Klegraf, 2005 http://www.wabag.com/wp-content/uploads/2012/04/Industrial-Water- Reuse.pdf
Textile	Dres Meerane (Germany)	Wastewater from textile pretreatment (dye house, printing, stretching, and laundry) is treated by anaerobic digestion for biological decolorization, highly loaded activated sludge treatment, MBR with ZENON membrane modules, and oxidation with ozone and recycled back to the textile pretreatment process.	highly economic because of reduction in sewage charges	Lahnsteiner and Klegraf, 2005 http://www.wabag.com/wp-content/uploads/2012/04/Industrial-Water- Reuse.pdf
Automotive	Chrysler (Toluca, Mexico)	Siemens installed water recovery system consisting of several multimedia filers, two-stage RO system, MF system, and crystallizer.	Facility has saved an estimated $359,000 per year in water costs.	http://sustainablemfr.com/water/water-reuse-recycling-conservation-manufacturing

Sector	Industry	Issue/Solution	Cost Saving	Source
Tannery	Kolkata, India	A composite tannery wastewater was treated at bench-scale using crossflow tubular ceramic MF, and permeate was treated further using spiral-wound. thin film composite polyamide membrane RO.	The proposed process reduces the cost of treatment compared to that of conventional processes. The process may be upscaled further for implementation in industries.	Bhattacharya et al., 2013
Pharmaceutical	Puerto Rico	Largest water usage at 65% was in cooling towers, with another 25% in process. The recommended alternative to reduce reliance on water supply consisted of using air-handling condensate with groundwater or stormwater and RO reject water. Reduction in the volume of influent to the wastewater treatment system because of water recycling and other water conservation efforts was found to have no impact on the mass of pharmaceutically active ingredients with discharge limits.	Capital cost estimated to be approximately U.S.$ 1,560,000, which included cost to provide 14-day contingency storage of 0.35 million gallons in case of surface supply disruptions. Annual O&M cost estimated to be about $115,000.	Cleary, 2006.
Textile	Changzhou, China	Pilot trials were conducted within an EC-funded project INNOWA to investigate a pilot MBR system as replacement to the conventional biochemical system.	Not reported. Suggested that novel membrane materials for MBR reactors need to be developed through R&D activities and under consideration through EC-funded project BioNexGen coordinated by Karlsruhe University of Applied Sciences.	Hoinkis et al., 2012

Notes: API= American Petroleum Institute; EC= European Commission; IC= integrated circuit; HPW= high purity water; MBBR= moving-bed biofilm reactor; MBR=membrane bioreactor; MF=microfiltration; NF=nanofiltration; O&M=operations and maintenance; R&D=research and development; RO=reverse osmosis; ROI=return on investment; TDS=total dissolved solids; UF=ultrafiltration; UV=ultraviolet; ZLD=zero liquid discharge.

Case Studies

Case Study 1: MBR-based treatment of tractor manufacturing wastewater (Colic et al., 2013)

Clean Water Technology Inc. and Kubota Corporation agreed to design, pilot test, and build a system capable of reusing as much as 75% of the wastewater produced from a new tractor manufacturing plant built in Jefferson, GA. The wastewater contains complex heavy metals, fine suspended solids, emulsified oils, grease, strong degreasing agents, nitrogen and phosphorus, and small dissolved organic molecules and inorganic ions. After completing treatability studies, installation of a full-scale system consisting of effluent collection tanks, screens, flocculation–flotation system, MBR, and RO was completed.

Initial testing determined that separate treatment strategies were needed for the streams containing degreaser. The very high COD to BOD ratios for the degreaser stream led to the decision to mix graywater from the plant with manufacturing water in a 50:50 ratio. To ensure performance of the RO system, two-stage granular active carbon filtration was designed prior to the membranes to remove additional COD compounds. For the full-scale installation, all concentrated streams from metal plating and cutting, painting, and degreasing will be diluted with graywater at a ratio of 10:1 before going into the MBR. Anticipated spikes of heavy degreaser solutions will be diluted into the stream or pretreated with primary treatment for heavy metal, FOG, and TSS removal and then discharged to the local POTW.

The full-scale system for wastewater from painting and metal finishing processes is mixed and pumped to an equalization tank and then pretreated in a series of reaction tanks. The first tank adjusts the pH to 10 for nickel removal with the addition of FLOMIN polymeric dixanthate precipitant. Aluminum sulfate is added to the second tank for phosphate removal, and the pH is reduced to 8. The third tank provides additional time for the precipitation. The water is then pumped to the flocculation–flotation GEM system (i.e., hybrid centrifugal hydrocyclone-dissolved air flotation for gas–energy mixing), where high molecular weight cationic and anionic flocculants are added, and solids are floated and removed. The GEM system (developed at Clean Water Technologies) provides efficient continuous flow mixing and in-line flocculation with the nucleation and entrainment of fine, dissolved air bubbles, which provides efficient removal of particulate contaminants, a small footprint, drier sludge, durable long lasting flocs, fast response and treatment of the total wastewater stream.

This GEM-treated wastewater and rotary drum-screened domestic wastewater are collected in an equalization tank, pumped to an anoxic tank for nitrogen removal, gravity-flowed to the pre-aeration activated sludge tank, and then treated in the Kubota flat sheet membrane tank. The MBR effluent can then either be discharged to the city or fed to an RO/UV system to enable water recycling back to the tractor manufacturing process.

Case Study 2: Recycling of wastewaters of textile dyeing industries (Ranganathan et al., 2007)

Textile dyeing industries located in Tirupur and Karur in Tamil Nadu, India, are being forced to adopt technology leading toward zero discharge systems because of the negative environmental impacts of the discharged effluents. Four dyeing facilities that have adopted advanced treatment to enable water reuse were profiled. The treatment processes used to recycle textile dyeing wash water and dye bath wastewater back to the textile dyeing process for the facilities are summarized in Table G.9.

Table G.9. Recycling Treatment Technologies at Four Textile Dyeing Industries in India

	M/s. Sivasakthi Textile Processors	**M/s. Renaissance Creations Processing Division**	**M/s. Leeds Spinning Mills Ltd.**	**M/s. Karur Amaravathi Textiles Industry**
Textile dyeing process wash water	Primary treatment with lime and ferrous sulfate addition, pressure sand filtration, iron removal filtration, ion exchange, and double-stage RO.	Primary treatment with lime and ferrous sulfate addition, biological oxidation through trickling filters, chlorination, activated carbon bed and pressure sand filtration, and double-stage RO. The combined permeate is recycled back to the textile dyeing process.	Primary treatment with lime and ferrous sulfate addition, sand filtration, iron removing cartridges, and double-stage RO.	Settling, 4 modules of disc-type RO membrane.
Dye bath wastewater	Prefiltration and nanofiltration.	Primary treatment with lime and ferrous sulfate and effluent mixed with RO reject and sent to evaporation system.	Gravitation settling and nanofiltration	Settling, 4 modules of disc-type RO membrane.

Note: RO = reverse osmosis.

It is important to remove suspended and colloidal impurities of organic and inorganic compounds and dissolved polyvalent ions to extend the life of the membrane. The industry using the disc-type membrane module saw better removal of TDS and ions but shorter membrane life through the absence of preliminary treatment. The water regenerated using the advanced technology is of good quality and directly useable in the dyeing process. Multiple effects evaporation (MEE) and solar evaporation treat the membrane concentrates at M/s. Sivasakthi Textile Processors and M/s. Leeds Spinning Mills Ltd. in order to achieve zero discharge.

Schematics of the advanced wastewater treatment technology for recycling of textile dyeing wastewaters and a flow diagram of conceptual zero discharge using this advanced wastewater treatment are provided in the reference. The technology is economically viable because the total expenses for the water treatment and recovery of about INR 80/m^3 is lower than the cost of the water (including transportation), which is approximately INR 100/m^3. The MEE is not economical, and use of a common facility is recommended.

Case Study 3: Water reuse in the power and steel production sector

The Essar steel and power plants are located adjacent to each other in Gujarat, India. The power plant uses 3.9 million m^3/yr of freshwater to generate 515 MW of power; the steel facility is the fourth largest steel factory in the world. To reduce the combined water footprint of both sites, blowdown water from the power facility that was previously discharged into the sea is utilized by the steel plant, and the wastewater from the steel plant is being treated for reuse in the power plant. This has resulted in a freshwater demand reduction of 835,000 m^3/yr at the power plant and a reduction of 644,000 m^3/yr at the steel factory.

Higher cycles of concentration in the power plant cooling tower were achieved by retrofitting Cu-Ni tubes in place of stainless tubes in the condenser. Implementation cost was $147,513, with resultant annual freshwater savings of 381 m^3/yr and a 1.1 year payback period. Alkaline blowdown water from the power plant was then used as makeup water in the steel plant furnace cleaning system. The water is also used at the steel facility for firefighting systems and dust control. This required an investment of $92,336, with resultant water savings of 644,000 m^3/yr and a 4.8 month payback period. Reuse of backwash wastewater recovered from the steel facility pressure sand filters and softeners are also now substituted for 2 to 3% of the power plant’s total raw water intake. The associated investment was $63,156, resulting in freshwater savings of 349,000 m^3/yr at a payback period of 4.58 months.

Although not an example of direct on-site industrial reuse, this case study demonstrates the water reuse potential that can be achieved when adjacent or co-located (i.e., industrial park) facilities are able to collaborate on water reuse opportunities.

Case Study 4: Reclamation of refinery/petrochemical effluents for boiler makeup water (Lahnsteiner et al., 2007)

The Indian Oil Corporation Ltd. Panipat contracted WABAG India to build a wastewater recycling plant that was commissioned at the end of 2006. The project driver was the need for zero discharge because of a lack of a receiving water body and the fact that freshwater from the municipal network is restricted for use as potable water or agricultural irrigation.

The refinery generates seven waste streams arising from two wastewater treatment plants, blowdown from three cooling towers, and two demineralization regenerates. The blended wastewater stream quality characteristics are 150 mg/l COD, less than 10 mg/l BOD_5, 10 mg/l oil, 2000 mg/l TDS, and 100 mg/l silica.

The reclamation plant, which has a 900 m^3/h design capacity, consists of clarification (including silica adsorption on magnesium hydroxide), pressure sand filtration, UF, and RO. The RO permeate is polished using mixed-bed ion exchange filters and then recycled mainly as boiler makeup water in the refinery plants and additionally as process water for the production of purified terephtalic acid (PTA), which is used in the textile industry. The manufacture of PTA requires high quality water with zero colloidal silica, low TOC, and practically absolute softened water.

The UF is a pressure-driven, inside-out, hollow-fiber system with six working skids (and one standby), with 18 horizontally mounted pressure vessels per skid operated in dead end mode. Regular backwashing with chemically enhanced permeate is needed to control fouling. Cleaning in place is also used when a preset transmembrane pressure is exceeded. The UF performed well for the 5 to 6 month period being reported. The design flux of 46 L/m^2/h (maximum capacity) has been maintained with a cleaning demand less than what was defined in the process design. Cleaning occurs every 24 hours using NaOCl blended with NaOH in the chemically enhanced backwash. Cleaning in place was used during start-up and only three additional times in the past 6 months of regular operation in order to maintain stable permeability.

The RO system consists of three stages, as shown in Figure G.1. The UF permeate is fed to the first stage (low fouling composite membranes), and this RO permeate is further desalinated in the second stage (low fouling composite membranes). The first-stage RO reject is fed to the third-stage RO (seawater membranes). The third-stage RO permeate is recycled to the second-stage RO. The overall process has close to 90% recovery. The second-stage RO permeate is degassed and polished in mixed-bed exchangers containing strong acid cation and base anion resins mixed in a single vessel.

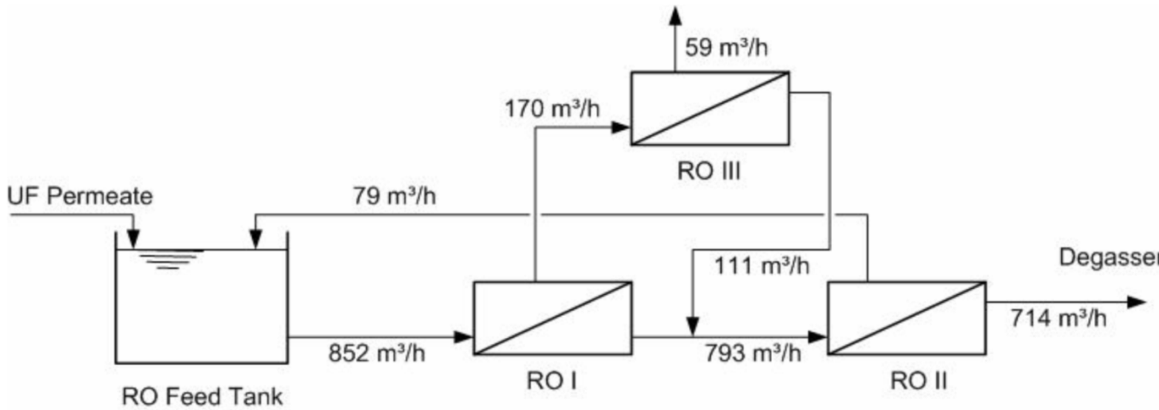

Figure G.1: RO system process diagram for Case Study 4.
Source: Lahnsteiner et al., 2007.

Overall removal of contaminants is excellent. Conductivity is reduced in the RO from 4000 to less than 5 µS/cm and further reduced in the mixed-bed filter to less than 0.05 µS/cm. Silica, reduced from 100 to 10 mg/L by adsorption on magnesium hydroxide in the clarification stage, is further reduced to less than 1 mg/L in the first-stage RO, to 0.03 mg/L in the second-stage RO, and to 0.006 mg/L in the mixed-bed exchanger. This is well within the 20 µg/L specified limit for boiler makeup water in power plant guidelines. Colloidal silica is completely removed in the RO stages.

Pending installation of evaporation and crystallization will result in zero discharge. Operating costs are approximately 0.46 EUR/m^3 of reclaimed water, with approximately 24% for energy, 24% for chemical consumption, 16% for labor, and 36% for maintenance and material replacement. Total investment costs were approximately EUR 10 million, which were amortized to EUR 0.18/m^3, assuming 10% interest and a 20 year depreciation period, for a total operating cost of EUR 0.64/m^3.

Conclusions

Water reuse and recycling implementation in the manufacturing sector is driven by the need to comply with more stringent discharge requirements or restrictions in available freshwater supplies. Industries generating wastewaters with more challenging pollutants and treatment requirements originally relocated to Third World regions with less stringent discharge requirements (e.g., textile dyeing, semiconductor chip manufacturing). In recent years global water scarcity has driven tighter discharge regulations across the globe, and a large amount of literature exists on treatment scenarios for these more challenging discharge waters, particularly in locations such as India and China. The most recent studies have begun to focus on treatment solutions that incorporate water reuse and recycling.

Within all manufacturing industries, the simpler water reuse and recycling opportunities tend to be exploited first. These include utilization of off-site water reuse opportunities when municipal wastewater is accessible as an alternative supply, on-site water reuse opportunities afforded through internal water cascade operations, and dilution of wastewater streams with source waters prior to consideration of reuse applications, or use of wastewater streams as cooling tower makeup water. Because many different industries utilize evaporative cooling towers that require large volumes of makeup water with clearly understood water quality requirements, this is often the first type of water reuse application actually put into practice. Utilization of marginal waters in cooling towers can often be accommodated through use of appropriate chemical additives, particularly if the water is being diluted with other freshwater sources. Even when additional treatment is needed, this often results in a better return on investment than other water reuse and recycling options because less energy-intensive advanced water treatment is required.

Major contaminants and typical treatment technologies utilized for wastewaters generated by different industrial wastewaters have been characterized, but often additional proprietary chemicals or the inability to segregate process streams prior to treatment create water reuse and recycling challenges that have created a tremendous need to capture findings of recent case studies describing successful water reuse and recycling installations. Often water reuse and recycling studies do not result in implementation because of unacceptably long returns on investment (in excess of 2 to 3 years), generation of residuals requiring costly evaporation and crystallization processes, or concerns over unacceptable risks to continual process production efforts. Concern about process production risks is why reuse is often first directed toward more ancillary facility processes such as cooling towers and boilers; facility and more direct process applications are only considered when wastewater discharges or source water needs threaten to compromise production requirements. Some other ancillary processes, such as facility sanitation, are often disregarded because their water usage volumes are too small.

Efforts to reuse water for process applications are occurring, mostly in response to regional environmental pressures. Membrane treatment is foundational to most applications, and focus should be on pretreatment requirements that prevent unacceptable membrane fouling and post-treatment to remove additional contaminants that persist in the permeate. Innovative developments that assist in elucidating and controlling membrane fouling, residual management, and cost-effective chemical- specific risk mitigation measures will be beneficial. In order to further drive water reuse and recycling implementation, methodologies for calculating the true value of water are needed in order to alleviate unfavorable ROI calculations based on the existing undervaluation of source water supplies and wastewater discharge environmental impacts.

References

Abid, M. F.; Zablouk, M. A.; Abid-Alameer, A. M. Experimental study of dye removal from industrial wastewater by membrane technologies of reverse osmosis and nanofiltration. *Iran. J. Environ. Health Sci. Eng.* **2012,** *9*, 17.

Agana, B. A.; Reeve, D.; Orbell, J. D. An approach to industrial water conservation—A case study involving two large manufacturing companies based in Australia. *J. Environ. Manage.* **2013,** *114*, 445–460.

Ataei, A.; Gharaie, M.; Parand, R.; Panjeshahi, E. Application of ozone treatment and pinch technology in cooling water systems design for water and energy conservation. *Int. J. Energ. Res.* **2009,** *34*, 494–506.

Barrington, D. J.; Prior, A.; Ho, G. The role of water auditing in achieving water conservation in the process industry. *J. Cleaner Prod.* **2013,** *52*, 356–361.

Bhattacharya, P.; Roy, A.; Sarkar, S.; Ghose, S.; Majumdar, S.; Chakraborty, S.; Mandai, S.; Mukhopadhyay, A.; Bandyopadhyay, S. Combination technology of ceramic microfiltration and reverse osmosis for tannery wastewater recovery. *Water Resour. Ind.* **2013,** *3*, 48–62.

Boix, M.; Montastruc, L.; Pibouleau, L.; Azzaro-Panetl, C.; Domenech, S. A multiobjective optimization framework for multicontaminant industrial water network design. *J. Environ. .Manage.* **2011,** *92*, 1802–1808.

Bruneau, J., Renzetti, S., Villeneuve, M. Manufacturing firms' demand for water recirculation. *Can. J. Agr. Econ.* **2010,** *58*, 515–530 (Manufacturing 253).

Byers, W.; Lindgren, G.; Noling, C.; Peters, D. *Industrial water management: A systems approach*, 2nd ed.; Wiley-AIChE: New York, 2003, pp 3-9 to 3-27.

Chertow, M. Industrial symbiosis: literature and taxonomy. *Annu. Rev. Energ. Env.* **2000,** *25* (1), 313–337.

Choi, J.; Chung, J. Reuse of semiconductor wastewater using reverse osmosis and metal-immobilized catalyst-based advanced oxidation process. *Ind. Eng. Chem. Res.* **2014,** *53*, 11167–11175.

Christophersen, D. Water Reuse Strategies: Steel Industry Case Studies, 2008. http://www.veoliawaterstna.com/crownsolutions/ressources/documents/2/21820,NACE-Steel_Mill_Water_Reuse_2008_r.pdf (accessed June 2015).

Cleary, J. Water conservation and reuse case study in pharmaceutical industry. Proceedings Paper, Water Environment Federation Technical Exhibition and Conference, Dallas, TX, October 21–25, 2006.

Colic, M.; Guthrie, R.; Lechter, A. MBR based treatment of tractor manufacturing wastewater. Proceedings Paper, 86th Annual Water Environment Federation Technical Exhibition and Conference, Chicago, IL, October 5–9, 2013. http://weftec2013.conferencespot.org/55109-wefb- 1.1182180/t-022-1.1185426/224-1.1185539/a-134-1.1185543 (accessed June 2015).

Ellouze, E.; Tahri, N.; Amar, R. B. Enhancement of textile wastewater treatment process using nanofiltration. *Desalination* **2012,** *286,* 16–23.

El-Naas, M.H., Alhaija, M.A., Sulaiman, A.-Z. Evaluation of a three-step process for the treatment of petroleum refinery wastewater. *Jour. Environ. Chem. Eng.* **2014,** 2, 56-62.

Enderle, P.; Nowalk, O.; Kvas, J. Potential alternative for water and energy savings in the automotive industry: case study for an Austrian automotive supplier. *J. Cleaner Prod.* **2012,** *34,* 146–152.

Equova, Critical ultrapure water applications for the semiconductor industry, not dated. http://www.evoqua.com/en/semiconductor-solar/semiconductor/Pages/upw-apps-semiconductor- industry.aspx

Feng, F.; Xu, Z.; Li, X.; You, W.; Zhen, Y. Advanced treatment of dyeing wastewater towards reuse by the combined Fenton oxidation and membrane bioreactor process. *J. Environ. Sci.* **2010,** *22* (11), 1657–1665.

Findley, T. Dow Corporation, personal communication, WateReuse Research Foundation Project 13-04 Workshop, June 18, 2014, MWH, Denver, CO.

Flörke, M.; Kynast, E.; Bärlund, I.; Eisner, S.; Wimmer, F.; Alcamo, J. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Global Environ. Chang.* **2013,** *23,* 144–156.

Gadipelly, C.; Pérez-González, A.; Yadav, G. D.; Ortiz, I.; Ibáñez, R.; Rathod, V. K.; Marathe, K. V. Pharmaceutical industry wastewater: Review of the technologies for water treatment and reuse. *Ind. Eng. Chem. Res.* **2014,** *53,* 11571–11592.

Galil, N. I.; Levinsky, Y. Sustainable reclamation and reuse of industrial wastewater including membrane bioreactor technologies: case studies. *Desalination* **2007,** *202,* 411–417.

Giurco, D.: Bossilkov, A.; Patterson, J.; Kazaglis, A. Developing industrial water reuse synergies in Port Melbourne: cost effectiveness, barriers and opportunities. *J. Cleaner Prod.* **2010,** *19,* 867–876.

He, Y.; Wang, X.; Xu, J.; Yan, J.; Ge, Q.; Gu, X.; Jian, L. Application of integrated ozone biological aerated filters and membrane filtration in water reuse of textile effluents. *Bioresour. Technol.* **2013,** *133,* 150–157.

Hoinkis, J.; Deowan, S. A.; Panten, V.; Figoli, A.; Huang, R. R.; Drioli, E. Membrane bioreactor (MBR) technology—A promising approach for industrial water reuse. *Procedia Eng.* **2012,** *33,* 234–241.

Hu, Y.; Cheng, H. Water pollution during China's industrial transition. *Environ. Dev.* **2013,** *8*, 57–73.

Huang, C. J.; Yang, B. M.; Chen, K. S.; Chang, C. C.; Kao, C. M. Application of membrane technology on semiconductor wastewater reclamation: A pilot–scale study. *Desalination* **2011,** *278*, 203–210.

International Petroleum Industry Environmental Conservation Association (IPIECA). Petroleum refining water/wastewater use and management, 2010. http://www.ipieca.org/publication/petroleum-refining-water-wastewater-use-and-management (accessed June 2015).

Into, M.; Jönsson, A.-S.; Lengdén, G. Reuse of industrial wastewater following treatment with reverse osmosis. *J. Membrane Sci.* **2004.** *242,* 21–15.

Jadhav, S. B.; Singhal, R. S. Polysaccharide conjugated laccase for the dye decolorization and reusability of effluent in textile industry. *Int. Biodeter. Biodegr.* **2013,** *85,* 271–277.

Jiménez, B.; Asano, T., Eds.; *Water Reuse: An International Survey of Current Practice, Issues and Needs.* IWA Publishing: London, 2008.

Jin, X.; Li, E,; Lu, S.; Qiu, Z.; Sui, Q. Coking wastewater treatment for industrial reuse purpose: Combining biological processes with ultrafiltration, nanofiltration and reverse osmosis. *J. Environ. Sci.* **2013,** *25* (8),1565–1574.

Juang, L.-C.; Tseng, D.-H.; Lin, H.-Y. Membrane processes for water reuse from the effluent of industrial park wastewater treatment plant: a study on flux and fouling of membrane. *Desalination* **2007,** *202*, 302–309.

Kamali, M.; Khodaparast, Z. Review on recent developments on pulp and paper mill wastewater treatment. *Ecotox. Environ. Safe.* **2015,** *114* (April), 326–342.

Lahnsteiner, J.; Klegraf, F. Industrial Water Reuse Case Studies. Published in IWA Newsletter of the Specialist Group on Water Reuse. November 2005. http://www.wabag.com/wp-content/uploads/2012/04/Industrial-Water-Reuse.pdf (accessed June 2015).

Lahnsteiner, J.; Klegraf, F.; Mittal, R.; Andrade, P. Reclamation of wastewater for industrial purposes—Advanced treatment of secondary effluents for reuse as boiler and cooling makeup water. Paper presented at the Sixth IWA Specialist Conference on Wastewater Reclamation and Reuse for Sustainability, October 9–12, 2007, Antwerp, Belgium.

Lawler, D. Final Report: Simultaneous water conservation/recycling/reuse and waste reduction in semiconductor manufacturing, ND. EPA Research Grant Number R828598C799. http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.highlight/abstract/5878/report/F

Lee, S.J., Lee, Y.-W., Chung, J., Lee, J.K., Lee, J.Y., Jahng, D., Cha, Y., Yu, Y. Reuse of low concentrated electronic wastewater using selected microbe immobilized cell system. *Wat. Sci. & Tech.*, **2008**, 57, 8, 1191-1197.

Levi Strauss & Co. Water Recycle/Reuse Standard, ND. http//levistrauss.com/wpcontent/uploads/2014/02/LSCo-Water-Recycle-Reuse-Standard.pdf (accessed June 2015).

Lopez-Fernández, M. R.; Villaverde, S. Membrane bioreactor for the treatment of pharmaceutical wastewater containing corticosteroids. *Desalination* **2012,** *300,* 19–323.

Lu, X.; Liu, L.; Yang, B.; Chen, J. Reuse of printing and dyeing wastewater in processes assessed by pilot-scale test using combined biological process and sub-filter technology. *J. Cleaner Prod.* **2009,** *17,* 11–114.

Manan, Z. A.; Alwi, S. R. W. Water pinch analysis evolution towards a holistic approach for water minimization. *Asia-Pac. J. Chem. Eng.* **2007,** *2* (6), 544–553.

Masmoudi, G.; Trabelsi, R.; Ellouze, E.; Amar, R. B. New treatment at source approach using combination of microfiltration and nanofiltration for dyeing effluents reuse. *INT. J. Environ. Sci. Technol.* **2014,** *11* (4), 1007–1016.

McCandless, R. Overview of membrane technology applications in industrial reuse. Proceedings of 85th Annual Water Environment Federation Technical Exposition & Conference [CD-ROM]; New Orleans, LA, September 29–October 3, 2012; Water Environment Federation: Alexandria, VA, 8578–8589.

Mohammadnejad, S.; Bidhendi, G. R. N.; Mehrdadi, N. Water pinch analysis in oil refinery using regeneration reuse and recycling consideration. *Desalination* **2010,** *265,* 255–265.

Mutamin, N. S. A.; Noor, Z. Z.; Hassan, M. A. A.; Olsson, G. Application of membrane bioreactor technology in treating high strength industrial wastewater: a performance review. *Desalination* **2012,** *305,* 1–11.

Natural Resources Canada. Pinch Analysis: For the Efficient Use of Energy, Water & Hydrogen. Catlogue # M39-96/2003E. **2003**. https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/canmetenergy/pdf/fichier.php/codectec/En/2009-052/2009-052_PM-FAC_404-DEPLOI_e.pdf

O'Connor, M.; Garnier, G.; Batchelo, W. Life cycle assessment comparison of industrial effluent management strategies. *J of Cleaner Production* **2014**, 79, 168–181.

Pang, Y. L.; Abdullah, A. Z. Current status of textile industry wastewater management and research progress in Malaysia: A review. *Clean Soil Air Water* **2013,** *41,* 751–764.

Pellegrin, M.-L.; Aguinaldo, J.; Arabi, S.; Sadler, M. E.; Min, D.; Lium, M.; Salamon, C.; Greiner, A. D.; Diamond, J.; McCandless, R.; Owerdieck, C.; Wert, J.; Padhye, L. P. Membrane processes. *Wat. Environ. Res.* **2013**, *85* (10), 1092–1175.

Watson, M., personal communication, MWH Confidential Client Preprogramming study, October 2013–March 2014.

Pizzichini, M.; Russo, C.; Di Meo, C. Purification of pulp and paper wastewater, with membrane technology, for water reuse in a closed loop. *Desalination* **2005,** *178,* 351–359.

Pokhrel, D.; Viraraghavan, T. Treatment of pulp and paper mill wastewater—A review. *Sci. Total Environ.* **2004,** *333,* 37–58.

Pugh, L.; Burghart, A.; Finlay, C. Wastewater reuse considerations at a petroleum refinery. Proceedings Paper, WEFTEC, Oct 2–6, 2010, New Orleans, LA.

Ranade, V. V.; Bhandari, V. M. *Industrial Wastewater Treatment, Recycling, and Reuse*; Elsevier: Amsterdam, The Netherlands, 2014, p 2.

Ranganathan, K.; Karunagaran, K.; Sharma, D. C. Recycling of wastewaters of textile dyeing industries using advanced treatment technology and cost analysis—Case studies. *Resour. Conserv. Recy.* **2007,** *50,* 306–318.

Ratcliffe, M.; Rogers, C.; Merdinger, M.; Prince, J.; Mabuza, T.; Johnson, C. Treatment of high strength chemical industry wastewater using moving bed biofilm reactor (MBBR) and powdered activated carbon (PAC) technology. Proceedings Paper, WEFTEC, October 21–25, 2006, Dallas, TX. http://www.environmental-expert.com/Files%5C5306%5Carticles%5C8890%5C131.pdf (accessed June 2015).

Richard, W. B. *Membrane Technology and Applications*; Wiley & Sons: New York, 2004.

Sala, M.; Gutiérrez-Bouzán, M. C. Electrochemical treatment of industrial wastewater and effluent reuse at laboratory and semi-industrial scale. *J. Cleaner Prod.* **2014,** *65,* 458–464.

Sallach, R.C., Olver, J.W., Jenkins, P. Treatment and reuse of pharmaceutical process water. Hazardous and Industrial Wastes – Proceedings of the 1997 29^{th} Mid-Atlantic Industrial and Hazardous Waste Conference, Roanoke, VA, July 1997.

Sheldon, M. S.; Zeelie, P. J.; Edwards, W. Treatment of paper mill effluent using an anaerobic/aerobic hybrid side-stream membrane bioreactor. *Water Sci. Technol.* **2012,** *65* (7), 1265–1272.

Torres, A. P.; Santiago, V. M. J.; Borges, C. P. Performance evaluation of submerged membrane bioreactor pilot units for refinery wastewater treatment. *Environ. Prog.* **2008,** *27* (2), 189–194 (Manufacturing 250).

U.S. Department of Energy (U.S. DOE) Advanced Manufacturing Office. Membrane Technology Workshop Summary Report, Final Report, November 2012. Workshop, July 24, 2012, Rosemont, IL. http://www.energy.gov/sites/prod/files/2013/11/f4/membrane_tech_workshop_summary.pdf (accessed June 2015).

U.S. DOE. Advanced Manufacturing Office. Advanced, energy-efficient hybrid membrane system for industrial water reuse, 2013. http://energy.gov/sites/prod/files/2013/11/f4/hybrid membrane systems factsheet.pdf (accessed June 2015).

Vajnhandl, S.; Valh, J. V. The status of water reuse in European textile sector. *J. Environ. Manage.* **2014,** *141*, 29–35.

Valta, K.; Kosanovic, T.; Malamis, D.; Moustakas, K.; Loizidou, M. Water consumption and wastewater generation and treatment in the Food and Beverage Industry. *Desal. Water Treat.* **2014,** *53* (12), 1–13.

Veil, J. A. Use of reclaimed water for power plant cooling, 2007. www.veilenvironmental.com/publications/pp/ANL-EVS-R07-3_reclaimedwater.pdf

Visvanathan, C.; Asano, T. The Potential for Industrial Wastewater Reuse. Wastewater Recycle, Reuse, and Reclamation – Vol. 1. http://www.eolss.net/sample-chapters/c07/e2-14-02-04.pdf (accessed June 2015).

Vourch, M.; Balannec, B.; Chaufer, B.; Dorange, G. Nanofiltration and reverse osmosis of model process waters from the dairy industry to produce water for reuse. *Desalination* **2005,** *172,* 245–256.

Wang, Y. P.; Smith, R. Wastewater minimization. *Chem. Eng. Sci.* **1994,** *49,* 981–1006.

Wu, M., Sun, D., Tay, J.H. Process-to-process recycling of high-purity water from semiconductor wafer backgrinding wastes. *Resources Conservation and Recycling* **2004,** *41*, 119–132.

Watson, A.; Umble, A. Reuse of water in the mining industry: feasible or fantasy. Presentation at SME Annual Meeting and Exhibit, February 23–26, 2014, Salt Lake City, UT.

Williams L. K. Challenges, Opportunities for Water Reuse in the Food & Beverage Industry, 2011. http://www.waterworld.com/articles/iww/print/volume-12/issue-04/feature-editorial/challenges-opportunities-for-water-reuse-in-the-food-beverage-industry.html

Woodard & Curran, Inc. *Industrial Waste Treatment Handbook*; Elsevier Butterworth-Heinemann: Oxfo**2013,** *114,* 445–460.

Wu, M.; Sun, D.; Tay, J. H. Process-to-process recycling of high-purity water from semiconductor wafer backgrinding wastes. *Resour. Conserv. Recy.* **2004,** *41,* 119–132.

Xiao, Y.; Chen, T.; Hu, Y.; Wang, D.; Han, Y.; Lin, Y.; Wang, X. Advanced treatment of semiconductor wastewater by combined MBR-RO technology. *Desalination* **2014,** *336,* 168–178.

Xu, F.; Jian, L.; Dan, Z.; Gao, X.; Duan, N.; Guimei, H.; Zhu, H. Water balance analysis and wastewater recycling investigation in electrolytic manganese industry of China—A case study. *Hydrometallurgy* **2014,** *149*, 12–22.

Appendix H

Water Recycling/Reuse in the Mining Industry

The mining and metals industry is one of the world's biggest users of water. Water is used by the minerals industry for operational activities that include:

- Transport of ore and waste in slurries and suspension
- Separation of minerals through chemical processes
- Separation of materials through physical processes such as centrifugal separation
- Cooling systems needed for power generation
- Suppression of dust, both during mineral processing and around conveyors and roads
- Washing equipment
- Dewatering of mines
- Drinking-quality water to support towns that have developed in remote areas to house mining staff

During 2005 an estimated 4.02 Mgal/day was withdrawn for mining purposes in the United States (USGS, 2005). Mining withdrawals were about 1% of total withdrawals and about 2% of total withdrawals for all industries, excluding thermoelectric power. Groundwater was the source for 63% of total withdrawals for mining. Sixty percent of the groundwater withdrawals for mining was saline. Most of the surface water withdrawal (87%) was freshwater. Saline groundwater withdrawals and fresh surface water withdrawals together represented 70% of the total withdrawals for mining. The water withdrawals based on source and type are presented in Table H.1.

Table H.1. Mining Water Withdrawals, by Source and Type, for the United States

Source	Freshwater (Mgal/d)	Saline water (Mgal/d)
Surface water	1300	1520
Ground	1020	1710

The sources of mine drainage are tailings, waste rock, mine workings, heap leach pads, acid-generating rock from nonmining operations, contaminated soils, and historic mining operations. According to the survey conducted by Zinck and Griffith (2013), the most common sources of mine drainage are tailings, waste rock, and mine workings. Water use and discharge practices are different in tailings and heap leach facilities, as shown in Figures H.1 and H.2. The noncontact water that does not originate from lands influenced by mine activities is directed to the surrounding receiving water bodies. However, all the remaining water in the mining facility is typically collected, monitored, and treated as necessary prior to discharging to the receiving environment (Golder Associates, 2011).

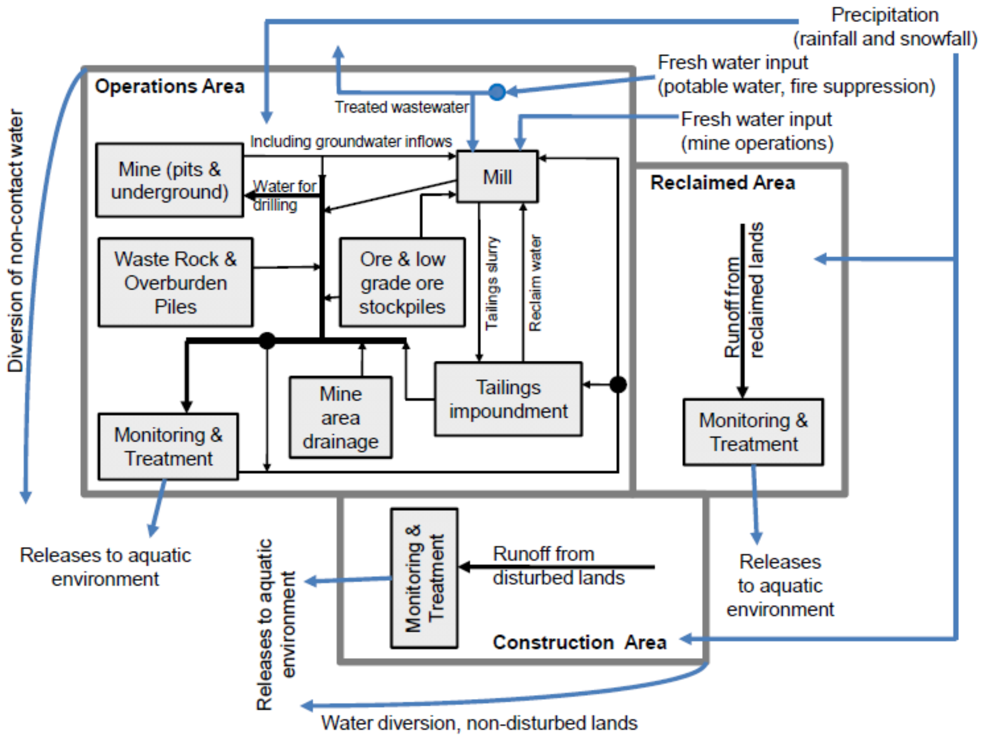

Figure H.1. Conceptual diagram of drainage sources, pathways, and discharges for mines operating tailing facilities.

Source: Adapted from Price, 2009.

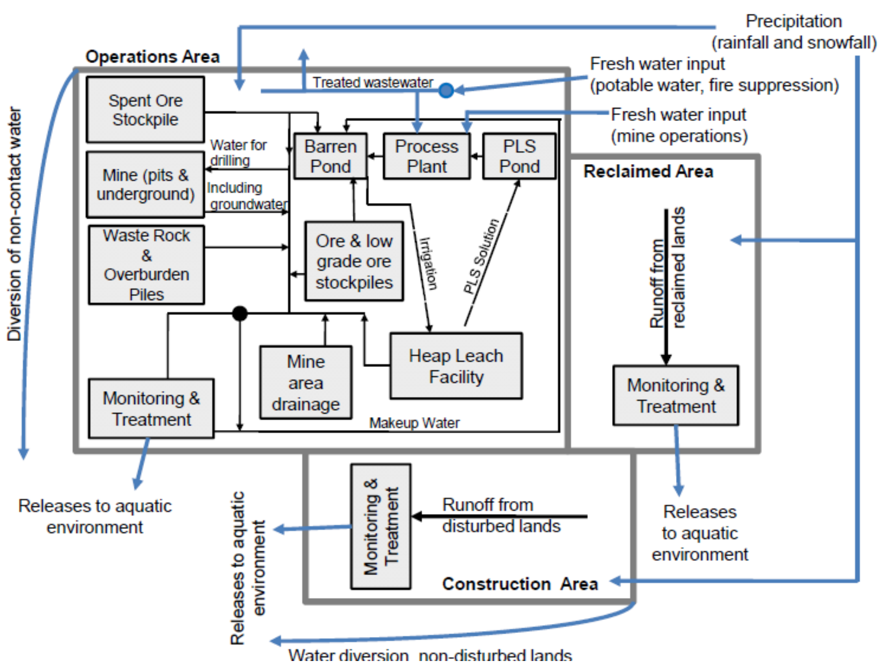

Figure H.2. Conceptual diagram of drainage sources, pathways, and discharges for mine operating, heap leach facilities.

Source: Adapted from Price, 2009.

Drivers for Water Reuse in the Mining Sector

Unlike other sectors, mining operations are fully reliant on the location of the ore. Therefore, water management is essential for both open pits and underground mining. A sustainable water management plan should ensure the following:

- Sufficient water is available for mine operations.
- Water management infrastructure (e.g., ponds and reservoir) is available to handle anticipated water flow and volume.
- The quantity and quality of mine water effluent are controlled to minimize potential impacts on the receiving environment.

Mine drainage water management is typically evaluated within the context of the integrated mine water system and determined based on flow, quality, cost, and intended uses. An overall hierarchy of mine water management is presented in Figure H.3.

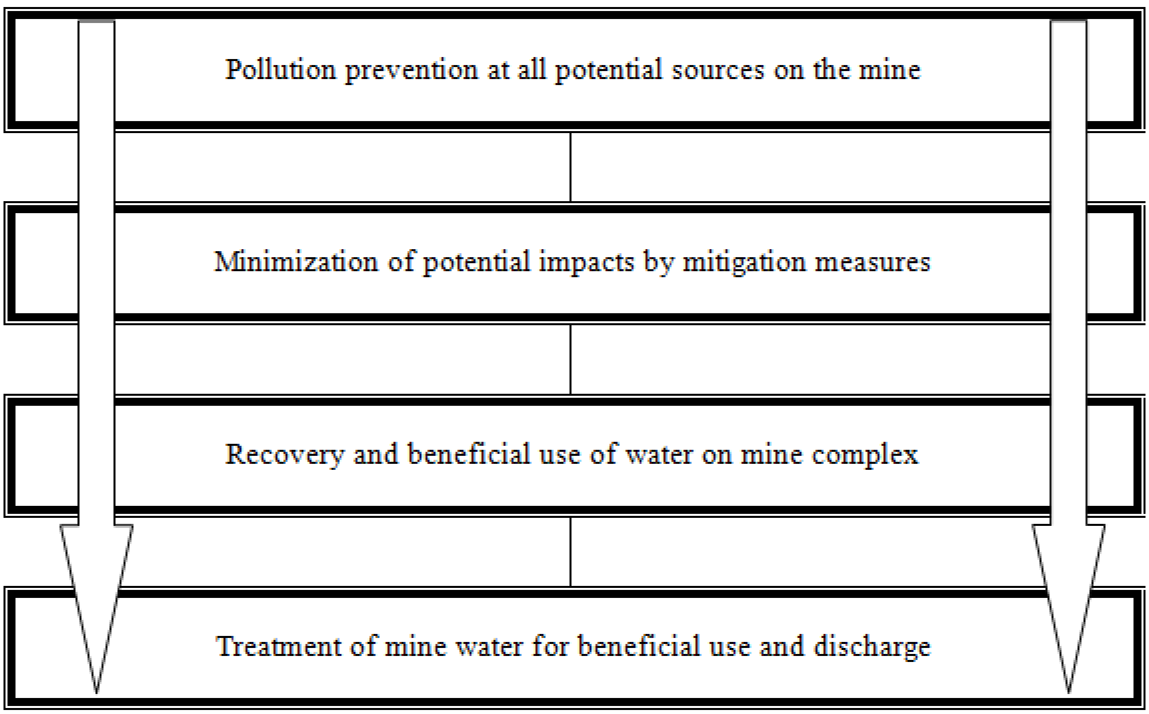

Figure H.3. Mine water management hierarchy.

As shown in Figure H.3, water reuse is an important management practice for miners. A growing number of mining companies are looking for water reuse and recycling alternatives for the following two primary reasons: (1) shortage of water, and (2) stringent discharge limitations.

North America, Australia, Chile, and South Africa dominate global mineral production, operating often in water-stressed regions. Issues associated with water shortages remain a big problem in many areas where mineable resources are abundant. As shown in Figure H.4, many of the world's largest mining projects are located in regions classified as moderate to high risk of water scarcity (Moody's Investor Service, 2013).

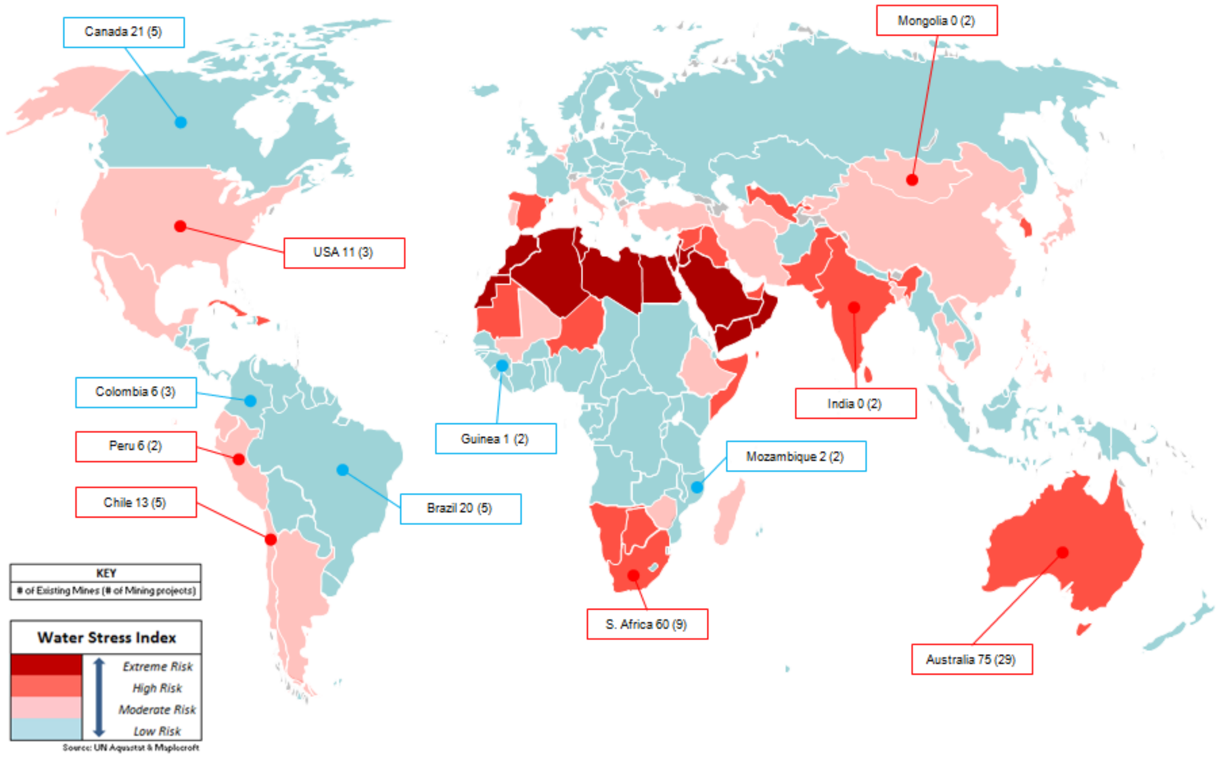

Figure H.4. Water stress conditions in the mining countries.

Source: Moody's Investor Service, 2013.

In many cases the primary driver for high-level treatment of mine water for reuse/recycling is increasingly stringent discharge requirements. Water discharge effluent limits to receiving water bodies are either based upon treatment technology (discharger's and permit writer's best professional judgment of the proposed wastewater treatment technology capacity) or water quality requirements that are imposed and enforced by the regulatory agency. High levels of conductivity, sulfate, chloride, and selenium are some of the primary causes of water quality impairments downstream from mine discharges. In the northern Appalachian coal mining region of the United States, the Environmental Protection Agency (U.S. EPA) is proposing a limitation between 300 and 500 µS/cm for conductivity in mine water discharges. A list of treatment performance based effluent limits for a mining facility in Washington state is presented in Table H.2 as an example of stringent regulatory requirements. Such water treatment goals are so high that advanced treatment approaches are rapidly becoming a necessity in order to meet these anticipated limitations. As the need to remove large amounts of constituents continues to grow, water reuse and recycling may soon become the only practical option for many mining operations.

Table H.2. Treatment Performance Based Effluent Limits for a Mining Facility in Washington

Parameter	Units	Average Monthly Limit[1]	Maximum Daily Limit[2]
Alkalinity (as $CaCO_3$)	mg/L	194	263
Chloride	mg/L	3.2	5.8
Specific conductivity	µS/cm	383	603
Nitrate + nitrite (as N)	mg/L	4.7	5.4
Oil and grease	mg/L	5.0	5.0
Sulfate	mg/L	2.7	5.4
Total dissolved solids	mg/L	214	290
Turbidity	NTU	2.8	3.8
Aluminum (total)	µg/L	80	120
Ammonia (total) as N	µg/L	346	483
Arsenic (total)	µg/L	0.4	0.7
Copper (total)	µg/L	7.9	9.6
Iron (total)	µg/L	60	71
Lead (total)	µg/L	0.8	0.8
Zinc (total)	µg/L	12.7	20.3
Dissolved oxygen	mg/L	5.9	0.5

Notes: [1] Average monthly effluent limit means the highest allowable average of daily discharges over a calendar month. [2] Maximum daily effluent limit means the highest allowable daily discharges. The daily discharge is the average discharge of a pollutant measured during a calendar day.

Typical Contaminants in Mine Drainage Water

According to Zinck and Griffith (2013), the most commonly reported contaminants are iron, sulfate, and pH, and key mine drainage treatment issues are:

- Algal blooms in the collection pond
- Gypsum scaling
- Lime handling and mixing
- Polymer mixing during winter
- Control of total suspended solids in the final effluent
- Difficulty in maintaining high-density sludge
- Manganese and sulfate concentration in the final effluent
- Inefficient mixing and acidity in water because of residual thiosulphate (S_2O_3) derived from mill processing
- Management of high flows

Mine Drainage Treatment Processes

In order to understand water reuse/recycling opportunities and challenges in the mining industry, it is important to review current water treatment practices. In general, water treatment at mine sites is considered a never-ending practice, and most mine sites project treatment requirements of decades or longer duration that are site specific. According to a survey conducted by Zinck and Griffith (2013), 23% of the 108 surveyed sites plan to conduct water treatment for less than 10 years, 25% plan for 10 to 50 years, 6% for 50 to 200 years, and 46% plan to conduct treatment in perpetuity. The water management systems are designed to handle high flood events—typically a 1:20 and a 1:100 year event or higher. A wide spectrum of drainage treatment technologies has been developed, proven, and applied to many different applications. A list of treatment technologies employed at the mining facilities is presented in Figure H.5. Both active and passive treatment processes are used in mining operations.

This survey also found, as shown in Figure H.6, that active treatment processes such as chemical treatment are more prevalent than physical and biological processes combined. Although membrane-based processes have been utilized in some of the surveyed sites, their application is still limited compared to other treatment technologies.

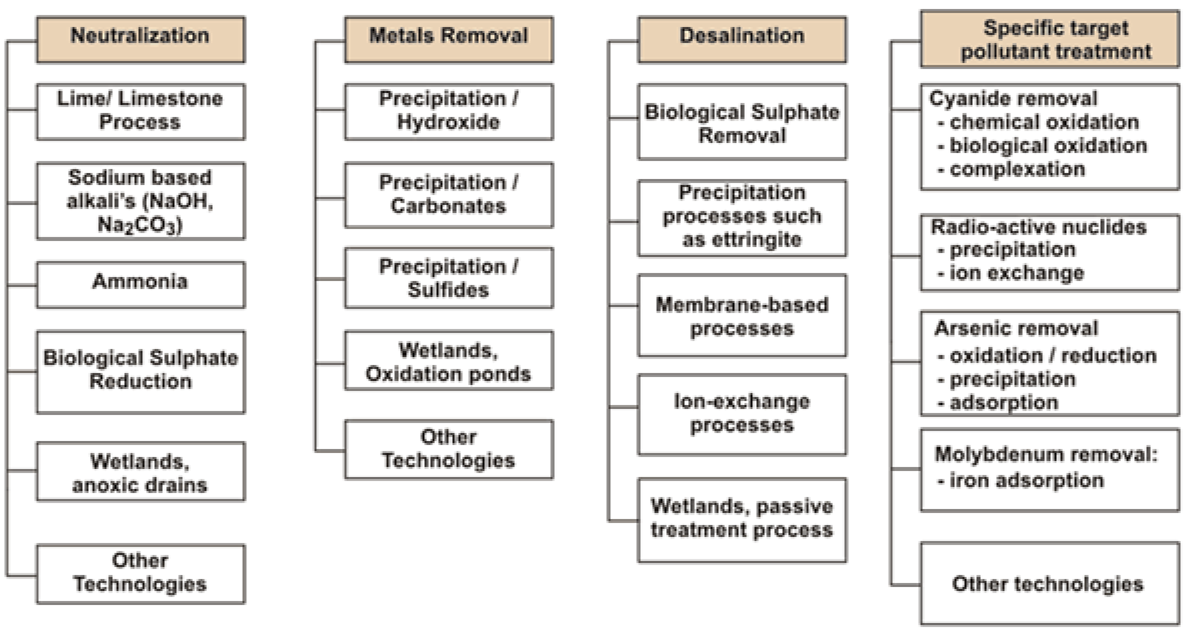

Figure H.5. Mine drainage treatment technologies.

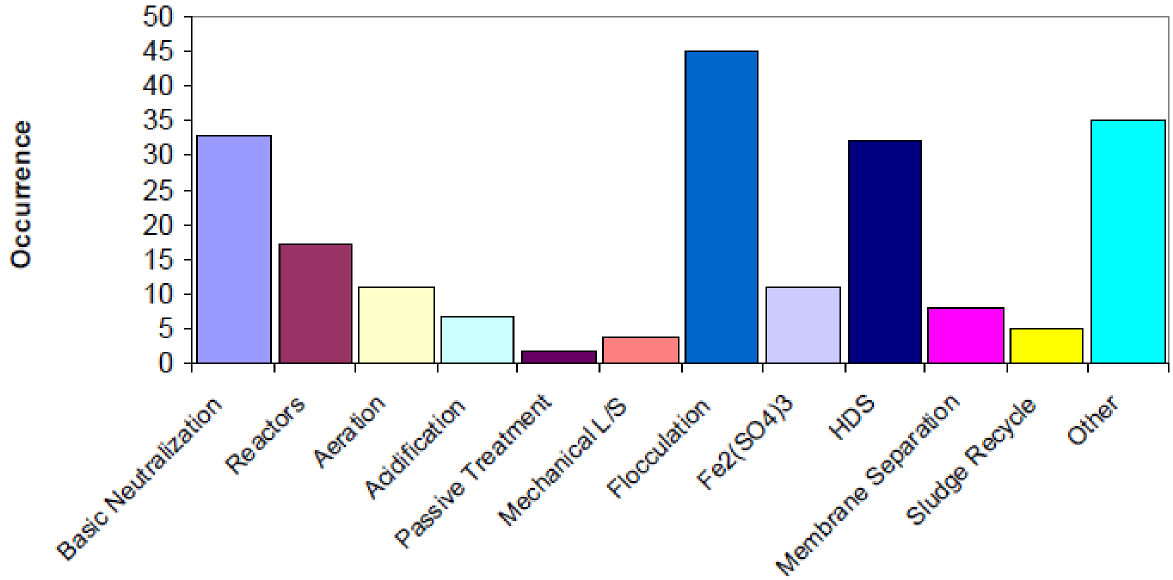

Figure H.6. Treatment processes used in a mining facility.

The common problems associated with mining water treatment that might drive or influence water reuse/recycling projects are:

Effluent Criteria and Compliance

The final effluent from a mining facility in most cases is discharged to sensitive aquatic environments, including fish-bearing water courses. In some cases the effluent is discharged into commercial and recreational fishing areas (Zinck and Griffith, 2013). Effluent discharge limits are increasingly becoming more stringent, in some cases close to receiving water background levels. Although tighter discharge criteria provide better environmental benefits, treatment processes need to be modified to meet these stringent regulations or treatment goals.

Treating Low Strength Waters

In low strength, low iron systems, solid–liquid separation can be difficult. Precipitates in such systems cannot agglomerate to form larger particles. As such, flocculant addition is often ineffective, as there are not enough particles present to form agglomerates.

Scaling

Calcite and gypsum scaling are common in mine drainage. If a high sludge treatment plant operates without a recycle, and a significant amount of sulfate is present, some precipitation may occur on the reactor wall.

Climatic Conditions

Some of the most difficult mine drainage treatment challenges are associated with weather, particularly in cold climates. Freezing lines can result in days of downtime when pumping and treating the water are necessary.

Another issue associated with cold climate sites is spring thaw. In permafrost areas the ground remains frozen during the thaw, which means that all the melting snow immediately becomes runoff. Under these conditions the water must be stored, as the treatment system cannot be economically designed to accommodate this temporary high flow.

Operating Costs

The typical range of operating costs varies from \$0.20 to \$1.00 per m^3, depending on factors such as raw water characteristics, choice of alkali, total volume treated, age of the treatment plant, and accessibility of the plant (Zinck and Aube, 2010).

Water Reuse/Recycling Case Studies

An increasing number of mining companies are looking for opportunities to utilize reuse water from municipal or other industrial sources. In addition, some mines are moving forward with on-site water recycling. There is growth potential for future efforts on the treatment and reuse of mining water, especially within arid locations (IWA, 2013). According to Watson and Umble (2014), the reuse and recycling opportunities in the mining industry are as follows:

- Process make-up water
- Dust suppression (haul roads)
- Restricted agricultural irrigation
- Reforestation/pastureland irrigation
- Aquaculture
- Boiler makeup water
- Environmental flow management
- Material washing
- Aquifer recharge
- Municipal water supply augmentation
- Cooling water

In 2013, the International Water Association (IWA) organized a workshop to critically review the current challenges and solutions in the mining sector in terms of water reuse/recycling and explore business opportunities for improving and expanding water reuse. The workshop participants identified a range of success factors to enable and improve water reuse in the mining industry (IWA, 2013). These included:

- Develop an easy-to-navigate regulatory environment and simple legislation, with a clear process to facilitate implementation of water reuse projects and demonstrate when it is an easier alternative to other available options.
- Use appropriate economics and finance strategies for water valuation and pricing in order to change perceptions.
- Define fit-for-purpose water reuse.
- Endorse technological developments for water reuse to enable and encourage innovation within and between industries.
- Demonstrate best practice reuse to local leaders and decision makers.

- Promote collaboration within, between, and outside businesses.
- Form coalitions with collaboration framework agreements open to other industries.
- Be willing to convince industry and financial institutions of the value of water reuse.
- Embrace the role of technology providers in innovation.

A number of case studies were also reviewed. Brief descriptions of these case studies are presented in the following sections.

Case Study 1: Collahuasi Mine

The Collahuasi Copper Mine, located in rural northern Chile, produces 3% of the world's copper. The facility processes the mined ore on-site, which creates a substantial volume of contaminated and saline water. The water was traditionally discharged to the environment with only minimal treatment; however, the surrounding area is arid and ecologically fragile, so the facility had to be operated at a zero discharge. The water from the copper mine contained high levels of total dissolved solids (TDS), total suspended solids (TSS), chemical oxygen demand (COD), hardness, silica, iron, and other metals. A multistage turnkey project was designed, built, and commissioned in 2008. The treatment processes include sedimentation, dissolved air flotation, media filtration, activated carbon filtration, ultrafiltration, and reverse osmosis. Some of the treated wastewater was reused for ore processing, and the remaining treated water was used to irrigate trees and other vegetation in a nearby reforestation project.

Case Study 2: Angas Mine—Achieving sustainability goals through water treatment

Angas Zinc Mine in South Australia mines and processes ore and minerals. This operation, owned and operated by Terramin, is committed to reducing its environmental impact whenever possible. Terramin partnered with Veolia to design, build, and commission a fully containerized reverse osmosis plant, which included pretreatment as well as spare parts. The plant was commissioned to produce 240 KL/day of treated water for use within the mine. This was essential, as the feed water from the mine water disposal was highly saline brackish water with high raw water turbidity and iron levels. Implementing this solution has allowed Terramin to have a reliable supply of desalinated water, yielding high recovery for reduced waste volumes.

Case Study 3: Anglo American plc eMalahleni Water Reclamation Project

The Witbank coal fields are located around eMalahleni, a city of half a million inhabitants located in Mpumalanga province in northeastern South Africa. Rainfall in the area is around 800 mm/year. The main water source is the Witbank Dam, with a capacity of around 104 billion L. Anglo American's thermal coal workings in the area contain approximately 140,000 ML of ingress groundwater. The region struggles with water scarcity that is expected to become more severe in the years to come. Both droughts and flash floods will increase in occurrence. The city of eMalahleni already has difficulty in meeting the water demands of its rapidly expanding population.

The water reuse initiative was started to ensure environmentally responsible management of excess water in the mines and continuous supply of treated water for mining activities as well as eliminate the need for import of new water and consequent competition with other stakeholders for a scarce resource. The water reclamation plant was first commissioned in

October 2007 with an establishment capital of U.S.$175 million. The plant currently has a capacity of 30 ML/day treated water, with a full expansion capacity of 50 ML/day, which commenced in 2011. Water from the mine is converted to drinking water, process/industrial water, and water that can be safely released into the environment. The water reclamation plant offers a reliable and potable water supply to eMalahleni. In the treatment process, gypsum is separated and used as a construction material. It provides a safe and secure water source to the city. Some of this treated water is used directly in Anglo American mining operations, but the majority is for social use and meets 12% of eMalahleni's daily water needs.

Case Study 4: Argyle Diamond Mine

Argyle Diamond Mine is located in northwest Australia in the Kimberley region, which is remote, arid, and hot, with temperatures reaching 40° C in the wet season and an annual rainfall of 750 mm. The mine is the world's largest single producer of diamonds, producing approximately 30 million carats each year. Argyle Diamond Mine used more than 3500 ML from Lake Argyle to run its operations in 2005. The mine has set a target of reducing this use to zero in its operations. The biggest user of water at the site is the processing plant, where water is needed to wash and separate the diamonds. Instead of being discharged to the environment, this water has been captured and recycled back through the processing plant since 2005, achieving a recycling rate of almost 40%. Water seepage from tailings is also captured and recycled for use in the process. Dewatering of the underground mine and from the surface pit operation provides additional water that is collected and stored in the two dams for drinking and operational use. By introducing these changes to water usage in the mine, Argyle has achieved a 95% drop in water taken from Lake Argyle since 2005, and by 2009 the use of water from the lake was reduced to 300 ML.

Case Study 5: CONSOL Energy and GE treat mine water, enable reuse of 99% in other operations

The Buchanan, a coal mine of CONSOL Energy, is the largest producer of high Btu bituminous coal in the United States. It installed a 1600 gpm water treatment plant to treat and reuse water (GE, 2014; Bowen, 2014). The treatment processes include GE's advanced filtration membranes and thermal water treatment technology and are expected to enable about 99% of the water to be reused in other mining operations throughout the Oakwood, VA plant.

The system incorporates ZeeWeed ultrafiltration technology, which employs hollow-fiber membranes to separate particulates from water, and reverse osmosis technology, which removes dissolved impurities from water through the use of a semipermeable membrane. The concentrated brine is then treated by thermal evaporation, crystallization, and drying technologies, achieving zero liquid discharge. The remaining solids are further purified into a saleable road salt. The benefits and resource savings from the new system significantly reduced the volume of mine water requiring management and the company's freshwater demand.

Case Study 6: AREVA Trekkopje uranium mine, Namibia

The Trekkopje uranium mine is located approximately 65 km northeast of Swakopmund in western Namibia. The mining license was obtained from the Namibian government in 2008, and the mine is currently entering its final phase of construction. It will be one of the largest in southern Africa and the 10th largest in the world. The estimated mine life is 12 years.

Because the freshwater aquifers do not yield sufficient water to supply all the mines and communities in the area, it was apparent that another solution had to be developed. Seawater desalination was the only clear option, and AREVA constructed a desalination plant, the first one for the country, to meet the water needs of the mine. The Erongo Desalination Plant (EDP) was built between 2009 and 2010 on the Namibian coast, approximately 50 km from the mine, and officially inaugurated on April 16, 2010. Desalinated water is obtained by a combination of a reverse osmosis process and extreme filtration. AREVA has also succeeded in reducing its expected annual water consumption requirement to 14 Mm_3 from an original prediction of 20 Mm_3. This was achieved primarily by building a small on-site water treatment plant and developing infrastructure so that water can be reused.

Case Study 7: Treatment of acid mine drainage in South Brazil

Conventional acid mine drainage (AMD) treatment techniques are a combination of neutralization and precipitation (mainly by lime softening), followed by settling of the precipitate in the pond. This research project tested an innovative flocs/liquid separation by flotation with microbubbles or lamellar settling. Then the AMD treated water was characterized by its quality for recycling in terms of inorganic or organic elements, suspended or dissolved solids. Flocculation of precipitates was carried out in a special proprietary flocculator, FGR. Main characteristics and advantages of this in-line mixing reactor over agitated tanks are no moving parts, plug flow (fewer short circuits and dead zones) operation, low volume/retention times, and low footprint (Rubio and Carissimi, 2005). Two types of flocs were formed: aerated and nonaerated. Aerated flocs formed within seconds and entered into a rapid solid–liquid separation by flotation (high rate). Conversely, the nonaerated flocs settled in a lamella settler. Both AMD treatment techniques showed similar efficiencies (>90% removal of ions), but the separation by lamella settling was advantageous because less reagent was required. The quality of the treated water is fairly good, nearly free of heavy metal ions, with low biological oxygen demand (BOD), total organic content (TOC), and solids content, and may be readily reused for irrigation, industrial processes, and wash water (including streets, vehicles, dust control).

References

Allen, S. C.; Nair, V. D.; Graetz, D. A.; Jose, S.; Nair, P. R. Phosphorus loss from organic versus inorganic fertilizers used in alleycropping on a Florida Ultisol. *Agr. Ecosyst. Environ.* **2006,** *117,* 290–298.

Bowen. Project Summary Sheet, 2014. http://www.bowenengineering.com/portfolio/buchanan-mine-wtp/ (accessed June 2015).

Da Silveira, N. A.; Silva, R.; Rubio, J. Treatment of acid mine drainage (AMD) in south Brazil: Comparative active processes and water reuse. *Int. J. Miner. Process.* **2009,** *93* (2), 103–109.

General Electric (GE). Water treatment solutions for the mining industry, 2014. A white paper published by GE.

Golder Associates. Guidance document on water and mass balance models for the mining industry. A report submitted to Yukon Government and Environment, Canada, 2011.

International Council on Mining and Metals (ICMM). Water management in mining—A selection of case studies, 2012.

International Water Association (IWA). Workshop on industrial water reuse in the mining sector, Ninth Water Reuse Conference, Windhoek, Namibia, October 27–31, 2013.

Moody's Investor Service. Global mining industry, 2013. https://www.moodys.com/research/Moodys-Water-scarcity-could-increase-rating-pressure-on-global-mining--PR_266225 (accessed June 2015).

NWL Water, 2014. On-site Water Treatment Plant for Collahuasi Copper Mine in Chile Case Study. http://www.rwlwater.com/case-study-collahuasi-copper-mine/ (accessed June 2015).

Price, W. A. (2009) Prediction manual for drainage chemistry from sulphidic geologic materials. Work performed for MEND program, by CANMET-Mining and Mineral Sciences Laboratories, Natural Resources Canada, Smithers, BC.

Rubio, J.; Carissimi, E. The flocs generator reactor—FGR: a new basis for flocculation and solid–liquid separation. *Int. J. Miner. Process.* **2005,** *75* (3–4), 237–247.

United States Geological Survey (USGS). 2005 mining water use. http://water.usgs.gov/edu/wumi.html (accessed June 2015).

Veolia. Angas Mine—Achieving Sustainability Goals through Water Treatment, 2014. http://www.veolia.com.au/major-projects/projects/terramin (accessed June 2015).

Watson, A.; Umble, A. Reuse of water in the mining industry: feasible or fantasy. A presentation given at SME Annual Meeting and Exhibit, February 23–26, 2014, Salt Lake City, UT.

Zinck, J.; Aube, B. Overcoming active treatment challenges. Paper published in *Mine Water and Innovative Thinking,* IMWA, 2010.

Zinck, J.; Griffith, W. Review of mine drainage treatment and sludge management operations. A report submitted to Mining Association of Canada, Project Number 603054, 2013.

Appendix I

Water Reuse in the Oil and Gas Industry

Areas with oil fields are generally water stressed, with limited freshwater resources (Fakhru'l-Razi et al., 2009). Water is, in fact, an essential component of shale development required for drilling, cool and drill bit lubrication, and hydraulic fracturing (U.S. EPA, 2011). The water that is returned to the surface through a well borehole is made up of water injected during the fracture stimulation process as well as natural formation water and is defined as "produced water." It is the largest wastewater stream generated in oil and gas extraction processes. Waters produced during flowback operations with excess fluids and sand returning through the borehole to the surface are also part of the produced water estimations. Approximately 10 to 25% of the water injected into the well is recovered within 3 to 4 weeks after drilling and fracturing. An estimated 250 million barrels of produced water per day (for a total of 80 million barrels of oil produced) is generated during oil extraction for a water-to-oil ratio of about 3:1 (70% water cut; Fakhru'l-Razi et al., 2009).

Produced water is typically produced for the lifespan of a well, although quantities may vary significantly by play (U.S. EPA, 2011). Volumes of produced water are different depending on the shale play. For example, onshore production generates higher water volumes than offshore (Ahmadun et al., 2009). Drilling and hydraulically fracturing a shale gas well is estimated to require approximately 2 to 4 million gallons of water (48,000–95,000 barrels, 8000–15,000 m^3). Historical data show that median water use for developing a shale gas well in Texas is 2.8 to 5.7 million gallons (67,000–140,000 bbl), depending on the specific shale play. The median volume of water used for hydraulically fracturing a horizontal well in Oklahoma is 3 million gallons (71,000 bbl). In the Marcellus shale region, drilling and hydraulically fracturing a horizontal well requires an estimated 2 to 7 million gallons (48,000−170,000 bbl). The percentage of this initial volume that is returned to the surface as flowback is specific to the well and has been estimated as 8 to 15%, 10 to 40%, 9 to 53%, and 30 to 70%.

Oil Extraction

The type of resource, geology, and subsurface condition influence how the oil is obtained (NPC, 2011). Oil extraction can be achieved with three methods of production (not necessarily in sequence):

- Primary (uses the natural pressure of the reservoir, artificial or mechanical lift, or both)
- Secondary (involves water or gas injection at ambient temperature to increase the reservoir pressure)
- Tertiary

- Enhanced oil recovery (EOR), which increases the mobility of the oil by reducing its viscosity using thermal, miscible gases or chemicals and involves the addition of energy-using mass and heat transfer. Thermal recovery is mostly used in California. Miscible gases are generally natural gas, nitrogen, or CO_2. Chemical injection uses long-chain polymers or surfactants that will strongly impact water quality.

As the oil reserves become scarce, the oil industry is moving toward improving extraction methods for conventional and unconventional oil (NPC, 2011).

Gas Extraction

Volumes and chemistry of water produced by gas operations differ from those generated during oil operations. The volume of water produced in gas fields is lower than that produced in oil fields and only includes formation water and condensed water; gas operations do not require water injections. Raw water withdrawal is an inherent part of the coal seam gas (CSG) extraction process and poses potential risks and impacts to the underground aquifers and the communities that depend on local water sources. CSG extraction may be assisted by hydraulic fracturing and involves the creation of fractures in underground coal seams and pumping water out to reduce the pressure, with the release of the methane adsorbed in the coal seams (Rimos et al., 2012). The National Water Commission of Australia released a report indicating that CSG production generated an average of 5 tons of associated water for every ton of CSG produced. One U.S. source argued that conventional natural gas has a lower extraction-related water footprint than unconventional sources, as conventional wells do not require hydraulic fracturing. Water consumption is suitable as an indicator for water usage in the whole system and the technology used in each process.

CSG extraction requires more wells than conventional gas; in Australia the annual number of onshore CSG wells drilled was around 600 in 2011; 64 wells (off- and onshore) were drilled in 2008 for conventional gas and associated gas across all states in Australia, with 69% of these total wells drilled being recoverable (Rimos et al., 2012). With the addition of shale gas reserves, estimated global technically recoverable gas reserves have increased by over 40% since 2010, prompting the International Energy Agency to speculate about a “Golden Age of Gas” that will be characterized by high energy demand in urbanizing regions and low cost, widely available, shale gas resources (Shaffer et al., 2013). CSG in particular draws significant quantities of poor-quality water from the ground, averaging around 14.2 GL in the 2008–2009 financial year (Rimos et al., 2012).

Freshwater and associated water withdrawal can be limited by introducing water savings from recycle streams and supplementation with rainwater collection, thus reducing the need for surface and groundwater use (Rimos et al., 2012).

Drivers for Water Reuse

Cost is the primary driver in producers’ decisions about how to manage and treat produced water generated by oil and gas producers (GAO, 2012). How produced water is managed and treated are primarily economic decisions made within the bounds of federal and state regulations (GAO, 2012). Produced water is considered an oil field waste, and its management has a cost (Ahmadun et al., 2009). In most cases underground injection is the lowest-cost option, with costs for underground injection ranging from $0.07 to $1.60 per barrel of produced water. Trucking is one of the most significant cost factors; however, it can be minimized by managing the water closer to the production site (GAO, 2012). Another significant component of cost is whether treatment will be required as part of the management practice being employed. Treatment costs depend heavily on the technologies used, which in turn depend on the quality of the produced water being treated and the level of treatment needed for the disposal or reuse option being considered. For example, the water associated with CSG extraction often requires treatment (e.g., reverse osmosis), which can be capital- and energy-intensive and produces waste brine with a high salt content to be disposed of or sold.

Though they are technically suitable, the capital and operating costs of these technologies must be reduced to facilitate their economical implementation. Capital costs may be reduced with modular and scalable systems that can be relocated or expanded to match the dynamic demand for produced water desalination. To this end, advancements in module design and operating parameters may reduce costs. Reducing the extent of pretreatment required for these desalination technologies and increasing the efficiency of pretreatment technologies themselves could also reduce the capital costs of produced water desalination (Pankratz, 2004). Significant savings could be realized by improving the hydraulic fracturing process to decrease the volume or reduce the total dissolved solid (TDS) concentration of produced water that must be desalinated (Shaffer et al., 2013).

Typical Contaminants in Waters

Produced water quality and chemistry can vary tremendously from brackish (not fresh, but less saline than seawater) to saline (similar salinity to seawater) to brine (which can have salinity levels multiple times higher than seawater). Some of the factors influencing the chemistry of the produced water include (Ahmadun et al., 2009):

- Geological location of the oil field
- Formation of the oil field
- Lifetime of its reservoir
- Type of hydrocarbon products
- Production methods and facilities
- Chemicals used for the production

The method of production can affect the quality of the water produced. These differences are largely attributable to the chemicals and other substances added during drilling or production processes. To be specific, methods of production that rely on hydraulic fracturing or enhanced recovery can result in poorer quality produced water than other methods. For example, the range of chemicals, sand, and water that are added to facilitate the hydraulic fracturing process can lower the overall quality of the produced water from these kinds of operations. The use of chemicals during enhanced recovery can also affect the quality of water produced. Enhanced recovery involves the addition of production chemicals such as biocides, corrosion inhibitors, and friction reducers, along with steam or carbon dioxide, and can yield produced water with levels of some production chemicals three to four times higher than produced water from wells that do not use enhanced recovery techniques (GAO, 2012). For details on the water produced, chemistry, and contaminant levels, refer to the review of Ahmadun et al. (2009). In summary, oil field wastewaters contain both organic and inorganic contaminants and include:

- Dispersed and dissolved oil compounds (total oil and grease)
- Dissolved formation minerals: cations and anions, heavy metals, naturally occurring radioactive materials (specifically barium and radium isotopes)
- Salts, which include chlorides, bromides, and sulfides of calcium, magnesium, and sodium
- Metals, which include barium, manganese, iron, and strontium, among others
- Production chemical compounds (which may include proppants, friction reducers to help with water flow, biocides to prevent growth of microorganisms, and additives to prevent corrosion, among others
- Production solids (such as formation solids, corrosion and scale products, and bacteria)
- Dissolved gas

The chemistry of water produced by oil field operations differs from that generated during gas operations. Water from gas operations can reach high levels of salinity (to about 14 times that of seawater) and contains higher concentrations of gas treatment chemicals (methanol, ethylene glycol) and volatile components than oil field produced water. Regardless of the origins of the produced water, each water's parameters can vary widely (Ahmadun et al., 2009). CSG resources exist mainly onshore and have an average composition of 97.5 mol% methane, with the rest being nitrogen, carbon dioxide, and ethane. Helium and argon exist in very small quantities (0.04 and 0.01 mol%, respectively), as well as traces of hydrogen and heavier hydrocarbons (<0.01mol%; Rimos et al., 2012). The ideal produced water for reuse has low TDS, low total suspended solids (TSS), and little to no scale or bacteria-causing compounds (U.S. EPA, 2011).

Current Technologies for Water Treatment and Treatment Issues

Treating produced water is a challenge because of its complex physicochemical composition, which may vary over the lifetime of the shale gas well. Because produced water characteristics vary from gas field to oil field, from well to well, and by age, a single treatment process cannot be recommended for achieving environmental standards or reuse requirements. The traditional aim of wastewater treatment for reuse in these industries is to remove soluble organics, suspended solids, sand, and dispersed oil and grease. In addition to these goals, other treatment requirements are to remove dissolved gas (light hydrocarbon gases, carbon dioxide, hydrogen sulfide), naturally occurring radioactive materials, and dissolved salts. Disinfection and softening might also be necessary for specific reuse applications.

Treatment technologies should be designed for these potential changes in produced water quality over time. Different treatment technologies are applied for on- and offshore activities. The treatment technologies that have commonly been used are classified as:

- Chemical treatments: hazardous sludge generation with consequent treatment or disposal process, high costs, and sensitivity to initial concentration of wastewater.
- Physical treatments: high initial capital costs and sensitivity to variable water inputs
- Biological processes: sensitivity to variations of organic chemicals and salt concentration of influent waste
- Advanced treatment

Although more expensive, physicochemical treatments are preferred offshore for their low footprint and are generally effective in removing suspended solids, oil and grease, hardness compounds, and other nondissolved components. However, physicochemical processes cannot remove minute suspended oil and hazardous, dissolved organics and inorganics; removal of these can be energy-intensive and involve heavy use of chemicals. Biological treatment is applied onshore and cost-effective in removing dissolved and suspended compounds using naturally occurring, acclimated, commercial, or selected microorganisms (Ahmadun et al., 2009). In general, a physicochemical pretreatment is preferred prior to a biological process. However, often the combination of physicochemical treatment with biological processes is not enough to meet the discharge and reuse requirements, and membrane processes are needed to refine final effluent quality.

TDS can be reduced in the reuse process by blending it with freshwater. Blending is necessary because high TDS can increase friction in the fluid, which is problematic in the hydraulic fracturing process. TSS can be managed with relatively inexpensive filtration systems. Scale and bacteria-causing compounds can be managed with chemical treatments or advanced filtration, but each additional treatment step reduces the economic efficiency of the process.

Advanced treatment includes energy-intensive processes such as reverse osmosis membranes, thermal distillation, evaporation, and crystallization processes. They are used to treat dissolved solids, primarily consisting of chlorides and salts but also including dissolved barium, strontium, and some dissolved radionuclides. Growing restrictions on produced water disposal and eventual contraction of reuse opportunities within the shale gas industry will ultimately move the industry toward desalination of produced water, but high salinity produced water is especially challenging and energy intensive to treat (Shaffer et al., 2013).

In the Marcellus shale region, and other shale plays worldwide with similar constraints, the anticipated combination of contracting internal reuse opportunities and economic, regulatory, and infrastructure drivers for external reuse will move the industry to desalinate produced water (Shaffer et al., 2013). Thus, various membrane processes can be used to treat produced water. Membrane processes, such as reverse osmosis, that produce low concentration permeate require chemical and biological pretreatment, high initial capital costs, chemical cleaning after fouling, and generation of chemical cleaner waste and concentrates that need further treatment or disposal.

Conventional thermal desalination technologies, such as multistage flash and multiple-effect distillation, are well established. However, the high investment costs, significant energy requirements, and associated energy costs of these technologies limit their implementation. The comparatively larger footprint and more costly materials and equipment of conventional thermal desalination technologies compared to membrane desalination technologies also make them less mobile and scalable (Shaffer et al., 2013). Mechanical vapor compression, membrane distillation, and forward osmosis are three desalination technologies for high salinity brines that are appropriate for the produced water in the Marcellus shale region as well as other shale gas plays worldwide where conditions promote external reuse. Mechanical vapor compression is a relatively well-established technology, although membrane distillation and forward osmosis are emerging technologies that show promise for low energy desalination of high salinity water (Shaffer et al., 2013). The potential location of these treatment processes at well sites, often away from substantial infrastructure, suggests that supplying energy may be a critical challenge to the widespread desalination of produced water for external reuse. Considerations and options for feasibly powering these technologies with available resources according to their thermal and electrical energy needs should be considered (Shaffer et al., 2013).

Table I.1 shows examples of water recycle and reuse in full-scale oil and gas industries.

Table I.1. Examples of Water Recycling and Reuse Full-scale Applications in the Oil and Gas Industry

Industry	Location	Technology	Reuse/Recycle	Reference
Crude oil production—Tempa Rossa Oil Field	Basilicata, Italy	GE's advanced evaporator and crystallizer for ZLD	reuse for firefighting	http://www.wwdmag.com/industrial-wastewater-recyclingreuse/ge-technology-recycle-produced-water-italian-oil-field
Grizzly Oil Sand ULC—Algar Lake Project	Fort McMurray, Alberta, Canada	GE's advanced evaporator and ZLD technology	high quality distillate produced for use as feed water to high-pressure drum boilers	http://www.wwdmag.com/canadian-oil-sands-project-recycle-produced-water-ge-evaporation-technology
Sunshine Oil Sand Ltd.—West Ells Project	Fort McMurray, Alberta, Canada	GE's advanced evaporator	Recycle 98% of produced water, boiler and heat recovery steam generator blowdown, and brackish makeup water to produce high quality distillate suitable for use as feed water for conventional drum boilers.	http://www.wwdmag.com/sunshine-oilsands-selects-ge-technology
MEG Energy Corp.—Christina Lake Project	Northern Alberta, Canada	GE's advanced evaporator	Recycle a portion of steam generator blowdown for reuse as boiler feed water as opposed to disposal by deep well injection.	http://www.wwdmag.com/water-recycling-reuse/meg-energy-selects-ge-evaporation-technology-water-reuse
Brion Energy—MacKay River Commercial Project	Fort McMurray, Alberta, Canada	GE's advanced evaporator	99% of produced and makeup water will be treated to produce high quality distillate suitable for use as feed water to conventional drum boilers.	
Athabasca Oil Corp.—Hangingstone oil sand	Fort McMurray, Alberta, Canada	GE's advanced evaporator	Recover 97% of produced and brackish makeup water as boiler feed water to drive the steam-assisted gravity drainage process.	http://www.wwdmag.com/athabasca-oil-selects-ge-technology-sagd-project
Oil Sand Project	Fort McMurray in Alberta, Canada.	GE's wastewater evaporation technologies	Recycle a portion of once-through steam generator blowdown, decreasing liquid waste from facility and increasing boiler-feed water available for generation of steam and production of bitumen.	http://www.wwdmag.com/industrial-wastewater-recyclingreuse/ge-supply-technology-sagd-project

Industry	Location	Technology	Reuse/Recycle	Reference
JACOS (Japan Canada Oil Sands Ltd.—Hangingstone Expansion Project	Alberta, Canada	Aquatech's Vertical Tube Falling Film Evaporator Technology	Treat and recover >95% of once-through steam generator blowdown to supply boiler feed water makeup for heavy oil production facility.	http://www.wwdmag.com/evaporators/aquatech-provide-evaporator-technology-hangingstone-oil-sands-project
Osum Oil Sands Corp.—Taiga Project	Cold Lake, Alberta, Canada	Veolia Water Solutions & Technology: • AutoFlot induced gas flotation • Power-clean oil removal filter technologies for secondary de-oiling process • HPD® evaporators process de-oiled produced water	Provide high quality water to once-through steam generators and treat resulting blowdown. Evaporator system will recover >93% of water from SAGD operations for reuse. No freshwater in the extraction process will be used, instead using high salinity water for makeup demand for steam generation.	http://www.wwdmag.com/veolia-water%E2%80%99s-produced-water-treatment-chosen-taiga-project-alberta
Barnett Shale—Chesapeake	Barnett		Treat and reuse 6% of water needed to drill and fracture Barnett Shale well southern play.	
Fayetteville Shale—Chesapeake	Fayetteville		Meet ~6% of drilling and fracturing needs in with produced water reuse, with a goal of 20% reuse.	
Marcellus Shale Play	WWTP in western PA; McKean Co. owned and operated by Casella-Altela Regional Environmental; Clarion Co. owned and operated by Clarion Altela Environmental	AltelaRain process - thermal distillation	Each facility can process up to 12,000 b/d (~500,000 gal) of wastewater, which can be reused for well operations or discharged into surface waterways.	http://www.halliburton.com/public/multichem/contents/Papers_and_Articles/web/Feb-2014-Oil-Gas-Facilities-Article.pdf

Industry	**Location**	**Technology**	**Reuse/Recycle**	**Reference**
Utica Shale—Chesapeake	Utica Shale	• Chemical precipitation with aluminum chloride to remove suspended solids • Simple 100 µ filter for remaining solid removal • Biocide dosing throughout process to control bacteria	Treated water is tested and blended in subsequent completion operations	
Mississippi Lime—Chesapeake	Mississippi Lime wells	Specially designed completion chemical packages can handle high volumes of high TDS produced water without reduction in well performance.	Direct reuse program on horizontal Mississippi Lime wells that utilized 100% high TDS produced water	http://www2.epa.gov/sites/production/files/documents/mantell.pdf
Wolfcamp play	TBD	Bosque Systems (water management)	Reuse 100% of flowback and produced water. Company leases land and sets up tanks containing up to 40,000 bbls of recycled water and other equipment to capture, treat, and make water available for operator. Bosque Systems allows for blending up to 30% recycled and treated water at the well site within producers' operations.	http://www.bosquesystems.com/reuserecycle.html
Texas's Eagle Ford shale	Texas	Dow Water & Process Solutions and Omni Water Solutions: Omni's Hippo mobile water treatment unit, includes Dow ultrafiltration and Dow Filmtec Reverse Osmosis	>245,000 barrels of flowback and produced water reused for subsequent well operations without having to blend in additional freshwater.	http://www.omniwatersolutions.com/blog/recycle-of-produced-and-flowback-water-in-eagle-ford-shale-texas-picks-up-momentum-with-omni-water-solutions-and-dow-water-process-solutions/

Industry	Location	Technology	Reuse/Recycle	Reference
Geopure Hydrotechnologies	TBD	TBD	Treat produced water and fracture flowback for reuse.	http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-water-use-in-association-with-oil-and-gas-activities/
Aftermath Environmental	TBD	TBD	Treat produced water and fracture flowback for reuse.	http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-water-use-in-association-with-oil-and-gas-activities/
Water Rescue Services Holdings	TBD	TBD	Treat produced water and fracture flowback for reuse.	http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-water-use-in-association-with-oil-and-gas-activities/
Halliburton Energy Services Inc.	TBD	TBD	Treat produced water and fracture flowback for reuse.	http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-water-use-in-association-with-oil-and-gas-activities/
Express Energy Services	TBD	trailer-mounted units with clarification, filtration, and reverse osmosis units	Treat produced water and fracture flowback water for reuse as fracturing fluid makeup.	http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-water-use-in-association-with-oil-and-gas-activities/
CES SWD Texas, Inc.	TBD	trailer-mounted units with separator, dissolved air flotation unit, water softening units, clarifier, and filters	Treat produced water and fracture flowback water for reuse as fracturing fluid makeup.	http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-water-use-in-association-with-oil-and-gas-activities/
Bear Creek Services	TBD	forward osmosis in its treatment process	Treat reserve out fluids, firewall water, and fracture flowback water for reuse during the well completion process.	http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-water-use-in-association-with-oil-and-gas-activities/

Industry	Location	Technology	Reuse/Recycle	Reference
Fountain Quail Water Management	Jacksboro	Instead of hauling unusable return fracture fluids to a disposal well, fracture flowback fluid is stored in tanks on location and piped into treatment equipment. Natural gas produced on location is used to fire distilling units that boil returned fracture fluid and produce distilled water.	Reuse ~80% of returned fracture fluids, involves on-site distilling units that apply heat to separate brine resulting from fracturing gas formations into a relatively small volume of concentrated brine disposed of in a disposal well and a large volume of distilled water that can be reused to fracture additional wells. Fountain Quail has processed >16.19 million barrels of returned fracture fluid to recover >12.38 million barrels of reusable distilled water, which can be used to fracture treat another well.	http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-water-use-in-association-with-oil-and-gas-activities/

Notes: SAGD=steam-assisted gravity drainage; TBD=to be determined; TDS=total dissolved solids; WWTP=wastewater treatment plant; ZLD=zero liquid discharge

Treatment Methods Based on Type of Reuse

Treatment processes may vary depending on the desired water reuse. Water reuse for external purposes requires water of higher quality than current internal reuse that recycles produced water within the shale gas industry for subsequent hydraulic fracturing operations.

A few examples on recommended treatment methods for underground reinjection, hydraulic fracturing, surface discharge, and irrigation are presented in the following sections.

1. *Underground injection*. Produced water managed through underground injection generally does not need to be treated because injection wells are designed to confine the produced water to the receiving formation and prevent it from migrating to underground sources of drinking water. In some cases, however, to meet an injection well's operating requirements or prevent premature plugging of the formation, the water may be treated to control excessive solids, dissolved oil, corrosion, chemical reactions, or the growth of bacteria and other microbes. Such treatment may include:
    - Storing the water in a tank to allow solids to settle out and passing it through a screen or filter to remove additional solids.
    - Adding chemicals to prevent corrosion of the injection well equipment.
    - Using filtration or biocides to prevent bacteria, algae, or fungi present in the water from clogging equipment or encouraging corrosion.
2. *Hydraulic fracturing*. Producers who reuse produced water for hydraulic fracturing treat the water to meet their own operating requirements. Water is typically treated to a very high quality before reusing it for hydraulic fracturing; however, current experiments are ongoing to evaluate the effect of lower levels of treatment. For example, salt might no longer be removed from the produced water reused for hydraulic fracturing. This lower level of treatment can reduce operating costs and operational problems, such as equipment corrosion.
3. *Discharge to surface water bodies or irrigation*. If produced water is going to be discharged to surface water or reused for irrigation, then pretreatment is often necessary to reduce hardness, salts, and other contaminants, in addition to settling and filtration methods to remove solids. Hardness is typically removed prior to removing salts by adjusting the pH of the water and adding chemicals that cause dissolved calcium and magnesium to form small solids, or precipitates, which then settle or are filtered out of the water with the aid of additional processes. As an alternative, when produced water is going to be reused for irrigation, calcium or magnesium may be added to the water to address sodium levels. Treatment technologies, including distillation, reverse osmosis, and ion exchange, are then used to remove salt and other contaminants. Reverse osmosis generally requires a high level of pretreatment to prevent fouling of the membranes.

Typical Reuse Applications

Produced water management decisions are influenced by a number of factors including (GAO, 2012; U.S. EPA, 2011):

- Costs
- Need for treatment and disposal
- Quantity of produced water generated. A continuous and conspicuous volume will increase the economic efficiency of reusing the produced water from one well in another.
- Duration in time of produced water generation (including the rate at which water is generated and how it declines over time).
- Water quality and chemistry
- Proximity and region-specific factors (e.g., geology, climate,)
- Regulatory requirements at the federal or state level
- Producers' risk management policies (e.g., liabilities associated with surface discharges and impoundments are a driving factor in moving away from those practices and toward underground injection)

Management of produced water includes the following options:

1. *Underground injection* to the same or a different formation to increase oil production (Ahmadun et al., 2009). The vast majority of produced water in the United States (>98% for produced water from onshore oil and gas wells) is injected underground via the federal Underground Injection Control program, either to maintain pressure in active formations or for disposal (Shaffer et al., 2013). This program is designed to prevent contamination of aquifers that supply public water systems by ensuring the safe operation of injection wells. Under this program, the U.S. Environmental Protection Agency (U.S. EPA) or the states require producers to obtain permits for their injection wells by, among other things, meeting technical standards for constructing, operating, testing, and monitoring the wells. EPA also regulates the management of produced water through surface discharges under the Clean Water Act. Other management practices, such as disposal of the water into surface impoundments, irrigation, and reuse for hydraulic fracturing, are regulated by state authorities (GAO, 2012).
2. *Reuse in oil and gas operations* for dust control, vehicle washing, power plant makeup water, and fire control (Ahmadun et al., 2009). Successful internal reuse can reduce the freshwater demands for subsequent hydraulic fracturing operations and produced water disposal costs. Internal reuse has expanded as shale gas producers have experimented with reusing produced water that has not been desalinated. For internal reuse, produced water is often blended with freshwater to reduce the high dissolved solid concentration and mitigate its effects on fluid viscosity. Internal reuse of produced water with elevated concentrations of dissolved solids must also consider factors such as corrosion of well materials, scaling that impedes gas flow to the well, and the effects of varying salinity on clay swelling within the formation.
3. *Hydraulic fracturing of additional wells*. The water is typically treated first, either on- or off-site, and then mixed with freshwater if salt concentrations remain high. Although no national estimate of producers' use of this practice is available, a 2009 report on shale gas development reported that interest in this type of reuse for produced water was high.

However, the report also noted that certain water treatment challenges needed to be overcome to make this type of reuse more widespread (GAO, 2012).

4. *Discharge into the environment*. Produced water is often permitted to be discharged to the environment (e.g., ocean, surface water, surface impoundments), depending on the water toxicity and organic loading, to meet on- and offshore discharge regulations. These management practices are typically employed only for high quality produced water with relatively low dissolved solid concentrations (Shaffer et al., 2013). Less than 1% of produced water generated from onshore oil and gas operations in 2007 was managed by discharging it to surface water (GAO, 2012).
5. *Beneficial reuse*. When reused, produced water is typically recycled for irrigation, wildlife watering and habitats, rangeland restoration, drinking water, or cattle and animal consumption. Produced water with lower dissolved solids (<30,000 ppm TDS) may be feasible for treatment to reuse outside of oil and gas operations. Water with higher dissolved solids (>30,000 ppm TDS) should only be reused where the high salt/salinity content can be kept in solution to avoid the intense energy input to separate salts. Conventional treatment processes can be used on high TDS waters, which are then managed by blending the fluids in hydraulic fracturing operations. These management practices are typically employed only for high quality produced water with relatively low dissolved solid concentrations (Shaffer et al., 2013). Direct beneficial reuse of produced water in the United States is limited by the Clean Water Act to livestock watering or agricultural uses west of the 98th meridian (Shaffer et al., 2013). The suitability of water for irrigation depends on a number of factors, including type of crops grown, soil type, irrigation methods, and types and quantity of salts dissolved within. In addition, the reliability of the produced water supply over time, proximity to the irrigation site, and costs also present challenges.

External reuse requires much higher water quality than current internal reuse practices that recycle produced water within the shale gas industry for subsequent hydraulic fracturing operations (Shaffer et al., 2013). In the Marcellus shale, from 2008 through 2011, new regulations caused the shift away from treatment facilities that ultimately discharge to surface water in favor of other management strategies in response to concerns about increasing TDS concentrations in the receiving waters. The primary disposal method has shifted from municipal wastewater treatment facilities to industrial wastewater treatment facilities to underground injection wells and reuse for subsequent well development.

Recent data from Pennsylvania show that internal reuse is now the most common produced water management practice, and in 2012, 90% of produced water was reused for hydraulic fracturing operations (without desalination to remove dissolved solids; Shaffer et al., 2013). The most significant regulatory changes were the requirement that produced water be treated at a centralized treatment facility before discharge to surface water or a municipal treatment facility and the establishment of a monthly average TDS concentration limit of 500 mg/L in the discharge. However, this reuse strategy is only a temporary solution. As shale gas production in the Marcellus shale play matures, opportunities to reuse produced water in developing new wells will decline while produced water pumping from established wells continues. Whenever produced water volumes exceed demand for internal reuse, producers in the region will be driven toward external reuse opportunities, which require desalination of produced water.

The associated water produced from the coal seam gas (CSG) wells is either pumped to a water treatment plant for desalination, discharged into the environment, reinjected into coal seam wells, or treated for beneficial uses. The desalination plant from the QCLNG project is reported to produce 10 ML of brine per day, with the recovery yield from reverse osmosis of 90% treated water and 10% saline brine (Rimos et al., 2012).

Environmental and economic benefits may directly correlate when evaluating reuse versus disposal. For example, in areas with extensive saltwater disposal well infrastructure like the Barnett Shale, saltwater disposal wells are in close proximity to operations and are a low cost, low energy, safe, and effective alternative to advanced reuse. The energy requirements needed to treat Barnett Shale produced water (outside of direct filtration and blending) is significant. Because all energy sources result in some form of air emissions, water use, or waste generation; reusing produced water in this area using an advanced treatment technology may have greater negative environmental impacts than saltwater disposal. Furthermore, oil and gas operations that keep dissolved solids in solution and use the fluid in completion operations for subsequent wells can effectively reduce the volume of freshwater needed for future operations by significant amounts.

The onshore shale oil and gas industry has recently been very successful in utilizing conventional, low energy treatment systems to remove suspended solids from produced water and using this water in hydraulic fracturing operations. This is a much more efficient use of energy and water than treating produced water to drinking water standards (U.S. EPA, 2011).

Performance Evaluation and Analysis of Treatment Technologies

Various methods are used to evaluate water treatment performance:

1. Five-step ranking
2. The Gas Research Institute proposed a program to assess technologies for control strategies and water management in the gas industry.
3. Treatment technologies comparison

Case Studies

Case Study 1: GE Technology to recycle produced water at Italian oil field

The crude oil production site at the Tempa Rossa oil field in Corleto Perticara, in the Basilicata region of southern Italy, will use General Electric (GE)'s advanced evaporator and zero liquid discharge (ZLD) technology to recycle up to 98% of produced water. Total E&P Italia SpA has six wells in the Tempa Rossa oil field, which, along with the nearby Val d'Agri oil field, will create enough oil to meet approximately 10% of Italian oil needs. The Tempa Rossa oil field needed an energy-efficient solution to treat the water and meet stringent discharge regulations, and GE's technology was deemed the best technology for recycling water at this facility. Oil wells can produce enormous quantities of water, and this produced water needs to be treated or hauled away from the site. At the Tempa Rossa oil field, GE's ZLD crystallizers will demineralize the produced water, which will be available for firefighting. The remaining brine will be concentrated into solid salt crystals for disposal. The ZLD technology will meet new national environmental regulations governing water discharge.

GE will provide two identical produced water treatment units that including de-oiling, forced circulation brine concentration, evaporation, and crystallization for ZLD. GE's multiple-effect, steam-driven units will be used for concentration and crystallization. Vapors generated during the evaporation process are condensed in GE energy air condensers and air coolers to meet the required temperature for demineralized water production and firefighting reuse. The technology will treat up to 52 m^3 per hour of feed water per line and will be able to recover up to 98% of produced water as distillate and solids. The delivery is expected to be completed by the first quarter of 2015, with installation by the third quarter of 2015.

Case Study 2: Canadian Oil Sands Project to recycle produced water with GE evaporation technology

Grizzly Oil Sands ULC has selected GE's produced water evaporation technology for its Algar Lake project near Fort McMurray, Alberta, Canada. Phase 1 of the Algar Lake Steam-Assisted Gravity Drainage (SAGD) project will produce 5000 to 6000 barrels per day of bitumen and, by using GE's produced water evaporation process, will recycle up to 97% of the produced water. Grizzly's Algar Lake is one of three recent projects, including Harvest Black Gold, to choose evaporative technology to treat and recycle its SAGD wastewater, helping to minimize water consumption and comply with the Alberta Energy Resources Conservation Board regulations and directives pertaining to water use.

Coupled with GE's proprietary contaminant reduction system, the technology can produce a high quality distillate suitable for use as feed water to high-pressure drum boilers. As projects in Alberta's oil sands continue to grow, so does the potential for large quantities of wastewater. Developers of oil sands resources are increasingly turning to evaporative and ZLD technologies to address this critical issue. Until recently, SAGD produced water could not be recycled as boiler feed water because conventional treatment technologies were unable to produce the necessary quality. The evaporation process and contaminant reduction system achieve complete water recycling. They dramatically reduce freshwater requirements and also offer lower total capital and operating costs.

Case Study 3: Canadian Oil Sands project to recycle produced water with GE evaporation technology

Sunshine Oilsands Ltd. has selected GE's produced water evaporation technology for its West Ells project in Fort McMurray, Alberta, Canada. The SAGD project will initially produce 10,000 bpd of bitumen—5000 bpd for each of the first two phases—and by using GE's produced water evaporation process will recycle 98% of the wastewater produced by the heavy oil production technique. Sunshine expects its West Ells site to eventually produce more than 100,000 bpd of bitumen. Sunshine continues a trend of oil producers choosing GE's patented evaporative technology to treat and recycle SAGD produced water, enabling it to minimize makeup water consumption and comply with the Alberta Energy Resources Conservation Board regulations and directives pertaining to water use. The GE evaporator systems at West Ells will treat de-oiled produced water, boiler and heat recovery steam generator blowdown, and brackish makeup water to produce a high quality distillate suitable for use as feed water for conventional drum boilers.

Under the contracts for Phases 1 and 2, GE is supplying its fourth-generation, fully modularized evaporator systems to achieve the lowest total installed costs. These module designs incorporate years of experience and optimizations resulting from numerous modularized evaporator projects designed and supplied by GE to clients in the Canadian Oil Sands. Sunshine currently is installing the Phase 1 evaporator system, with the first steam milestone scheduled for mid-2013. The Phase 2 system is expected to be delivered in December 2013.

The Canadian Oil Sands has emerged as a critical resource in the world oil market, producing 1.6 Mbpd of heavy oil or bitumen in 2011. This is up 13% from 2010, and growth is forecast to continue, reaching 3.3 Mbpd by 2020 and 5.4 Mbpd in 2045, according to the Canadian Energy Research Institute.

Case Study 4: Canadian Oil Sands Project to recycle produced water with GE evaporation technology

GE reported that MEG Energy Corp. has selected its evaporation technology for Phases 2B and 3A of the Christina Lake Project, located in northern Alberta, Canada. GE's evaporators will be used to recycle a significant portion of the steam generator blowdown for reuse as boiler feed water. The Christina Lake project uses both cogeneration and once-through steam generators (OTSGs) to drive the SAGD process for the production of bitumen, a heavy crude oil produced from oil sands. MEG Energy will use GE evaporators to treat its OTSG blowdown and recycle it as boiler feed water, as opposed to disposing of it by deep well injection. GE will supply fifth-generation, fully modularized evaporator systems, which are designed to achieve the lowest possible project costs.

Case Study 5: Canadian commercial project to recycle 99% of produced water

Brion Energy (formerly Dover Operating Corp.) selected GE's produced water evaporation technologies for Phase 1 of the MacKay River Commercial Project (MRCP) near Fort McMurray, Alberta, Canada. The MRCP will utilize a SAGD technique to responsibly produce bitumen. By using GE's produced water evaporation process, the project will recover 99% of the produced and makeup water for reuse as boiler feed water. The MRCP has an ultimate design capacity of 150,000 bpd that will be achieved across four phases; Phase 1 will contribute the first 35,000 bpd.

The MRCP joins many other projects in the Canadian Oil Sands region to choose GE's patented evaporative technology to treat and recycle its SAGD produced water. GE's technology is helping producers minimize water consumption and comply with the Alberta Energy Resources Conservation Board regulations and directives pertaining to water use. This project is an example of the growing trend toward produced water evaporation on green field SAGD projects that is due, in part, to economic benefits offered by evaporators and drum boilers over traditional water treatment and once-through steam generation technologies. With the addition of GE's proprietary contaminant reduction system, the produced water treatment system will produce a high quality distillate suitable for use as feed water to conventional drum boilers.

GE will provide the MRCP with a complete produced water treatment and reduced liquid discharge system, including three primary evaporator units and one concentrator unit. The system will incorporate GE's fifth-generation module design for enhanced project certainty and reduced total installed cost. The equipment and modules will ship to the site in early 2014; commercial operation is scheduled for late 2014.

Case Study 6: Athabasca Oil selects GE Technology for SAGD project

Athabasca Oil Corp. has awarded GE a contract to design and supply an integrated evaporator system for its 12,000 bpd Hangingstone Oil Sands operation located near Fort McMurray in northeastern Alberta, Canada. GE's produced water evaporation process will enable the treatment of produced water from the Hangingstone facility's SAGD process, combined with the use of brackish makeup water in lieu of fresh makeup water. The water treatment system will recover 97% of the produced water and brackish makeup water as boiler feed water to drive the SAGD process.

GE's produced water evaporation solution has become the technology of choice for SAGD projects in the Canadian oil sands region as it helps producers minimize water consumption and disposal, reduce environmental footprint, and improve operating efficiencies. GE will provide Athabasca with two evaporator units, which will include GE's split-sump design for enhanced energy efficiency. The system also will incorporate GE's fifth-generation module design to meet the customer's need for an enhanced project schedule and cost certainty. GE will deliver the equipment to the site in the third quarter of 2013; with commercial operation expected to begin in 2014.

Case Study 7: Aquatech to provide evaporator technology for Hangingstone Oil Sands project

Aquatech has been awarded a contract to provide its evaporator technology for the Japan Canada Oil Sands Ltd. (JACOS) Hangingstone Expansion Project in Alberta, Canada. Aquatech's Vertical Tube Falling Film evaporator technology will be used to treat and recover over 95% of the OTSG blowdown to supply boiler feed water makeup for the heavy oil production facility.

The Hangingstone project, which is located approximately 50 km southwest of Fort McMurray, is a joint venture of JACOS and Nexen Energy ULC, a wholly owned subsidiary of CNOOC Ltd. The bitumen production capacity during the initial stage will be approximately 20,000 bpd.

Case Study 8: Veolia Water's produced water treatment chosen for Taiga project in Alberta

Osum Oil Sands Corp. will use water treatment technologies from Veolia Water Solutions & Technologies to process produced water from its Taiga project at Cold Lake in Alberta, Canada.

Osum will produce bitumen utilizing the in situ SAGD process, beginning production in 2013. This produced water treatment system consists of AutoFlot induced gas flotation and power-clean oil removal filter technologies for the secondary de-oiling process.

Evaporators will then process the de-oiled produced water to provide high quality water to the OTSGs as well as treat the resulting blowdown. The produced water treatment system is an example of the adoption of technologies and directives by Osum to minimize the impact of the Taiga project on the surrounding environment. The evaporator system will recover over 93% of the water from SAGD operations for reuse in the process. More important, Osum will use no freshwater in the extraction process, instead using high salinity water for makeup demand for steam generation. The Silica Sorption Process used in the evaporator package was designed to tolerate the use of this brackish water that is unfit for consumption. Flexible disposal of the evaporator concentrate from the Silica Sorption Process allows minimal treatment and safe handling of waste prior to disposal. Osum plans to use on-site disposal facilities for this concentrate in an effort to reduce truck traffic in the area.

Case Study 9: Barnett Shale

Chesapeake is currently treating and reusing approximately 6% of the total water needed to drill and fracture Barnett Shale wells in the southern portion of the play. Current logistics and economics are the main limiting factors in preventing higher levels of reuse in this area. These factors as well as urban curfew limitations (limited 24 hour operations in urban Fort Worth areas) currently prevent the feasibility of reuse in Chesapeake's northern Barnett Shale operational areas (U.S. EPA, 2011).

Case Study 10: Fayetteville Shale

Chesapeake is currently meeting approximately 6% of drilling and fracturing needs in the Fayetteville Shale with produced water reuse, with a target goal of 20% reuse in the play. Because TSS levels are low, very limited treatment (filtration) is needed prior to reuse. As with Barnett Shale, logistics and economics are currently the main limiting factors in preventing higher levels of reuse.

Case Study 11: Altela's thermal distillation process

A recently introduced technology for water decontamination in the Marcellus shale play implements an internal heat transfer process. Altela's thermal distillation process heats wastewater to produce clean water vapor by using an internal heat transfer process that reuses the latent heat of condensation to offset the total latent heat of evaporation required in conventional thermal distillation.

Wastewater is converted into clean, distilled water and a concentrated solution of dirty water (Figure I.1). By recapturing the energy used to evaporate water, the AltelaRain process yields about four times the amount of distilled water per energy input as traditional distillation and evaporation techniques, without using pressure (Bruff and Jikich, 2011). The process begins with the produced water that is collected in an on-site holding tank. Following its transfer by pump to a containerized system, the produced water is circulated continuously through 10 towers. The towers are designed to evaporate pure water from the brackish produced water. The evaporated water is then condensed within the same tower, on the opposite side of thin plastic sheets.

The condensed water, which is of distilled water quality, is collected and transferred from the towers to a holding tank. The remaining water is eventually concentrated up to a TDS content five times higher and then pumped out of the system for disposal. The distilled water is also pumped from the system and made available for recycling and reuse. The water quality of the treated distilled water meets or exceeds Pennsylvania Department of Environmental Protection's water quality discharge requirements.

Two wastewater treatment facilities using the technology are located in western Pennsylvania. The facility located in McKean County is owned and operated by Casella-Altela Regional Environmental Services. Situated adjacent to the McKean County landfill, the facility uses landfill gas as its energy source. Owned and operated by Clarion Altela

Environmental Services, the facility located in Clarion County uses waste heat from the waste coal–fired Piney Creek Power Plant. Each facility is able to process up to 12,000 bpd (~500,000 gallons) of wastewater, which can then be reused for well operations or discharged into surface waterways. Bruff and Jikich (2011) reported the total treatment cost as U.S.$5.29/bbl at the completion of a National Energy Technology Laboratory demonstration project in 2011, prior to the technology's implementation at the wastewater treatment facilities. The cost included trucking and disposal of the concentrated dirty water. This total cost represented a savings of 16% compared to trucking and disposal costs without treatment by the system.

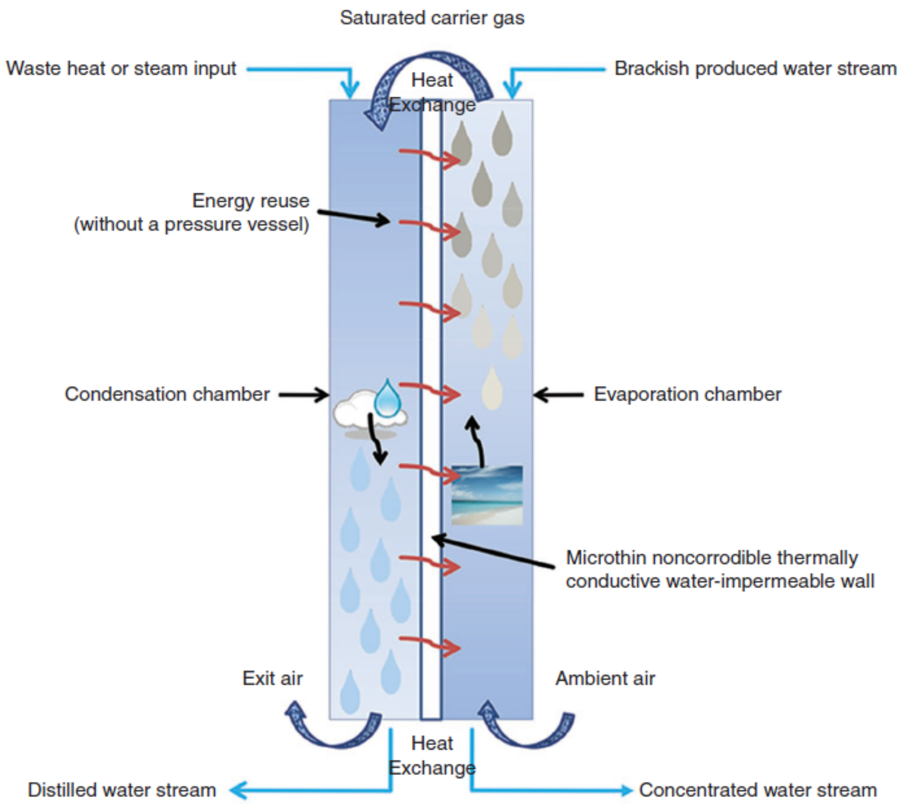

Figure I.1. Altela's thermal distillation process.

References

Bruff, M. and Jikich. S.A. Field Demonstration of an Integrated Water Treatment Technology Solution in Marcellus Shale. *U.S. Department of Energy/National Energy Technology Laboratory*. Presented at the SPE Eastern Regional Meeting held in Columbus, Ohio, August 17–19, 2011.

Fakhru'l-Razi, A.; Pendashteh, A.; Abdullah, L. C.; Biak, D. R. A.; Madaeni, S. S.; Abidin, Z. Z. Review of technologies for oil and gas produced water treatment. *J. Hazard. Mater*. **2009,** *170* (2), 530–551.

National Petroleum Council (NPC). North American oil and gas play types. Report by North American Resource Development Study, September 2011.

Pankratz, T. Desalination technology trends. Biennial Report on Seawater Desalination: Volume 2. Texas Water Development Board: Austin, TX, 2004. http://texaswater.tamu.edu/readings/desal/desaltechtrends.pdf (accessed June 2015).

Rimos, S.; Hoadley, A. F.; Brennan, D. J. Consequence analysis of scarcity using impacts from resource substitution. *Procedia Eng.* **2012,** *49*, 26–34.

Shaffer, D. L.; Arias Chavez, L. H.; Ben-Sasson, M.; Romero-Vargas Castrillón, S.; Yip, N. Y.; Elimelech, M. Desalination and reuse of high-salinity shale gas produced water: drivers, technologies, and future directions. *Environ. Sci. Technol.* **2013**, *47* (17), 9569–9583.

U.S. Environmental Protection Agency (U.S. EPA). EPA Hydraulic Fracturing Study Technical Workshop #4 Water Resources Management. A presentation by Chesapeake Energy, March 29–30, 2011.

U.S. Government Accountability Office (GAO). Energy–Water Nexus: Information on the Quantity, Quality, and Management of Water Produced during Oil and Gas Production. A Report to the Ranking Member, Committee on Science, Space, and Technology, House of Representatives, January 2012.

Appendix J

Water Recycling/Reuse in the Power Industry

Thermoelectric power plants produce 90% of the electricity used in the United States. These facilities can utilize several fuel sources (coal, nuclear, oil, natural gas, concentrated solar) and prime movers (steam turbines, gas combustion turbines, combined-cycle gas turbines that include combustion and steam turbines) to generate power (Scanlon, 2013). Power plants that produce electricity using steam turbine prime movers are the most water intensive because the steam-cooling step accounts for the majority of the water used in the power industry (Veil, 2007; Ayert et al., 2011; U.S. EPA, 2013b). In a steam-driven thermoelectric power facility, water is heated in a boiler to create high-pressure steam for the turbines that drive electricity generators, and then the steam is condensed back to water to be used in the process again. Figure J.1 presents a schematic of this power generation process. According to the U.S. Geological Survey's water use survey data (2004), power generation processes accounted for 39% (136 Bgpd) of all freshwater withdrawals in the nation in 2000 (Feeley et al., 2008) and 4% of total state water consumption in 2010 within Texas (Scanlon, 2013).

Three basic cooling technologies are utilized and influence the amount of cooling water that is required. Once-through or open-loop systems withdraw the cooling water from a source only one time and then discharge the heated water back to the source. Recirculating or closed-loop systems withdraw only a fraction of the volume used in once-through systems but consume more water because evaporation must be used to condense the steam. Dry-cooled systems use almost no water because they rely on air blown across steam-carrying pipes for cooling, but they are inefficient when ambient air temperatures are high. All these cooling systems, as well as hybrid combinations, contribute to environmental stress because of their high rates of water withdrawal and consumption.

Older thermoelectric power plants primarily utilized once-through cooling, but restrictions on their environmental impacts (e.g., aquatic life impingement and entrainment, warm water discharge) from enactment of the Federal Water Pollution Control Act in 1972, together with a decline in plentiful source water supplies in arid regions with growing populations, resulted in use of recirculating systems for new facilities installed since the mid-1970s (U.S. DOE, 2006). Within the United States, once-through cooling technology accounts for 30%, recirculating cooling technology accounts for 54%, dry-cooled technology accounts for 2%, and cooling ponds account for 13% of total power generation (Ayert et al., 2011). Because plants equipped with recirculating cooling water systems consume almost five times as much water as once-through systems on a gallon per kilowatt-hour basis, the quantity of water consumed by freshwater recirculating systems is a concern in light of Clean Water Act 316(b) regulations that favor the use of freshwater recirculating cooling systems for new thermoelectric power plant operations (Feeley et al., 2008).

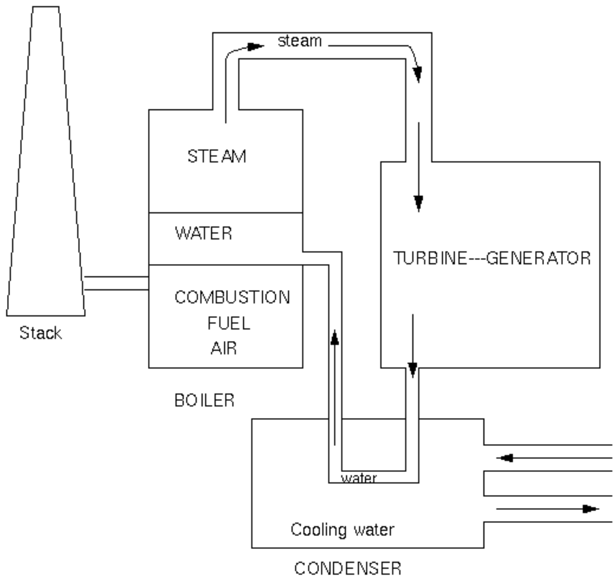

Figure J.1. Schematic of thermoelectric power facility.

Source: http://pubs.usgs.gov/chapter11/chapter11_AFrame_73.gif.

Water requirements for electric power generation are highly variable and primarily influenced by type of plant, fuel, and choice of cooling system and secondarily influenced by local climate, water source, environmental regulations to which the plant must comply, and the water management system employed (EPRI, 2008). A summary of national average water withdrawal and consumption factors for thermoelectric plants utilizing wet cooling towers is provided in Table J.1 (Feeley et al., 2008); values for Texas can be found in Scanlon et al. (2013). In China 80% of coal-fired power units operate their water cooling systems with a concentration ratio of less than three. Water consumption is reduced when the cycle of concentration (COC) in the cooling system is in the range of four to five (Pan et al., 2012). A plant with a 1000 to 1300 MW capacity would normally require around 60 to 80 million L/day of water (translates to a factor range of 0.51 to 0.88 gal/kWh) for a COC of five to six (Power Engineering International, 2012).

U.S. Department of Energy (U.S. DOE) National Energy Technology Laboratory cites higher water consumption factors for pulverized coal (PC) and integrated gasification combined-cycle (IGCC) facilities and provides values for fluidized-bed combustion (FBC), as summarized in Table J.2. The same source states that an IGCC plant generally produces fewer water effluents than PC and FBC plants, and that the amount of process water blowdown is about the same for these plants. In addition, the steam cycle in IGCC power plants yields lower amounts of wastewater blowdown because less than 50% of the total power generated comes from the steam cycle (http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/aqueous-effluents-wastewater).

Table J.1. Summary of National Average Water Withdrawal and Consumption Factors for Thermoelectric Plants Utilizing Wet Cooling Towers, 2005

Generation Type	Withdrawal factor (gal/kWh)	Consumption factor (gal/kWh)
Pulverized coal	0.463–0.669*	0.394–0.518*
Nuclear	1.101	0.624
Oil and natural gas	0.25	0.16
Natural gas combined cycle	0.15	0.13
Integrated gasification combined cycle	0.226	0.173

Note: *Range due to differences in boiler (subcritical or supercritical) and type of fluidized gas sulfurization (wet, dry, or none).
Source: Adapted from Feeley et al., 2008.

Table J.2. Water Consumption Estimates for IGCC vs. PC and FBC Plants

	Conventional PC-Fired Plant with Advanced Pollution Controls	FBC Plant	IGCC Plant
Water consumption, gallons/kWh	0.600–0.660	0.570–0.625	0.360–0.540

Notes: FBC=fluidized-bed combustion; IGCC=integrated gasification combined cycle; PC=pulverized coal.
Source: http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/aqueous-effluents-wastewater

Rutberg (2003) developed a system-level generic model (S-GEM) of water use at thermoelectric power plants in response to the limited granularity and poor quality of field data on U.S. power plant water use. The findings, summarized in Table J.3, provide ranges of water consumption intensities for combined-cycle gas, coal, nuclear, geothermal, and concentrated solar power from a metastudy of the literature. Validation of the S-GEM using a data set from Eskom, the main public utility in South Africa, which maintains detailed accounts of water use at each of its power plants, suggested accurate predictions by the model of water consumption at wet tower-cooled power plants. Subsequent sensitivity analysis revealed that the possibilities for reducing water consumption at power plants yield only incremental results. Tuning a wet tower-cooled plant for efficiency, implementing blowdown and process water recycling schemes, and using dry FGD and ash handling all result in reduced water consumption, but on the order of perhaps 5 to 20% collectively. To achieve water consumption reductions of a factor of two or more, there are only three options: (1) switch to a more thermally efficient generation technology; (2) implement topping-cycle cogeneration; (3) use a different type of cooling system.

Among the different fuel types utilized for thermoelectric power production, natural gas withdraws and consumes the least amount of freshwater compared with other feedstocks, such as PC (Ayert et al., 2011). With an IGCC facility, water consumption is reduced because the syngas avoids the use of steam as the primary means of transferring the energy from the coal to rotational energy, and steam is only used to recover the heat from the gas turbine exhaust in a heat recovery steam generator (http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/water-usage). Water usage and loss for different technologies (e.g., IGCC, PC, and natural gas combined cycle; U.S. DOE, 2007) show that 80 to 99% of the power plant raw water consumption is through a combination of cooling tower evaporation and blowdown, and that water loss differences are highest for PC. Differences between gasification facilities relate to plant condenser duty, tracing back to plant efficiency and other uses of condensing steam, such as methods of syngas humidification or dilution.

Table J.3. Water Consumption Intensities (L/MWh) Developed Using a System-Level Generic Model Applied to Coal, Gas (Combined Cycle), Nuclear, Geothermal, and Concentrated Solar Power Case Studies

Facility Fuel Type	Number of Facility Sources	Water Consumption Intensity Range (gal/kWh)
Coal	17	~0.396–1.109
Gas (combined cycle)	5	~0.132–0.291
Nuclear	6	~0.581–0.845
Concentrated solar power	17	~0.65–1.05

Source: Rutberg, 2003.

Meldrum et al. (2013) attempted to look at life-cycle water use factors as ratios of life-cycle water use per unit of generated electricity utilizing the following equation to calculate factors for the life-cycle water consumption and withdrawal associated with each generation technology:

$$waterLC = water_{FC} * \left(\frac{fuel_{lifetime}}{e_{lifetime}}\right) + water_{pp} * \left(\frac{1}{e_{lifetime}}\right) + water_{OP}$$

Where:

$water_{FC}$ is the amount of water used in the fuel cycle (FC) per unit of fuel (expressed as gal ton^{-1} for coal, gal $MMscf^{-1}$ for natural gas, and gal kg^{-1} for converted, enriched, and fabricated uranium fuel for nuclear);

$e_{lifetime}$ is the amount of electricity generated by a power plant over its lifetime (MWh/lifetime);

$fuel_{lifetime}$ is the amount of fuel used by a power plant over its lifetime (ton/lifetime, MMscf/lifetime, or kg/lifetime, as appropriate);

$water_{pp}$ is the amount of water used for component manufacturing, power plant construction, and power plant decommissioning (gal/lifetime);

and $water_{OP}$ is the amount of water used in the operations of the power plant per unit of generated electricity (gal MWh^{-1}).

This was done by a thorough review of available literature, consideration of collective combinations that define a production pathway (e.g., consideration of generation technology subcategories, cooling technologies, or full-cycle characteristics), and utilization of the median estimate as reflective of central tendency of available data for a production pathway. Although recycling and the use of degraded water were not explicitly addressed, the results demonstrate the dominance of water use in operational cooling for most electricity generation technologies (with the exception of photovoltaics and wind) and the potential for natural gas and concentrating solar power technologies to be ranked among either the highest or lowest water users depending on cooling and prime mover technologies.

The other key usage of water in power generating facilities is in scrubber solutions to remove sulfur dioxide (SO_2) from the exhaust flue gas that arises during burning of fossil fuel to produce the steam for the turbines that drive electricity generation (Scales, 2010) or steam production of syngas (http://en.wikipedia.org/wiki/Integrated_gasification_combined_cycle). These flue gas desulfurization (FGD) systems utilize slurries of alkaline sorbent to scrub the SO_2 gases, thereby protecting the environment from acid rain formation (Scales, 2010). Water is also used for ash handling, wastewater treatment, and wash water (Feeley et al., 2008).

Drivers for Water Recycling or Water Reuse

Rising demand for freshwater, electricity, and the water–energy nexus continues to drive research to reduce water usage and improve the quality of available water within the power generation process. Thermoelectric generating capacity has been projected to increase by nearly 15% between 2008 and 2035 by the Energy Information Administration's Annual Energy Outlook 2010, and the Electric Power Research Institute (EPRI) projects the potential for future constraints on thermoelectric power by 2025 for Arizona, Utah, Texas, Louisiana, Georgia, Alabama, Florida, and all the Pacific Coast states (U.S. DOE, 2010). There is also concern about future drops in surface water levels at U.S. steam electric power plants caused by drought conditions and competing demands that could interfere with power production (U.S. DOE, 2010). A decrease in surface water levels could drive receiving water bodies into a designated status of impaired water, which could result in more stringent permitted effluent limits and, in turn, require water recycling solutions to reduce or eliminate discharges (U.S. DOE, 2009). Arid western states must ensure that water discharge reductions also abide with appropriative rights doctrine that could impede zero liquid discharge options or water discharge reductions through enhanced utilization of recycled water within a cooling system (U.S. DOE, 2009). Water reuse is increasingly a condition for eligibility for freshwater permits needed for expansion at inland-based, coal-fired thermal facilities in India, resulting in adoption of membrane-based recycle systems as part of the effluent treatment plants in order to recycle the water for cooling tower makeup (Power Engineering International, 2012).

Also of potential impact is the notice of proposed rulemaking signed by U.S. EPA on April 19, 2013, to revise the technology-based effluent limitations guidelines (ELGs) for this industry (U.S. EPA, 2013a). Under a consent decree that was subsequently revised, EPA has agreed to sign a decision taking final action on the rulemaking by September 30, 2015 (http://water.epa.gov/scitech/wastetech/guide/steam-electric/proposed.cfm). The proposed rule would strengthen the existing controls on plant discharges and set the first federal limits on the levels of toxic metals in wastewater that can be discharged from power plants (http://water.epa.gov/scitech/wastetech/guide/steam-electric/proposed.cfm).

The steam electric ELGs codified at 40CFR 423 apply to generating units utilizing fossil or nuclear fuels in conjunction with a steam system to generate electricity as the predominant source of revenue, and they include limitations for the following waste streams: once-through cooling water, cooling tower blowdown, fly ash transport water, bottom ash transport water, metal cleaning wastes, coal pile runoff, and low-volume waste sources, including but not limited to wastewaters from wet scrubber air pollution control systems, ion exchange water treatment systems, water treatment evaporator blowdown, laboratory and sampling streams, boiler blowdown, floor drains, cooling tower basin cleaning wastes, and recirculating house service water systems (U.S. EPA, 2013b).

The current effluent guidelines and standards for the steam electric power generating point source category cover pH, polychlorinated biphenyls (PCBs), TSS, oil and grease, total residual chlorine, free available chlorine, and certain metals (copper, iron, chromium, zinc), but they have not adequately addressed the toxic pollutants being discharged or kept pace with changes that have occurred in the electric power industry over the last 3 decades that have altered or created new waste streams (U.S. EPA, 2013b).

The seven waste streams targeted for technology-based standards are FGD wastewater, fly ash transport water, bottom ash transport water, and combustion residual leachate, nonchemical metal cleaning wastes, coal gasification wastewater, and wastewater from flue gas mercury control systems (U.S. EPA, 2013b). These non-cooling processes, however, are usually an order of magnitude below what is needed for cooling (Rutberg, 2003; U.S. DOE, 2009). EPA is also proposing to add provisions to the ELGs that would clarify the acceptable conditions for discharge of reused process wastewater and establish effluent monitoring requirements.

The degree to which water use at power plants is impactful (thereby serving as a driver of water conservation and recycling initiatives) will be greater in regions where concerns over water use appear as a nonnegligible factor in the levelized cost of electricity (LCOE) produced by for-profit power producers. The mechanisms through which this can occur are described in Rutberg (2003). They include:

- Direct costs of water—water supply or disposal costs become a nonnegligible fraction of levelized electricity costs
- Capital costs—water use concerns force investment in more expensive infrastructure (e.g., discharged water treatment system)
- Operating costs—cost of running water-conserving cooling systems or water treatment systems appears in the LCOE
- Capacity factor—lack of available water forces plant shutdowns, driving plant capacity factor down and the LCOE up
- Thermal efficiency—water use concerns force implementation of a plant system that decreases efficiency, increasing fuel required and thereby LCOE
- Regulated emissions—water use concerns force implementation of a plant system that results in increased regulated emissions, which must be offset by buying credits or paying taxes, which raises LCOE
- Permitting delay—water use concerns force delays in plant construction, prolonging scarcity and raising LCOE

Typical Contaminants in Waters

The water makeup streams used at different types of power plants are summarized in Table J.4. All these facilities require high purity makeup water and service water, for the recirculating cooling tower. The contaminants that are generated in these streams as they are used in the power production process differ, and the key pollutants for each of these streams are summarized in Table J.5. The water purity requirements for boiler/reactor makeup are higher than those for cooling, and those for cooling have higher requirements than those for the limestone slurry used for scrubbing SO_x out of flue gas (EPRI, 2008).

Table J.4. Water Makeup Streams Required for Different Types of Power Plants

Type of Power Facility	**Makeup Streams**
Coal-fired thermoelectric	• High purity makeup to the steam generator • Freshwater makeup to the scrubber • Service water • Ash sluice water (possibly) • Recirculating cooling tower makeup water
Simple- or combined-cycle (utilizing natural gas or fuel oil)	• High purity water, injected into the combustion turbine for NO_x control or power augmentation • Makeup to combustion turbine evaporative coolers or fogging systems • Service water • High purity makeup to heat recovery steam generators • High purity makeup to the steam generator (combined cycle) • Recirculating cooling tower makeup water
Concentrating solar power	• High purity makeup to the steam generator • High purity water for mirror washing • Service water • Recirculating cooling tower
Nuclear	• High purity makeup to the steam cycle • Service water • Recirculating cooling tower makeup water

Sources: Buecker and Clarke, 2011; http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/aqueous-effluents-wastewater

Table J.5. Key Pollutants of Power Plant Stream Effluents

Power Plant Process Wastewater	Key Pollutants
Boiler, steam cycle, or gasification block recirculating water blowdown; demineralizer waste; captured rainwater	TSS, TDS
NO_x abatement	NH_3
Equipment maintenance (equipment purges and washdowns, mirror washing for solar)	TSS, TDS, oils
FGD wet scrubber	Cl, TDS, nutrients, metals
Recirculating cooling tower blowdown	TSS, TDS (Ca, Mg, alkalinity, SO_4, SiO_2, PO_4, pH); can also contain heavy metals and organic compounds
Fly ash or bottom ash transport water	TSS, metals (arsenic, beryllium, copper, vanadium), oxides of silica, aluminum, iron, magnesium, calcium
Landfill and surface impoundment leachate containing combustion process wastes	metals, Cl, Na (similar to FGD and ash transport waters)

Notes: FGD=flue gas desulfurization; TDS=total dissolved solids; TSS=total suspended solids.
Sources: Compiled from U.S. EPA, 2013c; EPRI, 2012 http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/aqueous-effluents-wastewater; http://mydocs.epri.com/docs/PublicMeetingMaterials/0712/watertreatment_RFI_Final.pdf

Higgins and Sandy (nd) describe the contaminants from coal combustion power generation facilities. Their study states that the nitrogen dioxide (NO_x) flue gas emissions sometimes can result in passage of unreacted ammonia to the FGD wet scrubber. They further state that the wastewater from a wet scrubber FGD process is frequently combined with other water discharges from the power plant (e.g., wet fly ash handling, cooling water, steam condensate). and discharge must meet National Pollutant Discharge Elimination System (NPDES) requirements, which usually include biochemical oxygen demand (BOD), total suspended solids (TSS), heavy metals, selenium, arsenic, boron, temperature, pH, total dissolved solids (TDS), and other contaminants.

The U.S. DOE characterization of power plant water effluent streams cites two similar streams produced by coal gasification plants and direct-fired power plants (http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/aqueous-effluents-wastewaters):

- Wastewater from the steam cycle (e.g., blowdown from boiler feed water purification system, cooling tower) that contains concentrated salts and minerals, with the quantity of water dependent on the hardness of the raw water and the power generated by the steam cycle
- Process water blowdown that is typically high in dissolved solids and gases, including trace metals, trace organics, and commonly found species of chloride, fluoride, sulfide, formate, nitrogen, cyanide, thiocyanate, and bicarbonate

Detailed analyses of combined process wastewater discharged at the Wabash River IGCC power plant, consisting of cooling tower blowdown, gasification plant process wastewater, regeneration wastewater from the demineralizer in the power block, rainwater collected in gasification and power blocks, equipment purges (blowdowns), and water washdowns during maintenance procedures, contained ammonia, cyanide, selenium, zinc, and occasional arsenic and copper (http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/waste-water-discharges).

Current Technologies for Treatment of Wastewater

Power plant process operation and treatment methods concentrate waste stream contaminants into low volumes that are becoming difficult to discharge in conformance with water quality and quantity requirements. These waste streams (wastewaters from cooling tower blowdown, filter backwash, boiler blowdown, roof and floor drains, and sump discharges) often require further volume reduction prior to discharge or need to become part of a zero liquid discharge configuration; this can be achieved using an evaporator/crystallizer or proper pretreatment to remove problem constituents ahead of reverse osmosis, which then potentially converts 75% of the waste stream into clean makeup water for the plant while further minimizing the volume of wastewater (Buecker and Clarke, 2011).

Typical recycling applications of the blowdown streams cited by U.S. DOE (http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/aqueous-effluents-wastewater) include the coal feed preparation area, scrubber after entrained solids have been removed, zero discharge water system, or a wastewater treatment system, provided that accumulation of salts can be effectively handled to meet the constraints or metallurgy requirements of the process.

For coal plants, additional treatment is needed for the wet FGD systems. Highly complex FGD wastewater typically requires multiple treatment steps such as calcium sulfate desaturation with lime injection to precipitate gypsum ($CaSO_4 \cdot H_2O$), primary solids removal, trace metals precipitation, possible addition of a sulfide active group polymer to capture mercury for removal as sludge, and secondary solids removal in order to meet NPDES requirements. Many of the primary and tertiary wastewater treatment technologies being constructed by the power industry today haven't been demonstrated full-scale on actual FGD wastewater, and there is a need to share lessons learned (Higgins and Sandy, nd; Buecker and Clarke, 2011).

Typical Reuse Applications

Power plants have historically relied upon reverse osmosis or evaporator/crystallizer systems to recycle waste streams and achieve zero liquid discharge (EPRI, 2008). Such applications have occurred on a case-by-case basis depending upon the size of the plant, quality of the blowdown stream, site-specific permitting requirements, and resultant costs (http://www.waterworld.com/articles/iww/print/volume-12/issue-05/feature-editorial/examining-zld-options-for-electric-power-facilities.html).

The NETL has been sponsoring research since 2002 examining the energy–water link in coal-based power plants under the Existing Plants, Emissions and Capture Program (formerly known as the Innovations for Existing Plants Program) that focuses on advanced cooling technologies, water reuse and recovery, nontraditional sources of process and cooling water, and advanced water treatment and detection technology (U.S. DOE, 2009). These studies have been performed with numerous research partners, and appropriate examples pertinent to on-site water reuse at power facilities are described herein..

Much of the research on use of reclaimed water for thermoelectric power plant cooling has focused on introduction of lower quality, nontraditional water sources such as municipal treated water/reclaimed water (Stillwell and Webber, 2014; U.S. DOE, 2009), produced waters from oil and gas wells, mine pool waters, produced waters from carbon dioxide (CO_2) storage in saline formations, and ash pond basins (U.S. DOE, 2009). At this time, on-site industrial water conservation and recycling for recirculating cooling towers is largely dependent upon development of technologies to minimize blowdown so higher COC can be achieved, capturing water lost in the evaporation process, or cooling the intake air to gas turbines used for power generation to condense pure water for reuse applications.

Drexel University is evaluating electrical pulse spark discharges in water to precipitate dissolved mineral ions and remove them using a self-cleaning filter from cooling water in order to demonstrate that mineral scale on condenser tubes can be prevented or minimized at a COC of eight or zero blowdown (Cho et al., 2008; Cho and Fridman, 2012). SPX Cooling Technologies built and operated the first Air2Air Water Conservation Cooling Tower at a power plant and demonstrated the capability of an air-to-air heat exchanger above the wet fill media of the cooling tower in order to condense water from the hot, saturated, moist air leaving the cooling tower at an evaporate water recovery rate of 10 to 25% annually based on cooling tower location climate (Mortensen, 2009, 2012). The University of Pittsburgh investigated an ice thermal storage (ITS) technology to cool the intake air to gas turbines, and results demonstrated that the use of the ITS technology improved power generation capacity, with the added benefit of water recovery in power plant operation, and further development is warranted (Chiang and Weismantel, 2004).

Utilization of RO-treated cooling tower blowdown for reuse as cooling tower makeup or boiler feed remains challenging because of mineral scaling of the membrane, which precludes acceptable technology performance. EPRI and the University of California, Los Angeles (UCLA) Water Technology Research Center are seeking to overcome this limitation through development and demonstration of a novel RO operational paradigm that builds upon a UCLA-patented membrane monitor (MeMo). The MeMo system will allow RO plants to operate self-adaptively near the maximum water recovery levels while maintaining operational reliability in mitigating mineral scaling through a self-cleaning cyclic mode of feed flow reversal or other cleaning methods, triggered by MeMo as shown in Figure J.2 (http://www.powermag.com/advanced-cooling-and-water-treatment-technology-concepts-for-power-plants/?pagenum=5).

The University of North Dakota's Energy and Environmental Research Center (EERC) developed a liquid, desiccant-based dehumidification technology to extract water vapor from coal-fired power plant flue gases in order to reduce makeup water requirements for the plant's cooling water system (Feeley et al., 2010). A 700 MW coal plant flue gas may contain approximately 1000 to 2400 equivalent liquid gpmof water, and the amount varies with coal moisture and treatment process (EERC, 2009).

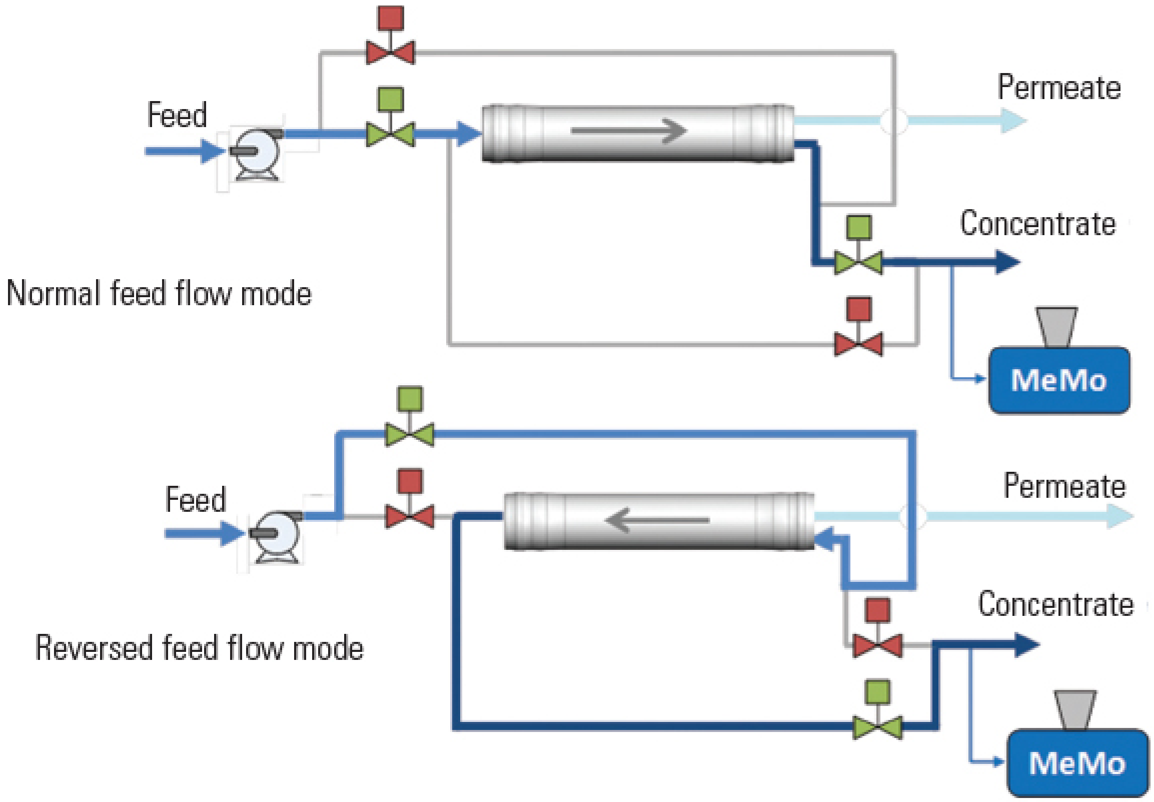

Figure J.2. Utilization of UCLA-patented membrane monitor (MeMo) for operation of reverse osmosis plants self-adaptively near maximum water recovery levels while maintaining operational reliability in mitigating mineral scaling.

Sources: http://www.powermag.com/advanced-cooling-and-water-treatment-technology-concepts-for-power-plants/?pagenum=5; Gu et al., 2013.

In addition to these NETL research activities, examples of water recycle/reuse or zero discharge being practiced at U.S. power plant facilities are provided in Table J.6.

Table J.6. Examples of Water Recycle/Reuse or Zero Discharge at U.S. Power Plant Facilities

Plant Name	Plant Type	Issue/Solution	Environmental Benefit	Cost Saving	Source
Wabash River	IGCC	Process wastewater is steam stripped to remove dissolved gases before recycling to slurry preparation or being discharged. An ammonia stripper is used to remove ammonia and remaining trace components.	Water is purified sufficiently to allow reuse or discharge within permit limits.	not reported	http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/aqueous-effluents-wastewater
Polk Power	IGCC	Process water (graywater) blowdown stream goes to a vapor compression concentrator, followed by crystallization of brine into a salt consisting mostly of ammonium chloride. Size of the blowdown stream that needs to be treated is determined by: (1) process water balance and distribution—is the water consumed by the process (the gasifier) more or less than the water coming in with the coal and purges?—and (2) salt (chloride) buildup in the process water loop, almost entirely a function of chloride in the coal.	The clean condensate from this system is recycled to the process.	Not reported, but the plant has eliminated process water discharge at a cost of operating several treatment systems.	http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/aqueous-effluents-wastewater
Edwardsport	IGCC	Denial by EPA of graywater disposal through deep injection wells resulted in selection of an alternative wastewater treatment solution utilizing evaporation and crystallization using Veolia HPD.	Usable distilled water is recovered, and hazardous solid stream requiring disposal is minimized.	Not reported, but, there is an energy penalty impacting the IGCC plant heat rate and significant capital for the brine concentrator plant.	http://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/aqueous-effluents-wastewater

Plant Name	Plant Type	Issue/Solution	Environmental Benefit	Cost Saving	Source
Reliant Energy	Coal-based thermos-electric power plant, Cheswick, PA	Evaluated feasibility of using three impaired waters (secondary treated municipal wastewater, passively treated abandoned mine drainage, and effluent from ash sedimentation ponds at power plants) for use as makeup water in recirculating cooling water systems at thermoelectric plants. Only ash sedimentation pond effluent fell within on-site industrial water reuse/recycling category; this portion of the study investigated the corrosivity of ash transport water to the metal alloys commonly used in cooling water systems and effectiveness of common corrosion inhibitors via a bench-scale recirculating water system configuration.	Average volume of bottom ash pond overflow should provide small portion (~25%) of average makeup water needed in a recirculating cooling system if corrosion can be controlled. A corrosion inhibitor, such as tolytriazole, was needed to inhibit corrosion from copper in the ash pond effluent, and a phosphorus-based corrosion inhibitor was needed to protect mild steel. Aluminum pitting corrosion was unacceptable with all corrosion inhibitors. Less scaling occurred with ash pond effluent than other off-site impaired waters.	not reported	Vidic and Dzombak, 2009
Panda Power Funds	Natural gas combined-cycle gas turbine, Sherman, TX	Facility, consisting of two combustion turbines and a combined-cycle steam generator, will utilize water from Lake Texoma as its cooling water source. Commercial operation is scheduled for late 2014.	GE's ZLD technology (brine concentrator and crystallizer) will treat 450 gpm of water, of which 98% will be reused in the process.	not reported	(http://www.waterworld.com/articles/2013/01/water-recycling-technology-to-help-two-tx-power-plants-reduce-wa.html); (http://www.watertechonline.com/articles/165965-ges-zld-wastewater-treatment-technology-to-be-installed-at-texas-power-plants
Panda Power Funds	Natural gas combined-cycle gas turbine, Temple, TX	Facility, consisting of two combustion turbines and a combined-cycle steam generator, will utilize nearby wastewater treatment plant effluent as its cooling water source. Commercial operation is scheduled for late 2014.	GE's ZLD technology (crystallizer) will treat 450 gpm of water, of which 98% will be reused in the process.	not reported	(http://www.waterworld.com/articles/2013/01/water-recycling-technology-to-help-two-tx-power-plants-reduce-wa.html); (http://www.watertechonli

Plant Name	Plant Type	Issue/Solution	Environmental Benefit	Cost Saving	Source
					ne.com/articles/165965-ges-zld-wastewater-treatment-technology-to-be-installed-at-texas-power-plants)
Progress Energy	Mayo Generation Station, Roxboro, NC	Installation of a new partial ZLD treatment system for flue gas desulfurization wastewater consisting of a falling film evaporator technology with a secondary forced circulation evaporator.	Distillate is recycled for use as scrubber makeup or boiler feed water. Brine is mixed with plant fly ash and disposed of in a new on-site landfill.	not reported	http://www.waterworld.com/articles/iww/print/volume-12/issue-05/feature-editorial/examining-zld-options-for-electric-power-facilities.html
	Indiantown Cogeneration plant in Martin County, FL	Replaced failing brine concentrator ZLD with microfiltration and RO to treat cooling tower blowdown. Initial problems with microbiological fouling were solved by microbiocide, and scaling in second-stage RO was solved by lowering pH of feed water to 5.	Filtered water is returned for use in the facility, and reject water is processed through a spray drier absorber system.	New RO system offers significant savings and is expected to pay for itself in 3 years.	http://www.waterworld.com/articles/iww/print/volume-12/issue-05/feature-editorial/examining-zld-options-for-electric-power-facilities.html
Georgia Power	Plant Bowen, Cartersville, GA	Demonstration support of EPRI's Water Management Technology program proof-of-concept pilot tests and near commercial scale system studies of cost-effective and reliable treatment technologies to achieve advanced cooling technologies to reduce water consumption through moisture recovery from flue gas and reuse of wastewater streams within the power plant by removing species that cause scaling or corrosion. Program inception occurred in 2013.	Seven distinct focus areas: • moisture recovery • cooling tower and advanced cooling systems • ZLD • low-volume wastewater treatment • solid landfill water management • carbon technology water issues • water modeling, monitoring, best management practices	not reported	http://www.epri.com/Our-Portfolio/Pages/Portfolio.aspx?program=073222; http://www.georgiapower.com/docs/environment/WRC-Brochure.pdf

Notes: EPA=U.S. Environmental Protection Agency; EPRI=Electric Power Research Institute; GE=General Electric; HPD=; IGCC=integrated gasification combined cycle; RO=reverse osmosis; ZLD=zero liquid discharge.

Case Studies

Case Study 1: Southern California gas-fired power plant cooling tower blowdown recycling (http://www.duraflow.biz/pdfs/Case-Study-Power-Plant-Cooling-Tower-Blowdown-Recycle.pdf)

A treatment process train consisting of chemical softening, tubular microfiltration, and two-stage RO was installed in 2004 at a gas-fired power plant located in Southern California. The RO permeate is recycled as makeup water to the cooling tower, and the RO brine is fed to a two-stage evaporator/crystallizer to create dry salt crystals that are sent to a landfill. The distillate from the evaporator/crystallizer is used as makeup water for the heat recovery steam generators, and the balance is recycled as makeup water for the cooling tower.

The chemically pretreated wastewater is pumped at a velocity of 12 to 15 ft/sec and an average flux of over 300 GFD through a cross-flow microfiltration (MF) membrane system with an automatic back-pulse mechanism for physical surface cleaning and a 1 to 1.5 week module cleaning frequency. There are 10 tubes per module, 36 modules per skid, and 6 skids for a total of 216 modules. The MF filtrate reduces the turbidity to less than 1.0 NTU, the calcium to less than 20.0 mg/L, magnesium to less than 10.0 mg/L, SiO_2 to less than 10.0, and the COD to less than 120 mg/L. The RO permeate reduces the turbidity to less than 0.5 NTU, the calcium to less than 1.0 mg/L, magnesium to less than 0.5 mg/L, SiO_2 to less than 1.0 mg/L, and the COD to less than 5.0 mg/L. A schematic of the process is provided in the reference.

Case Study 2: Membrane technology operational support of zero discharge Colstrip, MO coal-fired steam electric station (http://www.wwdmag.com/membranes-reverse-osmosis/power-plant-reuse)

When operations of a zero discharge permitted facility were threatened by maintenance of storage ponds with approximately 1 billion gallons of inventory, treatment capable of allowing reuse of the high TDS water was needed. Membrane treatment and evaporation/crystallization were short-listed because other options (e.g., ion exchange, electrodialysis, thermal evaporation) exhibited inherent qualities that made them unsuitable for this application. A tight project timeframe resulted in selection of MF and RO, but the need for two-stage softening with high lime and soda ash ahead of the MF–RO resulted in consideration of a vibratory shear-enhanced processing (VSEP) membrane technology. VSEP, manufactured by New Logic Research, uses nanofiltration (NF) or RO that incorporates torsional vibrating action to hinder contact fouling of the membrane, which eliminates the need for softening ahead of the process.

A 4-month pilot-testing period in 2008 demonstrated that 75% recovery at 210 psi could achieve the desired permeate quality, with cleaning required about every 5 days and permeate conductivity adequate for introduction into the raw water feed to the plant. Results of the pilot demonstrated that one membrane module could treat an average of 45 gpm with 75% recovery; the full-scale VSEP installation provides an average conductivity of 1600 uS/cm at this recovery. The selected NF-270 NF membranes are not capable of rejecting monovalent ions, which is not presently required.

Case Study 3: San Juan Generating Station water recycling system (EPRI, 2009)

A highly integrated water recycling system was described in EPRI (2009) for the San Juan Generating Station, a plant located in the Four Corners area of New Mexico. Five waste process streams consisting of cooling tower blowdown, boiler blowdown, plant drains, occasional coal pile runoff, and occasional ash system overflow enter a process wastewater pond and receive multipronged treatment in order to produce multiple levels of effluent water quality that are then reused for different processes within the power generating facility commensurate with the qualities that are produced.

The highest quality is achieved by using both distillation and demineralization for use as boiler makeup water. The intermediate quality distilled water is used as cooling tower makeup water, and the lowest quality goes directly from the wastewater point to the FGD limestone precipitation operation. Despite these reuse and recycling efforts, 97.5% of the incoming power station water is consumed by evaporation/drift from the cooling tower, FGD water loss to flue gas, or steam losses. Additional water that is lost through disposal includes FGD slurry dewatering, FGD purge water, ash system water, and occasional boiler cleaning water.

On September 26, 2014, U.S. EPA approved a revised state plan to comply with federal haze regulations and put New Mexico down the path toward compliance with new carbon regulations by closing two of four units at the San Juan Generation Station in order to achieve significant reductions of water use and emissions at the plant and a cleaner and more balanced power supply (http://www.poweronline.com/doc/epa-approves-revised-state-plan-for-pnm-s-san-juan-generating-station-0001).

Conclusions

The predominant use of water in the power industry arises from the cooling required to remove surplus heat from the steam circuit, the inherent limitation of turning heat into mechanical energy. Although direct or once-through wet cooling has minimal impact on the consumptive use of water, increasing water scarcity and more stringent regulatory restrictions limiting use of once-through cooling have greatly increased water consumption from implementation of recirculating cooling systems. In addition, power facilities that can no longer meet discharge restrictions are driven toward zero liquid discharge operations that are achievable through implementation of low-pressure membranes with RO or evaporators with crystallizers. Such systems are then able to recycle water as boiler feed makeup or for other uses within the facility.

As of 2011, only about 67 electric utilities in the United States were using reclaimed water for cooling at power generation facilities, and a U.S. DOE (2009) study found that nearly 50% of existing coal-fired power plants in the United States have sufficient off-site reclaimed water available within a 10-mile radius to meet their needs (Johnson Foundation at Wingspread, 2014). Implementation of reclaimed water for power plant cooling was documented (Veil, 2007), but current information remains highly dispersed, with a detailed list only maintained by certain agencies, such as Florida Department of Environmental Protection (http://www.dep.state.fl.us/water/reuse/industry).

Reclaimed water in use at power plant cooling towers is primarily an off-site supply of wastewater effluent or another outside source of impaired water because potential sources of recycled water within a power facility are inadequate for the cooling requirements. Although tuning a wet tower-cooled plant for efficiency, implementing blowdown and process water recycling schemes, and using dry FGD and ash handling all result in reduced water consumption, they still only represent a 5 to 20% reduction collectively.

To achieve a water consumption reduction factor of two or more, there are only a few options: (1) switch to a more thermally efficient generation technology; (2) implement topping-cycle cogeneration; (3) use a different type of cooling system; (4) use degraded water from off-site sources; or (5) implement recycled water offsets from a recycled water producer. Most new power installations utilize CCGT, which provides the benefits of items (1) and (2) ; numerous research projects have focused on furthering the evaluation, development, and implementation of items (3) and (4).

A summary of current water management technology research projects provided by EPRI focuses on: (1) technology watch of alternatives to current cooling and wastewater treatment; (2) removal of trace metals (e.g., selenium, mercury, arsenic) and other compounds of concern from wet FGD discharges; (3) alternative cooling tower techniques with lower water requirements through predictive monitoring of detrimental chemistry conditions and novel design of cooling systems and condenser tubing coatings; and (4) water conservation and recycling through use of degraded water sources for cooling, treatment of wastewater streams to enable reuse within the plant, and reducing water consumption needs of FGDs (http://www.,epri.com/Our-Portfoli/Pages/Portfolio.aspx?program=073222).

References

Ayert, K.; Fisher, J.; Huber-Lee, A.; Lewis, A.; Machnick, J.; Madden, N.; Rogers, J.; Tellinghuisen, S. Freshwater use by U.S. power plants: Electricity's thirst for a precious resource. A report of the Energy and Water in a Warming World Initiative: Union of Concerned Scientists: Cambridge, MA, November 2011.

Buecker, B.; Clarke, B. Controlling water usage and wastewater discharge. *Power Engineering*, September 1, 2011. http://www.power-eng.com/articles/print/volume-115/issue-9/features/controlling-water-usage-and-wastewater-discharge.html (accessed June 2015).

Chiang, S.-H.; Weismantel, G. A. Novel Concept for Reducing Water Usage and Increasing Efficiency in Power Generation. Final report, March 2004. http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/water/41544-Final-Report.pdf (accessed June 2015).

Cho, Y. I.; Fridman, A. A. Application of Pulse Spark Discharges for Scale Prevention and Continuous Filtration Methods in Coal-Fired Power Plant. Final technical report. October 2008–June 2012. U.S. Department of Energy National Energy Technology Laboratory, July 24, 2012. http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/water/05308-Final.pdf (accessed June 2015).

Cho, Y.; Fridman, A.; Starikovskii, A. Application of pulse spark discharges for scale prevention and continuous filtration methods in coal-fired power plant. U.S. Department of Energy National Energy Technology Laboratory. October 28, 2008. http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/water/Kickoff-NETL-mtg_NT0005308.pdf (accessed June 2015).

Electric Power Research Institute (EPRI). Water Treatment for Power Plant Cooling Towers: A supplement to the EPRI 2012 RFI for those unfamiliar with the power industry. Slide deckguide of resources available for the EPRI 2012 "Development of Innovative Water Treatment and Cooling Technologies for Power Plant Water Consumption Reduction" http://mydocs.epri.com/docs/PublicMeetingMaterials/0712/watertreatment_RFI_Final.pdf

Electric Power Research Institute (EPRI). Water Use for Electric Power Generation. EPRI: Palo Alto, CA, February 2008. www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductID=000000000001014026 (accessed June 2015).

Energy and Environmental Research Center (EERC). Water Extraction from Fossil Fuel-Fired Power Plant Flue Gas, ACC Users Group Workshop, Las Vegas, November 12–13, 2009. http://acc-usersgroup.org/wp-content/uploads/2011/02/Folkdale-Water-Presentation-ACC-Users-Group-11-11-09.pdf (accessed June 2015).

Feeley, T.; Pletcher, S.; Carney, B.; McNemar, A. T. Department of Energy/National Energy Technology Laboratory's Power Plant-Water R&D Program, 2010. http://www.circleofblue.org/waternews/wp-content/uploads/2010/08/Thermoelectric-Power-Plants.pdf (accessed June 2015).

Feeley, T. J. III; Skone, T. J.; Stiegel, Gary J. Jr.; McNemar, A.; Nemeth, M.; Schimmoler, B.; Murphy, J. T.; Manfredo, L. Water: A critical resource in the thermoelectric power industry. *Energy* **2008,** *33,* 1–11.

Gu, H., Bartman, A. R.; Uchymiak, M.; Christofides, P. D.; Cohen, Y. Self-adaptive feed flow reversal operation of reverse osmosis desalination. *Desalination* **2013**, *308*, 63–72.

Higgins, T. E.; Sandy, A. T. An overview of coal-fired power plant FGD wastewater treatment—Coal combustion and emissions control. *Industrial WaterWorld*, nd. http://www.waterworld.com/articles/iww/print/volume-6/issue-6/columns/trends-technology/an-overview-of-coal-fired-power-plant-fgd-wastewater-treatment-coal-combustion-and-emissions-control.html (accessed June 2015).

Johnson Foundation at Wingspread. Navigating to New Shores: Seizing the Future for Sustainable and Resilient U.S. Freshwater Resources. The Johnson Foundation at Wingspread: Racine, WI, 2014. http://www.johnsonfdn.org/sites/default/files/reports_publications/CNW_NavigatingToNewShoresFullReport.pdf (accessed June 2015).

Meldrum, J.; Nettles-Anderson, S.; Heath, G.; Macknick, J. Life cycle water use for electricity generation: A review and harmonization of literature estimates. *Environ. Res. Lett.* **2013,** *8*, 1–18.

Mortensen, K. Use of Air2Air Technology to Recover Fresh-Water from the Normal Evaporative Cooling Loss at Coal-Based Thermoelectric Power Plants. Final report, September 30, 2009. http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/water/42725--Final.pdf (accessed June 2015).

Mortensen, K. Improvement to Air2Air Technology to Reduce Fresh-Water Evaporative Cooling Loss at Coal-Based Thermoelectric Power Plants. Final report, June 30, 2012. http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/water/05647-Final.pdf (accessed June 2015).

Pan, L.; Liu, P.; Ma, L.; Li, Z. A supply chain based assessment of water issues in the coal industry in China. *Energ. Policy* **2012,** *48*, 93–102.

Power Engineering International. Rethinking coal fired power plants' water reuse. Print publication, January 5, 2012. http://www.powerengineeringint.com/articles/print/volume-20/issue-5/features/rethinking-coal-fired-power-plants-water-reuse.html (accessed June 2015).

Rutberg, M. J. Modeling Water Use at Thermoelectric Power Plants. MS Thesis, Swarthmore College, Swarthmore, PA, June 2003. http://dspace.mit.edu/bitstream/handle/1721.1/74674/815966188.pdf?sequence=1 (accessed June 2015).

Scales, K. Operation and performance testing of the Dominion, VA power plant's new FGD Densadeg clarifier system. Proceedings Paper, 83rd Annual Water Environment Federation Technical Exhibition and Conference, New Orleans, LA, October 2–6, 2010.

Scanlon, B. R.; Reedy, R. C.; Duncan, I.; Mullican, W. F.; Young, M. Controls on water use for thermoelectric generation: Case study, Texas, U.S. *Environ. Sci. Technol.* **2013,** *47,* 11326–11334.

Stillwell, A.S.: Webber, M. E. Geographic, technologic, and economic analysis of using reclaimed water for thermoelectric power plant cooling. *Environ. Sci. Technol*. **2014**, 48, 8, 4588-95.

U.S. Department of Energy (U.S. DOE). Energy Demands on Water Resources. Report to Congress on the Interdependency of Energy and Water. December 2006.. http://www.circleofblue.org/waternews/wp-content/uploads/2010/09/121-RptToCongress-EWwEIAcomments-FINAL2.pdf.

U.S. DOE. Power plant water usage and loss study. National Energy Technology Laboratory, revised May 2007. http://netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/WaterReport-Rev-May2007.pdf (accessed June 2015).

U.S. DOE. Use of non-traditional water for power plant applications: An overview of DOE/NETL R&D efforts. November 1, 2009. http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/water/Use-of-Nontraditional-Water-for-Power-Plant-Applications.pdf (accessed June 2015).

U.S. DOE. National Energy Technology Laboratory's Water–Energy Interface Research Program: December 2010 Update. http://www.alrc.doe.gov/technologies/coalpower/ewr/water/pdfs/Water_Program_Overview.pdf (accessed June 2015).

U.S. Environmental Protection Agency (U.S. EPA). Proposed Effluent Limitation Guidelines & Standards for the Steam Electric Power Generating Industry. EPA-821-F-13-002, April 2013a. http://water.epa.gov/scitech/wastetech/guide/steam-electric/upload/proposed_factsheet.pdf (accessed June 2015).

U.S. EPA. Technical Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category. EPA-821-R-13-002, April 2013b. http://water.epa.gov/scitech/wastetech/guide/steam-electric/upload/Steam-Electric_TDD_Proposed-rule_2013.pdf (accessed June 2015).

U.S. EPA. Environmental Assessment for the Proposed Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category. EPA-821-R-13-003, April 2013c. http://water.epa.gov/scitech/wastetech/guide/steam-electric/upload/Steam-Electric_EA_Proposed-rule_2013.pdf (accessed June 2015).

U.S. Geological Survey (USGS). Estimated use of water in the United States in 2000. Circular 1268. USGS: Reston, VA, March 2004.

Veil, J. A. Use of reclaimed water for power plant cooling, Argonne National Laboratory ANL/EVS/R-07/3. August 2007. http://www.veilenvironmental.com/publications/pp/ANL-EVS-R07-3_reclaimedwater.pdf

Vidic, R. D.; Dzombak, D. A. Reuse of Treated Internal or External Wastewaters in the Cooling Systems of Coal-Based Thermoelectric Power Plants, Final technical report, Cooperative Agreement Number: DE-FC26-06NT42722, September 2009. http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/water/42722FSRFG063009.pdf (accessed June 2015).




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