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Article

Opportunities and Challenges for Industrial Water Treatment and Reuse

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ABSTRACT: As the impact of water scarcity in the United States (U.S.) continues to grow through the 21st century, it is critical to develop strategies to reduce water use and improve the security of water resources. One such strategy is to diversify the sources from which water is supplied. Industrial withdrawals represent the fourth largest category of U.S. water use, the majority of which is sourced from fresh surface and groundwater. In this study, we critically explore the potential of industrial wastewater to serve as an alternative water resource through direct treatment and reuse. We begin by reviewing the state of the art of water use, treatment, and reuse across six representative industries: food and beverages, primary metals, pulp and paper, petroleum refining, chemicals, and data centers and campuses, highlighting key challenges and opportunities toward the expansion of reuse. We then employ a technoeconomic assessment of water treatment processes to analyze the capital investment, operating and maintenance costs, levelized cost of water, and electricity consumption of three specific industrial plants as case studies to better understand where research can promote impactful innovation. Finally, drawing together the results of our literature review and technoeconomic analyses, we provide a broad outlook on the future of industrial water reuse and discuss strategies for its expansion.

KEYWORDS: *water reuse, industrial wastewater treatment, manufacturing, techno-economic assessment, waste valorization*

1. INTRODUCTION

Direct water withdrawals by the industrial sector represents the fourth largest category of water use in the United States (U.S.), behind electricity generation, irrigation, and municipal supply.[1] According to the U.S. Geological Survey (USGS), self-supplied industrial water usage accounted for 56 million m^3/day (14 800 million gallons per day (MGD)) or ∼5% of all water withdrawals in the U.S. in 2015.[1] On the basis of previous estimates by Rao et al. of municipally supplied water for industry, another 1% of water withdrawals in the U.S. can be attributed to industry, bringing its share to 6% of total U.S. withdrawals.[2] Of all self-supplied industrial withdrawals, 82% were from surface water, 94% of which was freshwater.[1] Note that these figures do not include mining or the production of oil and gas, which are often categorized separately in the literature.

Just as people require clean and safe water for their daily living, industry requires suitably clean water to maintain its functions. A sustainable growth of industry cannot be guaranteed without a sustainable supply of water. However, water scarcity is increasingly being recognized as a challenge for industry in the U.S., potentially limiting its growth or even survival in some cases. The challenge is likely to be exacerbated by the effects of pollution and climate change as well as competition with other sectors that require water for their sustained growth, such as the agriculture, residential, and commercial sectors. As a result, the U.S. Government Accountability Office projects that a majority of U.S. states will experience a water shortage within the next two decades.[3] The U.S., along with China, India, Japan, Mexico, and Brazil, are among the countries where industrial and consumer sectors are at the highest risk for water shortages.[4] Water shortages can damage industrial growth by forcing businesses to relocate

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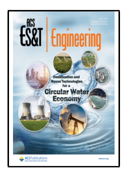

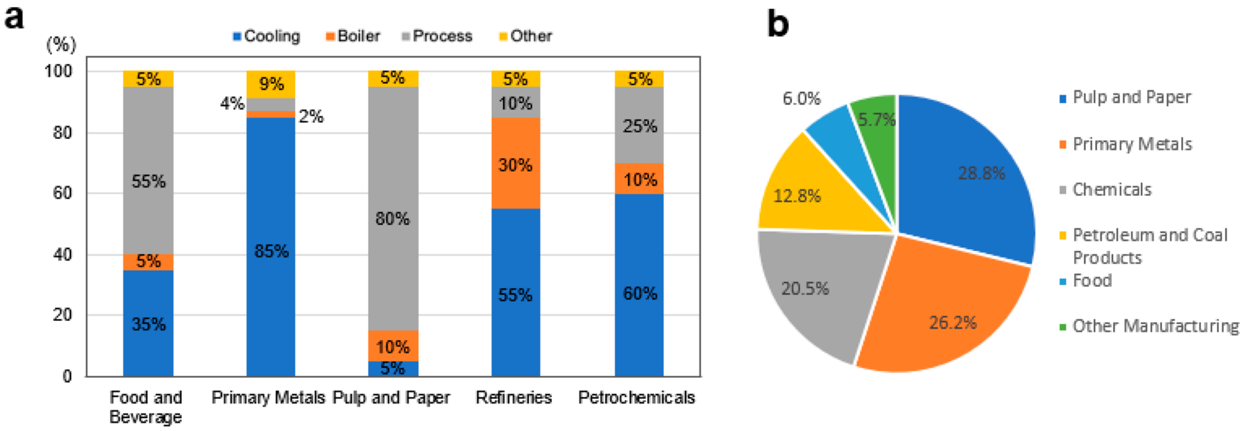

Figure 1. (a) Fraction of water used for cooling water, boiler feedwater, process water uses, and other uses based on a survey of manufacturing facilities in Texas, 1998.[10] (b) Estimated total U.S. manufacturing water intake by industry.[5] Note that the industrial subsectors denoted in each panel do not align exactly with one another. For instance, petrochemicals and refineries in (a) are not equivalent to chemicals and petroleum and coal products in (b), respectively.

their facilities, modify processes to require less water, or pay higher prices for water, which may lead to a manufacturing disruption or loss of competitiveness to those in more water-abundant regions.[5] These combined pressures call for industries to proactively reconsider their current water-use practices in favor of more sustainable and resilient solutions.

The U.S. Bureau of Labor Statistics recognizes 21 separate manufacturing industries by the North American Industry Classification System (NAICS) three-digit code in manufacturing alone (Table S2, note that the USGS considers these 21 manufacturing industries plus Construction when reporting on industrial water withdrawals).[6] Because of this considerable diversity, it is impractical to consider industry as a unified water-use sector. Rather, a careful examination of several representative industries can be extended to help a wider range of industries develop strategies that suit their specific needs and constraints. On the basis of several criteria, including the share of total industrial water withdrawals, economic importance, and wastewater composition, we therefore limit the scope of our study to food and beverages, primary metals, pulp and paper, petroleum refining, and chemicals. Additionally, we include data centers and large university campuses, as these have some overlapping water loads (e.g., process cooling and steam generation). We focus our discussion on the reuse and recycling of water within industrial facilities to understand how to provide a more sustainable water source for these industries and alleviate future water shortages in the U.S.

Though previous attempts to summarize the existing literature on this topic have been reported, some of the most recent holistic reviews of industrial water use and/or reuse were published over four decades ago.[7−9] We herein aim to bridge this gap by establishing a broad perspective on the current state of the art in industrial water use, reuse, and wastewater treatment in industry. We first discuss how water is used within each selected industry based on characteristics of their manufacturing processes. We then describe how wastewater is treated and recycled, with a focus on the identification of opportunities to expand water reuse and recycling. A new open-source decision support tool developed by The National Alliance for Water Innovation (NAWI) for technoeconomic assessments of water treatment processes, called Water-TAP3, is introduced and used to analyze total capital investment, operating and maintenance costs, levelized cost of water (LCOW), and electricity intensity of three specific industrial plants as case studies. Built upon an extensive review of six industries and the results of three example analyses, we further discuss opportunities, challenges, and research needs to enhance water reuse and recycling and to improve the resiliency of these water-dependent industries.

2. INDUSTRIAL WATER USE, TREATMENT, AND REUSE

Three dominant categories of water use in industry are cooling water, boiler feedwater, and process water. Proportions of water used for each of these three purposes vary greatly by industrial subsector and the type of facility (Figure 1). For example, water used for cooling can comprise as much as 90% of the total water use in petrochemical plants[10] or as little as 25% in some food-processing plants.[11] On the one hand, because systems for cooling water and boiler makeup, where water primarily serves as an energy transfer medium, share many common issues and configurations across industrial subsectors, we will first discuss these features collectively. The uses for process water, on the other hand, vary substantially across industry and will be covered individually for each subsector.

2.1. Cooling and Boiler Feed Waters. *Types of Cooling Systems.* Cooling accounts for the single largest category of water use in industries such as chemicals and primary metals manufacturing.[10,12,13] The purposes of cooling vary, ranging from air conditioning and refrigeration to direct or indirect cooling of molten metal. However, the configurations of cooling systems often share key commonalities. In general, cooling systems can be classified into three categories: once-through cooling systems, open-recirculating (evaporative) systems, and closed-recirculating systems, each of which presents unique advantages and disadvantages. Although direct quantitative comparisons between the water and energy impacts of these systems are scarce, there are numerous studies that compare once-through and open-recirculating cooling systems for hydrothermal energy production.[14−17] We therefore refer to data from hydrothermal powerplants in the following paragraphs to give the reader a general sense of how these categories of cooling systems compare to one another.

Once-through cooling systems operate by drawing water from a nearby source (typically fresh or saline surface water), passing

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it a single time through the facility or a heat exchanger outside of the facility, and discharging it directly back to the source.[13] These systems primarily rely on a sensible heat transfer (i.e., conduction and convection) to the water to achieve cooling. Because of a high potential for environmental impacts, chiefly from thermal shock, on the ecosystem and a discharge of pollutants, once-through systems have seen increased scrutiny from regulators and environmental advocates, leading industries to invest in other types of cooling systems.[18] This trend is further driven by the inability to economically pretreat such large volumes of water to prevent scaling and deposition.[11]

Open-recirculating cooling systems primarily rely on a latent heat transfer (i.e., evaporation) of water to cool products, equipment, and facilities. As water evaporates, more feedwater must be introduced to the system as makeup, and some water must be removed in order to prevent the buildup of constituents that can lead to common problems like scaling, corrosion, and biofouling.[13] Water removed for this purpose is referred to as *blowdown*. Common configurations of open-recirculating systems include cooling towers, evaporative condensers, and cooling ponds, all of which utilize the exchange of enthalpy from water to air.[11] The recycling of water in open-recirculating systems results in a significantly lower water intake as opposed to once-through systems. However, the evaporative losses associated with this configuration lead to problems such as scaling and microbial growth, demanding careful water quality monitoring and treatment within the system.[11,13,19] Moreover, because of evaporation, these systems will *consume* more water than once-through-cooling systems, thereby removing water from the watershed and potentially exacerbating any existing physical water scarcity issues. For a comparison, coal-fire power plants operating on once-through cooling withdraw 76 000−190 000 L/MWh and consume only 530−1140 L/MWh, while similar plants operating on wet tower once-through cooling withdraw just 1900−4430 L/MWh but consume 1700−4430 L/MWh.[15] It is also worth noting the additional energy intensity of continuous pumping that is required to prevent water quality issues in recirculating cooling systems. For example, Byers et al. reported energy penalties (i.e., energy expended on cooling) up to 3 times higher (1.8−6.3% of power plant electrical output) for power plants operating on open recirculating systems than for those with once-through systems (0.7−2.3%).[17]

It is estimated that, for a 500 ton cooling tower, ∼14 800 m^3/year (11 000 GPD) of water is wasted without being reclaimed.[20] However, high capital costs associated with current reuse technologies constitute a major challenge in economically treating blowdown water. For example, a simple blowdown treatment system with a recovery rate of 75% would cost ∼$300 000 for a 500 m^3/day (130 000 GPD) inflow.[21] If regulatory requirements demand zero liquid discharge (ZLD), systems at this level (including evaporation and crystallization) cost on the order of $3−$5 million.[21] Better treatment methods are needed to increase the number of water reuse cycles, make sure that close to 100% of water can be recycled, and reduce scaling in cooling towers.

Closed-recirculating cooling system uses cooling water an indefinite number of times within a closed system of pipes, absorbing heat from a given process. Heat is then transferred to another piece of heat-transfer equipment, typically an open-recirculating system or a series of air-cooled batteries, where it is dissipated to the atmosphere.[18] Although water loss is kept to a minimum within the closed loop, leaks are common and necessitate the addition of makeup water. Moreover, the presence of various metals in the pipe material can pose a risk of corrosion and metal leaching.[18] As a result, closed-recirculating cooling systems face many of the same problems as other cooling systems, such as corrosion, deposition, and biofouling.[11] The extent of these problems can be mitigated, however, through proper monitoring, maintenance, and control of the system.[18] Despite leaks, closed-recirculating cooling systems are typically the most water-efficient and allow for a high degree of control. Critical disadvantages, however, include a limited capacity for heat exchange as opposed to open-recirculating and once-through systems and the added complexity of piping.[13] As such, closed-recirculating systems are relatively less common throughout industry and are best suited for niche applications in industries such as chemicals and petroleum refining.[11]

Boiler Feedwater. The purpose of steam generation via boilers in industry is to transfer energy to various processes in the form of heat or for power generation. In a typical boiler process, liquid water is converted to steam through the combustion of a fuel source, such as coal or natural gas. Boiler systems require makeup water to overcome water losses attributed to steam leaks, lack of or insufficient condensate return, and blowdown. For example, it has been estimated that 1.34 million m^3/day (354 MGD) of makeup water is required annually for U.S. industrial boilers.[22] Because water is constantly leaving the boiler through evaporation, any minerals or other chemical constituents with a high boiling point contained in the feedwater are left behind, causing them to accumulate in higher concentrations. As a result, boiler feedwater, including the makeup water, must be pretreated and monitored to prevent potential issues such as scaling and corrosion. Common technologies used to treat boiler feedwater include precipitative softening, ion exchange (IX), and reverse osmosis (RO).[11] In addition, a portion of the water within a boiler must be removed (i.e., blowdown) to prevent an overaccumulation of problematic compounds. The recovery of condensate is one common approach to improving the water efficiency of boiler processes. Well-maintained steam systems can recover over 70% of condensate, with 90% recovery cited as the benchmark for best practices.[13,23] The implementation of condensate return systems may also provide large savings in terms of energy.[24]

Water Quality Concerns. Many issues that occur in cooling and boiler systems stem from three common phenomena: corrosion, scaling, and fouling. Surfaces of metallic pipes and equipment inherently feature microscopic irregularities, which lead to the formation of electrical potential differences. Corrosion occurs as the resulting electrochemical reactions drive the oxidation of metal species by oxygen or other oxidizing agents, eventually leading to an equipment failure.[11] Scaling takes place when cooling water becomes oversaturated with metal salts, such as calcium carbonate, calcium phosphate, zinc, and silicates, causing surface deposits to form within the system.[13] In addition to causing blockages, the relatively low thermal conductivity of scale reduces the efficiency of heat transfer within the system.[25] Fouling involves the deposition of suspended solids (including scaling and corrosion products) and/or growth of biofilms on equipment surfaces, which leads to blockages, thermal inefficiencies, and biocorrosion.[26] Each of these issues is closely related to one another and requires a careful system design, pretreatment, and costly maintenance

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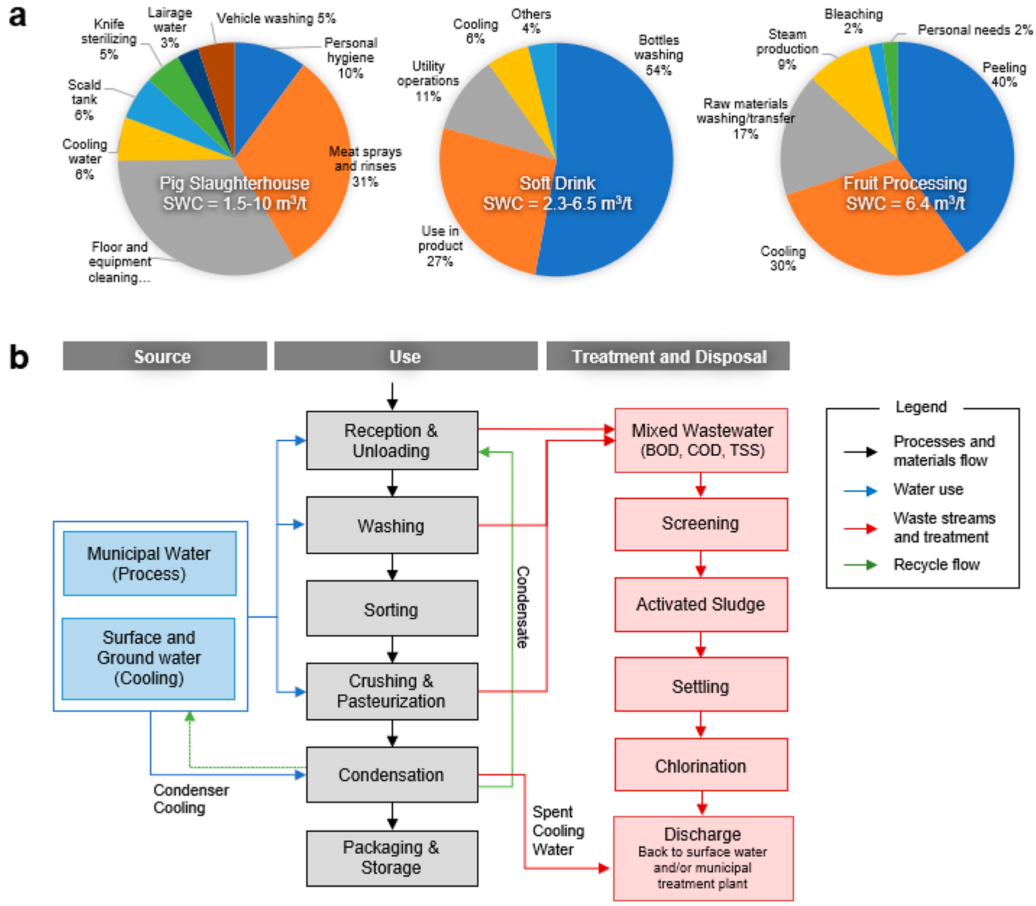

Figure 2. (a) Specific water consumption and water use breakdowns for pig slaughterhouse, soft drinks,[13,32] and fruit processing[31] industries. (b) Typical water flow diagram for a tomato processing and tomato paste canning facility.[31] The flow of water is divided into four stages: sources, use, treatment, and disposal. Blue arrows represent the flow of water, while black arrows indicate material flow.

for cleaning. For instance, corrosion can be controlled by a selection of noncorrosive metals and an addition of corrosion inhibitors; scaling can be managed by using water softeners and controlling the pH; and fouling can be prevented with a biocide addition and side stream filtration.[13]

2.2. Food and Beverage Industry. *Industry Overview.* The food and beverage industry is a major industrial water user, with the food industry representing 6% of total industrial water usage, or ~2.8 million m^3/day (740 MGD).[1,5] In 2018, food and beverage manufacturing plants accounted for 15% of the value of shipments (i.e., received or receivable net value of all products shipped) from all U.S. manufacturing plants and 13.6% of the value added (i.e., contribution of industry sector to U.S. gross domestic product (GDP)).[27] Some of the most important sectors of food and beverage manufacturing in the U.S., by market value, include meats (24%), dairy (13%), beverages (12%), and fruits and vegetables (8%).[27,28] From a water intensity standpoint, alcoholic beverages, seafood, and meats are among the highest in wastewater produced per unit product.[28] Unlike most other industries examined below, wastewater produced by the processing of food and beverages is typically absent of harmful or recalcitrant contaminants.[29,30] Therefore, the food and beverage industry is considered to have a high potential for reuse, recycling, and valorization of wastewater.[28]

Water Use. Among manufacturing industries classified in this study, food and beverage is also one of the most heterogeneous with its wide variety of products, manufacturing processes, and water uses. In the food and beverage industry, process water is typically used for purposes such as washing, rinsing, sanitation, temperature control, and as an ingredient in products. The relative proportions of water being used for each process varies across the industry and may depend on a number of factors, including the product(s) being manufactured,[31,32] the manufacturing technologies being used,[33] the size of a facility,[34] and its location.[13,33,35] A useful metric for comparing water use efficiencies across various facilities and/or industries is specific water consumption (SWC), or the amount of water used per unit product. Note that, although SWC includes the term *consumption*, which is often taken to mean the amount of water intake minus the amount discharged, it actually describes the water *use* of a given process, that is, gross water intake. A comparative benchmarking via SWC can play a key role in reducing process water use through identifying areas for improvement and establishing best practices.[33] A breakdown of water use and SWC within select food and beverage facilities is provided in Figure 2a for comparison. Figure 2b illustrates the flow of water through a generalized fruits and vegetables processing facility.

Wastewater Characteristics and Treatment. Common constituents of food and beverage wastewater include organic matter (measured as chemical oxygen demand (COD) and biochemical oxygen demand (BOD)), suspended solids (e.g., total suspended solids (TSS)), oils and grease (O&G), and nutrients (e.g., organic nitrogen, ammonia, phosphorus, etc.) (Table 1).[36−41] Especially notable is the relatively high

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Table 1. Wastewater Quality Characteristics Reported in Academic Literature, by Industry

industry	food and beverages				primary metals			pulp & paper[43,44]	petroleum refining		petrochemicals[45−48]	service sector	
	distillery[49]	olive mill[37,50]	beer[37]	dairy[37,51,52]	iron & steel mill[53]	coking plant[54]	gas cleaning plant[55]		processing[56,57]	spent caustics[57]		data centers (cooling)[58]	large campuses[59]
TS (mg/L)	37,000−130,000 (mg/L)	44,400 (±13,800)		275−5,000						40,800−90,300			
TSS (mg/L)	5,430−24,500	2,700 (±1,100)	200−1500	100−5,000	200−7000		85	342	28.9−950			0.8−4.1	310 (±305)
COD (mg/L)	57,000−150,000	15,200−199,200	1800−5500	660−77,000		940−2730		1500	53−2000	3,230−112,000	2500−8220		473 (±96)
BOD, 5-day 20 C (mg/L)	17,500−50,000	90,000−100,000	600−5000	308−16,000	64−94	186−462		475	60−1000	256−53,600	174−3378	2	292 (±121)
pH	2.5−5.5	4.5−5.5	3−12	5.3−7.5	1.5−9	8.7−9.3	11.5	6.3−6.8	6.7−10.8	9−13.2	5.6−9.5	7.4−7.9	7.1 (±0.3)
FOG (fats, oils, greases) (mg/L)		410−2980		6,000.00	2−50	2.2−33.4			20−20,223		400−1000 (870)		
Nitrate Nitrogen (mg/L)				0−0.5		9.9−18.2					22	60−160 as N	
chloride (mg/L)				1265−6852			180	13.9−38.5	25				
sulfate (mg/L)	2,000−5,300				20−2000		26	3−5100		2,440−3,760	5		29 (±12)
total nitrogen (mg/L)	30−2,500	1.8−966	25−100	5−38.8		212−298		8			187.7	0.5−2	64 (±22)
total phosphorus (mg/L)		42−495	10−100	6−280		074−6.7		2			1.3 (as phosphate)	0.02−0.12	5.7 (±1.5)
ammonia nitrogen (mg/L)				5.9−36.7	48−1500	93−790 (as N)			135−6,550		13.5	0.01−0.36	57 (±22)
others (mg/L)	temperature: 60−150 C phosphate: 30−370 Potassium: 2500−9000	polyphenols: 1−2.4%		phosphate: 0.79−6.84, turbidity: 15−30 NTU	total metals: 80−650, TDS: 400−2000	phenol: 18−290, T-CN: 3.0−18.5, Fluoride: 22−72	Ca: 206, Mg: 40, Na: 65, Fe: 120 TDS: 719	AOXs: 32, Sulfide: 1−270	BTEX: 1−100, Sulfide: 13−8,250	BTEX: 50−5,500, Sulfide: 2−3,060	Br: 138, Ca: 11.6, Mg: 1.9, Na: 620, turbidity: 150−350 NTU, BTEX: 550, Sulfide: 15−30	turbidity: 0.2−0.6 NTU, DO: 6−9	turbidity: 201 (±114) NTU, *E. coli*: 2.5 (±2.2) × 106 (CFU·100 mL−1)

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biodegradability of concentrated organic matter in wastewater generated from food and beverage subsectors such as the dairy and brewing industries. As a result, these wastewaters are subject to biological treatments, including activated sludge, anaerobic digestion (AD), and phytoremediation.[38,40,42] However, organic-rich wastewaters may also contain high concentrations of constituents, such as phenolic compounds and long-chain fatty acids, that can be detrimental to microorganisms,[39] requiring a careful process design and operation distinctive from typical biological processes employed in municipal wastewater treatment.

In addition to biological treatments, food and beverage facilities employ a blend of physical and chemical methods to target the removal of suspended solids, fats, proteins, and other organic material in wastewater.[29,40] Typical technologies used widely across the industry include screening, coagulation/flocculation, and chemical oxidation.[31,49,60,61] Membrane processes, such as RO, microfiltration (MF), and membrane bioreactors (MBR), also have a multitude of applications ranging from water softening to desalination and resource recovery.[39,62,63] Additionally, AD, microbial fuel cells (MFC), and conversion to biodiesel offer promising opportunities for combined treatment and renewable energy recovery, due to the high concentrations of oils, fats, and organics, and a typical absence of toxic compounds in food and beverage wastewaters.[37,64]

Similar to municipal water treatment trains, these technologies are typically employed in three stages: primary, secondary, and tertiary treatment.[40] The primary treatment stage targets the removal of solids and debris through a combination of screening, flotation, and flocculation/coagulation.[60] In the secondary treatment stage, biological methods are employed to remove the bulk of organics, suspended and dissolved solids, and nutrients.[40] Tertiary treatment consists mostly of polishing steps, targeting the removal of specific, recalcitrant compounds or further removal of organics to meet stringent discharge standards.[62]

Water Reuse and Valorization. Water reuse in the food and beverage industry faces a number of challenges, both technical and economic. Product safety concerns are of particular importance for water that comes into contact with raw materials and products either directly (i.e., washing and rinsing) or indirectly (i.e., equipment cleaning), and they are strictly regulated by the U.S. Food and Drug Administration's (FDA) guidelines.[65] Note, however, that some process water uses, such as vehicle and facility cleaning, may not require the same level of treatment as those previously mentioned, presenting additional opportunities for reuse (for instance, through downcycling). To address these safety concerns and prevent equipment breakdown, key contaminants in food and beverage wastewater that must be targeted prior to reuse include organic matter, salts, and pathogens.[29] In subsectors that require a heavy rinsing of raw agricultural products, such as the fruit and vegetables and sugar manufacturing industries, the presence of pesticides, including thiabendazole, imazalil, and diphenylamine in wastewater places an additional challenge for water reuse.[66−68] Although not as relevant to product safety, the aesthetic quality of water such as color, odor, and taste also impact reusability, as these characteristics affect the salability of food and beverage products.[69] Further limiting the widespread adoption of water reuse in the food and beverage industry are particularly slim profit margins in comparison to other industries, which makes it difficult for manufacturers to afford the capital costs of implementing reuse technologies.[28]

The recovery of valuable resources from waste streams, for example, energy recovered from AD, can serve to alleviate the costs of reuse technologies and, in some cases, reduce water and electricity use directly.[70] For instance, the Italian food manufacturer Italcanditi-Vitalfood reported annual savings of $400 000 after the installation of an up-flow anaerobic sludge blanket (UASB) reactor, which treats 1200 m^3/day (320 000 GPD) of wastewater and produces 14 MWh/day of electricity.[71] Similarly, Amón et al. studied the potential for recovery of water and waste-heat from mineral-free, 55−82 °C tomato water condensate at a tomato processing plant and predicted an annual savings of 7.3 GWh and $166 000.[72] Several studies have also demonstrated a combined COD removal of up to 98% alongside energy recovery from brewery wastewater via anaerobic membrane bioreactor (anMBR)[73] or anaerobic sequencing batch reactor (anSBR)[74] technologies, producing high-quality effluent with potential for reuse. The recovery of valuable organic materials presents another avenue for wastewater valorization. For example, in recent years, numerous opportunities for the valorization of organic-rich olive mill wastewater have been explored, including biofertilization[75,76] and pectin and antioxidant recovery.[77−79] However, additional research is needed on the economic feasibility of these technologies at the pilot scale.

The food and beverage industry includes some of the largest multinational and vertically integrated companies, which has resulted in a high concentration of ownership across certain subsectors.[13] Because these companies own a large number of manufacturing facilities, they also possess a high potential to replicate water innovations.[28] Kraft-Heinz, Coca-Cola, and Nestlé have set goals to reduce their total water withdrawals from 2010 benchmarks (2015 for Kraft-Heinz) by 15, 25, and 35% by 2020.[80−82] So far, water reuse has played a key role in each company's approach to achieving these targets. For example, Kraft-Heinz reported annual savings of 330 000 m^3 of water and $500 000 at its Newberry plant by using recycled water from its dissolved air flotation (DAF) system to cool vacuum pump seals.[83] The large-scale, facility-level monitoring of water quality and flow represents another important strategy. For instance, Coca-Cola has reported the use of water footprint studies, which aim to track and benchmark process water use, to guide investment in new, water-saving technologies and operating procedures.[80] Similarly, Nestlé has implemented real-time monitoring systems in its bottling facilities to gather data on water use and quality for efficiency-based decision making.[82]

2.3. Primary Metal Industry.

Industry Overview. In 2017, the primary metal manufacturing industry accounted for 4.3 and 3.6% of the total U.S. manufacturing revenue and value added, respectively.[84] Iron and steel mills and ferroalloys are the largest subsector, representing 40% of total sales within the industry, followed by copper (9%), aluminum (6%), and other nonferrous metals (6%).[85] The primary metals industry ranks second highest in water withdrawals among all U.S. industries, representing 26% of total manufacturing intake.[5] Primary metals manufacturing is defined by the NAICS as the smelting and refining of "ferrous and nonferrous metals from ore, pig, or scrap, using electrometallurgical and other metallurgical techniques."[85] Note that this definition excludes the mining, extraction, and transportation of ores prior to a refinement as well as the fabrication of most finished metal products.

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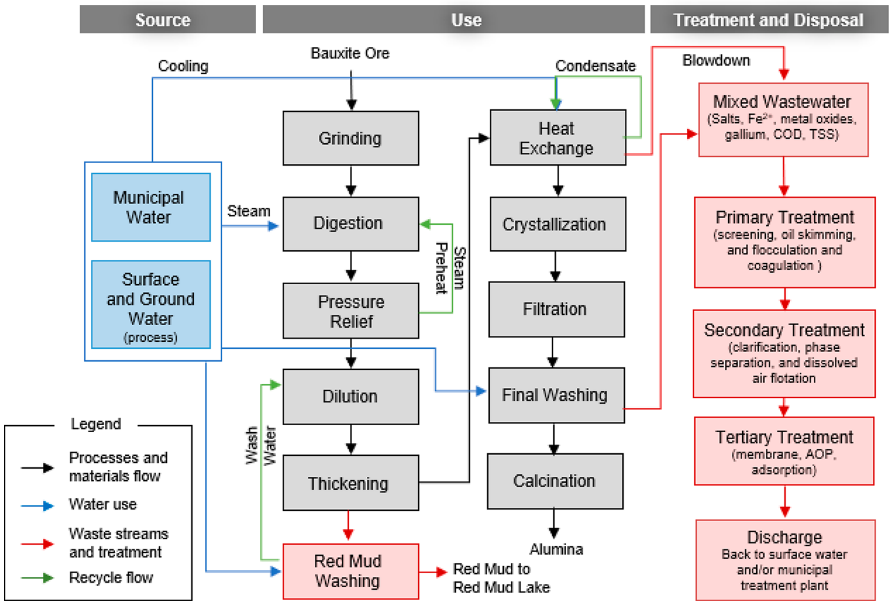

Figure 3. Typical water-flow diagram for the Bayer process for bauxite refining, a critical step in the primary production of aluminum.[91]

Water Use. Direct uses of water in primary metal manufacturing operations generally fall into six categories: (i) material conditioning (i.e., removing impurities and controlling the quality of intermediates and products via quenching dust and slag, rinsing ore and metal, and dissolving minerals); (ii) equipment cleaning to remove scale and residues; (iii) conveyance of materials from one process or stage to the next by dissolving or suspending them in water; (iv) air pollution control via wet scrubbing; (v) lubrication of rolling processes (i.e., to extend the life of the rolls); and (vi) cooling of equipment, materials, and gases either directly (sprays) or indirectly (heat exchangers).[11,86] Additionally, water is used in indirect processes, such as producing demineralized water, which is required for use as makeup in closed-loop recirculating cooling systems, and on-site electricity generation to meet energy demands.[86,87] The proportions of water use in these processes vary by plant and subsector, but in general, cooling comprises the largest share at an estimated 85% of the total.[11] Figure 3 describes one example system, namely, the Bayer process for alumina production from bauxite, and the uses for water at each stage.

The SWC at a primary metals facility is governed by a number of factors, including the type of metal being produced,[87] the processes and components being used,[86] and the water treatment and reuse technologies in place.[12] The variability of SWC across the primary metals industry is particularly apparent in integrated iron and steel plants, where reported values range from 4.12 to 60 m^3/mt among published sources.[12,84,86,88] Published data related to water use and wastewater characteristics for sectors other than iron and steel are scarce. For example, the aluminum industry has been the subject of life cycle assessments (LCA)[89,90] to understand the water scarcity or aquatic toxicity of aluminum manufacturing holistically, but these do not provide granular water use data, such as SWC values, that allow for a reasonable comparison of water use to other sectors.

Wastewater Characteristics and Treatment. Wastewater produced by the primary metals industry typically includes solids (total, suspended, and/or dissolved), oils and grease, organics, nitrogenous compounds, high acidity, and heavy metals (Table 1),[12,54,92] most of which are regulated by the U.S. Environmental Protection Agency (EPA) for discharge to the environment.[91] Similar to water use, specific characteristics of primary metals wastewater also vary by factors such as the types of metals being processed, plant configuration, and plant components. Iron and steel plants, for example, often consist of a variety of operations,[11] each of which may generate distinct wastewater constituents.[53] Coke ovens, associated with coke production, produce substantial quantities of wastewater effluent containing high concentrations of cyanides, phenol, ammonia, thiocyanate, and oil.[54] Blast furnaces also account for a significant share of wastewater production, contributing thermal pollution and copious suspended solids, ranging from 1000 to 5000 mg/L.[53] Lastly, the metal finishing operations of rolling and pickling contribute scales, debris, oils, acids, and dissolved heavy metals including iron, chromium, nickel, copper, and zinc.[53]

The primary treatment of primary metals wastewater targets the removal of solids, oils and greases, and other pollutants by physical and some chemical processes, including screening, oil skimming, and flocculation and coagulation.[53] Common secondary steps include clarification, phase separation, and dissolved air flotation.[53,93] Lastly, in a tertiary treatment, technologies such as advanced oxidation processes (AOPs) are commonly used along with membranes and adsorbents to disinfect and remove toxic compounds, such as polycyclic aromatic hydrocarbons (PAHs), phenols, and cyanide.[53]

Water Reuse and Valorization. The primary metals industry is subject to stringent environmental regulations, which has led to a major push for water conservation and reuse.[12,94] The substantial portion of water used for an indirect cooling in the primary metal industry presents a major opportunity for water reuse. However, while studies have frequently suggested the potential for cooling water recovery at integrated steel plants, primarily through a treatment or downcycling of blowdown to other process uses, it has not yet seen widespread adoption.[12,86] One reason for this may be due to the outdated, "legacy" treatment modes still in use at many

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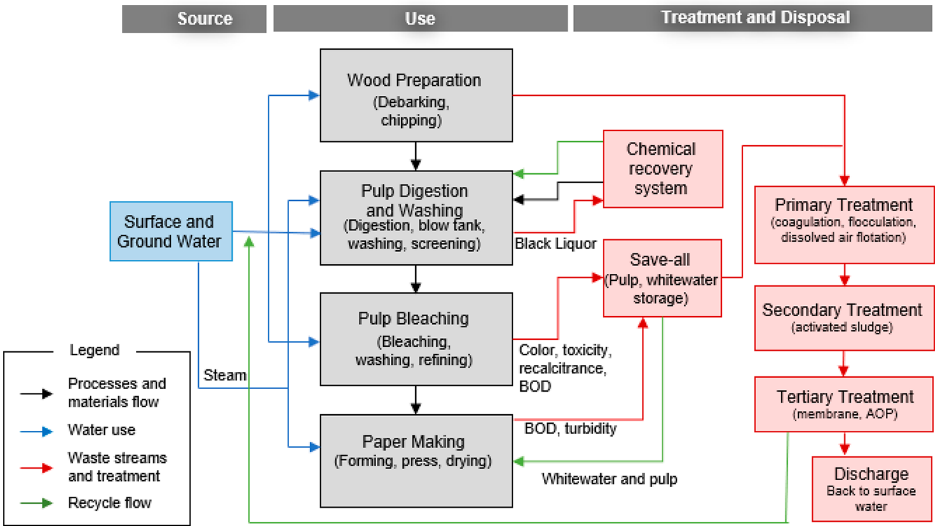

Figure 4. An overview of the pulp and paper production process and the resulting effluent constituents.

plants, which are incapable of treating water for reclamation.[95] In contrast, some iron and steel plants have reported water recovery rates as high as or even higher than 95% using advanced water treatment technologies.[86,96] Another reason is likely the fact that many steel plants are located in water-abundant regions.

The composition of wastewater that results from process uses in the primary metal industry stands as an important barrier to reuse. Salts and suspended solids, often present at high concentrations in primary metals wastewater, must be addressed prior to reuse in order to prevent the corrosion of mechanical equipment.[84] The use of treatment wetlands has been studied as a cost-effective means to address these consituents.[84,97] Furthermore, the presence of inhibitory and recalcitrant compounds, such as cyanide, PAHs, and heavy metals, limits the viability of typical biological treatments.[54,88] Advanced technologies such as MBR,[98] electrodialysis,[99] and Fenton processes[100] have been demonstrated effective in the removal of these contaminants, but they are often cost-inhibitive or overly complicated for a practical application.[88] Therefore, reducing the cost and increasing the applicability of these technologies may be a key approach in expanding water reuse in the primary metals industry.

Also worth mentioning is the potential for wastewater valorization in the primary metal industry. For example, heavy metals such as Cu, Au, Ag, Al, and Zn, which are toxic in wastewater and must be removed prior to discharge or reuse, can instead be recovered. A variety of technologies for metal treatment and recovery have been explored in the literature.[101−105] In the case of steel, 100% of coproducts can be recovered and used, including liquid slag, which has applications in cement, road construction, fertilizers, and hydraulic engineering.[96]

2.4. Pulp and Paper Industry. *Industry Overview.* The gross revenue generated by the paper manufacturing industry in the U.S. was nearly $40 billion in 2019.[106,107] Major products include paperboard and packaging products at 43.6% of total revenue, followed by paper (23.1%) and pulp (33.3%).[108] Pulp and paper manufacturing accounts for ~28% of the fresh water intake for U.S. manufacturing, the largest of any industry.[5] This study includes NAICS codes 32212 and 322130, which are mills that produce pulp and paper and mills that produce pulp and paperboard, respectively.

Water Use. Water is essential to many steps in the pulp and paper manufacturing process (Figure 4). In general anywhere from 10 to 50 m^3 of water is needed for each metric ton of paper produced in modern paper mills.[69] Overall, the pulp and paper industry withdraws nearly 4 million cubic meters of water from ground and surface sources annually.[109] The chemical wood pulp process, as depicted in Figure 4 and outlined below, is the most widely used manufacturing process in the pulp and paper industry, constituting 72% of the world production in 2013.[43]

In the chemical wood pulp process, wood material, known as bolts, is first debarked and formed into chips.[71] In this initial step, water is used to wash the bolts, but due to the mechanical nature of the debarking process, contamination levels in the effluent are low.[72] The chips are then sent to the pulping process. The most popular pulping method is known as Kraft pulping, which accounts for 80% of U.S. production.[71] Other noteworthy methods include thermomechanical pulping, mechanical pulping, and sulfite pulping.[65] The first step in Kraft pulping, referred to as cooking, involves the use of an alkaline mixture of sodium hydroxide and sodium sulfate to separate cellulose from the lignin in the wood.[71] Following the cooking process, pulp is separated from the black liquor and sent to pulp washing. In the pulp washing process, unwanted soluble substances in the pulp are replaced with clean water.[71] This process produces large quantities of wastewater that must be treated, but most of the solubilized matter is diverted away from the water treatment system to the chemical recovery boilers, where cooking liquid is recovered and steam is generated to heat the cooking process.[3,73] Depending on the product, the pulp is then bleached.[71] Because of the large amounts of water needed to wash the bleached pulp, up to 85% of the total effluent volume from the pulping process is generated during the bleaching stage.[74] Bleaching compounds include chlorine gas, chlorine dioxide, oxygen, ozone, sodium hypochlorite, and sodium hydroxide.[3] These bleaching agents can also be combined into single steps or used in series. Recent advances in the industry have pushed toward an elemental chlorine free (ECF) bleaching method using chlorine dioxide,

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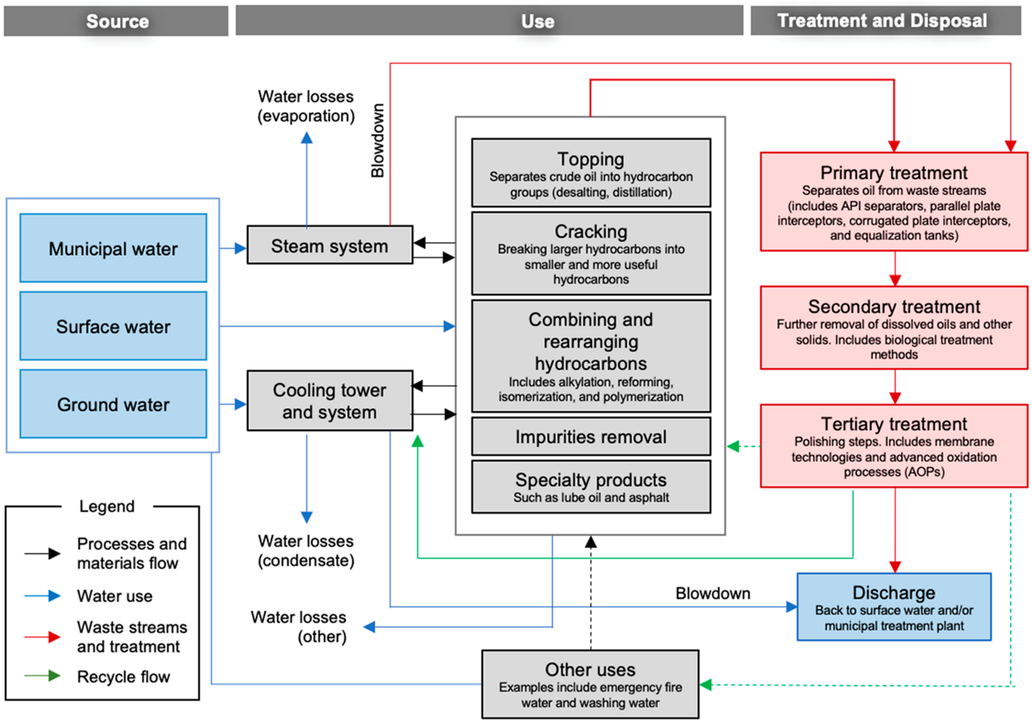

Figure 5. Process classification, example operations, and general waste streams that are found in a typical petroleum refinery.

which reduces the prevalence of halogenated organics in the effluent.[3]

The final steps in the process include pulp refining, wherein impurities are removed from the pulp, and papermaking, wherein the pulp is taken from a watery slurry that is less than 1% fiber (~99% water) to finished paper through a series of large rollers and heat.[3,75] The papermaking process is the most energy-intensive operation, accounting for ~36% of the total energy used, due to the large volume of steam being used to heat the rollers housed in the papermaking machine.[73] Approximately half of the steam used for the pulp and paper manufacturing process is generated from waste produced onsite.[73]

Wastewater Characteristics and Treatment. The pulp and paper industry has to meet the effluent limitation guidelines imposed by the EPA with regard to BOD_5 and TSS.[110] COD, nitrogenous compounds, and adsorbable organic halides are among other common effluent constituents.[111] One major challenge for the pulp and paper industry is the presence of lignin and lignin derivatives in the wastewater, which results in high suspended solids, COD, and a low biodegradability ratio (BOD/COD), ranging from 0.02 to 0.07.[112] The most common technique for the removal of suspended solids in the primary treatment phase is coagulation and flocculation using ferric chloride and polymers.[44] An alternative to coagulation and flocculation is dissolved air flotation (DAF), which also doubles as a pretreatment to thicken sludge and treat toxic compounds.[113] Activated sludge is the most common secondary treatment and is used to remove organic material from wastewater.[112] Membrane processes, particularly ultrafiltration (UF), as well as AOPs are becoming more popular as tertiary treatment steps.[44,112] AD has emerged as an excellent technology for treating certain high-strength pulp and paper waste streams with the added benefit of bioenergy production. However, Kraft mill bleaching wastewater often contains compounds that are toxic to the microorganisms found in AD tanks, which may inhibit the treatment.[114]

Water Reuse and Valorization. The pulp and paper industry is experiencing a growing push to reduce the water footprint of manufacturing facilities. Currently, 88% of the water used in the pulp and paper industry is treated and returned to surface waters.[109] Major efforts have been made in the past few decades to improve water efficiency and implement reuse strategies. As a result, the industry's SWC decreased from 97.6 m^3/t in 1970 to 44.4 m^3/t in 2012.[109] The whitewater, that is, the water removed from the pulp slurry during the papermaking process, is commonly reused in the conveyance of pulp on the paper machine.[115] It is then stored in the save-all tank, where valuable fiber and filler can be extracted and reused as raw materials.[74] The effluent from a tertiary treatment can also be reused as feedwater for the papermaking process or fed to another plant for reuse.[74,116]

Significant advances continue to be made in the area of waste valorization and reuse in the pulp and paper industry. Biomass fly ash has shown promising potential for use as an adsorbent for the removal of lignocelluloses, especially when used in conjunction with nonferric alum.[117,118] Lime mud, another common waste product, shows promise as a potential ingredient for clinker, an additive used in the manufacture of cement.[119] The pretreatment of pulp and paper mill sludge followed by solids separation was shown to provide up to 10 times the methane production via AD as compared to an untreated sample, suggesting unexploited energy opportunities in the industry.[120] Additionally, biomass-rich paper mill sludge has the potential for use as a feedstock in biorefinery applications, such as bioethanol production and deacetylation and mechanical refining (DMR), an emerging technology that converts lignocellulosic biomass to sugars via an enzymatic hydrolysis.[121−123]

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2.5. Petroleum Refining. *Industry Overview.* The petroleum refining industry produces a variety of essential products, including gasoline, diesel fuel, kerosene, and naphtha, and it has a paramount impact on the U.S. economy.[124] In the U.S. alone, an estimated 19 million barrels of crude oil are produced per day.[125] Regardless of their outputs, refineries require copious volumes of water for operation. U.S. refineries require between 1.0 and 1.9 m^3 of water per cubic meter of crude oil processed.[126,127] Total water withdrawals for U.S. petroleum refineries are estimated to be between 3 and 6 million m^3/day (1000−1500 MGD). The petroleum and coal products sector, delineated as NAICS code 324, has the fourth-largest annual water intake of any U.S. Industry.[5] Note that petroleum refineries and petrochemical plants may produce some common intermediates or products and are sometimes considered components of a single, broader industry within the literature. In this section, our discussion is focused solely on refineries. Petrochemical plants are discussed later, in Section 2.6, as part of the chemical industry.

Water Use. Each refinery follows its distinct processes and subsequent water network, but key steps and common waste streams are delineated in Figure 5.[57,128] Topping and cracking are highlighted as major water uses; distillation and fluid catalytic cracking in a typical U.S. refinery generate ∼44% and 26% of total refinery wastewater, respectively.[126,129] Temperature control is critical to separate and refine specific hydrocarbon fractions. As a result, cooling water and boiler feedwater constitute 48% and 20% of the total water requirement for a typical refinery, respectively.[130] During operation, a significant portion of this requirement is lost as blowdown, evaporation, and drift (i.e., losing water as droplets entrained in the humid air that is being rejected by the cooling tower).[131] These three routes comprise 96% of total water losses for a typical refinery, eliciting the need to develop strategies to conserve and reuse more cooling and boiling water.[132] Process water is used for product washing and catalyst regeneration and may contain various constituents and spent solvents that come into direct contact with the oil inputs.[133] Petroleum refineries also require water for processing, fire water, and backwashing.[130,134,135]

Wastewater Characteristics and Treatment. Wastewater from petroleum refining is generally characterized by high levels of COD, BOD, total dissolved solid (TDS), and total hydrocarbon content (THC).[136] Oil and grease are found in the waste streams of most major steps with concentrations ranging from 12.5 to over 20 000 mg/L.[56] Petroleum refinery wastewaters may also contain a multitude of other pollutants, such as metals (i.e., chromium), organics, and nutrients.[137] Alkylation, which produces high-octane alkylate for use as a gasoline blending component, can discharge spent caustics in the wastewater stream alongside varying amounts of oil and sulfides.[57,138] Petroleum refineries also employ various solvents and resultant solvent refining processes. Certain steps, such as aromatic extraction, may produce wastewaters containing small amounts of leached solvents as well as benzene, toluene, ethylbenzene, and xylene (BTEX) compounds.[57] Sour water, which is produced from atmospheric and vacuum crude columns, contains high levels of hydrogen sulfide (H_2S) and ammonia, which are stripped away and sent to a sulfur plant for elemental sulfur recovery and ammonia destruction.[131] Additionally, benzene is a principal concern for many refinery plants due to its carcinogenicity and low threshold for discharge (0.005 mg/L) as set by the EPA.[137,139] A benzene recovery unit is often necessary to ensure benzene-containing oils do not contaminate combined wastewater streams.[140]

The primary treatment of petroleum refinery wastewater targets the separation of oil from wastewater and is divided into two stages. The first stage is used for relatively higher concentrations of oil (>500 mg/L) and consists of oil separators and equalization tanks.[136,141,142] The second stage removes remaining oil droplets and suspended solids, further refining the waste stream. Dissolved air flotation is frequently used, with reported oil removal percentages between 70 and 90%.[129,143,144] Next, a secondary treatment targets the degradation of dissolved oil and other organic constituents primarily via biological processes.[56,145,146] Activated sludge is the most-employed technique, although other methods have also been reported, including adsorption and MBRs.[131,147−149] Finally, tertiary polishing steps are employed to ensure an adequate removal of recalcitrant pollutants missed by earlier steps. Example processes include sand filtration, AOPs, and membrane filtration.[135,150−154]

Reuse and Valorization: Trends and Challenges. With the pressing concerns of water insecurity, more refineries are initiating projects to enhance and implement methods of recycling and reuse of available water. Some refineries have targeted an increased recovery of boiler condensate, which may be reused as process water or for other purposes. Another approach is to incorporate the use of alternative source water.[155] The majority of plants currently rely primarily on fresh surface and municipal water to meet plant needs.[156] However, seawater is used as makeup water for once-through cooling at an estimated 5% of refineries,[156] and several large oil companies, including Marathon and Chevron, have reported reclaimed water as a major source at a handful of refineries.[157,158] For example, the Singapore Refining Company recently constructed a membrane-based recycling plant to treat wastewater that would otherwise be discharged to the ocean. After treatment, the recycled water meets standards for industrial and potable reuse and is reused onsite to supply 20% of the refinery's total water demand.[157]

An initiative revolving around wastewater recycling and reuse that has sparked global interest is the implementation of membrane-based filtration systems, namely, UF and RO technologies.[132,137] In 2001, the PEMEX refinery in Minatitlan, Mexico, was the first to implement both in its recycled water system; the output RO permeate was utilized as a boiler feed and for processes requiring high-purity water, and the reported overall water efficiency with respect to the total RO permeate production was ∼70%.[159] Similar projects continue to be reported, including the implementation of RO systems in the CCRL Refinery in Regina, SK in Canada, the Shell Pearl Gas-to-Liquid Refinery in Qatar, and the Repar Refinery in Brazil.[159]

2.6. Chemical Industry. *Industry Overview.* The petrochemical and allied chemical (hereby referred to as chemical) industry, which consists of organics, inorganic, resins, and agricultural chemical subsectors, produces a wide range of chemical products via processes characterized by markedly heterogeneous and complex unit operations. Chemical manufacturing is a critical component of the U.S. economy, representing 12.8% of the total revenue and 15.8% of value added in 2017. It is also the third-largest industry in terms of water use, representing an estimated 20.5% of total industrial withdrawals or ∼11 million m^3/day (2900 MGD).[1,5]

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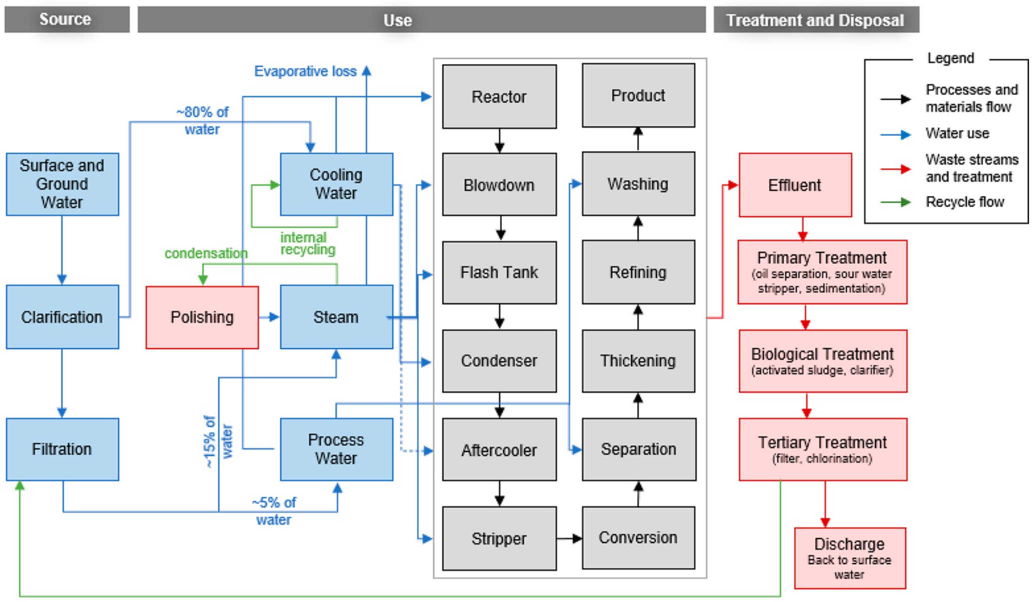

Figure 6. Generalized water flowchart for a petrochemical plant.[160,170]

Within the industry, organic chemicals constitute ∼45% of the total water use.[10]

Water Use. The amount of water used in the chemical industry varies by specific plant products. At the higher end, silicon nitride manufacturing can require 15 000 kg of water to produce 1 kg of product,[11] while sulfur production requires only 8−10 kg of water per kilogram of product.[10] Because many reactions generate heat and require specific temperatures to maximize the yield and process efficiency, the majority (up to 90%) of water entering a chemical plant is used for cooling.[10] Steam generation comprises the second-largest share of water use, as much as 15% of the total in some plants.[11] Other water uses include hydraulic conveying (1.5%−5%), cleaning and washing (3%), and use as part of the finished product.[11] Figure 6 presents a generalized chemical manufacturing process and water flow in a typical chemical plant.

Water used in chemical plants often undergoes a treatment prior to circulation due to the need for specific influent characteristics such as a low turbidity (<30 ppm kaolin) and low suspended solids (<30 mg/L) as well as the control of pH, hardness, and metal levels.[10] Common types of water used as influent include clarified water (after coagulation and flocculation), demineralized water (obtained through an IX and RO process), ash handling recycled water (operating in a semiclosed system), and filtered water (obtained through sand filters).[160]

Wastewater Treatment. Because of the wide array of chemicals used and produced in the chemical industry, the resulting wastewater is difficult to generalize meaningfully. Common constituents of concern include BOD_5,[48] COD,[45] O&G,[48] BTEX,[46] and trace metals (Table 1), which are typically introduced by processes, such as washing and conveyance, in which water comes into contact with intermediates, products, or residues. Because of the complex chemical pathways observed in many manufacturing operations, chemical plants are especially concerned with treating toxic, mutagenic, carcinogenic, or non-biodegradable intermediates. Specific examples include free and emulsified hydrocarbons, ammonia, cyanides, and phenols used in adhesives manufacturing.[161] This implies that the treatment of wastewater can be variable but target-specific. Water treatment for reuse, rather, places less emphasis on addressing toxicity and more on meeting the requirements for use in specific processes, such as the prevention of buildup, fouling, or corrosion. In a recent characterization of manufacturing wastewater in the U.S., Fuchs and Rao found that some contaminants in the chemical industry wastewater are already being treated to sufficient levels for reuse.[162]

Wastewater treatment in the chemical industry generally follows a three-stage process. The primary treatment stage is mostly mechanical, aimed at the separation of suspended solids, and often includes American Petroleum Institute (API) oily water separators, corrugated plate interceptors (CPI), sour water strippers, or buffer tanks.[163] Dissolved air flotation (DAF) can be used to remove oil (>100 ppm) and grease to an oil storage tank.[163] Deoiled water is then sent to the secondary step, which typically consists of a biological process, aimed at the removal of suspended solids and dissolved solids through an aerobic-anaerobic treatment, hydrolysis acidification, or bio(photo)degradation. Generated sludge can be used for bioenergy recovery, which is an avenue for a cost-saving enhancement.[164] The final step of the physicochemical or chemical treatment is critical toward allowing wastewater effluents to meet regulatory standards and eliminate specific compounds that are otherwise recalcitrant. Various technologies have been explored, including membrane filtration, adsorption, AOPs, and electrochemical processes.[164−169]

Water Reuse and Valorization. Many chemical plants are located next to freshwater sources to meet the large demand for cooling. Considering the high costs of treating wastewater for reuse (a standard water treatment unit operating at 570 m^3 per day can add an additional cost of $500 000 to $1.5 million),[21] and that wastewater has traditionally been regarded as a liability rather than an asset, water recycling has not been a major focus of water treatment in the chemical industry. The on-site reuse of petrochemical wastewater is often technically feasible but operationally cost-prohibitive due to the high costs of benchmark RO and nanofiltration (NF) processes.[171] Rapid membrane fouling due to the high oil content and slow return

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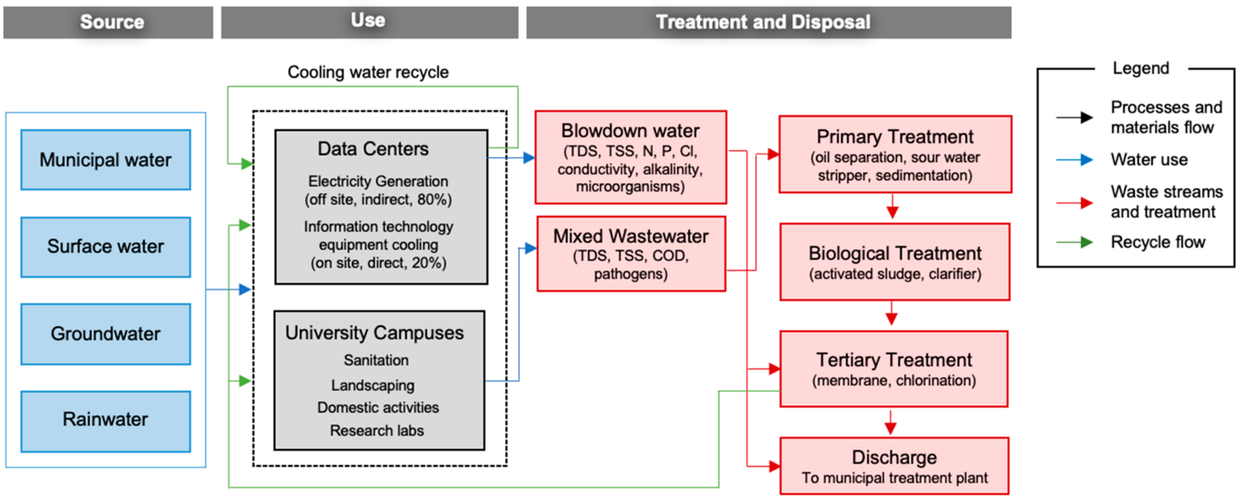

Figure 7. General water flow of data centers and campuses.

on investment of concentrated brine disposal present additional challenges.[172,173]

Despite these barriers, economically viable opportunities exist to expand water reuse in the chemical industry. For example, a thorough characterization of wastewater streams and mathematical modeling can help to identify sources for on-site reuse that require little or no additional treatment. Hansen et al. reported annual water savings of 385 440 m^3 at a petrochemical plant in Brazil through the onsite reuse of wastewater from equipment cooling, ash carryover, and treated effluent in its cooling towers.[160] Additionally, although ZLD remains the gold standard for plant water efficiency, many chemical plants have set goals to achieve a minimal liquid discharge (MLD), which instead targets the liquid recovery of up to 95% and is considered much less cost-prohibitive.[174]

2.7. Data Centers and Campuses. *Industry Overview.* Industrial service sectors play important supporting roles in providing service resources for other industries and communities. Representative service sectors include business services (e.g., data centers of tech companies) and research services (e.g., large university campuses, national laboratories, and private research and development (R&D) centers). A data center is a place used to house computer systems and associated components including telecommunications and storage systems.[175] As of 2019, there are more than 500 hyperscale data centers in the world, with ∼40% built in the U.S.[176] Data centers include those of individual tech companies (e.g., Microsoft, Google, Amazon, Facebook) and colocation data centers (e.g., Switch Communications), whose equipment, space, and bandwidth can be rented to retail customers.[177] There are 31 colocation data centers in the U.S. based on Cloudscene's marketplace.[178] The number of colleges and universities reached ∼5300 in the U.S. in 2019.[179]

Water Uses. The bulk of water withdrawn by data centers is used to reject heat from equipment, typically via on-site cooling tower-based chillers. A large data center with 15 MW of information technology capacity can consume up to 1400 m^3/day (360 000 GPD).[180] It was estimated that U.S. data centers used a total amount of 626 million m^3 of water in 2014.[181] Water sources used by data centers are site-dependent and commonly include municipal water and fresh surface and groundwater.[182]

Large university campuses use water for different purposes, including sanitation, outdoor landscaping, domestic activities such as showering, dishwashing, swimming pool maintenance, and food preparation, laboratory use (high-quality water production, plant propagation, equipment cleaning), and cooling systems.[183] The distribution of water use varies among different universities.[183−185] For example, Yale University uses an average of over 2.3 million m^3 of water every year supplied by the local municipality.[183] A report of the University of Kansas indicates that 36% of the water intake is used by housing alone, and the irrigation of landscapes and athletics fields contributes a significant amount (more than 42 000 m^3/year) to the university's water use.[185] University of Colorado Boulder reported that the majority of their water is used for housing, academic, and power house operation (cooling).[184]

Wastewater Characteristics and Treatment. Wastewater from data centers largely consists of blowdown from cooling systems, the characteristics of which depend on pretreatment methods and number of use cycles, and are generally consistent with those that occur in aforementioned industries (Table 1).[58,180,186] Currently, some of this blowdown water is either discharged to surface waters without treatment, discharged to municipal plants for further treatment, or treated by RO/membrane distillation on site to be reused (Figure 7).[20] The main compositions of wastewater from university campuses include TSS, TDS, organic nitrogen, nitrates, ammonia, organic and inorganic carbon, phosphate, and bacteria, and they mostly resemble those of municipal wastewater.[187] Detailed characterizations of campus wastewater are scarce, and the composition is expected to vary among campuses.[183−185]

Many universities rely on local municipalities to treat their wastewater. For example, wastewater from University of Colorado Boulder is delivered to the City of Boulder's wastewater treatment plant (WWTP).[184] Some universities, such as University of California, Davis, have built their own wastewater treatment facilities.[188] A sanitary sewer collection system across this campus carries wastewater that is flushed down the drain from all campus facilities to the treatment plant for the processing of 14 000 m^3 of wastewater per day.[189] University of Connecticut has also built an on-site water-reclamation facility that employs tertiary treatment processes

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(microfiltration and ultraviolet disinfection)[190] to divert 4000 m^3/day (1 MGD) of nonpotable water to meet campus needs such as power plant cooling. Some universities have created their own wetlands for wastewater treatment, such as Clatsop Community College in Oregon, which treats sewage from its campus using an enclosed artificial wetland.[185]

Water Reuse and Valorization. For data centers, water treatment and reuse is often considered a low priority, and fewer than one-third of data center operators track any water metrics.[191] Consequently, water supply and wastewater discharge are not often evaluated or regulated thoroughly in the site selection.[192] The lack of priority on water use and treatment is mainly due to the absence of legislation.

A major water reuse (and conservation) initiative that has been gaining momentum among large data centers is the replacement of traditional source waters with alternatives such as reclaimed municipal wastewater or rainwater. For instance, in coordination with the local municipality, Google recently constructed a treatment facility, located five miles from its data center in Douglas County, Georgia, that diverts up to 30% of treated effluent from the local municipal wastewater plant. The diverted effluent undergoes additional treatment at Google's treatment facility before being routed to the data center, where it is used to satisfy 100% of the location's cooling needs.[193] Similarly, Microsoft's Azure data center located in San Antonio, Texas, operates exclusively on recycled water purchased from the local, municipally run San Antonio Water System (SAWS).[180] By using low-cost, recycled gray water produced from treated municipal wastewater effluent at SAWS recycling centers, Microsoft avoids the use of 220 000 m^3/year (58.3 million gal/year) of potable water and saves over \$140 000 annually.[194] At another of its U.S. data centers, Google processes rainwater runoff that is collected in retention ponds providing between 40 and 100% of the center's water needs at different times of the year.[182] Implementing state-of-the-art cooling technology is another potential strategy for data centers to reduce water use. For instance, a thermosyphon hybrid cooling system installed by the National Renewable Energy Laboratory (NREL) at its High-Performance Computing Data Center in 2016 reduced the facility's water usage by 4400 m^3, or nearly 50%, in its first year of operation.[195]

For research-oriented university campuses, ensuring that wastewater does not contain hazardous agents remains the chief difficulty, which is primarily due to the complexities of controlling the large number of laboratory users on campus. Efforts should be put into decreasing permit violation cases by adopting better water management practices. On-site wastewater treatment plants can lower costs and increase environmental sustainability by using renewable energy sources such as wind or solar photovoltaic.[196]

3. CASE STUDIES

We herein analyze the water use and treatment systems of three particular facilities and identify potential strategies to improve water usage. To account for the heterogeneity of industry, each case represents a distinct class of water/wastewater generated from industry: (i) wastewater that contains high concentrations of recalcitrant organics, such as oil and metals, which are often found in the primary metal, petroleum refining, and petrochemical industries using an integrated steel plant as an example; (ii) wastewater that contains high concentrations of biodegradable organics from pulp and paper and food and beverage industries, using a Kraft mill plant as a representative example; and (iii) high-purity water that requires advanced treatment to produce, which is often required for cooling and boiler feedwater across all industries and for process uses in select industries, such as pharmaceuticals and semiconductor manufacturing,[197] using a wafer fabrication plant as an example. Although only three specific case studies are presented, we expect that the general findings and discussion are relevant to a wide range of industries that deal with similar wastewater challenges. Moreover, we hope that these studies will demonstrate the usefulness of and serve as a framework for analysis and modeling of treatment systems at other facilities using Water-TAP3 or similar tools.

Methods. Case studies were selected on the basis of relevance to the study, diversity of water treatment systems, and availability of data. For the case studies analyzed in this paper, raw data were collected from the facilities discussed herein, while some information, such as cost data for specific processes, was missing, and standardized cost assumptions, defined within Water-TAP3 as a default, were used in place. All relevant data collected from the three facilities can be found in Figures S1−S3 and Table S1. A more in-depth discussion of the Water-TAP3 tool can be found in the official Water-TAP3 documentation, available publicly on GitHub.[198] This includes detailed descriptions of the tool's framework, built-in assumptions, and unit models.

Cleveland-Cliffs Integrated Steel Plant. The Cleveland-Cliffs integrated steel plant, established in 1847 in Cleveland, Ohio, intakes various water sources including municipal, river, and recycled water. The wastewater treatment consists of two trains: (i) the oily waste treatment system, which treats combined wastewater (cold mill and hot mill wastewater and hot mill blowdown) having a high TSS oil/grease content through primary oil separation, coagulation, and flocculation/flotation processes, and (ii) the metals removal system, which manages iron-rich, low-pH (∼1−2) waste streams from the metal surface treatment steps (e.g., pickling) in the cold mill through a series of neutralization, aeration, clarification, and sludge dewatering steps. The schematic of water flow and detailed water quality and flow data are provided in Figure S1 and Table S1, respectively.

Table 2 summarizes the results of a Water-TAP3 analysis of the plant, which estimates the levelized cost of water (LCOW), the cost per unit volume of water produced by a process or facility across all cost categories and/or components (e.g., capital costs, O&M, fixed operating), to be \$0.27/m^3. Although the results were generated using default cost metrics (built into Water-TAP3) for each treatment train, they are in agreement with the data gathered from the facility. For example, the electricity consumption estimated from the rated power of individual mechanical components was found to be 0.30 kWh/m^3, within the range estimated by Water-TAP3. A breakdown of the levelized cost by the major cost category (Figure 8a,b; left figures) indicates that the capital investment is the greatest cost due to large volumes of flow handled and corresponding infrastructure needs for both systems. The breakdown of the levelized cost by treatment step presented in Figure 8a,b highlights the most cost-intensive areas of each treatment train. The model outputs indicate that most of the total cost of oily wastewater treatment (63%) is associated with the addition of chemicals (ferric chloride and flocculant) and the mechanical energy spent for a rapid mixing of the wastewater in the coagulation/flocculation step. Note that

Table 2. Summary of Case Study Data and Water-TAP3 Analysis Results

	Cleveland-Cliffs steel plant	Camas Pulp and Paper Mill	Fab25 Wafer Fabrication Plant
total capital investment[a,b,c] (MM$)	9.23 (6.47−13.85)	12.55 (8.79−18.83)	18.25 (12.78−27.38)
operating and maintenance (MM$/year)	0.488 (0.34−0.73)	1.06 (0.74−1.59)	0.77 (0.54−1.16)
LCOW ($/m^3)	0.274 (0.192−0.411)	0.063 (0.044−0.095)	4.88 (3.42−7.32)
electricity consumption (kWh/m^3)	0.275 (0.193−0.413)	0.584 (0.409−0.876)	9.8 (6.9−14.7)
inlet water recovery (%)	94.7	100	25

[a]MM$ denotes million U.S. dollars. [b]All U.S. dollar values are inflation-adjusted to the values in 2020 (expressed in $2020). [c]Values in parentheses indicate ranges estimated based on the expected uncertainty of the Water-TAP3 model of −30% to +50%.

4500−5300 m^3/day (1.2−1.4 MGD) of the total volume of wastewater (6400−7200 m^3/day or 1.7−1.9 MGD) treated by the oily wastewater treatment system bypasses the primary treatment and is instead introduced during the flocculation/coagulation step, further explaining this large contribution to total costs. Waste disposal, that is, capture and transport of tramp oil by trucks, is the second-largest cost (12%). For the metal treatment system, the aeration process is the most cost-intensive component (53%) due to the high energy demand of subsurface air blowers. Specialized chemicals used for neutralization and clarification also contribute substantially to the total cost of metal removal (11%).

Camas Pulp and Paper Mill. The Camas Pulp and Paper mill, established in 1883, is located in the South-West of Washington on the Columbia River. As of 2015, the mill produces 600−900 mt/day of paper utilizing the aforementioned Kraft process. The facility draws water from both surface sources and groundwater wells for the Kraft process. After water is used in the primary plant processes, the wastewater is collected in a central sewer before being transferred to a central treatment facility that removes AOX, BOD, COD, and VOCs prior to discharging it back into the Columbia River. Wastewater treatment is carried out by two major steps, namely, a clarifier and a set of aerated stabilization basins (ASBs) (see Figure S2 for more details). The results of a Water-TAP3 analysis (Figure 8c, Table 2) suggest that LCOW is as low as $0.063/m^3, which is much lower than that of the steel plant discussed above. Most of the costs are associated with the capital investment and electricity consumption, and unlike the steel plant, there is little chemical cost. This plant reuses water once or multiple times to minimize chemical costs. Additionally, the process of capturing a woody biomass and burning it for electricity generation helps to offset the water treatment costs and makes this a very economical form of water treatment.

Fab25 Wafer Fabrication Plant. The Fab25 plant in Austin, Texas, built by Spansion LLC in the early 1990s and

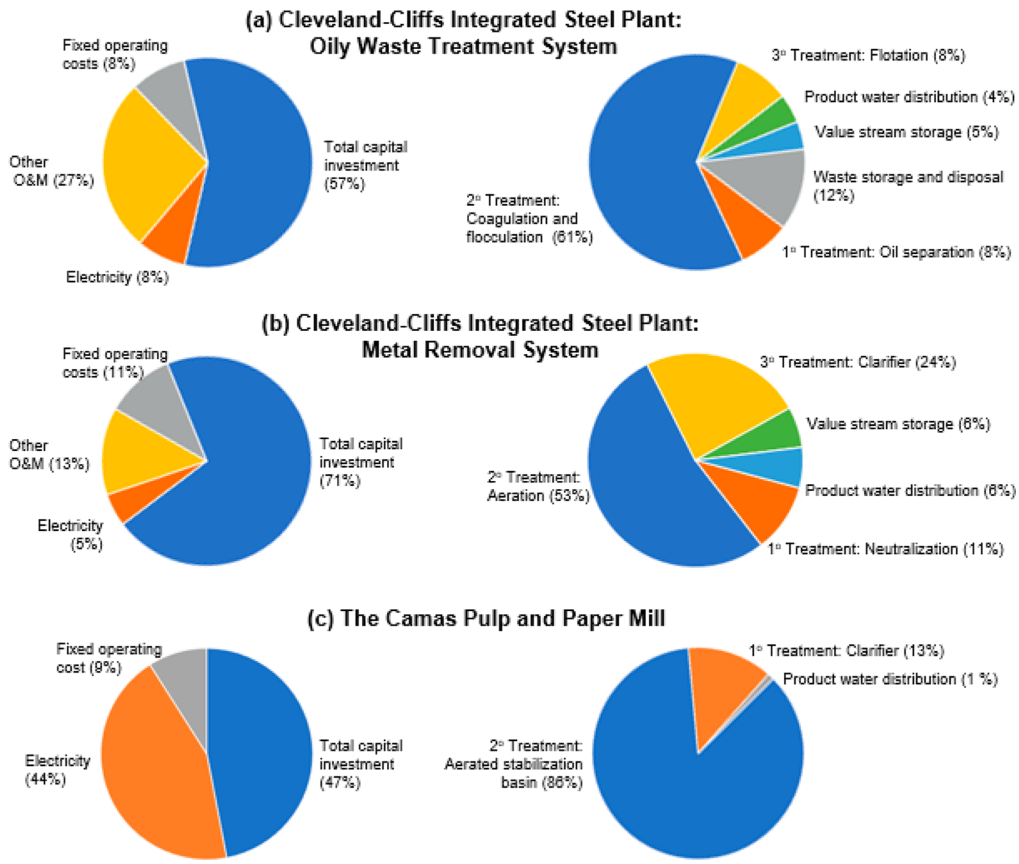

Figure 8. Detailed LCOW breakdown obtained by Water-TAP3 for the industrial wastewater treatment system by cost category (left) and treatment step (right). A similar breakdown for the Fab25 Wafer Fabrication Plant is provided in Figure S4.

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now owned by Infineon, manufactures primarily 200 mm silicon wafers that are precursors for memory chips. Silicon wafer fabrication involves multiple steps including etching, cleaning, rinsing, photolithography, re-etching, and deposition. Water is used for many of these processes including rinsing wafers, chemical dilution (both in situ and bulk), maintenance (parts cleaning, tool maintenance, and facilities maintenance), and facilities operations (cooling towers, exhaust scrubbers, humidification, chemical aspirators, boilers, chillers, seal water, and irrigation). Some of these uses (e.g., wafer rinsing and tool washing) require ultrapure water that has been treated using RO and deionization to achieve the highest purity; other uses have less stringent quality needs.

During the 2000s, the plant underwent major water conservation projects to reduce its reliance on municipal water for ultrapure water production from 10 000 m^3/day down to 4000 m^3/day (2.6 MGD down to 1.1 MGD) via a process optimization (i.e., water intensity reduction), use of external reclaimed water, and internal reuse and recycling.[199] Internal reuse and recycling, which is the primary focus of this case study, was achieved through tool bath/drain redesign, facilities drainage segregation, and advanced treatment. Three treatment trains added to the existing plant (Figure S3) include (i) a staged RO system receiving 8720 m^3/day (2.3 MGD) to treat the source water after a pretreatment, (ii) a UF system treating 2200 m^3/day (580 000 GPD) of a segregated waste stream from 30 tools in the fabrication processes, and (iii) an RO system to treat the remaining 2200 m^3/day (580 000 GPD) of a segregated waste stream from 22 fabrication tools to produce 1100 m^3/day (290 000 GPD) water for a cooling tower supply. Preliminary modeling of the three reuse treatment processes in FAB25 using Water-TAP3 produced the overall system metrics as shown in Table 2. The modeled system LCOW for Fab25 is \$3.48/m^3, which is 36% higher than the value of \$2.55/m^3 reported by the facility.

Discussion. A closer look at each plant's water process and Water-TAP3 analysis can help to develop strategies for improved water reuse and recycling. For example, in the case of the integrated steel mill plant, we note that the solid and metal constituents (TSS: 0−23.3 mg/L, oil: 0−6.9 mg/L, zinc: 0.01−0.03 mg/L) in the effluent from the two treatment trains are sufficiently low. However, they are currently discharged directly to the river, suggesting a significant potential to reuse this stream within cold mill operations or reclaim it for other purposes. While processes with higher-quality requirements (e.g., hot dip galvanizing line) would require the water source to be further treated by RO or an equivalent process, most operations at the cold mill could readily accept the treated effluent at its current quality. This finding is in agreement with the conclusions of Fuchs and Rao in their survey of U.S. industrial water reuse.[162] An additional Water-TAP3 simulation assuming the complete replacement of city water currently used in the cold mill (25% of total city water intake) by this recycled water suggests an annual cost savings of \$2.84 M, which is 1.8% of the total utility cost. The plant retrofitting requires mostly piping, and therefore the capital investment is likely minimal. This would also reduce the facility's dependence on municipal infrastructure, resulting in improved resilience.

Another opportunity for water reuse at this facility involves the management of slag, the most abundant solid-phase residual associated with steelmaking (15%−30% of steel product generated). The water associated with processing, moving, and storing slags is significant, overlooked, and undervalued. For example, the Cleveland-Cliffs Integrated Steel Plant consumes 9100 m^3/day (2.4 MGD) of water for slag processing. Unlike the adjacent raw steel processing stream, most of the water used to cool slag is lost to evaporation and not recovered. High-quality condensates recovered from slag processing could be used to offset the municipal water demand to reduce 20%−30% of the facility's municipal water demand; this could save up to \$3.5 M in annual water costs at current municipal rates. Considering the scale, the condensate recovery associated with slag processing may have significant, beneficial water management and cost impacts for the entire steel industry. It is important to note, however, that these estimates are not considering the capital cost of infrastructure or the return on investment for condensate recovery infrastructure. Condensate collection and reuse from slag processing is not optimized and remains understudied.

Also, it is worth noting that the domestic slag inventory remains tremendous (17 million metric tons).[200] Slag inventories contribute high-alkalinity stormwater from a continuous environmental exposure. Diverting this water source to treatment trains that need high alkalinity (e.g., pH neutralization in the metals removal system) is one potential way to reuse this leachate water. This could offset the cost associated with chemicals and catalysts in applicable treatment trains. Additionally, slags have mechanical and thermodynamic characteristics that have an unrealized value for a beneficial reuse in concrete construction, wastewater treatment, thermal energy storage, carbon sequestration, and energy recovery sectors.[201,202] Byproduct valorization is a significant opportunity to improve on the sustainability of steel production, particularly in response to current and future needs of the water reuse and energy sectors. This arena remains understudied.

As illustrated in this case study, the energy and water use resulting from steel making and its associated wastewater treatment and byproduct cooling is significant. This case study demonstrates that there are opportunities for water recycling that would reduce the plant's need for municipal water as well as byproduct valorization that would enable the plant to operate with an improved economy that leverages synergies with other sectors.[203] Although this case study describes a midsized integrated steel plant, we believe the findings will be useful to other plants across the sector, though the economics will vary depending on site-specific conditions, such as the amount of self-supplied versus municipally purchased water used.[204,205] Additionally, improved water data monitoring in the steel production process would improve our understanding of the water use footprint associated with modern steel making.

The Camas pulp and paper mill presents a markedly different situation compared to the integrated steel plant. The water usage volume is drastically larger, but the wastewater contains mostly organics that can be removed relatively easily by a conventional clarifier and aerated stabilization basin. Consequently, LCOW is very low—only one-third of that of the steel plant—leaving little room to reduce costs by a treatment process innovation. Instead, high concentrations of biodegradable organics provide the opportunity to use wastewater as input streams for biorefineries to manufacture other wood-fiber-based products. This "waste to inlet" approach is an example of innovations in water treatment

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and management that could provide value to create economic incentive for wise water management.[206,207]

A similar strategy can be applied to the food and beverage industry, in which wastewater also commonly contains a large amount of BOD (Table 1). For example, many breweries discharge ~70% of the incoming water as effluent.[208] Some brewers will pretreat their effluent via a solids removal and pH balancing before sending it to the local WWTP,[208,209] while others employ biodigesters (e.g., enhanced dissolved air flotation or moving-bed biofilm reactors)[210,211] to meet the discharge standards of NPDES permits set by the EPA. This presents an opportunity for valorization, as much of this organics-rich wastewater can be side-streamed and used directly as a fertilizer after the pH balancing.[209] Alternatively, wastewater can be used as a carbon source for denitrification processes. For example, Avery Brewing in Boulder, Colorado, sends a carbon-rich "weak wort" solution produced at the end of the lautering process to Boulder Water, which drastically reduces the consumption of acetic acid, its default carbon source, in exchange for a reduced fee for wastewater discharged to the municipality.

The Fab25 Wafer Fabrication Plant presents an example at the opposite end of the spectrum, where ultrapure water is required for wafer fabrication processes and facility cooling, resulting in a significantly higher LCOW compared to other cases. These challenges have motivated the plant to invest in significant modifications to existing water usage and treatment approaches, including the active segregation of wastewater from conductivity monitoring and automated flow diversion equipment to feed to separate downstream treatment trains. It is noteworthy that one of the projects to reclaim process waste reportedly cost $930 000 while avoiding $1.4 million per year in water and wastewater fees, thus providing a return on investment within less than one year.[212] We performed further Water-TAP3 simulations of three possible ZLD scenarios for this plant (Figures S4). Results suggest that a combination of additional RO, brine concentration, and an evaporation pond or crystallizer could achieve 100% water recovery for an additional \$1.47−4.52/m^3 in LCOW. Other ultrapure water facilities have adopted centralized treatment systems for reuse, as opposed to waste stream-specific,[213] and future research should quantitatively compare the pros and cons of various water reuse strategies, as exemplified by our Water-TAP3 analysis. Typical semiconductor facilities use 8000−15 000 m^3/day (2.1−4.0 MGD), and the largest semiconductor company (Intel) reported 34 million m^3 total use across all its facilities in 2015.[214] Intel's semiconductor manufacturing facility in Chandler, Arizona, which sends 7600 m^3/day (2.0 MGD) of its wastewater to the Ocotillo Brine Reduction Facility for treatment and aquifer recharge, provides another example of beneficial wastewater management. Of the 34 000 m^3/day (9.0 MGD) of water used by the Chandler facility, 19 000 m^3/day (5.0 MGD) is reused or reclaimed water.[215,216] The continued growth in this industry sector suggests significant opportunities, and the case study of Fab25 Wafer Fabrication Plant epitomizes the potential to enhance water recycling and reduce LCOW through technological innovations.

4. CONCLUSIONS

Barriers to Water Reuse. Access to cheap and abundant conventional freshwater sources and the financial cost of renovating existing treatment trains or installing new ones appear to be among the most critical barriers to a widespread adoption of industrial water reuse. Many large-footprint industrial facilities are located close to surface freshwater bodies or groundwater aquifers, providing sufficient quantities of water at little or no cost. As illustrated by the Camas Pulp and Paper Mill, which draws most of its water from the Ohio River, such facilities operate at minimal LCOW and therefore have limited or nonexistent cost incentives for water reuse. Capital costs stemming from the purchase and installation of equipment and piping may be cost-prohibitive, particularly for facilities with low profit margins, such as food and beverage manufacturers.[28] A small-scale survey of 10 industrial facilities by Oppenheimer et al. concluded that reuse/recycling opportunities reach implementation when they can demonstrate a return on investment of two to three years or shorter.[217] Another critical challenge stems from the complex heterogeneity of industrial water uses, wastewater characteristics, and water-quality requirements, which limits the applicability of overarching, one-size-fits-all approaches for achieving a widespread adoption of industrial water reuse (there are, of course, several noteworthy exceptions, as detailed in the *cross-cutting innovations* section below). Intensifying this challenge is the lack of consistent reporting of water-quality data, treatment system configurations, and minimum quality requirements for the source water. For example, the data presented in Figure 1a, obtained from a 1998 study by Ellis et al., are to our knowledge the most recent of its kind available in the literature and are limited only to manufacturing facilities within Texas. A regular collection of such data at the national scale would provide a clearer understanding of the distribution of water uses across industry sectors and help to identify key areas to target for reuse. Other notable barriers to reuse include water quality and safety concerns and the proprietary nature of industry.[162,217] Examples of additional industry-specific challenges to water reuse are included in Table 3.

Extending Water-TAP3 Analysis. To improve the security and efficiency of water use at industrial facilities, proper decision-making requires a comprehensive knowledge of existing and state-of-the-art water use and treatment technologies. The quantitative analysis of LCOW by treatment step, enabled by the Water-TAP3 tool, helps to identify the most cost-intensive areas of a treatment train, which often have the greatest potential for water process renovations. Moreover, the ability for a side-by-side comparison of financial and energy costs of prospective modifications to existing treatment trains is critical toward optimizing the cost-effectiveness of potential water reuse solutions. Considering the heterogeneity of industrial sectors and the types of processes found within them, there likely exist many industry-specific opportunities beyond the examples discussed in this paper. Although only three case studies were performed in our work, we believe that a Water-TAP3-like analysis can be readily adopted in a variety of cases to prioritize research needs and guide facility-to-facility decision-making. The case studies discussed in this paper illustrate the usefulness of Water-TAP3 in analyzing a diverse set of facilities. Also note that, in addition to the capabilities of Water-TAP3 showcased in this paper, several outputs are currently in development, including a life-cycle assessment of environmental impacts, the extent of withdrawals from alternative water and energy resources, and an assessment of system resiliency and security.

Geographical Considerations. The geographical variation of water source availability is a key factor impacting water

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Table 3. Examples of Relevant Wastewater Constituents, Treatment Challenges, Commonly Employed Treatment Technologies, and Reuse and Valorization Technologies/Strategies in Six Representative Industries[a]

industry	wastewater constituents	challenges	treatment technologies 1°	2°	3°	reuse & valorization
Food & Beverages[32,36,39,49,73]	Organics, solids, oils and grease, nutrients	Phenols and fatty acids can inhibit microorganisms	Screening, coagulation/flocculation, air flotation	Activated sludge, AD	AOP, RO, MF, MBR	AD, MFC, biopolymers
Primary Metals[53,84,86,203]	Solids, oils and grease, organics, heavy metals, high acidity	Removal of heavy metals, cyanides	Oil skimming, screening, flocculation	Clarification, phase separation, dissolved air flotation (DAF)	AOP, membrane filtration	Metals recovery, slag
Pulp & Paper[44,111−113,122]	Solids, organics, nitrogen compounds, organic halides	Presence of lignin and lignin derivatives, low biodegradability	Coagulation/flocculation, DAF	Activated sludge, AD	AOP, UF	AD, bioethanol, DMR
Petroleum Refining[56,131,136,140,145,151,158]	Organics, solids, hydrocarbons (BTEX)	High benzene, H_2S concentrations	Oil separators, equalization, DAF	Activated sludge, MBR	AOP, sand filtration, membrane filtration	Source-water diversification, condensate recovery
Chemicals[45,48,161,163,164]	Organics, oils and grease, BTEX, trace metals	Many toxic organic, mutagenic, carcinogenic, and nonbiodegradable compounds	API/CPI separation, sour water stripping, buffer tanks	Aerobic-anaerobic, hydrolysis acidification, photodegradation	Adsorption, membrane filtration, AOPs, electrochemical processes	Cooling tower blow-down recovery, MLD
Data Centers and Campuses[20,58,187,218]	Solids, organics, nutrients, pathogens	Lack of data, reporting	Oil separation, sour water stripping, sedimentation	Activated sludge, clarification	Membrane filtration, chlorination	Source-water diversification, on-site treatment and reuse

[a]Note that these data are intended only to highlight and provide examples of wastewater constituents, challenges, and treatment technologies in each industry; they do not provide a complete or exhaustive listing.

use and management in many industries, especially those that require large volumes of water. Historically, industrial facilities with high water demand have been strategically placed in close proximity to large bodies of water, or in areas where anthropogenic water demands are less than water restoration rates.[5,219] These facilities often have little or no legislative, financial, or risk-driven incentives to adopt water reuse technologies. However, because of considerations such as the proximity to supply chains and/or population centers, many industries have seen growth in water-scarce regions of the U.S., including Texas, California, and Louisiana. This is particularly the case for rapidly growing, tech-centered industries such as data centers and semiconductor manufacturing, which place an additional stress on local water supplies and increase operational risks of water shortage.[220,221] As a result, replacing municipally supplied cooling water with nontraditional sources, most notably reclaimed municipal wastewater effluent, has been key in making these facilities economically feasible and environmentally secure. Although specific success stories among industry giants have been reported (see Sections 2.5 and 2.7) demonstrating the feasibility of this approach for large industrial facilities, the technical details are often not reported, including the minimum quality requirements for cooling makeup. The co-location of industrial facilities, although currently rarely practiced, also carries the potential to facilitate water reuse and/or valorization and boost water and energy security. For instance, pulp and paper mills can be colocated with bioethanol refineries to provide biomass-rich waste streams with relatively low toxicity as a feedstock. Similarly, data centers can be constructed adjacent to beverage manufacturers to easily treat and reuse water from bottle washing for use in cooling.

Cross-Cutting Innovations. Despite the aforementioned diversity among industry sectors, there exist some opportunities to impact a wide swath of industry through the innovation of current water treatment systems and technology. One notable example lies with water used in cooling systems and boilers. Because of the considerable amount of water used for cooling and boiler feedwater across nearly all industrial sectors, cooling and boiler systems possess an enormous potential for reuse. However, minimum water-quality requirements for these systems remain poorly defined and are typically governed by the common issues of corrosion, scaling, and fouling. Developing cost-effective strategies to simultaneously address these issues and improve the reusability of the recirculating water remains as a significant challenge, especially in large systems. In addition, there are numerous constituents that are commonly found in more than one industry (Table 3). Technologies that can address these will have a broader impact across many industry sectors. For instance, recalcitrant organics, O&G, and heavy metals are common problematic constituents that make discharge or recycling challenging across various industries, including food and beverages, chemicals, and petroleum refining. Technologies to remove these pollutants efficiently and selectively are in critical need to maximize water reuse and recycling opportunities. These processes include the pretreatment and recovery of hydrocarbons, petroleum, grease, and oil from waste streams, sludge, or waste solids to improve phase separations prior to a downstream treatment or integrated within treatment systems. There is also a need for enhanced, resilient methods of handling complex industrial wastewaters with TSS and/or

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TDS to increase efficiencies of precision separations for reuse and disposal of waste streams.

Modular Treatment Systems. For advanced treatment technologies to be widely adopted for water reuse, especially by small-scale manufacturers, there is a need for modular approaches that can be easily integrated in various process situations. While some existing processes such as membrane filtration are modular by nature, others require forethought to conceptualize into modular designs that increase the overall system flexibility and allow for distributed applications. In addition, many of these processes require a pretreatment to ensure that they are not hindered by the presence of nontargeted species (e.g., silica, suspended solids, and organics to reduce fouling, solids removal prior to biological treatment). For these systems, current pre- and post-treatment technologies often require large amounts of space and relatively long periods of downtime for construction and installation, and they may carry prohibitively high installation costs due to extensive onsite engineering and integration requirements. They do, however, carry the highly valued advantage of proven reliability, which presents a major challenge to the adoption of alternative water sources, especially those that are temporally or spatially variable.

Autonomous Monitoring and Control. It is also noted that many small- and medium-sized facilities do not have automated controllers for their treatment operations but, instead, rely only on inefficient on/off systems, often managed by human operators. Therefore, decision making in response to perturbations in source water quality, process upsets, and other unpredictable events is dependent on heuristics and institutional memory, which may or may not be dependable. The capability to inexpensively monitor the status of an operative treatment system and the quality of water prior to and after a treatment is a prerequisite for the collection of large quantities of operational data that would enable the development of autonomous processes. Monitoring must be in real-time to allow for a real-time process control, a successful example of which can be found in our Fab25 Wafer Fabrication Plant case study. A high degree of autonomous system optimization and control will also enable industries to prepare for longer-term changes including source water depletion, quality deterioration, and climate change.

Future Outlook. In summary, there is a considerable potential for water reuse within the U.S. industrial sector. Although major challenges still remain, such as complex and widely varying process wastewater characteristics, access to relatively cheap and abundant surface, ground, and municipal water sources, and a general lack of data reporting and transparency, some progress has already been made among industrial facilities to adopt water reuse practices, particularly those located in water-scarce regions. Future research should focus on the development of new treatment technologies that are low-cost, autonomous, precise, and modular in order to fit the needs of specific plants and/or industry at large. In addition, a particular emphasis should be placed on the acquisition of industrial water use, treatment, and reuse data at the national scale and on promoting the potential cost, environmental, and security benefits inherent in sustainable water reuse practices. With appropriate research prioritization and some initiative, the industrial sector will play a major role in improving the sustainability and security of water resources in the U.S.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestengg.1c00282.

Raw data and diagrams of water use/treatment systems for Cleveland Cliffs Integrated Steel Plant, Camas Pulp and Paper Mill, and Fab25 Wafer Fabrication Plant, full listing of manufacturing industries by three-digit NAICS code (PDF)

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Notes

The authors declare no competing financial interest.
This study is limited by the availability of data. The discussion presented herein reflects what has been reported in academic literature, government reports, and corporate Web sites, among other formats. We acknowledge that, due to the proprietary nature of industry, gaps likely exist in the information contained in the available literature regarding industrial practices.

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