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Survey of Available Information on U.S. Manufacturing Wastewater and Energy Requirements for Reuse

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Table of Contents

1. Introduction

Manufacturing represents a significant portion of the U.S. economy, making up 12 percent of gross domestic product (GDP) and one quarter of energy consumption, directly employing 12 million people, and selling products valued at nearly $6 trillion in 2016 (DOE 2016). Manufacturing also demands an estimated 6 percent of U.S. water intake, around three quarters of which are self-supplied (Rao *et al*. 2015). At the same time, water is a critical component of many manufacturing processes, with manufacturing water demand globally expected to increase by 400 percent between 2000 and 2050, more than any other sector (OECD 2012). However, its valuation does not accurately reflect the vital role water plays in manufacturing. In addition, little robust information exists on the amount of water used by different manufacturing subsectors, the manner in which water is used at manufacturing plants, and the costs of pumping and treating or buying water of sufficient quality and quantity, as well as the associated physical, regulatory, and reputational risks.[1] In a changing world with increasing constraints on water availability and quality, on-site reuse has the potential to alleviate watershed impacts of manufacturing by reducing the use of water sourced from the watershed. In addition, it may offer substantive benefits to manufacturing facilities, such as reducing risk and increasing resilience via decreasing reliance on outside water resources. Some cost savings may also result; however, a fuller accounting of risks, costs, and benefits is precluded by the current poor understanding of the many and varied constituents of manufacturing effluent, as well as the complexity and heterogeneity of treatment trains.

Water is a critical input to manufacturing, and the water-energy nexus also deserves closer attention in the industrial context in order to deepen our understanding of the choices manufacturers face in terms of resource use. Manufacturing plants see interdependencies between water and energy. In some instances, conserving energy also saves water (e.g., returning condensate from industrial steam systems); in others, instituting water efficiency measures may require additional energy. On-site manufacturing water reuse requires energy for treating effluent to a standard suitable for reuse, but outside of a number of case studies reviewed in this paper, there is a paucity of published information on the energy-related implications of such reuse. In addition, the magnitude of this additional energy use depends upon where system boundaries are drawn.

This report seeks to inform an improved understanding of the energy tradeoff associated with manufacturing water reuse in the United States, in part by developing an analytical framework for understanding when this tradeoff for reuse is beneficial. In order to apply this approach, existing literature and publicly available information on typical contaminants in industrial effluent and available treatment technologies are reviewed and summarized. An existing case study is then discussed in light of how the analytical framework could be applied if sufficient data were available. We conclude that the shortcomings of the available data severely restrict our ability to apply this framework. These limitations are highlighted with the intent of providing the broader research community information on where data gaps need to be filled.

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[1] For the purposes of this report, we define manufacturing water use as a broad term that includes consumptive and non-consumptive uses.

Finally, note that this report complements a recently published journal article by the same authors (Fuchs and Rao 2021); this longer report can be viewed as a supplement to that work. In the interest of providing sufficient context to understand the information contained in this report, it is necessary to include some figures, equations, and text from the journal article here.

2. Analytical Framework

An idealized analytical framework that would compare the energy required for single use of water to that for on-site reuse was developed. Its aim was to answer the following question: For a given manufacturing process, when is it energy beneficial (i.e., on-site energy consumption plus embedded energy in water is less than the alternative) to implement on-site reuse to replace a single use of water? Necessary parameters are presented in Table 1; our initial research approach centered on discovering manufacturing processes for which all these parameters can be identified.

Table 1: Parameters necessary for analytical framework

Input to on-site treatment	Process	Output from on-site treatment
Effluent contaminant mix and concentration after reuse (contaminant concentration will increase with every reuse cycle)	Energy intensity of on-site treatment process	Process water minimal water quality (contaminant concentration) requirements (fit-for-use)
Effluent water flow rate	Number of times water can be reused	Process water flow rate requirement
	Chemical requirements	

It is proposed that the energy requirement for a single use of water per unit volume ($E_{tot,single\ use}$) can be calculated using the following equation:

$$E_{tot,single\ use} = E_{w,ex} + E_{w,tr} + E_{w,dist} + E_{wwt,comp} + E_{wwt,con} + E_{wwt,tr} + E_{wwt,dis}$$

Where:

$E_{w,ex}$ = energy per unit volume for freshwater extraction to off-site water treatment plant; dependent on source water characteristics such as: depth to water (zero for surface water sources), conveyance distance, pipe friction factor and diameter, volume flow rate, and other parameters

$E_{w,tr}$ = energy per unit volume for freshwater treatment to clean (*e.g.*, potable, recycled) water requirements; dependent on treatment characteristics such as: quantity and types of contaminants needing to be removed, volume flow rate, temperature, pH, and other parameters

$E_{w,dist}$ = energy for clean water distribution to manufacturing facility; dependent on water distribution system characteristics such as: elevation gain to facility, distance to facility, pipe friction factor and diameter, volume flow rate, and other parameters

$E_{wwt,comp}$ = energy for treating wastewater onsite to meet compliance requirements before sending to municipal wastewater plant; dependent on characteristics of the treatment process such as: energy and chemical requirements of treatment technology(ies), and other parameters

$E_{wwt,con}$ = energy for wastewater conveyance to municipal wastewater plant; dependent on municipal wastewater system characteristics such as: elevation gain to facility, distance to facility, pipe friction factor and diameter, volume flow rate, and other parameters
$E_{wwt,tr}$ = energy for treatment at municipal wastewater plant; dependent on wastewater characteristics such as: quantity and types of contaminants needing to be removed, volume flow rate
$E_{wwt,dis}$ = energy for treated water discharge; dependent on wastewater system characteristics such as: elevation gain to facility, distance to facility, pipe friction factor and diameter, volume flow rate

Conversely, the energy requirement for reuse can be conceptualized as:

$$E_{tot,reuse} = E_{w,ex} + E_{w,tr} + E_{w,dist} + \sum_{i}^{x} E_{reuse,i} + E_{wwt,con} + E_{ww,tr} + E_{wwt,dis}$$

Where:

x = number of times water is reused at facility
$E_{reuse,i}$ = energy requirement to treat after ith reuse; function of quantity and types of contaminants needing to be removed, volume flow rate, embedded energy in chemicals for treatment

Reuse becomes energy beneficial when the treatment requirements for the ith reuse of water is less than $E_{tot,single\ use}$. More generally, reuse is energy beneficial when:

$$\frac{\left(\left(E_{tot,reuse}\right/_{x}\right)}{E_{tot,single\ use}} < 1.$$

The content of this report is as an effort to synthesize the information required to apply this framework. In other words, the initial objective of this information assessment was to evaluate the current and prospective energy implications for manufacturing wastewater treatment technologies in order to facilitate a more comprehensive economic analysis of the benefits of water reuse. The approach taken involved several specific steps, as follows. First, identify typical contaminants in wastewater discharges for each manufacturing subsector. Second, define, identify, and quantify emerging contaminants in manufacturing wastewater. Next, identify current and emerging technologies for treating the contaminants identified in previous steps. Lastly, evaluate the energy requirements for treatment technologies identified in the first step for the contaminants identified in the second and third steps.

This report reviews what is known about manufacturing wastewater by reviewing the literature and publicly available permit data, and it attempts to characterize wastewater streams by manufacturing sector. We employ several methods in this paper. After surveying and synthesizing the existing literature on manufacturing water reuse, we present the results of an analysis of U.S. Environmental Protection Agency (EPA) data that are pertinent to manufacturing wastewater: industrial Effluent Guidelines, National Pollutant Discharge Elimination System (NPDES) data, and Toxics Release Inventory (TRI) data. Next, we provide introductions to promising manufacturing wastewater technologies with an eye toward their applicability and energy implications. We then use several existing case studies as a basis to determine the energy and water cost implications of on-site reuse in these particular cases. Finally, we discuss the gaps that remain in our understanding and identify the data required for a comprehensive tradeoff analysis of the energy required for on-site manufacturing wastewater reuse.

3. Literature Review

Our search of the recent literature related to industrial water use and reuse included both domestic and international sources in order to cast a wide net to gather information. We uncovered a great deal of dissimilar information, a sizeable share of which were centered on heavily polluting industrial sectors such as tanneries, textile dyeing, oil and gas extraction, petrochemicals, and paper manufacturing (for example, Ben Amar *et al.* 2009, Benito-Alcazár *et al.* 2010, Venzke *et al.* 2017, Zhang *et al.* 2017, Ghani *et al.* 2018, Sundarapandiyan *et al.* 2018, Sousa *et al.* 2018). Many of these publications included details on various relevant treatment technologies, but focused mainly on treatment to meet industrial process discharge requirements instead of considerations relevant to on-site water reuse. Almost no surveyed publications included a full accounting of the water savings, water and wastewater cost savings, and required energy for on-site reuse. More broadly, we found that wastewater treatment research and technology development is largely focused on municipal wastewater, which has a small overlap with manufacturing wastewater in terms of constituents—and that within the manufacturing sector, treatment processes are largely driven by the need to meet regulations. This section presents an overview of recent literature relevant to manufacturing water reuse to help frame the analysis present in the remainder of the paper.

3.1 Current State of Reuse

First, Kuo and Smith (1998) make a distinction between industrial wastewater "treatment" vs. "regeneration" in the process industries. The former refers to when treated wastewater is discharged to the environment, while the latter pertains to when treated water is recycled (can re-enter operations in which it has previously been used) or reused (can only be reused for another purpose within a plant). In this report, we discuss manufacturing water reuse in terms of both recycling and reuse for another process or purpose at the same plant. Next, Kim *et al.* (2008) survey industrial water reuse practices around the world. They determine the global potential for industrial water reuse, assuming 10 percent of industrial water is recycled, to be 110,000Mm3/yr—equivalent to three times the storage capacity of the Hoover Dam. Domestically, the National Research Council (NRC) establishes that because of better efficiency, higher energy and water prices, and a shift away from water-intensive manufacturing (as well as offshoring), per capita industrial water use within the U.S. has been declining since 1965. They also find that in Florida and California, industrial reuse represents 13 percent and 7 percent, respectively, of all reuse, while global hotspots of industrial water reuse are Australia and Singapore (NRC 2012). In recent years, water reuse more generally has become seen far more acceptance from utilities, regulators, and the general public alike (BIER 2020); one example of this is illustrated by the EPA's draft National Water Reuse Action Plan released in September 2019, which states that 39 of 50 U.S. states have already adopted regulations or guidelines governing water reuse, with three more states in the process of putting them in place (EPA 2019).

The WateReuse Research Foundation investigated the motivations, difficulties, achievements, and opportunities for on-site industrial water reuse and recycling (focusing on NAICS codes 21 [mining and oil and gas extraction], 22 [power], and 31–33 [manufacturing]) via a literature review, vendor outreach activities, survey, and workshops with industry participants (Oppenheimer *et al.* 2016).[2] Authors of this comprehensive report reach several important conclusions. They find that industrial water use data published by the government largely are not disaggregated into sector classifications, and that publicly available corporate data is inconsistent between and within these classifications. In addition, Moore and Buzby (2017) contend that industry has historically only considered the cost of acquiring water instead of its total cost, which when considered holistically also encompasses energy to move, heat, cool, and/or treat, treatment chemicals, labor for systems operation, pretreatment, wastewater discharge, waste management, and capital and regulatory obligations.

In its draft National Water Reuse Action Plan, EPA sets forth several proposed actions with direct relevance to this paper.[3] First, the plan recommends amassing pollution prevention concepts for water sources of potential reuse, including industrial process water, as well as creating and disseminating related best practices. Second, it proposes the development of informational materials and training materials for permit writers and inspectors relating to how NPDES permits can facilitate reuse. Next, in order to provide better access to water reuse research and existing water reuse applications, it suggests that a data clearinghouse be created for research data, findings, and case studies. Finally, it includes industry process and cooling water in the scope of the proposed action to quantify the volume of current water use and potential reuse nationwide. An online platform for the current status of proposed actions is available.[4]

3.2 Motives for Reuse

In surveying the literature for drivers of manufacturing water reuse, we found some commonalities supporting the statement that treatment processes are mainly implemented as a consequence of mandatory regulations governing discharge. Kuo and Smith (1998) identify the main incentive for cutting water use to be reducing effluent treatment costs, while Oppenheimer *et al.* (2016) emphasize that wastewater discharge regulations and local or regional water supply restrictions are the largest motivations for industrial water reuse. In addition, they assert that regional water limitations are typically managed via water conservation, while more costly reuse and/or recycling is generally employed on the basis of minimizing wastewater discharges that cannot be cost-effectively treated to required standards. Their survey of 10 industrial participants demonstrates on a small scale that in regions without source water limitations, reuse and/or recycling projects are typically only implemented when the cost differential between the treatment needed to meet discharge quality requirements and that needed for water recycling or reuse is small enough to produce a return on investment within two to three years (Oppenheimer *et al.* 2016). Looking forward, Lazarova *et al.* (2001) highlight the potential of

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[2] Individual appendices exist for water reuse in: the food and beverage industry, cooling towers, manufacturing industries, the mining industry, the oil and gas industry, and the power industry. Survey respondents and workshop participants represented the following sectors: mining, power, food and beverage, metal manufacturing, and chemical manufacturing.

[3] See Action 2.2.5 Compile and Develop Protection Strategies for Different Sources of Waters for Potential Reuse; Action 2.2.6 Develop Informational Materials to Better Enable Water Reuse in CWA NPDES Permits; Action 2.7.1 Develop and Maintain an Inventory of Water Reuse Research; and Action 2.10.1 Compile National Estimates of Available Water and Water Needs.

[4] https://www.epa.gov/waterreuse/national-water-reuse-action-plan-online-platform

wastewater reuse as a strategy for integrated water management, highlighting technical, financial/economic, regulatory, and social keys to success for water reuse projects, in line with the recent emphasis on the circular economy within the research community (Voulvoulis 2018). The Beverage Industry Environmental Roundtable (BIER), an industry group working to advance environmental sustainability, echoes this reasoning, arguing for an attitudinal shift by industry from looking at water linearly (intake, use, and discharge) to integrating a circularity perspective with the objective of reducing plants' net water use and impact on local watersheds—while addressing the production risks of scarce or unreliable water supplies. In addition to mitigating risks, manufacturers implementing reuse would likely also benefit from positive views of this reuse by consumers and the broader public given its contribution to the sustainability of community water supplies (BIER 2020).

Next, Rao *et al.* (2019) assess which U.S. manufacturing subsectors are most at risk of physical water shortages by determining whether the geographic distribution of water intake for manufacturing facilities is located in water-stressed regions as defined by the Water Supply Stress Index (WaSSI). Statistics Canada's biennial Industrial Water Survey presents valuable industrial water data. Because comparable data are not available for the U.S. the authors estimate U.S. water intake by subsector by relating Canadian manufacturing water and employment data from Statistics Canada's biennial Industrial Water Survey to county-level U.S. manufacturing employment and water data. They find that the subsectors with the greatest water intake in absolute terms are, in descending order: pulp and paper (322), primary metals (331), chemical (325), petroleum and coal products (324), and food (311). Combined, these five subsectors represent more than 90 percent of all manufacturing water intake in the U.S., while the first three mentioned collectively make up more than three quarters of total intake. At the same time, the three sectors where the share of water intake occurs in water-stressed counties exceeds 10 percent are primary metals (331), fabricated metal products (332), and transportation equipment (336), followed closely by petroleum and coal products (324) and plastics and rubber products at 9 percent each. These estimates are somewhat uncertain, but in the absence of statistically representative surveys of manufacturing facilities' water use, they may represent the best information currently available on how to best target efforts to alleviate water shortage risks by manufacturing subsector and location.

3.3 Barriers to Reuse

A variety of challenges complicate the successful widespread implementation of water reuse, with Moore and Buzby (2017) classifying impediments to increased water efficiency into four types: resource, regulatory, motivational, and data and information gap barriers. A 2012 National Research Council report sets out a research agenda designed to help overcome technical, financial, and institutional hurdles to make wastewater a reliable source of alternative source of water supply (NRC 2012). This report covers industrial applications of reclaimed municipal wastewater, but does not explore on-site reuse. However, more broadly the NRC cautions that financial costs of reuse vary greatly, given their dependence on site-specific aspects, and that one barrier to reuse is the imperative to safeguard the quality of ongoing manufacturing operations. Along these lines, Kim *et al.* (2008) identify major quality concerns associated with reuse as corrosion, foaming, scaling, biological growth, and process fouling. Additionally, they highlight that very small amounts of persistent organic pollutants in reclaimed water can be problematic in terms of human and environmental health, even if these concentrations do not directly affect industrial water usage. In terms of specific contaminants, Environment Protection Authority Victoria (2017)'s guidelines for manufacturers cover commonly encountered environmental and health hazards include pathogens; nutrients (nitrogen and phosphorus); biodegradable organics; refractory organics that cannot be successfully treated via conventional treatment (e.g., pesticides, phenols); dissolved inorganics (e.g., calcium, sodium); metals (e.g., cadmium, chromium, lead, mercury); suspended solids; toxic organic and inorganic compounds; and non-pathogenic organisms that can cause equipment scaling or corrosion, as well as odor problems.

Beyond quality and safety concerns, Oppenheimer *et al.* (2016) identify the following challenges to the increased uptake of industrial water reuse: the heterogeneity of processes and wastewater constituents within facilities, the proprietary character of industry, technological feasibility concerns, lack of training and information, how to manage different waste streams and treatment byproducts, and an economic environment that tends to favor rapid return on capital investments while source water is generally available at extremely low prices or for free, if self-supplied. However, while most companies consider the cost of water to be only the price they pay to a utility for that water, the true cost of water is commonly two to three times what most companies anticipate, because it accounts for pumping, treating, moving, heating, cooling, and using water in operations (BIER 2020). Several sources discuss the need for more comprehensive planning tools and economic analyses that account for the full range of benefits of water reuse (Lazarova *et al.* 2001, Oppenheimer *et al.* 2016, Moore and Buzby 2017, BIER 2020).

3.4 Reuse Technologies

Regarding appropriate wastewater treatment technologies and their application, we include the following sources. The NRC's summary of wastewater reclamation technologies with wide application in industry highlights membrane bioreactors—with recent developments in longer membrane lifetimes, reductions in cost for membrane modules, and small-scale designs allowing for decentralized reclamation—and chemical oxidation, which is well-suited to treating resistant chemicals like industrial solvents (NRC 2012). In more detail, Moore and Buzby (2017) provide synopses of "the more commonly employed/encountered recycle technologies": granular activated carbon, organoclay, ion exchange, organophilic resins, ultrafiltration, reverse osmosis and nanofiltration membranes, sand/multi-media filters, bag filters, cartridge filters, rotary vacuum-drum filters, advanced oxidation processes, and ozone. These overviews are made more useful with the inclusion of estimated equipment cost and annual operating expenditure curves across a range of flow rates for treating certain contaminants within a certain concentration range for highlighted technologies, as well as tables that approximate relative effectiveness and costs of treatment via different technologies for different wastewater streams across a number of given influent concentrations and desired effluent concentration targets. The authors do not state whether the operating expenditure curves take energy into account, either uniformly or at all.

Real-world application of these technologies are covered in many individual case studies and papers focusing on single technologies. Taking a wider view, Kim *et al.* (2008) present relatively straightforward reuse applications in the literature for automobile manufacturing, meat processing, breweries and beverages, paper mills, and metal plating industries, while short case studies spanning wafer fabrication (Singapore), aluminum can manufacturing (USA), precision glass (South Korea), a piggery (Australia), and the steel industry (South Korea) are also included. In addition, Moore and Buzby (2017) feature case studies in aerospace, automotive, flat glass, food and beverage, paint and coatings, and pharmaceuticals and chemicals manufacturing, although these summaries generally do not address the energy costs of water reuse. Finally, the BIER recently created a decision guide for organizations considering implementing reuse projects—even those outside the beverage sector—that covers unique considerations for on-site industrial reuse (but does not include those related to energy requirements) and points to additional resources and tools. It suggests that water reuse technology development is rapidly advancing, with viable options that did not exist even a few years ago, and that reusing water within a manufacturing plant's "'four walls' provides complete operational and cost control" (BIER 2020).

3.5 Resources for Manufacturers Considering Reuse

Several sources provide general practical guidance on reusing manufacturing water. For example, the Environment Protection Authority Victoria (Australia) created guidelines that govern managing environmental and health risks related to reusing industrial water (Environment Protection Authority Victoria 2017). These guidelines characterize the quality and quantity of industrial water as extremely variable and recommend reuse for a range of cooling and washing or rinsing processes. Similarly, the NRC recommends that reclaimed water first be applied in industrial processes with less stringent water quality requirements (e.g., cooling). Table 2 summarizes general water quality concerns for cooling water, boiler feedwater, and process water from this report.

Table 2: Water quality concerns for industrial applications of reclaimed water; adapted from National Research Council (2012)

Industrial application of reclaimed water		**Water quality concerns**
Cooling water		• Power plants: scale formation, biological growth, corrosion
Boiler feedwater		• Scale formation from calcium, magnesium, silica, and aluminum • Foaming from high alkalinity and too much sodium and potassium • Steam acidity and corrosion from bicarbonate alkalinity leading to release of carbon dioxide • Quality requirements increase with boiler's operating pressure
Process water	Textiles	• Water must be non-staining; iron, manganese, and organic matter can compromise product quality • Divalent metal cations incompatible with dyeing processes using soap • Nitrates and nitrites may also be problematic
	Electronics	• Water for washing circuit boards needs RO treatment to remove salts
	Pulp & paper	• Metal ions (*e.g.*, iron, manganese) can discolor paper • Microorganisms can change paper texture and uniformity • Suspended solids modify paper brightness
	Food/beverage containers	• Reclaimed water prohibited in some states, given human health concerns related to consumable products
	Chemicals	• Requirements vary widely depending on process involved, but generally look for neutral pH (6.2 to 8.3), moderately soft, and relatively low in silica, suspended solids, and color • Typically not critical: total dissolved solids and chloride content

In addition, Table 10-3 in the NRC report contains data for seven states on quality limits and treatment required for industrial cooling water applications. Next, Ranade and Bhandari (2014) is a reference of industrial water treatment methods, with overviews of existing and new advanced treatment technologies, as well as case studies on zero liquid discharge. This book began as a workshop entitled Indus Water, organized by Council of Scientific & Industrial Research–National Chemical Laboratory in India., and can serve as a practical resource on water reuse and recycling technologies for industry.

In terms of conceptual models, Oppenheimer *et al.* (2016) recommend water pinch analysis to identify the most cost-effective combination of treatment options that will increase water efficiency, and then suggest that low-volume wastewaters with high pollutant concentrations tend to be suited for recycling to the same process after treatment, while high-volume wastewaters with lower pollutant concentrations are more appropriate for on-site reuse in other processes. In addition, Kuo and Smith (1998) present a conceptual methodology for regeneration system design that (1) divides streams into two groups, one requiring fresh water and one requiring regenerated water; (2) allows streams to be migrated between these groups to refine targets; (3) develops targets for number of treatment units in addition to fresh water and regeneration targets. Another method to identify conservation and reuse opportunities was conceived of by Moore and Buzby (2017), who propose a Kaizen Blitz process based on LEAN Manufacturing principles.

4. Characteristics of Manufacturing Wastewaters

Our literature review uncovered a lack of nationally representative data on the characteristics of manufacturing effluent, especially directly after water-using processes that might benefit from reusing water after some form of treatment. However, a comprehensive analysis of the economic, resilience, and environmental benefits of on-site reuse—in concert with estimating the additional energy needed—requires a good understanding of which and what concentration of contaminants exist in various plant wastewater streams. In the absence of fit-for-purpose data, we turned instead to investigating and assessing publicly available EPA wastewater guidelines, permits, and data as a potential source of useful information. This section summarizes relevant material from EPA’s industrial Effluent Guideline before introducing some basic analyses of the available data that are reported by manufacturers to comply with EPA’s wastewater discharge permits: Discharge Monitoring Reports (DMR), which govern discharges to surface waters, followed by the Toxics Release Inventory (TRI), which regulate toxic contaminants discharged to municipal treatment plants). We then took a conservative approach to combining the DMR and TRI datasets to determine common contaminants by manufacturing subsector before using EIA's Annual Energy Outlook (AEO) to project how contaminant loading might reflect the changes in growth of various subsectors across time. Our goal was to explore EPA data in order to evaluate to what extent they are representative of US manufacturing facilities, which in turn would enable us to establish which contaminants, processes, and sectors are good targets for economically beneficial on-site reuse in line with the framework presented in section II.

4.1. EPA Industrial Effluent Guidelines

EPA's Effluent Guidelines are national technology-based, industry-specific standards governing wastewater discharges from industrial plants to surface waters and municipal wastewater treatment plants. They are based on how treatment and control technologies perform, and are theoretically set to attain the largest pollutant reductions that are economically achievable for each industry (EPA 2018). EPA develops these standards without accounting for the potential impacts of a discharge on a receiving water body—instead, these impacts are addressed through water quality standards and water quality-based effluent limitations in individual facility permits. As such, Effluent Guidelines can be thought of as setting minimum technology-based standards for industry, while permitting authorities, which are generally states, set limits for water quality protection in part based upon these guidelines, with implementation through the NPDES Permit Program or the National Pretreatment Program.

EPA considers the following inputs in formulating these standards: data on industry practices, characteristics of wastewater discharges, available treatment technologies or practices, and economic data. To sufficiently understand wastewater discharges, such as pollutant concentrations and flow variability, EPA conducts statistical sampling. For enforceable numeric discharge limits on pollutants, an EPA-approved analytical method (a test procedure to measure the parameter) must be available. Biannual Effluent Guideline Program Plans are intended to set a timeline for yearly review and amendment, as well as "identif[y] industries discharging more than trivial amounts of toxic or nonconventional pollutants, such as nutrients, for which the Agency has not yet promulgated Effluent Guidelines. EPA is required to establish a schedule for completing Effluent Guidelines for these industries within three years." (EPA 2018). In practice, each rulemaking often takes more than three years to formulate[5]; associated Technical Development Documents run from the hundreds to thousands of pages, and are not formatted consistently across time.

We examined published Effluent Guidelines in the hopes of learning more about typical contaminant concentrations by manufacturing sector and understanding which are historically difficult to treat. Results are summarized in tabular form in Appendix 1: EPA Effluent Guidelines by Category in Manufacturing Sector, which displays effluent guideline category, year of most recent revision, NAICS subsector, types of facilities covered, wastewater streams, and significant regulated pollutants. This table demonstrates that the most recent year of revision for any manufacturing sector was 2005 for Iron and Steel Manufacturing, and that 34 of 43 categories, or 79 percent, were completed more than 30 years ago. It is improbable that none of these categories' manufacturing processes have significantly changed in the past three decades. Effluent Guidelines drive inclusion in EPA discharge permits (see next section); because the former are out of date, it is very unlikely that EPA data on what contaminants exist in manufacturing wastewater are comprehensive. However, our review did not locate any additional sources necessary for a good understanding of what is present in the wastewater.

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[5] For the most recently completed rulemakings, which have a presence on regulations.gov (Dental Office, Steam Electric Power Generating, Construction and Development, and Airport Deicing), the length of time between docket opening and the publication of a Final Rule in the *Federal Register* ranged from 2.6 years (Dental Office) to more than 10 years (Steam Electric Power Generating, still pending).

4.2 EPA National Pollutant Discharge Elimination System Data on Contaminants in Manufacturing Wastewater

EPA maintains two relevant national databases of industrial wastewater discharges as part of its NPDES permit program, which began in 1972 under the Clean Water Act (CWA). NPDES permits allow facilities to discharge into receiving waters stipulated amounts of contaminants, with permit renewal required at least every five years. EPA's Integrated Compliance Information System - NPDES (ICIS-NPDES) contains Discharge Monitoring Report (DMR) and Toxics Release Inventory (TRI) data, accessible through the Water Pollutant Loading Tool (EPA 2020).

DMR data cover "major" industrial and municipal dischargers in all point source categories that emit effluent directly to receiving waters (e.g., lakes, streams). The regulatory definition of "major facility" is "any NPDES 'facility or activity' classified as such by the Regional Administrator, or, in the case of 'approved State programs,' the Regional Administrator in conjunction with the State Director" (40 CFR § 122.2). It is thus unclear whether one national definition of a major industrial facility exists. For example, the state of California defines a major industrial facility as one "determined based on specific ratings criteria developed by US EPA/State" (California SWRCB 2015). As another example, both EPA Region 10 (Pacific Northwest) and the state of Tennessee use the EPA NPDES Permit Rating Work Sheet to designate major vs. minor facilities (EPA Region 10 2018, Tennessee Department of Environment & Conservation 2019). The worksheet scores facilities based on data provided for the following factors: toxic pollutant potential, flow/stream flow volume, conventional pollutants, public health impact, water quality factors, and proximity to near coastal waters; a combined score of equal to or greater than 80 results in the facility receiving a "major" designation (EPA 1990).

TRI reporting is limited to industrial facilities in the manufacturing, electric power generation, and mining sectors that use a TRI-listed chemical in quantities that exceed annual threshold levels and also employ at least 10 full-time equivalent employees. TRI-listed chemicals for each reporting year are available online[6]; currently, this list comprises 33 categories and 755 individual chemicals.

Other data of potential interest are those collected under the National Pretreatment Program (NPP), which governs commercial and industrial facilities discharging to publicly owned treatment works (POTWs), otherwise known as municipal wastewater treatment plants. In the mid-1980s, EPA assessed that up to one third of priority pollutants entering U.S. waters stemmed from industrial releases into public sewers (NRC 2012). The General Pretreatment Regulations of the NPP promulgated by EPA in 1983 require POTWs to establish local pretreatment programs that enforce national pretreatment standards as well as any more stringent local requirements. Today, NPP is implemented as a partnership between EPA, states, and POTWs. However, as of the time of writing, NPP data were available only as paper files or scanned PDFs at individual permitting authority levels (i.e., 36 individual states as well as EPA), in contrast to being available nationally in a consistent electronic format. These data could in theory be manually collated via a very labor-intensive process involving requests to individual permitting authorities, which is outside the scope of this report. The three datasets introduced

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[6] https://www.epa.gov/toxics-release-inventory-tri-program/tri-listed-chemicals. Last accessed February 5, 2020.

here are further summarized in Table 3, with a graphical depiction of which data source applies to which flow in Figure 1.

Figure 1 tracks the possible fates of effluent discharges out of a manufacturing facility to municipal wastewater treatment and onsite water treatment, the latter further discharging effluent to municipal wastewater treatment, to a water body, or as sludge. P_1 represents the pollutants (composition and mass) in the facility's wastewater before any treatment, while V_1 is the volume of water containing these pollutants. P_1, V_1 can also be thought of as the input into a water reuse process; thus, we are interested in assessing the characteristics of these flows.

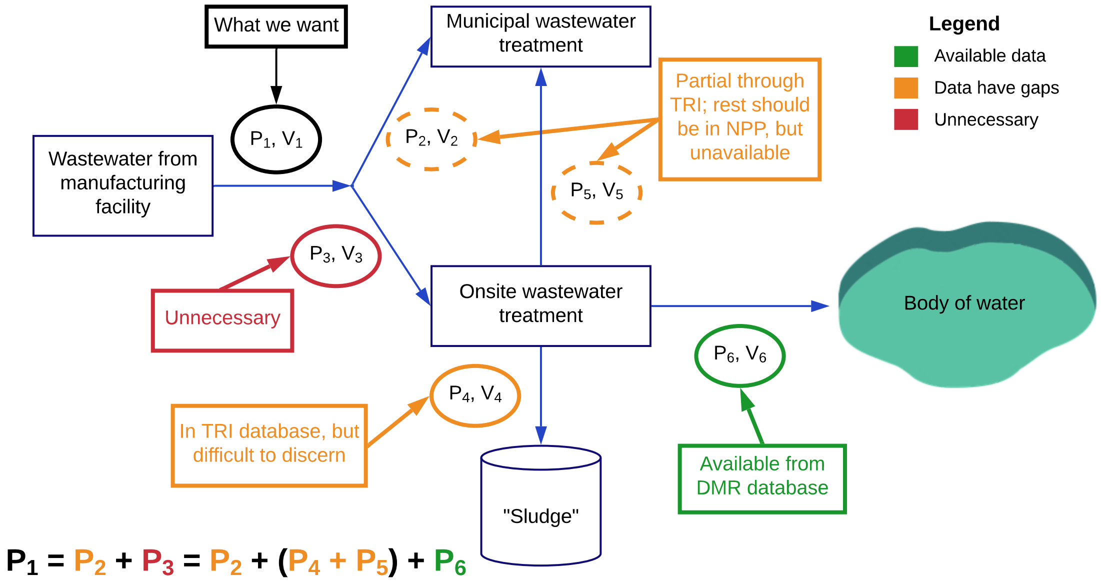

Figure 1: Pollutant and discharge volume balance with annotations to indicate data sources

Because few data exist for P_1, V_1 beyond those presented in a few case studies, the equation at the bottom left of the figure displays an alternative way of discerning P_1 via examining national-level data on other flows. The figure and equation are color-coded, with light green indicating that data are available, yellow indicating partial availability, and red indicating that data are unavailable and also unnecessary. P_1 can be obtained by gathering data on P_2 (facility effluent discharged directly to municipal treatment), P_4 (effluent discharged as sludge after on-site treatment), P_5 effluent discharged to municipal treatment after some on-site treatment), and P_6, effluent discharged to a surface water body after on-site treatment.

Table 3: Summary of EPA data sources for industrial wastewater

Data source	Who reports?	What is reported?	What is not reported?	Applies to which flow?	Status
Discharge Monitoring Report (DMR)	Over 60,000 industrial and municipal facilities discharging directly to receiving waters	Any pollutant discharged to receiving water that facilities are required by permit to monitor	Discharges from "minor" dischargers; releases to POTWs	P_6	Usable; publicly available
Toxics Release Inventory (TRI)	Industrial facilities that: discharge to POTWs, have >10 employees, exceed reporting minimum	Toxic pollutants listed on the TRI-list (692 individual chemicals and categories)	Common contaminants (*e.g.*, BOD, TSS); volumes	Toxic portions of P_4, P_5	Semi-usable; publicly available
National Pretreatment Program (NPP)	Industrial & commercial facilities discharging to POTWs that: • Make up ≥5% of POTW capacity, and/or • Exceed 25,000 gpd	• Toxics (defined in CFR 401.15) • Conventional pollutants: BOD, TSS, fecal coliform, pH, oil and grease • Non-conventional pollutants	Unknown (see last column)	P_5, P_2	Unusable; not currently available in a consistent electronic format

Because NPP data were effectively not publicly available, we were unable to use this dataset. We employed DMR and TRI data in an effort to characterize the typical contaminants in wastewater discharges for each industrial subsector. At the start of this analysis, 2016 was the latest complete year for which all EPA water pollution data were available; as such, figures and tables presented in this paper using EPA data are from 2016.

4.2.1 Discharge Monitoring Report Data

On January 23, 2018, we queried the DMR database, yielding a database with 133,039 rows and 60 columns, with 10,020 unique industrial facilities and 537 unique pollutants.[7] Each individual row, or record, holds data on the reported discharge of one specific pollutant at one particular industrial facility in 2016. At the time, only Standard Industrial Classification (SIC) codes were associated with each facility, so we used a SIC-to-NAICS mapping from Argonne National Laboratory to look up how each listed SIC code corresponded to an appropriate six-digit NAICS

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[7] This database is available at https://echo.epa.gov/trends/loading-tool/get-data/custom-search/. Key search parameters included: 2016 was the *Year of Data*; "Industrial Point Sources (non-POTW)" was selected for *Facility Type;* all 4-digit SIC codes within NAICS 31-33 were entered under *Industry Classification*; and under *Loading Calculation Options* we selected "Use permit limits where DMR data unavailable", set non-detects equal to ½ detection limit, and set to "ON" the estimation function, parameter grouping function, and nutrient aggregation function.

code, which was then truncated to a three-digit NAICS code to which we added the appropriate description (NAICS Association 2018). In the downloaded data, pollutant load (kg/yr) and hybrid load (kg/yr) were in separate columns. The hybrid column contains the output of the hybrid method for nondetects, as outlined on page 3-37 of EPA (2012b). If the pollutant was measured nondetect for all monitoring periods in the reporting year, this value was set to zero in accordance with our search parameters. If the pollutant was detected for at least one monitoring period in the reporting year, this value was set equal to one half the detection limit.[8] In order to assess these data, we created a new column where if the pollutant load had zero value, the value in the hybrid load column was listed instead.

Next, we created a pivot table that summed this new column (pollutant load (kg/yr) or hybrid load if zero value pollutant load) with pollutant description as rows and three-digit NAICS descriptions as columns. This pivot table could be filtered by three-digit NAICS description and by pollutant load (kg/yr) or hybrid load if zero value pollutant load. By selecting each individual sector via the former, and filtering for all non-zero values in the latter, we were able to determine pollutants with non-zero annual load summed across U.S. facilities in each three-digit NAICS manufacturing sector. We arranged them in decreasing order of pollutant load for each manufacturing sector.

In investigating whether manufacturers are reporting permitted limits for pollutant loadings instead of values that imply actual or measured discharges, we first determined that only 26,634 of 133,039 records, or 20 percent, contain data for both of two fields: pollutant load and maximum allowable load. This also serves as one indicator of the incompleteness of this dataset. Of the 20 percent in question, fewer than 0.1 percent contain pollutant load exactly equal to maximum allowable load; the overwhelming majority of facilities report pollutant loading values that differ from the maximum allowable under their permits. Dividing the pollutant load by the maximum allowable load yields a distribution of this ratio in boxplot form as displayed in Figure 2, with the 25th and 75th percentile marked by the bottom and top of the box, respectively, and the median displayed as the horizontal line within the box. Points outside of the interquartile range (the whiskers) are not shown. This figure implies that most manufacturers are reporting pollutant loadings well below their permitted maxima.

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[8] We chose loading calculation options with the aim of taking a conservative approach, in order not to overestimate pollutant loadings. These settings mirror those of EPA's "EZ Search Load Module", which incorporates calculations to replicate EPA's 304(m) Annual Review process that examines previous industrial effluent guidelines and standards for potential revisions (EPA 2012b).

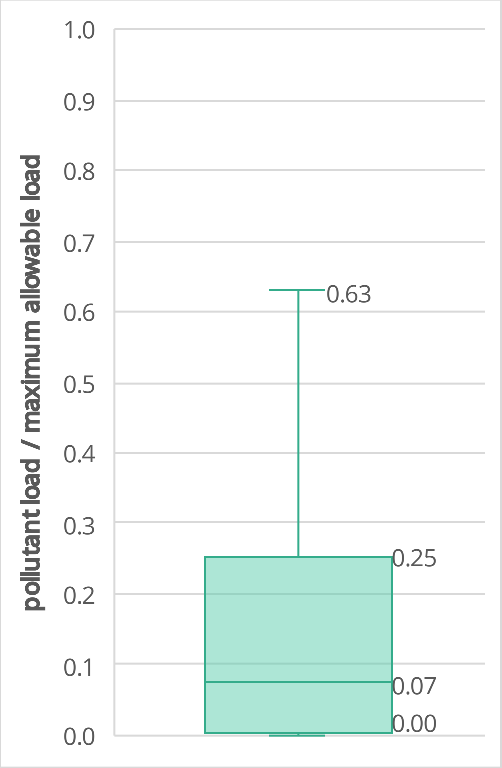

Figure 2: Distribution of pollutant load to maximum allowable load ratio in 2016 EPA DMR data

To determine how representative DMR data might be for the manufacturing sectors covered in this report, we found that only 4,366 unique manufacturing facilities within NAICS 31–33 were included in the 2016 DMR dataset, in contrast to the 175,107 manufacturing establishments in the 2014 Manufacturing Energy Consumption Survey (MECS) (EIA 2014). Thus, overall only 2.5 percent of the number of establishments in MECS were present in the 2016 DMR data. This share varied widely by sector, as seen in Figure 3. This figure can be interpreted as the percentage of MECS facilities within each sector with DMR permits for discharges to surface water bodies. As shown in Table 3, only those industrial facilities designated as “major” by NPDES permitting authorities (generally states and/or EPA Regions) are required to monitor effluent under DMR permits. Figure 3 could thus indicate to some extent which manufacturing sectors have higher concentrations of “major” facilities.

On the high end, 18.9 percent of establishments in the petroleum & coal products sector and 10.1 percent of establishments in the chemical sector were present in 2016 DMR data, with more than 5 percent of MECS establishments in the textile mills, paper, nonmetallic minerals, and primary metals sectors reflected in the EPA dataset. On the low end, with 0.1 percent of establishments with EPA DMR reports in 2016, were the furniture and related product, printing, and apparel sectors. To our knowledge, no data exist to ascertain whether these shares are so low because significant discharges are not occurring into receiving waters, because the criteria for what constitutes a “major” discharger is variable across permitting authorities, some other factor, or some combination thereof. In any case, this lack of representativeness is an important limitation of the analysis in this report, and points to an enormous blind spot in what non-“major” manufacturing facilities are discharging into water bodies.

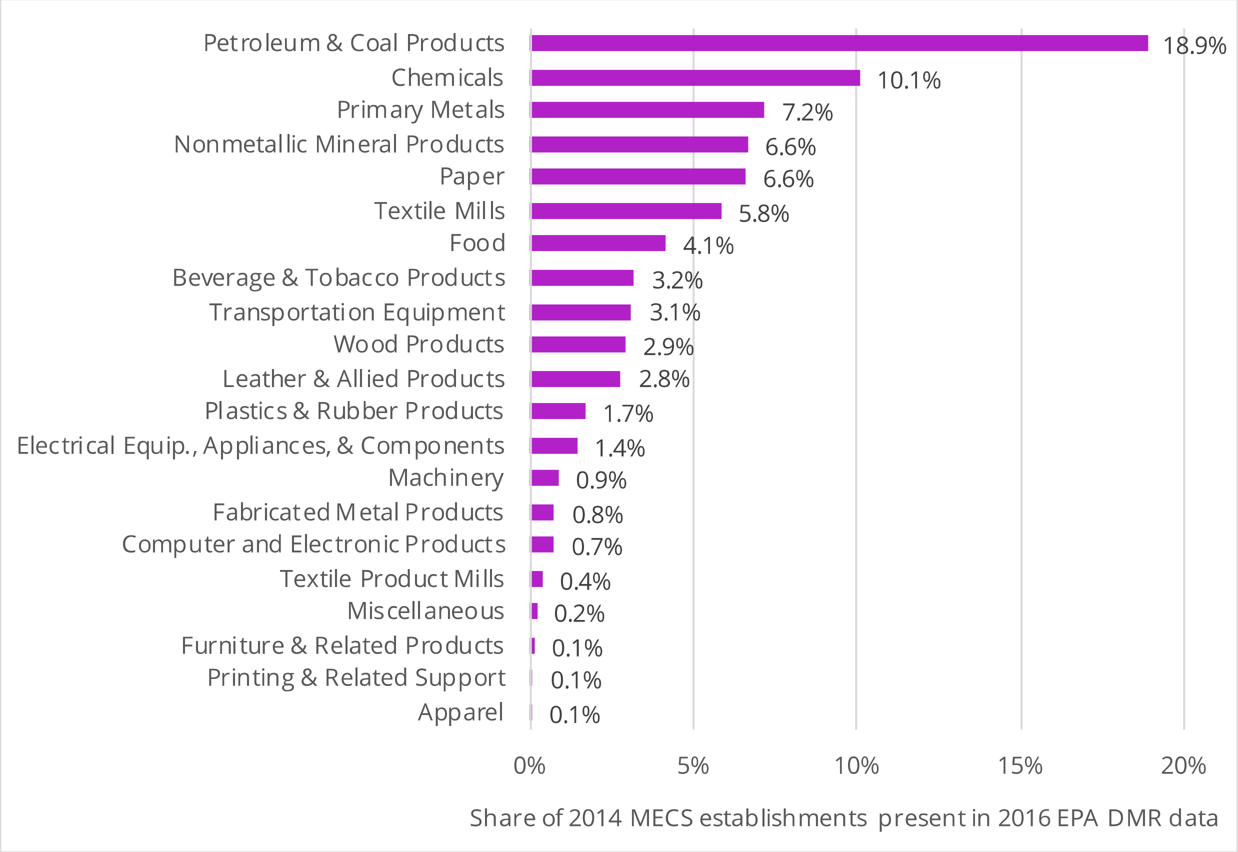

Figure 3: Share of individual establishments in 2014 MECS present in 2016 EPA DMR data, by manufacturing subsector

4.2.2 Toxics Release Inventory Data

On February 1, 2018, we queried the TRI Explorer's Waste Transfer Chemical Report for dischargers to POTWs from each of the 21 individual manufacturing subsectors of interest within NAICS 31-33.[9] Other than in the header, the ensuing file contained no data about which sector had been queried, necessitating downloading individual CSV files for each separate three-digit NAICS manufacturing sector. Records were then manually appended to one another, preserving all data while adding two new columns, NAICS code and NAICS description, which were manually populated with the appropriate data. We also added a third new column that summed two columns together: (1) Transfers to POTWs Non Metals and (2) POTWs (Metal and Metal Compounds).

We then generated a pivot table similar to the one for DMR data. It summed the column that summed transfers to POTWs Non Metals and POTWs (Metal and Metal Compounds) with chemical names as rows and three-digit NAICS descriptions as columns. This pivot table could

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[9] The database is available at https://iaspub.epa.gov/triexplorer/tri_transfer.chemical. Key search parameters included: 2016 was the *Year of Data*; each unique three-digit NAICS code within 31–33 was selected for *Industry*, and selected report columns to include were "Transfers to POTWs Non-Metals" and "Transfers to POTWs Metals and Metal Compounds".

be filtered by three-digit NAICS description and by transfer loads. By selecting each individual sector via the former, and filtering for all non-zero values in the latter, we were able to determine pollutants with non-zero annual load summed across U.S. facilities in each three-digit NAICS manufacturing sector. We arranged them in decreasing order of pollutant load for each manufacturing sector, and then converted units from lb/yr (the unit used in TRI) to kg/yr (the unit used in DMR).

4.2.3 Summing Pollutants from DMR and TRI Databases

As established earlier, EPA DMR data cover discharges to surface waters of pollutants industrial facilities are required by permit to monitor, while EPA TRI data pertain to transfers of toxic listed pollutants from industrial facilities to POTWs. From each database, and in each three-digit NAICS manufacturing sector, we had produced a list of pollutants in decreasing order of mass, as well as the mass quantity of each pollutant discharged or transferred in kg/yr. To examine which pollutants are discharged to surface waters and to POTWs, we took a conservative approach in assembling these datasets into one. For each three-digit NAICS manufacturing sector, we summed these data only where the pollutant name exactly matched between these two databases. For example, consider the Fabricated Metal Product (332) sector for several example contaminants and quantities as shown in Table 4.

Table 4: Conservative summation of example discharge quantities from EPA DMR and TRI datasets

	Quantity in each database (kg/yr)		
Contaminant	**DMR**	**TRI**	**DMR + TRI**
Aluminum	23,069	--	23,069
Organics, total toxic (TTO)	18,609	--	18,609
N-Methyl-2-pyrrolidone	37	15,188	15,224
Zinc compounds	--	14,010	14,010
Zinc	10,617	--	10,617
Nickel	6,067	2,753	8,820
Manganese	4,343	1,744	6,087
Ammonia	--	5,715	5,715
Chromium	1,280	3,825	5,105
Copper	1,823	2,910	4,733
Nickel compounds	--	4,418	4,418

This table is illustrative of divergent naming of contaminants within and between DMR and TRI datasets. For example, while both DMR and TRI data contain nickel discharges, only TRI reports discharges of nickel compounds; it is not clear whether nickel discharge quantities are a subset of nickel compound discharge quantities. When it comes to zinc, TRI contains data on zinc compounds but not on zinc, while DMR reports the converse. Such a discrepancy is one example of a significant limitation of the EPA DMR and TRI data: there is no universal definition for many contaminants, because the regulatory definition for contaminants is extremely broad, and different permitting authorities (generally states) differ in their more specific requirements.

4.2.4 Ubiquitous Contaminants

To determine whether certain contaminants are commonly discharged in industrial wastewater across manufacturing sectors, we considered which contaminants appear in the top ten, in terms of mass released into wastewater, of each three-digit NAICS manufacturing sector, by summing pollutants from the DMR and TRI databases as discussed in a previous section. Those contaminants that appear among the top 10 in more than half of these 21 sectors can be thought of as particularly abundant, or ubiquitous. With this analytical framing, eight separate ubiquitous contaminants emerge, depicted in Table 5 along with the number of three-digit NAICS manufacturing subsectors in which they appear in the top 10 in terms of mass discharged. The remaining contaminants in this table (in italics) appear among the top 10 in more than one of these 21 sectors. See Appendix 2 for sector-specific lists of the top 10 contaminants.

The chemicals listed in Table 5 can be understood as the most common industrial contaminants present in industrial wastewater as seen from the EPA DMR and TRI data. However, we note several important limitations of this approach. No nationally representative data are available that characterize contaminants in the effluent flowing directly from manufacturing processes prior to any treatment, which would be more appropriate to analyze for on-site reuse applications. As shown in Figure 1, EPA DMR and TRI data represent only portions of possible effluent flows, and they reported on at the point of discharge into surface water bodies (DMR) or only concern toxic contaminants (TRI). Figure 3, meanwhile, demonstrates that many times more manufacturing establishments as defined by MECS exist than report DMR data. As such, this list is created from underlying data which are incomplete, and must be interpreted accordingly.

Table 5: Summary of top contaminants across manufacturing subsectors, from 2016 DMR and TRI data; ubiquitous contaminants (among the top 10 by mass in more than half of 21 manufacturing subsectors) are above the bold line and are not italicized

Contaminant*	**# manufacturing subsectors in which contaminant is among top 10 of mass discharged**
Solids, total suspended	21
Chemical oxygen demand (COD)	16
Solids, total dissolved	15
BOD, 5-day, 20 deg. C	13
Hardness, total (as $CaCO_3$)	13
Oil and grease	13
Nitrate compounds	12
Chloride	11
Sulfate	*10*
Nitrogen	*7*
Ethylene glycol	*5*
Oxygen	*5*
Alkalinity, total (as $CaCO_3$)	*4*
N-methyl-2-pyrrolidone	*4*
Residue, total filterable (dried at 105 deg. C)	*4*

Certain glycol ethers	*3*
N,N-Dimethylformamide	*3*
Phosphorus	*3*
Ammonia	*2*
Ammonia as N	*2*
Iron	*2*
Nitric acid	*2*
Sodium nitrite	*2*
Solids, total	*2*
Total Kjedahl nitrogen	*2*
Zinc compounds	*2*

*Contaminant names are drawn directly from NPDES permits as detailed in preceding paragraph

The results in this table suggest that while manufacturing wastewaters contain hundreds of unique known and measured contaminants as seen in EPA DMR and TRI data, only a small subset are present in large quantities in a majority of sectors.

Looking ahead, the future of U.S. manufacturing will be influenced by several emergent factors. On-shoring, automation, new products, novel materials, and better understanding of environmental hazards will result in a future that looks markedly different from today. As such, data from recent permitting years may not provide adequate insight into future ubiquitous contaminants. As a rough estimate, we weighted by 2016 contaminant loading the reference case economic growth projections from the 2018 Annual Energy Outlook (EIA 2018) for each manufacturing subsector from 2016 to 2050 (indexed to 2016) in accordance with the following equation:

$$Loading_{i,j} = \frac{Economic\ output_{i,j}}{Economic\ output_{i,2016}} \times 100 \times \frac{Contaminant\ loading_{i,2016}}{Total\ contaminant\ loading_{all,2016}},$$

where i = sector and j = year. The growth in total contaminants across subsectors is depicted in Figure 4; note that in the absence of other data, these projections assume that water reuse processes and technologies or drivers for using these methods are static over this period. This figure projects that a few manufacturing subsectors will dominate contaminant loading later this century, chief among them nonmetallic mineral products, chemical manufacturing, and transportation equipment.[10]

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[10] Note that within the nonmetallic mineral products subsector, one gypsum quarry in Wyoming represents 97 percent of total pollutant loading for the subsector (2016 EPA DMR), potentially biasing the data for this subsector.

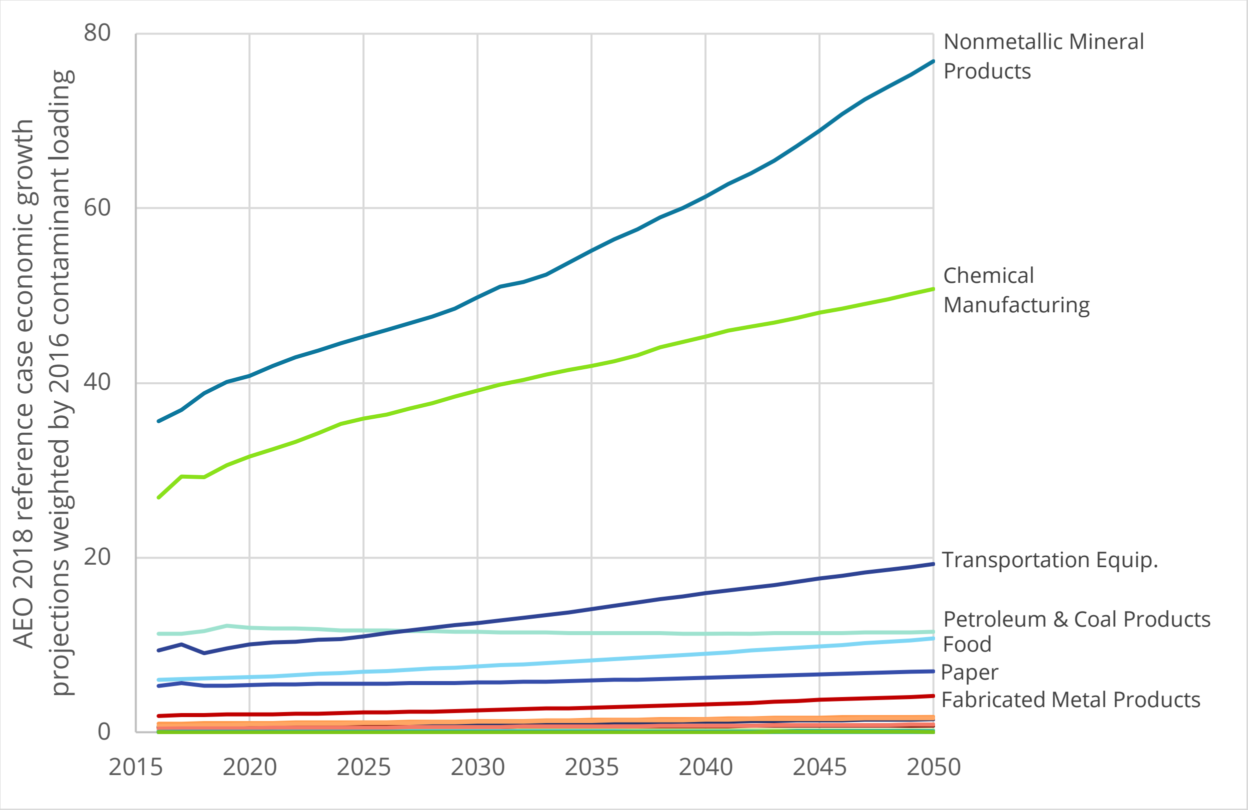

Figure 4: Industrial macroeconomic indicators by manufacturing subsector 2016–2050, indexed to 2016 contaminant load

We caution that the trends shown in Figure 4 are indexed only to those contaminants monitored via EPA DMR and TRI permits in 2016. We note that emerging contaminants—otherwise known as contaminants of emerging concern—are unregulated because health-based standards under the Safe Drinking Water Act do not yet exist for them. However, a large number of these compounds, which are present in pharmaceuticals, personal care products, cleaning supplies, pesticides, and chemicals used in commerce, have been detected on a widespread basis in surface waters at low levels, while the research on their negative effects on human and environmental health continues to accrete evidence. EPA publishes Contaminant Candidate Lists (CCLs) every five years, comprising pollutants "that are currently not subject to any proposed or promulgated national primary drinking water regulations, but are known or anticipated to occur in public water systems" (EPA n.d. -a). The latest available version (as of the publication of this report), CCL4, was finalized in November 2016 and contains 97 chemicals or chemical groups and 12 microbial contaminants. One family of contaminants of particular concern, per- and polyfluoroalkyl substances (PFAS), is represented on CCL4 with "legacy" PFAS chemicals perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA). Strong evidence for PFAS toxicity, persistence, mobility, and harms to public health exists, and EPA set a goal in 2018 to evaluate the need for a maximum contaminant level (MCL) for PFOS and PFOA. However, at the time of publication, regulatory uncertainty still surrounds PFAS, with Cordner *et al.* (2019) calling for "a sufficiently protective, scientifically sound, and enforceable federal standard".

Because emerging contaminants are not currently regulated via effluent discharge permits, we have little idea which manufacturing industries are discharging these contaminants, in what amounts, and where. In addition, because no common regulatory definition of contaminants exists, each rulemaking requires years of effort, and statistical sampling requires approved analytical methods—which do not exist for contaminants of emerging concern—, our informed opinion is that EPA's industry-specific guidelines will always be playing catchup to regulate new industrial processes.

5. Manufacturing Wastewater Treatment Technologies

5.1 Overview of Treatment Technologies

Various technologies are commonly employed in, or hold promise for, treating manufacturing wastewater. Our survey of the literature established that most wastewater treatment research and technology development has focused on municipal wastewater, which is significantly dissimilar from manufacturing wastewater. Most municipal wastewater has similar properties nationwide in terms of the composition and concentration of its constituents. However, manufacturing wastewater is characterized by a wide diversity of contaminants depending on sector and process, and some streams are highly concentrated. Figure 5 depicts typical municipal wastewater parameters in comparison to those found in large quantities in manufacturing wastewater, as well as their overlap.

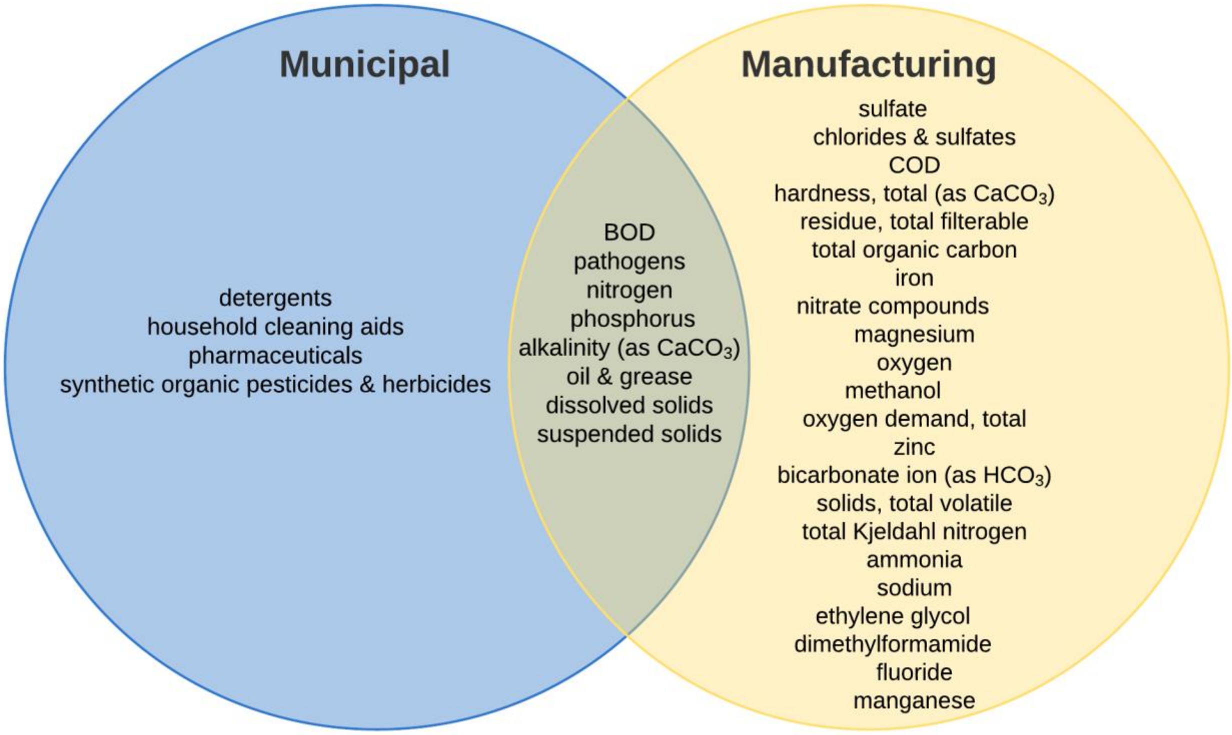

Figure 5: Venn diagram with typical parameters in municipal wastewater (EPA 2004, Pescod 1992) and top 30 contaminants by mass across all manufacturing subsectors (2016 EPA DMR & TRI)

As seen in Table 10, criteria for manufacturing water reuse are typically centered on inorganic constituents such as solids, metals, and hardness. However, many organic contaminants stemming from manufacturing are persistent, toxic, and bioaccumulative—marking a key distinction between manufacturing and municipal wastewater chemistry. These contaminants, the presence of which are likely reflected in high oxygen demand (COD), as seen in Figure 5, are strictly regulated at discharge points and POTWs (EPA n.d. -b). Testing for typical inorganic constituents is standardized and easily accomplished, while testing for toxic compounds generally necessitates highly specific testing with high cost and long turnarounds if performed by external laboratories (S. Garcia, personal communication, April 23, 2021). While Figure 5 contains two specific organic compounds (ethylene glycol and dimethylformamide), Table 6 displays broader classes of commonly regulated organic contaminants in industrial wastewater.

Table 6: Organic contaminant classes and example contaminants, adapted from Federal Remediation Technologies Roundtable (n.d.)

Organic contaminant class	Examples of specific contaminants
Nonhalogenated volatile organic compounds (VOCs)	Acetone, ethanol, methanol
Halogenated VOCs	Ethylene dichloride (DCE), freons, perchloroethylene (PCE), trichloroethylene (TCE)
Nonhalogenated semivolatile organic compounds (SVOCs)	Phenols, phthalates, polycyclic aromatic hydrocarbons (PAHs)
Halogenated SVOCs	Chlorinated hydrocarbon derivatives, chlorinated paraffins such as short-chain chlorinated paraffins (SCCPs), organochlorine pesticides,
Fuels and additives	Benzene, oxygenates (methyl tert-butyl ether [MTBE], tosyl-arginine methyl ester [TAME], tertiary butyl alcohol [TBA]), toluene, total petroleum hydrocarbons (TPH)

In addition, successful manufacturing wastewater treatment typically requires treatment trains with a series of steps at which certain technologies are employed; for example, settling and filtration may need to occur prior to UV or RO treatment. Finally, the proprietary and competitive nature of industry likely means that the successful application of technologies to manufacturing wastewater streams, as well as the associated energy consumption, are not documented in publicly accessible sources.

Classifying treatment technologies by mechanism can facilitate a better understanding of energy requirements; for example, physical skimming processes generally require minimal direct energy in contrast to thermal processes. While it is outside the scope of this paper to classify all technologies, we drew upon our literature review to classify common technologies by primary mechanism (physical, chemical, or biological) in Figure 6. The second tier of the figure displays categories that encompass examples of individual treatment technologies in the third tier. Note that this categorization is not definitive and some lines between categories are blurred. For example, certain chemical and physical technologies can rightly be considered to be at different points among a physicochemical spectrum. In addition, this figure is meant to be illustrative, rather than exhaustive, of the universe of treatment technologies that can be applied at scale.

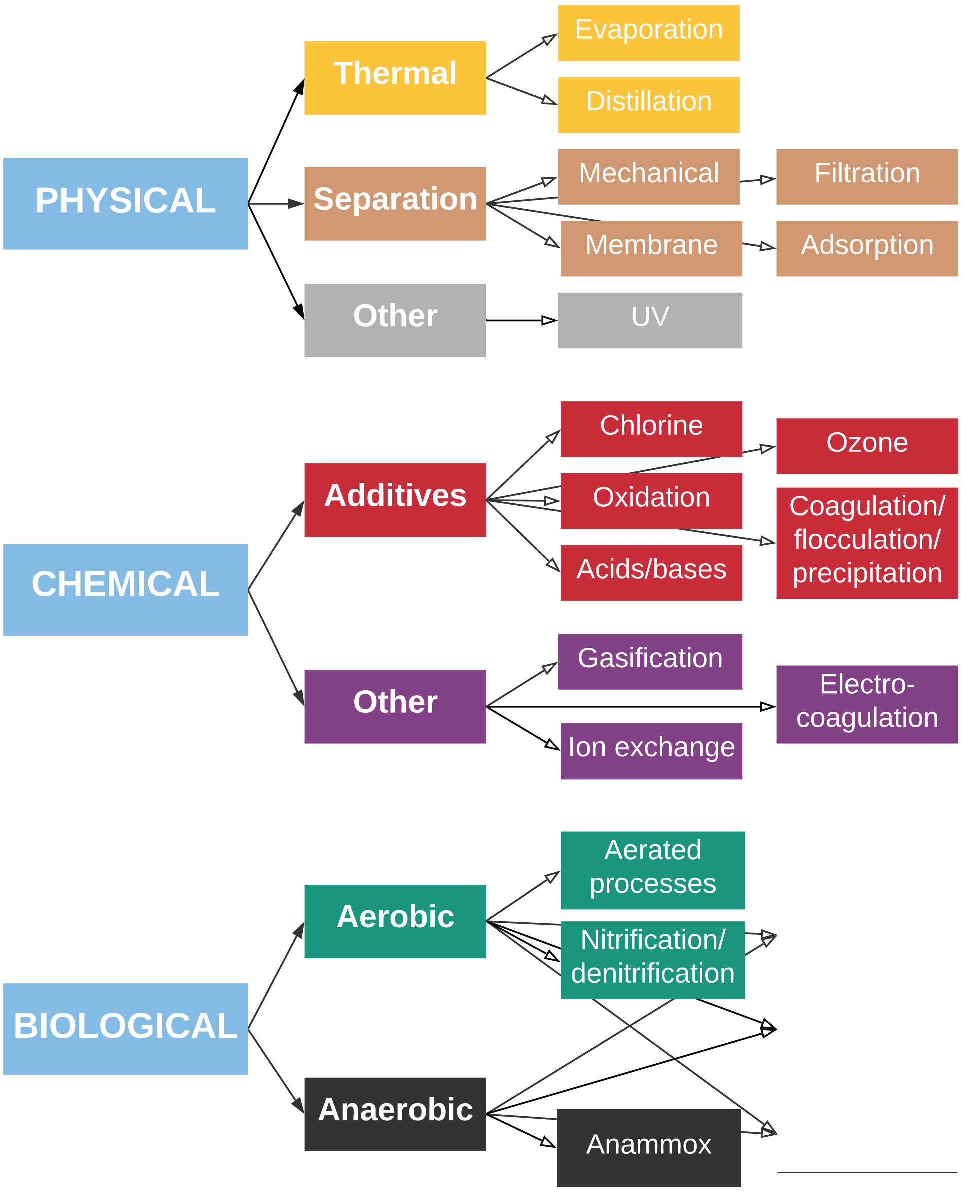

Figure 6: Categorizing manufacturing wastewater treatment technologies by mechanism

Next, Table 7 displays high-level summaries of some common treatment technologies that appeared among reviewed case studies of on-site industrial wastewater treatment. Instead of being fully comprehensive, this table is meant to illustrate that similar information may be useful for those looking to implement on-site reuse via facilitating comparison of technologies in terms of application examples and pertinent characteristics. Published case studies for several emerging technologies not shown in Table 4 indicate they also hold promise for treating manufacturing wastewater, such as hydrodynamic cavitation (Dular *et al.*, 2016, Joshi & Gogate, 2019), advanced oxidation processes (Hodaifa *et al.*, 2013, Güyer *et al.*, 2016), and nanotechnologies (Jassby *et al.*, 2018).

Table 7: Comparison of several manufacturing wastewater treatment technologies

Technology	Coagulation/ flocculation	Electrocoagulation	Reverse osmosis	Micro/ultrafiltration	Anaerobic membrane bioreactor (MBR)	Anaerobic ammonium oxidation (annamox)
Description	• Destabilize suspended particles for floc formation via charge attraction • Use chemical coagulant (metallic salts, polymers) to settle out solids: colloidal particles come out of solution to form flocs that are separated via clarifier or filtration	• Use electric current to generate *in situ* coagulants from metal anode • Generated ions form metal hydroxides that readily precipitate, allowing water-soluble pollutants to be adsorbed & removed	• Pressurize effluent stream in excess of osmotic pressure • Use a membrane barrier to “push” contaminants out of effluent stream	• Pump water through a membrane sieve to separate contaminants from water	• Anaerobic processes: many different microbial communities convert complex organic compounds into methane & CO_2 • Adding membranes helps retain biomass & better separate solids	• Chemo-litho-autotrophic bacteria use ammonium as electron donor, nitrite as electron acceptor, & HCO_3^- or CO_2 as carbon source • Anaerobically convert ammonium & nitrite to nitrogen gas
Application examples	Textiles, food processing, pulp & paper, tanneries	Electroplating, food processing, refineries	Any ionic stream; specific examples in metal finishing, food processing, paper, computers & electronics	Automobiles, computers & electronics, food processing, metal finishing, pharmaceuticals, textiles	Food processing, textiles	Electroplating, food processing, refineries
Advantages	• Low energy (0.011–0.12 kWh/m^3) • Simple design	• Low-cost, simple treatment • Versatile, effective (removes heavy metals, FOG, organic compounds, etc.) • Less & better-quality sludge than with chemical coagulants/flocculants	• Well-established, stable, & readily available technology • Used throughout the water sector	• Low energy requirements (<0.2 kWh/m^3) • Widely used/known	• Lower energy consumption (no aeration required) • Potential to be energy-positive through methane production • Smaller footprint • High-quality effluent with less sludge production, effective solids separation	• Significantly less sludge than biological treatment like activated sludge & nitrification/ denitrification • Lower energy consumption from lower oxygen demand

Technology	**Coagulation/ flocculation**	**Electrocoagulation**	**Reverse osmosis**	**Micro/ultrafiltration**	**Anaerobic membrane bioreactor (MBR)**	**Anaerobic ammonium oxidation (annamox)**
						• Less greenhouse gas (CO_2, N_2O) production
Dis-advantages	• Ineffective in removing heavy metals & emerging contaminants • Creates a large amount of (toxic) sludge	• Consistent maintenance required given electrode passivation • Requires highly conductive water • Modeling and scale-up issues	• Extremely energy intensive process (~1.5 kWh/m^3 not including pre- & post-processing) • Membrane replacement required • Membrane fouling inhibits performance • Cannot operate at variable loads • In-situ membrane diagnostics are difficult	• Cannot filter contaminant below a certain size range • Fouling inhibits performance • Sensitive to oxidative chemicals	• Membrane fouling • Slow-growing; slow start-up time • Very sensitive to temperature changes • Low-quality effluent with low-strength wastewater	• Many inhibitors: pH outside 8–9, organic carbon, salinity, heavy metals, phosphates, sulfides • Needs nitrite through nitrite addition or partial nitritation • Slow doubling & shock recovery times
References	Verma *et al.* (2012), Ranade & Bhandari (2014), Teh *et al.* (2016)	Kabdaşli *et al.* (2012), Sahu *et al.* (2014), Hakizimana *et al.* (2017), BakerCorp (*n.d.* -a), BakerCorp (*n.d.* -b)	Benito and Ruíz (2002), Chan (2011), Dhagumudi and Yan (2012), Huang *et al.* (2011), Rao *et al.* (2016), Valladares *et al.* (2018)	Benito and Ruíz (2002), Huang *et al.* (2011), Connery *et al.* (2013), Pugh *et al.* (2014), Rao *et al.* (2016)	Martin *et al.* (2011), Martinez-Sosa *et al.* (2012), Jegatheesan *et al.* (2016), Evoqua Water Technologies (2019)	Jermakka *et al.* (2015), Liang *et al.* (2016), Zhang *et al.* (2019), Paques Technology B.V. (*n.d.*)

5.2 Industrial Water Treatment Technology Database

EPA released to the public the Industrial Water Treatment Technology (IWTT) database in early 2018.[11] This database provides technology performance data on pilot- or full-scale systems that treat industrial wastewater, stemming from sources that meet certain data quality requirements for accuracy, reliability, representativeness, and reasonableness.[12] As of March 2020, it contains 199 references from peer-reviewed journals, conference proceedings, and government reports. Reported performance data include influent and effluent concentrations as well as removal efficiency; an abstract and summarized findings are included for each reference. Information on energy requirements is not included in the IWTT database. These performance data can be accessed via industry, treatment technology, or pollutant queries. Industry classifications are related to either point source categories (PSCs) as defined in EPA's Effluent Guidelines program or two-digit standard industrial classification (SIC) codes, while the pollutant query uses a simplified naming convention that groups parameters; the given example is that searching for the pollutant "nitrogen" may return results for both "nitrogen, total" and "nitrogen, organic". The treatment technology query relies on an individual technology or unit process13—yet nearly all performance data are reported for a treatment train instead of from a single technology or unit process.

5.3 Treatment Technologies for Common Pollutants

The IWTT database's downloadable results do not capture the full scope of the information in the database in any one place. On April 17, 2018, we downloaded all the data available in the IWTT database. In addition, we downloaded the IWTT Data Set and Data Dictionary from https://watersgeo.epa.gov/iwtt/download-database. The Data Set contains keys for NAICS codes, parameter (pollutant) codes, performance statistics, treatment technology codes, and a crosswalk between PSC and SIC codes; a list of parameter characteristics by reference ID and system ID; reference information; and treatment system information. To convert from name of the point source category (PSCName) to the three-digit NAICS sector, we used the IWTT crosswalk between PSC and SIC codes, as well as a SIC to NAICS crosswalk provided by Argonne National Laboratory. In cases where the point source category name and the name of the assigned NAICS sector seemed divergent, we looked up the abstract, or, in some cases, the full-text article of each pertinent reference in order to assign the correct NAICS sector. This reference table organizes data from the IWTT database to show all pilot- and full-scale treatment trains for common pollutants (i.e., ubiquitous contaminants) in each NAICS manufacturing sector such that it serves as a crosswalk between technologies and sectors. For illustrative purposes, data from this table is excerpted below in Table 8 to show, for the eight ubiquitous contaminants as defined in section 4.2.4 as being among the top 10 contaminants by mass in more than half of the manufacturing subsectors from NAICS 31–33, the associated industry, treatment train, scale (i.e., pilot or full-scale implementation), and IWTT reference IDs, to facilitate looking up fuller details. Definitions for treatment technology abbreviations follow in Table 8, from https://watersgeo.epa.gov/iwtt/treatment-technologies.

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[11] https://watersgeo.epa.gov/iwtt

[12] These criteria are further explained at https://watersgeo.epa.gov/iwtt/about.

[13] The list of treatment technology descriptions in IWTT is at https://watersgeo.epa.gov/iwtt/treatment-technologies.

Table 8: Ubiquitous contaminants coupled with existing treatment trains from IWTT

Ubiquitous contaminant	Industry	Treatment train	Scale	IWTT ref. ID
Solids, total suspended	Iron & steel manufacturing	ChemPre, AIR, BCLAR	Pilot	183
	Metal finishing	EQ, ION, ChemPre, MF, RO, EVAP	Full	88
		EQ, ChemPre, CS, DAF	Full	207
		MBR, AD	Pilot	184
		AFF, ChemPre, PAC	Pilot	185
		BCF, OW, EQ, MF	Pilot	240
	Misc. foods & beverages	MPT, CLAR, MPT, MBR, EQ	Full	138
	Non-classifiable establishments	AND, ChemPre, BNR, CLAR	Pilot	160
	Transportation equip. cleaning	OW, EQ, ChemPre, CLAR, MF	Pilot	282
		OW, EQ, MF	Pilot	282
Chemical oxygen demand (COD)	Metal finishing	MBR, AD	Full	184
		EQ, ChemPre, CS, DAF	Full	207
		MBR, AD	Pilot	184
		AFF, ChemPre, PAC	Pilot	185
		BCF, OW, EQ, MF	Pilot	240
	Misc. foods & beverages	MPT, CLAR, MPT, MBR, EQ	Full	138
		CLAR, EQ, AIR, CLAR	Pilot	191
		MBR	Pilot	191
	Non-classifiable establishments	AND, ChemPre, BNR, CLAR	Pilot	160
	Pharmaceutical manufacturing	MPT, EQ, BIO, CLAR, MBBR, ASG, CLAR	Full	194
		EQ, MBR	Full	229
		EQ, AD, MBR, OZ, DGS	Full	234
		EQ, ANSG, BASR	Pilot	150
	Pulp, paper & paperboard	MBR	Full	232
	Transportation equip. cleaning	OW, EQ, ChemPre, CLAR, MF	Pilot	282
		OW, EQ, MF	Pilot	282
Solids, total dissolved	Ferroalloy manufacturing	EQ, MF, RO	Pilot	209
	Metal finishing	EQ, ION, ChemPre, MF, RO, EVAP	Full	88
	Pharmaceutical manufacturing	EQ, MBR	Full	229
	Wholesale trade: durable goods	ChemPre, MF, RO	Pilot	44
BOD, 5-day, 20 deg. C	Metal finishing	MBR, AD	Pilot	184
		AFF, ChemPre, PAC	Pilot	185
		BCF, OW, EQ, MF	Pilot	240
	Misc. foods & beverages	MPT, CLAR, MPT, MBR, EQ	Full	138
		CLAR, EQ, AIR, CLAR	Pilot	191
		MBR	Pilot	191
	Non-classifiable establishments	AND, ChemPre, BNR, CLAR	Pilot	160
	Pharmaceutical manufacturing	EQ, AD, MBR, OZ, DGS	Full	234
	Transportation equip. cleaning	OW, EQ, ChemPre, CLAR, MF	Pilot	282
		OW, EQ, MF	Pilot	282
Hardness, total (as $CaCO_3$)	Wholesale trade: durable goods	ChemPre, MF, RO	Pilot	44
Oil and grease	Iron & steel manufacturing	ChemPre, AIR, BCLAR	Pilot	183
	Metal finishing	MBR, AD	Full	184
		AFF, ChemPre, PAC	Pilot	185
		MF	Pilot	218
		MPT, MF	Pilot	220

Ubiquitous contaminant	Industry	Treatment train	Scale	IWTT ref. ID
		BCF, OW, EQ, MF	Pilot	240
	Transportation equip. cleaning	OW, EQ, ChemPre, CLAR, MF	Pilot	282
		OW, EQ, MF	Pilot	282
	Wholesale trade: durable goods	ChemPre, MF, RO	Pilot	44
Nitrate Compounds	Ferroalloy manufacturing	EQ, MF, RO	Pilot	209
	Metal finishing	EQ, ANFF, AFF, UV	Pilot	219
	Pharmaceutical manufacturing	EQ, MBR	Full	229
	Pulp, paper & paperboard	MBR	Full	232
Chloride	Ferroalloy manufacturing	EQ, MF, RO	Pilot	209
	Metal finishing	CLAR, FI, MF, BCF, UV, RO	Pilot	217

Table 9: Definitions for treatment technology abbreviations in Table 8 as stated in IWTT

Code	Treatment technology	Code	Treatment technology
AD	Aerobic digestion/biological treatment	DAF	Dissolved air flotation
AFF	Aerobic fixed film biological treatment	DGS	Degasification
AIR	Aeration	EQ	Flow equalization
AND	Anaerobic digestion/biological treatment	EVAP	Evaporation
ANFF	Anaerobic fixed film biological treatment	FI	Granular-media filtration
ANSG	Anaerobic suspended growth	ION	Forward osmosis
ASG	Aerobic suspended growth	MBBR	Moving bed bioreactor
BASR	Biofilm airlift suspension reactor	MBR	Membrane bioreactor
BCF	Bag & cartridge filtration	MF	Micro- and ultra-membrane filtration
BCLAR	Ballasted clarification	MPT	Mechanical pre-treatment
BIO	Unspecified biological treatment	OW	Oil/water separation
BNR	Biological nutrient removal	OZ	Ozonation
ChemPre	Chemical precipitation	PAC	Powdered activated carbon
CLAR	Clarification	RO	Reverse osmosis
CS	Centrifugal separators	UV	Ultraviolet light

Overall, the IWTT identifies 40 different individual treatment technologies used to treat manufacturing wastewater (NAICS 31–33). Those listed most frequently are flow equalization (n=27), micro- and ultra-membrane filtration (n=20), chemical precipitation (n=13), clarification (n=13), bag and cartridge filtration (n=11), membrane bioreactor (n=11), mechanical pre-treatment (n=9), aerobic biological treatment (n=7), oil/water separation (n=7), electrocoagulation (n=6), reverse osmosis (n=6), and UV (n=5).

5.4 Water Quality Requirements for Reclaimed Water

A good understanding of the extent to which various effluent streams need to be treated is necessary in considering on-site reuse applications. Our literature review uncovered little comprehensive sector-specific data on water quality requirements for process water reuse. Table 10 synthesizes information from the two most comprehensive sources available, for five separate manufacturing sectors. Rommelman *et al.* (2004) identified these sectors as those capable of using large volumes of reclaimed water year-round.

Table 10: Summary of water quality requirements for reclaimed manufacturing water (values in mg/L except color [color units] and pH) from DOI (1981) and Rommelmann *et al.* (2004); where values differed between references, table displays a range to be consistent with both

Contaminant	**Process water by manufacturing subsector**					**Recirculating cooling systems**	**Boiler feedwater, by pressure***		
	Chemical	Petroleum & coal products	Primary metals	Pulp & paper	Textiles		Low (<150 psig)	Intermediate (150–700 psig)	High (>700 psig)
Metals									
Calcium (Ca)	68	75	—	20	—	50	—	0.4	0.01
Copper (Cu)	—	0.05	—	—	0.01–0.05	—	0.5	0.05	0.05
Iron (Fe)	0.1	1.0	—	0.1–1.0	0.1–0.3	0.5	1	0.3	0.05
Magnesium (Mg)	19	30	—	12	—	—	—	0.25	0.01
Manganese (Mn)	0.1	—	—	0.05–0.5	0.01–0.05	0.5	0.3	0.1	0.01
Others									
Chloride (Cl)	500	300	500	200–1,000	—	500	—	—	—
Bicarbonate (HCO_3)	128	480	—	—	—	25	170	120	48
Nitrate (NO_3)	5	10	—	—	—	—	—	—	—
Silica (SiO_2)	50	60	—	50	—	50	30	10	0.7
Sulfate (SO_4)	100	600	—	—	—	200	—	—	—
Dissolved solids (TDS)	1,000	1,000	1,500	100	100	500	700	500	200
Suspended solids (TSS)	5	10	3,000	10	5	100	10	5	0.5
Hardness ($CaCO_3$)	250	350	1,000	100–475	25	130–650	350	1.0	0.07
Alkalinity ($CaCO_3$)	125	500	200	—	—	20–350	350	100	40
Color	*20*	25	—	*10–30*	*5*	—	—	—	—
pH	*5.5–9.0*	*6.0–9.0*	*5.0-9.0*	*4.6–10.0*	*6.0–8.0*	*6.9–9.0*	*7.0-10.0*	*8.2-10.0*	*8.2-9.0*

*For requirements for narrower pressure ranges, refer to EPA (2012a), which uses 2005 data from the American Boiler Manufacturers Association.

Because quality needs are process-dependent, this table should be interpreted as broader guidance instead of specific goals for treatment for every process within listed sectors. Its listing of relevant contaminants by sector is not exhaustive. Where requirements differed between the two references, the table displays a range rather than a single value. Outside of industry-specific requirements are those for cooling and boiler feed water, also shown in Table 10.

Next, we can compare data on discharges to surface waters from DMR permits to each of the contaminant-specific water quality requirements within each manufacturing subsector presented in Table 10**Error! Reference source not found.**. If this effluent already meets i nlet water quality requirements, manufacturers could theoretically reuse it on-site with little expense beyond new piping. Building upon this assumption to estimate national manufacturing water reuse potential would thus be very conservative, serving as a floor on this potential. Table 11 displays how subsectors and contaminants mentioned by Rommelman *et al.* (2004) map to EPA DMR data, as well as the share of records containing data on average concentration within each subsector. These values were calculated only for contaminants with at least 10 non-blank records in each subsector. The number of observations in the DMR data varies by contaminant and subsector, with a mean of 201. We excluded any contaminant with fewer than 10 occurrences from this analysis, while the maximum number of observations is 1,482 for total suspended solids in the chemical sector.

Table 11: Crosswalk between inlet water quality requirements and reported concentration values in 2016 EPA DMR data, by subsector

		Manufacturing subsector			
From Rommelman *et al.* 2004		Chemical	Petrochemical & coal	Pulp & paper	Textiles
Mapped to NAICS (2016 EPA DMR)		Chemical	Petroleum & coal products	Paper	Textile mills
Total number of records (2016 EPA DMR)		29,359	17,340	3,720	1,164
Share of records with non-blanks for average concentration, 2016 EPA DMR data (2016 EPA DMR)		68%	41%	63%	74%
Contaminant		**Share of records where index value ≤ 1**			
Rommelman *et al.* 2004	2016 EPA DMR				
Cu	Copper	--	92%	--	53%
Fe	Iron	17%	61%	24% (HQR)*	40% (HQR)*
				61% (LQR)**	50% (LQR)**
Mg	Magnesium	81%	--	--	--
Mn	Manganese	46%	--	--	--
Cl	Total residual chlorine	100%	100%	100% (HQR)*	--
				100% (LQR)**	
NO_3	Nitrogen, nitrate dissolved	89%	--	--	--
SO_4	Sulfate	47%	--	--	--
TDS	Solids, total dissolved	62%	65%	--	--

TSS	Solids, total suspended	26%	43%	37%	34%
Hardness	Hardness, total (as $CaCO_3$)	68%	70%	18%	--
Alkalinity	Alkalinity, total (as $CaCO_3$)	33%	--	--	--

[*] Calculated based upon the higher quality requirement (lower concentration) given at the bottom of the range for this contaminant in Table 10

[**] Calculated based upon the lower quality requirement (higher concentration) given at the top of the range for this contaminant in Table 10.

Figure 7 shows the statistical distribution of these data for each contaminant by manufacturing subsector. Given the wide variation in reported concentrations in the DMR data, we indexed these values to the water quality requirement by dividing each of the former values by the fixed latter value, and present these boxplots accordingly. In each plot, the top and bottom of the box represent the 75th and 25th percentile, respectively, the horizontal line within each box is the median value, and values lying outside the interquartile range (denoted by vertical lines extending from each end of the box) are excluded from view. A dashed line in each figure represents the index value of one for easier visual comparison. In addition, Table 11 contains the share of records where the calculated index value is less than or equal to one; in other words, this proportion of the DMR records with concentration data meets the inlet water quality requirements from Table 10.

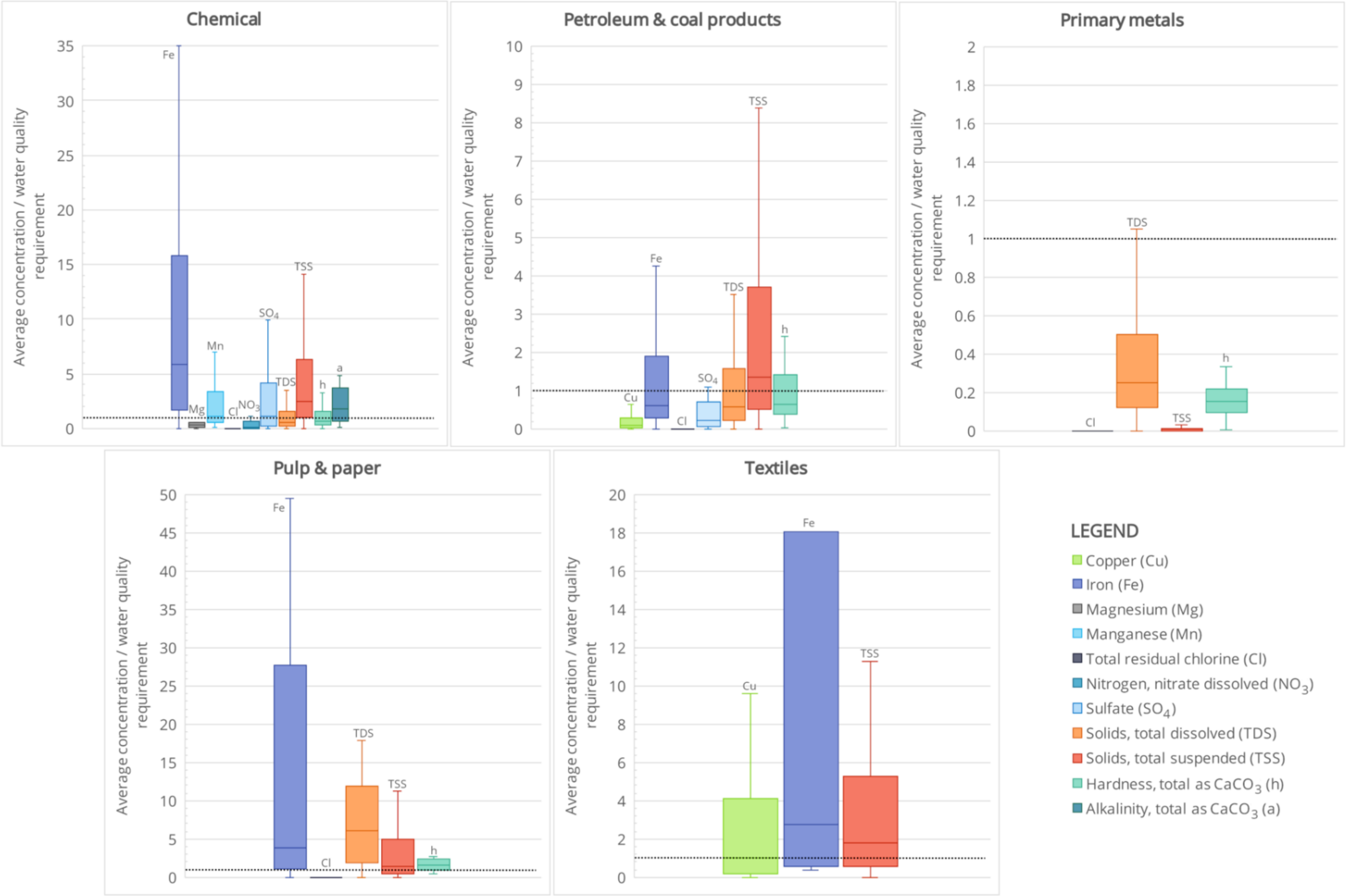

Figure 7: Distribution of average concentration of selected contaminants in five manufacturing subsectors (2016 EPA DMR data), indexed to water quality requirements from Table 10. The 25th and 75th percentiles are the bottom and top of each box, respectively, with medians as the horizontal line within each box and points outside of the interquartile range (the whiskers) not shown. The dashed line in each figure is at index value of 1. Values above 1 require additional treatment of that specific contaminant before reuse, while those at or below 1 meet reclaimed quality requirements for that specific contaminant. Note that there may be additional water quality requirements related to other contaminants before reusing. Number of observations for each contaminant within a subsector ranges from a low of 10 to a high of 1,482.

Figure 7 demonstrates that the primary metals sector is generally already treating contaminants identified in Table 10 to a level sufficient for reuse, with the share of records where the index value is at or below one ranging by contaminant from 91–100 percent. Excepting total suspended solids, more than 60 percent of observations for contaminants in the petroleum & coal products sector meet water quality requirements for reclaimed water. This implies that these sectors have high potential to realize the water savings and resilience benefits of reuse at minimal added cost. Conversely, the textiles and pulp and paper sectors would require higher adoption of new treatment technologies to harness the advantages of reuse. Looking across sectors at contaminants, all occurrences of total residual chlorine fall well below reclaimed water quality requirements—likely a function of stringent limits on chlorine for surface water discharges reported in DMR. Nitrogen, copper, and magnesium are also removed to suitable levels for reuse for more than 80 percent of the permits reviewed, while iron and alkalinity meet water quality requirements in fewer than one third of observations. Ultimately, these results are meant to illustrate an approach to estimating reuse potential that would be more rigorous given richer, representative data.

5.5 Energy Requirements for Treatment Technologies

The comparison in the previous section between water quality requirements and contaminant concentrations in DMR effluent embodies an example of one approach to estimating the nationwide potential for on-site reuse at manufacturing facilities. The energy implications of this reuse, however, demand further attention. After surveying the literature more generally (as summarized in section 3 of this report), we performed a second pass looking specifically for the energy needed by various treatment technologies, with our findings summarized in Table 12 below. These values are a critical input to any comprehensive assessment of the benefits and costs of implementing on-site water treatment for reuse. Note that this table reports only direct energy intensity ranges from the literature for individual treatment technologies or unit processes. The energy embedded in any specific treatment train will vary according to its unique configuration.

Table 12: Ranges of direct energy intensities for various commercialized treatment technologies from the literature; where reported, we distinguish electrical energy with a subscript [kWh$_e$])

Treatment technology/train	Direct energy intensity	Units	Source(s)
Activated sludge	0.23–0.71	kWh/m^3	Lazarova *et al.* (2012)
Activated sludge, MBR	0.6	kWhe/m^3	Wang *et al.* (2016)
Aeration as part of secondary treatment	0.18–0.8	kWh/m^3	Longo *et al.* (2016)
Anaerobic MBR	0.15–0.5	kWh/m^3	Ranade & Bhandari (2014)
Anaerobic sludge	0.074–0.15	kWh/m^3	Longo *et al.* (2016)
Anoxic/aerobic (A/O) treatment	0.5	kWh$_e$/m^3	Wang *et al.* (2016)
Clarification, filtration, chlorination	0.43	kWh/m^3	Water in the West (2013)
Coagulation, flocculation, clarification, UF, RO, UV/advanced oxidation	0.85	kWh/m^3	Water in the West (2013)
Electrocoagulation (Al)	0.72–14	kWh/m^3	Hakizimana *et al.* (2017)

Electrocoagulation (Fe)	0.68–12	kWh/m^3	Hakizimana *et al.* (2017)
Filtration	0.0027–0.0074	kWh/m^3	Longo et al. (2016)
Filtration, demineralization, chlorination	0.26	kWh/m^3	Water in the West (2013)
Filtration, UV	0.45	kWh/m^3	Water in the West (2013)
Flocculation, filtration, UV/advanced oxidation	0.40	kWh/m^3	Water in the West (2013)
Forward osmosis distillation	1.2	kWh/m^3	Mazlan *et al.* (2016)
Forward osmosis, NF	2.4–3.3	kWh/m^3	Mazlan *et al.* (2016)
Gravity-settling sludge	0.0084–0.012	kWh/m^3	Longo *et al.* (2016)
MBR	0.5–15	kWh/m^3	Lazarova *et al.* (2012), Giurco *et al.* (2011)
MBR, RO	28	kWh/m^3	Giurco *et al.* (2011)
Mechanical equipment to dose chemical reagents	0.009–0.015	kWh/m^3	Longo *et al.* (2016)
MF, RO	1.2–2.2	kWh/m^3	Water in the West (2013)
Mixing (anoxic reactors)	0.053–0.12	kWh/m^3	Longo *et al.* (2016)
Nitrification/denitrification	4	kWh/kg-N removed	Longo *et al.* (2016)
Oxidation pond	0.047–0.12	kWh/m^3	Lazarova *et al.* (2012)
Ozonation	12	kWh_e/kg	Yin *et al.* (2019)
Partial nitration/anammox	0.8–2	kWh/kg-N removed	Longo *et al.* (2016)
Primary screening	0.000029–0.013	kWh/m^3	Longo *et al.* (2016)
Primary settling	0.000043–0.000071	kWh/m^3	Longo *et al.* (2016)
Sludge dewatering through centrifugation	0.018–0.027	kWh/m^3	Longo *et al.* (2016)
Trickling filter	0.12	kWh/m^3	Lazarova *et al.* (2012)
UF, RO, UV	1.1	kWh/m^3	Water in the West (2013)
UV disinfection	0.045–0.11	kWh/m^3	Longo *et al.* (2016)

Table 12 draws attention to significant gaps in the reported data, as reported energy intensity values should be accompanied by the specific system configuration and an indicator of the extent to which contaminants are removed. Additionally, these values should include embodied energy, which can be significant depending on technology (e.g., treatment chemicals).

Next, a physics-based understanding of the energy requirements for treating manufacturing wastewater would be useful as it would provide benchmarks for developing and assessing treatment technologies/processes; they are likely a function of input water quality, needed quality for reclaimed water, and flow rates. Two recent papers on minimum energy requirements for treating saline water are suggestive of how energy consumption for manufacturing water reuse could be estimated theoretically. As summarized in Rao *et al.* (2016), a thermodynamic minimum energy requirement to desalinate pure water from saline water is well established. These minimum energy requirements are a function of certain parameters, such as temperature, salinity, the constituents in the water, recovery, and the amount of constituents removed. We can relate this to the analytical framework presented in section 2 of this report, where $E_{reuse,i}$ is a function of the types and amounts of contaminants in the wastewater, the desired output water quality, volume flow rates, and the embedded energy in any treatment chemicals. Similarly, Ahdab *et al.* (2018) estimate minimum energy requirements for desalination of brackish groundwater within the United States. They find that the least work of separation can similarly be considered a baseline for the specific energy consumption of brackish desalination systems. This least work depends upon the water recovery variable and some proxy variable for the composition of the water (i.e., TDS, specific conductance, ionic strength, or molality). They also establish that brackish groundwater with similar TDS concentrations can nevertheless require different amounts of energy depending on their specific chemical compositions; for example, more energy is required to treat brackish water where the major cation is sodium instead of calcium, and also increases from where the major anion is bicarbonate, to sulfate, to chloride (Figure 10 in their paper).

In considering the applicability of these authors' research to the topic of this report, we posit that the range and concentration of contaminants (but not the concentration mix) in manufacturing wastewater would be similar or worse to that found in brackish groundwater, and thus the minimum energy required for treatment would be the same or higher. Note that these theoretical minimum energy requirements are agnostic with respect to process, while real-world energy requirements for treatment instead depend on the specific implemented treatment process and conditions. In addition, Rao *et al.* note that the system configuration and operating conditions operators employ is in service of minimizing the cost to produce desalinated water, which may not accord with those that minimize energy consumption. We suggest that these two papers can serve as exemplars of the type of theoretical research that would be useful to illuminate the energy intensity and associated costs of treatment for common or high-priority manufacturing contaminants and appropriate treatment methods.

6. Understanding the Economics of On-Site Reuse Using an Exemplary Case Study

After performing the general literature review detailed in section 3 of this paper, we executed a secondary search of refereed journals for recent case studies with real-world applications of manufacturing water reuse that include data on water savings, water cost savings, and energy consumption and costs associated with the implementation of such reuse. Our search unearthed only a few qualifying case studies: Agana *et al.* (2013), Eyvaz *et al.* (2014), and Yin *et al.* (2019)—underlining the need for more such real-world examples. As the most comprehensive case study that allows us to estimate when on-site reuse is economically beneficial, we look at the Yin *et al.* (2019) paper more closely.

The case study from Yin *et al.* (2019) encompasses a large textile plant in China that generated 75,000 cubic meters of wastewater daily before implementation of reuse. This plant has two reuse systems, one primary and one secondary, that involve similar treatment trains of coagulation, ozonation, filtration, UF, and RO. Table 13 displays pertinent data from the paper on water volumes, energy intensity, and electricity costs in USD (electricity costs in this case study are $0.10/kWh).

Table 13: Water reuse volumes and associated treatment energy adapted from Yin *et al.* (2019)

System	Influent volume (m^3/d)	Energy for O_3 production (kWh/d)	Energy for pumps (kWh/d)	Reclaimed water (m^3/d)	System energy intensity (kWh/m^3)	Electricity cost ($/d)
Primary reuse	75,000	81,000	60,288	50,250	1.88	$14,129
Secondary reuse	24,750	35,046	21,384	14,850	2.28	$5,643
Total	n/a	116,046	81,672	65,100	1.98	$19,772

From these case study data, as well as information on industrial water and wastewater rates in the United States, we estimate in Table 14 the theoretical water cost savings and electricity costs of reuse if this plant were to be located domestically. These estimates rest on some significant assumptions, namely that this plant buys treated municipal water for 25 percent of its influent—in line with the Rao *et al.* (2015) assessment that three-quarters of manufacturing water is self-supplied—and sends all of its effluent to a municipal plant for treatment at U.S. costs. In addition, capital costs for the reuse technologies were present in the case study.

Table 14: Estimated values for water vs. energy tradeoff analysis of reuse for Yin *et al.* (2019)

Water savings	65,100 m^3/d
Water cost savings[a]	$13,812/d
Wastewater cost savings[b]	$75,315/d
Electricity costs	$19,772/d
Total operating costs of treating wastewater[c]	$28,644/d
Net economic savings of reuse	$60,483/d

[a] Uses median industrial variable cost of $3.21/kgal water, AWWA and RFC (2017); excludes minimal fixed costs

[b] Uses median industrial variable cost of $4.38/kgal wastewater, AWWA and RFC (2017); excludes minimal base cost

[c] From p. 16 of source: 0.44 USD/m^3 of reuse water

While it is unlikely that this plant sources one quarter of its influent from treated municipal water and disposes of 100 percent of its effluent via a municipal wastewater treatment plant at U.S. prices, these estimates provide some basis of comparison for expenditures on reuse energy and savings on source water and wastewater disposal. Ultimately, Yin *et al.* (2019) was the only one of the peer-reviewed case studies we located that provided suitable data to allow for an assessment of the tradeoffs during reuse between additional energy consumption, water and wastewater savings, and the associated financial impacts.

7. Discussion

This paper surveys the literature with respect to manufacturing wastewater and describes wastewater streams by manufacturing sector in accordance with publicly available EPA permit data. Its aim was to support a more comprehensive analysis of the energy implications of wastewater treatment technologies as well as better accounting for the economic benefits of on-site water reuse at manufacturing plants. Some of the findings presented here may be of use, but they have significant limitations in terms of the underlying data—or lack thereof. While this constrains their utility to researchers and manufacturers, perhaps the most valuable outcome of this project is pointing to the paucity of data, as well as the research needed to fill these gaps in our understanding.

The main limitations to a better understanding of the characteristics of aqueous manufacturing effluent can be delineated as follows:

- EPA Effluent Guidelines for many manufacturing sectors are out-of-date, and their underlying methodology is not comparable to that of the most recent guidelines.
- EPA DMR data exclude releases from “minor” dischargers; across manufacturing sectors, only 2.5 percent of the number of 2014 MECS establishments were present in 2016 DMR data.
- EPA TRI data exclude small manufacturers, common contaminants, and reported volumes, and it is difficult to discern which effluent streams aside from transfers to POTWs are aqueous.
- EPA NPP data characterizing pretreated effluent sent to POTWs are not yet available as a nationwide electronic database.
- Names of contaminants or groupings of contaminants are not standardized nationwide, nor across DMR and TRI data.
- Emerging contaminants are not included in NPDES permits.

In sum, robust and representative data on what is in manufacturing wastewater largely do not exist.

In addition, blind spots exist for other components of a comprehensive tradeoff analysis of manufacturing water reuse, as displayed in Table 15. Because wastewater treatment research and technology development has largely been focused on municipal wastewater, which has a small overlap with manufacturing wastewater in terms of constituents, we cannot currently develop analytical models for these technologies due to the absence of contaminant and energy data. However, very few recent case studies include enough information to perform even individual tradeoff analyses, because treatment processes are largely driven by the need to meet regulations.

Table 15: Data required for tradeoff analysis of manufacturing water reuse

Category	Available data	Desired data
Contaminant mixes	EPA DMR and TRI data; case studies; EPA Effluent Guidelines	Mixes for smaller manufacturing plants not required to have NPDES permits; mixes in effluents sent to POTWs
Flow rates of effluent	Several case studies contain process flows	Effluent discharges by disposal locations (*e.g.*, POTW, surface water)
Water quality requirements for industrial uses	Parameters for pulp & paper, chemical, petrochemical, and textile sectors, plus recirculating cooling systems (DOI 1981 and Rommelmann *et al.* 2004)	Data for other manufacturing sectors
Treatment technology effectiveness	EPA IWTT database; several case studies	In-situ performance data
Energy requirements for treatment	Ranges compiled from literature review	In-situ performance data that ideally encompass embodied energy

Against this backdrop of data scarcity, the imperative for more reuse will increasingly make itself known in a future of local water constraints. As a result of the research that underpins this paper, we identify the following research needs in this arena.

First, the data on manufacturing wastewater contaminants presented earlier in this report are by necessity from EPA's DMR permits. These data are reported to reflect the makeup of effluent at the point of discharge into surface water bodies. However, reuse at the point of use would in all likelihood be easier to deploy and more energy-efficient than treating wastewater after all separate wastewater streams have mixed just prior to discharge, given the presence of fewer contaminants and fewer interactions between those contaminants. While some case studies report on these opportunities, often identified through water pinch analysis (for example, Agana *et al.* 2013, Colic *et al.* 2013, Altech Environmental Consulting and OCETA n.d.), there is a research need for systematic understanding of treatment trains occurring directly after water-using processes that are suitable for reuse—especially because manufacturers may recover contaminants as inputs into the same process or as saleable material.

Given the wide range of contaminant concentrations in manufacturing wastewaters, there is a need for variable load treatment. One treatment technology that could treat a wide range of concentrations would be applicable across multiple sectors. A necessary first step to achieving such cross-cutting applicability would be to determine how the energy consumption of treatment technologies varies with contaminant loads.

Next, developing physics and chemistry-based models to estimate the energy requirements of treating various industrial contaminants would foster the creation of a taxonomy for grouping contaminants into classes that are characterized by treatment processes and associated energy needs. This would also enable EPA to integrate energy requirements into the IWTT database, such that it could serve as a more comprehensive source for demonstrated applications. In practical terms, updates to the industrial Effluent Guidelines would allow for better information on industry practices, effluent characteristics (e.g., flow, pollutants), treatment technologies, and economic implications, because the guidelines rely on statistical samples of wastewater streams. Creating standardization around EPA contaminant definitions would also enable more robust analysis of permit data.

Our analysis of EPA DMR data also shows that some facilities may already be treating their wastewater to levels suitable for reuse, as seen in Figure 7. Note that these results do not apply to any specific facility. Instead, they illustrate how available DMR data on particular contaminant concentrations compare to water quality requirements, thus suggesting the variable potential for reuse by sector. In these cases, raising awareness about the benefits of water reuse and alleviating any perceived risks would help to capture some of the cost-effective industrial water reuse potential. In addition, an opportunity exists for collecting data from or on manufacturers regarding the cost of supply water, flow rates, critical treatment needs (e.g., recalcitrant organics, salt-handling capabilities with an economical sink [Oppenheimer *et al.* 2016]), and process water quality requirements beyond those established by Rommelmann *et al.* (2004). This could occur via several mechanisms, including interviewing, surveying, or convening focus groups; connecting with municipal wastewater treatment plants that service small manufacturers to collect information on their waste streams; and creating a multi-sectoral collection of case studies of facilities already reusing manufacturing wastewater. One potential outcome of this could involve integrating and applying wastewater analysis into existing water auditing tools for manufacturing plants, while another might be developing an ROI calculator for water reuse technologies that better captures the true cost of water.

To conclude, this data assessment investigated publicly available datasets to synthesize information about typical contaminants in manufacturing wastewaters, with the aim of advancing our understanding of the opportunities for and associated energy requirements of manufacturing water reuse. First, we developed a theoretical framework to clarify when on-site reuse is beneficial in terms of energy. We then surveyed the literature to assess the current state of reuse and motives and barriers for such reuse, along with existing reuse technologies and useful resources for manufacturers considering implementing on-site reuse. Subsequently, we detailed the scope and limitations of three EPA datasets (Effluent Guidelines, Discharge Monitoring Reports, and Toxics Release Inventory) before deriving a set of “ubiquitous contaminants”, defined as those among the top ten, in terms of mass discharged, in more than half of the manufacturing sectors (NAICS 31–33) according to DMR and TRI permit data. Next, we presented proven treatment trains for these common pollutants, along with the sector in which they have been implemented. We also compared water quality requirements for reclaimed water to those characteristic of wastewater streams currently being discharged from manufacturing plants into surface waters under the EPA DMR program, and compiled from the literature energy requirements for treatment technologies. A recent case study is used to illustrate how the analytical framework of energy-beneficial reuse can be applied. Ultimately, while the lack of representative, robust data on wastewater streams within and from manufacturing plants precludes good understanding of reuse opportunities and their energy implications, this effort served to emphasize critical data gaps. Working to fill in these gaps with an eye toward better comprehending the dependencies between energy and water in the manufacturing context will allow manufacturers to implement on-site reuse that decreases regulatory, physical, and reputational risks while reducing watershed impacts and enhancing resiliency.

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Appendix 1: EPA Effluent Guidelines by Category in Manufacturing Sector

This table displays Effluent Guidelines that fall within the manufacturing sector and the NAICS subsector we assigned to each category, using the NAICS Association's NAICS Lookup tool (NAICS 2018), in descending order of the year of last revision. In addition, this table displays information from each individual webpage listed by industry category at the Effluent Guidelines website, https://www.epa.gov/eg/industrial-effluent-guidelines. More specifically, it includes facilities covered (labeled on these webpages either as "facilities covered" or "regulation subcategories"), wastewater streams (described as "wastestreams", "wastewater generated mainly as…", or "water used in…"), and significant regulated pollutants (labeled as regulated pollutants or significant pollutants). For consistency, data in this table is assembled only from these individual webpages, instead of from the actual text of each rulemaking or its technical development document, which differ substantially from rulemaking to rulemaking; where a category is not available on each individual webpage, it is denoted in this table by "Not on webpage".

Category	**Year last revised**	**NAICS subsector**	**Facilities covered**	**Wastewater streams**	**Regulated pollutants**
Iron and Steel Manufacturing	2005	331	Cokemaking; sintering; ironmaking; steelmaking; vacuum degassing; continuous casting; hot forming; salt bath descaling; acid pickling; cold forming; alkaline cleaning; hot coating; other operations (direct-reduced iron production, briquetting, forging)	*Not on webpage*	*Not on webpage*
Meat and Poultry Products	2004	311	Meat first processors (slaughterhouses); meat further processors generating >6,000 lb/day finished products; independent renderers of meat & poultry products using >10M lb/y raw material; poultry first processors slaughtering >100M lb/y; poultry further processors generating >7M lb/y finished products	*Not on webpage*	*Not on webpage*
Metal Products and Machinery	2003	332, 333	Aerospace; aircraft; bus & truck; electronic equipment; hardware; household equipment; instruments; mobile industrial equipment; motor vehicle; office machine; ordnance; precious metals & jewelry; railroad; ships & boats; stationary industrial equipment; miscellaneous metal products	*Not on webpage*	Oil & grease (as hexane-extractable material), total suspended solids (TSS)

Category	**Year last revised**	**NAICS subsector**	**Facilities covered**	**Wastewater streams**	**Regulated pollutants**
Pharmaceutical Manufacturing	2003	325	Fermentation products; extraction products; chemical synthesis products; mixing/compounding & formulation; research	*Not on webpage*	*Not on webpage*
Pulp, Paper and Paperboard	2002	322	Dissolving kraft; bleached papergrade kraft & soda; unbleached kraft; dissolving sulfite; papergrade sulfite; semi-chemical; mechanical pulp; non-wood chemical pulp; secondary fiber deink; secondary fiber non-deink; fine & lightweight papers from purchased pulp; tissue, filter, non-woven, & paperboard from purchased pulp	*Not on webpage*	*Conventional:* biochemical oxygen demand, suspended solids, pH *Priority:* 2,4,6-trichlorophenol, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD), pentachlorophenol, zinc *Nonconventional:* adsorbable organic halides (AOX), chemical oxygen demand, chloroform, trichlorosyringol, 2,4,5-trichlorophenol, 3,4,5-trichlorocatechol, 3,4,5-trichloroguaiacol, 3,4,6-trichlorocategchol, 3,4,6-trichloroguaiacol, 4,5,6-trichloroguaiacol, tetrachlorocatechol, tetrachlorguaiacol, 2,3,4,6-tetrachlorophenol, 2,3,7,8-tetrachlorodibenzofuran (TCDF)
Leather Tanning and Finishing	1996	316	Hair pulp, chrome tan, retan-wet finish; hair save, chrome tan, retan-wet finish; hair save or pulp, non-chrome tan, retan-wet finish; retan-wet finish-sides; no beamhouse; through-the-blue; shearling; pigskin; retan-wet finish-splits	*Not on webpage*	Biochemical oxygen demand, chromium, pH, oil & grease, suspended solids, sulfide

Category	**Year last revised**	**NAICS subsector**	**Facilities covered**	**Wastewater streams**	**Regulated pollutants**
Pesticide Chemicals	1996	325	Organic pesticide chemicals manufacturing; metallo-organic pesticide chemicals manufacturing; pesticide chemicals formulating & packaging; repackaging of agricultural pesticides performed at refilling establishments	*Not on webpage*	*Not on webpage*
Organic Chemicals, Plastics and Synthetic Fibers	1993	325, 326	Rayon fibers; other fibers; thermoplastic resins; thermosetting resins; commodity organic chemicals; bulk organic chemicals; specialty organic chemicals	*Not on webpage*	*Not on webpage*
Nonferrous Metals Manufacturing	1990	331	Bauxite refining; primary aluminum smelting; secondary aluminum smelting; primary copper smelting; primary electrolytic copper refining; secondary copper; primary lead; primary zinc; metallurgical acid plants; primary tungsten; primary columbium-tantalum; secondary silver; secondary lead; primary antimony; primary beryllium; primary & secondary germanium & gallium; secondary indium; secondary mercury; primary molybdenum & rhenium; secondary molybdenum and vanadium; primary nickel & cobalt; secondary nickel; primary precious metals & mercury; secondary precious metals; primary rare earth metals; secondary tantalum; secondary tin; primary & secondary titanium; secondary tungsten & cobalt; secondary uranium; primary zirconium & hafnium	Smelter furnace & filtration residues; rinsing of materials; spent solutions; equipment cooling, air pollution controls (wet scrubbers)	*Not on webpage*
Nonferrous Metals Forming and Metal Powders	1989	331, 332	Lead-tin-bismuth forming; magnesium forming; nickel-cobalt forming; precious metals forming; refractory metals forming; titanium forming; uranium forming; zinc forming; zirconium-hafnium forming; metal powders	*Not on webpage*	*Not on webpage*

Category	Year last revised	NAICS subsector	Facilities covered	Wastewater streams	Regulated pollutants
Aluminum Forming	1988	331, 332	Rolling with neat oils; rolling with emulsions; extrusion; forging; drawing with neat oils; drawing with emulsions or soaps	Atmosphere scrubber liquor; caustic, acid, seal, or detergent solutions bath solution; rinse water; scrubber liquor; spent neat oil, emulsion, or soap solution; spent lubricant; contact cooling water; spent solvents	*Not on webpage*
Battery Manufacturing	1986	335	[Organized on the basis of anode material and electrolyte]: cadmium; calcium; lead; leclanche; lithium; magnesium; zinc	Formation area washdown; plate curing; product rinsing; cooling, equipment, & floor area washing; laboratory washing; hand washing; laundry; truck washing; wet scrubbers (air pollution controls)	Cadmium, chromium, cobalt, copper, cyanide, iron, lead, manganese, mercury, nickel, oil & grease, silver, zinc
Copper Forming	1986	331	Manufacture of formed copper and copper alloy products, excluding: forming of beryllium copper alloys, forming of precious metals, casting of copper and copper alloys, and copper powders	Lubricants used in forming processes; solution heat treatment (cooling water); alkaline cleaning bath & rinse; annealing (cooling water); pickling bath & rinse; pickling fume scrubber; tumbling or burnishing (lubricant); surface coating; miscellaneous	Chromium, copper, lead, nickel, zinc, toxic organic compounds, suspended solids, pH, oil & grease
Metal Finishing	1986	332	Electroplating; electroless plating; anodizing; coating (phosphating, chromating, and coloring); chemical etching & milling; printed circuit board manufacture	*Not on webpage*	*Not on webpage*
Metal Molding and Casting (Foundries)	1985	331	Aluminum casting; copper casting; ferrous casting; zinc casting	*Not on webpage*	TSS, phenols, copper, lead, zinc, oil & grease for monitoring total toxic organics (TTO) for indirect dischargers
Porcelain Enameling	1985	332, 335	Porcelain enameling on steel, cast iron, aluminum, and copper	Water-based alkaline cleaners; acid pickling solutions; rinse	*Toxic:* antimony, arsenic, cadmium, chromium,

Category	Year last revised	NAICS subsector	Facilities covered	Wastewater streams	Regulated pollutants
				water; nickel salts solution; washing out ball mills; cooling ball mills; entrapping waste slip from overspray	copper, lead, nickel, selenium, zinc *Conventional*: suspended solids, pH, oil & grease *Unconventional:* aluminum, cobalt, fluoride, iron, manganese, phosphorus, titanium
Plastics Molding and Forming	1984	326	Extrusion; molding; coating & laminating; thermoforming; calendaring; casting; foaming; cleaning; finishing	Cooling or heating plastic products; cleaning surfaces of plastic products & equipment; finishing plastic products	Biochemical oxygen demand (BOD_5), oil & grease, total suspended solids (TSS), pH
Sugar Processing	1984	311	*Not on webpage*	*Not on webpage*	*Not on webpage*
Coil Coating	1983	332	By basis material: steel; galvanized (zinc-coated steel, galvalum, brass & other copper-base strip); aluminum (including aluminum alloys and aluminum-coated steel); canmaking	Water-based alkaline cleaners; acid pickling solutions; rinse water; water-based chemical conversion coating processes; strip cooling	*Toxic*: chromium, zinc, nickel, lead, copper, cyanide, total toxic organics *Conventional:* suspended solids, pH, oil & grease *Unconventional*: iron, aluminum, phosphorous, fluoride
Electrical and Electronic Components	1983	325, 334	Semiconductor; electronic crystals; cathode ray tube; luminescent materials	Water cooling, lubrication, carrying away removed material for cutting and slicing and lapping or polishing processes; cleaning; rinsing; degreasing	Fluorine, arsenic, organic compounds
Electroplating	1983	332	Common metals; precious metals; anodizing; coatings; chemical etching & milling; electroless plating; printed circuit board	*Not on webpage*	Cyanide, lead, cadmium, copper, nickel, chromium, zinc, silver, total metal discharge (sum of individual concentrations of copper, nickel, chromium, & zinc)

Category	Year last revised	NAICS subsector	Facilities covered	Wastewater streams	Regulated pollutants
Inorganic Chemicals Manufacturing	1982	325	*Not on webpage*	*Not on webpage*	*Not on webpage*
Petroleum Refining	1982	324	Topping; cracking; petro-chemical; lube; integrated	Desalter water; sour water; other process water; spent caustic; tank bottoms; cooling tower; condensate blowdown; source water treatment system; stormwater; ballast water	*Not on webpage*
Textile Mills	1982	313	Wool scouring; wool finishing; low water use processing; woven fabric finishing; knit fabric finishing; carpet finishing; stock & yarn finishing; nonwoven manufacturing; felted fabric processing	*Not on webpage*	*Not on webpage*
Timber Products Processing	1981	321	Barking; veneer; plywood; dry process hardboard; wet process hardboard; wood preserving—water borne or nonpressure; wood preserving steam; wood preserving—Boulton; wet storage; log washing; sawmills & planing mills; finishing; particleboard; manufacturing insulation board; wood furniture & fixture production	*Not on webpage*	Arsenic, biochemical oxygen demand, chemical oxygen demand, copper, chromium, pH, phenols, oil & grease, suspended solids
Carbon Black Manufacturing	1978	325	Furnace process; thermal process; channel process; lamp process	*Not on webpage*	Direct dischargers cannot discharge process wastewater; indirect dischargers have limitations on oil & grease
Canned/Preserved Fruits and Vegetable Processing	1976	311	*Not on webpage*	*Not on webpage*	*Not on webpage*
Explosives Manufacturing	1976	325	Manufacture of explosives; explosives load, assemble, and pack plants	Aqueous waste from reactors, filtration systems, decanting systems, distillation vacuum exhaust scrubbers, caustic	COD, BOD_5, TSS, pH, oil & grease

Category	Year last revised	NAICS subsector	Facilities covered	Wastewater streams	Regulated pollutants
				scrubbers, process equipment cleanouts, area washdowns, formulation equipment cleanup, spill washdowns	
Gum and Wood Chemicals Manufacturing	1976	325	Char & charcoal briquets; gum rosin & turpentine; wood rosin, turpentine, & pine oil; tall oil rosin, pitch, & fatty acids; essential oils; rosin-based derivatives	Product washing; solvent separators; equipment washing; crude tall oil acid treatment wash; rosin reactor condensate; non-contact cooling water	BOD_5, TSS, pH
Asbestos Manufacturing	1975	327	*Not on webpage*	*Not on webpage*	*Not on webpage*
Canned & Preserved Seafood	1975	311	Farm-raised catfish; conventional blue crab; mechanized blue crab; non-remote Alaskan crab meat; remote Alaskan crab meat; non-remote Alaskan whole crab & crab section; remote Alaskan whole crab & crab section; Dungeness & tanner crab in the contiguous states; non-remote Alaskan shrimp; remote Alaskan shrimp; northern shrimp in the contiguous states; southern non-breaded shrimp in the contiguous states; breaded shrimp in the contiguous states; tuna; fish meal; Alaskan hand-butchered salmon; Alaskan mechanized salmon; West Coast hand-butchered salmon; West Coast mechanized salmon; Alaskan bottom fish; non-Alaskan conventional bottom fish; non-Alaskan mechanized bottom fish; hand-shucked clam; mechanized clam; Pacific Coast hand-shucked oyster; Atlantic & Gulf Coast hand-shucked oyster; steamed & canned oyster; sardine; Alaskan scallop; non-Alaskan scallop; Alaskan herring fillet; non-Alaskan herring fillet; abalone	*Not on webpage*	*Not on webpage*

Category	**Year last revised**	**NAICS subsector**	**Facilities covered**	**Wastewater streams**	**Regulated pollutants**
Fertilizer Manufacturing	1975	325	Phosphate; ammonia; urea, ammonium nitrate; nitric acid; ammonium sulfate production; mixed & blend fertilizer production		Ammonia, BOD_5, fluoride, nitrate, organic nitrogen, pH, total phosphorus, TSS
Ink Formulating	1975	325	*Not on webpage*	*Not on webpage*	*Not on webpage*
Paint Formulating	1975	325	*Not on webpage*	*Not on webpage*	*Not on webpage*
Paving and Roofing Materials (Tars and Asphalt)	1975	324	*Not on webpage*	*Not on webpage*	*Not on webpage*
Soap and Detergent Manufacturing	1975	325	Soap manufacturing by batch kettle; fatty acid manufacturing by fat splitting; soap manufacturing by fatty acid neutralization; glycerine concentration; glycerine distillation; manufacture of soap flakes & powders; manufacture of bar soaps; manufacture of liquid soaps; oleum sulfonation & sulfation; air-SO_3 sulfation & sulfonation; SO_3 solvent & vacuum sulfonation; sulfamic acid sulfation; chlorosulfonic acid sulfation; neutralization of sulfuric acid esters & sulfonic acids; manufacture of spray dried detergents; manufacture of liquid detergents; manufacture of detergents by dry blending; manufacture of drum dried detergents; manufacture of detergent bars & cakes	Steam pretreatment; soap boiling; equipment cleanouts; scrubber waters; scrap reclamation; condensers; still bottoms; leaks and spills	*Not on webpage*
Cement Manufacturing	1975	327	Nonleaching; leaching; materials storage piles runoff	Equipment cooling; water contacted by kiln dust; water used in wet scrubbers to control kiln stack emissions	TSS, temperature, pH
Dairy Products Processing	1974	311	Receiving stations; fluid products; cultured products; butter; cottage cheese & cultured cream cheese; natural & processed cheese; fluid mix for ice cream & other frozen desserts; ice cream, frozen desserts, novelties & other dairy desserts;	Cleaning out of product remaining in tank trucks, cans, piping, tanks, & other equipment; spillage produced by leaks, overflow, freezing-on, boiling-over, equipment	BOD_5, TSS, pH

Category	Year last revised	NAICS subsector	Facilities covered	Wastewater streams	Regulated pollutants
			condense milk; dry milk; condensed whey; dry whey	malfunction, or operator error; processing losses, including sludge discharges from clarifiers and product wasted during pasteurizer start-up, shut-down, & product change-over; wastage of spoiled products, returned products, or byproducts; detergents & other cleaning compounds	
Ferroalloy Manufacturing	1974	331	Open electric furnaces with wet air pollution control devices; covered electric furnaces & other smelting operations with wet air pollution control devices; slag processing; covered calcium carbide furnaces with wet air pollution control devices; other calcium carbide furnaces; electrolytic manganese products; electrolytic chromium	Thermal pollution; water from air pollution control devices (baghouses, wet scrubbers, & electrostatic precipitators)	*Not on webpage*
Glass Manufacturing	1974	327	Insulation fiberglass; sheet glass; rolled glass; plate glass; float glass; automotive glass tempering; automotive glass laminating; glass container; glass tubing (Danner process; television picture tube envelope; incandescent lamp envelope; hand pressed & blown glass	Cullet quenching; cooling water (usually non-contact); air emission control devices (*e.g.*, scrubbers); product rinsing	Ammonia, BOD_5, COD, fluoride, lead, oil, phenol, phosphorus, pH, TSS
Grain Mills	1974	311	Corn wet milling; corn dry milling; normal wheat flour milling; bulgur wheat flour milling; normal rice milling; parboiled rice processing; animal feed; hot cereal; ready-to-eat cereal; wheat starch & gluten	Grain cleaning; cooking; modified starch washing; condensation from steepwater evaporation; syrup refining	BOD5, TSS, pH
Phosphate Manufacturing	1974	325	*Not on webpage*	*Not on webpage*	*Not on webpage*
Rubber Manufacturing	1974	326	*Not on webpage*	*Not on webpage*	*Not on webpage*

Appendix 2: Top Contaminants in Each Manufacturing Subsector

These tables display the conservative summation of 2016 TRI and DMR data (as explained on page 18) for all manufacturing subsectors considered in this analysis, arranged alphabetically by subsector. Each subsector table displays the total contaminant discharge in kg/y, the number of unique contaminants found, the top 10 contaminants (if applicable) in terms of mass discharged (kg/y), and the share by mass of the top 10 contaminants.

Apparel (NAICS code 315)	
Total contaminant discharge (kg/y)	2,283
Number unique contaminants	4
Share by mass of top 10 contaminants	100%
Contaminant	**Mass discharged (kg/y)**
Solids, total suspended	2,098
Oil and grease	184
BOD, 5-day, 20 deg. C	0.51
Zinc Compounds	0.23

Beverage & Tobacco Product (312)	
Total contaminant discharge (kg/y)	27,889,407
Number unique contaminants	63
Share by mass of top 10 contaminants	96.3%
Contaminant	**Mass discharged (kg/y)**
BOD, 5-day, 20 deg. C	9,541,475
Solids, total suspended	7,287,926
Chemical oxygen demand (COD)	4,039,101
Sulfate	2,484,570
Oil and grease	1,657,032
Chloride	563,308
Petrol hydrocarbons, total recoverable	449,010
Nitrate Compounds	346,971
Ethanol	241,767
Phosphorus	240,872

Chemical (325)	
Total contaminant discharge (kg/y)	3,801,437,162
Number unique contaminants	460
Share by mass of top 10 contaminants	97.8%
Contaminant	**Mass discharged (kg/y)**
Solids, total dissolved	1,435,746,103
Chlorides & sulfates	1,196,915,537
Chloride	511,264,834
Hardness, total (as CaCO3)	175,594,009
Solids, total suspended	148,610,618
Sulfate	128,239,970
Chemical oxygen demand (COD)	38,736,693
Alkalinity, total (as CaCO3)	33,417,101
BOD, 5-day, 20 deg. C	29,549,878
Nitrate Compounds	20,679,402

Electrical Equipment, Appliance, & Component (335)	
Total contaminant discharge (kg/y)	6,844,586
Number unique contaminants	103
Share by mass of top 10 contaminants	99.6%
Contaminant	**Mass discharged (kg/y)**
Hardness, total (as CaCO3)	4,108,644
Solids, total suspended	1,873,194
Nitrate Compounds	483,272
Oil and grease	158,627
Solids, total dissolved	68,113
Chemical oxygen demand (COD)	52,917
Chloride	22,193
N-Methyl-2-Pyrrolidone	21,875
Certain Glycol Ethers	20,377
Sodium Nitrite	10,550

Computer & Electronic Product (334)	
Total contaminant discharge (kg/y)	58,113,152
Number unique contaminants	74
Share by mass of top 10 contaminants	99.6%
Contaminant	**Mass discharged (kg/y)**
Nitrogen	44,251,583
Oxygen	3,773,404
Nitrate Compounds	3,495,942
BOD, 5-day, 20 deg. C	3,058,969
Solids, total dissolved	893,654
Solids, total suspended	764,938
Certain Glycol Ethers	506,893
N-Methyl-2-Pyrrolidone	400,020
Ethylene Glycol	378,173
Ammonia	376,010

Fabricated Metal Product (332)	
Total contaminant discharge (kg/y)	263,320,275
Number unique contaminants	161
Share by mass of top 10 contaminants	99.5%
Contaminant	**Mass discharged (kg/y)**
Solids, total dissolved	141,511,115
Solids, total suspended	109,410,961
Nitrate Compounds	7,438,412
Oil and grease	1,485,587
Chloride	421,147
Residue, tot fltrble (dried at 105 C)	419,889
Chemical oxygen demand (COD)	412,796
Sulfate	361,534
Hardness, total (as CaCO3)	280,962
Ethylene Glycol	253,084

Food (311)	
Total contaminant discharge (kg/y)	848,973,068
Number unique contaminants	153
Share by mass of top 10 contaminants	97.1%
Contaminant	**Mass discharged (kg/y)**
Solids, total dissolved	405,100,576
Chloride	221,033,018
Solids, total suspended	71,475,719
BOD, 5-day, 20 deg. C	69,244,327
Nitrate Compounds	18,855,107
Sulfate	9,989,627
Nitrogen	9,351,841
Chemical oxygen demand (COD)	7,273,985
Hardness, total (as CaCO3)	6,488,367
Bicarbonate ion- (as HCO3)	5,625,575

Leather & Allied Product (316)	
Total contaminant discharge (kg/y)	*442,780*
Number unique contaminants	36
Share by mass of top 10 contaminants	97.5%
Contaminant	**Mass discharged (kg/y)**
Solids, total suspended	212,015
Ammonia	104,220
Chromium Compounds (Except Chromite Ore Mined In The Transvaal Region)	29,641
BOD, 5-day, 20 deg. C	23,101
Hardness, total (as CaCO3)	23,018
Chemical oxygen demand (COD)	15,975
Manganese Compounds	8,218
Sulfate	6,145
Oil and grease	5,820
Potassium N-Methyldithiocarbamate	3,424

Furniture & Related Product (337)	
Total contaminant discharge (kg/y)	50,421
Number unique contaminants	27
Share by mass of top 10 contaminants	99.8%
Contaminant	**Mass discharged (kg/y)**
Solids, total suspended	39,851
Nitric Acid	5,581
Nickel	2,329
Lead	891
Oil and grease	679
Chromium	651
Copper	153
Manganese	115
Organics, total toxic (TTO)	38
Zinc Compounds	22

Machinery (333)	
Total contaminant discharge (kg/y)	102,246,437
Number unique contaminants	110
Share by mass of top 10 contaminants	99.6%
Contaminant	**Mass discharged (kg/y)**
Total Organic Carbon	72,506,890
Oil and grease	18,434,149
Solids, total suspended	6,307,003
BOD, 5-day, 20 deg. C	1,425,717
Solids, total dissolved	836,621
Total Kjeldahl Nitrogen	690,584
N,N-Dimethylformamide	671,415
Ethylene glycol	467,354
Nitrate Compounds	300,720
Chemical oxygen demand (COD)	147,523

Miscellaneous (339)	
Total contaminant discharge (kg/y)	1,497,267
Number unique contaminants	64
Share by mass of top 10 contaminants	96.5%
Contaminant	Mass discharged (kg/y)
N-Methyl-2-Pyrrolidone	354,665
Nitrate Compounds	298,427
Sodium chloride	284,859
Solids, total dissolved	165,375
N,N-Dimethylformamide	102,095
Ethylene Glycol	70,537
Solids, total suspended	65,405
Sodium Nitrite	56,155
Tert-Butyl Alcohol	25,711
Nitric Acid	21,102

Nonmetallic Mineral Product (327)	
Total contaminant discharge (kg/y)	5,037,668,139
Number unique contaminants	136
Share by mass of top 10 contaminants	99.9%
Contaminant	Mass discharged (kg/y)
Solids, total dissolved	3,078,713,173
Sulfate	1,861,546,019
Solids, total suspended	49,318,413
Chloride	19,976,976
Chemical oxygen demand (COD)	18,546,028
Hardness, total (as CaCO3)	3,364,972
Oil and grease	2,882,052
Alkalinity, total (as CaCO3)	978,673
Oxygen	438,946
Potassium	387,046

Paper (322)	
Total contaminant discharge (kg/y)	749,791,538
Number unique contaminants	118
Share by mass of top 10 contaminants	95.9%
Contaminant	Mass discharged (kg/y)
Solids, total dissolved	302,419,015
Solids, total suspended	124,101,688
Sulfate	88,982,411
BOD, 5-day, 20 deg. C	74,923,702
Chemical oxygen demand (COD)	73,272,987
Solids, total volatile	14,146,515
Oxygen demand, total (tod)	13,288,550
Hardness, total (as CaCO3)	10,977,190
Chloride	8,635,339
Total Kjedahl Nitrogen	8,272,485

Petroleum & Coal Products (324)	
Total contaminant discharge (kg/y)	1,598,011,282
Number unique contaminants	202
Share by mass of top 10 contaminants	96.6%
Contaminant	Mass discharged (kg/y)
Solids, total suspended	619,143,258
Chemical oxygen demand (COD)	309,431,574
Solids, total dissolved	167,155,690
Sulfate	159,676,616
Residue, tot fltrble (dried at 105 C)	117,843,863
Iron	72,406,404
BOD, 5-day, 20 deg. C	32,097,558
Nitrogen	24,362,918
Chloride	20,777,260
Hardness, total (as CaCO3)	20,153,492

Plastics & Rubber Products (326)	
Total contaminant discharge (kg/y)	89,081,891
Number unique contaminants	134
Share by mass of top 10 contaminants	98.0%
Contaminant	Mass discharged (kg/y)
Solids, total suspended	20,626,371
Solids, total dissolved	19,375,828
Phosphorus	17,296,022
Sulfate	12,157,164
N,N-Dimethylformamide	6,451,751
Nitrogen	5,398,180
Nitrate Compounds	2,738,020
Chemical oxygen demand (COD)	1,993,817
Hardness, total (as CaCO3)	890,609
BOD, 5-day, 20 deg. C	406,797

Printing & Related Support Activities (323)	
Total contaminant discharge (kg/y)	1,518,068
Number unique contaminants	34
Share by mass of top 10 contaminants	99.9%
Contaminant	Mass discharged (kg/y)
Solids, total suspended	1,067,037
Chloride	211,188
Nitrate Compounds	136,528
Oil and grease	63,099
Certain Glycol Ethers	18,126
Ethylene Glycol	11,490
Diethanolamine	7,416
N-Methyl-2-Pyrrolidone	1,742
Iron	445
Toluene	285

Primary Metal (331)	
Total contaminant discharge (kg/y)	71,767,161
Number unique contaminants	142
Share by mass of top 10 contaminants	96.3%
Contaminant	Mass discharged (kg/y)
Solids, total dissolved	30,417,489
Solids, total suspended	10,433,580
Residue, tot fltrble (dried at 105 C)	7,712,430
Hardness, total (as CaCO3)	7,462,215
Chloride	5,307,203
Nitrate Compounds	4,100,754
Oil and grease	1,146,095
Nitrogen	1,050,819
Chemical oxygen demand (COD)	821,954
Sulfate	625,338

Textile Mills (313)	
Total contaminant discharge (kg/y)	19,448,133
Number unique contaminants	125
Share by mass of top 10 contaminants	95.6%
Contaminant	Mass discharged (kg/y)
Solids, total dissolved	9,275,580
Chemical oxygen demand (COD)	3,277,928
Solids, total suspended	2,052,399
BOD, 5-day, 20 deg. C	1,262,249
Sodium	1,091,113
Solids, total	571,763
Alkalinity, total (as CaCO3)	358,610
Nitrogen	308,712
Hardness, total (as CaCO3)	214,958
Residue, tot fltrble (dried at 105 C)	179,945

Textile Product Mills (314)	
Total contaminant discharge (kg/y)	1,490,236
Number unique contaminants	33
Share by mass of top 10 contaminants	98.9%
Contaminant	Mass discharged (kg/y)
Solids, total suspended	734,149
Chemical oxygen demand (COD)	445,946
Ammonia as N	182,049
BOD, 5-day, 20 deg. C	34,610
Biphenyl	24,563
Methanol	16,885
Phosphorus	9,481
Oil and grease	8,813
1,2,4-Trimethylbenzene	8,663
Oxygen	8,466

Wood Product (321)	
Total contaminant discharge (kg/y)	138,991,009
Number unique contaminants	90
Share by mass of top 10 contaminants	99.8%
Contaminant	Mass discharged (kg/y)
Solids, total suspended	87,065,043
Chemical oxygen demand (COD)	18,207,268
Oil and grease	14,717,739
BOD, 5-day, 20 deg. C	7,466,183
Chloride	6,605,423
Ammonia as N	2,363,708
Solids, total dissolved	2,001,635
Oxygen	135,115
Hardness, total (as CaCO3)	97,775
Nitrogen	90,184

Transportation Equipment (336)	
Total contaminant discharge (kg/y)	1,323,536,712
Number unique contaminants	157
Share by mass of top 10 contaminants	99.7%
Contaminant	Mass discharged (kg/y)
Solids, total	1,052,946,459
Hardness, total (as CaCO3)	147,913,924
Oil and grease	43,045,245
Magnesium	32,450,565
Solids, total suspended	19,960,150
Chemical oxygen demand (COD)	9,481,836
Solids, total dissolved	7,547,674
Alkalinity, total (as CaCO3)	2,737,589
Nitrate Compounds	2,304,940
Oxygen	919,923