Title

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Permalink

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Journal

Journal of Industrial Ecology, 25(5)

ISSN

1088-1980

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Publication Date

2021-10-01

DOI

10.1111/jiec.13121

Peer reviewed

DOI 10.1111/jiec.13121

Energy Technologies Area
Lawrence Berkeley National Laboratory

Characterizing Manufacturing Wastewater in the United States for the Purpose of Analyzing Energy Requirements for Reuse

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March 2021

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, of the U.S. Department of Energy under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Article Type: Research and Analysis

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Conflict of Interest Statement: The authors declare no conflict of interest.

Keywords: manufacturing, water reuse, wastewater, energy, water-energy nexus, industrial ecology

Abstract: This paper seeks to inform an improved understanding of the energy tradeoff associated with on-site manufacturing water reuse in the U.S. from a lifecycle perspective, in part by developing an analytical framework for understanding when this tradeoff for reuse is beneficial. We survey the literature to assess the current state of reuse and its motives and barriers in the U.S., before synthesizing information from publicly available EPA data on contaminants in U.S. manufacturing wastewaters and technologies for treating them. Using the available data, we derive a set of “ubiquitous contaminants” among the top ten in terms of mass discharged in more than half of U.S. manufacturing subsectors (NAICS 31–33) according to EPA permit data. We also present information on proven treatment trains and their energy requirements. We then compare water quality requirements for specific contaminants in reclaimed water to those characteristic of wastewater streams currently being discharged from manufacturing plants into surface waters to highlight sectors with reuse opportunities that could require little cost to realize, such as primary metals and, to a lesser extent, petroleum and coal products. We conclude by highlighting data limitations that need to be rectified before applying the framework more broadly and discussing how these data gaps could be filled. Better understanding the relationship between energy and water in the context of on-site manufacturing water reuse would allow manufacturers to improve resiliency by reducing regulatory, physical, and reputational risks while lessening their footprint on local watersheds.

INTRODUCTION

1. Motivation

Manufacturing represents a significant portion of the U.S. economy, making up 12% of gross domestic product 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% of U.S. water intake, around three quarters of which are self-supplied (Rao *et al.*, 2015). Conserving water is typically not a priority for manufacturers, likely because its costs are negligible, accounting for less than 1% of operating expenses according to some manufacturers (Rao, 2016). At the same time, water is a critical component in many manufacturing processes, with manufacturing water demand globally expected to increase by 400% between 2000 and 2050, more than any other sector (OECD, 2012). Moreover, in a changing world with increasing and variable constraints on water availability and quality, water scarcity stands to threaten manufacturing operations and global economies.

On-site manufacturing water reuse presents an opportunity to reduce intake water requirements and improve resiliency. However, given the interdependencies between water and energy (the energy-water nexus), on-site reuse requires energy to treat wastewater to a standard suitable for reuse. Outside of a number of case studies reviewed in this paper, there exists a paucity of published information on the energy-related implications of reuse. Increasing energy consumption carries its own problems of higher energy costs and greenhouse gas emissions, as well as working against corporate energy efficiency goals. A stronger understanding of the energy tradeoff associated with reuse would help inform manufacturers of the sustainability and cost impacts of reuse, as well as assist sustainability policymakers in making better decisions regarding policy priorities.

This paper proposes a comprehensive but simple framework for evaluating whether or not manufacturing water reuse is energy beneficial from the perspective of the entire water and wastewater system.[1] To the extent possible using publicly available data, we develop a comprehensive summary of contaminants in U.S. manufacturing wastewater by manufacturing activity (characterized using the North American Industrial Classification System [NAICS] codes 31–33) and the established treatment technologies for removing these contaminants. With a focus on the U.S., we analyze the data to better understand reuse potential, treatment requirements, and identify shortcomings of the available data that need to be addressed in order to apply the proposed analytical framework. We conclude by providing recommendations to the broader community regarding where data gaps need to be filled in order to better understand the energy-water tradeoff of U.S. manufacturing water reuse.

2. Background

2.1 Literature Review

Our search of recent literature related to industrial water use and reuse uncovered a sizeable share of studies centered on heavily polluting sectors such as tanneries, textile dyeing, oil and gas extraction, petrochemicals, and paper manufacturing (Ben Amar *et al.*, 2009, Benito-Alcazár *et al.*, 2010, Venzke *et al.*, 2017, Zhang *et al.*, 2017, Ghani *et al.*, 2018, Sousa *et al.*, 2018, Sundarapandiyan *et al.*, 2018). Many publications included details on various relevant treatment technologies, but focused on treatment to meet process discharge requirements instead of considerations relevant to on-site water reuse. Almost no surveyed publications included a full accounting of water savings, water and wastewater cost savings, and required energy for on-site

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

reuse; Yin *et al.* (2019) is the most comprehensive exception located, presenting data on water volumes, energy intensity, and electricity costs associated with reusing 75,000 cubic meters of water daily at a Chinese textile plant. 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[2]—and that within the manufacturing sector, treatment processes are largely driven by the need to meet regulations.

This section gives an overview of recent relevant literature to help frame subsequent analysis. It is organized as follows: the current state of reuse and barriers to greater adoption are reviewed, followed by a summary of the publicly available data on wastewater contaminants and reuse water quality requirements in the U.S., concluding with an enumeration of relevant treatment technologies and their energy requirements.

2.1.1 Current State of Reuse

Kuo and Smith (1998) distinguish industrial wastewater "treatment" from "regeneration" in the process industries. The former refers to when treated wastewater is discharged to the environment, while the latter is 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 paper, we discuss both recycling and reuse. Next, Kim *et al.* (2008) survey industrial water reuse practices globally. They determine the worldwide potential for industrial water reuse, assuming 10% of industrial water is recycled, as 110,000Mm^3/yr—three times the Hoover Dam's storage capacity. Domestically, the National Research Council (NRC) establishes that given better efficiency, higher energy and water prices, and a shift away from water-intensive

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[2] Refer to Figure S1-4 in the SI for a Venn diagram depicting typical constituents in municipal vs. manufacturing wastewater.

manufacturing (plus offshoring), per capita industrial water use within the U.S. has been declining since 1965. They find that in Florida and California, industrial reuse represents 13% and 7%, respectively, of all reuse, while global reuse hotspots are Australia and Singapore (NRC, 2012). In recent years, water reuse more generally has seen far more acceptance from utilities, regulators, and the general public alike (BIER, 2020); one example is illustrated by the U.S. Environmental Protection Agency (EPA)'s draft *National Water Reuse Action Plan* from September 2019, which states that 39 U.S. states have already adopted regulations or guidelines governing water reuse, with three more states doing so (EPA, 2019).

The WateReuse Research Foundation investigated motivations, difficulties, achievements, and opportunities for on-site industrial water reuse and recycling (focusing on North American Industry Classification System (NAICS) codes 21 [mining and oil and gas extraction], 22 [power], and 31–33 [manufacturing]) via a literature review, vendor outreach, survey, and workshops with industry participants (Oppenheimer *et al.*, 2016).[3] The authors find that governmental industrial water use data 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 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.

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[3] 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.

In its draft *National Water Reuse Action Plan*, EPA sets forth several proposed actions with direct relevance to this paper.[4] 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 developing informational and training materials for permit writers and inspectors relating to how National Pollutant Discharge Elimination System (NPDES) permits can facilitate reuse. Next, 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.

2.1.2 Motives for Reuse

There are commonalities supporting the idea that a main driver for implementing treatment processes is to meet mandatory regulations governing discharge. Kuo and Smith (1998) identify the main incentive to cut water use as reducing wastewater treatment costs, while Oppenheimer *et al.* (2016) emphasize discharge regulations and local/regional water supply restrictions as the largest motivations for industrial water reuse. They also assert that regional water limitations are typically managed via water conservation, while more costly reuse/recycling generally occurs to minimize 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/recycling projects are

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[4] 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.

typically only implemented when the cost differential between the treatment needed to meet discharge quality requirements and that needed for water recycling/reuse is small enough to produce a return on investment within two to three years (Oppenheimer *et al.* 2016).

In addition, Lazarova *et al*. (2001) underscore the potential of wastewater reuse in many sectors 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 that fosters environmental sustainability in the beverage sector, echoes this reasoning, arguing for an attitudinal shift by industry from looking at water linearly to integrating a circularity perspective with the objective of reducing plants' net water use and impact on local watersheds—while addressing production risks of scarce or unreliable water supplies. Also, manufacturers implementing reuse would likely benefit from favorable opinions by consumers and the broader public given its contribution to community water supply sustainability (BIER, 2020).

Water scarcity may also drive adoption of reuse. To this end, 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. Statistics Canada's biennial Industrial Water Survey presents valuable industrial water data. Because comparable data are not available for the U.S., Rao *et al.* estimate U.S. water intake by subsector by relating Canadian manufacturing water and employment data 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, primary metals, chemical, petroleum and coal products, and food. Combined, these five subsectors represent more than 90% 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% are primary metals, fabricated metal products, and transportation equipment, followed closely by petroleum and coal products and plastics and rubber products at 9% each. These estimates are somewhat uncertain, but without statistically representative surveys of manufacturing facilities' water use may represent the best information currently available on water shortage risks by manufacturing subsector and location.

2.1.3 Barriers to Reuse

Various challenges complicate the successful widespread implementation of water reuse, with Moore and Buzby (2017) classifying impediments into four types: resource, regulatory, motivational, and data and information gap barriers. A 2012 NRC report sets out a research agenda designed to help overcome technical, financial, and institutional hurdles to make reclaimed[5] municipal wastewater a reliable source of alternative water supply for industry (NRC, 2012). More broadly, the NRC cautions that financial costs of reuse vary greatly, given dependence on site-specific aspects, and that one barrier 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 for human and environmental health even if

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[5] In this paper, we define "reclaimed" water/wastewater as wastewater that has been discharged from buildings and processes and treated for reuse in various applications.

these concentrations do not directly affect industrial water usage. Regarding specific contaminants, Environment Protection Authority Victoria (2017)'s guidelines for Australian manufacturers cover commonly encountered environmental and health hazards including 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 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, industry's proprietary character, technological feasibility concerns, scarce training and information, difficulties of managing different waste streams and treatment byproducts, and an economic environment that favors 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 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 water reuse benefits (Lazarova *et al.*, 2001, Oppenheimer *et al.*, 2016, Moore and Buzby, 2017, BIER, 2020).

2.1.4 Energy Requirements for Treatment

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 like temperature, salinity, the constituents in the water, water recovery rate, and the amount of constituents removed. Similarly, Ahdab *et al.* (2018) estimate minimum energy requirements for desalination of brackish groundwater desalination within the United States. They show that the least work of separation 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.

Next, we broaden the focus to consider what is known about wastewater contaminants and water quality requirements for reuse.

2.2 Review and Limitations of Publicly Available Data on Wastewater Contaminants

Our literature review uncovered a lack of nationally representative data on manufacturing wastewater characteristics, especially directly after water-using processes that might benefit from reusing water after some 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 the contaminants occurring in various manufacturing wastewater streams. In the absence of fit-for-purpose data, we turned to evaluating publicly available EPA wastewater guidelines, permits, and data as potentially useful information. This section summarizes EPA's wastewater discharge permits. Our goal was to explore EPA data to characterize manufacturing wastewaters for the purposes of analyzing energy requirements for treatment and assess whether they are representative of U.S. manufacturing facilities. In turn, this would facilitate identifying contaminants, processes, and sectors that are good targets for economically beneficial on-site reuse. EPA's Industrial Effluent Guidelines were also evaluated for use in this analysis as well, but ultimately could not be leveraged; for more detail, see the SI.

EPA maintains two relevant national databases of industrial wastewater discharges under its NPDES permit program, which began in 1972 under the Clean Water Act. NPDES permits allow facilities to discharge stipulated amounts of contaminants into receiving waters, 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, 2020a,c).

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, for 'approved State programs,' the Regional Administrator in conjunction with the State Director" (40 CFR § 122.2). Based on our review, one national definition of a major industrial facility does not exist; for more detail, see the SI.

TRI reporting is limited to industrial facilities in the manufacturing, electric power generation, and mining sectors that use a TRI-listed chemical in quantities exceeding 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 potentially relevant data are those collected under the National Pretreatment Program (NPP), which governs commercial and industrial facilities discharging to publicly owned treatment works (POTWs), or municipal wastewater treatment plants. In the early 1980s, EPA found 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. At 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 regions), instead of 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 paper. The three datasets introduced here are further summarized in Table 1.

Table 1: Summary of U.S. Environmental Protection Agency (EPA) data sources for manufacturing wastewater

Data source	**Who reports?**	**What is reported?**	**What is not reported?**	**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	Publicly available

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

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	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)	Not currently available in a consistent electronic format

2.3 Water Quality Requirements for Reuse

A good understanding of process water quality requirements is necessary to determine effluent treatment requirements for reuse and their associated energy consumption. Our literature review uncovered little comprehensive sector-specific data on water quality requirements for process water reuse. Table 2 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. 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. As will be shown in Section 4, 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. Standing outside of industry-specific requirements are those for cooling and boiler feed water, also shown in Table 2.

Table 2: Summary of water quality requirements for reclaimed manufacturing water (values in mg/L except color [color units] and pH) from DOI (1981) & 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 (2012), which uses 2005 data from the American Boiler Manufacturers Association

2.4 Review of Technology Options

In 2018, EPA published the Industrial Water Treatment Technology Database (IWTT) (EPA, 2020b). IWTT provides technology performance data on pilot- or full-scale systems that treat industrial wastewater, stemming from sources meeting data quality requirements for accuracy, reliability, representativeness, and reasonableness.[7] As of July 2020, it contained 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 present for each reference. Information on energy requirements is not included. The IWTT identifies 40 different individual treatment technologies used to treat manufacturing wastewater (NAICS 31–33). Those listed most frequently, in descending order, 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). For the full list, refer to Table S1-2 in the SI.

Real-world applications of these technologies are found in individual case studies and papers focusing on single technologies. Taking a wider view, Kim *et al.* (2008) present reuse applications for automobile manufacturing, meat processing, breweries and beverages, paper mills, and metal plating industries, while including short case studies spanning wafer fabrication (Singapore), aluminum can manufacturing (U.S.), precision glass (South Korea), a piggery (Australia), and the steel industry (South Korea). In addition, Moore and Buzby (2017) feature case studies in aerospace, automotive, flat glass, food and beverage, paint and coatings, and

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

pharmaceuticals and chemicals manufacturing, although these summaries generally do not address energy costs of water reuse. Finally, the BIER recently created a decision guide for organizations considering implementing reuse projects that covers unique considerations for on-site industrial reuse (excluding energy requirements), suggesting that water reuse technology development is rapidly advancing, with viable options that did not exist even a few years ago (BIER, 2020).

METHODS

Here we develop an inequality that can be used to estimate when manufacturing wastewater reuse is energy beneficial compared to freshwater utilization. To evaluate this inequality to the extent possible, we identify datasets (EPA DMR and TRI, summarized in Table 1) that help characterize typical contaminants in manufacturing wastewater discharge, which affect the energy required for reuse.

3.1 Energy Balance

To study the energy tradeoffs of on-site water reuse from a lifecycle perspective, we propose a theoretical analytical framework comparing the energy required for single use of water to that for on-site reuse. Our aim was to develop a simple quantitative metric that answers the following: For a given manufacturing facility/process, when is it energy beneficial to implement on-site water reuse to replace single use of water (*i.e.*, energy required for on-site reuse is less than the embedded energy of new water)? Such a metric can help manufacturers and the research communities supporting them identify the energy implications of reuse from a lifecycle perspective. Note that this framework ignores energy required to use the water within the facility (*e.g.*, circulating pumps) because these energy requirements will be the same whether the water is used once or reused.

The energy requirement for a single use of water per unit volume ($E_{tot,single\ use}$) is a function of the energy required to bring clean water to a manufacturing facility and safely discharge it after use. It can be calculated using Equation 1:

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

Equation 1

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

Depending on the water sources utilized and the location of wastewater treatment, the energy requirements expressed by the terms in Equation 1 will be incurred at the facility ('direct'), outside of it ('indirect'), or a mixture of both. Direct energy requirements will be the responsibility of the facility, whereas indirect requirements will not (aside from costs passed to the facility by the outside entity). For facilities only utilizing municipal water sources, the energy consumption for $E_{w,ex}$, $E_{w,tr}$, and $E_{w,dist}$, will be indirect. For facilities only utilizing self-supplied sources, these same terms will be direct. In either case, $E_{wwt,comp}$ will be direct. Similarly, for facilities disposing their wastewater entirely through the municipal system, $E_{wwt,con}$, $E_{wwt,tr}$, and $E_{wwt,dis}$ are indirect, whereas for facilities entirely treating their wastewater onsite and disposing to a local water body, these terms will be direct. Other embedded energy, such as energy required to manufacture treatment chemicals, is indirect and not reflected in Equation 1.

The energy requirement for reuse ($E_{tot,reuse}$) is shown in Equation 2.

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

Equation 2

Where:

x = number of times water is reused at facility

$E_{reuse,i}$ = energy requirement to treat onsite after i^{th} reuse, either for reuse again or discharge per permit requirements; function of quantity and types of contaminants needing to be removed, volume flow rate, embedded energy in chemicals for treatment

The same characterization of a facility's direct and indirect responsibility for each term in Equation 1 applies to the terms in Equation 2, and $E_{reuse,i}$ is direct. Equation 1 and Equation 2 are identical except for the inclusion of energy requirements for reuse in Equation 2. Reuse becomes energy beneficial when the treatment requirements for the i^{th} reuse of water is less than $E_{tot,single\ use}$. More generally, reuse is energy beneficial when:

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

Equation 3

Our initial research approach centered on discovering manufacturing processes for which the following necessary parameters can be identified:

- ◊ *Input to on-site treatment:* contaminant mix, water flow rate, and concentration after reuse (contaminant concentration will increase with every reuse cycle)
- ◊ *On-site treatment process:* energy intensity of on-site treatment process, number of times water can be reused, chemical requirements
- ◊ *Output from on-site treatment:* water quality (contaminant concentration) requirements for reuse, (fit-for-use), water flow rate requirement for reuse

Except for $E_{reuse,i}$ and $E_{wwt,comp}$, the terms in Equation 2 can be estimated using publicly available data (Elliott et al., 2003; EPRI, 2002; EPRI, 2013; Navigant, 2006; NYSERDA, 2008). However, the understanding of $E_{reuse,i}$ is currently poor; it requires more insight into manufacturing wastewater contaminants, their concentrations and potential interactions, and the treatment trains needed for this effluent to be of sufficient quality for reuse.

The next section presents a mapping of wastewater flows from a manufacturing facility and relates them to the publicly available data on contaminants introduced in the Background section to underpin our exploration in the Results section of to what extent, given data limitations, these data can help inform $E_{reuse,i.}$

3.2 Water Flows

Figure 1 tracks the possible fates of wastewater discharges from a manufacturing facility to municipal wastewater and onsite treatment, the latter further discharging effluent to municipal 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. For the purposes of the proposed energy framework, P_1,V_1 are the input into a water reuse process; thus, we are interested in assessing the characteristics of these flows. Because few data exist for P_1,,V_1, the equation at the bottom of the figure displays an alternative way to discern P_1 via examining national-level data on other flows. The figure and equation are color-coded; based on the EPA data sources reviewed in this paper, green indicates data are available, orange signifies partial availability, and red specifies data are unavailable and also unnecessary. Based on the principles of a mass balance, 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).

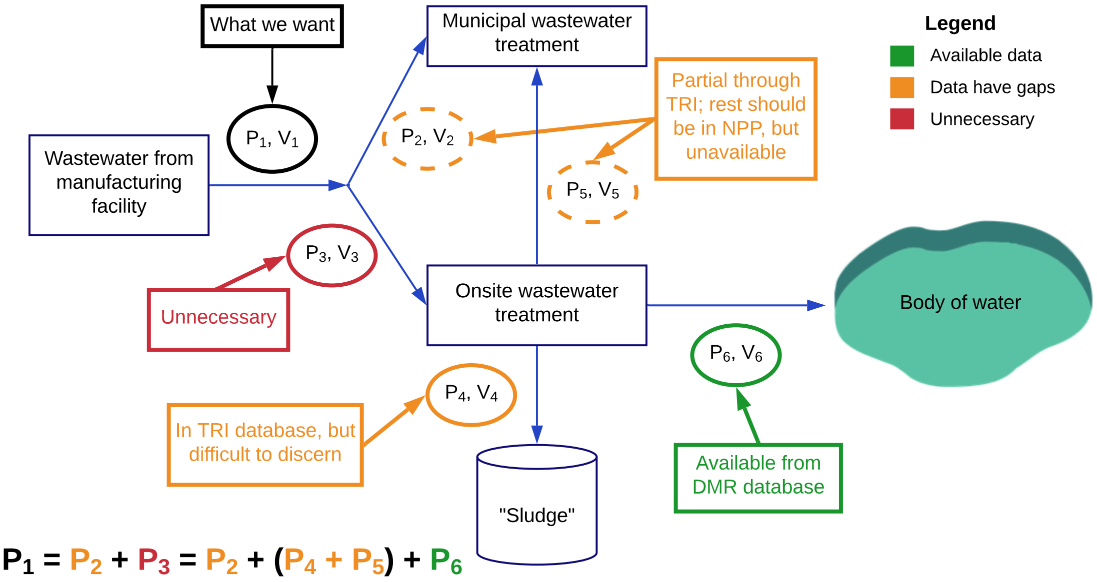

Figure 1: Pollutant and discharge volume balance with annotations to indicate data sources

As discussed earlier, because NPP data were effectively not publicly available, we were unable to use this dataset (partially P_2 and P_5). Instead, we employed DMR (P_6) and TRI (partially P_2

and P_5) data in an effort to characterize the typical contaminants in wastewater discharges for each manufacturing subsector.

3.2.1 Discharge Monitoring Report (DMR) Data

As detailed in the SI, in January 2018 we queried the DMR database, yielding a database of 10,020 unique manufacturing facilities and 537 unique pollutants, where each individual row, or record, contains data on the reported discharge of one specific pollutant at one particular facility in 2016, the last year for which complete data were available. We then created a pivot table of pollutants with non-zero annual load summed across U.S. facilities in each three-digit NAICS manufacturing sector. In the context of Figure 1, DMR data can provide insight into P_6 and V_6.

To understand how representative DMR data might be for the manufacturing sectors covered in this paper, 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% of the total establishments in MECS were present in the 2016 DMR data. This share varied widely by sector, as shown by Figure S1-3 in the SI. On the high end, 18.9% of MECS establishments in the petroleum & coal products sector and 10.1% of establishments in the chemical sector were present in 2016 DMR data, with more than 5% of establishments in the textile mills, paper, nonmetallic minerals, and primary metals sectors reflected in the DMR dataset. On the low end, with 0.1% of MECS establishments having 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.

3.2.2. Toxics Release Inventory (TRI) Data

In February 2018 we queried the TRI Explorer’s Waste Transfer Chemical Report for 2016 discharges to POTWs from each of the 21 individual manufacturing subsectors within NAICS 31-33, as detailed in the SI. We generated a pivot table similar to the one for DMR data, with pollutants with non-zero annual load transferred to POTWs summed across U.S. facilities in each three-digit NAICS manufacturing sector. In the context of Figure 1, TRI data give insight into P_4 and V_4 and partial insight into P_2, V_2, P_5, and V_5. Pollutants that are removed from wastewater effluent and stored on site could not be distinguished from those that originated elsewhere and were also stored on site. As a result, pollutants from wastewater effluent that are stored on site were excluded from this analysis.

RESULTS

4. Summary of Wastewater Contaminants

For each three-digit NAICS manufacturing sector using the DMR and TRI datasets, we produced a pollutant list in decreasing mass order, as well as the mass quantity of each pollutant discharged or transferred in kg/yr. However, we found divergent naming of contaminants within and between DMR and TRI datasets. No universal definition for many contaminants exists because the regulatory definition for contaminants is extremely broad, and different permitting authorities (generally states) differ in their more specific requirements. To overcome this limitation and examine which pollutants are discharged to surface waters and to POTWs, we took a conservative approach by summing these data for each manufacturing sector only where the pollutant name exactly matched between these two databases; see the SI for details. To determine whether certain contaminants are commonly discharged in manufacturing wastewater, we established which appear in the top ten, in terms of mass released, of each three-digit NAICS manufacturing sector, across DMR and TRI data. Those appearing among the top ten in more than half of these 21 sectors can be considered particularly abundant, or ubiquitous. With this analytical framing, eight ubiquitous contaminants emerge, depicted in Table 3. Others in this table (in italics) appear among the top ten in more than one of these 21 sectors. Results suggest that while manufacturing wastewaters contain hundreds of unique known and measured contaminants as seen in DMR and TRI data, only a small subset are present in large quantities in a majority of sectors.

Table 3: Summary of top contaminants across manufacturing subsectors, from 2016 Discharge Monitoring Report (DMR) and Toxics Release Inventory (TRI) data; ubiquitous contaminants (appearing among the top ten by mass in more than half of 21 manufacturing subsectors) appear 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 contaminants in Table 3 can be understood as the most common contaminants present in manufacturing wastewater as seen from DMR and TRI data. However, we note several important shortcomings. No nationally representative data are available characterizing contaminants in effluent flowing directly from manufacturing processes prior to treatment, which would be more appropriate to analyze for on-site reuse applications. Figure 1 shows that DMR and TRI data represent only portions of possible effluent flows, and these data are at the point of discharge into surface water bodies (DMR) or only concern toxic contaminants (TRI). Meanwhile, many times more manufacturing establishments as defined by MECS exist than report DMR data.

With manufacturing wastewater contaminants enumerated to the extent afforded by the publicly available data, we could better determine how applicable energy intensities for municipal wastewater treatment are to manufacturing. Our literature review established that most wastewater research and technology development has focused on municipal wastewater. If the manufacturing and municipal wastewater sectors exhibit similarities in wastewater characteristics, then finding solutions to Equation 3 will be made easier by borrowing learnings from the municipal wastewater sector. Most municipal wastewater has similar properties nationwide in terms of composition. However, manufacturing wastewater is characterized by a wide diversity of contaminants depending on sector and process, and some streams are highly concentrated. This heterogeneity has significant implications for the feasibility and energy requirements of on-site reuse. To illuminate the contrast between municipal and manufacturing wastewater and highlight that reuse in the latter context deserves its own consideration, we compared typical contaminants in municipal wastewater (EPA, 2004 and Pescod, 1992) to the top 30 contaminants by mass across all manufacturing subsectors (2016 EPA DMR and TRI data), finding that only eight of 30 contaminants commonly present in manufacturing wastewater are also present in municipal wastewater.[8] See Figure S1-4 in the SI for a Venn diagram of this comparison. While the DMR and TRI data do not facilitate a comprehensive enumeration of manufacturing wastewater contaminants, they do provide enough insight to suggest that assuming broad similarities in municipal and manufacturing wastewater treatment technologies and subsequent energy requirements is not justified.

5. Summary of Technology Options

$E_{tot,reuse}$ in Equation 3 will be a function of the treatment technology utilized. Here we categorize typical technologies by mechanism, compare six applicable technologies, and summarize reported energy intensity ranges where possible. The information presented here is as an example of the types of information manufacturers and policymakers will need in order to evaluate whether reuse is energy beneficial.

5.1 Treatment Technologies

Table 4 displays high-level summaries of some common treatment technologies that appear in more than five separate manufacturing applications in the IWTT. This table is not

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[8] These contaminants are BOD, pathogens, nitrogen, phosphorus, alkalinity (as $CaCO_3$), oil & grease, dissolved solids, and suspended solids.

meant to be exhaustive, but 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. In addition to describing the technology, providing examples of applications, and highlighting advantages and disadvantages of each, the table also includes a characterization of the primary mechanism used for treatment. 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 the technologies in the IWTT, we drew upon our review of the literature to classify common technologies by primary mechanism: physical, chemical, and biological. Each mechanism is then divided into several categories (*e.g.*, within physical are “thermal”, “separation”, and “other”). For an illustration meant to reasonably represent the universe of treatment technologies in the IWTT that can be applied at scale, refer to Figure S1-5 in the SI.

Table 4: Comparison of several common manufacturing wastewater treatment technologies

Technology	**Coagulation/ flocculation**	**Electrocoagulation**	**Reverse osmosis**	**Micro/ultrafiltration**	**Anaerobic membrane bioreactor (MBR)**
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, which then are separated via clarifier, sand filtration, or membrane 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 and 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
Primary treatment mechanism[*]	Physical - separation	Chemical - other	Physical - separation	Physical - separation	Biological - anaerobic
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
Advantages	• Low direct energy intensity (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 direct energy requirements (<0.2 kWh/m^3) • Widely used/known	• Lower energy consumption (no aeration requirement) • Potential to be energy-positive through methane production • Smaller footprint • High-quality effluent with less sludge production, effective solids separation
Dis-advantages	• Not very effective in removing heavy metals,	• Consistent maintenance required given electrode passivation	• Extremely energy intensive process (~1.5 kWh/m^3 for ~ 3% TDS,	• Cannot filter contaminant below a certain size range	• Membrane fouling • Slow-growing; slow start-up time

	refractory pollutants & emerging contaminants • Creates a large amount of (toxic) sludge	• Requires highly conductive water • Modeling & scale-up issues	not including pre- & post-processing) • Membrane replacement required • Membrane fouling inhibits performance • Cannot operate at variable loads • In-situ membrane diagnostics are difficult	• Fouling inhibits performance • Sensitive to oxidative chemicals	• Very sensitive to temperature changes • Low-quality effluent with low-strength wastewater
References	Ranade & Bhandari (2014), Teh *et al.* (2016), Verma *et al.* (2012)	BakerCorp (n.d.-a), BakerCorp (n.d.-b), Hakizimana *et al.* (2017), Kabdaşli *et al.* (2012), Sahu *et al.* (2014)	Benito & Ruíz (2002), Chan (2011), Dhagumudi & Yan (2012), Huang *et al.* (2011), Rao *et al.* (2016), Valladares *et al.* (2018)	Benito & Ruíz (2002), Connery *et al.* (2013), Huang *et al.* (2011), Pugh *et al.* (2014), Rao *et al.* (2016)	Evoqua Water Technologies (2019), Jegatheesan *et al.* (2016), Martin *et al.* (2011), Martinez-Sosa *et al.* (2012)

[*] See SI for details on characterization

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), annamox (Liang *et al.*, 2016 Paques Technology B.V., n.d.), and nanotechnologies (Jassby *et al.*, 2018).

5.2 Energy Requirements

Table 5 summarizes findings from the literature on the energy intensity of various manufacturing wastewater treatment technologies and treatment trains. These values are critical to calculating $E_{tot,reuse}$ and conducting a comprehensive assessment of 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 5 draws attention to significant gaps in the reported data. As stated in section 2.1.4 based on the literature for determining energy requirements for desalination technologies, reported energy intensity values should be accompanied by the specific system configuration and an indicator of the extent to which contaminants are removed. Additionally, they should include embodied energy, which can be significant depending on technology (*e.g.*, treatment chemicals).

Table 5: 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	kWh_e/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)

Given the lack of contextual information (*i.e.*, recovery rates, contaminants removed) on reported energy intensities, the values reported in the literature cannot be confidently applied to determine $E_{tot,reuse}$ in Equation 3 without making broad assumptions with unknown associated errors.

6. Current Wastewater Concentrations Compared to Water Quality Requirements

While publicly available data do not allow for comprehensively applying our proposed framework due to insufficient information on wastewater contaminants and treatment technology energy intensities, we can compare data on discharges to surface waters from DMR permits to each contaminant- and sector-specific water quality requirement presented in Table 2. If this effluent already meets inlet water quality requirements, manufacturers could theoretically reuse it on-site with little expense beyond new piping. Therefore, the inequality in Equation 3 would be less than one, where reuse is energy beneficial. Building upon this assumption to identify sectors/processes with a high likelihood of energy beneficial reuse opportunity would thus be conservative, serving as a floor of this opportunity.

We mapped the water quality requirements in Table 2 to DMR data, and display the statistical distribution for each contaminant by manufacturing subsector as boxplots in Figure 2. 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; where Table 2 contains a range for water quality rather than a single value, we use only the value for the higher quality requirement (*i.e.*, at the low point of the range) to be more conservative regarding identifying reuse opportunities. The SI presents the number of observations and the share of records where the calculated index value is less than or equal to one, or in other words those that meet process water quality requirements for a specific contaminant. 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.

Figure 2 shows that the primary metals sector is generally already treating contaminants identified in Table 2 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%. Excepting total suspended solids, more than 60% 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% 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.

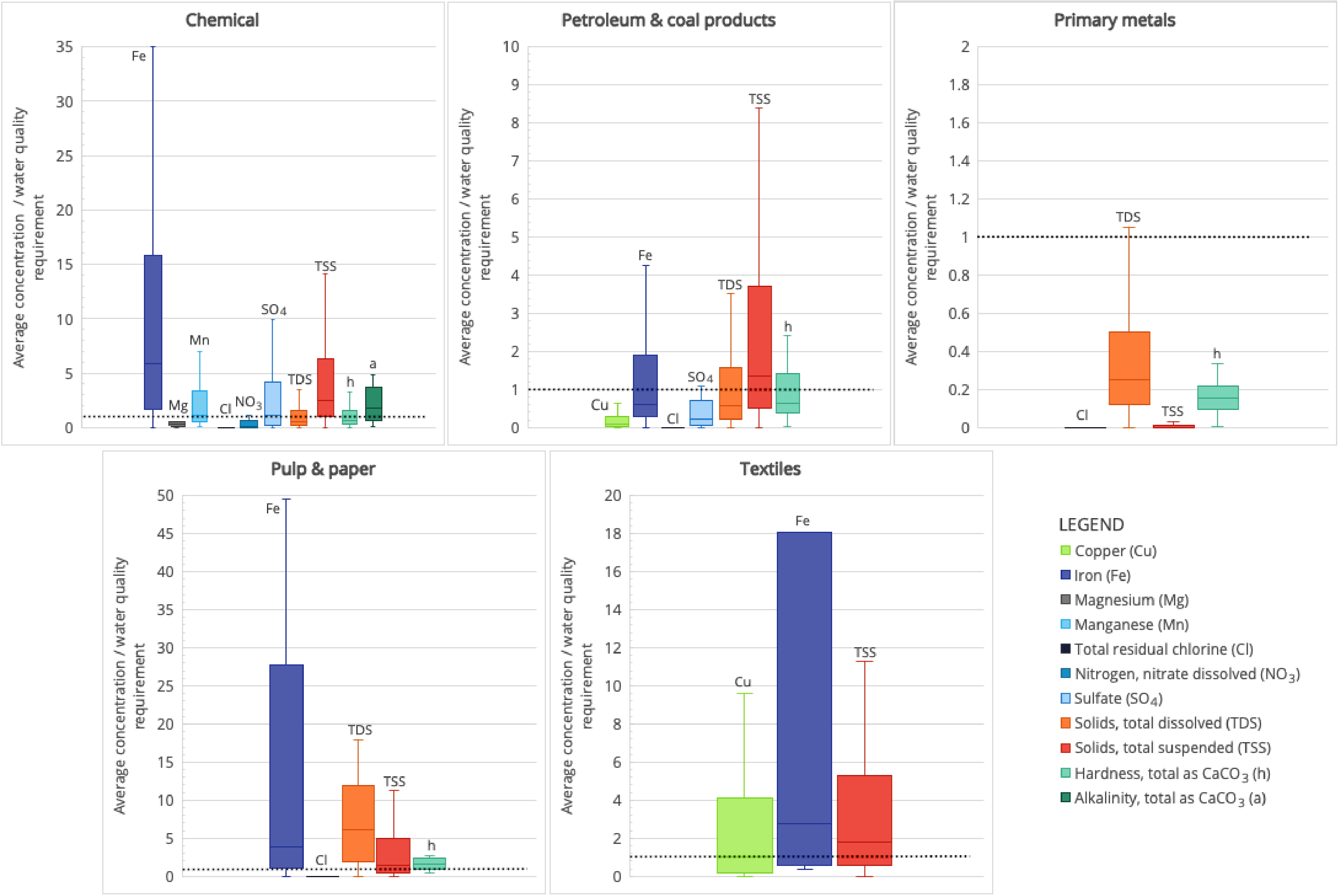

Figure 2: Distribution of average concentration of selected contaminants in five manufacturing subsectors (2016 Environmental Protection Agency Discharge Monitoring Report data), indexed to water quality requirements (Table 2). The 25th and 75th percentiles are the bottom and top of each box, respectively, 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, with full data available in SI.

DISCUSSION

The aim of this research was to support a more comprehensive analysis of the energy implications of wastewater treatment technologies and identify when on-site manufacturing water reuse is energy beneficial from a lifecycle perspective. This paper synthesizes relevant information on manufacturing wastewater in the U.S. and describes it by sector using publicly available EPA permit data. Some of the findings presented here may be useful, but the underlying data introduce significant limitations. While this constrains their utility for researchers and manufacturers, perhaps the most valuable outcome of this paper is emphasizing the paucity of data and the future work needed to fill critical gaps.

The main limitations to better understanding manufacturing wastewater characteristics can be summarized as follows. First, DMR data exclude releases from “minor” dischargers; across manufacturing sectors, only 2.5% of 2014 MECS establishments were present in 2016 DMR data. Also, 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. Meanwhile, NPP data characterizing pretreated effluent sent to POTWs are not yet available as a nationwide electronic database. When considering EPA data, names and/or groupings of contaminants are not standardized nationwide, nor across DMR and TRI datasets. Moreover, emerging contaminants are not included in NPDES permits. In sum, robust and representative data on characteristics of manufacturing wastewater largely do not exist.

In addition, blind spots exist for other components of a comprehensive tradeoff analysis of manufacturing water reuse, as Table 6 shows. Because wastewater treatment research and technology development has largely been focused on municipal wastewater, with small overlap with manufacturing wastewater constituents, we cannot currently develop analytical models for these technologies due to the absence of contaminant and energy data. Further, very few recent case studies include enough information even for individual tradeoff analyses, in part because treatment processes are largely driven by the need to meet regulations.

Table 6: 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 manufacturing uses	Parameters for pulp & paper, chemical, petrochemical, and textile sectors, plus recirculating cooling systems (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 as climate change stresses water supplies. Arising from the enquiry that underpins this paper, we identify the following research needs in this arena.

First, data on manufacturing wastewater contaminants presented earlier are by necessity from EPA's NPDES permits. These data are reported to reflect effluent makeup at the point of discharge into surface waters or POTWs. 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 them. While some case studies report on these opportunities, often identified through water pinch analysis (Agana *et al.*, 2013, Colic *et al.*, 2013, Altech Environmental Consulting and OCETA, n.d.), research is needed to systematically evaluate 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.

Next, developing physics and chemistry-based models to estimate the energy requirements of treating various industrial contaminants would foster creating 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 so it could serve as a more comprehensive source for demonstrated applications. Creating standardization around EPA contaminant definitions would also enable more robust analysis of permit data.

Our DMR data analysis also shows that some facilities may already be treating their wastewater to levels suitable for reuse, as seen in Figure 2. 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 water reuse benefits and alleviating perceived risks would help realize some cost-effective industrial water reuse potential. 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 presented here would be beneficial. This could occur via several mechanisms, including interviewing, surveying, or convening focus groups, connecting with municipal wastewater treatment plants servicing small manufacturers to collect data on waste streams, and creating a multi-sectoral collection of case studies for facilities already reusing manufacturing wastewater. One potential outcome could involve integrating wastewater analysis into existing water auditing tools for manufacturing plants, while another might be developing a return on investment (ROI) calculator for water reuse technologies to better capture the true cost of water.

Ultimately, while the lack of representative, robust data on wastewater streams within and from manufacturing plants in the U.S. precludes good understanding of reuse opportunities and their energy implications, this research serves to: 1) propose a framework for determining when reuse is energy beneficial from a lifecycle perspective, and 2) emphasize critical data gaps needed to apply the framework. Working to fill these in with an eye toward elucidating the dependencies between energy and water in manufacturing will allow manufacturers to implement on-site reuse that decreases regulatory, physical, and reputational risks while reducing watershed impacts and enhancing resiliency.

ACKNOWLEDGEMENTS

The authors would like to thank the following individuals for their valuable insights:

- ◊ Joe Cresko, Advanced Manufacturing Office, U.S. Department of Energy
- ◊ Sujit Das, Oak Ridge National Laboratory
- ◊ Susana Garcia González, Ph.D., Oak Ridge National Laboratory
- ◊ James McCall, National Renewable Energy Laboratory
- ◊ Sarang Supekar, Ph.D., Argonne National Laboratory
- ◊ Christian White, University of California, Berkeley

This manuscript has been authored by an author at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy. The U.S. Government retains, and the publisher, by accepting the article for publication,

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FUNDING INFORMATION

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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SUPPORTING INFORMATION

The supporting information below provides additional detail and context largely for EPA information. It summarizes EPA Effluent Guidelines and their limitations; investigates the EPA definition of a major facility; reviews information on treatment technology applications for manufacturing wastewater within EPA's Industrial Wastewater Treatment Technology database; explains data queries for and relevant characteristics of EPA Discharge Monitoring Report (DMR) and Toxics Release Inventory (TRI) data; explores the divergent naming of compounds between DMR and TRI; contains a Venn diagram of common constituents in municipal and manufacturing wastewaters; classifies common manufacturing treatment technologies by primary mechanism; and further contextualizes water quality requirements compared to concentrations reported in EPA DMR data. The supporting information (.xlsx file) at the *Journal of Industrial Ecology* website provides the numerical data underlying Figure 2 in the manuscript and Figures S1-1, S1-2, and S1-3 in the supporting information document.

EPA 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 set to attain the largest pollutant reductions economically achievable for each sector (EPA, 2018). EPA develops these standards without accounting for potential impacts of discharges on receiving water bodies—instead, these impacts are addressed through water quality standards and water quality-based effluent limitations in individual facility permits. Effluent Guidelines can be seen as setting minimum technology-based standards for a sector, 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 sector 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[9]; associated Technical Development Documents run from the hundreds to thousands of pages, and are not formatted consistently across time.

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[9] 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).

We examined published Effluent Guidelines hoping to learn more about typical contaminant concentrations by manufacturing sector and understand which are historically difficult to treat. The SI displays tabular results by effluent guideline category, most recent revision year, NAICS subsector, facility types covered, wastewater streams, and significant regulated pollutants. This review demonstrates that the most recent revision year for any sector was 2005 (Iron and Steel Manufacturing), and that Effluent Guidelines for 34 of 43 categories, or 79 percent, were completed more than 30 years ago. It is highly improbable that none of these categories' manufacturing processes have significantly changed in the past three decades, especially in sectors with rapid technological evolution. Effluent Guidelines drive inclusion in EPA discharge permits; because the former are generally outdated, it is very unlikely that EPA data on which contaminants exist in manufacturing wastewater are comprehensive. However, our review did not locate any additional sources necessary for a good understanding of wastewater contaminants.

Table S1-7 displays Effluent Guidelines that fall within the manufacturing sector (NAICS codes 31–33), along with the year of last revision and the NAICS subsector we assigned to each category, using the NAICS Association's NAICS Lookup tool (NAICS 2018). 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".

Table S1-7: Summary of EPA Effluent Guidelines for manufacturing sectors listed in reverse chronological order of latest revision

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)
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

Category	Year last revised	NAICS subsector	Facilities covered	Wastewater streams	Regulated pollutants
					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
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;	Smelter furnace & filtration residues; rinsing of materials; spent solutions; equipment cooling, air pollution controls (wet scrubbers)	*Not on webpage*

Category	Year last revised	NAICS subsector	Facilities covered	Wastewater streams	Regulated pollutants
			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		
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*
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

Category	**Year last revised**	**NAICS subsector**	**Facilities covered**	**Wastewater streams**	**Regulated pollutants**
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 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 water; nickel salts solution; washing out ball mills; cooling ball mills; entrapping waste slip from overspray	*Toxic:* antimony, arsenic, cadmium, chromium, 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

Category	**Year last revised**	**NAICS subsector**	**Facilities covered**	**Wastewater streams**	**Regulated pollutants**
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)
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	COD, BOD_5, TSS, pH, oil & grease

Category	**Year last revised**	**NAICS subsector**	**Facilities covered**	**Wastewater streams**	**Regulated pollutants**
				exhaust scrubbers, caustic 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*
Fertilizer Manufacturing	1975	325	Phosphate; ammonia; urea, ammonium nitrate; nitric acid; ammonium sulfate production; mixed & blend fertilizer production	Process condensate; treatment plant effluent; cooling tower blowdown; boiler blowdown; gypsum pond water; crystal	Ammonia, BOD_5, fluoride, nitrate, organic nitrogen, pH, total phosphorus, TSS

Category	Year last revised	NAICS subsector	Facilities covered	Wastewater streams	Regulated pollutants
				wash water (formulated fertilizer plants); compressor blowdown (ammonia plants); spills and leaks; surface runoff from precipitation	
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; condense milk; dry milk; condensed whey; dry whey	Cleaning out of product remaining in tank trucks, cans, piping, tanks, & other equipment; spillage produced by leaks, overflow, freezing-on, boiling-over, equipment malfunction, or operator error; processing losses, including	BOD_5, TSS, pH

Category	**Year last revised**	**NAICS subsector**	**Facilities covered**	**Wastewater streams**	**Regulated pollutants**
				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*

EPA Definition of a "Major" Facility

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). Based on our review, one national definition of a major industrial facility does not exist. 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).

EPA Industrial Water Treatment Technology Database

In 2018, EPA published the Industrial Water Treatment Technology Database (IWTT) (EPA 2020b). IWTT provides technology performance data on pilot- or full-scale systems that treat industrial wastewater, stemming from sources meeting data quality requirements for accuracy, reliability, representativeness, and reasonableness.[10] As of July 2020, it contained 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 present for each reference. Information on energy requirements is not included. The IWTT identifies 40 different individual treatment technologies used to treat manufacturing wastewater (NAICS 31–33), shown in Table S1-8 along with the number of instances each technology appears.

Table S1-8: Treatment technologies and their number of occurrences in manufacturing applications (NAICS sectors 31–33) in U.S. Environmental Protection Agency (EPA) Industrial Water Treatment Technology (IWTT) database

Treatment technology	***n***	**Treatment technology**	***n***
Flow equalization	27	Centrifugal separators	2
Micro- and ultra-membrane filtration	20	Dissolved air flotation	2
Chemical precipitation	13	Granular-media filtration	2
Clarification	13	Liquid extraction	2
Bag and cartridge filtration	11	Adsorptive media	1
Membrane bioreactor	11	Advanced oxidation processes, not classified elsewhere	1
Mechanical pre-treatment	9	Anaerobic suspended growth	1
Aerobic biological treatment	7	Ballasted clarification	1

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

Oil/water separation	7	Biofilm airlift suspension reactor	1
Electrocoagulation	6	Biological nutrient removal	1
Reverse osmosis	6	Chemical oxidation	1
UV	5	Cloth filtration	1
Aerobic fixed film biological treatment	4	Constructed wetlands	1
Anaerobic biological treatment	4	Degasification	1
Biological activated carbon filters	4	Evaporation	1
Ion exchange	4	Granular activated carbon adsorption	1
Aeration	3	Moving bed bioreactor	1
Aerobic suspended growth	3	Ozonation	1
Nanofiltration	3	Powdered activated carbon	1
Anaerobic fixed film biological treatment	2	Unspecified biological treatment	1

Discharge Monitoring Report (DMR) Data

On January 23, 2018, we queried the DMR database at https://echo.epa.gov/trends/loading-tool/get-data/custom-search/[11] (EPA 2020a). This data query yielded a database with 133,039 rows and 60 columns, with 10,020 unique industrial facilities and 537 unique pollutants. 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 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 2012. 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.[12] 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

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[11] 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.

[12] 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 2012).

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 S1-3, 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 pollutant loadings are reported to be below their permitted maxima. However, a small share (6.8%) of records show a pollutant load exceeding permitted maxima, with a mean value of pollutant load divided by maximum allowable load of 6.4, pulled upward by one outlier maximum value of 139,535.

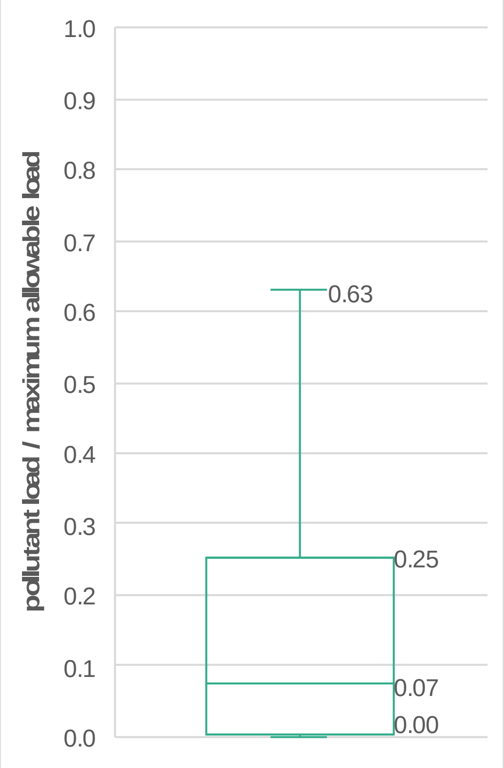

Figure S1-3: Distribution of pollutant load to maximum allowable load ratio in 2016 EPA DMR data

Similarly, we compare reported average concentrations to the field entitled “limit concentration 2 (avg)”, both in mg/L. Only 9.8% of records (12,973 of 133,039 records) contain data for both of these fields. Dividing average concentration by the average concentration limit yields a distribution as shown in Figure S1-4. As in Figure S1-3, points outside of the interquartile range (the whiskers) are not shown. 5.8% of records report average concentration above the average concentration limit, with a mean value of 1.7 and a maximum value of 11,627.

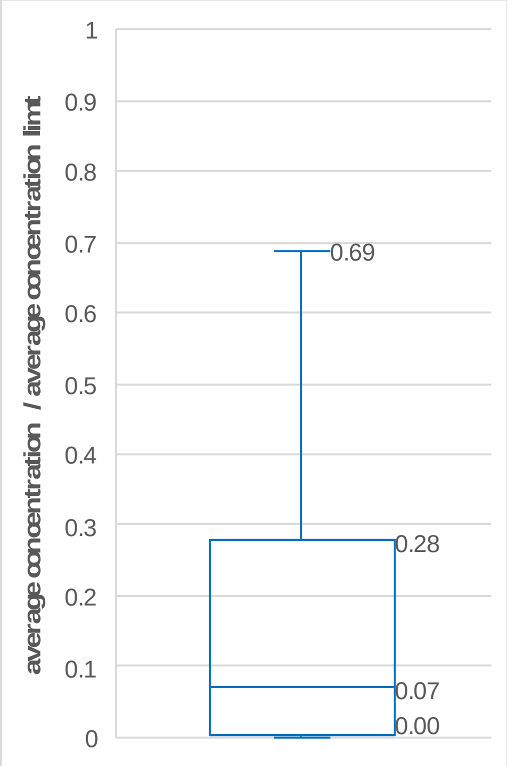

Figure S1-4: Distribution of average concentration to average concentration limit in 2016 EPA DMR data

Next, in order to determine how representative DMR data might be for the manufacturing sectors covered in this report, we found that 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 2.5% of the number of establishments in MECS were present in the 2016 DMR data. This share varied widely by sector, as seen in Figure S1-5. This figure can be interpreted as the percentage of MECS facilities within each sector with DMR permits for discharges to surface water bodies. 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 S1-5 could thus indicate to some extent which manufacturing sectors have higher concentrations of “major” facilities.

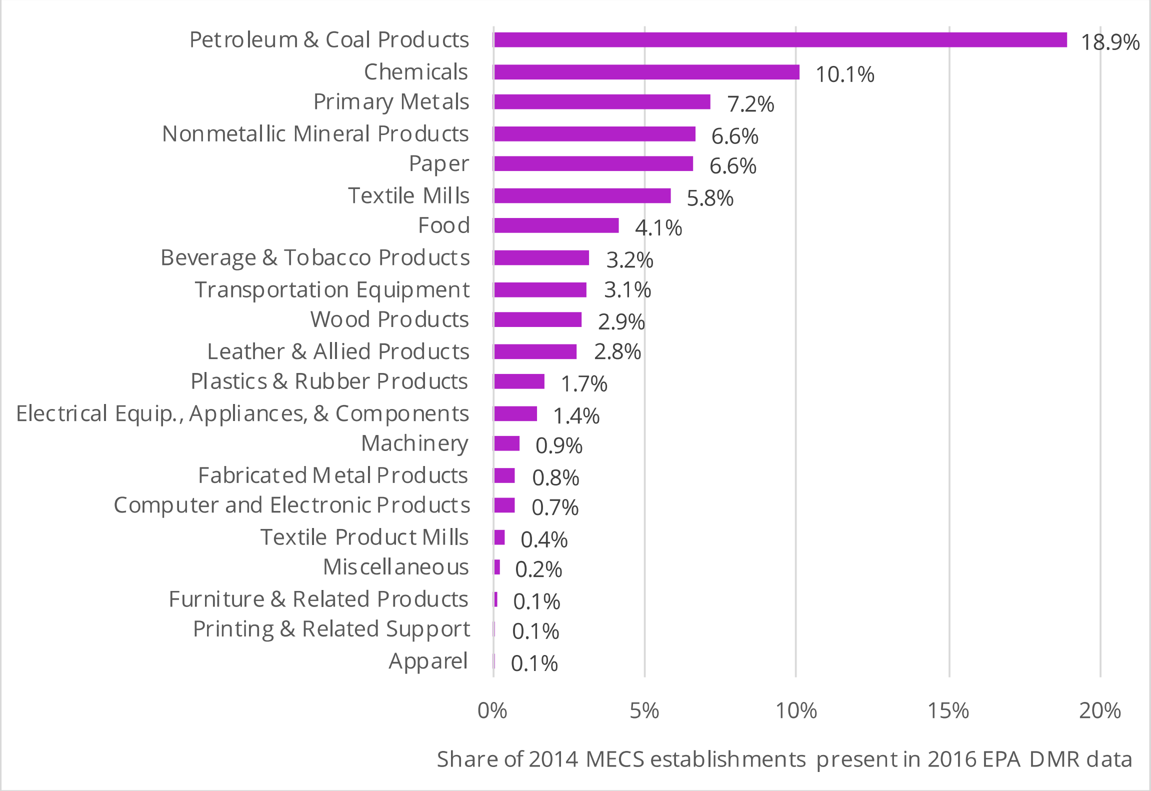

Figure S1-5: Share of individual establishments in 2014 MECS present in 2016 EPA DMR data, by manufacturing subsector

Toxics Release Inventory (TRI) Data

On February 1, 2018, we queried the TRI Explorer's Waste Transfer Chemical Report at https://iaspub.epa.gov/triexplorer/tri_transfer.chemical for discharges to POTWs from each of the 21 individual manufacturing sectors of interest within NAICS 31-33[13] (EPA 2020c). 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 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

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[13] 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".

manufacturing sector, and then converted units from lb/yr (the unit used in TRI) to kg/yr (the unit used in DMR).

Divergent Naming of Contaminants Between DMR and TRI Datasets

We found divergent naming of contaminants within and between DMR and TRI datasets. For example, consider the Fabricated Metal Product sector for several example contaminants and quantities as shown in Table S1-9.

Table S1-9: Conservative summation of example discharge quantities from EPA DMR and TRI datasets for the Fabricated Metal Product sector

	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.

No universal definition for many contaminants exists because the regulatory definition for contaminants is extremely broad, and different permitting authorities (generally states) differ in their more specific requirements. To overcome this limitation and examine which pollutants are discharged to surface waters and to POTWs, we took a conservative approach by summing these data for each manufacturing sector only where the pollutant name exactly matched between these two databases.

Venn Diagram with Typical Municipal Wastewater Contaminants and Top 30 Contaminants by Mass Across All Manufacturing Subsectors

Manufacturing wastewater is characterized by a wide diversity of contaminants depending on sector and process, and some streams are highly concentrated. This heterogeneity has significant implications for the feasibility and energy requirements of on-site reuse. To illuminate the contrast between municipal and manufacturing wastewater and highlight that reuse in the latter context deserves its own consideration, we compared typical contaminants in municipal wastewater (EPA, 2004 and Pescod, 1992) to the top 30 contaminants by mass across all manufacturing subsectors (2016 EPA DMR and TRI data), finding that only eight of 30 contaminants commonly present in manufacturing wastewater are also present in municipal wastewater. See Figure S1-6.

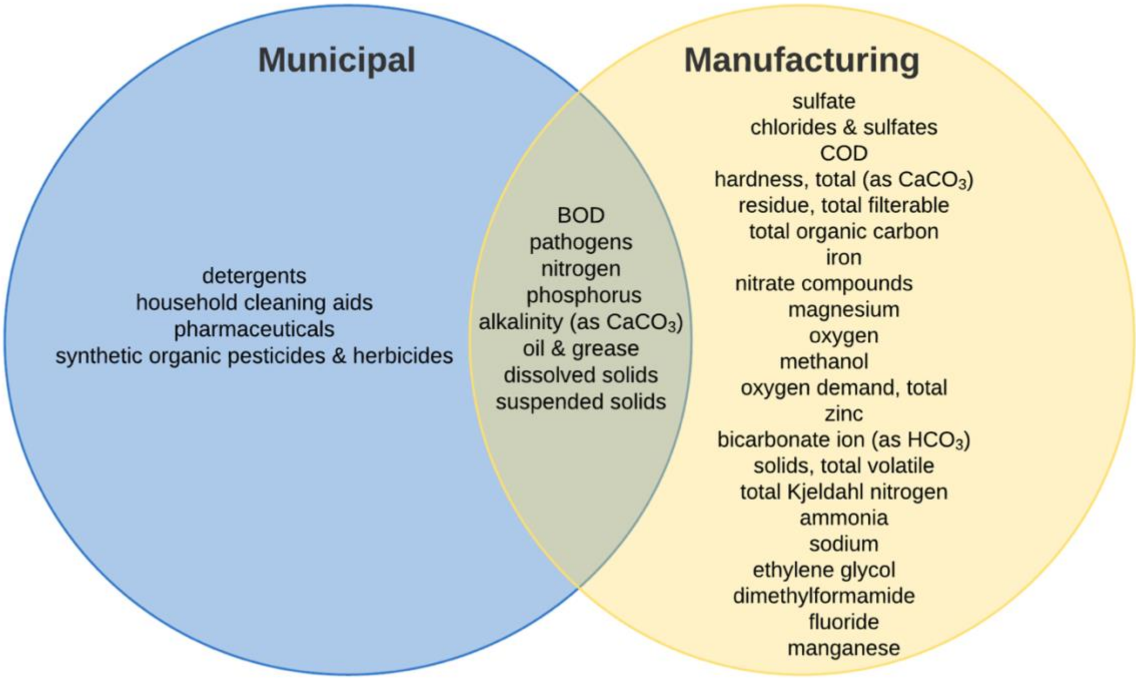

Figure S1-6: Venn diagram with typical contaminants in municipal wastewater (EPA, 2004, Pescod, 1992) and top 30 contaminants by mass across all manufacturing subsectors (2016 U.S. Environmental Protection Agency Discharge Monitoring Report & Toxics Release Inventory

Treatment Technologies by Primary Mechanism

Figure S1-5 draws upon our literature review to categorize common treatment technologies by primary mechanism on the leftmost portion of the figure: physical, chemical, and biological. The second tier displays categories encompassing examples of individual treatment technologies, shown in the third tier. This figure is not meant to be exhaustive, but to reasonably represent the universe of treatment technologies that can be applied at scale. Classifying them by mechanism helps determine their energy requirements by facilitating a better understanding of how energy is used to remove contaminants. For example, physical separation processes use energy to physically remove contaminants from wastewater. 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.

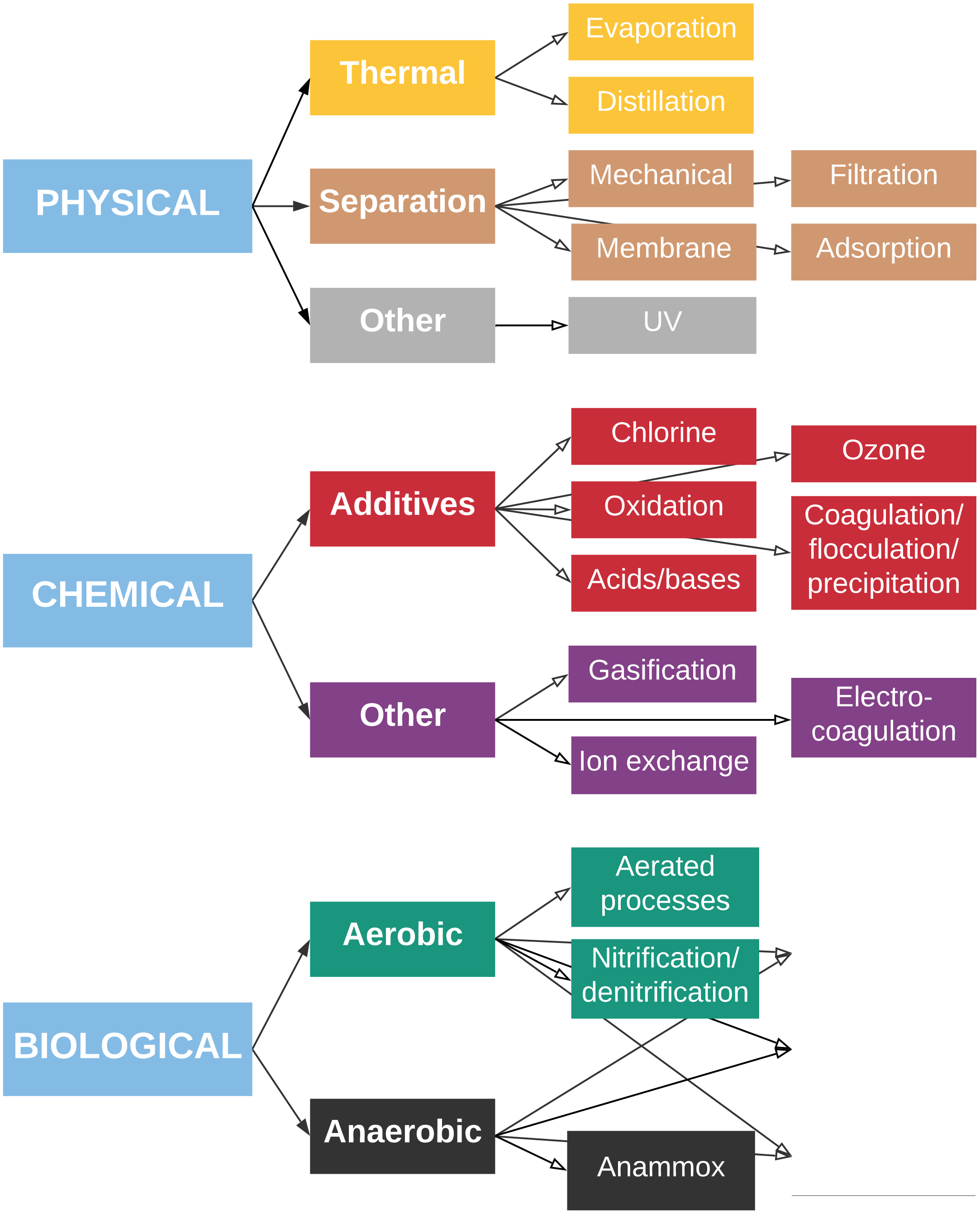

Figure S1-5: Categorization of treatment technologies by primary mechanism

Water Quality Requirements Compared to Reported Concentrations from EPA DMR

Table S1-10 helps to further contextualize Figure 2 in the manuscript; also refer to the Excel version of supporting information for the number of observations and actual data plotted in Figure 2.

Table S1-10: Crosswalk between inlet water quality requirements and reported concentration values in 2016 EPA DMR data, by subsector

		Manufacturing subsector				
From DOI (1981) & Rommelman *et al.* 2004		Chemical	Petroleum & coal products	Primary metals	Pulp & paper	Textiles
Mapped to NAICS (2016 EPA DMR)		325	324	331	322	313
Total number of records (2016 EPA DMR)		29,359	17,340	4,489	3,720	1,164
Share of records with non-blanks for average concentration, 2016 EPA DMR data (2016 EPA DMR)		68%	41%	58%	63%	74%
Contaminant		**Share of records where index value ≤ 1**				
DOI (1981) & Rommelman *et al.* 2004	2016 EPA DMR					
Copper (Cu)	Copper	--	92%	--	--	53%
Iron (Fe)	Iron	17%	61%	--	24%	40%
Magnesium (Mg)	Magnesium	81%	--	--	--	--
Manganese (Mn)	Manganese	46%	--	--	--	--
Chloride (Cl)	Total residual chlorine	100%	100%	100%	100%	--
Nitrate (NO_3)	Nitrogen, nitrate dissolved	89%	--	--	--	--
Sulfate (SO_4)	Sulfate	47%	81%	--	--	--
Dissolved solids (TDS)	Solids, total dissolved	62%	65%	91%	15%	--
Suspended solids (TSS)	Solids, total suspended	25%	43%	99%	37%	34%
Hardness	Hardness, total (as $CaCO_3$)	68%	70%	100%	18%	--
Alkalinity	Alkalinity, total (as $CaCO_3$)	33%	--	--	--	--

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