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Industrial Steam Systems and the Energy-Water Nexus

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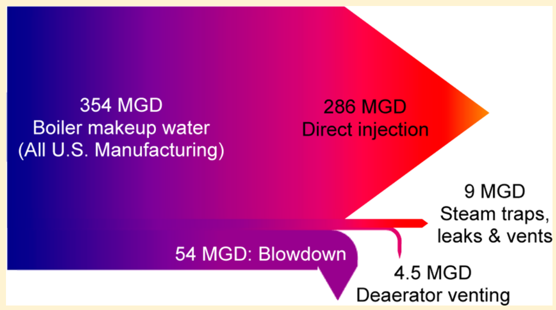
S *Supporting Information*

ABSTRACT: This paper presents estimates for water consumption and steam generation within U.S. manufacturing industries. These estimates were developed through the integration of detailed, industry-level fuel use and operation data with an engineering-based steam system model. The results indicate that industrial steam systems consume approximately 3780 TBTU/yr (3.98×10^9 GJ/yr) to generate an estimated 2.9 trillion lb/yr (1.3 trillion kg/yr) of steam. Since a good portion of this steam is injected directly into plant processes, vented, leaked, or removed via blowdown, roughly 354 MGD of freshwater must be introduced to these systems as makeup. This freshwater consumption rate is approximately 11% of that for the entire U.S. manufacturing sector, or the total residential consumption rate of Los Angeles, the second largest city in the U.S. The majority of this consumption (>94%) can be attributed to the food, paper, petroleum refining, and chemicals industries. The results of the analyses presented herein provide previously unavailable detail on water consumption in U.S. industrial steam systems and highlight opportunities for combined energy and water savings.



INTRODUCTION

The U.S. manufacturing sector consumes large amounts of water and energy. The sector accounts for approximately 31 quadrillion BTU (3.3×10^{10} GJ) of primary energy use and 6.6 billion gallons (25,000 ML) of freshwater withdrawals every year, as of 2010 and 2005, respectively.[1,2] Manufacturing plants use water for a number of purposes including: process mixing, chemical reactions, extraction, process cooling, steam generation, product washing, and equipment sanitization. Energy is required to power electric motors, operate pumps, run machinery, light floorspace, heat processes, and generate steam. While many incentives exist for the adoption of energy-efficient industrial technologies – including equipment rebates, tax incentives, and technical assistance – comparatively few incentives exist to spur the adoption of water-efficient industrial technologies in the U.S.[3] Such incentives are critical for accelerating technology deployment. As shown by Therkelsen and McKane,[4] the adoption of steam system efficiency improvements is particularly dependent on economic factors.

One key barrier to water efficiency incentives is the lack of credible data on water use for manufacturing industries, which, unlike energy use, are not compiled at the industry subsector or process level in regular national surveys.[5] This lack of data contributes to a general lack of awareness of the sources and scale of industrial water use within the engineering and policy communities, which limits broader attention to water efficiency as well as external incentives for manufacturers to reduce freshwater use. However, rising prices for water, increasing freshwater scarcity, and growing demands for corporate environmental reporting are likely to raise the importance of industrial water efficiency moving forward.[6,7] Addressing the lack of data on industrial water use is, therefore, an important first step toward improving the water efficiency of the U.S. manufacturing sector. Note that this paper focuses on energy and water use for U.S. manufacturing industries. Throughout this paper, the term 'industry' and its related forms refer specifically to the manufacturing industry, which does not include thermoelectric power generation, agriculture, mining, commercial or service industries.

This paper aims to fill the existing data gap by characterizing the energy-water nexus for industrial steam systems, which are important for several reasons. First, steam systems account for roughly 29% of all primary energy consumption in the U.S. manufacturing sector.[8] As such, they are a common target of industrial energy efficiency improvements that can also save freshwater through reduced steam demand.[9] Second, steam systems are ubiquitous across the manufacturing sector and, therefore, may provide an opportunity for combined energy-water savings that can be realized at nearly all U.S. plants. Third, existing incentives for improved steam system efficiency might become more attractive when water savings are considered in addition to energy savings. A better under-

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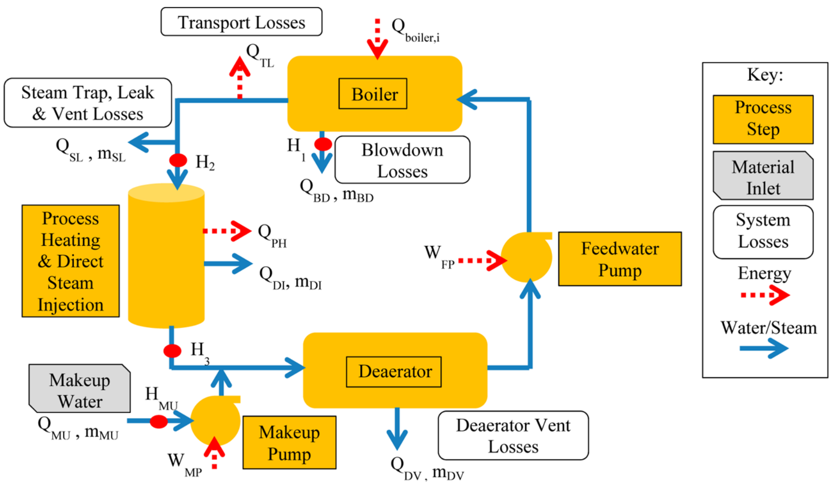

Figure 1. Simplified flow diagram of an industrial steam system. This simplified representation does not include items such as valves, heat recovery apparatuses, or holding tanks.

standing of the energy-water nexus for industrial steam systems can help raise the visibility of steam system water use and efficiency.

Existing estimates of industrial freshwater use are both limited in scope and infrequent in the literature. On a national level, the United States Geological Survey (USGS) reports data on the annual freshwater withdrawals of the entire U.S. manufacturing sector. As of 2005—the latest year for which USGS data are available—they report that the U.S. manufacturing sector withdrew 18,200 million gallons per day (MGD).[2] Industrial consumption estimates are harder to come by; the most recent estimates from the USGS indicate that 3,370 MGD of the freshwater withdrawn by the U.S. manufacturing sector in 1995 was consumed in industrial processes.[10] While such estimates are useful for understanding the rough magnitude of industrial water use, they are of limited use for understanding actionable water efficiency opportunities since they are not broken down by industrial subsector or industrial process. Moreover, the age of data and disparities in estimates associated with such national level figures make them difficult to use with confidence for analyzing today's industrial systems. Blackhurst et al.[11] derived detailed estimates of water use by industry subsector as of 2002 in the context of an input-output life-cycle assessment model. While the subsector detail offers much more insight into where water is used in U.S. industry than aggregate, national-level estimates, these data were not further disaggregated by process within each subsector. A number of studies have documented process-level water use of specific industrial processes,[12] plants,[13] or regions;[14] however, such estimates are difficult to extrapolate to broader U.S. industry in a credible way. Others have quantified the energy consumption of water services, such as steam generation, across the U.S.,[5,15] but not the water consumption in these systems.

This study improves upon past work by deriving engineering estimates of the freshwater consumed in U.S. industrial steam systems by industry subsector. Estimates are derived using a thermodynamic steam system model and are based on industry-specific steam system fuel use and operating characteristics. These estimates further subdivide the source of steam/water demand in each subsector, including direct injection into processes, boiler blowdown, vent losses, and system leaks and failures. The model and methods can also be applied to future energy use data to derive freshwater use estimates over time or applied to estimate the water use of steam systems in specific plants or regions by the research community. Importantly, by characterizing the steam system energy-water nexus in detail, the results can be used to identify opportunities for combined energy and water savings through steam system efficiency improvements across the U.S. manufacturing sector.

METHODS

System Description. Steam systems are used to supply thermal energy to processes in a manufacturing facility.[16] Figure 1 depicts a simplified flow diagram of an industrial steam system. As shown, boiler feedwater is first pumped to the appropriate pressure before it is introduced to the boiler system. Within the boiler unit, pressurized feedwater is converted to steam through indirect contact with hot boiler gases. The generated steam is then transported to provide heat to plant processes. This can be accomplished through the direct injection of steam into the process or via indirect contact in a heat exchanger. Condensate return that results from indirect process heating is then sent through a deaerator step to remove oxygen and noncondensable gases[9] before returning to the boiler feedwater pump.

Water consumption in steam systems occurs when process steam leaves the steam cycle boundaries. Clearly, this occurs when steam is directly injected into plant processes. However, as shown in Figure 1, there are a number of other sources of steam/water loss that are typical in industrial steam systems. The magnitude of these losses will vary from plant to plant and can be particularly pronounced at inefficient facilities. To balance the consumption of water due to injection and system losses, an equal amount of makeup water must be introduced to the system, as depicted in Figure 1.

Certain consumption parameters are inherent to the operation of steam systems. Boiler water blowdown is an example of this type of inherent loss. When steam vapor is generated from feedwater in a boiler unit, the nonvolatile components present in the boiler feedwater become more concentrated. Ultimately, these nonvolatile components can degrade heat transfer properties in the boiler and corrode boiler surfaces. To prevent the buildup of problematic species in the boiler water, a portion is periodically released or "blown down". A report by Harrell[17] indicates that blowdown loss can

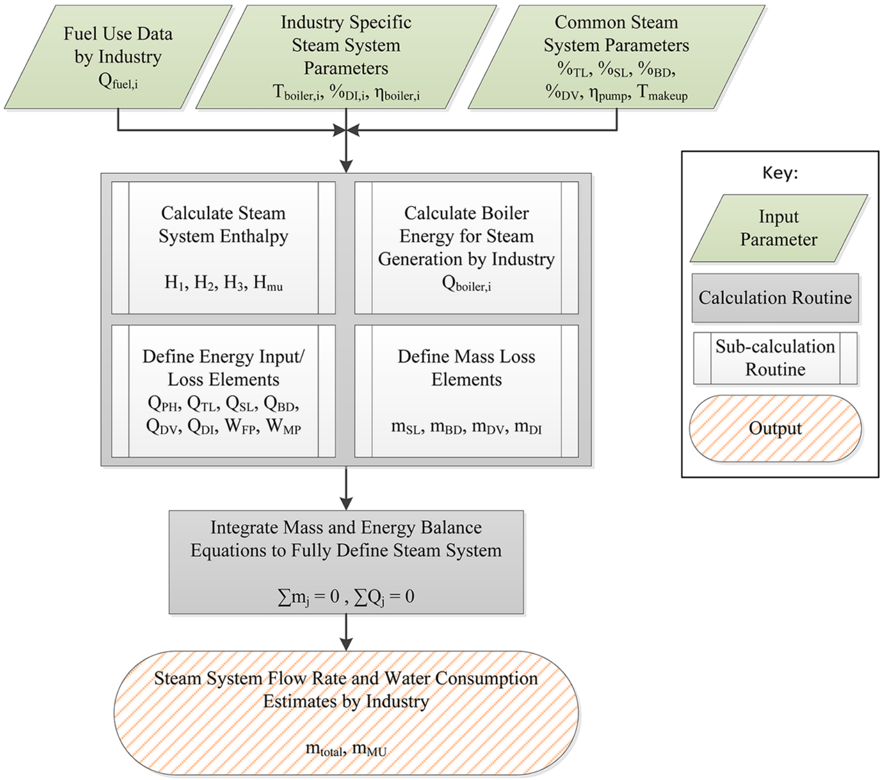

Figure 2. Model structure: calculating water use from MECS fuel data and boiler operation information.

constitute up to 10% of the boiler water flow; however, properly maintained systems with high-quality makeup water or treatment can achieve blowdown losses below 5%.

Deaerator vent losses are another example of inherent system losses. A deaerator is a tank in which a small portion of steam, on the order of 0.5% of the total steam flow,[18] is used to heat the feedwater to its saturation point. This process step is performed to remove oxygen and other dissolved gases from the feedwater.[17] The presence of such species in the feedwater can be problematic because they contribute to corrosion in the steam system equipment.

The remaining system mass losses highlighted in Figure 1 include those due to steam trap, leak, and vent losses. Steam traps are devices that allow spent condensate to exit a process heat exchanger without the loss of steam vapor. During operation these devices can leak or fail, resulting in the unnecessary loss of steam.[17] Steam leaks can occur when pressurized steam passes through piping, joints, and valves. Leaks may occur as a result of improper installation or develop during the course of operation due to corrosion or erosion of steam lines or process equipment. Steam venting occurs when steam generation exceeds process needs. Proper process control and optimization can help minimize losses due to venting.[19] Steam trap, leak, and vent losses are heavily dependent on maintenance routines, monitoring, and process operation and are therefore particularly variable from plant to plant.

Industrial steam systems may also incorporate a combined heat and power (CHP) generation strategy. CHP generation can be advantageous because these systems can achieve a higher total thermal efficiency than is possible through the production of steam and electricity in separate processes.[20]

Model Description. The basic flow and calculation structure of the steam system energy-water model employed in this study is shown in Figure 2. The model calculates water consumption estimates based on boiler fuel use data and steam system parameters. General forms of the mass and energy balances that form the foundation of the model are given in eqs 1 and 2, respectively. The individual elements of these equations represent mass and energy flow entering and leaving the steam system, as depicted in Figure 1.

$$m_{SL} + m_{BD} + m_{DV} + m_{DI} - m_{MU} = 0 \tag{1}$$

$$Q_{PH} + Q_{TL} + Q_{SL} + Q_{DI} + Q_{DV} + Q_{BD} - Q_{MU} - Q_{boiler,i} - W_{FP} - W_{MP} = 0 \tag{2}$$

To determine the amount of water consumed by industrial steam systems, the model calculates the mass of makeup water required by the boiler, m_{MU}. This is accomplished by fully defining the balance equations and the constituent equations that describe the steam system. The relevant equations for the mass balance elements are given in eqs 3 and 4. Two additional mass flow elements are introduced in eq 3, m_{PH} and m_P which describe the amount of steam used for indirect process heating and the total amount of steam generated for heating, respectively. As shown in eq 4, these elements are utilized as the basis for determining the mass of steam lost through leaks, venting, and traps (m_{SL}), direct injection (m_{DI}), boiler blowdown (m_{BD}), and deaerator operation (m_{DV}). The parameters $\%_{SL}$, $\%_{DI}$, $\%_{DV}$, and $\%_{BD}$ are input by the model user and represent the fraction of the steam system flow rate that is lost to the respective system operation.

$$m_P = m_{PH} + m_{DI} \tag{3}$$

$$m_l = [m_P * \%_l]|_{l=SL,DI,BD,DV} \tag{4}$$

Energy balance constituent equations are described in eqs 5–9. Equations 5 and 6 describe the amount of energy that exits the system with the flow of mass out of the system. As shown, these equations have similar forms to their mass flow counterparts but include stream enthalpy information. Equation 7 describes the energy introduced to the system with the makeup water feed. Equation 8 describes the amount of energy that is utilized for process heating. Here H_1 is the enthalpy of the boiler blowdown water, H_2 is the enthalpy of the steam generated in the boiler, H_3 is the enthalpy of the condensed steam that exits the process heating step, and H_{MU} is the enthalpy of the makeup water. These enthalpy values are related to the operating temperature of the boiler system streams. The model assumes that all steam streams have a quality of 1 (all vapor) and all water/condensate streams have a quality of 0 (all liquid). Equation 9 details the relationship between energy transferred to the steam system, $Q_{\text{boiler},i}$, the fuel energy burned in the boiler, $Q_{\text{fuel},i}$, and the efficiency of the boiler $\eta_{\text{boiler},i}$.

$$Q_k = [m_P{*}\%_k{*}H_2]|_{k=\text{TL,SL,DI,DV}} \tag{5}$$

$$Q_{BD} = m_P{*}\%_{BD}{*}H_1 \tag{6}$$

$$Q_{MU} = m_{MU}{*}H_{MU} \tag{7}$$

$$Q_{PH} = m_{PH}(H_2 - H_3) \tag{8}$$

$$Q_{\text{boiler},i} = Q_{\text{fuel},i}{*}\eta_{\text{boiler},i} \tag{9}$$

The remaining energy balance constituents include W_{FP}, and W_{MP}. These work terms represent energy input to the system to drive the boiler feedwater pump and makeup water pump, respectively. The magnitude of these pump work components is small when compared to the overall energy balance.

Study Description. This paper adopts the North American Industrial Classification System (NAICS), which uses three- to six-digit numerical codes to classify industry subsectors in hierarchical fashion as shown in Table S-1 (see the Supporting Information).[21] As shown in Figure 2, this study relies on industry fuel use data and steam system operating parameters to determine the amount of steam generated in industrial boilers and, more importantly, the amount of freshwater consumed by industrial steam systems in the U.S.

Industry-specific fuel use data were obtained from the U.S. Department of Energy's 2010 Manufacturing Energy Consumption Survey (MECS).[5] To account for all energy used in industrial steam systems, this study considered the end-use fuel consumption in boiler and combined heat and power (CHP) systems. For major fuels, such as coal, natural gas, fuel oils, and electricity, this information was available directly from an industry survey. For 'other' fuel sources such as pet coke, pulping liquor, wood bark, and waste gas, however, the MECS survey did not provide a detailed fuel end-use breakdown. To bridge this gap, this study leveraged relative fuel end-use information from available industry studies to estimate the amount of energy from 'other' fuels that could be attributed for the generation of steam in industrial steam systems.[8,22−24] Further detail on the end-use estimates applied in this study and development of fuel parameters is provided in the Supporting Information documentation (Tables S-1 and S-2). Table S-1 also provides details on the fuel use information applied to this study, $Q_{\text{boilfuel},i}$, and $Q_{\text{CHPfuel},I}$.

To estimate the total fuel energy applied to steam generation, fuel end-use information for boiler and CHP systems were combined as shown in eq 10. Note that this equation assumes 52% of energy utilized in CHP systems can be attributed to steam generation. This value was adopted from a U.S. Department of Energy assessment of steam systems in U.S. manufacturing industries.[24] It was obtained by assuming an electricity production cycle with 35% efficiency that yields a waste stream with 80% recoverable heat, [(1−35%)*80%] = 52%.

$$Q_{\text{fuel},i} = Q_{\text{boilfuel},i} + 0.52{*}Q_{\text{CHPfuel},i} \tag{10}$$

Steam system operation parameters for each industry were obtained from a variety of literature sources.[12,17−19,24,25] To properly classify the steam systems, three important parameters were estimated for each subsector: average steam generation temperature ($T_{\text{boiler},i}$), the average percent of generated steam directly injected into the process ($\%_{\text{DI},i}$), and the average efficiency of the boiler system ($\eta_{\text{boiler},i}$). These parameters provide the fundamental connection between fuel use, steam flow, and water consumption. These parameters are listed in Table S-1 for each industry subsector.

Boiler efficiency was estimated by weight averaging the boiler efficiency for typical fuel types across the fuel use for each industry subsector. A breakdown of typical boiler efficiency by fuel is given in Table 1, along with a set of typical steam system parameters that were applied across all industry subsectors. These parameters were chosen as representative values for common system settings such as pump efficiency (η_{pump}), steam trap loss ($\%_{SL}$), transmission loss ($\%_{TL}$), and makeup water temperature (T_{makeup}).

Table 1. Steam System Settings Common to All Analyses

steam system parameter	value	reference
$\eta_{\text{boiler},i}$ electric (%)	95	24
$\eta_{\text{boiler},i}$ fuel oil (%)	83	24
$\eta_{\text{boiler},i}$ natural gas-LPG (%)	82	24
$\eta_{\text{boiler},i}$ coal (%)	81	24
$\eta_{\text{boiler},i}$ waste-oil,gas,tar (%)	70	24
$\eta_{\text{boiler},i}$ petcoke (%)	70	24
$\eta_{\text{boiler},i}$ liquor (%)	65	24
$\eta_{\text{boiler},i}$ agri-waste (%)	64	24
η_{pump} (%)	85	25
T_{makeup} (F)-(C)	75 (24)	Assumed
$\%_{TL}$ (%)	2	17
$\%_{SL}$ (%)	1	17
$\%_{BD}$ (%)	6	17
$\%_{DV}$ (%)	0.5	18

■ RESULTS

Steam System Estimates. Results of this analysis suggest that the total steam generation rate in U.S. manufacturing plants can be estimated at 2.93 trillion lb/yr (1.33 trillion kg/yr). A large fraction of this steam is raised from returned condensate. As a result, the actual steam system makeup water demand for U.S. manufacturing industries is significantly less, approximately 354 MGD. Figure 3 summarizes the results of this study. Here, m_{TOTAL} represents the total steam flow rate of each industry subsector, and m_{MU} is the related water consumption rate. As shown, steam systems in the paper, chemicals, petroleum refining, and food manufacturing subsectors account for the majority of steam generation and freshwater consumption in U.S. industries.

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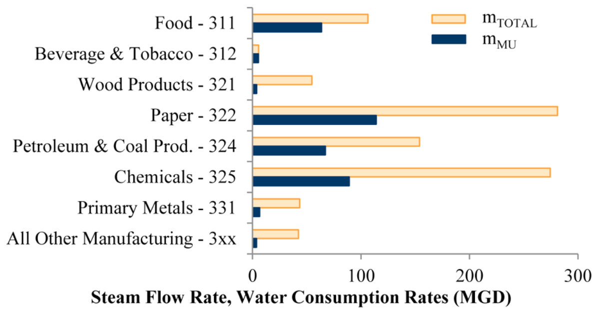

Figure 3. Steam cycle flow rate and water consumption rates in the U.S. manufacturing sector (2010). For comparative purposes steam flow in this figure is expressed in terms of MGD, based on mass of steam generating water at STP.

Water consumption information is broken down further in Figure 4, which highlights the contribution of the individual water consumption elements: steam trap, leak and vent losses (m_{SL}), blowdown losses (m_{BD}), deaerator vent losses (m_{DV}), and direct-injection steam (m_{DI}). The influence of direct steam injection (m_{DI}) on the total freshwater consumption of U.S. industrial steam systems can be clearly seen in Figure 4. In total, direct injection accounts for 286 MGD, or 81% of the total estimated water consumption for industrial steam systems. Water consumption associated with boiler blowdown losses is the second largest contributor, at approximately 54 MGD. Further detail on the estimates presented herein is provided in Table S-3 of the Supporting Information. Table S-3 lists steam system generation and consumption data with the same subsector resolution given in Table S-1.

Figure 4 sheds light on the availability of freshwater conservation opportunities for these manufacturing subsectors. While it is obvious that reducing steam used for direct injection $\%_{DI}$ can lead to significant water savings, these figures also highlight the potential water saving benefits associated with other best practice steam system efficiency improvements such as: a leak/excess vent prevention program, installation of makeup water treatment to reduce blowdown rates, or optimization of steam use for deaerator venting. Such improvements are often identified in industrial steam system audits,[4] but presently much potential remains to implement them and achieve combined energy-water savings. This is particularly true in the food, chemicals, paper, and refining industries.[6]

Sensitivity Analysis. The estimates provided herein were developed with a combination of literature data and assumptions on steam system operation. Certain data, such as MECS fuel use information, were available on a subsector-specific basis along with information on the relative error expected for each data point. Other information, such as boiler temperatures, η_{boiler} and $\%_{DI}$, were obtained on a subsector-specific basis from literature that did not delineate an expected error or confidence interval for reported data. In addition, several other boiler operation parameters such as $\%_{BD}$, $\%_{SL}$, $\%_{DV}$, and η_{pump} were not available on a subsector basis as these parameters are understood to vary based on the location, age, and operation of the steam system. This study assumed reasonable values for all system parameters based on available literature, but the estimates provided herein are clearly influenced by the operating values assumed. To provide a better understanding of how the values chosen for these parameters influence the water consumption estimates determined in this study, a sensitivity analysis was conducted using the parameters and ranges given in Table 2.

The bounds chosen for this analysis are at, or slightly beyond, the practical limits for what would be expected in manufacturing plants and were chosen for illustrative purposes.[12,17−19,24,25]

The results of the sensitivity analysis indicate that water consumption estimates can vary in the range of 340−420 MGD for the parameter variation considered in Table 2. This variation was most strongly influenced by $\%_{DI}$, followed by $\%_{BD}$, the percent of CHP fuel attributed to steam generation (as applied in eq 10), and η_{boiler}. Interestingly, Q_{fuel} plays a relatively minor role in the variation observed in this analysis. This is

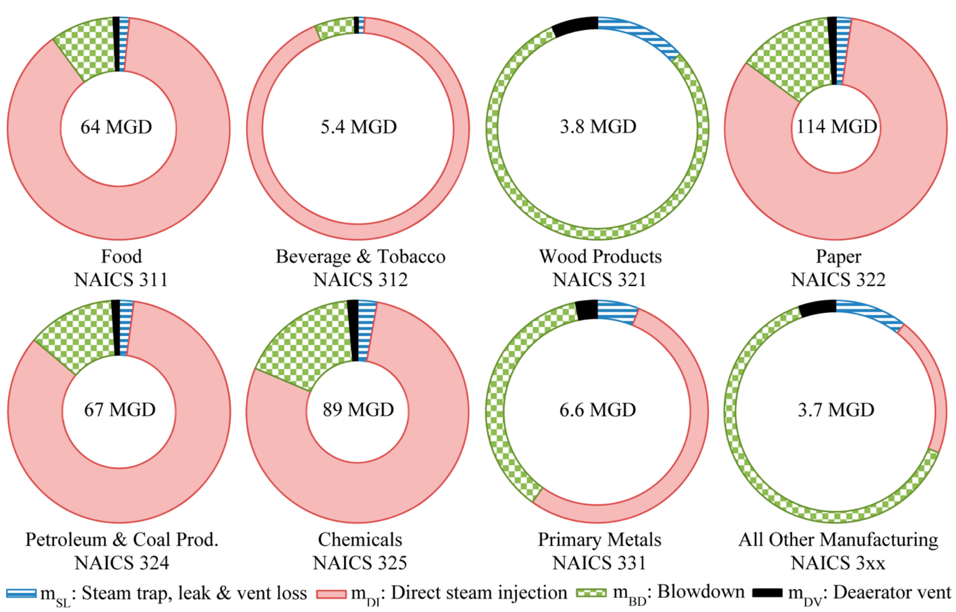

Figure 4. Freshwater consumption rates in the U.S. manufacturing sector: broken down by consumption type. Annulus area corresponds to total water consumption for each subsector.

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Table 2. Sensitivity Analysis: Steam System Parameter Bounds

steam system parameter	lower bound	upper bound
η_{boiler} (%)	−5%pts[a]	+5%pts
η_{pump} (%)	75	95
T_{makeup} (F)-(C)	65 (18)	85 (29)
$\%_{TL}$ (%)	0	10
$\%_{SL}$ (%)	0	10
$\%_{BD}$ (%)	0	10
$\%_{DV}$ (%)	0	5
$\%_{DI}$ (%)	−10%pts	+10%pts
Q_{fuel} (%)	from MECS[b]	from MECS
% CHP fuel attributed to steam generation (%)	42	62
boiler pressure (psia)-(MPa)	25[c] (0.17)	500 (3.4)

[a](%pts) refer to percentage point changes in identified parameters. [b]Lower and upper bounds for individual fuel data were obtained from MECS relative standard error data (see Table S-4). [c]Lower and upper bounds for subsectors with higher process temperature requirements were 1000 and 1500 psia, respectively (6.9 and 10.3 MPa, respectively).

because the primary fuel data reported in MECS has a relatively low error for many of the most energy intensive industry subsectors.[5]

Figure 5 shows the contribution to variance for the steam system parameters considered in this sensitivity analysis. Future

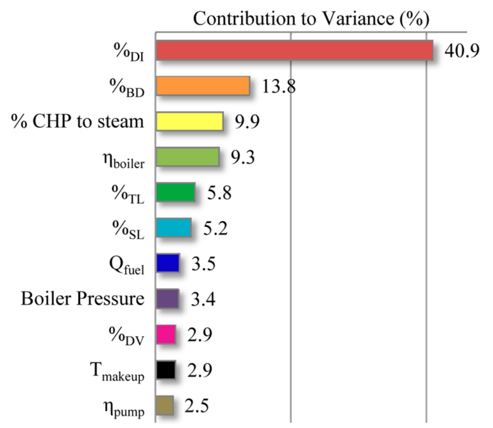

Figure 5. Sensitivity analysis: parameter contribution to variance.

work should be focused on obtaining well-representative information for the most influential parameters to accurately model water use in industrial steam systems. This could be accomplished through an industry survey. The accuracy of results would be best improved by obtaining information from large-scale manufacturers that use the most boiler-related energy.

Comparison: 2006 vs 2010. This paper investigates freshwater use in industrial steam systems based on fuel use data from 2010. Previous estimates of freshwater consumption in industrial steam systems have been performed for an earlier MECS fuel use data set from 2006.[6] A comparison of these estimates indicates a slight decrease in water consumption in industrial steam systems, from 376 MGD in 2006 to 354 MGD in 2010. These estimates were obtained with the same methods and the same assumptions, and this drop is related to a decrease in the steam generating fuel estimated from the MECS data. Table S-5 in the Supporting Information provides detail on fuel use data and water consumption estimates at the subsector-level for 2006 and 2010.

■ DISCUSSION

The results presented here characterize the total freshwater consumption of U.S. industrial steam systems in an engineering fashion. As such, they provide a more credible and detailed view of the energy-water nexus in U.S. industrial steam systems than previous studies. First, the magnitude of freshwater use was found to be substantial. The estimated makeup water use of 354 MGD represents roughly 11% of the total freshwater consumption for U.S. manufacturing industries and is comparable to the total residential consumption rate of Los Angeles, the second largest city in the U.S.[10] This suggests that industrial steam systems can be an attractive target for water efficiency measures in many industrial plants, particularly within the food, paper, petroleum refining, and chemicals industries. Moreover, because saving water in steam systems also saves energy, the estimates presented here suggest that the combined energy-water savings of steam system efficiency measures should make them increasingly attractive to manufacturers and policy makers seeking to improve industrial sustainability.

By quantifying the freshwater use associated with specific industry subsectors and steam system components, the estimates presented here shed light on which industry subsectors, and components might be most attractive for water efficiency improvements. Specifically, reducing the steam used for direct injection and the water lost in blowdown for the food, chemicals, refining, and paper plants may offer the greatest potential for steam system water savings and thus should be the target of policy and manufacturer initiatives for water efficient technologies and operating practices. Such opportunities have been well documented in the literature,[4,6,9,24] and efforts to implement them should be redoubled in the face of growing freshwater scarcity and expense moving forward. The results can also be used to quantify the energy-water nexus for steam systems in industrial energy systems models (e.g., GCAM − Global change assessment model),[26] thereby enhancing the ability of such models for analyzing resource savings opportunities at the detailed NAICS level.

Furthermore, the model and methods presented here, along with the Supporting Information, can be used by energy analysts, manufacturers, and policy makers to quantify the energy-water nexus of industrial steam systems based on widely available industrial energy data or to estimate the water used by steam systems in a particular plant or region.

■ ASSOCIATED CONTENT

Supporting Information

Tables S1−S5. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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LIST OF SYMBOLS AND ACRONYMS

CHP combined heat and power
GCAM global change assessment model
H_1 enthalpy of boiler feedwater
H_2 enthalpy of generated steam
H_3 enthalpy of returned condensate
H_{MU} enthalpy of makeup water
m_{BD} mass of blowdown discharge
m_{DI} mass of steam directly injected into processes
m_{DV} mass of steam utilized in deaerator venting
MECS manufacturing energy consumption survey
m_{MU} mass of makeup water inlet
m_P mass of steam produced for direct steam injection and indirect process heating
m_{PH} mass of steam produced for indirect process heating
m_{SL} mass of steam leaks, vent and trap losses
m_{TOTAL} total steam mass produced from boiler
MGD million gallons per day
NAICS North American Industry Classification System
η_{pump} pump efficiency
$\eta_{boiler,i}$ average boiler efficiency for industry subsector i
$\%_{BD}$ blowdown as % of total process steam generated in boiler
$\%_{DI,i}$ direct-injection steam as % of total process steam generated in boiler
$\%_{DV}$ deaerator vent as % of total steam generated in boiler
$\%_{SL}$ steam trap, leak, and vent loss as % of total steam generated in boiler
$\%_{TL}$ transmission energy loss as % of process steam energy generated in boiler
$Q_{boilfuel,i}$ boiler fuel energy for industry subsector i
$Q_{CHPfuel,i}$ CHP fuel energy for industry subsector i
$Q_{boiler,i}$ steam generating energy transferred through boiler for industry subsector i
Q_{BD} energy contained in blowdown water stream
Q_{DI} energy contained in steam directly injected into process
Q_{DV} energy contained in steam utilized for deaerator venting
$Q_{fuel,i}$ total steam generating fuel energy for industry subsector i
Q_{MU} energy contained in makeup water stream
Q_{PH} energy utilized for indirect process heating
Q_{TL} heat losses through pipe walls/insulation
Q_{SL} energy contained in steam leaks, trap losses, and vented steam
$T_{boiler,i}$ boiler operation temperature (i.e., steam generation temp) for industry subsector i
T_{makeup} makeup water temperature
W_{FP} energy required for boiler feedwater pumping
W_{MP} energy required for makeup water pumping

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