Perspective

Energy-Water Efficiency and U.S. Industrial Steam

Eric Masanet
Dept. of Chemical and Biological Engineering, and Dept. of Mechanical Engineering, Northwestern University, Evanston, IL 60208

Michael E. Walker
Dept. of Chemical and Biological Engineering, Northwestern University, Evanston, IL 60208

DOI 10.1002/aic.14148
Published online June 5, 2013 in Wiley Online Library (wileyonlinelibrary.com)

Keywords: steam, energy efficiency, water efficiency, energy water nexus

Introduction

Steam systems are a ubiquitous element in nearly every type of manufacturing plant. In the United States, steam systems are the single largest consumer of energy in the industrial sector, where they account for 37% of annual onsite energy use.[1] Steam use is particularly prominent in the chemicals, paper, petroleum refining, and food and beverage industries, where it is used in a wide range of processes, including reforming, distillation, concentration, cooking, and drying.[2] Together, these four industries comprise nearly 90% of U.S. industrial steam demand, with chemicals manufacturing (30%) and paper manufacturing (30%) holding the largest shares.[1,3]

At the national level, industrial steam systems account for around 6% of U.S. total primary energy use, or 5,900 trillion British thermal units (TBtu).[1,4] As such, much attention has been paid to steam system energy efficiency improvements as part of corporate, utility, and government energy and air pollution initiatives. Key incentives include local utility rebates, tax incentives, and low- or no-cost steam system energy efficiency audits.[5] Steam system energy efficiency not only makes sense from an environmental perspective, but also from an economic perspective. As of 2006, U.S. manufacturers spent $21 billion on externally purchased boiler fuels. The actual price tag of industrial steam is likely much higher; nearly one-half of U.S. boiler fuels are self-generated within plants in the form of waste gas, black liquor, wood wastes, and other byproducts.[1,3] These byproduct fuels are not free, as they are generated from purchased materials and typically require further processing for efficient combustion. Reducing demand for boiler fuels can, therefore, help reduce operating costs and improve profit margins.

While clearly justified, the historical focus on reducing energy use has overlooked an increasingly compelling benefit of steam system efficiency: namely, reduced water use. Compared to the many public and private incentives for industrial energy efficiency, there are surprisingly few external incentives for industrial water efficiency. One key barrier to such incentives is the lack of credible data on industrial water use, which, unlike data on energy use, are not compiled at the manufacturing industry or process level in regular national surveys.[6] This dearth 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 beyond the plant floor. Another barrier to steam system water efficiency is that the cost of boiler water—and the associated chemicals required for its treatment—typically only represents a small fraction of boiler operating costs, which are dominated by the costs of fuel.[7] However, as we discuss in this Perspective, U.S. industrial steam systems consume copious amount of water. It follows that steam systems are worth a closer look as a manufacturing water efficiency target.

Several current trends suggest that water efficiency will play an increasingly prominent role in the financial and sustainability plans of U.S. manufacturers. Recent water stress due to droughts and rising water infrastructure costs have led to increased public water rates around the country.[8] These conditions may worsen with a changing climate.[9] An increasing number of manufacturers are reporting water use as an important environmental indicator in annual corporate sustainability reports, which raises both public awareness of and accountability for water efficiency. Many manufacturers are also being asked by their corporate customers for environmental "footprint" data as part of large-scale sustainable

Correspondence concerning this article should be addressed to E. Masanet at eric.masanet@northwestern.edu; M.E. Walker at mwalker9@hawk.iit.edu.

supply chain initiatives.[10] In light of these trends, the combined reductions in energy and water use that come with improved steam system efficiency should appear more and more attractive to most manufacturers.

In the remainder of this Perspective, we explore the water use of U.S. industrial steam systems, discuss their potential for energy-water efficiency in U.S. plants, and describe pathways toward greater steam system water efficiency moving forward.

Water, Energy, and Industrial Steam

A boiler system is the heart of many manufacturing facilities.[11] Its energy filled arteries spread out in a dizzying array of pipes to supply steam heat to processes throughout the plant. Steam is particularly well suited as an energy transfer medium in the plant environment for several reasons (1) steam and condensed water can easily be transported throughout a facility, (2) steam pressure can be tuned to supply heat to plant processes at the appropriate temperature, and (3) condensing and evaporating steam has favorable heat-transfer characteristics.[11,12]

As chemical engineers, we all learn about the thermodynamics of steam in the classroom, but many of us have never seen an industrial steam generation and distribution system in operation. The practical nature of these systems is not covered in much detail unless one chooses to specialize in energy engineering. Even then, there is little focus on steam system water use. Hence, we provide here a brief review of the energy and water flows associated with a typical industrial steam system.

As depicted in Figure 1, water enters the steam system as makeup water (point 1), the purpose of which is to replace water mass leaving the system in the form of process steam and/or water and steam losses. Makeup water entering a steam system joins with returned condensate and is first pumped to the deaerator, which removes oxygen and noncondensable gases. Upon leaving the deaerator, the boiler feedwater is brought up to system pressure via the feedwater pump and is introduced to the boiler (point 2).[2] Within the boiler unit, feedwater is converted to steam with heat supplied by the combustion of fuel (point 3). The steam generated in the boiler can be utilized for a number of purposes, including power production, direct steam injection, and indirect process heating (point 4). Note that the system depicted in Figure 1 is a simplified representation of an industrial steam system; items such as valves, boiler heat recovery apparatuses, and holding tanks are not included.

In many plants, the majority of water use in the steam system is attributable to direct injection of steam into production processes. However, as shown in Figure 1, there are also several other sources of steam and water loss that are present in a typical system. These other losses can be particularly pronounced at inefficient plants.

Certain losses are inherent to the operation of the steam system; the most significant example of this is boiler water blowdown. As steam is generated in a boiler unit, nonvolatile components in the boiler water become more concentrated and may ultimately degrade the performance of boiler equipment. To prevent this, a portion of the boiler water is periodically released or "blown down." Blowdown losses have been reported to constitute up to 10% of boiler water flow in many plants; however, properly maintained systems and high-quality makeup water treatment can reduce these losses to below 5%.[13]

Another source of inherent losses is the deaerator vent, where a small fraction of steam is released as part of deaerator operation. A deaerator is a tank that is heated to the saturation point of the feedwater for the purpose of removing oxygen and other dissolved gases.[2] Oxygen present in the feedwater is problematic because it is corrosive at high temperatures and can, therefore, deteriorate process equipment.

Other system losses include steam venting, steam leaks, and steam trap losses. Venting of steam may occur at steam headers or from unit processes when steam generation exceeds process needs. Proper process and boiler control and optimization can help to minimize these venting losses. Steam leaks can occur when high-pressure steam passes through piping, joints, and valves (particularly relief valves).[14] While leaks may exist due to faulty installation, they can also develop over time through corrosion or erosion. Therefore, proper maintenance and monitoring is important to prevent these losses.

Steam traps are devices utilized to remove steam condensate from a unit process such as a heat exchanger. This condensate is typically returned to the boiler to reduce the need for makeup water. When functioning properly, these devices allow the discharge of condensate with only minor loss of steam. However, over the course of operation erosion can cause the trap to wear down and leak or fail, thus, releasing steam unnecessarily and leading to energy and water losses.

Steam leaks and steam trap losses are particularly variable between plants and depend heavily on plant maintenance routines and monitoring. On the other hand, deaerator vent losses are needed for proper operation, but monitoring and control can help to minimize deaerator steam requirements. Deaerator losses can be estimated to be on the order of 0.5% of the system steam flow.[15]

Figure 1 also highlights the fact a number of industrial steam systems incorporate a combined heat and power (CHP) generation strategy. The particular CHP configuration shown above (boiler/steam turbine) is only one of several CHP strategies. Other examples include combustion turbines with heat recovery steam generators and combined cycles adapted for CHP. The use of CHP can be advantageous because it can achieve higher thermal efficiency than is possible through the production of steam and electricity through separate processes.[16]

While makeup water use can be minimized through efficient operations, energy inefficiencies that are common at many U.S. plants result in unnecessary and avoidable makeup water demand.

Pervasive Inefficiencies

Even at well managed plants, audits routinely reveal numerous opportunities for energy use reductions through the adoption of proven, cost-effective energy efficient technologies and operations strategies. Energy engineers often refer to such opportunities as "low-hanging fruit," and further know that such fruit can "grow back" over time due to

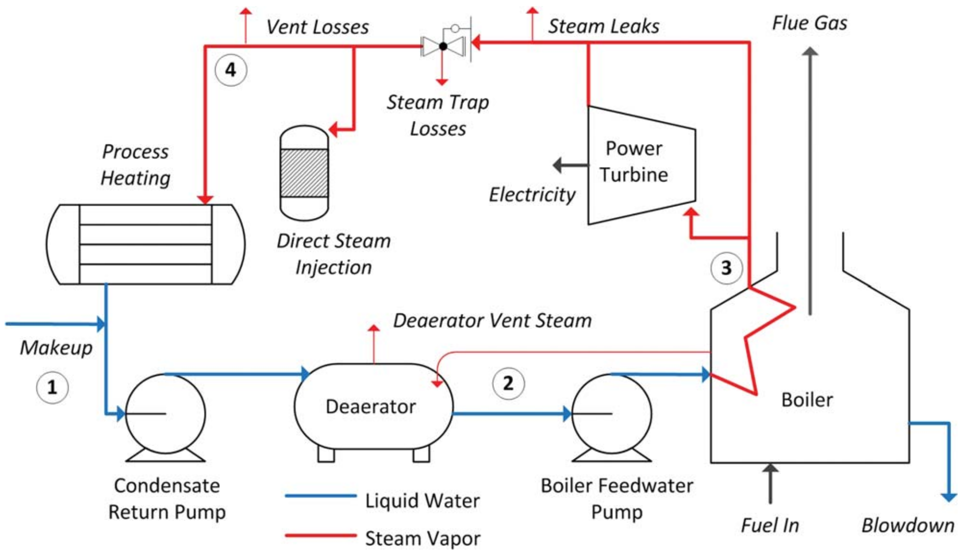

Figure 1. Simplified schematic of an industrial steam system.

equipment degradation, suboptimal maintenance practices, changing priorities on energy efficiency, and technology evolution.

For steam systems in particular, energy audits frequently identify significant savings potentials if plants were to adopt more efficient boiler operations, improved heat containment and recovery, improved condensate return, better maintenance programs, and improved process designs. For example, a 2002 U.S. Dept. of Energy (DOE) study of steam system efficiency opportunities in the U.S. chemicals, paper, and petroleum refining industries concluded that each industry might reduce its boiler fuel use by as much as 12% through the adoption of efficiency best practices.[17] Moreover, the simple payback periods for the identified improvements were generally less than 2 years, indicating quick returns on investment.

Just how pervasive are these opportunities in U.S. industry today? To help answer this question, we turn to data from recent energy audits at over 1,000 major U.S. manufacturing plants, which were conducted through the U.S. DOE's Save Energy Now (SEN) program between 2006 and 2011.[18] The SEN program targeted the nation's largest energy using plants—those with energy use exceeding 1 TBtu per year—with strategic audits of steam, compressed air, process heating, fan, and pump systems. As of this writing, summary data have been provided for 346 SEN steam system audits at plants whose combined annual energy use totaled 2,650 TBtu, or 17% of the direct energy use of U.S. industry. These audits resulted in over 2,200 identified steam system improvement opportunities. In total, these opportunities could save the audited plants over $660 million in energy costs each year and reduce their annual energy demand by 82 TBtu. These data are summarized in Table 1, which indicates that energy savings opportunities were particularly significant among the audited chemicals, paper, and primary metals plants. Thus, for a sizable segment of U.S. industry—which includes some of the nation's largest and best managed plants—the SEN data suggest that low-hanging fruit for steam system efficiency improvements are still plentiful.

Not all steam system energy efficiency improvements will reduce water use. For example, both improved boiler combustion controls and better distribution system insulation can save energy, but neither will affect the mass throughput of water. However, a number improvements—including reducing steam leaks and vented steam, improving condensate return, reducing blowdown rates, and lowering process steam—can directly reduce makeup water demand while also saving energy. The SEN audit results for these specific opportunities are summarized in Table 2, which indicates that 887 of the 2,220 identified opportunities (40%) across all industries held strong potential for combined energy-water savings.

Table 1. Summary of 346 SEN Steam System Audits, 2006–2011

U.S. Industry (NAICS)	Total identified energy savings (TBtu/yr)	Total identified energy cost savings ($\$10^6$/yr)	Number of opportunities identified
Chemical manufacturing (325)	32.6	225	547
Paper manufacturing (322)	17.9	210	485
Primary metals (331)	11.4	59	129
Food processing (311)	5.4	52	471
Petroleum refining (324)	4.9	46	86
Transportation equipment (336)	3.4	28	206
Wood products (321)	2.5	8	12
Textile mills (313)	1.4	6	17
Plastics and rubber (326)	1.3	14	112
Computer and electronics (334)	0.4	2	22
Textile products (314)	0.3	6	51
Fabricated metals (332)	0.3	3	21
Miscellaneous manufacturing (339)	0.2	1	21
Machinery manufacturing (333)	0.1	1	24
Total	82	662	2,200

Notes: NAICS = North American Industry Classification System. Totals and column sums may not be equal due to rounding.

Table 2. Summary of SEN Steam System Audit Opportunities with Energy-Water Savings Potential, 2006–2011

Energy saving opportunity	Number	Average energy savings (10^9 Btu/yr)	Total energy savings (10^{12} Btu/yr)	Average energy cost savings ($\$10^3$/yr)	Total energy cost savings ($\$10^6$/yr)	Average payback period (yr)
All SEN audits						
Change condensate recovery rates	139 [28]	27.7 [34.1]	3.8 [1.0]	248 [237]	34.5 [6.6]	1.1 [1.0]
Implement steam leak maintenance program	112 [50]	14.8 [16.9]	1.7 [0.8]	75 [123]	8.4 [6.2]	0.8 [0.7]
Implement steam trap maintenance program	163 [69]	21.6 [16.4]	3.5 [1.1]	163 [131]	26.6 [9.1]	0.6 [0.5]
Reduce or recover vented steam	68 [21]	20.1 [14.3]	1.4 [0.3]	138 [70]	9.4 [1.5]	0.8 [0.5]
Change boiler blowdown rate	100 [27]	15.8 [7.7]	1.6 [0.2]	137 [58]	13.7 [1.6]	2.1 [1.3]
Reduce process steam demand	305 [71]	81.2 [149]	24.8 [10.6]	480 [562]	146.3 [39.9]	1.9 [0.5]
Total	887 [266]	41.4 [52.8]	36.7 [14.1]	269 [243]	238.9 [64.8]	1.3 [0.7]
Chemicals manufacturing SEN audits						
Change condensate recovery rates	40 [8]	51.5 [64.8]	2.1 [0.5]	328 [433]	13.1 [3.5]	1.5 [0.6]
Implement steam leak maintenance program	40 [24]	10.3 [8.0]	0.4 [0.2]	54 [54]	2.1 [1.3]	0.9 [0.8]
Implement steam trap maintenance program	49 [28]	33.5 [18.2]	1.6 [0.5]	264 [144]	12.9 [4.0]	0.6 [0.5]
Reduce or recover vented steam	14 [4]	36.5 [39.4]	0.5 [0.2]	234 [83]	3.3 [0.3]	1.3 [0.4]
Change boiler blowdown rate	17 [6]	22.1 [18]	0.4 [0.1]	171 [158]	2.9 [0.9]	1.2 [2.3]
Reduce process steam demand	74 [21]	142 [430]	10.5 [9.0]	701 [1,390]	51.9 [29.2]	1.3 [0.7]
Total	234 [91]	66.3 [115]	15.5 [10.5]	369 [431]	86.3 [39.3]	1.1 [0.8]

Notes: Numbers without brackets refer to identified opportunities; numbers with brackets refer to implemented opportunities. Totals and column sums may not be equal due to rounding.

Table 2 contains SEN data of two types: those which refer to identified opportunities and those which refer to implemented opportunities. An implemented opportunity is one that was reported by plant staff as installed/pursued in post-audit follow-up communications to the SEN program. Comparison of identified and implemented results sheds light on the characteristics of opportunities that were ultimately pursued by the audited plants. Table 2 also provides a summary of results for chemicals plant audits alone, which showed particularly high potential for combined energy-water savings.

Across all audited plants, less than 40% of the identified energy savings and less than 30% of the identified cost savings in Table 2 were actually implemented at the time of this writing. Comparison of identified and implemented data reveals that, in general, audited plants chose to implement a subset of opportunities with faster-than-average payback periods and greater-than-average energy savings, indicating a rational preference for the most compelling investments. The greatest savings were realized through reductions in process steam demand, with the vast majority of these realized savings (85%) occurring in the audited chemicals manufacturing plants. Across the board, the audited chemicals plants realized much higher fractions of total identified energy and cost savings than the industry average, and did so through a focus on opportunities with energy savings much higher than the industry average. These data suggest a strong commitment to action at the audited chemicals plants, as well as a willingness for (sometimes difficult) reengineering of key processes to reduce overall plant steam demand.

Still, the data in Table 2 suggest that many low cost opportunities for combined energy-water savings are not being pursued at the audited plants. As of this writing, these plants had still left around \$175 million of the available energy cost savings on the table. Furthermore, \$47 million of that amount remained unrealized at the audited chemicals manufacturing plants. Despite the low-cost, high-return nature of opportunities identified through SEN audits, the history of the program suggests that many opportunities are ultimately rejected by participating plants. Of the 2,200 opportunities listed in Table 1, one-half were rejected by the time of this writing. Another 260 were designated as "in progress of implementation" and 360 were designated as "in planning." Thus, while there is still potential for additional energy savings as a result of the SEN audits, it is clear that many opportunities will be left unrealized, including many of the energy-water savings opportunities listed in Table 2.

Why would U.S. manufacturers leave so many compelling energy savings opportunities on the table? The SEN data show that of all rejected opportunities across industries and system types (i.e., steam, fans, pumps, process heaters, and compressed air), nearly half were rejected due to initial investment and cash flow restrictions or unsuitable return on investment. While such fiscal restrictions may seem surprising given the low-cost nature of SEN opportunities, such restrictions are pervasive across U.S. industry and have likely been exacerbated in recent years due to the economic recession. Common reasons for fiscal restrictions include: priorities placed on short-term revenue generation over longer-term energy cost savings; increasingly limited budgets for capital energy investments; shorter budget cycles; and insufficient engineering staff time dedicated to energy efficiency projects.[19] These restrictions can be particularly pronounced at small and medium-sized manufacturers, whose pockets and staff rosters are typically far less deep than those of the large plants covered by the SEN audits.

Another 25% of rejected opportunities were due to unacceptable process/equipment changes or opportunities deemed impractical, which can include unacceptable plant downtime. Opportunities rejected for these reasons can often be a tougher sell. However, companies that are committed to energy savings at the highest levels of their organizations are often willing to address the (sometimes) complex engineering and operations challenges associated with process and equipment changes.

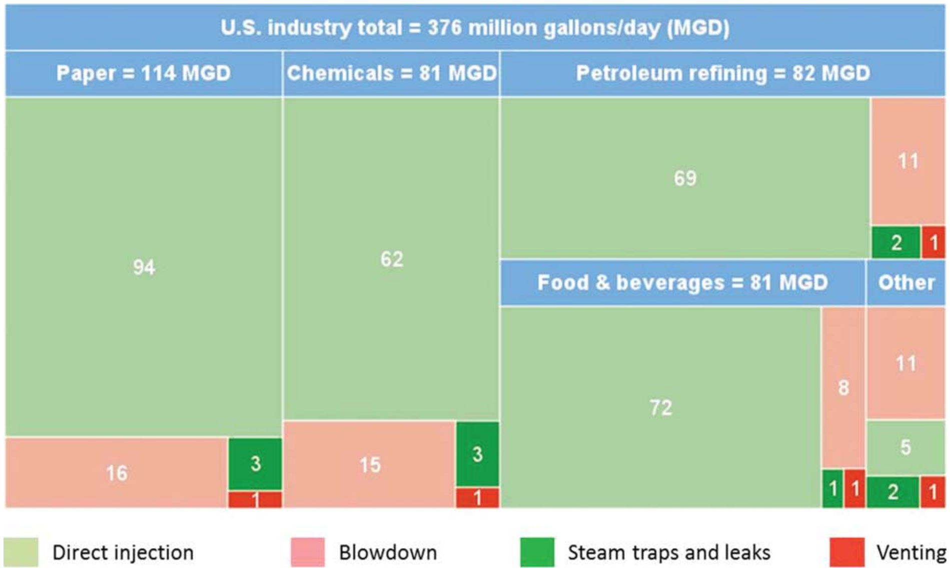

Figure 2. Estimated annual makeup water use by U.S. manufacturing industry and source. Note: Totals and header sums may not be equal due to rounding.

As manufacturers become increasingly mindful of water use, however, the makeup water savings that come along with many steam energy efficiency opportunities might improve their attractiveness as sustainability investments.

Makeup Water Demand

As mentioned previously, detailed industrial water use data are not compiled in a regular basis in U.S. national surveys. The few studies that have attempted to fill this gap have focused mostly on estimates of the total water use of specific manufacturing industries.[20,21] Moreover, these studies have no explicit treatment of boiler makeup water use. As engineers, however, we need not be completely in the dark; rather, we can use thermodynamic principles to estimate the magnitude of US industrial steam system water demand.

Specifically, national data on boiler fuel inputs by manufacturing industry and fuel type are available from the U.S. DOE's Manufacturing Energy Consumption Survey (MECS).[3] These data quantify the total thermal inputs on the boiler side of the nation's steam systems. Additional data from process energy demand studies and models of specific industries shed light on the quantities and properties of various steam end uses in U.S. plants.[1,22,23] A basic thermodynamic model of a steam generation and distribution system can connect the dots between total fuel inputs and total process demand to estimate annual makeup water requirements.

Figure 2 summarizes makeup water demand estimates based on this thermodynamic approach for U.S. industrial steam systems as of 2006, which is the latest year MECS data are available. These estimates were generated using typical values for industrial steam system blowdown rates, venting losses, boiler efficiencies, and leak rates as discussed above. Further details on the analysis can be found in Walker et al.[24]

The data in Figure 2 are presented as a treemap, in which the total makeup water use of each listed manufacturing industry is represented by a box with a blue header. Each box is broken into four regions corresponding to different sources of steam and water loss (see Figure 1). In total, an estimated 376 million gallons per day (MGD) of makeup water are consumed by U.S. industry. This amount is equivalent to the daily domestic water use of 3.8 million U.S. residents, which is roughly the population of Los Angeles, the nation's second-largest city.[6,25]

The paper, chemicals, petroleum refining, and food and beverage industries account for the vast majority of estimated makeup water demand. These results are not surprising given that these four industries also account for the lion's share of industrial steam demand. Within each industry, direct injection of steam comprises by far the largest source of makeup water use, which suggests that energy efficiency measures that reduce process steam demand might also deliver significant water savings. While the data in Figure 2 are engineering estimates only, their magnitude demonstrates that massive quantities of water are required for steam provision in U.S. plants. This, in turn, implies that steam systems may be a worthwhile target for water efficiency initiatives at many manufacturers, and within the paper, chemicals, petroleum refining, and food and beverage industries in particular.

This point is underscored by Figure 3, which depicts the estimated makeup water savings associated with the SEN audit opportunities listed in Table 2. These estimates were generated using the thermodynamic analysis approach described earlier, and are plotted for the five industry categories depicted in Figure 2. Estimated water savings associated with both identified and implemented SEN opportunities are listed numerically, with bubble sizes proportional to water savings magnitudes.

The estimated makeup water savings achievable through the 887 identified energy-water saving opportunities in Table 2 sum to around 7.3 MGD, or an amount equivalent to the daily domestic water use of around 74,000 U.S. residents. Of this total water savings potential, however, only an estimated 2.3 MGD were realized although the implemented opportunities. Of all audited plants, those in the chemicals industry realized the greatest fraction of their estimated water savings potential (ca. 60%), primarily by pursuing process steam demand

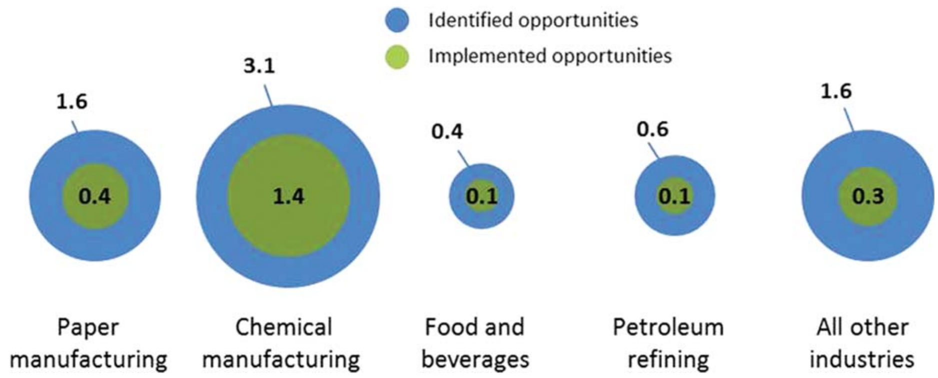

Figure 3. Estimated makeup water savings (MGD) from SEN audits by manufacturing industry.

reduction opportunities as seen in Table 2. The other four industry categories realized 20% or less of their estimated water savings potentials. It is clear from Figure 3 that, in addition to leaving many compelling steam system energy savings opportunities on the table, many of the audited plants may have forgone sizeable makeup water savings as well.

The Path Forward

The combined energy-water savings associated with steam system efficiency improvements should prove attractive to manufacturers seeking to reduce their environmental footprints, especially in light of the growing importance of water efficiency. The estimates summarized here suggest that the makeup water footprint of U.S. industrial steam is substantial, and that this footprint can be reduced through improved steam system efficiency. In particular, reductions in process steam demand in the paper, chemicals, petroleum refining, and food and beverage industries are especially important. While the importance of water efficiency may vary from plant to plant based on local water resource availability and water stress, a greater focus on water-efficient steam systems is warranted in general given growing pressures on the nation's water resources and delivery infrastructure. There are several opportunities both within and external to the engineering community that can enable this change moving forward.

First, while the engineering estimates summarized here fill an important information gap, better water use data reported by manufacturing plants on a regular basis would offer a more precise picture of the water footprint of U.S. industry. Water use data reported at the process level within specific manufacturing industries would be particularly valuable for broadening awareness of the sources and scale of industrial water use at the regional and national levels. While a number of manufacturers provide corporate water use data as part of annual sustainability reports, these data are rarely reported at the individual plant or process levels. Moreover, many manufacturers do not report on water use, and many have yet to issue sustainability reports. A greater commitment to water efficiency at the highest levels of manufacturing organizations might spark the widespread culture change needed among plants to regularly track and report water use data. Regional and national government agencies might collect industrial water use data with greater detail and frequency as another catalyst for change. For example, the DOE's MECS questionnaire might be easily augmented to request annual boiler makeup water use data along with annual boiler fuel use data since many plants have access to both types of data via their existing boiler control software systems.

Second, improved public and private sector incentives for industrial water efficiency can make investments with combined energy-water savings more financially attractive to plants that might otherwise reject opportunities on the basis of energy savings alone. Such incentives are often critical for accelerating technology deployment, especially for small and medium sized facilities, which often have severely limited capital budgets for efficiency improvements. Better plant water use data will be critical for making the case for such incentives, which can include equipment rebates from local utility companies or tax breaks at the regional or federal levels. Such incentives are widely available for energy efficiency investments,[5] and thus several successful models of incentives design exist for water utilities and water resource agencies to adopt.

Third, at the plant level, manufacturers can adopt a strategic water management plan that allows for goal setting and water use performance tracking. Such plans are critical for enabling continuous improvement across the plant, including the minimization of steam demand and inherent system losses. A strategic water management plan can be integrated with strategic energy management plans—successful examples of which are plentiful in U.S. industry[26]—for clear identification and pursuit of energy-water savings opportunities. One component of such plans can be to extend the concept of corporate "energy teams"[27] by creating analogous "water teams." The job of the water team would be to seek out water savings opportunities and instill heightened awareness of the importance of water efficiency among plant staff. Again, for such initiatives to succeed, a commitment to water efficiency at the highest levels of plant management is often required.

Last, we have a clear opportunity for improving education on the nature and importance of energy and water use in steam systems as part of the undergraduate engineering curriculum. While nearly every engineering student is introduced to steam tables as part of basic courses on thermodynamics, very few receive training in the practical aspects of real-world steam generation and distribution systems. Yet it is these practical aspects that have the most profound impacts on energy-water efficiency (e.g., the performance of steam traps, condensate return systems, and heat recovery). As such, many engineers are fairly blind to the true costs of the hissing steam traps and vents, poorly insulated pipes, and dripping valves that surround us in the typical plant environment. Visits to local manufacturing plants to witness the operation of core plant systems would be invaluable toward helping students connect engineering theory to real-world equipment operations. Such in-depth understanding of the energy-water connection is particularly critical for our nation's chemical engineers, who are typically on the front lines of process design for major steam-consuming processes in most manufacturing industries. As discussed previously, it is these processes that hold the greatest potential for combined energy-water savings through more efficient process design, control, and operations. Indeed, increased awareness among all engineers who work in manufacturing plants—and perhaps among chemical engineers in particular—might be the most important opportunity for increasing the water-energy efficiency of U.S. industrial steam systems moving forward.

Acknowledgments

The authors thank Sachin Nimbalkar of Oak Ridge National Laboratory, who graciously provided the SEN audit summary data as well as much advice to help ensure their proper interpretation.

Literature Cited

1. Brueske S, Sabouni R, Zach C, Andres H. *US Manufacturing Energy Use and Greenhouse Gas Emissions Analysis*; 2012. Oak Ridge National Laboratory, Oak Ridge, TN; 2012. ORNL/TM-2012/504.
2. U.S. Department of Energy (DOE). *Improving steam system performance: a sourcebook for industry*. 2nd ed. Advanced Manufacturing Office; 2012. DOE/GO-102012-3423.
3. U.S. Department of Energy (DOE) *Manufacturing Energy Consumption Survey: 2006*. Washington, Washington, DC: Energy Information Administration; 2009. http://www.eia.gov/consumption/manufacturing/.
4. U.S. Department of Energy (DOE). *Annual Energy Outlook 2012*. Washington, DC: Energy Information Administration; 2012. DOE/EIA-0383.
5. *North Carolina Solar Center and the Interstate Renewable Energy Council*. North Carolina State University: Database of State Incentives for Renewables and Efficiency; 2013. http://www.dsireusa.org/.
6. Kenny JF, Barber NL, Hutson SS, Linsey KS, Lovelace JK, Maupin MA. *Estimated Use of Water in the U.S. in 2005*. US Geological Survey Circular 1344; 2009.
7. U.S. Department of Energy. *How to Calculate the True Cost of Steam: A Best Practices Steam Technical Brief*. Washington, DC: Industrial Technologies Program; 2003. DOE/GO-102003-1736.
8. Walton B. *The Price of Water 2012: 18 Percent Rise since 2010, 7 Percent over Last Year in 30 Major U.S. Cities*. Circle of Blue; 2012.
9. California Natural Resources Agency. *2009 California Climate Adaptation Strategy*. Sacramento, CA; 2009.
10. Sathaye JA, Lecocq F, Masanet E, Najam A, Schaeffer R., Swart R, Winkler H. Opportunities to change development pathways towards lower greenhouse gas emissions through energy efficiency. *J Energy Efficiency*. 2009;2:4.
11. Kitto JB, Stultz SC, eds. *Steam: Its Generation and Use*. 41st ed. Barberton, OH: The Babcock and Wilcox, Co.; 2005.
12. Seider WD, Seader JD, Lewin DR. *Product and Process Design Principles: Synthesis Analysis and Evaluation*. 2nd ed. New York: Wiley, Inc.; 2004.
13. Harrell G. *Steam System Survey Guide*. Oak Ridge National Laboratory, Oak Ridge, TN; 2002. ORNL/TM-2001/263.
14. U.S. Department of Energy (DOE). *Steam Pressure Reduction: Opportunities and Issues*. Washington, DC: Industrial Technologies Program; 2005. DOE/GO-102005-2193.
15. Zeitz R. ed. *CIBO Energy Efficiency Handbook*. Burke, VA: Council of Industrial Boiler Owners; 1997.
16. U.S. Department of Energy (DOE). *Review of Combined Heat and Power Technologies*. Washington, DC: Industrial Technologies Program; 1999.
17. U.S. Department of Energy (DOE). *Steam System Opportunity Assessment for the Pulp and Paper, Chemical Manufacturing, and Petroleum Refining Industries*. Main Report. U.S. Dept of Energy: Energy Efficiency and Renewable Energy; 2002. DOE/GO-102002-1639.
18. Martin M, Wright A, Nimbalkar S, Schoeneborn F. In: *From Energy Assessment to Maximum Implementation: Reducing the "Implementation Gap" for Save Energy Now LEADERS*. Proceedings of the 2011 ACEEE Summer Study on Energy Efficiency in Industry: Niagara Falls, NY; 2011.
19. Russell C. Barriers to industrial energy cost control: The competitor within. *Chem Process*. 2005.
20. Blackhurst M, Hendrickson C, Sels VJ. Direct and indirect water withdrawals for US industrial sectors. *Environ Sci Technol*. 2010;44:6.
21. Ellis M, Dillich S, Margolis N. *Industrial Water Use and Its Energy Implications*. Washington, DC: U.S. Dept of Energy, Office of Energy Efficiency and Renewable Energy; 2001.
22. Jacobs and IPST. *Pulp and Paper Industry. Energy Bandwidth Study*. Report for American Institute of Chemical Engineers (AIChE). Atlanta, GA: Jacobs Greenville and Institute of Paper Science and Technology (IPST) at Georgia Institute of Technology; 2006.
23. Brown HL, Hamel BB, B. Hedman B. *Energy Analysis of 108 Industrial Processes*. Englewood Cliffs, NJ: Prentice Hall; 1996.
24. Walker ME, Lv Z, Masanet E. *Industrial Boiler Systems and the Energy-Water Nexus*. Submitted Jun. 2013.
25. U.S. Census Bureau. *State and County QuickFacts*. Washington, DC: Dept of Commerce; 2013. http://quickfacts.census.gov.
26. Masanet E, Worrell E, Galitsky C. *Energy Efficiency Improvement and Cost Saving Opportunities for the Fruit and Vegetable Processing Industry: An ENERGY STAR® Guide for Energy and Plant Managers*. Berkeley, CA: Lawrence Berkeley National Laboratory; 2007. LBNL-59289.
27. U.S. Environmental Protection Agency (EPA). *Teaming Up to Save Energy: Protect Our Environment Through Energy Efficiency*. Washington, DC: Climate Protection Division; 2007. Report 430-K-05-007.