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WATER AND ENERGY USE OF ANTIMICROBIAL INTERVENTIONS IN A MID-SIZE BEEF PACKING PLANT

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WATER AND ENERGY USE OF ANTIMICROBIAL INTERVENTIONS IN A MID-SIZE BEEF PACKING PLANT

R. M. M. Ziara, S. Li, B. I. Dvorak, J. Subbiah

ABSTRACT. *Data regarding the water and energy usage of current antimicrobial interventions in beef packing plants is scarce. The objective of this study was to collect representative water and energy usage data in a beef packing plant, with emphasis on antimicrobial interventions, to provide baseline data for comparison of new intervention technologies developed by researchers. Permanent and portable water flow meters were installed on the plant's plumbing system to collect water flow data from March 2014 to March 2015. A local utility company was hired to meter electricity at the different subsystems using portable data loggers. The natural gas used in each subsystem was estimated by the amount of steam required to heat the water to the desired temperature and assuming the boiler efficiency as 82%, as estimated by the plant personnel. All data was normalized per 1000 kg live body weight (1000 kg LBW). The overall plant-wide water usage was 2968 L/1000 kg LBW (355 gal/1000 lb LBW). The antimicrobial interventions used 15.7% of the total water usage while viscera and byproducts processing, and overnight cleaning water accounted for 19% and 39% of the total water usage, respectively. The water usage was 100, 16, 253, and 97 L/1000 kg LBW for the pre-evisceration wash, organic acid spraying, carcass wash, and thermal pasteurization, respectively. The total metered electrical energy was 110.5 MJ/1000 kg LBW, over 96% of which was used by the plant's cooling and hydraulic systems. The overall plant-wide natural gas usage was 512.6 MJ/1000 kg LBW, 11.6% of which was used by antimicrobial interventions for water heating. The viscera and byproducts processing, overnight cleaning, and other usage and losses, accounted for 11.7%, 36.1%, and 40.6% of the total natural gas, respectively.*

Keywords. *Antimicrobial interventions, Beef packing, Beef safety, Water and energy usage.*

The beef industry in the United States is the largest agricultural sector (Otto and Lawrence, 2001). The world food demand is expected to increase by 70% by 2050 due to the world population growth (Capper, 2011). Therefore, with limited available resources, it becomes important to monitor the water and energy usage and their impact on the environmental footprint of the beef sector. Food safety is a major priority for the food industry, regulators, and consumers. Conversion of meat animals to meat invariably results in contamination of the carcasses with microorganisms originating from the hides and or the intestines. Prevention of contamination of meats is difficult to achieve, and the majority of processors incorporate antimicrobial intervention steps during processing to reduce the foodborne pathogen loads. Washing of carcasses consumes a large amount of water and spraying of antimicrobials generates significant waste streams. While they are resource intensive, antimicrobial interventions are necessary steps required to assure beef safety. Several new antimicrobial intervention technologies are being developed to improve the safety of beef products, like electrostatic spraying of organic acids (Nam et al., 2011; Phebus et al., 2014) and electron beam irradiation (Li et al., 2015). While most research focuses on the efficacy of these technologies in reducing microbial loads, scarce data are available in the literature about their water and energy consumption. The objective of this study was to collect representative data on the water and energy usage of current antimicrobial interventions in a beef packing plant for researchers to evaluate current and new technologies. In addition, the overall plant-wide water and energy usage of the beef packing plant were collected. The data were collected from one mid-size plant located in the Midwest, which highlight proportions of water and energy usage inside the plant.

MATERIALS AND METHODS

This study focused on quantifying the water and energy usage at each antimicrobial intervention, major water and energy consuming processes and overall usage. The data were collected for 12 months using a combination of permanent and temporary meters. In this study, water and energy usage only for cattle processing was concerned, data about the water and energy usage of the office building, human

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consumption and landscaping were beyond the scope of this study.

PLANT DESCRIPTION

This study was conducted at a mid-size beef packing plant located in the Midwest. Each beef packing plant has a unique process flow diagram and some aspects are considered proprietary, but basic processing steps are common for most plants. The process flow diagram developed for this study is illustrated in figure 1. Different system boundaries were considered in this study to focus on antimicrobial interventions and major water and energy consuming subsystems as shown in figure 1.

In a typical beef packing plant, cattle processing starts with holding the cattle in pens for a couple of hours to release stresses gained during transportation. In cattle holding pens, cattle are sprayed with water for evaporative cooling to prevent hyperthermia (Standing Committee on Agriculture and Resource Management, 2002). Cattle are then stunned and bled. Blood is collected, mixed with anticoagulant, and transported for further processing. Some plants may have hide-on wash to clean the hides from potential contaminants. As the cattle legs are trimmed and carcasses are de-hided, proper antimicrobial safety measures are taken; e.g. tails are rubber-banded with plastic bags and legs are washed with a special leg washing-vacuum mechanism. Before evisceration and splitting, carcasses go through hot water pre-evisceration wash and organic acid spraying. At this plant, the viscera was processed for edible use mostly. The system boundary of the viscera and byproducts processing, no. 3 in figure 1, included offal washing processes, abomasum, omasum and tripe washing and refining processes, small and large intestines washing processes, feet cooking processes, and tongue and tail washers. After evisceration and splitting, they go through carcass wash, thermal pasteurization, and organic acid spraying before chilling and fabrication. The arrangement of the organic acid spraying may differ from plant to plant. Some plants may even mix the organic acids with the different water washes instead of spraying separately.

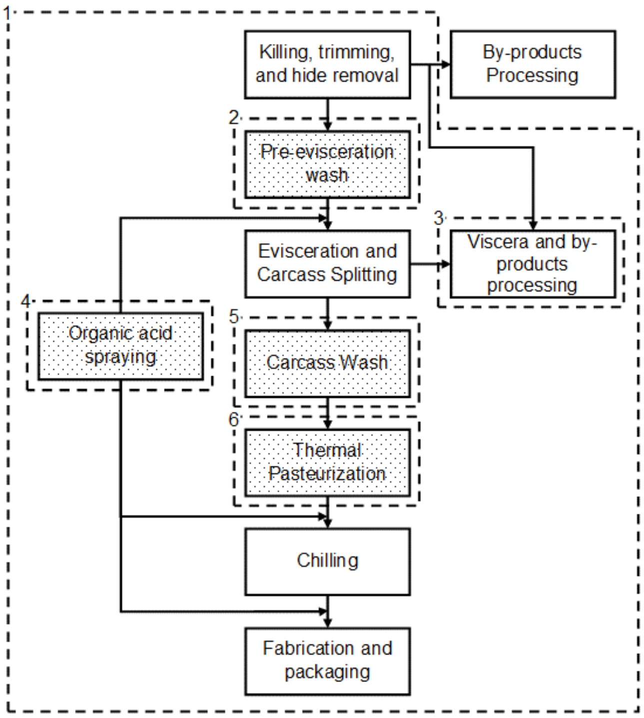

Figure 1. Simplified process flow of a beef packing plant, examined subsystems (dashed line) and antimicrobial interventions (hatched).

Table 1 provides a description for each of the subsystems examined in this study, as shown in figure 1. It also provides details about the measured inputs for each subsystem. The reference numbers of the subsystems in table 1 are also shown in the top left corner for each subsystem in figure 1. The antimicrobial interventions investigated at this plant were the pre-evisceration wash, the carcass wash, the organic acid spraying, and the thermal pasteurization. To normalize the collected data, head count and live weight data were obtained from the plant for the period of the study.

The plant received its cattle processing water from the city through a separate main at around 15.6°C (60°F). Water used between 5:00 A.M. and 5:00 P.M. was for cattle processing and called, hereafter, *processing water*. Water used between 5:00 P.M. and 5:00 A.M. was water used mainly for facility cleaning and called, hereafter, *overnight use* water. The temperature of the overnight use water was 49°C (120°F).

Natural gas was used to heat water to different temperatures using multiple boilers. Hydraulic systems were used to move carcasses through the different processing steps. The refrigeration system uses several ammonia compressors for operation.

WATER

To accommodate for the different water temperatures required for different processes, shown in table 1, different water flow meters were used in this study. Seven permanent flow meters were installed and connected to a computer database, which was programmed to continuously record water flow data at 5 min intervals. The permanent meters were two M170, an M120, an M70 and an M35 Recordall Disc Meters and two M2000 Badger Meter M-Series (manufactured by Badger Meter, Inc., Milwaukee, Wis.). The manufacturer accuracy charts for the meters indicate measurement within 1% error. Metering the water use of the viscera and byproducts processing was not possible, therefore it was estimated based on the hydraulics of its wastewater collection pipe, using the following jet water flow equation (Gray, 1998):

$$Q = A \times \sqrt{2\Delta Hg} \qquad (1)$$

where

Q = water flow rate ($m^3\ s^{-1}$)
A = cross-sectional area of the pipe (m^2)
ΔH = net available head at discharge point after accounting for friction and minor losses (m)
g = acceleration of gravity ($m\ s^{-2}$).

In addition, a portable type ultrasonic flow meter, flow transmitter type FSC-2 and detector type: FSSD-1 (manufactured by Fuji Electric Co., Ltd., Japan), was used to collect water flow data where needed for at least a week at each location. The ultrasonic flow meter was tested for accuracy

Table 1. Description of measured resources at each subsystem.

	Subsystem Examined (Reference number describing system boundary in fig. 1)					
Resource	Total Use (1)	Pre-evisceration Wash (2)	Viscera and Byproducts Processing (3)	Organic Acid Spraying (4)	Carcass Wash (5)	Thermal Pasteurization (6)
Water	P(15.6°C)[a]	P(38°C)	E(38°C)[b]	P(60°C)	P(38°C)	P(85°C)
Natural gas	P	E	E	E	E	E
Electricity	-	T[c]	T	T	T	T

[a] P = permanent meters.

[b] E = estimated.

[c] T = temporary meters.

and precision at an external lab as well as University of Nebraska-Lincoln hydraulics lab and less than 2% error was found.

ELECTRICITY

A local utility company was hired to collect electricity usage data of each subsystem for at least one week. ELITEpro data loggers (manufactured by DENT Instruments, Bend, Ore.) were installed at the plant's distribution boards to collect electricity usage data. The technical sheets for the data loggers were reviewed and the error was found at less than 0.2%. Electricity usage was measured for the antimicrobial interventions, refrigeration compressors, and hydraulic systems for at least one week at each location.

NATURAL GAS

The daily natural gas usage data during June 2014 was obtained from the plant for the purpose of this study. A summer month was chosen as no heating was used for the buildings. The plant uses multiple boilers that generate steam at 724 kPa (105 PSIG), which is used to heat the water to the desired temperature. The boilers efficiency was estimated by the plant personnel to be between 82% and 87% based on internal energy audit. The lower value of 82% was used to be conservative on estimation.

The natural gas usage of each subsystem was estimated by the amount of steam required to heat the water to the desired temperature. Fundamental thermodynamics principles including specific heat capacity of water, latent heat, and natural gas energy content were combined with water and temperature data to estimate the natural gas usage as follows.

The amount of heat absorbed by water was calculated using the following relationship (Widder, 1976):

$$Q=m\times c_p\times \Delta T \tag{2}$$

where

m = mass of water from measured flow rates (kg)

c_p = water specific heat (0.0042 MJ $kg^{-1}\cdot K^{-1}$, Tipler and Mosca, 2003)

ΔT = temperature difference between the initial water temperature and the target final temperature (K).

The amount of natural gas required was calculated using the following equation:

$$NG_{req}=\frac{Q}{C_{NG}\times \varepsilon_{boiler}} \tag{3}$$

where

NG_{req} = volume of natural gas required (m^3),

C_{NG} = heat content of natural gas [38.75 MJ m^{-3} (1040 BTU cft^{-1}), US-EIA, 2013]

ε_{boiler} = boilers efficiency.

RESULTS AND DISCUSSION

All water and energy data were normalized per 1000 kg cattle live body weight (1000 kg LBW). The average head live weight was 630 kg. The operating capacity of the plant is presented as a percentage of the maximum capacity to maintain confidentiality of the plant information.

WATER

The overall plant-wide water usage of the plant was 2968 L/1000 kg LBW. The water use of a beef packing plant is a less than a percent of the water footprint of beef (e.g., Rotz et al., 2013). However, a typical large beef packing plant in the United States slaughters 1 million cattle/year and therefore is a large water user in its community and a major wastewater emitter. The portion of water used for cattle processing was 54.5% of the total water usage at the plant; including the antimicrobial interventions (16%). The overnight water usage was 39% and other usage, including losses and water usage outside the subsystems shown in figure 1, was 26% of the total water usage. Over the past three decades, the reported total water usage for U.S. slaughterhouses ranged from 4,200 to 16,700 L/1000 kg LBW and for U.S. meat packing plant ranged from 6,300 to 29,200 L/1000 kg LBW (Schultheisz and Karpati, 1984; Johns, 1995; Hansen et al., 2000). The collected data from this plant suggest notable improvement on the total water use of a beef packing plant.

To understand the diurnal use pattern, an ultrasonic flow meter was used for a week to collect instantaneous data every 10 min on the overall water usage of the plant, which was 2968 L/1000 kg LBW. The water flow pattern for the week of measurement is shown in figure 2.

Figure 2a shows that the start of the shift was at 6:30 A.M. and the end of the shift was around 3:15 P.M. each day for the week of data collection. The flow rates were made dimensionless by normalizing with the highest instantaneous flow measure at 2 P.M. on Friday. Similarity in the water use during the weekdays is noticed, especially during the period when cattle were processed, this is reflected on the data variability presented in figure 2b. The water flow pattern shows that the water usage was reduced during the breaks and the

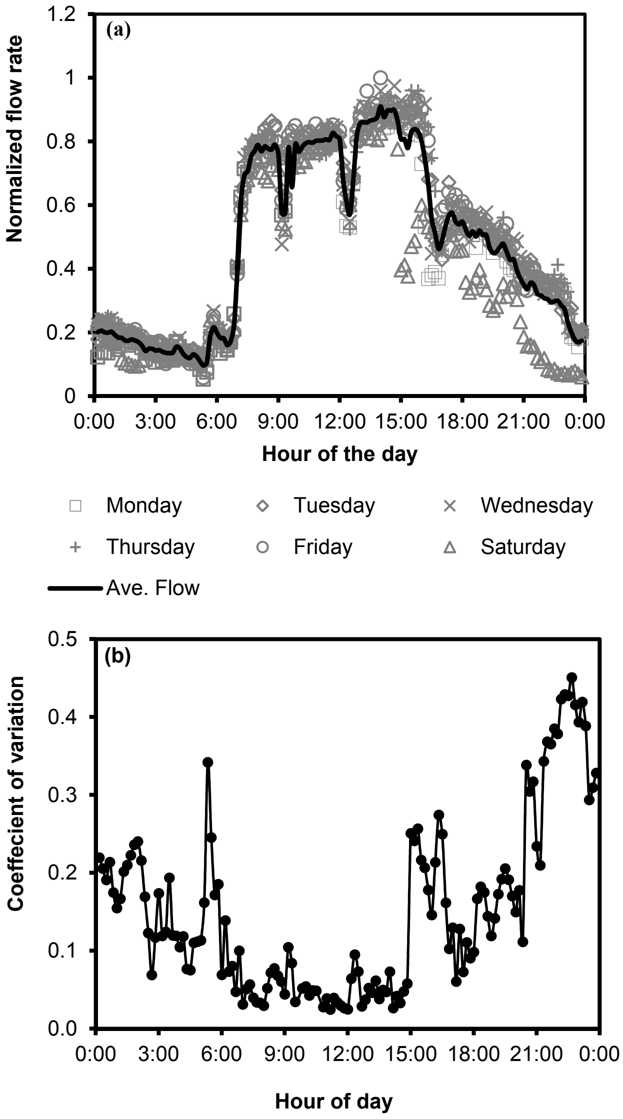

Figure 2. 24-h patterns for (a) total water usage of the plant and (b) coefficient of variation of total water usage based on data collected in (a). The flow rates in (a) were normalized by dividing the water flow readings by the maximum flowrate observed at 2 P.M. on Friday.

water usage slightly increased after 12:00 P.M., because minor cleaning activities started in the afternoon. Figure 2a also shows that the overnight cleaning of the plant started around 5:00 P.M. every day.

The 10-min based coefficient of variation (ratio of standard deviation and mean) for the data collected in figure 2a is shown in figure 2b. It is noticed that the coefficient of variation between 6:30 A.M. and 3:30 P.M. was lower than elsewhere. Because most of cattle processing operations are consistent each day, the variability of the water use during this period is relatively lower. On the other hand, the variability of the overnight water use, mainly facility cleaning, was relatively high, because most of the facility cleaning was performed manually and starting and ending time might have varied from day to day.

Figure 3 provides a breakdown of the water usage at the plant in various categories. Antimicrobial interventions con-

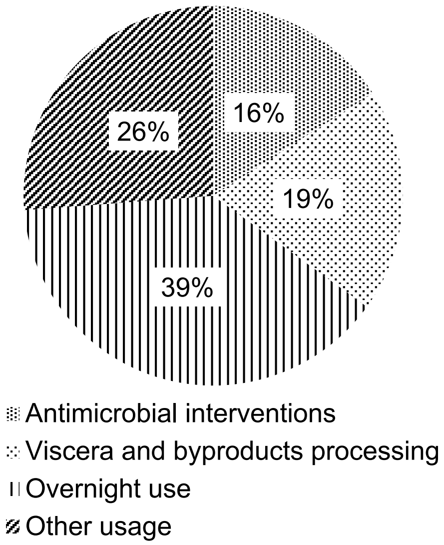

Figure 3. Percent of water usage per category, Total water usage was 2968 L/1000 kg LBW.

sidered in this study were the pre-evisceration wash, the organic acid spraying, the carcass wash, and the thermal pasteurization, as shown in figure 1. Figure 3 shows that antimicrobial interventions used a small portion of the total water use. The pre-evisceration wash, which used 38°C (100°F) water, consumed 100 L/1000 kg LBW. At this plant, three organic acid cabinets were used for microbial disinfection at the places shown in figure 1. Measuring the water usage by the three cabinets was not possible, and therefore water usage of two cabinets was measured and the data was extrapolated for three cabinets. The organic acid spraying, which used 60°C (140°F) water, consumed 16 L/1000 kg LBW. The carcass wash, which uses 38°C water, was the highest water consumer among the antimicrobial interventions. The carcass wash consumed 253 L/1000 kg LBW. Carcass wash uses a relatively high amount of water because microbial contamination risk is higher after evisceration and splitting. Thermal pasteurization at this plant used water recycling system. The water was heated to 85°C (185°F) and the temperature of the recycled water was measured at an average of 60°C, using a portable infrared thermometer. The water was renewed at least twice a day and the process used steam injection to reheat the water. The thermal pasteurization used 97 L/1000 kg LBW (56 L/head). The manufacturer's recommended water usage for hot water pasteurization without recycling was 190 L/head (Chad Equipment LLC, hot water pasteurization system technical sheet, personal communication, Nov. 2014). Thus, the recycling system at this plant reduced the water use of the thermal pasteurization by approximately 70%.

The variability of water use for each process step is essential to perform further risk assessment studies. Using the collected date over the 12 months, distribution plots of the water usage were developed for the subsystems shown in figure 1. These distribution figures are provided in figure 4 and were developed using XLSTAT (a statistical analysis Excel add-in provided by Addinsoft SARL). Developing

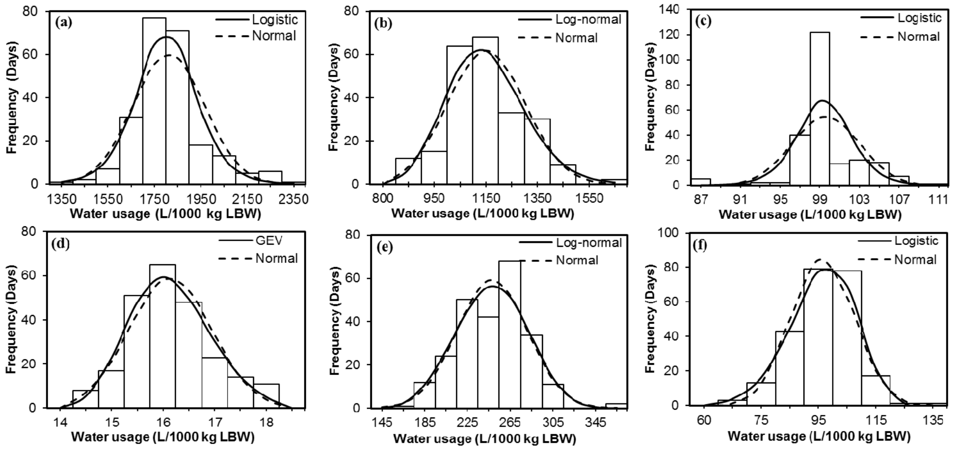

Figure 4. Water use variability for (a) processing water, (b) overnight use, (c) pre-evisceration wash, (d) organic acid spraying, (e) carcass wash, and (f) thermal pasteurization.

water use distribution for the viscera and byproducts processing was not possible due to the flow measurement method used. Figure 4 shows the distribution of the discrete water usage data and the continuous distribution curves for the best-fit and normal distributions. XLSTAT automatically selects the best-fit distribution based on the highest p-value of the Kolmogorov–Smirnov test (K-S test), given a significance level (0.05). If the K-S test p-value is larger than the significance level, the data are consistent with the specified distribution. The higher the K-S test p-value, the better the fit with the specified distribution. On these plots, the water usage is shown on the x-axis and the frequency (day count for each water usage) is shown on the y-axis. The statistical parameters of the fitted distributions are provided in table 2.

As seen in table 2, the normal distribution did not fit (a) processing water, (b) overnight use, and (c) pre-evisceration data well; p-values less than 0.05. On the other hand, the normal distribution fitted the water use data of (d) organic acid spraying, (e) carcass wash, and (f) thermal pasteurization was statistically acceptable; p-value larger than 0.05. The best-fit distribution for the pre-evisceration wash data was not good with very small K-S test p-values. This is also evident in the figure 4. While it is not clear why the variability in carcass wash was high, the higher variability of the processing water and the overnight use may be attributed to manual processes like viscera washing and cleaning of the facility.

ELECTRICITY

The electricity was monitored by a local utility company for at least one week for each location. Data loggers were programmed to record average power use (kW) on 5 min intervals. A summary of collected electricity and natural gas usage, normalized per head and per 1000 kg LBW, is provided in table 3.

The equivalent total electrical energy metered was 110.5 MJ/1000 kg LBW. The total electrical energy used by antimicrobial interventions at this plant was minimal. Most of the antimicrobial interventions use pumps, fans, and vacuums that are relatively low electric consumers. The cooling system and hydraulic systems, which use several ammonia compressors and high capacity pumps, respectively, are the largest electric consumers. The cooling system metered includes the refrigeration system for the chilling, cooling for the storage area, and the air conditioning for the fabrication floor.

NATURAL GAS

Fundamental thermodynamics principles, water flows, and temperatures were combined to calculate natural gas used at each subsystem. The overall natural gas plant usage was obtained for the month June 2014 from the plant for verification of these calculations. June 2014 was picked as a representative month because the plant was running at relatively high capacity and no gas was used for the buildings heating.

At this plant, the overall natural gas usage was 512.6 MJ/1000 kg LBW, including the antimicrobial interventions (11.6%), as listed in table 3. Among the antimicrobial interventions, the carcass wash used the highest amount of natural gas and water. Because the thermal pasteurization system recycled hot water, it also recycled heat energy. The manufacturer's recommended recycled and make-up water use for a hot water thermal pasteurization system is 190 L/head. At this plant, the recycled water temperature was measured at an average of 60°C. The mass and energy balance analysis showed that using a water recycling system reduced the natural gas usage by about 64%.

Table 2. Water use distribution-fitting parameters.

	Best Fit Distribution			Normal Distribution		
Water Use	Type	Parameters	K-S Test p-Value	μ	σ	K-S Test p-Value
Processing water	Logistic	μ = 1800.85, s = 79.13	0.5168	1811.56	150.94	0.0087
Overnight use	Log-normal	μ = 1151.44, σ = 0.13	0.3457	1151.35	147.90	0.0611
Pre-evisceration wash	Logistic	μ = 99.43, s = 1.68	< 0.0001	99.61	3.40	< 0.0001
Organic acid spraying	GEV	k = 0.19, β = 0.74, μ = 15.59	0.5870	15.90	0.79	0.2305
Carcass wash	Weibull (3)	β = 3.62, γ = 118.36, μ = 146.35	0.3487	253.20	32.25	0.2455
Thermal pasteurization	Weibull (3)	β = 6.51, γ = 67.21, μ = 33.21	0.4070	96.38	10.62	0.1469

Table 3. Metered electricity and natural gas usage at the beef packing plant.

	Electricity			Natural Gas		
Process	kW·h/head	MJ/1000 kg LBW	%	m^3/ head	MJ/1000 kg LBW	%
Pre-evisceration wash	0.02	0.1	<1	0.18	11.3	2.2
Organic acid spraying	0.01	0.1	<1	0.08	5.0	1.0
Carcass wash	0.28	1.6	1.5	0.52	31.8	6.2
Thermal pasteurization	0.34	1.9	1.8	0.18	11.1	2.2
Viscera and byproducts processing	0.04	0.2	<1	0.98	60.1	11.7
Cooling	17.55	100.4	91	-	-	-
Hydraulic systems	1.07	6.1	5.5	-	-	-
Overnight use	-	-	-	3.01	185.2	36.1
Other use	-	-	-	3.381	208.1	40.6
Total	19.31	110.5	100	8.33	512.6	100

The overnight use and the viscera and byproducts processing used 47.8% of the total natural gas usage of the plant. Other usage accounted for 40.6% of the total natural gas usage of the plant, which included usage on the fabrication side of the plant, heating of water used outside the studied subsystems, heat losses during conveyance, pipe leaks and usage on the plant's wastewater treatment facility.

The energy usage of food processing plants is highly variable and depends on many factors including plant size and location, mechanization of the processes, utilization of processing capacity, equipment age and efficiency (Cierach et al., 2000; Tkacz et al., 2000; Houska et al., 2003; Markowski et al., 2004; Marcotte et al., 2008; Norton and Sun, 2008; Banach and Ywica, 2010; Campañone and Zaritzky, 2010; Li et al., 2010; Gogate, 2011; Wojdalski et al., 2013). The combined electrical and natural gas energy used at this plant was 623.1 MJ/1000 kg LBW or 392.6 MJ/ head, which represents less than 2% of the energy footprint of beef (e.g., Rotz et al., 2013). A breakdown of the total energy usage at this plant is shown in figure 5. The antimicrobial interventions used 10% of the total energy usage of the plant, while viscera and byproducts processing, overnight use, and hydraulic and cooling systems combined used 57% of the total energy usage. This suggests that any improvements in the efficiency of the viscera and byproducts processing, antimicrobial interventions, and overnight use processes would positively affect the plants total energy usage. Processes like viscera and byproducts processing and overnight cleaning of the facility, which may have greater variability in the water use and done manually, can be further investigated for potential water and energy savings.

CONCLUSIONS

Although this study was carried out at one plant, it highlights the relative proportions of water and energy usage in a modern beef packing plant. Collected water and energy data for antimicrobial interventions presented in this study can be used in further food safety risk assessment studies. The overall plant-wide water usage was 2968 L/1000 kg LBW (355 gal/1000 lb LBW) and energy was 623.2 MJ/1000 kg LBW. Antimicrobial interventions used less than 16% of the total water use, less than 12% of the total natural gas usage and less than 4% of the metered electricity use while cleaning and viscera and byproducts processing consumed majority of the water and energy at the plant. Manually operated processes, such as cleaning of the facility, had the highest degree of day-to-day variability, which suggest that improvements on the efficiency of these processes should enhance the plant's overall environmental sustainability. In addition, it is shown that using water recycling in processes that consume a large amount of energy and water, like thermal pasteurization, can effectively reduce the amount of water and energy used. The representative data provided in this study can serve as a baseline for comparison of new intervention technologies developed by researchers and for risk and environmental assessments of current technologies.

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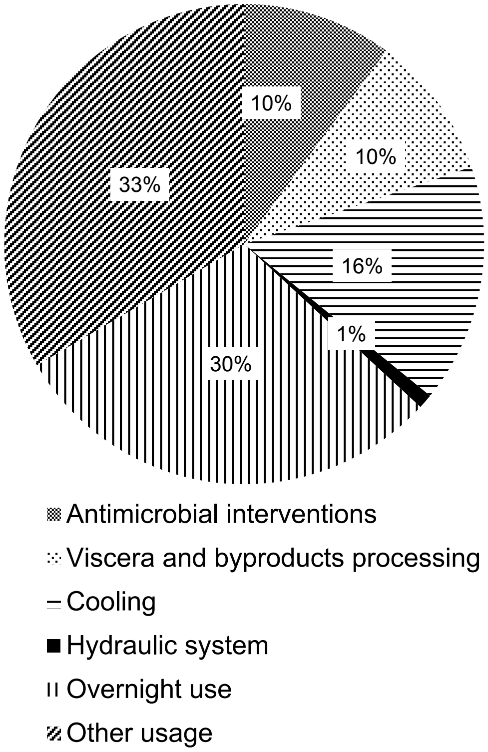

Figure 5. Quantified energy usage (623.1 MJ/1000 kg LBW) in the beef packing plant.

REFERENCES

Banach, J. K., & Ywica, R. (2010). The effect of electrical stimulation and freezing on electrical conductivity of beef trimmed at various times after slaughter. *J. Food Eng., 100*(1), 119-124. http://dx.doi.org/10.1016/j.jfoodeng.2010.03.035

Campañone, L. A., & Zaritzky, N. E. (2010). Mathematical modeling and simulation of microwave thawing of large solid foods under different operating conditions. *Food Bioprocess Technol., 3*(6), 813-825. http://dx.doi.org/10.1007/s11947-009-0249-0

Capper, J. L. (2011). The environmental impact of beef production in the United States: 1977 compared with 2007. *J. Anim. Sci., 89*(12), 4249-4261. http://dx.doi.org/10.2527/jas.2010-3784

Cierach, M., Bialobrzewski, I., & Markowski, M. (2000). Investigation of meat product heating and cooling processes [in Polish]. *Inżynieria Rolnicza, 5*(15), 39-46.

Gogate, P. R. (2011). Hydrodynamic cavitation for food and water processing. *Food Bioprocess Technol., 4*(6), 996-1011. http://dx.doi.org/10.1007/s11947-010-0418-1

Gray, D. D. (1998). *A first course in fluid mechanics for civil engineers.* Englewood, CO: Water Resources.

Hansen, P., Christiansen, K., & Hummelmose, B. (2000). Cleaner production assessment in meat processing. Denmark: UNEP DTIE, DEPA.

Houska, M., Sun, D.-W., Landfeld, A., & Zhang, Z. (2003). Experimental study of vacuum cooling of cooked beef in soup. *J. Food Eng., 59*(2-3), 105-110. http://dx.doi.org/10.1016/S0260-8774(02)00435-1

Johns, M. R. (1995). Developments in wastewater treatment in the meat processing industry: A review. *Bioresour. Technol., 54*(3), 203-216. http://dx.doi.org/10.1016/0960-8524(95)00140-9

Li, C. B., Zhou, G. H., & Xu, X. L. (2010). Dynamical changes of beef intramuscular connective tissue and muscle fiber during heating and their effects on beef shear force. *Food Bioprocess Technol., 3*(4), 521-527. http://dx.doi.org/10.1007/s11947-008-0117-3

Li, S., Kundu, D., & Holley, R. A. (2015). Use of lactic acid with electron beam irradiation for control of *Escherichia coli* O157:H7, non-O157 VTEC *E. coli*, and Salmonella serovars on fresh and frozen beef. *Food Microbiol., 46*, 34-39. http://dx.doi.org/10.1016/j.fm.2014.06.018

Marcotte, M., Taherian, A. R., & Karimi, Y. (2008). Thermophysical properties of processed meat and poultry products. *J. Food Eng., 88*(3), 315-322. http://dx.doi.org/10.1016/j.jfoodeng.2008.02.016

Markowski, M., Bialobrzewski, I., Cierach, M., & Paulo, A. (2004). Determination of thermal diffusivity of Lyoner type sausages during water bath cooking and cooling. *J. Food Eng., 65*(4), 591-598. http://dx.doi.org/10.1016/j.jfoodeng.2004.02.025

Nam, K. C., Seo, K. S., Jo, C., & Ahn, D. U. (2011). Electrostatic spraying of antioxidants on the oxidative quality of ground beef. *J. Anim. Sci., 89*(3), 826-832. http://dx.doi.org/10.2527/jas.2010-3326

Norton, T., & Sun, D.-W. (2008). Recent advances in the use of high pressure as an effective processing technique in the food industry. *Food Bioprocess Technol., 1*(1), 2-34. http://dx.doi.org/10.1007/s11947-007-0007-0

Otto, D., & Lawrence, J. D. (2001). Economic impact of the United States beef industry. Retrieved from http://www.beef.org/uDocs/Econ Impact Beef v2.doc

Phebus, R. C., Sevart, N. J., Baumann, N. W., & Phebus, R. K. (2014). Electrostatic spray cabinet evaluation to verify uniform delivery of chemical and biological solutions to pre-chilled meat animal carcasses. In *Cattlemen's Day* (pp. 115-118). Manhattan, KS: Kansas State University. Agricultural Experiment Station and Cooperative Extension Service.

Rotz, C. A., Isenberg, B. J., Stackhouse-Lawson, K. R., & Pollak, E. J. (2013). A simulation-based approach for evaluating and comparing the environmental footprints of beef production systems. *J. Anim. Sci., 91*(11), 5427-5437. http://dx.doi.org/10.2527/jas.2013-6506

Schultheisz, Z., & Karpati, A. (1984). The improvement of meat processing technology and management of water supplies from the viewpoint of pollution. *Int. Symp. Food Industries and the Environ.* (pp. 377-385). Amsterdam : Elsevier.

Standing Committee on Agriculture and Resource Management. (2002). Model code of practice for the welfare of animals: Livestock at slaughtering establishments (SCARM Report No. 79). Australia: Cisro.

Tipler, P. A., & Mosca, G. (2003). *Physics for scientists and engineers: Mechanics, oscillations and waves; Thermodynamics* (5th ed., Vol. 1). New York, NY: W. H. Freeman.

Tkacz, K., Budny, J., & Borowski, J. (2000). Energetic characteristics of beef steak thermal processing [in Polish]. *Inżynieria Rolnicza, 5*(16), 241-248.

US-EIA. (2013). Heat content of natural gas consumed. Retrieved from http://www.eia.gov/dnav/ng/ng_cons_heat_a_epg0_vgth_btucf_a.htm

Widder, D. V. (1976). *The heat equation* (Vol. 67). New York, NY: Academic Press.

Wojdalski, J., Dróżdz, B., Grochowicz, J., Magryś, A., & Ekielski, A. (2013). Assessment of energy consumption in a meat-processing plant: A case study. *Food Bioprocess Technol., 6*(10), 2621-2629. http://dx.doi.org/10.1007/s11947-012-0924-4