A REVIEW OF THE SUSTAINABILITY OF RESIDENTIAL HOT WATER INFRASTRUCTURE: PUBLIC HEALTH, ENVIRONMENTAL IMPACTS, AND CONSUMER DRIVERS

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ABSTRACT

Residential water heating is linked to the primary source of waterborne disease outbreaks in the United States, and accounts for greater energy demand than the combined water/wastewater utility sector. Furthermore, home water heating is the second largest energy consumer in the home and thus represents an integral part of the water-energy nexus. To date, there has been little practical research that can guide decision-making by consumers, public health officials and regulators with regards to water heater selection and operation to minimize energy costs and the likelihood of waterborne disease. Scientific uncertainties associated with existing "green" advice have potentially created misguided policy with long-term negative repercussions. This review is aimed at defining the current state of knowledge related to hot water infrastructure and in highlighting current gaps in the research. While there are many sustainability claims of certain water heater types (i.e., hot water recirculation systems and instantaneous water heaters) these claims have not been substantiated in head-to-head testing of the interplay between water temperature, energy, microbial growth, and scaling, all measures that need to be better defined.

KEYWORDS

water heaters, energy, water-energy nexus, sustainable design, green energy, premise plumbing, pathogens

1. BACKGROUND

Residential water heating infrastructure is tied to the primary source of waterborne disease outbreaks in the U.S. [1] and has a total energy demand exceeding that of the water and wastewater utility sector combined (Table 1) [2]. Considering the high stakes, it is unfortunate that there has been little practical research that can guide rational decision-making by consumers, public health officials, regulators and legislators. In fact, the numerous scientific uncertainties associated with existing "green" advice has the potential to create misguided

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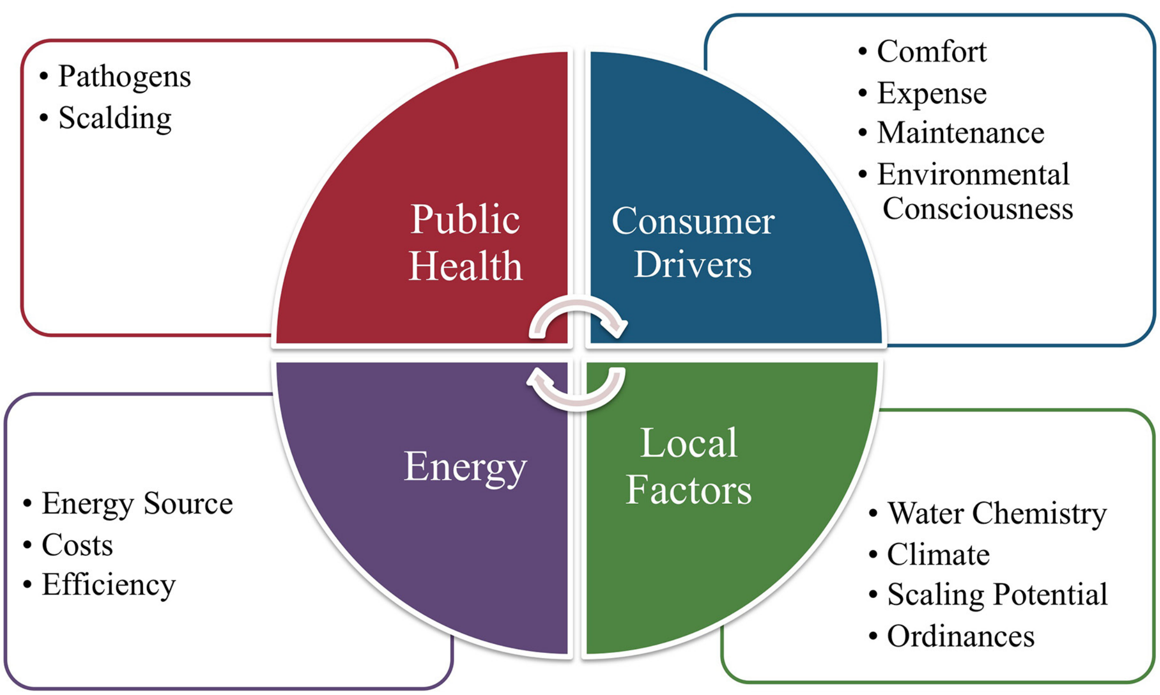
policy with long-term repercussions for energy consumption and public health. This research is aimed at reducing that liability by conducting the first practical assessment of residential water heating infrastructure performance in terms of public health, environmental impacts, and consumer drivers (Figure 1).

To elaborate, selection of an "optimal" new or retrofit water heater system from amongst the myriad options available is a complex decision that often begins and ends at the consumer level by considering capital costs, comfort, reliability, maintenance, and occasionally genetic/immuno-susceptibility to waterborne disease (Figure 1). By outlining the various factors that should be considered with respect to water heater selection, the potential scale of complexity becomes apparent. While water heater selection is probably most driven by consumer drivers (i.e., costs, availability, and consumer comfort reports), environmental impacts, local factors, and public health (Figure 1) could play a larger role if more reliable, practical assessment were readily available.

Although some information regarding environmental impacts including water conservation, greenhouse gas emissions, and operating costs (Table 2) are available through EPA web sources and EPA Energy Star ratings, such recommendations are based on extrapolation of very limited new system performance data. Home owners can upfit existing systems following specific Energy Star guidelines to be eligible for up to $1500 dollars in tax incentives for choosing certain water heaters; other systems are eligible for a 30% tax rebate with no upper limit [3]. EPA's WaterSense program that has been developed to "help consumers identify water efficient products and programs" specifically does not include water heaters [4]. The USGBC LEED certification program rates certain models as "green" for LEED building certification; however, some of the qualified models do not coincide with the Energy Star

FIGURE 1. Water Heater Selection. A consumer's selection of water heater infrastructure should consider public health and environmental impacts.



tax eligibility criteria. Furthermore, some cities, where water conservation has become a top priority, have adopted ordinances which mandate new construction to have specific, water saving, "green" plumbing designs. The Marina Coast Water District (MCWD) in California, for example, requires that any hot water fixture more than 10 linear feet from the hot water heater has a hot water recirculation system or point-of-use demand heater [5]. Although both nationwide and globally, these sustainable designs are being implemented to the supposed benefit of the environment and consumer and, in some cases by government mandate, there has been very limited research assessing the water quality, health factors, and comparative energy efficiency associated with these initiatives [6, 7].

The existing recommendations can be misleading and unfounded under actual field conditions due to scaling, corrosion, and climate impacts (Table 2). Moreover, it is believed that the type of hot water system and the quality of the water supply (i.e. nutrients and secondary disinfectant residual level) can control the occurrence of pathogens (Table 2). But research on this important emerging subject is only beginning, and existing data covers just a few water heater systems and water supplies. The interdisciplinary nature of the research involving plumbing, water chemistry, microbiology, and human pathogen exposure has also been a barrier.

This paper will review various types of water heating systems and will highlight specific gaps in the literature while focusing on the mechanics, chemistry, microbiology, environmental impacts, and consumer considerations (Figure 1) with respect to residential hot water systems. In the sections that immediately follow, a summary of the different types of water heating infrastructure that are available, what is known about their likely environmental and public health impacts, and consideration of how local factors might dramatically alter performance are provided.

2. WATER HEATING SYSTEMS

2.1. Energy and Public Health Implications of Residential and Commercial Water Heater Infrastructure

Water heating in the United States has the largest energy consumption of any water related use. Additionally, water heating represents the second largest residential energy use (second only to heating and cooling) and uses more energy than all other home appliances combined (Figure 2) [8]. The actual portion of the energy consumption of water heating in the home varies depending on the given year and reporting source, [9-14] but the most recent data from Energy Star [8] suggests water heating accounts for 14% of residential home energy consumption (Figure 2). Over the past decade, between 3.3–5.5% of total U.S. energy demand is used in residential water heating, which slightly exceeds the estimated 3–4% combined energy demand of the water

FIGURE 2. 2010 Data for Residential Energy Consumption.

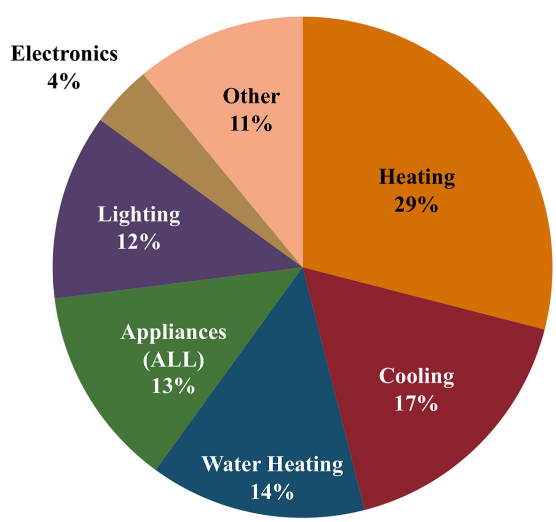


TABLE 1. Impacts of Residential Water Heating.

	Total Energy Costs	% of US Energy Demand	Funded Research in Progress?
Residential Water Heating	$9 Billion[1] [10]	3–5% [9]	Very little
Water and Waste Water Utility Sector	$4 Billion [2]	3–4% [2]	Numerous projects

[1]Electric Water Heating Only

and wastewater utility sectors (Table 1) [2, 9]. The costs of residential water heating are high with 100 billion kWh used for electric water heating alone in 2001 at a cost of $9 billion dollars assuming average electric rates of 9 cents per kWh, which more than doubles the $4 billion estimated energy costs for the entire water and wastewater utility sector (Table 1) [2, 9-11, 14-16]. This cost does not even include the 58 million homes that use natural gas or the remaining 8 million homes that use an alternative source of energy for water heating. With well over 100 million households in the United States using some type of water heating system, research needs to address not only the relative energy consumption, but also the potential public health risks with regards to scalding and microbial growth, the relative economic constraints, and the water saving potentials of different choices widely available for use.

In terms of public health, growth of opportunistic pathogens in premise plumbing was identified as a "high priority" for research by National Research Council in 2006 [17]. "Premise plumbing" refers to the portion of potable water distribution systems beyond the property line in buildings. This portion of the water distribution system water infrastructure poses unique challenges for public health and has a net present value that probably exceeds that of the main distribution system operated by water utilities [17, 18]. The ability of premise plumbing pathogens to amplify is controlled by water temperature, residual disinfectant concentrations, water nutrient levels, and water age: factors directly influenced by water heating infrastructure type, design and operation. Hence, there will be inextricable direct linkages between goals of reducing energy demand and maintaining public health (Figure 1), both antagonistic and synergistic, which are only beginning to be appreciated and studied.

2.2. Overview of Water Heater Systems

This section provides an overview of the ongoing consumer dilemmas of choosing appropriate water heating strategies for individual residences. Water heating infrastructure can be characterized into four broad categories (Figure 3) including: 1) tank storage with no hot water recirculation, 2) tank storage with hot water recirculation, 3) centralized demand with no storage and no hot water recirculation, and 4) point-of-use demand with no storage and no hot water recirculation. Each of these further needs to be assessed considering key areas of local factors, energy, and public health, and consumer drivers (Figure 1). While there is a high degree of uncertainty in relation to defining performance for some variables, each type of infrastructure and energy source will have characteristic impacts and susceptibility to problems (Table 2).

The subsequent sections highlight some important inter-dependencies that are emerging in relation to design and operation of specific types of water heating infrastructure relevant to public health, energy, water conservation, and consumer considerations. Illustrative areas emphasized include storage vs. on-demand systems, concerns about scaling and scalding, electric vs. gas tanks, hot water recirculation, and "green" high efficiency heaters.

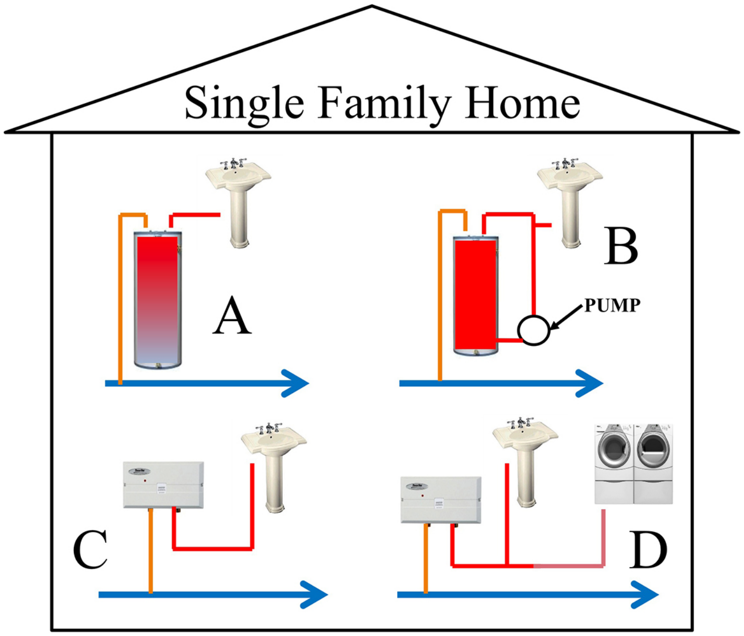


FIGURE 3. Common Residential Hot Water Heaters. A single family residence using standard energy resources (i.e., electricity, natural gas, propane, or oil) could have several different water heater systems: A) storage tank with no recirculation, B) storage tank with hot water recirculation, C) point-of-use demand with no storage, and D) centralized demand with no storage.

2.2.1. Residential Storage Water Heaters with No Hot Water Recirculation (STAND)

Residential storage water heaters are the most widely used system to heat domestic water supply. While there are many different sizes and types of water heaters depending on use, a standard residential water heater storage tank as defined by this paper (Figure 4) consists of a steel cylindrical tank that may have a porcelain (or vitreous) enamel glass lining to limit corrosion. Ambient temperature water flows to the bottom of tank from the main water line and heating elements or gas combustion raise the water temperature to a range of 48 to 77 °C which flows out the top of the tank to the pipe system and ultimately the destination faucet. To minimize corrosion within the tank, a sacrificial anode rod made of either aluminum or magnesium alloy is placed within the tank. Other elements that comprise the hot water storage tank are a drainage tap to remove accumulated sediment at the bottom of the tank and insulation (fiberglass or urethane) to control environmental heat loss [21, 30].

Energy efficiency of water heaters must include considerations of energy input to heat the water, energy output in terms of heated product water, and losses of heat to the ambient environment and along the pipe system [31]. Standby heat losses are defined as the energy input required for maintaining hot temperatures in the storage tank when the system is not in use. On-demand water heaters virtually eliminate standby losses. Any water heater with a storage tank will have standby losses that depend on the type and quantity of insulation, surface area of the tank and hot water distribution system, and differential temperature between the hot water tank and the environment [32]. More complex energy equations might account for the potential benefits of the heat loss in a cold climate, in terms of reduced costs associated with heating the dwelling, or increased cost from cooling a dwelling in a hot climate.

2.2.1.1. Electric Versus Gas Tanks. There are certain key differences with regard to electric heating and gas heating that are critical in differentiating their performance with regards to energy efficiency, public health, environmental air quality, and cost (Figures 4 and 5, respectively). First, electric water heaters typically heat the inflow water through either one or two

TABLE 2. Key Characteristics of Representative Residential Water Heater Systems.

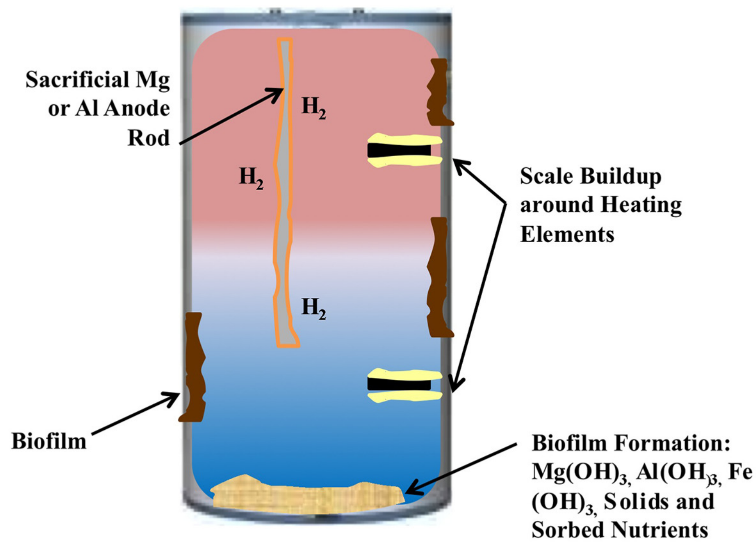
	Energy Efficiency and Relative Energy Demand	Standby Energy Loss	Scaling Potential	Pathogen Growth Potential	Installation and Maintenance Costs	Scalding and Consumer Concerns
Electric Heater with Storage and No Recirculation (STAND)	Energy Efficiency: HIGH 90 – 95% [19] Energy Demand: BASELINE FOR COMPARISON	MEDIUM – HIGH (Figure 6)	MEDIUM (Scaling can reduce energy efficiency but has moderate recovery after maintenance) [20]	MEDIUM – HIGH (Stratification in tank, AOC2 generation, sediment accumulation; see Figure 4) [21]	LOW	Scalding Risk: LOW – MEDIUM (Dependent on temperature setting) Temperature Stability during Shower: HIGH
Gas Heater with Storage and No Recirculation	Energy Efficiency: MEDIUM 60-65% [19] Energy Demand: LOWER than STAND due to more efficient production and transportation of source energy [19]	MEDIUM – HIGH (Same as STAND)	MEDIUM – HIGH (Scaling can increase energy demand and be irreversible) [20]	LOW – MEDIUM (Water heated from bottom eliminating stratification, AOC generation and sediment accumulation still probable)	LOW- MEDIUM (Permanent scaling effects may increase fuel costs)	Scalding Risk: LOW – MEDIUM (Dependent on temperature setting) Temperature Stability during Shower: HIGH
Electric Heater with Storage and Recirculation	Energy Demand: HIGHER than STAND due to increased energy consumption from pump and increased energy losses [22]	HIGH (Figure 6)	MEDIUM (Same as STAND)	HIGH (Higher Legionella incidence in and lower disinfectant residual?) [22, 23]	MEDIUM (Pipe costs doubled due to return line; initial pump costs; increased fuel costs to run pump)	Scalding Risk: MEDIUM (Hot water arrives immediately at tap) Temperature Stability during Shower: LOW [22]
On-demand (Electric) with No Storage and No Recirculation	Energy Efficiency: HIGH 95-100% [22] Energy Demand: 8 – 50% LOWER energy demand than STAND [24]; High energy demand during short use that may lead to grid failure [25]	NONE	HIGH (Scaling has shown to render on-demand systems inoperable with no recovery in as little as 4 months) [26]	LOW (No tank for microbial growth, AOC generation or sediment accumulation)	MEDIUM – HIGH (Electrical upgrades may be necessary; scaling can render systems inoperable needing replacement; high energy draw during use; if point-of-use: high capital costs) [25-27]	Scalding Risk: HIGH (Temperature dependent on flow rate and incoming water temperature – not setting) [24, 27] Temperature Stability during Shower: LOW (Consumer issues related to inconsistent temperature and flow rate) [24, 27]

TABLE 2. *(continued)*

	Energy Efficiency and Relative Energy Demand	Standby Energy Loss	Scaling Potential	Pathogen Growth Potential	Installation and Maintenance Costs	Scalding and Consumer Concerns
On-demand (Gas) With No Storage and No Recirculation	Energy Demand: LOWER than electric demand due to more efficient production and transportation of source energy [19]	NONE	HIGH (Same as above)	LOW (Same as above)	MEDIUM (Same as electrical demand; if point-of-use: high capital costs to extend gas lines throughout home; Energy Star tax rebate eligible) [3]	Scalding Risk: HIGH (Same as above) Temperature Stability during Shower: LOW (Same as above)
Heat Pump (Exchanger) Water Heater with Storage	Energy Efficiency: HIGH 2 – 3 times more energy efficient than STAND [28] Energy Demand: LOWER than STAND in temperate climate; may be increased demand in cold winter months	MEDIUM – HIGH (Same as STAND)	MEDIUM (Same as STAND)	MEDIUM – HIGH (same as STAND)	LOW- MEDIUM (Same as STAND but with increased energy costs in cold winter months; Energy Star tax rebate eligible) [3]	Scalding Risk: LOW – MEDIUM (Same as STAND) Temperature Stability during Shower: HIGH
Solar Panels with Electric Storage Backup and No Recirculation	Energy Demand: LOWER than STAND (dependent on regional/climate factors and type of solar heater) [29]	MEDIUM – HIGH (Same as STAND)	MEDIUM (Same as STAND)	MEDIUM – HIGH (same as STAND)	HIGH (High capital installation costs; payback potential depends on climate/ region; Energy Star tax rebate eligible) [3]	Scalding Risk: LOW – MEDIUM (Same as STAND) Temperature Stability during Shower: HIGH

[2]AOC = Assimilable Organic Carbon

FIGURE 4. Electric Storage Heater. A cross-section of a typical electrical hot water tank with no hot water recirculation.

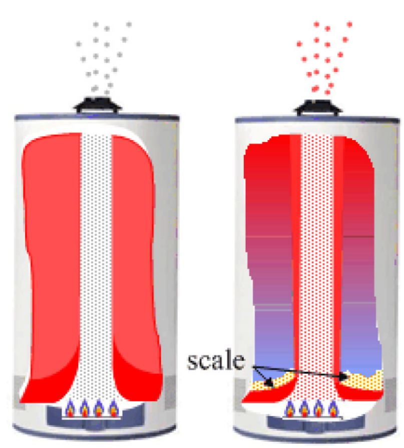


electric components located at the top or middle of the tank whereas gas-fired storage tanks heat from the bottom (Figure 5). The placement of the electrical components causes vertical thermal stratification within the tank because denser, cooler water will sink to the bottom of the tank and is not directly heated by the components (Figure 4) [21, 30, 33]. Thermal stratification can be beneficial when considering a solar collector system with electric backup to improve performance and efficiency. In fact, studies have concluded that in certain systems, the greater the temperature difference, the larger the efficiency [21, 33]. However, when considering a traditional water heater with tank storage, water stratification and relatively cool water at the bottom can lead to increased microbial contamination (Table 2). In fact, *Legionella pneumophila*, a known opportunistic pathogen that is discussed in more detail later in this review, is believed to occur in electric storage tank heaters in high numbers due to this stratification [21, 33].

In contrast, natural gas heating in non-scaling waters tends to break up stratification typical of electric heaters due to heating from the bottom of the tank; however, in scaling waters, the internal insulating properties of thick scale may induce stratification in gas heaters by reducing heat transfer to the tank (Figure 5). In non-scaling waters, occurrence of *L. pneumophila* was dramatically higher in electric tanks versus natural gas as a result of stratification (Table 2), but with high scaling, this benefit might not be significant [21, 34] Additionally, gas-fired systems typically cost less to operate than electric storage tanks if operating at full efficiency.

The California Energy Commission (CEC) estimates that a water heater using natural gas or propane as an

FIGURE 5. Scaling and Gas Water Heaters. Gas water heaters will lose efficiency as scale builds up at the bottom of the tank in hard water areas. This may cause temperature stratification and heat loss through the vent.



energy source in deference to electricity will save the consumer 25–65% in energy costs [35]. Calculations of lifecycle emissions and energy consumption of natural gas heaters predicts improvements of about 40–50% versus electric [35, 36]. However, the natural gas heaters modeled were assumed to have a high efficiency of 85%. Due to build-up of scale and other deposits (Figure 5), actual gas heater efficiencies can drop 27–30% in a few months and calculations based on theoretical reductions in heat transfer coefficients suggest possible reductions in heat transfer efficiency by up to 95% with an associated increase in operation costs (Table 2) [20, 26, 37]. Electric tanks tend to be less susceptible to energy loss due to scaling and can be more easily maintained because the heating element is located inside the tank and might be subject to some self-cleaning with contraction/expansion [20].

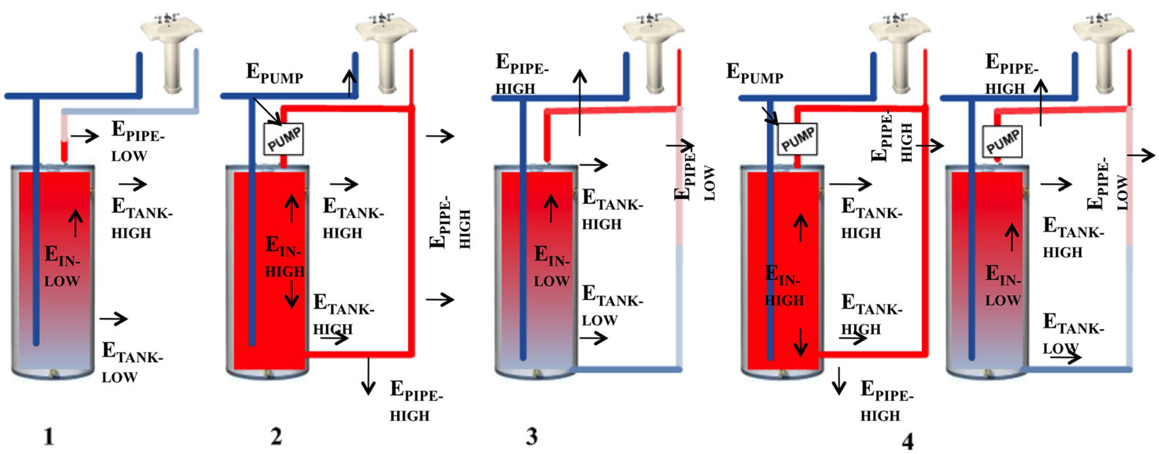
2.2.2 Residential Storage Water Heaters with Hot Water Recirculation

Traditionally found in multi-family homes and hotels, but gaining increasing attention for single-family residential use, a recirculation system will continuously circulate hot water from a central water heater tank so hot water is "instantaneous" at various point-of-uses throughout the buildings [38]. Hot water tanks with recirculation lines eliminate the "waiting" time for hot water to reach the tap by rapidly circulating hot water via an electric pump from the water heater to each faucet that utilizes hot water (Figure 3). The theory behind the water saving advantages of a hot water recirculation system depends largely on behavioral patterns; a person taking a shower, for instance, no longer needs to allow water to run or "waste" until the water is at a comfortable temperature. As fresh hot water is pumped from the tank, water not utilized in the hot water line is cooled as it is returned the tank to be re-heated and re-circulated. Hot water recirculation tanks are dependent on the electric pump forcing flow (sometimes at high velocity) from the heater to multiple point-of-use faucets [39]. In addition to the added energy of using a pump, recirculation systems may increase other energy losses due to increased surface area and higher temperatures, and resultant energy losses to ambient air from the hot water distribution system. (Figure 6). Even without operation of a pump, addition of a return line increases heat loss due to natural convection (passive recirculation) in the system via a thermosiphon.

Optimization of pump operation is key to limit heat loss and maximizing efficiency. Instead of running a pump continuously, the pump should be turned off during periods of low demand, and turned on via a sensor located at the point-of-use or at a specific time to meet demand. There are four system conditions (Figure 6) that need to be identified and analyzed for energy considerations: 1) standard systems with no recirculation (STAND), 2) continuous recirculation via a pump (return line, pump always on, RECIRC-C), 3) recirculation via thermosiphon effect (return line, no pump, RECIRC-T), and 4) an optimized recirculation system (return line, pump not on continuously, RECIRC-O). RECIRC-O can be thought of as a combination system since it will act as a RECIRC-C during periods when the pump is operating and a RECIRC-T when the pump is off (Figure 6).

The Oak Ridge National Laboratory (ORNL) in conjunction with the City of Paolo Alto conducted a study examining the use of hot water recirculation [40]. They estimated that nearly 1–3 gallons of potable water could be drained as a user waits for water to reach a comfortable level. While they assert that the water wastage can virtually be eliminated by hot water recirculation, it is noted several times that this is an "ideal" situation where user behavior encourages immediate use of the hot water. Water saving estimates for this study ranged from 900–3000 gallons per point-of-use per year. However, it should be noted that study

FIGURE 6. Hot Water Systems and Energy Balance. There are four different water heater configurations for the standard and recirculation systems: 1) STAND (no recirculation), 2) RECIRC-C (hot water recirculation line, pump continuously operating), 3) RECIRC-T (no pump, thermosiphon return line to tank), and 4) RECIRC-O (optimized pump operation, hot water recirculation or thermosiphon). E_{IN} represents the energy required to heat the tank to the desired temperature. EPUMP represents the added energy of running a pump. E_{TANK} and E_{PIPE} correspond to the heat loss from the tank and pipes, respectively. "HIGH" and "LOW" represent EXPECTED energy consumption/loss where "HIGH" refers to a higher temperature differential between internal (tank and pipe) water temperature and ambient (i.e., due to stratification or heat loss through the pipes, the temperature at the bottom of the tanks and pipes are cooler and thus have a lower ΔT between internal temperature and ambient temperature. "LOW" also represents the lower energy input expected to heat the partial tank from stratification as opposed to the entire tank (i.e., "HIGH") due to pipe recirculation. "HIGH" and "LOW" are simply expected energy inputs/losses and will be fully developed through experimentation.



had many limitations including small sample size, inconsistent study parameters, inconclusive results, and a narrow range of home age not comparable to current age distribution of homes in the U.S.

It was also asserted that the use of recirculation pumps would probably save energy. But The Paolo Alto study used pump systems that were consumer activated just before use, and a heat sensor was employed to turn off the pump when a desired temperature is reached[40]. The assertion that the system would save energy failed to consider energy demands to run the pump and possible increased heat loss from the recirculation system [40], with a pump that runs continuously. It has been suggested that intermittent use of the pump consistent with reduced energy use could cause damage to the pump and system [38].

Another study in a multi-family building analyzed four different pump operations: 1) pump continuously on, 2) pump off at night (between 11:50 pm–5:20 am), 3) pump off during "peak" use (5:45 am–8:15 am and 5:45 pm–9:15 pm), and 4) pump activated when return line water temperature falls below a set point (i.e., 43 °C in study) [39]. While the study was limited in scope to one unit and short study period, it was found that compared to the baseline pump operation of case 1, scenario 2 and 3 reduced energy consumption by 5% and scenario 4 reduced energy consumption by 11%. No comparison was made to a situation without a return line. Moreover, it was determined that hot water recirculation configured with a pump operating continuously consumes nearly 40% of the total fuel used to heat domestic hot water under that condition. The researchers also noted increased user complaints of decreased hot water and lower temperature water during condition 3 [39]. It is imperative that more research be conducted on various pump use and hot water recirculation relative to consumer behavior and improved energy audits. The local code requiring recirculating systems in MCWD mentioned earlier required that the pump not run more than "10 minutes in any hour" [5]. While these types of recommendations may optimize system performance, there is little uniformity in recommendations and it requires the users to maintain a regimented use schedule.

Another potential problem that arises with recirculation systems is rapid cooling due to mixing and backflow from the return line [22]. As discussed previously, in storage type systems the cold water enters at the top of the tank and is delivered to the bottom of the tank via a closed pipe. Since recirculation systems have a return line that also enters at the bottom of the tank, fresh cold water entering the tank during flushing can "short circuit" the tank and immediately backflow through the return line to the faucet without any storage. This is likely due to the pressure differential in the tank versus atmospheric pressure at the tap. Additionally, it is hypothesized that the pump and return line create a mixing effect within the tank where colder water mixes with the heated water lowering the overall temperature of the water within the tank as opposed to the more plug flow conditions of a standard storage tank. There have been no studies characterizing the temperature profiles within a recirculation system tank during flushing. The backflow issue can be eliminated through installation of a check valve at the end of the return line [5, 41]. Again, proper installation and optimization of this system could have dramatic effects on the overall efficiency of the design.

Other considerations with water recirculation loops include pin hole leaks and copper corrosion due to high velocity flow through copper pipes. A hotel near Lake Tahoe experienced near total water pipe failure due to a recirculation pump installed to eliminate long waits for hot water in multiple rooms. Flow-accelerated corrosion (a.k.a. erosion corrosion) is a common occurrence where flowing hot water erodes the oxide film formed by the reaction of the copper pipe and dissolved oxygen which causes a thinning of the pipe wall and overall scaling effect. This scaling effect can cause increased turbulence and increased failures [42].

2.2.3. Tankless On-Demand Systems: Centralized and Distributed (Point-of-Use)

Residential storage water heaters are the current U.S. standard. Storage type systems are prone to heat loss during stagnation (i.e., stand-by losses). On-demand tankless water heater systems have no anode, virtually no hot water storage and eliminate standby losses which can be as much as 50% of the total energy demand in storage systems [26]. The DOE estimates that use of electric, centralized on-demand systems can result in energy savings between 8–34% versus electric tank storage units depending on average daily water use and using a point-of-use demand system can reduce energy use by 27–50% (Table 2) [24]. These savings are dependent on flow rate, total water use, and the installation of low-flow devices. Additionally, the data for point-of-use heaters do not include energy savings from water use at the production phase and could potentially underestimate total energy savings. The downside of on-demand heaters include high cost, high peak energy use, limited flow potential, variable temperatures with tap distance, and increased possibility of scalding at taps near the heater (Table 2) [24].

On-demand, tankless, or instantaneous water heaters eliminate storage tank heating by using heat exchange coils that raise water to a set temperature only when needed. The cold water from the distribution line passes through the unit where a gas burner or electric element heats the water to a pre-set temperature. [26] Two types of tankless water heaters will be defined in this review: located central in the building or distributed or point-of-use (Figure 3). While both types of on-demand systems function similarly, they have marked differences with regards to advantages, disadvantages, energy consumption, and public health considerations (Table 2).

In centralized systems, a large central demand system would be located somewhere in the residence and a hot water distribution system would deliver hot water to various faucets within the house (Figure 3). Water would be heated through the heat exchange coils rather than stored in a tank thus eliminating the standby losses of a storage type system; however, with this type of system, the same heat losses through the pipe network would need to be considered. The distributed or point-of-use models consist of a series of smaller tankless units installed directly at the faucet (Figure 3). These systems will either provide single-source use (i.e., one shower/tub) or small multiple point use (i.e., all faucets in a given bathroom including the sink and shower/tub). This type of system eliminates both standby losses from the storage tank and pipe loss through the network since the heated water does not need to "travel" to get to the tap.

There are several limitations with the use of on-demand systems (Table 2). Even using the largest model, gas-fired unit which should theoretically provide the most "power" for water heating, on-demand systems typically cannot provide enough hot water to supply multiple faucets and simultaneous uses at any given time [24]. Additionally, the maximum flow rate of on-demand systems are limited by several variables including the water temperature setting, cold water influent, and the heat input to the unit itself. This will lower the maximum rate at which hot water can be delivered when compared to a tank system.

Water temperature can also be inconsistent when using an on-demand system leading to consumer complaints. If a centralized demand water heater is being used, the temperature setting needs to be high enough to negate any heat loss in the pipe to the farthest faucet without causing scalding at the nearest tap. Lower temperature settings and flow rate can be more acceptable with low-flow devices, when point-of-use systems are in place, in a washing machine where comfort and scalding are not a consideration, or if the water later gets electrically heated by the appliance, as in the case of a dishwasher [43]. While gas-fired demand water heaters provide higher flow rates than electrical demand heaters, flow rates average between 2–5 gallons per minute and still may not provide hot water to multiple locations throughout a household.

With electric systems, increased power may be an issue. Even the smallest on-demand heaters require more power (i.e., energy input) than tank systems. While standby losses are virtually eliminated, the peak energy draw during use can be a problem in neighborhoods with a taxed power grid [25, 27], and may require the homeowner to upgrade wiring or the utility to upgrade the grid. Finally, scale buildup in the system causing damage to the unit has been noted in areas with hard water in as little as four months, leading to costly repairs and/or replacement [26]. To combat the limitations of on-demand water heaters, consumers could consider using multiple units in parallel or point-of-source heaters that supply hot water directly to the tap used. Other solutions include installing ultralow-flow showerheads (which may lead to consumer dissatisfaction) and water softeners. Furthermore, the energy costs associated with running multiple electric tankless water heaters simultaneously has not been reviewed.

2.2.4. Alternate Energy Water Heaters

Incentive tax credits exist for solar, electric heat pump, and on-demand natural gas residential water heater infrastructure (Table 2). However, the practical long-term performance of these devices under scaling conditions, or in terms of pathogen control, has never been rigorously assessed. Concerns have been expressed about pathogen re-growth in solar applications although limited data available to date is inconclusive [44, 45]. In general, it might be expected that electric heat pump and solar systems would behave like electric tank systems relative to possible growth of premise plumbing pathogens, but with much higher storage volumes. However, more practical performance data must be obtained. Due to variation in temperature, climate, and weather, solar systems will typically have a back-up non-renewable energy source (i.e., electric or natural gas) and are thus susceptible to the same detriments and benefits of these systems. Since solar water heaters require maximum sun exposure to be most effective, there may be regional, climate limitations to this type of system.

2.3. Scaling

In certain "hard" or other waters, calcium and silica can precipitate and coat the surface of the heating elements and pipe surfaces. These deposits can cause water heater noise, increase corrosion, clog pipes, reduce heater life and dramatically reduce energy efficiency via formation of scale layers that reduce heat transfer from the energy source to the water. The reduced energy efficiency is attributed to internal insulating properties and reduced heat transfer from the scale layer to the tank. On-demand systems are especially prone to scaling problems (Table 2) because of the small diameter tubes required for maximum heat transfer and constant flow of water over the heating element. In some cases these devices can be rendered virtually inoperative in a matter of months due to clogging, and acidic solutions must be used to clean the scale and maintain efficiency and flow [20, 26].

The Water Quality Research Council (WQRC) in conjunction with New Mexico State University found that the effects of hard water scaling on a gas fired water heater was an increase in energy demand of 30% in just 14 days; moreover, after the scale was cleaned out, only 5% of the increase was reversed (Table 2) [20]. Water scaling and liming (i.e., calcite precipitation) are most common in hard water, although silicates, sulfates, and waters with high total suspended solids can also form sediment or "scale" layer at the bottom of the tank for gas-fired systems and around the electrical heating components in electric water heaters. The WQTC study also showed that in a head to head comparison, scaling had a worse overall effect on energy efficiency of the gas-fired heaters than the electric water heaters by nearly 8% [20]. In a recent practical study that examined this issue, efficiency of on-demand systems dropped dramatically in just a few months and some were even rendered inoperative, practical trends that might make on-demand less efficient than comparable tank systems [26]. Thus, benefits of on-demand systems will not be possible in all waters, and its use in heavily scaling waters might not save energy without frequent maintenance.

2.4. Overall Implications of Various Water Heating Systems

Given the multitude of variables and characteristics of the different types of water heating systems (Table 2), it is expected that various chemical, microbial and physical properties would differ from system to system dependent on the actual configuration of specific water heater types (i.e., Figure 6). There has been a noticeable lack of research that provides insights to these important issues. Future research is needed to identify how these variables are affected by altering the operation and configurations of different water heating systems.

3. PUBLIC HEALTH CONSIDERATIONS

There are two serious public health concerns when it comes to water heating: pathogen growth and scalding. The former has already been described as a major area of concern for new research and the latter may become a high priority with new "green" advice in water heating systems.

3.1. Pathogen Growth

Traditionally, control of pathogens in water leaving the treatment plant via disinfection, coagulation, and filtration has been the paramount concern of water utilities and the U.S. Environmental Protection Agency (U.S. EPA)—the successful mitigation of this hazard represents one of the 10 greatest engineering achievements of the 20th century [17]. The CDC estimates that between 8,000–18,000 people in the United States are hospitalized each year with Legionnaires' disease [1]. There is also a similar growing concern with non-tuberculosis mycobacterial (NTM) lung disease tied to drinking water [46-48]. Estimates of NTM disease incidence range from 15–30 per every 100,000 persons with some 30,000 NTM infected patients in the United States [18]. Because susceptibility to both NTM and Legionnaire's disease increases with age and diagnosis is improving, incidence of documented waterborne disease from premise plumbing pathogens will likely continue to increase [49, 50]. Representative opportunistic pathogens of concern in premise plumbing include *Legionella pneumophila, Acanthamoeba, Mycobacterium avium* complex and *Pseudomonas aeruginosa* (Table 3). Control of waterborne disease from these and other premise plumbing pathogens will require a noteworthy paradigm shift versus conventional water treatment practice and approaches.

Specifically, "opportunistic" pathogens do not typically cause disease in healthy persons, but can be fatal to humans with a compromised immune system such as the elderly, HIV infected persons, or hospitalized patients. Premise plumbing pathogens grow in shower heads, faucets, along pipe walls, or in water heaters, whereas conventional pathogens are naturally present in the source water from fecal contamination and do not multiply in the water itself. Finally, the primary mode of transmission and exposure is via inhalation or through wounds as opposed to ingestion (Figure 7).

TABLE 3. Premise Plumbing Pathogens of Concern.

Pathogen	Disease(s)	Host Organism Required?	Mode of Exposure	Source
Legionella pneumophila	Legionnaires' Disease or Pontiac Fever in Children	Yes	Inhalation or Aspiration	CDC, 2008 [51]
Pseudomonas aeruginosa	Urinary Tract Infections, Respiratory Infections, Dermatitis, Soft Tissue Infections, Bacteremia, Bone and Joint Infections, GI Infections	No	Wound infection; other modes of transmission are unknown	Todar, K, 2008 [52]
Mycobacterium avium	Pulmonary Disease Cervical Lymphadenitis (children)	No	Inhalation or Aspiration	CDC, 2005 [53]
Acanthamoeba	*Acanthamoeba* keratitis	No	Wound Infection	CDC, 2008 [51]

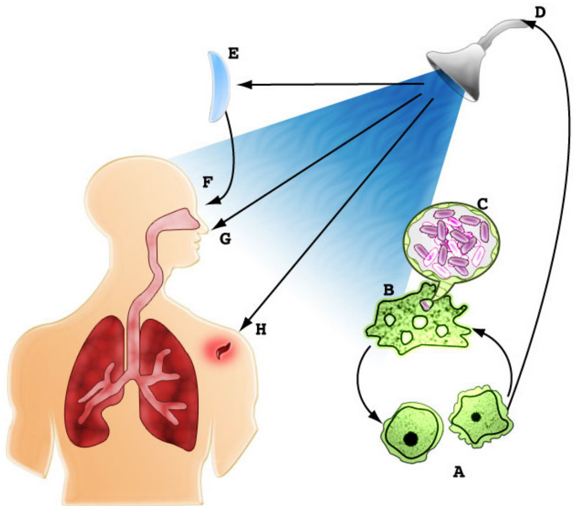


FIGURE 7. Pathways of Pathogen Exposure. Pathogen exposure in premise plumbing systems. *Acanthamoebae* and other protists occur in cyst (A) and trophozoite (B) forms. Vesicles within trophozoites can harbor up to 20–1500 pathogenic bacteria such as *L. pneumophila* (C), which can eventually burst and lead to pathogen occurrence in tap water and shower water (D). Contact lens wearers are vulnerable to keratitis infection from *Acanthamoebae* (E–F). Inhaling mists containing *L. pneumophila* and nontuberculosis mycobacteria (NTM) can cause lung infections (G). Exposure to *Acanthamoebae*, *P. aeruginosa* and NTM through skin lesions can cause infection (H).

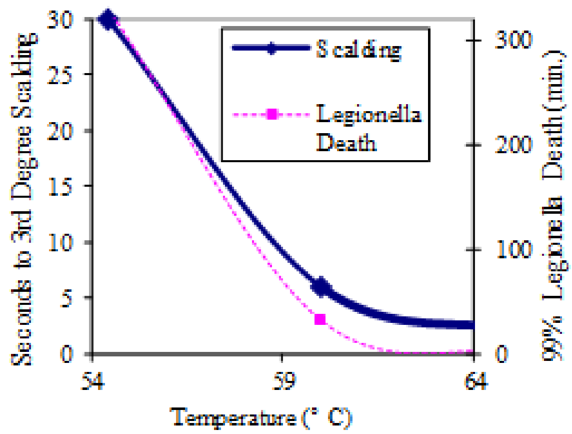
Systems that maintain a consistent inflow of water from the main distribution line will tend to have continuous levels of disinfectant; however, as water remains stagnant in the system or recirculating for any length of time, such as the systems found in water heaters, disinfectants will decay and water quality will decrease [54, 55]. Chlorine decay is dependent on several variables, including pipe material, inorganic and organic material in the water, and hydraulic effects [56]. Since disinfectant decay over time will affect residual levels in the water, it would also be expected that disinfectant decay can be directly associated to increased biofilm production and thus decreased water quality. "Biofilm" in this paper and the research conducted by Momba, *et al.* [57] describes "a layer of microorganisms in an aquatic environment held together in a polymetric matrix attached to a substratum such as pipes." Biofilms are an integral part of microbial resistance to disinfectants [57]. If disinfectant residuals drop below the normalized or designed level for any length of time, biofilm can show substantial re-growth with the new biofilm more resistant to disinfectants [58]. It is important, therefore, to understand how various water heating systems affect disinfectant decay and other chemical parameters in premise plumbing as this will have a direct effect on biofilm formation, resilience, and re-growth potential.

Certain types of water heating systems may be linked to increased incidence of *Legionella* in premise plumbing. The team of Moore, *et al.* [23] related the presence of hot water recirculation systems to increased occurrence of *Legionella* in Pinellas County, Florida. In fact, the study found that buildings that contained a recirculation system were five times more likely to have viable *Legionella* in the plumbing. This type of study has been limited in nature and pathogens such as *Mycobacterium avium* and *Acanthamoeba* also may be impacted by water heater type. Thus far, there is a real, tangible gap in the research with respect to specific pathogen growth and water heating infrastructure.

3.2. Scalding

System operating temperature has profound implications for control of scalding and pathogens (Figure 8), and different countries have different strategies. The consumer product safety commission estimates that scalding from hot tap water results in 3,800 injuries and 34 deaths annually in homes, with children at special risk [59, 60]. To reduce energy costs, potential for scaling and scalding, the EPA recommends that water storage tanks be set at 48 °C [61]. Unfortunately, this increases the likelihood of pathogen growth in water heaters relative to higher temperatures (Figure 8). Other countries and the World Health Organization (WHO) recommend setting temperatures for tanks systems above 60 °C to control pathogens, and then reduce dangers of scalding by requiring installation of mixing valves at all fixtures to maintain dispensed water below 48 °C [61, 62]. A preliminary cost-benefit analysis of the higher temperature and mixing valve requirement in Canada indicated a benefit of $0.7–4.2 million in reduced scalding versus a cost of $48–119 million per year [61]; however, the estimated benefit did not include costs of reduced *Legionella* infections and death.

FIGURE 8. Pathogen Growth and Scalding Concerns with Temperature. Higher water heater storage temperature decreases the time required for Legionella death and the time to acquire severe burns from scalding. Data from National Research Council (16).



5. CONCLUSIONS AND FUTURE WORK

There are serious long-term public health and energy implications that arise from consumer installation and operation of residential hot water heating systems. An "optimal" decision might consider individual preferences, consumer susceptibility to problems (i.e., scalding and children and immune-status for elderly), household hot water demand, climate, scaling potential, presence of nutrients in the water supply, availability of natural gas connections, and the type/concentration of residual disinfectant in the supply water. Unfortunately, due to a lack of prior research, much of the evidence is anecdotal, and head-to-head comparisons have been absent.

Most data generated on water heaters has been provided by manufacturers, plumbers, consumers, and government agencies. There has been surprisingly little practical research on head-to-head performance on water heating infrastructure despite its relevance in the water-energy nexus. Yet, municipalities and agencies are mandating certain water heaters or providing incentive for consumer selection based largely on manufacturer claims of water conservation or other "green" initiatives. Given that water heating infrastructure has important implications for green engineering, energy efficiency, water conservation, environmental microbiology, and public health, it is imperative that more research be done to quantify actual differences in these systems. The discrepancy between WHO and U.S. temperature setting recommendations has implications on energy efficiency, scalding potential, scale build-up and microbiological growth. Nevertheless, no applied direct measurements are available to understand the practical extent of the difference.

The ability of premise plumbing pathogens to amplify is controlled by water temperature, residual disinfectant concentrations, water nutrient levels and water age: factors directly influenced by water heating infrastructure type, design and operation. Hence, there will be inextricable direct linkages between goals of reducing energy demand and maintaining public health, both antagonistic and synergistic, which are only beginning to be appreciated and studied.

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