Residential Compact Domestic Hot Water Distribution Design: Balancing Energy Savings, Water Savings, and Architectural Flexibility

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ABSTRACT

The goal of the study is to develop compact domestic hot water (DHW) distribution strategies in single family homes to save both energy and water, and to reduce hot water waiting time. The study developed compact design measures that can be implemented through voluntary programs or building energy efficiency standards. Laboratory testing is planned to validate performance model development, and a field study is underway to assess installed performance and demonstrate measure feasibility.

The project team performed a literature review, stakeholder engagement, and analysis to determine the impact of compact designs on water waste and time-to-tap. Stakeholder engagement indicated that time savings, energy savings, and cost effectiveness are the highest priorities for stakeholders. Analysis yielded that installing a water heater close to fixtures can result in significant water savings and time savings. Conventional demand recirculation, while delivering excellent time-to-tap and water savings, has not been shown to save energy due to larger heat losses from the distribution loop piping.

The project team selected three preliminary compact DHW measures for further testing. The measures intend to eliminate behavioral waste by delivering hot water to all showers within 5 seconds, and to all other fixtures within 10 seconds. The measures require builders to install water heaters close to fixtures, limit the total length of trunk piping installed, and introduce pump priming for fixtures that still have long time-to-tap wait times after the first two measures are implemented.

Study Background

This study was commissioned by Pacific Gas and Electric Company to develop compact design solutions for single family DHW distribution systems that can be incorporated California's building energy efficiency standards (Title 24 Standards), incentive programs, and design guidelines.

Most single family DHW distribution systems are poorly designed, or not based on design. Hastily routed indirect pipe paths are often taken by field installers even when plumbing designs may exist. In most homes, people experience long hot water delivery times from a cold start (hot water has not been used for a long time and water in the hot water pipe is cold). A significant amount of water must be drained before hot water arrives at the fixture, leading to both energy and water waste.

[1] The authors would like to thank other project team members Gary Klein, Marc Hoeschele, and Peter Grant for the contributions to the project and this paper.

For example, a field survey looking at 97 new construction homes throughout California found that distribution systems were designed and installed on site by plumbers, and often avoids direct paths from the water heater to the fixtures (DEG 2012). This study also found that average pipe volume between water heater and use points was fairly consistent with a 2006 sixty home California field survey, about one gallon of water for a 2000 ft^2 house, suggesting that there was little improvement in single family DHW distribution systems during the period between the two studies. A recent study found that based on 283 individual shower events, average bathroom total warm-up waste was 1.8 gallons, with 0.7 gallons categorized as structural waste (time to get water to adequate temperature) and 1.1 gallons categorized as behavioral waste (Sherman 2014).[2, 3] Behavioral waste refers to the situation when building occupants leave the hot water fixture turned on to do other things because the hot water waiting time is too long, even after hot water has arrived to the fixture.

Title 24 Standards have tried to promote compact designs by providing compliance credits to compact design options and penalties to inefficient distribution systems. The 2013 Title 24 Standard defines a compact design option by prescribing maximally allowed pipe length from the water heater to hot water fixture shown in Table 1. However, this option has made very limited impacts on industry practice on distribution system design as evidenced by the studies discussed above. One reason is that there is a lack of documentation and inspection processes for distribution plumbing systems. Another reason is that the Title 24 compact design requirements are not supported with any design guidelines, which also means that the practicality of meeting these requirements, and opportunities for further improving them, are unknown.

Table 1. Title 24 compact DHW criteria

Floor area served by the water heater (ft^2)	**< 1000**	**1001 – 1600**	**1601 – 2200**	**2201 – 2800**	**> 2800**
Maximum measured distance from water heater to use point (ft)	28	43	53	62	68

The US Environmental Protection Agency (EPA) defines compact hot water delivery system in its WaterSense® New Home Specifications as having no more than 0.5 gallons of water volume between the fixture and hot water source. In addition, no more than 0.6 gallons can leave the fixture before the temperature has risen 10°F above the ambient water temperature (EPA 2014). The hot water source can be either a water heater or recirculation loop. It is very difficult to meet this specification when using the water heater as the hot water source, and the EPA does not provide any guidance on how to do so. It is very easy to meet this specification using recirculation loop as the hot water source, but, as discussed below, recirculation systems usually have higher energy use than non-recirculation systems.

[2] The structural waste number is a blended number that includes cold starts (the entire hot water line had cooled off and the total volume of the line would need to be purged prior to hot water arrival) as well as clustered events (the line already had hot water in it to some degree).
[3] The author of this study has generally concluded that there is ~1 minute of behavioral waste for every shower taken. A set time of behavioral waste will lead to various wasted volume for showerheads with various flowrates.

This study aims to develop compact distribution measures based on practical design strategies addressing variations in home architectural designs. The goal is to improve both energy and water efficiency by significant reducing pipe volumes and avoiding occupant behavior related waste.

Development Approach

Development of compact design measures faces the following major challenges:

- Hot water fixtures can be placed at different locations in homes due to variations in architectural designs. To achieve compact distribution, compact design strategies should be able to accommodate a variety of home designs and avoid imposing architectural barriers, which will also help the strategies be more acceptable to the building industry.
- There are several pipe layout methods (discussed below in Compact Design Options) and many options in pipe routing to consider in search for optimal solutions.
- Hot water draw schedules are uncertain due to their dependence on occupant behavior. Some designs may work well for certain draw patterns, but not others. Therefore, it is difficult to determine the performance of a design, and compare performance among different design solutions.
- Potential conflicts exist between energy and water savings. Recirculation design is considered by many practitioners the only solution that is able to bring the hot water source close enough to all fixtures to significantly reduce hot water waiting time and water waste. However, studies have shown that recirculation designs consume more hot water energy than other designs even when advanced controls are used (Henderson 2015, and Weitzel and Hoeschele 2014). So, are there practical design options that can provide high performance in both energy and water efficiency?

The project team addressed the above challenges through technical analysis in the four following areas: characterization of fixture layout compactness, compact design option assessment, and piping layout performance analysis. The project team also conducted a stakeholder workshop and interviewed industry practitioners to seek input improve methodologies and refine preliminary compact design measures.

Fixture Layout Compactness

Homes have different sizes and fixtures can be placed at all possible locations in homes. The project team developed a unique method, called the fixture layout polygon method, to effectively compare fixture layout compactness among different homes. For a given home floor plan, a polygon can be formed by using straight lines to connect fixtures. The area of the polygon is then divided by the home footprint, excluding garage areas, to obtain a normalized polygon size as the indicator of fixture layout compactness. In the example shown in Figure 1, the polygon area is 1200 ft^2, compared to a conditioned floor area of 3300 ft^2, resulting in a normalized polygon size of 36%.

The project team randomly sampled fourteen floor plans and obtained their normalized fixture layout polygon sizes, which range from 10% to 50%, as shown in Figure 2. Results roughly reflect the range of fixture layout compactness in the market. Sampling more floor plans to provide more polygon size data will increase the accuracy of findings. This finding was used to determine the pipe length limit discussed in a following section.

The polygon analysis also clearly shows the importance of have the water heater placed near or within the fixture polygon. If the water heat is placed away from the fixture polygon, usually in the garage, additional piping is needed for the space between the water heater and the polygon and large diameter pipes must be used to serve multiple downstream fixtures.

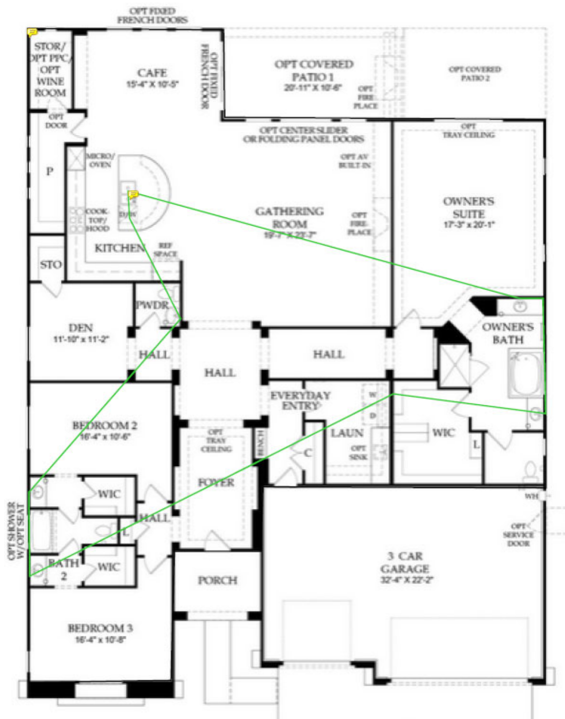

Figure 1. Example of the polygon drawn to characterize fixture compactness.

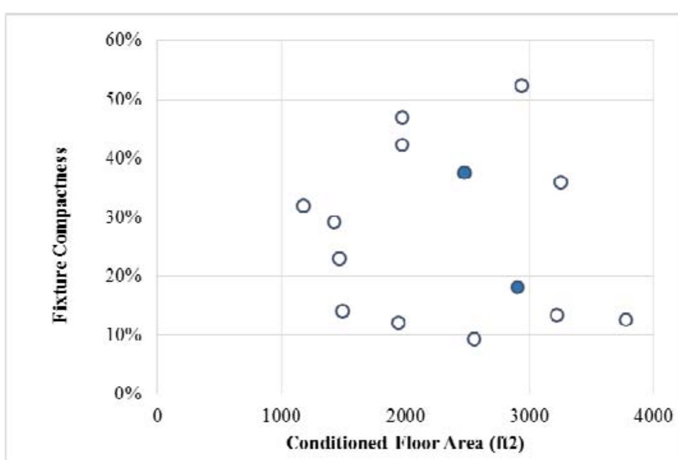

Figure 2. Fixture compactness compared to floor area.

Compact Design Options

The project team investigated various water heater locations and pipe layout methods as potential compact design strategies. The fixture layout polygon analysis clearly shows that it is important to place the water heater close to fixtures. Therefore, as the first step of design option analysis, the project team compared the following water heater locations:

- Water heater away from the polygon, in the garage
- Water heater near the polygon, e.g. on the side wall of the kitchen
- Water heater inside the polygon, e.g. in attic.

The team then considered the following four common pipe layout methods:

- Trunk and Branch – The most commonly used distribution design scheme, this method has the benefit of sharing pipes among different fixtures. After one fixture receives hot water, other fixtures connected to the same trunk and branch pipes can receive hot water quickly, reducing water and energy waste in instances of clustered hot water draws.
- Home Run – This method dedicates a pipe path for each fixture and appliance originating from a manifold in close proximity to the water heater. This approach allows a small pipe volume from the manifold to each individual fixture, reducing water and energy waste due to shared pipes in instances of sporadic hot water draws.
- Hybrid **–** This method combines the design concepts used in the trunk and branch and home run in order to take advantage of the benefits of each. There are several ways to mix the use of trunk and branch and the home run piping layouts.
- Recirculation **–** This method uses one loop of pipe that goes near each fixture to reduce branch length and returns to the water heater. By circulating hot water around the loop, this design can drastically reduce hot water wait times and water waste.

The project team selected two floor plans to investigate the impact of the design options discussed above on system performance. The two sample floor plans, a one-story and a two-story as highlighted in dark blue in Figure 2, have similar floor areas but large differences in normalized polygon size, and adequately cover the range of sample variation. Table 2 provides a summary of design options considered for the two floor plans.

Table 2. Design Option (water heater location and pipe layout method) for Two Floor Plans

Design Options	Floor Plan 1 (1-story)	Floor Plan 2 (2-stories)
Base case: Water heater away from polygon (in garage), trunk & branch	√	√
Water heater near polygon (near corner of garage), trunk & branch	√	
Water heater inside polygon (in attic), trunk & branch	√	
Water heater inside polygon (in pantry), trunk & branch	√	√
Water heater inside polygon (two water heaters), trunk & branch		√
Water heater inside polygon (in attic), home run	√	
Water heater inside polygon (in pantry), home run	√	√
Recirculation (water heater in garage)	√	√
Recirculation (water heater in garage), two zones		√

Preliminary Performance Analysis

To investigate compact design, the project team needed an easy-to-use performance analysis tool to quickly estimate the impacts of several design options. The performance analysis at this stage focused on understanding relative hot water wait times and water waste among various strategies, rather than accurately estimating annual energy use.

The project team developed a spreadsheet-based model instead of using existing simulation software, such as TRNSYS or HWSIM, to have full control over analysis assumptions. The model takes detailed pipe layout inputs, such as pipe diameter, length, and connections between different pipe sections, to estimate of pipe volume, hot water waiting time, and water waste. The model uses a set of hot water draw events from the most frequently used fixtures, including the kitchen faucet, master shower, master bath faucet, and second bath shower, to estimate the overall distribution performance. The initial fixture draw was from a cold start, and the remaining fixture draws assume that the hot water has filled the trunk and branches leading to the initial fixture, thus capturing the impact of clustered events.

Findings

The results shown in Table 3 indicate that moving the water heater more centrally (near or inside fixture layout polygon) can result in significant water savings and time savings. For trunk and branch and home run systems, water and time savings are indicative of the potential for energy savings (25-38%). Furthermore, a conventional trunk and branch system is capable of delivering hot water to many high use fixtures in an average of under 25 seconds if the water heater location is centralized. Home run systems may show even better performance than trunk and branch. Recirculation systems clearly show the best results for reducing water and time waste, though, as mentioned earlier, are unlikely to deliver energy savings.

Table 3. Results from varying piping layouts and water heater locations for two floor plans

Description	Wasted Gallons/Day	% of Base Case	Avg Wait Time (sec)	% of Base Case
Base case	4.9	100%	38	100%
Trunk & branch, WH near/inside polygon	3.7	75%	25	67%
Home run, WH near/inside polygon	3.0	62%	15	39%
Recirculation	0.6	12%	4	9%

Stakeholder Engagement

The project team organized a workshop held in Gold River, CA in October 2015 to obtain industry input and vet the analysis methodologies and results. Seventeen people attended including builders, plumbing engineers, policymakers, and the project team. Recurring themes voiced by attendees include:

- Reducing water, energy, and time wasted is an important issue to all stakeholders, and provides value to homebuyers. 15 seconds time-to-tap may be marketable, which is near to the American Society of Plumbing Engineers (ASPE) 10-second criteria for acceptable performance (ASPE 2013).
- Barriers to relocating water heaters closer to fixtures (rather than in the garage) include dealing with potential leaks, a slight increase in labor costs, and the possible repurposing of valuable conditioned floor area to accommodate the water heater.
- Compact design needs to be easily assessed and enforceable by builders and the building department, so that plumbing is installed according to design.
- Revising floor plans is likely the most economical method for compact DHW distribution, though the least palatable from a builder standpoint.

As a result of feedback received during the workshop, the project team sought to gain a broader understanding of strategies most acceptable to California builders, gather best practices, and collect cost data. Interviews with seven builders and two plumbers showed that:

- Builders commonly receive wait time complaints. Two builders indicated that they often pre-plumb homes to be compatible with demand recirculation, except for the final point of connection to the water heater, in case of complaints.
- Builders would rather install a demand recirculation system than a pipe priming system, because the recirculation system is more likely to reduce hot water wait times to all fixtures.
- Respondents indicated that locating water heaters closer to fixtures and designing homes more compactly would be their most preferred methods of compact DHW distribution.

Compact Design Strategies

In developing comprehensive compact design strategies, the project team considered all related issues summarized in Table 4. It is important to note:

- Energy savings and waiting time reduction are the highest priorities
- Cost and cost effectiveness is a priority for all perspectives. Builders and plumbers want to satisfy homeowners in the least costly way possible, while Title 24 requires life cycle cost effective energy savings.
- Water savings are not the top priority. However, as the California is facing a long-term drought condition, saving water is very important.

Table 4. Priorities from perspectives impacted by a compact DHW measure

Perspective	Priority #1	Priority #2	Priority #3	Priority #4
Homeowner	Waiting time reduction and convenience	Reliability	Low incremental cost	Water savings
Builder	Minimize homeowner complaints	High value (i.e., Title 24 credits) compared to incremental cost	Reliability (low maintenance)	-
Plumber	Minimize homeowner complaints & callback	Low installation cost, easy implementation	-	-
Title 24	Energy savings	Cost effectiveness	Water Savings	Reliability

The project team developed the following compact design strategies based on technical analysis results and stakeholder feedback. Table 5 presents performance characteristics of the compact strategies based on technical analysis conducted by the project team and stakeholder feedback:

- **Proximate Water Heater –** Locating the water heater near high use fixtures can significantly reduce the volume of entrained water in the distribution system, regardless of the distribution system type. The water heater can be located in an attic or a closet near the kitchen or master bathroom, which contain the fixtures with the most hot water usage. The project team suggests implementing this strategy first.
- **Minimize Pipe Lengths –** Once the water heater in properly located, the pipe volume can be further reduced through a streamlined pipe layout. In particular, it is beneficial to have only one or two plumbing zones and use a trunk line to serve each zone. This strategy would limit the allowed lengths of large pipe diameters, reducing pipe volume, energy loss, and time-to-tap. While the floorplan, including water heater location and fixture locations, determines the overall plumbing layout, direct requirements for floorplans that are architecturally compact (i.e., group fixtures close to each other and locate them close to the water heater) are unfavorable to builders. This measure sets limits on pipe lengths, rather than floorplan layout, to allow for flexibility in architectural design.
- **Pipe Priming –** Even with the above two strategies in place, hot water wait time may still not be short enough to avoid behavior waste. A pump can be installed specifically to

serve a fixture far away from a water heater. When turned on by an occupant, the pump will prime the trunk and branches leading to the fixture with hot water before the fixture is used. Until hot water arrives at the fixture, the purged cold water can be diverted into the cold water line or returned to the water heater. This strategy should only be used after the first two to ensure overall pipe volume is small. When properly implemented, this strategy yields the water and waiting time reduction as conventional demand recirculation without the high heat losses, thus also saving energy.

- **Multiple Water Heaters –** The project team also considered using multiple water heaters in a home. Each water heater serves nearby fixtures to reduce the distance to the furthest fixture and entrained pipe volume.

Table 5. Characteristics of Compact Distribution Design Strategies

Compact Design Strategies	**Wait Time Savings**	**Energy Savings**	**Cost**	**Reliability**	**Water Savings**
Proximate Water Heater	Medium	High	Medium	Medium	Medium
Minimize Pipe Lengths with Proper Zoning	Medium	Medium	Low to none	High; same as status quo	High
Trunk Pipe Priming	Medium	Medium	Medium	Medium	Medium
Installing Multiple Water Heaters	Medium	Medium; penalty with storage	High	Medium; more maintenance	Medium

Preliminary Compact Design Measures

While compact design *strategies* are general approaches, compact design *measures* aim to specify design goals. These measure specifications are intended to inform future incentive program and building standards development. However, they need to be further refined before consideration for adoption. The project team used the first three design strategies in Table 6 to develop compact design specifications. Installing multiple water heaters is also a viable compact design solution, but is deemed as the least likely measure to be cost effective and not recommended for further evaluation.

Specifically, measures aim to reduce hot water waiting time to a level where behavioral waste can be avoided. According to ASPE criteria, the acceptable hot water waiting time should be no more than 10 seconds, though this may still be too long to avoid behavioral waste. Showers are only used after hot water is available, so the hot water waiting time for showers should be even shorter. Thus, the preliminary measures aim to achieve a wait time of less than 5 seconds for showers, and less than 10 seconds for all other fixtures. Each of the measures achieve the EPA water sense criteria of a pipe volume of <0.5 gallons to each fixture (a volume of 0.5 gallons is approximately equal to a wait time of 15-20 seconds, depending on the flow rate of the fixture).

While the preliminary measures do not exclude any pipe layout methods, they may be more difficult to achieve with some pipe layout methods.

Measure 1 - Proximate Water Heater

This measure requires that the water heater be located close to hot water fixtures with the most hot water use, namely the master bath shower and the kitchen faucet. Volume performance analysis suggested that distribution pipe volume can be significantly reduced by moving the water heater closer to these fixtures.

Pipe length estimates are developed based on the two most feasible locations for keeping the water heater close to the master shower and the kitchen faucet: on a home exterior wall (with or without a water heater closet), and the attic. The lengths associated with pipe volumes are calculated using PEX pipe characteristics. The measure requirements are specified in pipe volume so that builders can implement with a variety of pipe sizes.

Measure Specification. The water heater must be located close to the kitchen faucet or the master bath shower to meet one of the following specifications.

1. Pipe volume from the water heater to the kitchen faucet shall be ≤ 0.20 gallons (the volume of 1 foot of 1” pipe + 3 feet of 3/4" pipe + 11 feet of 1/2” pipe);
2. Pipe volume from the water heater to the kitchen faucet on a kitchen island shall be ≤ 0.25 gallons (the volume of 1 foot of 1” pipe + 3 feet of 3/4" pipe + 16 feet of 1/2” pipe);
3. Pipe volume from the water heater to the master bath shower shall be ≤ 0.20 gallons (the volume of 1 foot of 1” pipe + 3 feet of 3/4” pipe + 11 feet of 1/2” pipe).

Measure 2 – Minimize Pipe Lengths

This measure reduces entrained volume by specifying different length limits for different pipe diameters. Pipes greater than ½” typically form the trunks and recirculation loop supply lines, and small diameter pipes (equal or less than 1/2”) are used as branch pipes. The length limit formula was developed based on polygon analysis, a conceptual two-zone design concept, straight pipe runs, and pipe runs between floors in two-story buildings. Preliminary polygon analysis yielded that the maximum fixture compactness ratio (FCR, polygon area divided by the conditioned floor area) was 52% for a one-story home, and 32% for a two-story home. These values are used to determine maximum pipe lengths per home.

Measure Specification. Pipe installations must meet all of the following specifications:

1. Total pipe length for pipes > 1/2" in diameter shall not exceed the following length:

   Total Pipe Length = √((Conditioned Floor Area × FCR)/(Length to width ratio))×(1+Length to width ratio)
   where, FCR = 52% for one-story homes and 32% for two-story homes,
   Length to width ratio for homes is assumed to be 1.2

2. Pipes > 3/4" inch shall be ≤ 3 feet. This length of pipe is enough to connect several branches of 3/4” diameter pipe near the water heater.

3. For each fixture, pipes ≤ 1/2" shall be ≤ 15 feet total, or the total pipe length to the water heater is ≤ 30 feet.

Examples of the formula output based on conditioned floor area are provided in Table 10 below.

Table 7. Examples of Maximum >1/2” Diameter Pipe Lengths

Home Area (ft^2)	One-Story Home Max Pipe Length (ft)	Two-Story Home Max Pipe Length (ft)
1200	50	39
2400	71	56
3600	87	68

Note that this measure does not currently account for recirculation or pipe priming return pipe requirements. The project team is considering how to refine the measure to address these pipes.

Measure 3 – Trunk Pipe Priming

The pipe volume performance achieved through the prior two measures will not be able to satisfy the hot water waiting time goal for all fixtures. Therefore, using circulation pumps to prime the distribution system with hot water can help to meet the waiting time performance target of 10 seconds (or 5 seconds for showers). This can be essential for showers and the kitchen faucet because of their frequent uses and related behavioral waste.

Measure Specification. Pipe Priming may only be implemented in conjunction with the Proximate Water Heater and Minimize Pipe Lengths measures. Pipe Priming shall be implemented in all of the following ways:

1. For fixtures with a pipe volume to the water heater of more than 0.2 gallons, implement pipe priming to ensure the pipe volume from the fixture to the primed pipe is less than 0.2 gallons.
2. For showers and kitchen faucets with a pipe volume of more than 0.1 gallons, implement pipe priming to ensure the pipe volume from the fixture to the primed pipe is less than 0.1 gallons (approximately 5 seconds or 10 feet of 1/2" pipe),
3. Pumps must be manually turned on via demand switches. Pumps will automatically turn off once hot water arrives at the fixture.

Next Steps

The project team has recruited California builders to install all these measures in some of their new construction single family homes. The team will document the entrained volume and time for hot water to reach the fixture for homes with the measure installed, and identical homes with conventional plumbing installation. Laboratory tests will develop data on the flow and heat loss characteristics of PEX pipe, and energy savings estimates will be developed through a dynamic performance model validated by the lab data. Estimated increases in wait time will be developed based on potential future low-flow fixture flow rates.

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