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Evaluation of Waste Heat Recovery and Utilization from Residential Appliances and Fixtures

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Energy and Transportation Science Division

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EXECUTIVE SUMMARY

In every home irrespective of its size, location, age, or efficiency, heat in the form of drainwater or dryer exhaust is wasted. Although from a waste stream, this energy has the potential for being captured, possibly stored, and then reused for preheating hot water or air thereby saving operating costs to the homeowner. In applications such as a shower and possibly a dryer, waste heat is produced at the same time as energy is used, so that a heat exchanger to capture the waste energy and return it to the supply is all that is needed. In other applications such as capturing the energy in drainwater from a tub, dishwasher, or washing machine, the availability of waste heat might not coincide with an immediate use for energy, and consequently a heat exchanger system with heat storage capacity (i.e. a regenerator) would be necessary.

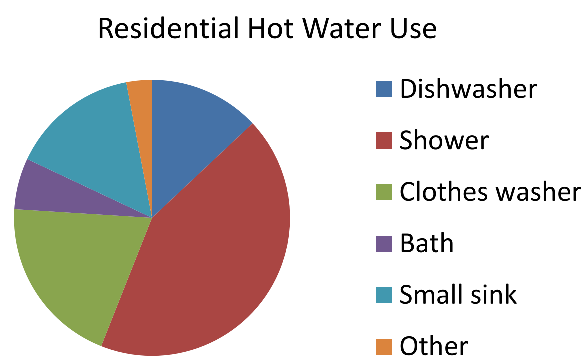
This study describes a two-house experimental evaluation of a system designed to capture waste heat from the shower, dishwasher clothes washer and dryer, and to use this waste heat to offset some of the hot water energy needs of the house. Although each house was unoccupied, they were fitted with equipment that would completely simulate the heat loads and behavior of human occupants including operating the appliances and fixtures on a demand schedule based on the Building American (BA) protocol (Hendron and Engebrent, 2009). While the BA protocol is a constant hot water demand, the schedule used for these homes was discretized with realistic water draws. The heat recovery system combined (1) a gravity-film heat exchanger (GFX) installed in a vertical section of drainline, (2) a heat exchanger for capturing dryer exhaust heat, (3) a preheat tank for storing the captured heat, and (4) a small recirculation pump and controls, so that the system could be operated anytime that waste heat from the shower, dishwasher, clothes washer and dryer, and in any combination was produced.

The study found capturing energy from the dishwasher and clothes washer to be a challenge since those two appliances dump waste water over a short time interval. Controls based on the status of the dump valve on these two appliances would have eliminated uncertainty in knowing when waste water was flowing and the recovery system operated. The study also suggested that capture of dryer exhaust heat to heat incoming air to the dryer should be examined as an alternative to using drying exhaust energy for water heating.

The study found that over a 6-week test period, the system in each house was able to recover on average approximately 3000 W-h of waste heat daily from these appliance and showers with slightly less on simulated weekdays and slightly more on simulated weekends which were heavy wash/dry days. Most of these energy savings were due to the shower/GFX operation, and the least savings were for the dishwasher/GFX operation. The 3000 W-h of recovered energy amounted to a 32.8% reduction in water heating load.

1 INTRODUCTION

Significant accomplishments continue to be made to reduce the energy consumption in homes. Improved insulation, construction techniques and materials that reduce undesirable heat transfer and air infiltration through the building exterior, appliances and HVAC equipment that exceed minimum efficiency standards are readily available. They can be made to work together in a cost effective manner to produce a house that uses 50% of the energy consumed by a new house built with conventional building practices and fitted with appliances and heating/cooling systems that meet today's efficiency standards. As further improvements in the energy efficiency of building equipment in addition to "tighter" envelopes that require demand-controlled ventilation systems continue to play a role on the path toward affordable zero energy homes, the fraction of building energy consumption dedicated to hot water production will increase. Equipment such as electric heat pump water heaters, point-of-use and demand water heaters, condensing gas water heaters and solar water heaters save energy needed to produce hot water. However, most of the hot water that is produced albeit more efficiently with this equipment is drained away as waste water. This waste water carries with it energy that could be extracted and used to preheat water to the home. Showers, tubs, sinks, dishwashers, clothes washers, dryers – even refrigerator condensers exhaust heat energy that could be collected and reused. Estimates by the Department of Energy indicate that the equivalent of 235 billion kWh worth of hot water is discarded annually through drains, and a large portion of this energy is recoverable (A. D. Little Inc., 1996). In particular, showers, dishwashers and clothes washers constitute a majority of residential hot water use as shown above. Waste water from showers is warm and continuous for the full shower cycle; waste water from clothes washers can be hot to cold depending on the wash cycle and is produced quickly as the tub is draining; and since all of the inlet water to dishwashers is hot, the waste water is still hot and drained away quickly in the wash and rinse cycles. While not producing warm waste water, evaporative dryers produce warm air that is exhausted outside the home. With dryers, the exhaust air comes from the conditioned space and ultimately adds to the air infiltration of the home. An air-to-water heat exchanger as part of the dryer exhaust duct could be used to extract some of the exhaust heat and transfer that energy into the domestic hot water stream.



The extent to which waste energy recovery and reuse is possible and realistic depends on a number of factors: the timing of the waste heat stream as compared to the need for hot water within the home, the characteristics (temperature, flow, duration) of the waste heat, a reasonable technique to extract the energy, the efficiency of the extraction technique, and ultimately, the practicality and cost-effectiveness of the heat recovery design. This study, an experimental evaluation of waste heat recovery, was conducted to address some of those issues and to provide answers to those questions.

2 THE OBJECTIVES OF THE STUDY

This was an experimental evaluation of a design for capturing waste heat from a dryer, shower, clothes washer and dishwasher in a home. The objective elements were as follows:

a. To design a simple system that could capture waste heat from these appliances;

b. To implement the design and measure the amount of heat captured, stored and reused;

c. To determine the impacts of timing and overlap between the waste heat streams;

d. To examine the effects of losses in the recovery system so that the need for keeping the components close together could be evaluated;

e. To determine the parasitic energy requirements for the recovery system;

f. And in the case of the dryer, to pose alternative designs for the capture of exhaust heat.

3 EXPERIMENTAL APPROACH

Two houses have been constructed near Oak Ridge, Tennessee, and were used to in this study to evaluate the potential for waste heat recovery from fixtures and appliances (Christian et al., 2010). One of the houses, designated as CC3 and located in Knoxville's Campbell Creek Subdivision, is a conventional two story, slab-on-grade home carefully constructed using "flash and batt" optimal-value framing practices. Storage water heating is done in CC3 with an 85-gallon Marathon electric resistance water heater, and the hot (and cold) water distribution is done with home run PEX piping between each fixture and the mechanical room where the water heater is located. This arrangement is ideal for monitoring the use of hot water throughout the house. The second house, located in Oak Ridge's Wolf Creek subdivision, is termed WC1. This is a 3700 sq. ft. house counting the walkout basement with an open floor plan and constructed using structural insulated panels. With the basement, WC1 is ideally-suited for the installation of a waste heat recovery heat exchanger downstream of all of the drain piping in the house, i.e. waste water energy from all appliances and fixtures in the house can be extracted and put to use. WC1 is unique in that many of the appliances and kitchen fixtures are co-located adjacent to a single nonstructural utility wall that runs from the basement to the kitchen above. This wall (ZEHcor, or zero energy home core) is designed to put the utility services (hot water, drains, cold water, kitchen appliances as close together as possible so that a waste heat stream from one appliance can be used to satisfy a need for the waste heat by another with little thermal distribution losses from piping.

Neither house is occupied. Both houses have computer-controlled systems for operating the appliances and fixtures to simulate the habits of occupants. In CC3, this capability includes operation of the stove, the doors of the refrigerator, the TV, thermostat, dishwasher, clothes washer, dryer, lighting, and HVAC system. Further, CC3 has in place a device for producing sensible and latent thermal loads representative of occupants just as if the house were occupied by real people. The operation of each house's components is done according to a daily schedule that is the product of the DOE Building America Program for a 4-person household (Hendron and Engebrent, 2010). Each house is fitted with arrays of temperature, humidity, electrical energy, heat flow and water flow sensors sufficient to measure and determine thermal and humidity loads on the structure as well as to measure the performance of individual components within the structure.

Into each house in this study was installed a heat exchanger in the drain line to capture waste heat present in drain water, and an air-to-water heat exchanger as part of the dryer exhaust duct.

3.1 The Waste-Water Heat Exchanger

A commercially-available, 60-inch long gravity-film heat exchanger, GFX Model P3-60 manufactured by Waterfilm Ltd was installed in each house The GFX is a counter-current heat exchanger comprised of a central 3-in vertical drain line which is wrapped with a single length of copper tubing through which fresh water flows.   The operation of the GFX is simple: drain water that descends through the central pipe tends to cling to the walls of the pipe affording good heat transfer to the inside wall of the pipe. This heat is conducted radially outward through the wall of the pipe and to the cold water flowing through the coil around the pipe. The secondary coil is flattened a little where it touches the inner drain tube, and this reduces contact resistance. With no moving parts, the GFX has a number of advantages including:

1. Ruggedness
2. All copper construction,
3. Compact, i.e. it replaces about five feet of vertical drain line and can be installed in a stud wall cavity,
4. Conventional sweat connections are used at each end of the secondary coil,
5. Ease of installation (as long as there is headroom) using Fernco rubber connectors (www.fernco.com) to attach each end of the GFX to the drain line and sweat copper connections to the secondary (fresh water) side of the heat exchanger.

3.2 The Dryer Heat Exchanger

A dryer heat exchanger to capture exhaust heat was not commercially available, so a simple heat exchanger was designed, constructed and installed. This field-fabricated design is simply a 3/8-in diameter, 100-foot long section of ACR copper tubing wrapped around the aluminum dryer exhaust duct and the entire assembly insulated as a unit. This heat exchanger was fabricated by rolling copper tubing around a section of dryer duct with no thermal mastic between the two and no special efforts to eliminate point-to-point contact between the surfaces of the copper coil and the aluminum exhaust duct. To reduce the pressure drop that would be present in the small-diameter copper coil, we split the coil into two sections and arranged the sections along the duct so that each section was in piped in parallel on the secondary (water) side. The benefit of a dual-parallel circuits for the HX is detailed in the Appendix to this report.   Vents were added to purge air from the secondary side of the heat exchanger upon initial operation. The design of the balance of the system was based on combining the need for a capability for the simultaneous capture/reuse of waste heat as would be present in a shower with the need for a regenerator-type system where the generation of waste heat is not concurrent with a need for that heat (i.e. tubs, dishwashers, clothes washers). Moreover, the design needed to accommodate the possibility that more than one appliance/fixture could be operating at the same time. The design that we developed for accomplishing both of these goals is shown in Figure 1.

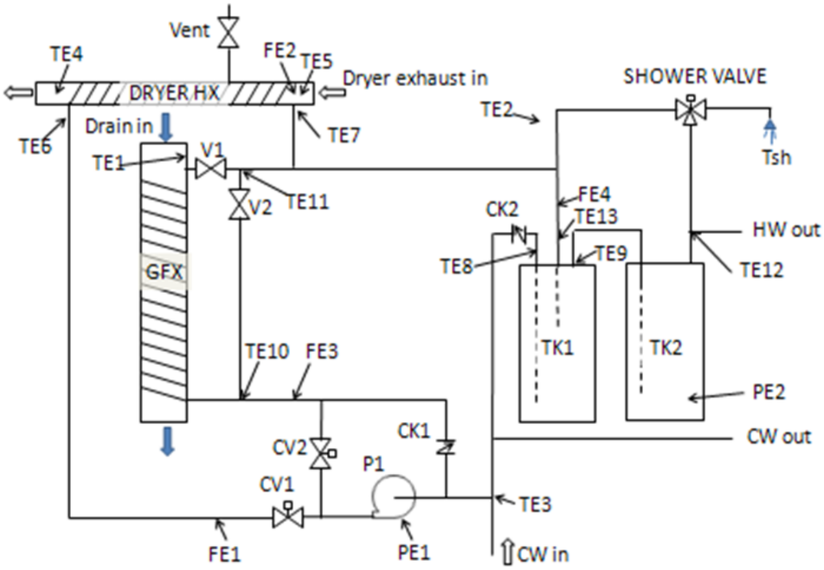


Figure 1. Waste Heat Recovery Study

Prior to the study, the storage water heater TK2 and the shower tempering valve were already in place. Essentially, the heat recovery system design consisted of three flow paths that can operate in parallel. The first was the one for shower heat recovery as shown in Figure 2.

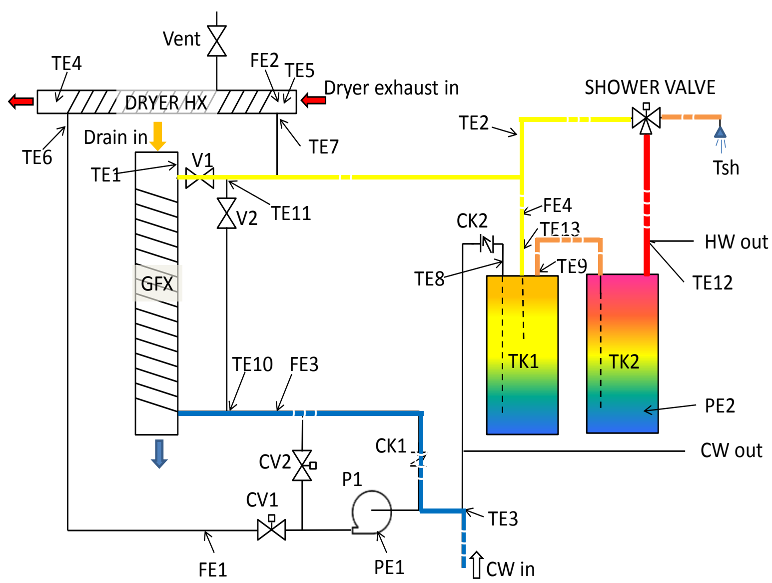


Figure 2. Shower Heat Recovery Mode

Its operation is as follows: During a shower, cold water (CW in) travels up on the secondary side of the GFX at the same time as waste water passes down through the center of the GFX. And depending on the shower temperature setting and the temperature of CW in, the cold water is warmed by about 15 – 20°F by the GFX. This warmed water then splits with a portion going to the cold side of the shower valve and the rest going to a 30-gallon preheat tank, TK1. Warm water from TK1 enters TK2, and TK2 feeds the hot side of the shower valve. Overall, the GFX does two things: 1) it warms the water to the cold side of the shower valve, and in so doing, the flow rate on the cold side of the valve is increased, and the flowrate on the hot side of the valve is in turn reduced; and 2) it preheats water entering TK2. The line with valve V2 is simply a bypass that can be operated manually.

A second flow path is shown in Figure 3. In this mode and the next mode of operation, the demand for hot water does not coincide with its availability, and so hot water must be stored. A small pump, P1 is used to recirculate water between the dryer heat exchanger and the preheat tank. For this mode, control valve CV1 is open, CV2 closed and P1 is activated throughout the dryer cycle. In the event that a shower is taken while the system is in the dryer mode, the shower water simply bypasses the pump. Check valves CK1 and CK2 are used to ensure that the incoming cold water passes through the dryer HX or the GFX and not to preheat tank TK1.

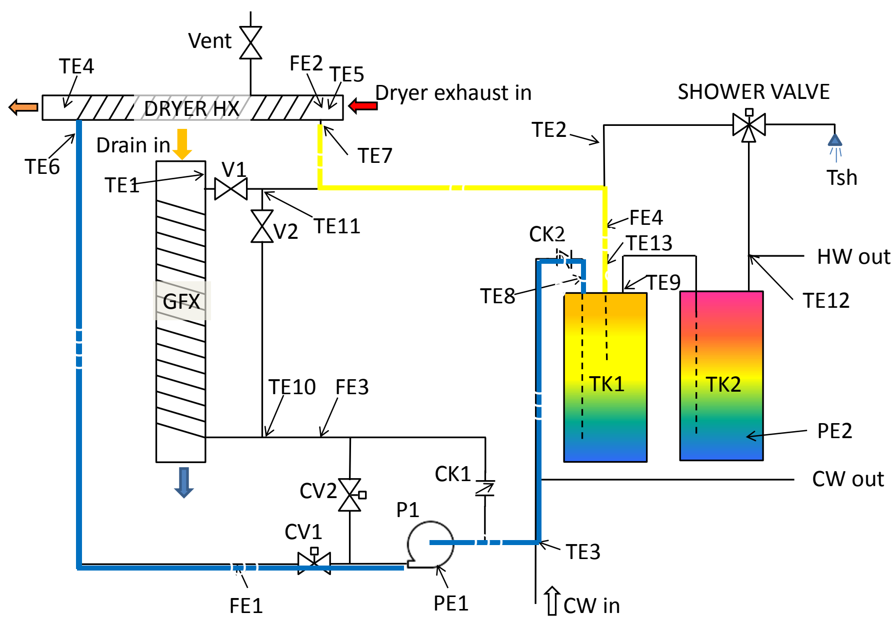


Figure 3. Dryer Exhaust Heat Recovery Mode

Finally, there is a third mode of operation (shown in Figure 4) that is used to capture heat in the drainwater from the clothes washer and the dishwasher. In this mode, valve CV1 is closed and CV2 open, and the pump runs whenever there is warm drainwater passing through the GFX. Drainwater produced from clothes washers and dishwashers is of short duration, and this makes the collection of energy from the wastewater in these appliances challenging. Therefore, it is important to have the pump and control valves set and ready to go when a drain takes place. We evaluated several approaches for controlling the pump and valves including (A) looking for a sudden rise in the temperature of sensor TE1 indicating the arrival of warm waste water at the GFX entrance, (B) operating the pump when TE1 reached a certain level, and (C) comparing temperatures TE11 and TE13 and operating the pump and valves whenever there was justification for heat recovery. The idea with each of these approaches was to operate the heat recovery system based only on temperatures in the heat recovery system itself, i.e. without needing a mode sensor installed in the clothes washer or the dishwasher.

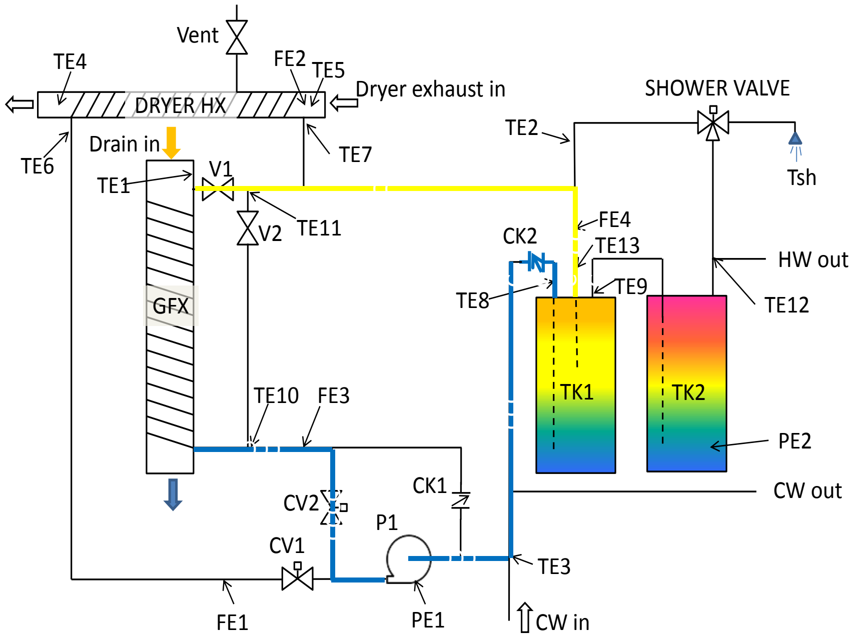


Figure 4. Clothes Washer/Dishwasher Heat Recovery Mode

4 THE EXPERIMENT

The performance of any heat exchanger including the GFX described above depends on the difference in temperature approach. In the case of the GFX, this is the temperature difference between the wastewater inlet and the fresh water inlet on the heat exchanger’s secondary. The wastewater inlet temperature depends on the temperature of the shower. For this experiment, the shower temperature was set at 105°F year round. However, the inlet fresh water temperature CW in, depends on the temperature of the ground. During summer, the ground (and ground water) is warmer than in winter, and for this reason, the GFX and the dryer heat exchangers would capture more energy during the winter than during the summer. Installation of the heat recovery system began the first week of May 2011 in CC3 and the third week of May in WC1 when ground water temperatures were still somewhat cool. However, over the short test period for this current study, the CW in temperatures have increased, and for this reason, the heat recovery data that has been collected thus far would tend to under represent what would be obtained during the cooler parts of the year.

Since house WC1 has a basement and the first floor of the house has all of the appliances, the waste water that comes through the vertical drainline into the basement area includes water from clothes washer as well as the dishwasher. So, heat recovery from WC1 includes both of these appliances as well as the shower. However, CC3 is on a slab as mentioned, the clothes washer is on the second level and the dishwasher is on the main level as would be expected. So, the vertical GFX on the main level is able to capture waste water from the upstairs only, i.e. from the main shower, the clothes washer, but not the dishwasher. Since the dryer heat recovery does not use the GFX, dryer heat recovery data was available in both houses.

The measured data consisted of temperatures (TE1 through TE12), flows (FE1 through FE4) and electrical energy (PE1) shown in Figure 2. In addition, instrumentation already in place in each house enabled us to gather data on the following appliances:

- Dishwasher: hot water inlet temperature and flow; electric energy consumption;
- Clothes washer: hot and cold inlet water temperatures and flow, electrical energy consumption;
- Dryer: electric energy consumption;
- Shower: flow and temperature of the water to the shower head.

Drain water flowing through a pipe is essentially open-channel flow, and flowrates are difficult to measure accurately without changing the characteristics of the flow by the measurement system. For that reason, we chose to measure the flow of fresh water to each appliance or fixture, and to infer the production of wastewater passing into the GFX from these measurements. In the case of the shower, the combined hot and cold flows would equal the production of wastewater because the flows occur simultaneously, except for the small amount that evaporates into the bathroom. With dishwashers and clothes washers however, the volume of wastewater produced after a wash or rinse cycle could only be estimated from the measured amount of hot and cold water used by the appliance during the immediately preceding cycle. Water temperatures (inlet to the appliance and fixtures, and inlet to the waste side of the GFX) were measured for all of the fixtures and appliances studied.

Using calculated values for the volume of wastewater produced by the dishwasher and clothes washers following a drain cycle and measured drain and fill water temperatures, and assuming that the tubs of each appliance are approximately adiabatic (i.e. tub heat losses ignorable), we were able to estimate the enthalpy of the drainwater leaving the tub.

Thermal flows were calculated based on measured temperatures in and out of the device and measured flowrates. All temperatures were measured with temperature-compensated thermistors. Water flows to each appliance and fixture studied were made with inline turbine flowmeters. The airflow in the dryer duct was measured with fixed pressure probes that sense static and total pressure inside the duct and base airflow (cfm) on these measurements. Electrical power measurements were made with watt-hour transducers.

Campbell Scientific dataloggers were used for data collection, and the control system for operating the fixtures and appliances were based on LabView. The fact that this control and data acquisition system were already setup and operating at the houses, led to a swift implementation of the heat recovery experiment and the development of these findings.

5 APPLIANCE AND FIXTURE SCHEDULE

The heat recovery systems were operated in both houses for several weeks and data collected. The appliances and shower fixtures were operated according to the following schedule in compliance with the Building American protocol (Boudreaux, Christian, and Gehl, 2012):

Clothes washer runs 6 times per week with:
- 2 cycles on Wednesday at 7:00 and 17:00,
- 2 cycles on Saturday at 8:00 and 10:00,
- 2 cycles on Sunday at 8:00 and 10:00.

Dryer runs 5 times per week with:
- 1 cycle on Wednesday at 19:00,
- 2 cycles on Saturday at 9:45 and 11:25,
- 2 cycles on Sunday at 9:45 and 11:35.

Dishwasher runs 6 times daily at 19:30 except for Saturday.

Master shower runs 5 times per day with:
- 20 gallons at 7:00,
- 5 gallons at 8:30,
- 5 gallons at 12:00,
- 10 gallons at 17:00,
- 20 gallons at 21:00

A master shower flowrate of 1.5 gpm was set throughout the experiment in both houses, and the total daily water consumption for showers (mixed water at 105°F) was maintained at 60 gallons.

6 HEAT RECOVERY RESULTS – ANALYSIS APPROACH

The instrumentation shown in Figure 1 was sufficient to characterize heat recovered at each waste heat stream source as well as the energy used to preheat water to tank TK2. In addition, the instrumentation was sufficient to allow redundant energy measurements (e.g. both sides of the GFX and the dryer heat exchanger) so that heat losses associated with pipe runs could be estimated. The quantities that were calculated[1] include the following:

Dryer Exhaust Heat:

[1] For clarity, the equations that follow are intended to show the measurement instrumentation and how measurements were used to calculate the quantities listed. The calculations for energy added to or removed from water (or exhaust air in the case of the dryer) take into account the specific heat and density of water (or air) at the average working temperature and also apply conversion units to produce energy values in units of W-h as shown in subsequent charts.

Heat Captured	= FE1(TE6-TE7); hydronic side
Heat extracted from exhaust	= FE2(TE5-TE4)
Heat stored	= FE1 (TE13-TE8)

GFX heating during shower mode:

Heat captured	= FE3(TE11-TE10)
Heat utilized or extracted from storage	= flow (TE12-TE9)
	= FE3(TE12-TE9)(Tsh-TE12)/(TE2-TE12)
GFX heating to cold water	= FE4(TE13-TE10)

GFX heating not during shower, i.e. during clothes washing or dishwashing:

Heat captured	= FE3(TE11-TE10) = FE4(TE11-TE10)
Heat stored	= FE3(TE13-TE8) = FE4(TE13-TE8).

Although these measurements of heat energy into and out of the preheat tank could have been used to establish a working inventory of the thermodynamic state of the tank, i.e. changes in average tank temperature over 24-h (daily operation) this was not done due to the brevity of the experiment. However, the data were sufficient to allow the value of heat recovery from the shower, dishwasher, clothes washer and dryer to be determined.

Since there are periods in which only one heat recovery mode (one appliance) is active, we studied the detailed individual performance of each one of the appliances (clothes washer, dryer, shower, dishwasher) in WC1 and (clothes washer, dryer, shower) in CC3. Data were taken every 15 seconds, energy flows for each period were calculated and cumulative energy changes for each cycle were calculated. For batch appliances (dishwasher, clothes washer) as well as for the dryer where heat can be lost in the piping between the active heat exchanger and the storage tank TK1, the cumulative energy stored would be less than that captured at the heat exchanger. The extent to which the components of the heat recovery system can be co-located or very near the source of waste heat, the less energy would be lost in the piping. This is one of the main reasons the ZEHcor wall was utilized in the WC houses.

7 Shower Performance – Individual Cycle

We elected to describe much of the performance of the heat recovery performance graphically. Temperature data taken for a typical 20-minute shower run in the two test houses are shown in Figure 5 for WC1 and in Figure 6 for CC3. The first thing that is apparent is the difference in shower temperature. The shower temperature in WC1 was closer to 100°F than to 110°F as it was for CC3. This meant that the temperature of the waste water entering the GFX was a little higher in CC3 than it was in WC1. The incoming cold water temperature to both houses is about the same as expected since the two locations are about 10 miles apart. Important to these results is the temperature rise across the GFX: In both houses, when temperatures stabilized a few minutes into the shower cycle, the temperature rise across the GFX secondary was found to be about 15°F even for WC1 with a lower setpoint temperature.

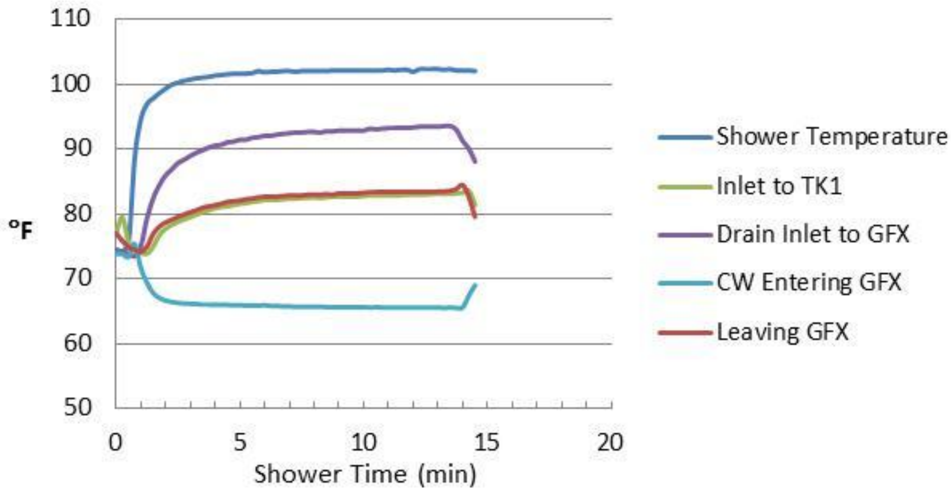


Figure 5. Shower recovery temperatures – WC1

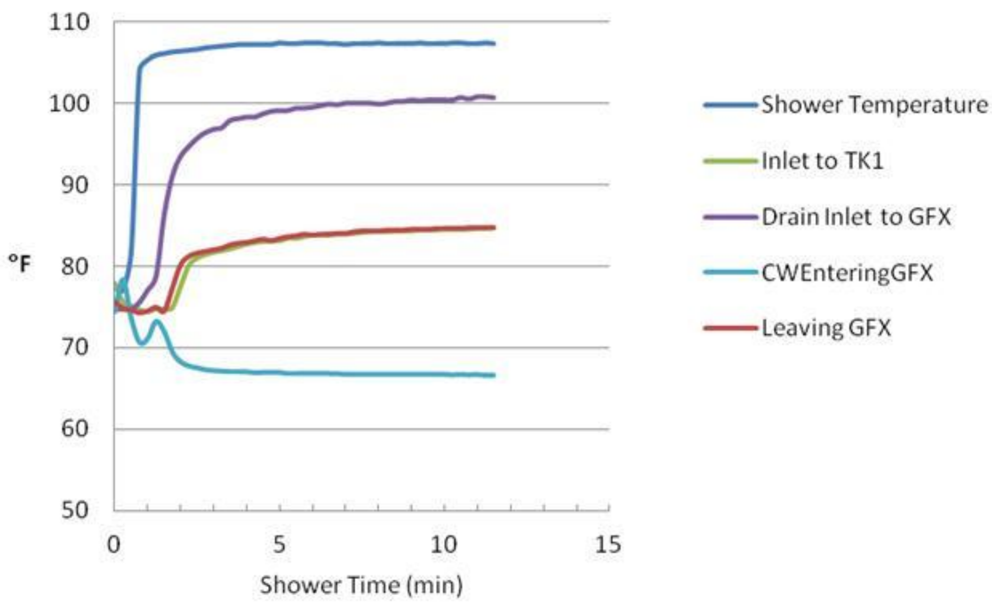


Figure 6. Shower recovery temperatures – CC3

The performance of the GFX in terms of energy that it captures and delivers to tank TK1 is of prime importance in heat recovery. As shown in Figure 7 for WC1, energy recovered by the GFX from the 20-gallon shower reached 813 W-h and of this amount, 534 W-h reached the preheat tank TK1 and would be used to reduce the energy that would otherwise be required by the main hot water tank, TK2. The balance of energy between the 813 W-h delivered by the GFX and the 534 W-h sent to the preheat tank was delivered to the cold water line to the shower valve. This amount of energy (279 W-h) warmed the cold water to the shower mixing valve, and with warmer water to the cold side of the mixing valve, the flow of hot water to the mixing valve is reduced as will be described subsequently in this report.

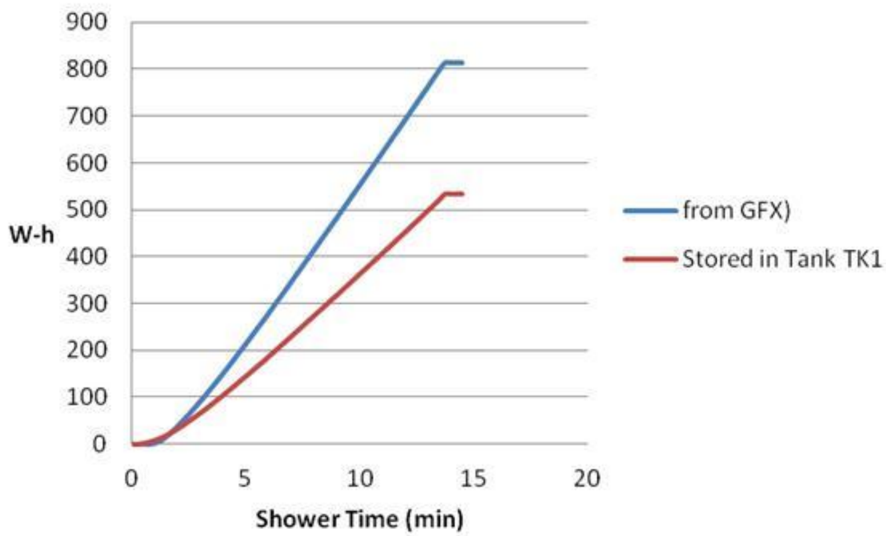


Figure 7. Shower recovery energy – WC1

Water temperature and flow data from showers in house CC3 showed similar behavior as shown in Figure 8.

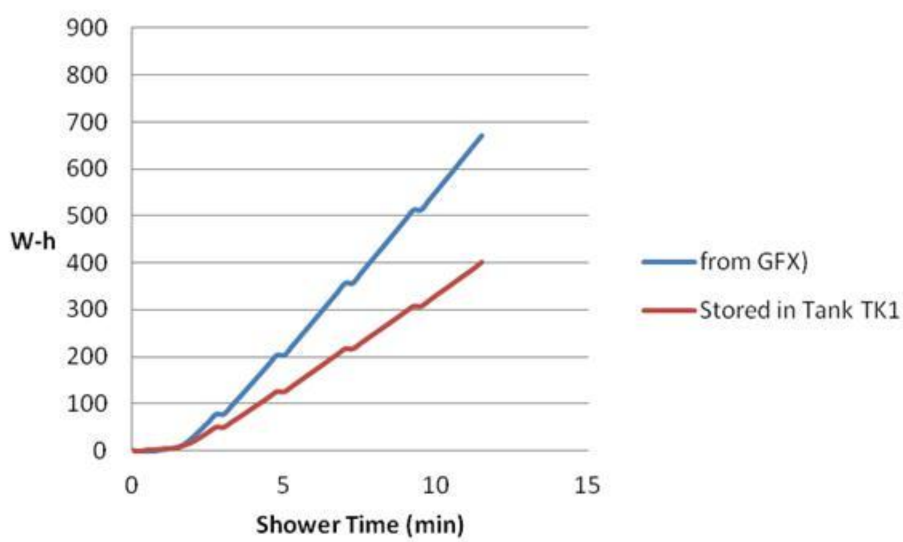


Figure 8. Shower recovery energy – CC#

A 20-minute shower in CC3 produced 671 W-h of waste heat that was captured by the GFX. Of this amount, 402 W-h was stored in preheat tank TK1 and the balance (269 W-h) was added to the cold water going to the cold water side of the shower mixing valve. In this calculation, we assumed that heat losses to ambient from the piping between the GFX and preheat tank TK1 (i.e. points TE11 and TE13 in Figure 1) are ignorable. During this shower test, the average temperature of TE11 and T13 was 81.4°F which is only marginally higher than the ambient air temperature. Consequently, it appears that heat losses associated with the uninsulated piping between the GFX and TK1 would be small as compared to the energy recovered by the GFX.

The system layout shown in Figure 1 and used for shower heat recovery was designed such that the flow of drainwater through the GFX always matches the flow of fresh water through the outside coil of the GFX. And since the flow of freshwater leaving the GFX splits with some going to the hot water preheat tank and the balance to the cold side of the mixing valve, the GFX benefit is shared. First, energy from the GFX serves to preheat water to preheat tank TK1, and this reduces the purchased energy needed by TK2, the main hot water storage tank. Secondly, a portion of the GFX-warmed water enters the cold side of the shower mixing valve as described earlier. Sensing warmer water at the cold side of the valve, the mixing valve increases the flow of water on its cold side and reduces the flow of water on its hot side to maintain a constant shower supply temperature and overall flowrate. The increase in cool water flow to the cold side of the valve matches the reduction in hot water flow to the hot side of the valve. In this manner, the GFX provides a two-fold benefit of hot water preheating as well as reducing the amount of hot water required for the shower. Consequently, the GFX effectively reduces the amount of hot water from TK2 needed for the shower. We analyzed the savings in hot water by examining 20-minute shower data from both houses. As a baseline, we assumed that without a GFX in place, the incoming water to the cold side of the shower valve would be the temperature measurement for TE10, and that with the GFX in place, the cold side of the shower valve would sense TE2 (as shown in the Figure 1 schematic). The results are shown in Figure 9.

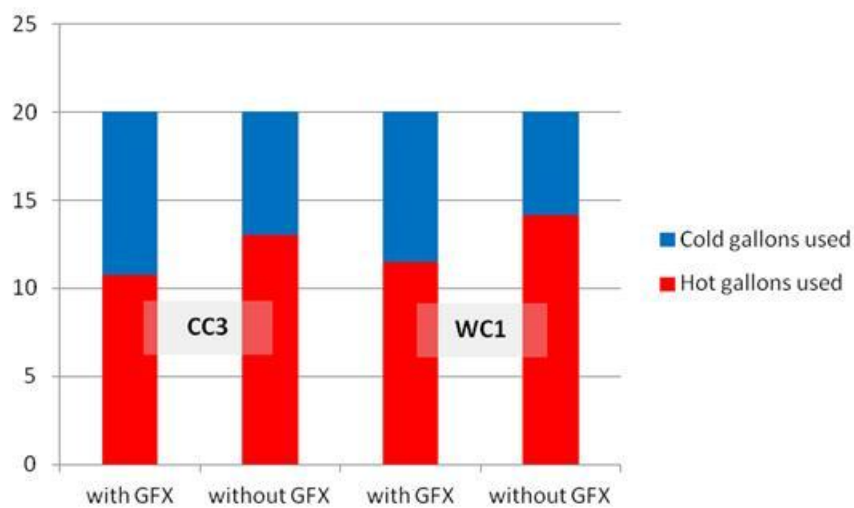


Figure 9. GFX effect on shower water consumption for houses CC3 and WC1

In house CC3, use of the GFX for a 20-gallon shower reduced the hot water consumption from 13.0 gallons to 10.7 gallons (an 18% decrease), and increased the cold water consumption from 7.0 gallons to 9.3 gallons (a 33% increase). The average shower temperature for this test was 105°F and the hot water delivery temperature from tank TK2 to the mixing valve was 125°F.

In house WC1, the GFX dropped the hot water consumption for a 20-gallon shower from 14.2 gallons to 11.5 gallons (a 19% decrease), and increased the cold water consumption from 5.8 gallons to 8.5 gallons (a 46% increase). In this house, the average shower temperature was 100°F and the hot water delivery temperature was 114°F.

In both houses, the boost in freshwater temperature through the GFX averaged approximately 15°F during the shower. It is expected that during the winter with cooler water temperatures to the houses and fixed shower temperatures, the GFX would boost the freshwater temperature by more than 15°F, and in summers by less than this amount.

8 DRYER EXHAUST HEAT RECOVERY – INDIVIDUAL CYCLE

The clothes dryers, clothes washers, and dishwashers used in house CC3 and house WC1 were from two major US manufacturers. The dryers were evaporative with 4-inch dryer ducting leading from the dryer to the outside wall of each house. The HX described earlier was installed into the horizontal exhaust duct. In the airstream on both sides of the HX, a temperature probe was installed and downstream of the HX, an airflow sensor installed as well. With the installation of flow measurements on each side of the HX as well as temperature measurements on both streams before and after the HX, the performance of the heat exchanger could be determined. The fact that the dryer HX involves two fluids (air and water), the fact that the design was simple so that lint fouling would not be an issue, and the HX did not involve design calculations led us to characterize its performance in terms of heat exchange effectiveness, E as defined by Equation 1,

$$E = C_c(T_{c\ out} - T_{c\ in})/(C_{min}\ (T_{h\ in} - T_{c\ in})), \qquad \text{Eq. 1}$$

Where,

C_c = the heat capacity flow rate of the colder fluid (the water); heat capacity flow rate is the product of the fluid’s specific heat and mass flow rate;

C_h = the heat capacity flow rate of the warmer fluid (exhaust air), and it can be shown that the minimum heat capacity flow rate is that of air, so $C_h = C_{min}$;

$T_{c\ out}$ = the temperature of water leaving the HX;

$T_{c\ in}$ = the temperature of water entering the HX;

$T_{h\ out}$ = the temperature of exhaust air leaving the HX;

$T_{h\ in}$ = the temperature of the exhaust air inlet to the HX.

Effectiveness compares the actual heat transfer rate of the HX to the maximum thermodynamic rate (i.e. the rate in which the outlet temperature of the hotter fluid – exhaust air in this case – equals the inlet temperature of the colder fluid – the water). Effectiveness is a useful parameter because it permits rate of heat transfer, Q, to be calculated based only on entering fluid (air and water) temperatures and airflow as shown in Equation 2 below.

$$Q = EC_{min}\ (T_{h\ in} - T_{c\ in}) = EC_{min}\ (T_{air\ in} - T_{water\ in}). \qquad \text{Eq. 2.}$$

Where,

$T_{air\ in}$ = the temperature of the inlet air to the HX,

$T_{water\ in}$ = the temperature of the inlet water to the HX,

C_{min} = the heat capacity flow rate of the exhaust air, and

E = the heat exchange effectiveness.

Clearly, the closer the HX effectiveness approaches the theoretical limit of 100%, the more efficient is the HX. During a dryer cycle, all of the temperatures and flows were measured and recorded on a 15-second basis. The temperatures and results of effectiveness calculation for the dryer HX at WC1 is shown in Figure 10, and the results for the HX at CC3 are shown in Figure 11. In WC1, the dryer HX effectiveness was about 10%, and in CC3, it was only marginally higher. Although small, this performance is reasonable based on the simplicity of the HX design and fabrication in the field. Clearly, more attention could be focused on the design to improve HX effectiveness.

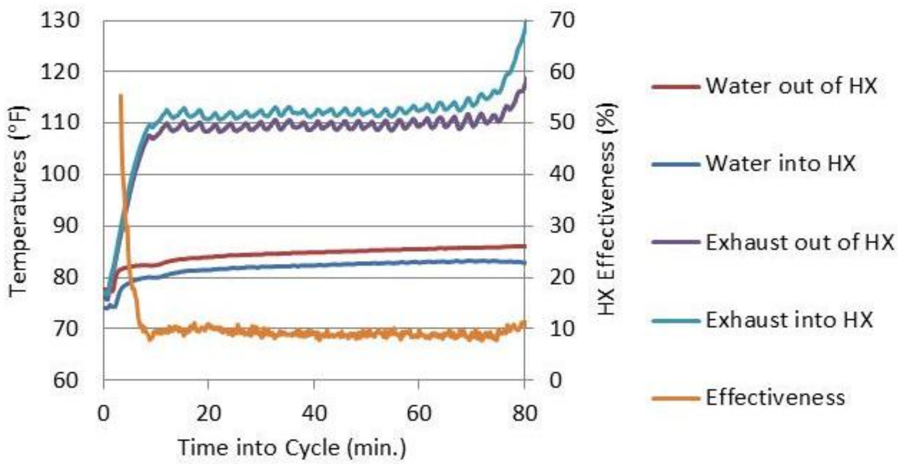


Figure 10. Dryer HX performance – WC!

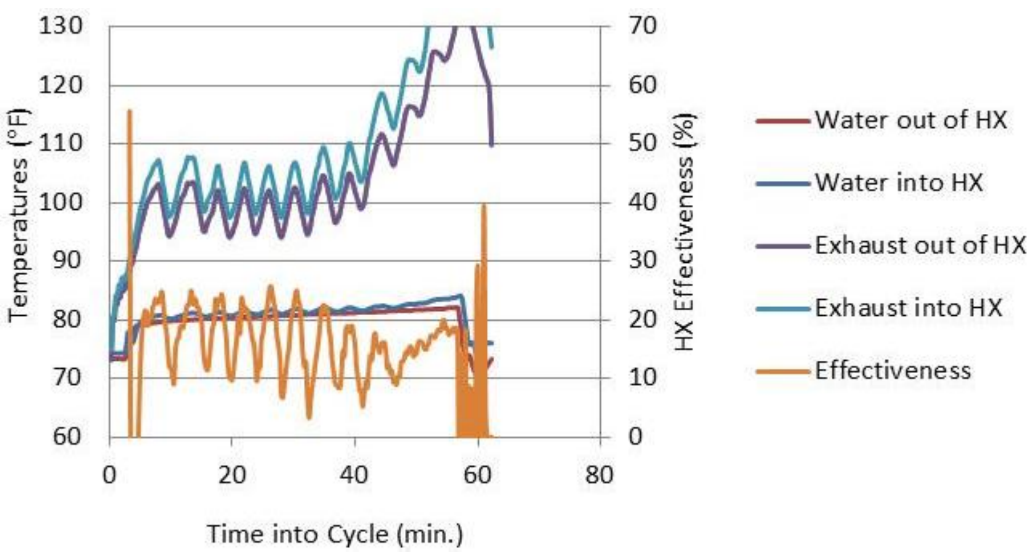


Figure 11. Dryer HX performance – CC3

Figures 10 and 11 also reveal differences in the dryers themselves. A cycle in WC1 took about 80 minutes whereas a drying cycle in CC3 took only 60 minutes. In addition, differences in how each dryer controls average drying temperatures by cycling the heating element on and off can be seen. In WC1, controls on the dryer cycled the heating element on and off frequently so that there was little variability in the exhaust air temperature as shown in Figure 10. Since the heat exchange effectiveness calculation is based on the inlet air temperature to the heat exchanger (the exhaust air temperature from the dryer), there is little variation seen in the effectiveness. In CC3 however, the controls on the dryer cycled the heating element about every 5 minutes and delivered an exit exhaust temperature that oscillated more than 10°F as shown in Figure 11. And because of these oscillations, the calculated effectiveness varied as well.

In both houses, air-side and water-side heat flows were calculated based on Equation 2. The electric energy to the dryer and to the pump were measured directly, and the heat energy recovered on the water side of the heat exchanger (part of which was delivered to tank TK1) was calculated from measurements of water flow through the heat exchanger and the temperature difference of the water across the heat exchanger. These quantities are shown in Figure 12 for WC1 and in Figure 13 for house CC3 for a typical dryer cycle. Total heat recovered and delivered to tank TK over a dryer cycle was in the 150 W-h to 160 W-h range for both houses. This is quite small as compared to approximately 8000 W-h of electricity consumed by each dryer over this same cycle time. An additional complication with the air-to-water dryer heat exchanger is the fact that the rise in water temperature across the heat exchanger is much less than the drop in exhaust air temperature due to differences in the properties and flowrates of air and water. In this experiment, the rise in water temperature across the heat exchanger averaged much less than 1°F making accurate calculations of heat exchanger performance a challenge particularly during the beginning of a dryer cycle. In the Conclusions section of this report, we comment further on improved dryer heat recovery options that do not require an air-to-water heat exchanger.

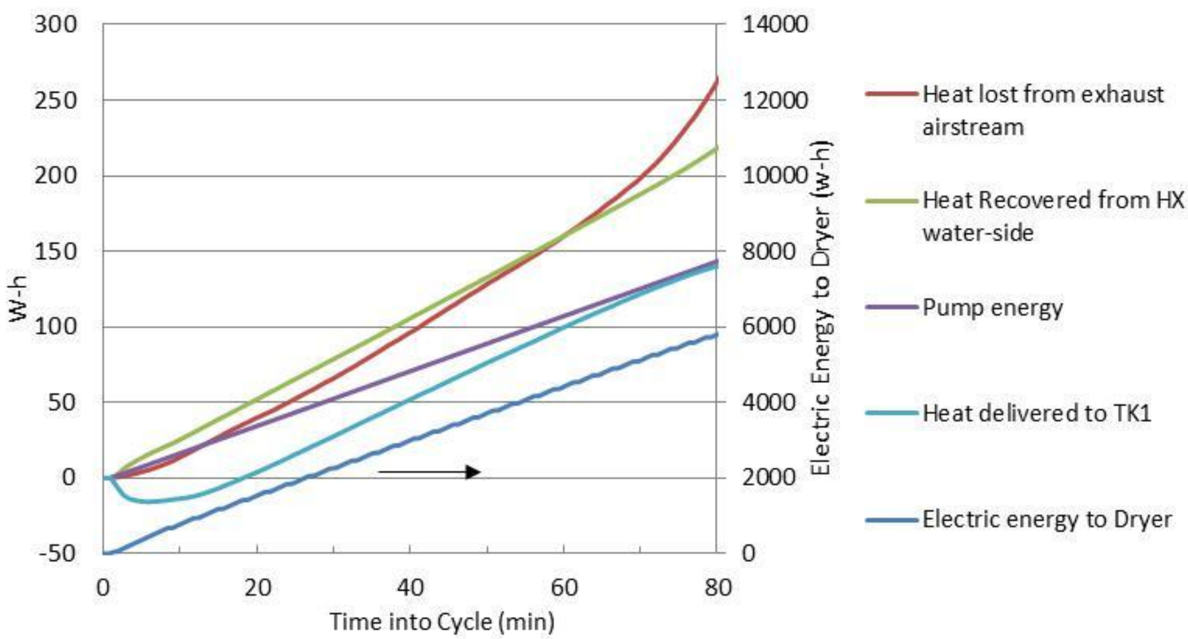


Figure 12. Dryer recovery energy – WC1

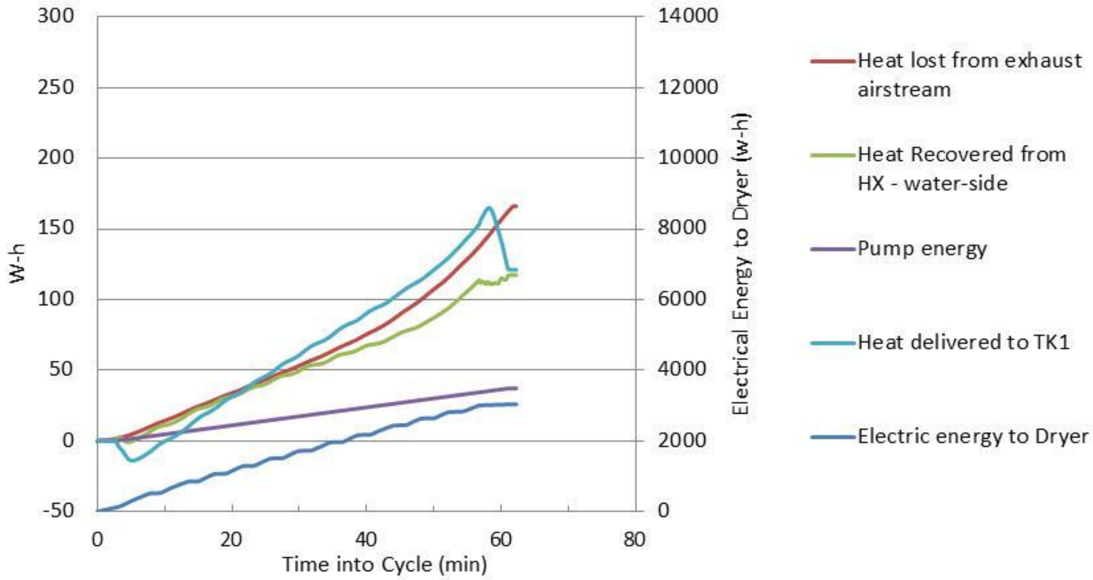


Figure 13. Dryer recovery energy – CC3

9 CLOTHES WASHER HEAT RECOVERY PERFORMANCE – INDIVIDUAL CYCLE

Capturing heat from the drain water of a clothes washer requires that the circulating pump of the heat recovery system pump be working for only a short portion of the cycle, e.g. for as little as one minute as the washer is draining. To make sure that all of the waste water in a drain cycle was available for heat recovery, we chose to bypass the automatic controls that were set up to activate the recovery system, and to activate the pump, close CV1 and open CV2 manually by noticing when there was a tub drain occurring. We listened for operation of the washer's pump, dump valve, the audible sound of drain water beginning to exit the tub, and somewhat later evidence of a rise in temperature TE1 (see Figure 1). Surprisingly, dumps from the tubs of the washers did not drain all at once as expected. By manufacturer design of the washer cycle, there were a number of small drains followed by refills – a process that retains most of the heat in the tub, but reduces water turbidity through dilution of water in the tub. For example, visual data on the clothes washer in CC3 showed the following behavior as typical. For a wash load started at 10:00 a.m.:

10:10, Fill ended and washing cycle began;

10:39, small drain occurred; volume insufficient to trigger TE1;

10:45, replacement water added by machine;

10:51, significant volume of drain water; TE1 reached 95.3F;

10:53, spin with intermittent water spray and drain water produced;

10:55, 10:56: two more sprays with drain open;

10:58, Rinse cycle begins with filling of the tub;

11:02, drain opens, significant drain water produced

11:03, spin with intermittent additions of water; drain open

11:12, washer off, TE1 at 85.7□F so we ran the pump for 1 minute to capture GFX heat.

This behavior suggests that in house CC3, a control system to operate the pump and control valves would be most effective if it could sense the status of the dump valve on the washer in conjunction with temperature TE1.

We determined the maximum available thermal energy in the tub by measuring the hot and cold water inlet temperatures and flows during fill periods. This obviated any need to measure drainwater flow and temperatures which are short and highly variable. Based on a simple mixing model along with the assumption that the amount of water drained at any point in the cycle would be equal to any fresh water subsequently added to the cycle, and that the tub is adiabatic, we were able to estimate the temperature and amount of water inside the washer throughout the cycle. The opportunity for capture of waste heat occurs during the drain period which is very short. This information is shown in Figure 14 for WC1 and in Figure 15 for CC3. The differences between these two washers is quite apparent: The water use per cycle in WC1 is only seven gallons with about two gallons of hot for the wash cycle followed by a double rinse of 2.2 and 2.8 gallons of cold water. In the first of three drain cycles shown in Figure 15 for house CC3, the drain water temperature at the entrance (top) of the GFX rose to about 100°F, the pump was turned on to capture heat from the waste stream, and as the draining ended, the inlet to the GFX had fallen to about 82°F. For the subsequent coldwater rinse cycles, the GFX inlet (TK1) remained cool. The point to be made is that the drain water from clothes washers is produced and eliminated quickly – typically less than a minute –and the heat recovery controls need to be responsive or the waste heat recovery opportunity is lost. Also shown in Figures 14 and 15 are the adiabatic tub temperatures. Notable here is the fact that the tub temperature and TE1 remain quite far apart for most of the wash cycle when there is no drain water flow. However, when the drain valve of the washer is opened, temperature TE1 rises rapidly and approaches tub temperature. Since the rinse cycle is with cold water, the tub temperature is cooler than TE1, and this would suggest that running the pump to extract heat from the cold rinse water would not be effective. However, if the GFX were already warmer than the cold rinse water, a little of the residual heat in the GFX could be captured even without simultaneous waste water flow. With cooler incoming water temperatures in the winter, the use of the GFX as a regenerator in this fashion would be more beneficial than in summer.

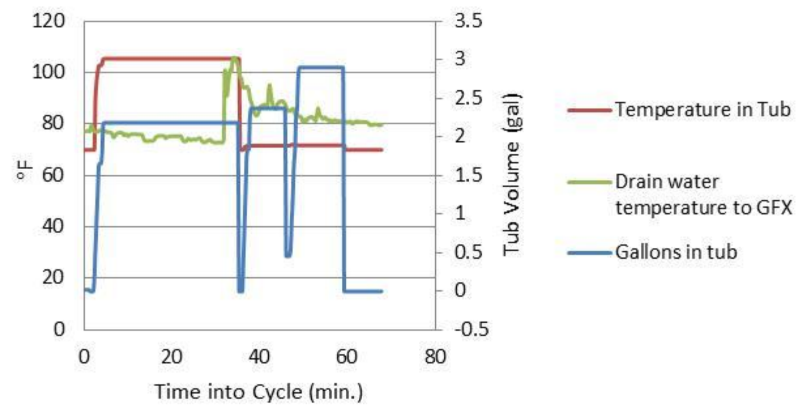


Figure 14. Clothes washer characteristics – WC1

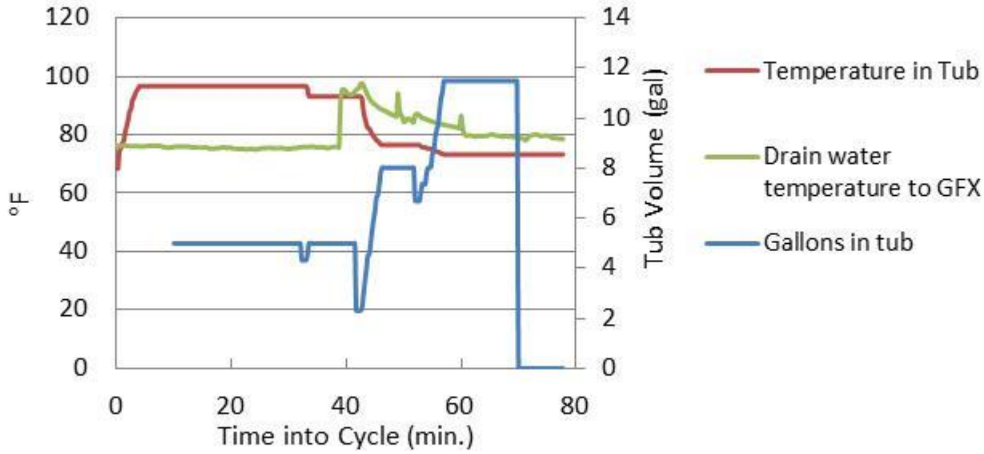


Figure 15. Clothes washer characteristics – CC3

A parallel analysis was made for the clothes washer at CC3, and the analysis is shown also in Figure 15. Based on flow measurements, the total water consumption of this machine is 16.2 gallons per cycle, more than double that for house WC1. Of this amount, 4.6 gallons was hot and the remaining 11.6 gallons cold spread over two rinse cycles.

We measured the temperatures across the GFX and preheat tank as well as flow rates to determine the cumulative thermal energy recovered by the GFX from the clothes washers in each house, the pump energy required, and the thermal energy that ends up being stored in TK1. Figure 16 shows these data for WC1 and Figure 17 for CC3. Of interest is the finding that the heat energy recovered by the GFX can be almost as much as the electrical energy that runs the washer. In CC3 for example, the cumulative electrical energy per cycle is 225 W-h whereas about 175 W-h of heat energy is recovered.

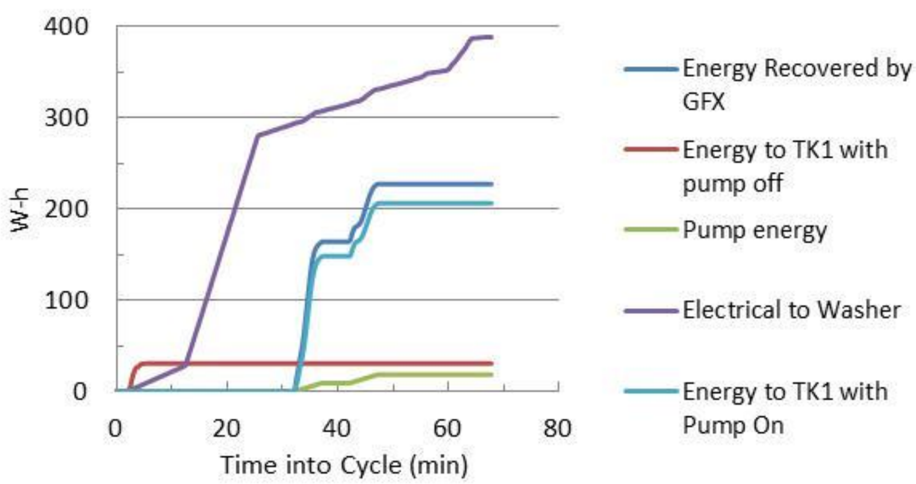


Figure 16. Clothes washer recovery energy – WC1

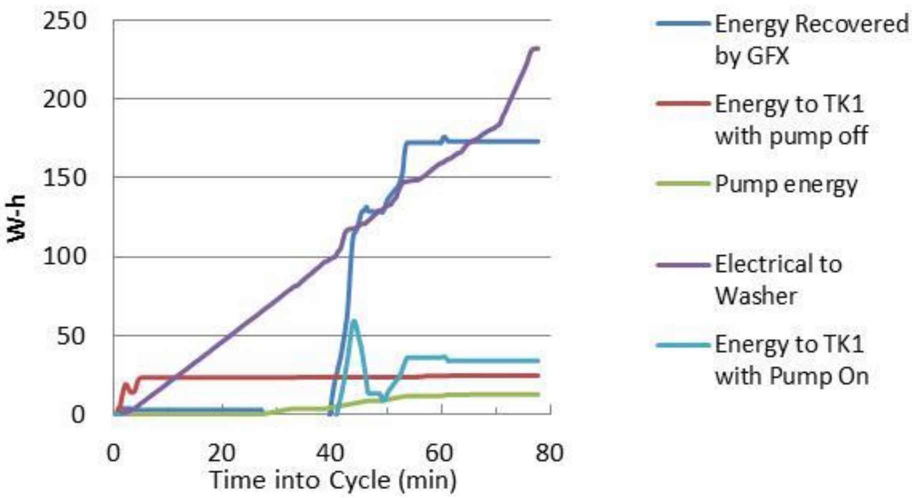


Figure 17. Clothes washer recovery energy – CC3

Since clothes washers operate in a batch mode (fill, wash or rinse, drain) the heat energy captured must be stored for use later. In the case of WC1, the energy that was stored is close to the energy collected as shown in Figure 16. However, in CC3 the energy stored is much less (Figure 17). The explanation for this behavior is principally due to the temperature of TK1 during this time. For the time shown, the temperature of TK1 was higher than the temperature of the water at the GFX during heat capture, and rather than heating TK1 further i.e. storing additional heat, the tank cooled off. This is shown by negative slopes in two regions of the CC3 storage curve where the inlet secondary water to the GFX was warmer than the outlet. The heat storage performance at WC1 was better with a large positive slope when capture was made during dump of warm wash water, and a positive slope of lesser duration during the dumping of rinse water. As mentioned, the success of capturing the heat energy in drain water from clothes washers is highly dependent on timing, on the temperature of the preheat tank, and on the tub temperature at the initiation of drain water production.

10 DISHWASHER – INDIVIDUAL PERFORMANCE

As mentioned, only WC1 had a heat recovery system on the dishwasher. Here as in the case of the clothes washer, we calculated the dishwasher tub volume based on measured hot water flow into the tub, and as in the case for the clothes washer analysis, we used a mixing model to determine tub volume. The dishwasher also has a heating element that automatically heats the water in the tub to sanitize dishes being washed. Data on the electrical energy consumption of the dishwasher throughout a cycle combined with tub volume allowed us to calculate the tub temperature throughout a cycle, and the results are shown in Figure 18. During the wash cycle, the tub temperature rose to about 120°F with operation of the heater inside the tub of the dishwasher. As this water was drained, it was replaced by water from the house water heater that was below 120°F. Consequently, the tub temperature fell at about 60 minutes and just before the tub was refilled. The recovery pump was operated, and some waste heat was recovered by the GFX. Finally, the washer refilled and operated over a long period with the internal heater on. The final drain took place about 2 h into the cycle, the inlet temperature into the GFX rose to 130°F, and during this final drain, most of the drainwater heat was captured. Figure 18 shows that during this final dishwasher drain, temperature TE1 located at the GFX inlet was about 20°F lower than the tub temperature. This loss in temperature would have been less if the dishwasher drain had been physically closer to the inlet of the GFX.

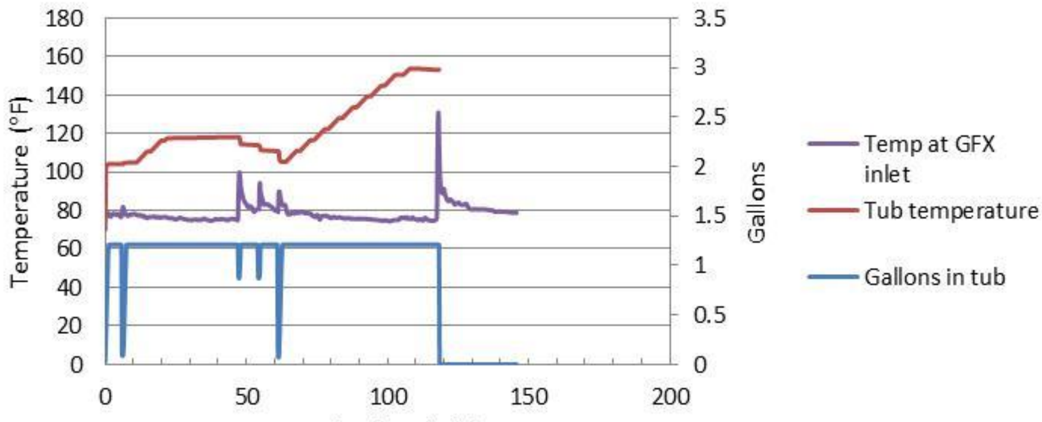


Figure 18. Dishwasher characteristics – WC1

Figure 19 shows the cumulative heat energy extracted by the GFX, the pump energy needed to circulate the water to the storage tank TK1 and the energy stored in TK1. Approximately 60 W-h of heat was recovered during the first drain cycle from the dishwasher, and 90 W-h in the final dishwasher drain cycle. It is interesting to note the energy stored in tank TK1 during the dishwasher cycle (the green plot in Figure 19). Here we see that efforts to capture heat from the GFX early in the full cycle were not very successful. The early part of the full cycle is a wash in which the dishes are wetted, a period of agitation follows, and the water is then drained. For this wash cycle, the drainwater temperature was lower than the temperature of the water in TK1, so when the pump was operated to capture heat from the GFX, heat was extracted from TK1 rather than being added, i.e. the energy stored in TK1 is negative. At about 50 minutes into the entire cycle, there were three short drain periods, and the pump was operated, but there was little heat stored in tank TK1 as a result. It was not until the final drain at end of the rinse cycle when the tub had reached its highest temperature did the benefit of the GFX become significant with a reasonable amount of heat stored in tank TK1. This occurred at 120 minutes into the full dishwasher cycle. Although for this study, operating the GFX/pump system was done anytime that there was a drainwater produced by the dishwasher, a simple control system activated by the dishwasher as it enters the final drain cycle would be an advantage. Morover, a more sophisticated control system that senses the temperature of tank TK1, the temperature of the drainwater entering the GFX, and makes a decision on when to operate the pump based on these two temperatures would give the ability for useful heat capture across all of the drain periods in the dishwasher cycle.

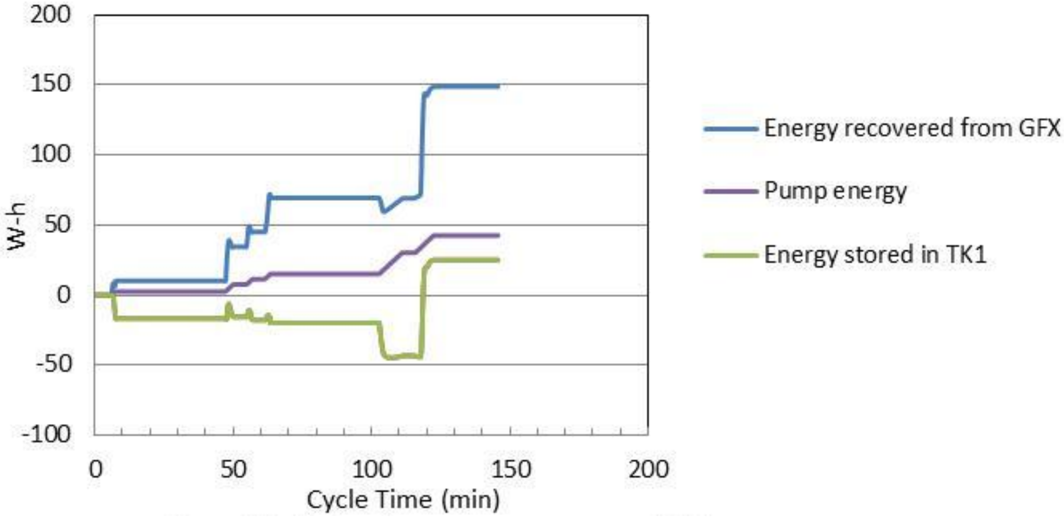


Figure 19. Dishwasher recovery energy – WC1

The fact that the dishwasher is plumbed to the hot water line only (i.e. all wash and rinse cycles use hot water) makes it a good target for wastewater heat recovery. The downside is that the dishwasher uses (in this case at least) little water, and the drain cycles are short so that capturing a worthwhile portion of the waste heat is a challenge.

11 THE EFFECT OF APPLIANCE CYCLE OVERLAP

For most periods, each appliance in the study operated without interference from other appliances. During the week for example, the first shower of the day occurs at 7:00 a.m. when no other appliances are operating. However, there are times particularly on weekends when appliances with heat recovery may be operating simultaneously as shown in Figure 20.

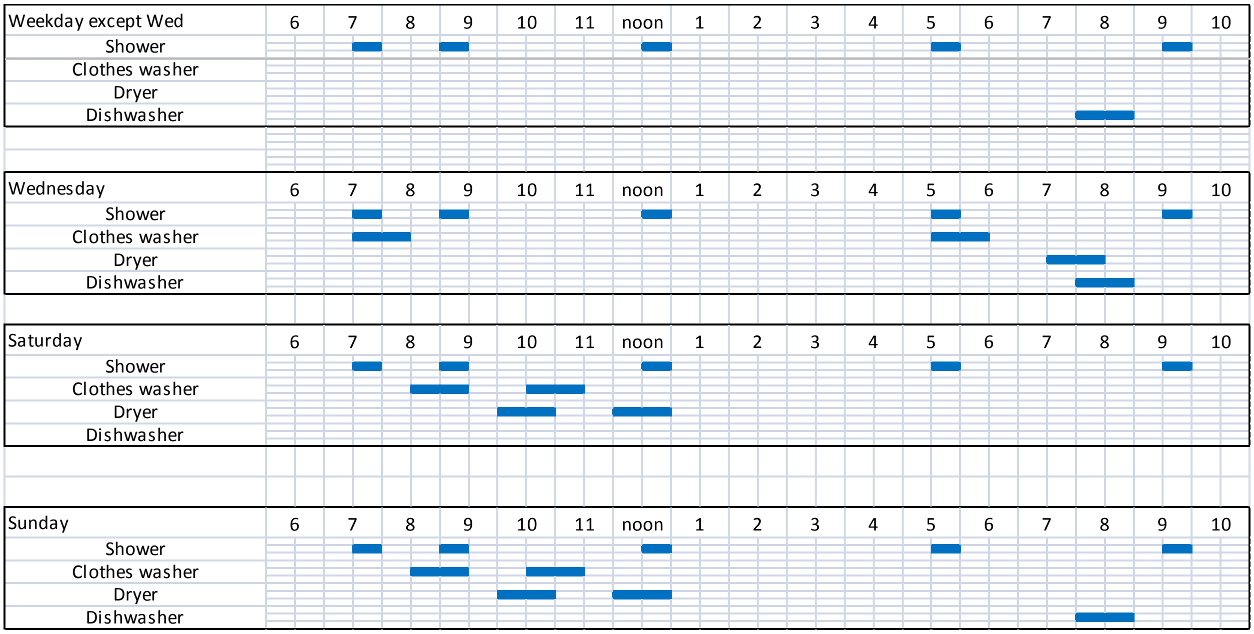


Figure 20. Overlaps in appliance/fixture operation

The master shower runs daily five times per day with two 20-gallon showers, two 5-gallon showers and one 10-gallon shower. The shower flow rate is fixed at 1.5 gal/min. Consequently, the shower run profiles for WC1 and CC3 are the same. However, the run times for the dishwashers, clothes washers and dryers in WC1 and CC3 were different. A dishwasher cycle in WC1 took a little over 147 minutes and only 87 minutes in CC3. A dryer cycle in WC1 took 37 minutes whereas one took 61 minutes in CC3. And a clothes washer cycle in WC1 took 70 minutes and 80 minutes in CC3. Consequently, the duration of simultaneous operation of appliances in WC1 and CC3 were different so that the opportunity for heat recovery was somewhat different as well. Event data from CC3 were evaluated to uncover overlap times and energy recover during these periods, and from these data, a determination of the effects of overlap were determined.

To evaluate the impact of overlap in appliance operation, we examined periods in the data for CC3 where each appliance/fixture operated by itself and periods where more than one appliance was operating. This was done by filtering the data according to event type. For events such as dryer operation and clothes washer operation, we filtered records that included pump power and the type of event. From the filtered records, we evaluated the total number of 15-second periods for each mode of operation, the average energy recovered in each mode and the maximum rate of energy recovery in each mode including overlap modes where more than one appliance was operating at the same time. The results are shown in Figure 21. For 90% of the time that any appliance is "on", it operates alone. The remaining 10% of the time, the appliance operates together with another appliance, i.e. in an overlap mode. The right hand side of this figure indicates that most of the overlap periods were times when the dryer and clothes washer were "on" at the same time, and when the shower and dishwasher were "on" together. However, it should be remembered that clothes washer and dishwasher heat recovery takes place only when there is waste water being dumped, and this takes place over a minute or so at the most. Of more interest is the overlap between the dryer cycle and a shower cycle because they are both relatively long. Consequently, we chose the shower & dryer mode for further examination.

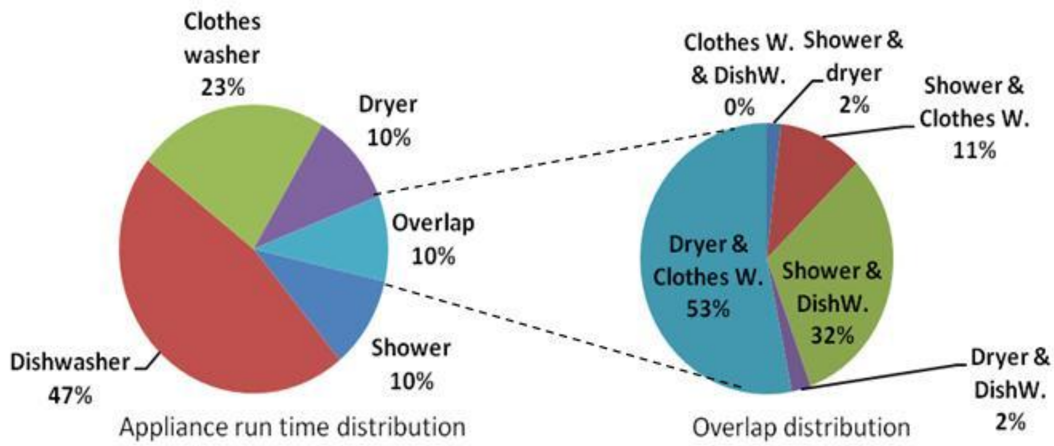


Figure 21. Appliance run time - individual and overlap distribution

To do this, we examined the flowrate of water through the shower and dryer operating individually and at times when the shower and dryer operated together (overlapping cycles). The impact of overlapping cycles is shown in Figure 22. We found that when the shower was operated by itself, the flowrate on the secondary (fresh water) side of the GFX was 1.7 gpm, and the GFX heat exchanger was delivering heat exchange at a rate of 2190 W. The second set of bars shows the performance of the dryer exhaust heat exchanger operating alone. Despite a reasonable flow of 1.1 gpm through the dryer HX, the heat energy produced by the exhaust HX in this mode was small. When the shower and dryer were operated together, the flow rate of water through the GFX fell to 0.53 gpm, the GFX no longer had balanced flow, i.e. the flow of fresh water on the secondary side of the GFX did not match the flow rate of waste water, and the performance of the GFX fell as shown in Figure 22. The performance of the dryer HX improves however when the dryer is operated in conjunction with the shower in an overlapping mode. This improvement is the result of a lower inlet temperature to the dryer heat exchanger due to the shower being used at the same time. With the shower "on", the inlet temperature to the GFX as well as to the dryer HX is lower than it is when the dryer alone is operated in the recirculation mode. We measured this temperature reduction to be 7°F. For all seasons, the lowest temperature in the system is the temperature of the CW supply, so anytime that either the GFX or the dryer HX can use this temperature as a source, there is a decided improvement in efficiency. Had this experiment been initiated during winter, this argument would be even more convincing.

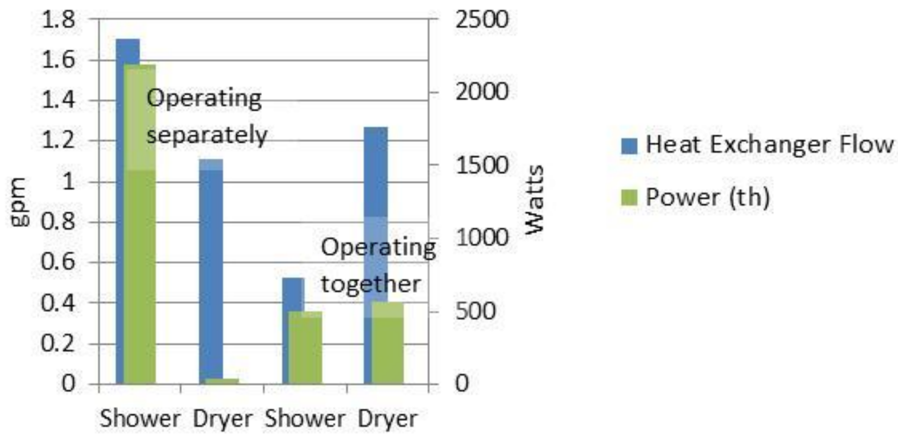


Figure 22. Comparison of shower/dryer performance when operated separately and simultaneously

12 RESULTS, CONCLUSIONS, RECOMMENDATIONS

Waste heat recovery from appliances is an untapped resource for reducing hot water energy consumption in homes. Waste water from the shower in particular is a significant resource for heat recovery for a number of reasons: (1) showers occur multiple times during every day of the week depending on the size of a family so the waste heat resource is present quite often, (2) the availability of warm waste water from a shower coincides with the need for water heating, therefore storing recovered heat for later use is unnecessary and this simplifies the equipment needed for waste heat recovery, and (3) a shower heat exchanger design – the GFX - is readily available and suitable for adaptation to existing houses (provided sufficient headroom is available). The purpose of this study was to examine a comprehensive approach to appliance and fixture heat recovery of which the GFX would be a part. A second heat exchanger was used to capture waste heat from the dryer exhaust, and would function like the GFX to preheat water. And finally, the study included a system design that would have the flexibility for capturing waste heat energy without restrictions on when or by which appliance it was produced.

The benefit of waste heat recovery rests largely in the amount of energy that is recovered and the cost of that displaced energy. We found that the recovery systems in both test houses were able to capture energy from all appliances (with the exception of the dishwasher in CC3 for which there was no heat recovery system) for all days of the week as shown in Figures 23 and 24. Clearly showers provide the bulk of recovered heat. However on Wednesdays and weekends when clothes washing and drying are done, the heat recovery from other appliances becomes significant. On average, it can be seen that for both houses, the total amount of daily heat energy recovered was about 3000 W-h, and this was energy that otherwise would have been purchased for storage heating water. If this study and experiment were expanded to include the seasonal effects of cooler incoming water to the houses during winter when most water heating energy is used, the energy savings of the heat recovery system would be higher.

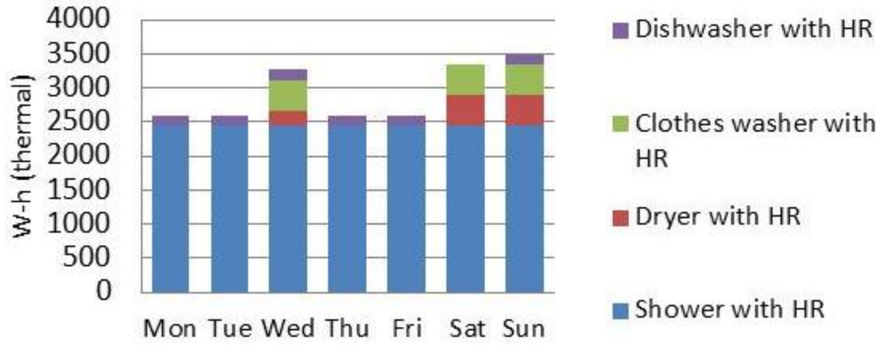


Figure 23. Weekly heat recovery in WC1 – June

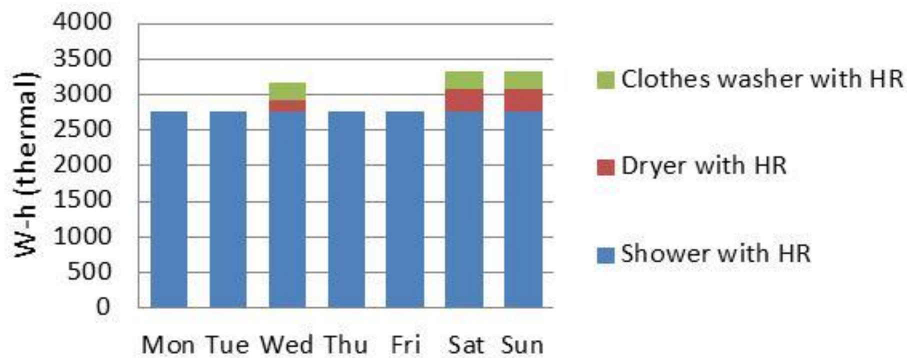


Figure 24. Weekly heat recovery in CC3

The value of recovered heat depends on the efficiency (coefficient of performance) of the equipment that would otherwise be needed to replace the recovered energy. Without heat recovery, the missing 3000 W-h of heat energy would need to come from another source, e.g. by electric resistance heating in tank TK2, by a solar system, or by a heat pump (water-to-water in the case of a ground loop system). Since this study was limited to heat recovery systems only, we calculated the thermal load reduction for the recovery system based on measured data. For the baseline (no heat recovery system in place), whenever there was a hot water "event" (shower, clothes washer, dishwasher), we used data on the inlet temperature (TE3), the hot water delivery temperature (TE12) and the flow of hot water (FE3) to determine the thermal energy delivered. We found that the average daily hot water load for the test houses under baseline conditions was 9130 W-h. Since the heat recovery systems had been able to recover 3000 W-h on a daily basis, the percent reduction in water heating load was determined to be 32.8% (i.e. 3000/9130) with shower heat recovery as the principal contributor.

12.1 Dryer Improvements

In Figures 23 and 24 it can be seen that heat recovery from the dryer is comparatively small. On a per cycle basis, the CC3 dryer heat recovery system saves 155 W-h, which is small given the overall dryer power consumption at 3036 W-h. Clearly, a better method for capturing waste heat from the dryers is needed. A big issue for an air-to-water dryer HX is lint management. A extended surface HX located inside the duct would have greater effectiveness than the one that was used in the study; however, it would clog. We considered ideas for eliminating the clogging by forcing the airstream away from the active part of an internal HX, and these ideas included a cyclonic separator that would allow the dryer exhaust to enter the heat exchanger section tangentially to the axis of the HX. As the exhaust swirls, the inertia of the lint would cause it to collect and move along the walls towards the exit so that the center of the passage would remain relatively line-free. The active part of the air-to-water heat exchanger could be located at the center of the duct where there would be high airflow with essentially no lint. Other filter designs could be evaluated and tested as well. However, based on a history of trying to extract waste heat from dryer exhaust, nothing seemed to work well enough to retain a reasonable ability for heat removal while at the same time remaining unclogged. As an alternative approach, we suggest the following: that dryer exhaust heat recovery not be part of the water heating system, but rather that it be used to preheat air to the dryer. The heat exchanger in this case would be a concentric, double-walled duct with fresh air passing through the annular region to the dryer and dryer exhaust moving countercurrent through the center of the duct. The generation of lint would not be an issue, and waste heat would be captured. Once captured, the waste heat would be added immediately to the incoming airstream to the dryer; therefore, no pump or storage would be necessary, and the performance of the heat exchanger would not be compromised by having unbalanced flow on opposite sides. The energy savings would be manifested in reduced dryer energy consumption rather than reduced energy for water heating.

12.2 System Improvements

The data taken in this experiment suggest other improvements. We found that the temperature of the piping between the GFX and the pump and valves was never far from the temperature of the surroundings. Typical temperatures on the secondary side of the GFX and associated piping between the circulating pump, control valves and preheat tank were in the 80°F range – not far from ambient temperatures. Moreover, the piping distribution temperatures were only above ambient when energy recovery was "on". For clothes washer or dishwasher cycles, this recovery interval was quite brief, i.e. only when there was waste water draining from the tub or either appliance. Therefore, there would be little difference in the heat lost from the piping system in a conventional heat recovery system and a ZEHcor, close-coupled piping system. However, if the recovery interval were so short that the circulating water did not reach the preheat storage tank in one time step, but was heated by the source and left to reside in the piping system, then having the source and tank close together would be beneficial.

Piping heat losses are not only a function of pipe length, but also a function of the surface temperature of the pipe. It is in this operating temperature area that we see an advantage to a ZEHcor wall. Heat losses occur where temperatures are highest (e.g. right at the dishwasher drain, right beneath the shower floor, right at the drain of the clothes washer). The extent, to which a ZEHcor wall can put the inlet of the GFX close to these sources of energy, will make the greatest improvement in the performance of the waste heat recovery system. In terms of pipe insulation, insulating the upper section (but not insulating the lower part) of the GFX would be appropriate as well.

In summary, the size of the heat resource for waste heat recovery is large and on a relative basis, continues to grow as other opportunities for energy savings are exploited. Shower hot water use is stable, driven by how (and how long) we prefer to shower. The efficiency of conventional evaporative dryers is limited by the heat of evaporation of the water left in the load of clothes. With clothes washers and dishwashers on the other hand, hot water use is a function of technology, and today, both appliances require less hot water than older appliances. These two factors suggest that waste heat recovery first with showers and dryers, and secondly in clothes washers and dishwashers, will become increasingly important in moving towards ZEH. Systems (e.g. the GFX) that capture waste heat from showers are available and require no controls. With clothes washers and dishwashers where capture of waste heat requires a "regenerator" capability (storage, pumps) that can respond quickly, additional work on controls that perhaps are integrated into the appliance itself is needed.

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APPENDIX A LOOP DESIGN AND EQUIPMENT

The GFX and dryer heat exchangers in the loop are in parallel so that either can be active according to the mode of operation and flow provided by pump P1. Each heat exchanger has a system curve (pressure drop vs. flow rate) that must be matched to the pump characteristics. The secondary of the GFX is comprised of 88 feet of ½-in. Type L copper tubing wrapped around the drain tube, and the dryer heat exchanger consists of 100-feet of 3/8-in ACR tubing. We estimated the pressure drop characteristics of each heat exchanger using the Hazen-Williams relation:

P = (4.52)(Q exp 1.85)/(C exp 1.85)(D exp 4.87)

Where

P = friction loss, psi per linear foot,

Q = flow in GPM

D = average tubing i.d. in inches

C = 150, a constant.

A plot of system curves for each heat exchanger based on the above is shown in Figure A1. The large pressure drop for the single pass dryer heat exchanger coupled with a relatively small pressure drop for the GFX secondary led to significant differences in the operating point using a single pump. Pump selection options were better by converting the header of the dryer heat exchanger into a two-circuit configuration, i.e. the original 100-foot coil to be converted into two 50-foot coils in parallel. The system curve of this dual-circuit dryer coil more closely matches that of the GFX secondary, and this made selection of a single pump which could operate with both heat exchangers straightforward as shown in Figure 5. The pump chosen, a 1/15-hp B&G booster pump, should push about 3.4 gpm through the GFX coil and approximately 1.5 gpm through the dryer coil.

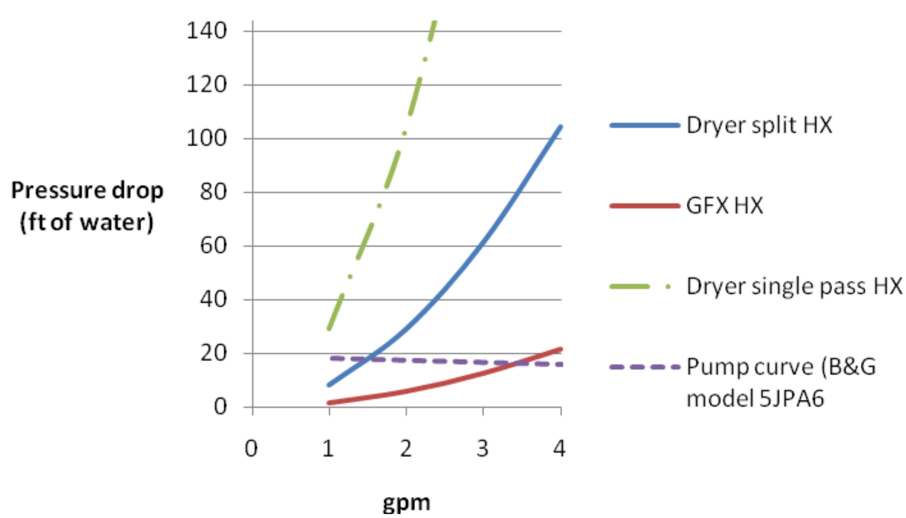

Figure A1. System and pump curves for Loop Heat Exchangers

Loop instrumentation and Equipment consisted of the following:

1. Temperature sensors TE1-12 are thermistors located inside the pipes and located to always be wet (or in the middle of the duct) and to give an accurate reading of the flow stream. Sensors at piping junctions need to be in the middle of the tee.
2. Control valves CV1 and CV2 are Red Hat II, 8000 series sized for ½ or ¾-inch piping,
3. Valves V1 and V2 are ¾-in manually operated, full flow ball valves,
4. Storage tank TK2, 85-gallon, Marathon brand (existing),
5. Storage tank TK1, 30-gallon, American brand model E62-30H-045DV, unfired and with a small footprint and large height to enhance thermal stratification. An additional dip tube of a length to take advantage of thermal stratification in the tank was added,
6. Check valves CK1 and CK2, ¾-inch swing checks provided the orientation is appropriate for good operation,
7. Pump P1: B&G circulator pump, 1/15 hp, Model 5JPA6
8. Vent, small valve teed into the copper tubing,
9. GFX, Model P3-60 by WaterFilm Ltd.,
10. Flowmeters FE1, FE3, FE4 Omega,
11. Flowmeter FE2 based on static and total pressure