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OF WISCONSIN

Drain Water Heat Recovery

A field study of commercial applications

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Author

Dan Cautley, Senior Research Engineer, Energy Center of Wisconsin

ENERGY CENTER
OF WISCONSIN

749 University Row, Suite 320

Madison, WI 53705

608.210.7120

www.ecw.org

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REPORT SUMMARY

Drain water heat recovery (DWHR) as discussed in this report is the recovery of useful heat through a heat exchanger placed in the building drain system. This project was an effort to characterize the performance of drain water heat recovery systems as installed in commercial facilities. The concept was based on the observation that commercial occupancies can have hot water loads much larger than those in single family residences, and thus larger energy savings potential.

We found identifying commercial facilities suitable for retrofit installation of DWHR systems to be a major challenge. In identifying four sites for use in the project, we screened over 150 facilities through phone conversations, and visited at least 38. The most common reasons for classifying a facility as unsuitable were lack of an accessible vertical drain line of at least four feet in length, lack of significant hot water loads carried by an accessible drain, and excessive distance from drains carrying hot water loads to the water heating system. We believe new construction, when systems such as DWHR can be planned into design, would offer many more opportunities for use of the technology, and would offer cost advantages as compared to retrofits.

We installed four DWHR systems for purposes of the project. The selected sites included an apartment building, a restaurant, a self-service laundry, and a student housing facility. Several different plumbing configurations were used in the systems. One heat exchanger was installed in parallel with a balance valve intended to induce flow through the system; this did not work well and did not produce usable results. Two of the systems were installed using a pump to circulate water through the heat exchanger.

The three systems that produced usable results recovered from 7.6 to 43 million Btu of useful energy annually, with a value of about $80 to $460 in natural gas savings.

The restaurant installation recovered by far the most energy of the installed systems. This was somewhat surprising, because the main hot water load at the restaurant is a dishwasher. The best applications for DWHR are generally thought to be continuous loads with simultaneous water flow on both the supply side and the drain side of the heat exchanger, but the dishwasher operates as a batch load with non-simultaneous supply flow and drain flow. We believe that very high average drain temperatures, the absence of cold water flow in the drain, and the energy storage effect of the heat exchanger thermal mass are key elements in the performance of this system.

The systems at the laundry and student housing facility were exposed to very different use conditions. In both cases, drain water passing through the heat exchanger included large cold water flows, and the warmest drain water is much cooler than at the restaurant. At the laundry, open drain pans encourage mixing of warm and cold drain water and allow extra heat loss before waste water enters the closed drain system. The student housing facility has vertical cast iron drain lines that allow substantial heat loss in drain water before reaching the heat exchanger.

Average heat recovery by hour of day and day of year follow expected patterns, tracking the operating patterns in each facility type.

Short term monitoring tested the "system effectiveness" (heat recovery as a fraction of delivered water heating energy, which includes the effects of system piping) at each site. With one exception, these tests produced values that were, as expected, somewhat lower than effectiveness values for the heat exchangers alone.

Thermosiphoning in the cold water line serving the water heating system, the location of hot water recirculation returns in the system, and reverse flow of hot water were all identified as factors that may increase the cold water temperature at the heat exchanger and decrease heat recovery performance.

Using regression analyses to explore the net effect of cold water temperature entering the heat exchanger on overall heat recovery, we found an effect of about a three percent change in heat recovery per degree F change in cold water temperature at the restaurant. Results for the other systems appeared questionable, and linear regression analysis may not be applicable to those systems.

Other regressions show a fairly strong relationship between recovered energy and the combined factors of cold water temperature and measured exterior drain line temperature. Measurement of drain line temperature appears to have promise as a method for predicting the availability of recoverable energy, though we did not have enough information to formulate a general method.

INTRODUCTION

Heat content in drain water leaving a building is generally lost or wasted energy. Drain water heat recovery as discussed in this report means the recovery of useful heat from waste water passing through a drain. Drain water heat recovery (DWHR) systems as commonly used are based on a heat exchanger that consists of a section of copper drain pipe (most commonly three inch or four inch diameter), with copper supply tubing wrapped around the drain pipe in close physical contact (Figure 1).[1] When installed in the simplest configuration, these heat recovery systems have no moving parts, and even more complex configurations may add little more than a circulation pump and controller. The recovered energy is usually delivered as pre-heated water to the domestic water heating system.[2]

Drain water in a vertical pipe tends to adhere to the wall of the pipe and allows excellent convective heat transfer to the pipe material; as a result, this type of heat exchanger is sometimes called a "falling film" or "gravity film" heat exchanger.[3] Heat is readily transferred through the copper and to water in the supply lines. Convective heat transfer to the supply side water is better if there is active flow in the system, but can occur even in the absence of flow. If the drain carries water from loads that include hot water use (e.g. bathing or dishwashing), and the supply line carries cold water, the heat transfer will generally be from drain line to supply line. Heat transfer can occur equally well in the other direction if the temperature difference is reversed. The best applications for drain water heat recovery are generally thought to be those that offer sustained and simultaneous flows of cold supply water and warm or hot drain water. Simultaneous flow improves heat exchanger performance, and longer flows bring system temperatures toward steady state conditions where more energy gets to the heat exchanger.

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[1] The terms "supply" and "supply side" will be used in this report when referring to the pressurized, potable water portion of the heat exchanger and related plumbing.
[2] See Appendix A for a list of drain water heat exchanger manufacturers.
[3] A good description of heat recovery from wastewater using a gravity-film heat exchanger is available in this DOE Technology Focus fact sheet
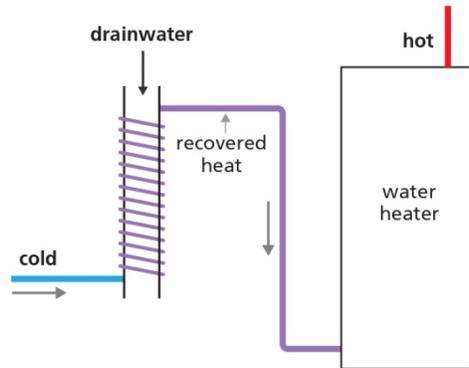
Figure 1 Schematic view of drain water heat recovery system

Drain water heat recovery making use of vertical-pipe heat exchangers has been used for some years. We believe the majority of sales have been in residential applications, and some utilities have offered energy incentives for its use in residences. Minnesota Power offers efficiency rebates for installation of drain water heat recovery in homes using electric water heating; at least one other U.S. utility offers incentives and one state has a tax credit.[4]

Application of the technology in commercial occupancies with significant hot water use seems attractive, since water heating loads and potentially recoverable energy may be much greater than in single family homes. However, little systematic and independent work appears to have been done to investigate the applicability of and performance of DWHR in retrofit commercial applications.

The benefits of DWHR are expected to be greater in northern than southern latitudes, since heat exchange processes are related to temperature differences, and cold water temperatures are generally lower in the north. Colder incoming water temperature also means water heating energy use is generally higher in northern areas.

The overall goal of this project was to characterize the performance of drain water heat recovery as an energy efficiency technology in commercial applications.

Our approach in addressing this goal included:

- Site identification, using screening criteria for the expected hot water use and the practicality of installing a heat recovery system at the site.
- Installation of a DWHR system at each site, including selection of heat exchangers and piping configurations, and installation of the system and monitoring equipment.
- Monitoring of the performance of each system over a period of months, and short-term system performance testing.

SITE IDENTIFICATION

We weren't confident we would be able to find existing installations for monitoring in Wisconsin and Minnesota, so our plan included identification of suitable facilities, and installation of systems for the project. We started with site screening criteria intended to identify attractive applications:

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[4] Details of Minnesota Power's rebate are available on their website. Other examples include the Oregon Department of Energy Tax Credit and Clallam County, Washington Public Utility District's rebate.

- Commercial occupancy, which we defined fairly broadly. Our primary intent was to work in common occupancy types, and avoid unusual buildings and water usage. We included multifamily housing and institutional buildings in our definition.
- Significant hot water usage. This was judged based on occupancy type and discussion with the business owner or facility manager.
- An accessible vertical drain line, with an unbroken length of somewhat over four feet, allowing installation of a heat exchanger at least four feet long. We allowed for the possibility of moving connections up or down.
- A drain serving a significant warm/hot water fixture load (if the building was served by multiple drain lines).
- Distance from the selected drain to water heating system (cold water feed into water heating system)— about 40 feet or less, and considering the practicality of running pipe through barriers between water heating system and drain location.

These criteria evolved somewhat over time due to the difficulty of finding suitable sites. Initially, we hoped to find drain lines with a vertical length of at least six feet (since longer heat exchangers perform better), but later relaxed this to about four feet. Two of our selected facilities had multiple drain lines passing through the level of the mechanical space; in each case a single drain fairly near the water heating system was selected for installation of the heat exchanger. We used short-term temperature monitoring to confirm that these drains carried warm drain water at times, but in each case the selected drain carried only a fraction of the total drain water energy leaving the building.

Our primary means of soliciting participation was direct outreach to facility owners and managers who we identified or who were referred to us by utility representatives, architects, engineering firms, and non-profit organizations working with commercial property owners. We targeted business and organization types that we expected to have high hot water use in their faculties, including restaurants, health clubs, colleges and universities with on-campus housing and sports or exercise facilities, and laundries, but spoke with owners and managers of a number of other building types.

When contacting facility owners and managers, we discussed the nature of the project, including the offer of no-cost installation of a system that promised to reduce energy costs. We then scheduled site visits with those who expressed interest, screened the sites, and made final arrangements for participation with the owners or managers of selected facilities.

We had direct contact with owners or managers with access to more than 150 facilities including:

- An apartment management firm with more than 12 properties
- Energy and facility managers of least 8 colleges and universities, one with at least 70 buildings
- The energy manager of a major chain of fitness clubs
- Individual managers of several other fitness facilities
- A number of restaurant owners and mangers
- President of a self-service laundry trade association
- Several YWCA and YMCA facility managers
- The energy manager for a county government with several candidate facilities
- Managers of several hotels

We visited at least 38 facilities at the invitation of these owners and managers.   The striking result of these site visits was finding that, in spite of interest on the part of owners and managers, we judged the great majority of these sites impractical for installation of a DWHR system.

The factors most commonly limiting the practical installation of DWHR systems included:

- Inaccessibility of vertical drains. In one facility, the drains serving a bank of heavily-used showers were hidden between concrete block walls. In one hotel, the drains serving guest rooms on upper floors passed through finished frame walls on the first level of the facility and then passed down through a slab floor. The placement of shower areas over slab floors was also a barrier in several health clubs. A number of facilities had easily accessible horizontal drain runs, but lacked accessible vertical drains.
- Adequate vertical length of drain. A number of potential sites had vertical drain lengths too short for a four foot long heat exchanger, or with fittings that broke up the accessible length (Figure 2).
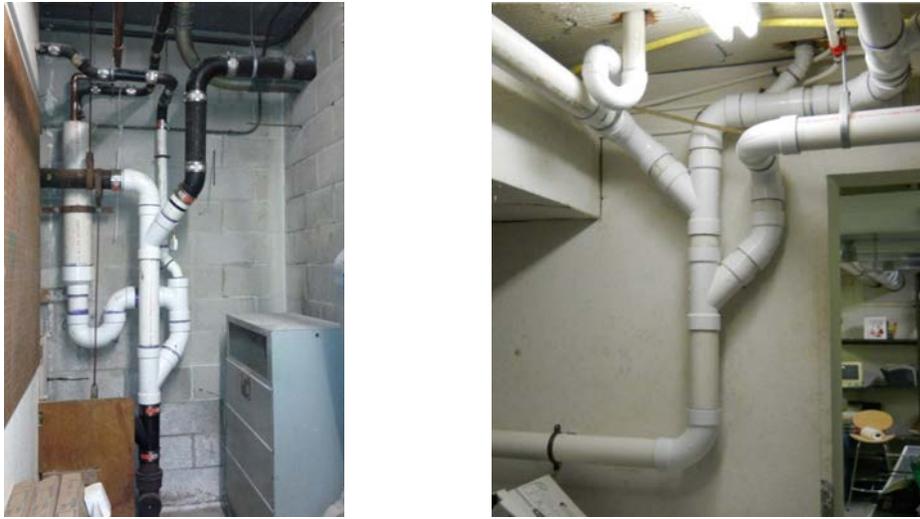
Figure 2 Drain lines broken by fittings

- Drain diameter. Some multi-family, student housing, and institutional buildings we visited had drain lines larger than four inches in diameter (Figure 3). While this doesn't preclude the installation of DWHR technology, it does require either fabrication of a larger diameter heat exchanger, or following the recommendations of some manufacturers, use of a system in which two or more heat exchangers are installed in parallel. This type of installation was beyond the scope of our project.

Figure 3 Large drain lines

- Other odd drain configurations, such as 45 degree angled lines (Figure 4).

Figure 4 Drain run at angle

- Distances from drains to water heating system. Excessive distances were a factor in a number of larger health clubs and university facilities.

Our efforts to identify facilities for retrofit application of drain water heat recovery lead us to believe that the technology simply won't be practical in a majority of existing commercial facilities. This is one reason to suggest that new construction may be a better target market for this technology.

SITES SELECTED

We selected four sites for the project, including an apartment building in Madison, Wisconsin, and three facilities in the Twin Cities area of Minnesota. As discussed above, we faced difficulties finding facilities that allowed for the practical installation of drain water heat recovery systems, and the sites we selected may not represent ideal applications for the technology.

APARTMENT – SITE 1

This is a 26-unit apartment building in Madison Wisconsin. The building has a central water heating system consisting of two storage tank water heaters (100 gallons each), and has a hot water recirculation loop. The ground level of the building consists of indoor heated garage space, a mechanical room, a self-service laundry room, and a separate leased commercial space. The apartment units, all located on higher floors, are connected to one of four separate four-inch PVC drain lines. One of these drain lines, which serves six apartment units, passes through the mechanical room and was selected as the location for the heat recovery unit.

RESTAURANT – SITE 2

This site is a Minneapolis restaurant with about 120 seats, open for breakfast, lunch, and dinner seven days a week except on some holidays. The kitchen and dining areas are located on a single above-grade level, with storage and mechanical equipment located below on a walk-out basement level. Hot water is provided by an indirect heating system with an 80 gallon storage tank heated by a gas boiler. Kitchen and plumbing fixtures are connected to several different drain lines passing through the basement. The single dishwasher in the kitchen appeared to be the largest hot water load in the facility, and we selected the two inch drain serving the dishwasher and a spray sink as the best opportunity for heat recovery. The dishwasher is designed to operate at a water temperature of 150° F during wash cycles, and 180° F during rinse cycles, and has an electric heater to boost the temperatures coming from the water heating system.

LAUNDRY – SITE 3

This is a self-service laundry that also performs some commercial laundry services, located in St Paul, Minnesota. It has about 38 washing machines on a single above-grade level, with a full basement below. Hot water is provided by an indirect heating system with two 115-gallon storage tanks heated by a gas boiler.

Waste water from the washing machines drains into open metal pans with several square feet of open surface area located behind each bank of machines. Each pan is connected to a PVC drain line exiting the side of the pan before passing through the floor to the basement (Figure 5). Water in the pans needs to reach a certain height to drain, creating a lag in drain flow to the basement, allowing mixing water of different temperatures and encouraging heat loss from drain water— all of which probably affects heat recovery performance.

All the washing machine drain water ultimately passes into to a single four-inch PVC drain line on the basement level, and the heat recovery system was installed in a vertical section of this drain.

STUDENT HOUSING FACILITY – SITE 4

The final facility identified for the project is a college residence hall in suburban St. Paul. The ground level of the building includes a mechanical room and common areas. Forty-eight student suites are located on three upper levels of the building. Each suite houses six residents, and has a kitchenette and a bath area with two shower stalls. The plumbing fixtures are connected to several drain lines passing separately though the ground floor level. We selected a three-inch cast iron drain line that passes through the mechanical room for our project; the drain serves three suites (eighteen students when fully occupied), and drains showers, toilets, and lavatory sinks in these suites.

**Figure 5 Front corner of drain pan located behind washing machines.
Drain pipe exiting pan shows in foreground.**

HEAT RECOVERY SYSTEM DESIGN AND INSTALLATION

Design and installation of drain water heat recovery systems should take several basic factors into consideration.

One key design considerations in drain water heat recovery is pressure drop on the supply side of the heat exchanger. If the maximum expected supply water flow rate can pass through the heat exchanger without excessive pressure drop or flow velocity, then the cold supply water feeding the water heating system can simply pass through the supply side of the heat exchanger. Some drain water heat exchanger designs use multiple supply side tubes in parallel, reducing pressure drop at any given supply side flow rate.[5]

If the maximum expected flow is too great, the heat exchanger can be put on a separate piping loop with a pump to create flow. Other options may exist; at one of our sites, we used a balance valve as a bypass to divide the supply water flow, with part of the flow passing through the heat exchanger. Manufacturers of heat recovery equipment should be able to provide information about the pressure drop at any given supply water flow rate for their products.

Drain size is another consideration in heat exchanger selection. Plumbing codes generally prohibit reducing the size of existing drains, and the heat exchanger drain line is usually the same size as the drain.[6]

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[5] The commercial heat exchanger models we used in three systems had six 3/8 inch copper tubes in parallel forming the supply side flow path, while the fourth, a residential model, had four tubes in parallel.
[6] Manifolded systems (using multiple heat exchangers in parallel) are possible, but are beyond the scope of this report.

INSTALLED SYSTEMS

Restaurant (Site 2)

We start with a description of this system since it made use of the simplest possible plumbing configuration, a "flow-through" design with all the supply side flow to the water heating system passing through the heat exchanger. This configuration was shown in Figure 1 above. As mentioned earlier, the main hot water loads captured by this heat exchanger are the dishwasher and spray sink. The dishwasher is entirely a batch load process; filling and draining are always offset in time. The dependence on thermal mass of the heat exchanger to absorb drain water energy and then release it during supply flows was expected to limit heat recovery at the site. (The spray sink can produce simultaneous supply and drain flow, but with relatively short flow episodes.)

The heat exchanger used at this site is a 2-inch diameter model that is 72 inches long.[7]

Apartment (Site 1)

At the apartment site, the pressure drop associated with passing the maximum expected flow through the heat exchanger was judged too great, and we selected a configuration that allowed a part of the supply flow to bypass the heat exchanger. This "bypass" configuration made use of a balance valve with an adjustable setting, creating a pressure drop intended to force part of the supply flow through the heat exchanger (Figure 6).
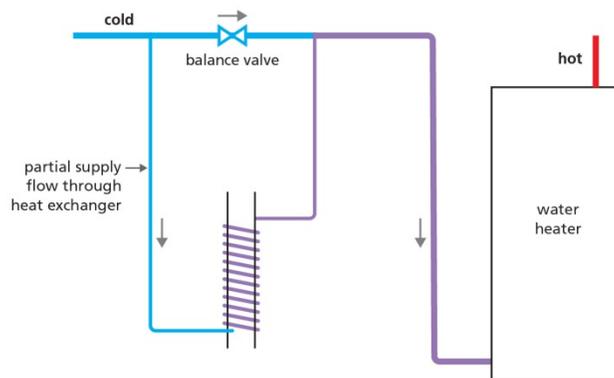

Figure 6 Bypass configuration used at apartment site

A section of the cold water line to the water heaters was noticeably heated by recirculation return flow, and we kept our system upstream of this point.

Difficulty finding an appropriate setting for the balance valve meant this system never performed well, and we obtained very little useful data from this system. Results from this site are excluded from most of our remaining analysis and discussion.

The heat exchanger used at this site is a 4-inch diameter model that is 78 inches long.[8]

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[7] PowerPipe™ R2-72
[8] PowerPipe™ C4-78

Laundry and student housing (Sites 3 and 4)

Large expected hot water flow rates drove the decision to use a "pumped loop" system configuration at the laundry and student housing sites (Figure 7). A pump circulates water from the cold line feeding the water heater through the heat exchanger and back to the cold water line. This configuration makes use of the thermal mass of the water in the loop to store more heat than would occur in the mass of the heat exchanger alone, so should have real benefits where batch loads are found, such as at a laundry. The thermal mass of this piping loop depends on the length and size of piping in each case.
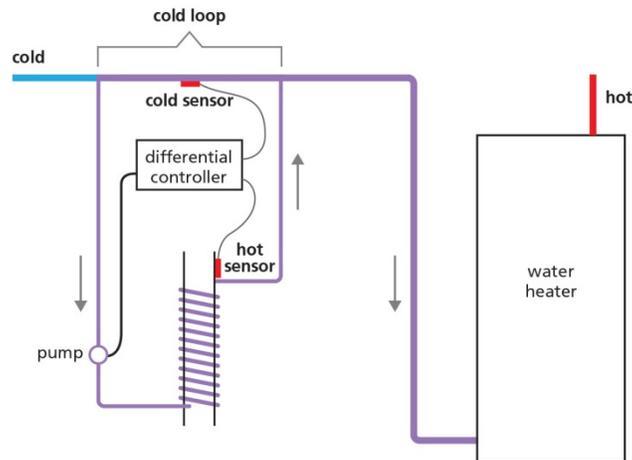

Figure 7 Pumped loop system configuration used at laundry and student housing sites

The heat exchanger used at the laundry is a 4-inch diameter model that is 48 inches long; the student housing facility used a 3-inch diameter model that is 72 inches long.[9]

Control of the pumps in these systems is done with differential temperature controls. A differential control compares the temperature at two points (the heat exchanger and in the cold water piping in this case), and operates the system pump when the heat exchanger is warmer than the cold water. We used fixed speed, on-off controls, although some manufacturers recommend controllers that vary pump speed in proportion to the available temperature difference.

The "hot" sensor at the heat exchanger is placed on the exterior of the drain line just above the supply line tubing (Figure 8). The temperature at this location intentionally reflects heating by drain water, as well as the cooling effect of water flow through the supply tubing when the pump operates.

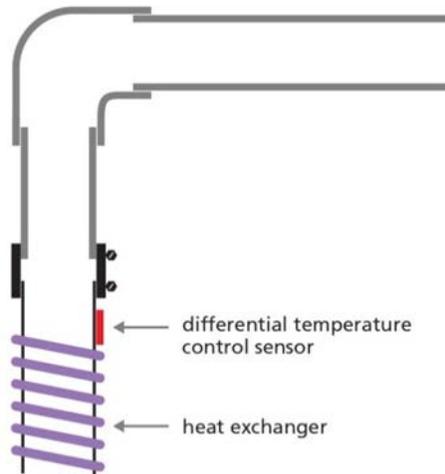[9] PowerPipe™ C4-48 and PowerPipe™ C3-72

Figure 8 Location of "hot" side differential control sensor

Another sensor is placed in contact with the cold water piping in the common section shared by the pumped loop and the water heater feed line. We use the term "cold loop" for this portion of the piping system. This sensor then reflects the temperature of water in the pumped loop, acting as the thermal sink for energy storage, and responding to the introduction of cold water when water draws occur.

The intended result is that the system will operate when warm drain water brings the heat exchanger above the temperature in the cold loop, but turns off when the heat exchanger temperature approaches the temperature at the cold loop. Either an increase in drain temperature due to warm drain flow, or a decrease in cold loop temperature due to water draws (or both), can trigger pump operation.

Differential controls usually use different setpoints for turning pumps on and off. This prevents rapid pump cycling and provides more stable operation. We set the controllers to start pump operation at a temperature difference of 15 F, and stop operation when the difference drops to 3 F.

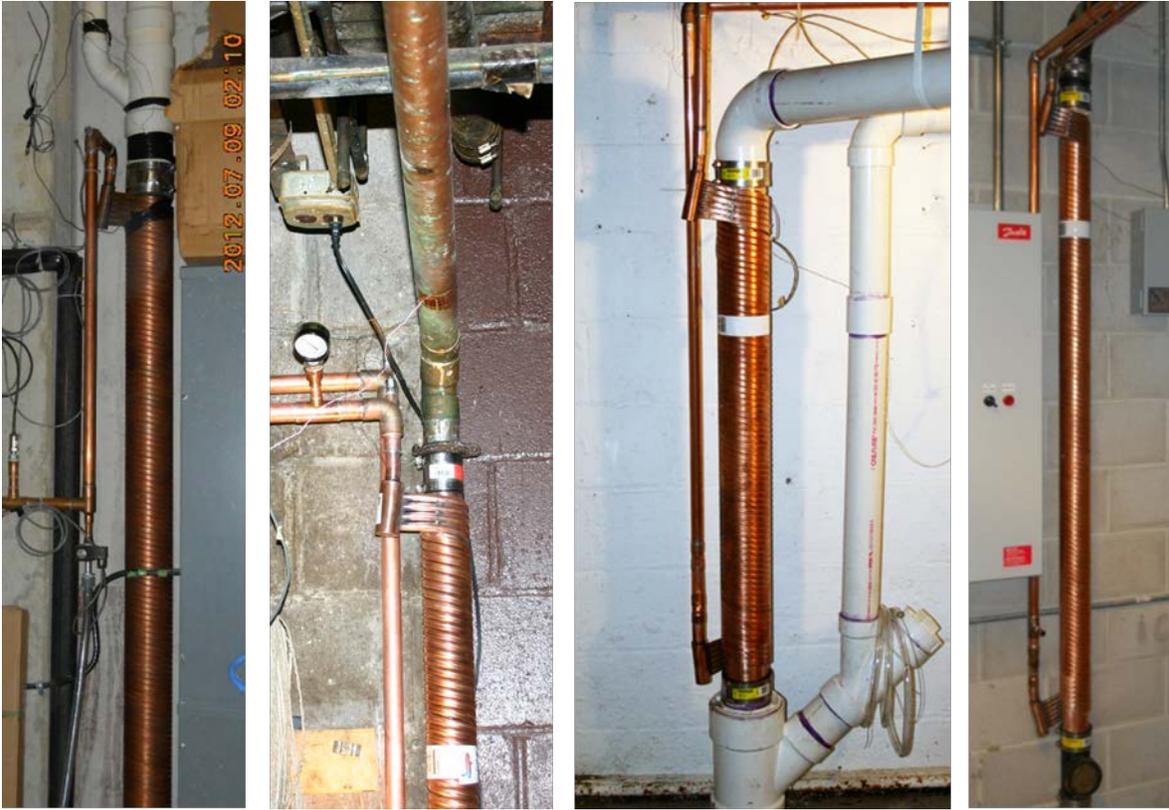Figure 9 shows each of the four heat exchangers as installed.

Figure 9 Installed heat exchangers at apartment, restaurant, laundry, and student housing facility

Other practical design and installation considerations

Another installation configuration is sometimes recommended for drain water heat recovery systems in which recovered energy is delivered both to the water heating system and to the cold water lines feeding showers (Figure 10). This piping configuration increases the flow rate on the supply side of the heat exchanger, which yields better heat exchange performance, and in the case of showers or similar loads using controlled mixed temperatures, reduces the volume of hot water required. This configuration doesn't make sense if the pre-heated water feeds loads for which lower temperature water is acceptable or desirable.
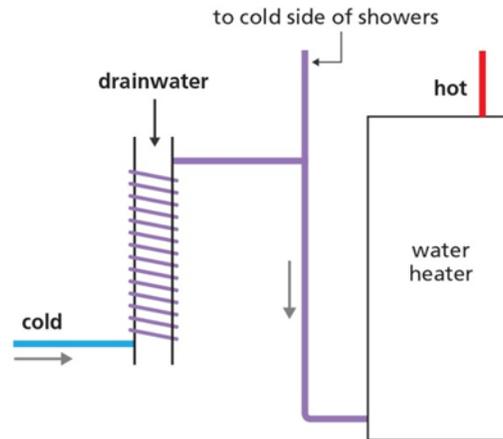
Figure 10 Delivery of recovered energy to cold side of showers

The performance of a drain water heat recovery system will vary with the temperature of the cold supply water. The larger the temperature difference across a heat exchanger, the more heat is recovered. And, in the case of pumped loop systems, increased temperature in the cold supply water means the differential control will run the pump less often. A couple of common plumbing issues can significantly affect the temperature of water available for heat recovery.

Thermosiphoning currents, that carry the warmer water upwards and then back down as it cools, can occur within a single pipe, especially in larger pipe sizes (Figure 11). We found evidence of thermosiphoning in the cold water line feeding the water heating system at two of our project sites. If this accidental heating of the cold water line extends to the DWHR piping loop connections, it can artificially raise the supply water temperature at the heat exchanger, reducing heat recovery. (Thermosiphoning also adds to overall water heating system heat loss.) Installation of a check valve where piping nears a storage tank should prevent this type of thermosiphoning, as can addition of piping with a local high point (i.e. an inverted "U" shape).
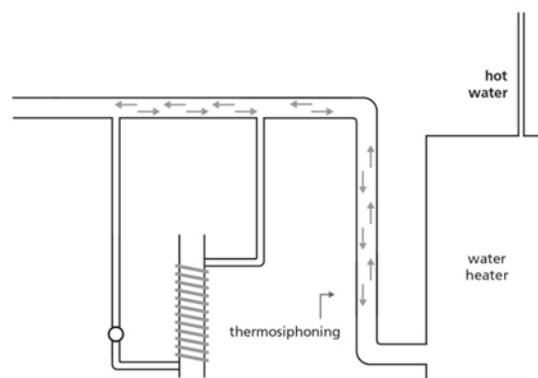
Figure 11 Thermosiphoning can heat the cold water line feeding the water heating system

Similar to the thermosiphoning issue, hot water recirculation can have implications for DWHR performance. Recirculated water returned to the cold water feed line upstream of the DWHR loop connections will increase the temperature of the loop, decreasing heat recovery performance. Placement of the DWHR loop connections upstream of the recirculation return point will reduce this effect, though

thermosiphoning above the return point may still increase temperatures some distance above the return point (Figure 12).

Figure 12 Hot water recirculation return can increase temperature of cold water available for heat recovery

Some building fixtures that mix hot and cold water together can allow the reverse flow of cold water into the hot water lines. This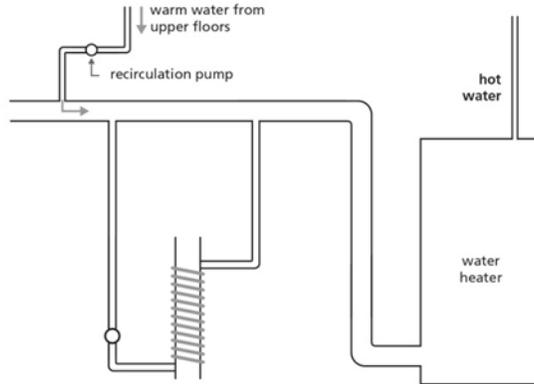 leads to the flow of hot water backwards out of the water heating system and is yet another factor that can undesirably increase temperature on the supply side of a heat exchanger and reduce heat recovery performance. We encountered this situation at our restaurant site, and corrected it with the installation of a check valve.

MONITORING METHODS AND RESULTS

MONITORING SYSTEM

We installed a dedicated monitoring system at each of the four test sites. The parameters measured and methods used are listed in the Table 1 below.

Table 1 Monitoring system elements

Parameter measured	Measurement method	Terminology used in this report
Supply water temperature entering heat exchanger	Thermistor probes with low thermal mass, immersed in flow	Cold water temperature, t_cold
Supply water temperature exiting heat exchanger	Thermistor probes with low thermal mass, immersed in flow	Recovered water temperature, recovery temperature, t_recovered
Supply water flow through heat exchanger	Nutating disk water meter equipped with pulse output (100 pulses/gal)	Flow rate, pulse_count_water_meter
Cold loop temperature	Thermistor sensor mounted on exterior of cold loop, insulated	Cold loop temperature, t_cold_loop

Parameter measured	Measurement method	Terminology used in this report
Hot water delivery temperature	Thermistor sensor mounted on exterior of hot water supply line, insulated	Hot water temperature, t_hot
Room air temperature	Thermistor suspended near ceiling of mechanical area	Room air temperature, t_room
Water heater or boiler run time (at 3 sites)	Current switch on gas valve power	
Surface temperature of drain line (above heat exchanger at one or more locations)	Thermocouple and/or thermistor, fastened tightly to exterior of drain line	Drain temperature 1, Drain temperature 2, t_drain1, t_drain2
Heat flux across surface of drain line (above heat exchanger)	Low-mass heat flux transducer	Heat flux output, v_heat_flux
Recovered energy	Calculated from water flow rate and difference between cold water temperature and recovered water temperature	Q_rec_bldg

All sensors were connected to a Campbell Scientific CR1000 data acquisition system. The inputs were scanned and values recorded once per second. Some data was averaged and recorded over longer time intervals, but all our final analysis was based on the one-second interval data. Each system was connected to the internet either by piggybacking on the owners' internet service or by setting up independent service. Data was delivered to servers at Energy Center offices once each hour.

Our monitoring systems included a solenoid valve positioned to allow a controlled draw of water through the heat exchanger, with the intent of exploring the energy benefits of drawing energy off the heat exchanger when no hot water draw occurred. These valves were found to be unreliable, however, and did not work well for the intended purpose.

CHARACTERISTIC PERFORMANCE

Graphs of the 1-second resolution data can help in understanding typical patterns of heat recovery system performance at the three sites that yielded useful data.

The restaurant (site 2) is characterized by many brief flow episodes (Figure 13). A large number of these are dishwasher fill cycles at a rate of about 6.6 gpm over 10 seconds, or about 1 gallon total. Recovery temperatures and heat recovery rates during these flow episodes can be quite high (significantly higher than observed at the other sites), with recovery temperatures over 130°F, and heat recovery rates of 40 Btu/sec (140,000 Btu/hr) and higher.

These high recovery rates are the consequence of several factors. The water used at the dishwasher is very hot, with the temperature boosted electrically at the dishwasher as needed to meet operating requirements. There is no mixing with cold water during dishwasher cycles. The length of the drain from the dishwasher to the heat exchanger is less than 15 feet, and is horizontal, resulting in lower heat loss between the load and the heat exchanger than at our other sites. Finally, the batch flow operation of the dishwasher means that supply water is often sitting still in the heat exchanger when drain flow occurs.

The water in the heat exchanger can reach higher temperatures when the supply side is stagnant than when there is supply water flow continuously removing energy, resulting in high peak temperatures when supply flow begins. That said, overall heat recovery will be lower with batch flow than with continuous flow, since optimal heat exchange depends on simultaneous flow.

Room temperature is very high (close to 100°F) at the time of these observations (in August, 2012), a consequence of heat rejection from a refrigeration system placed in the basement. Cold water temperature is also very high, which results from long runs of tubing upstream of the water heating system exposed to the high basement air temperature. Compared to more typical conditions where cold water temperature is lower, this reduces the amount of energy consumed in water heating, and also reduces the amount of energy that can be recovered at the heat exchanger (since the rate of heat exchange is always related to temperature difference). The amount of energy gained from the room air will be discussed later.
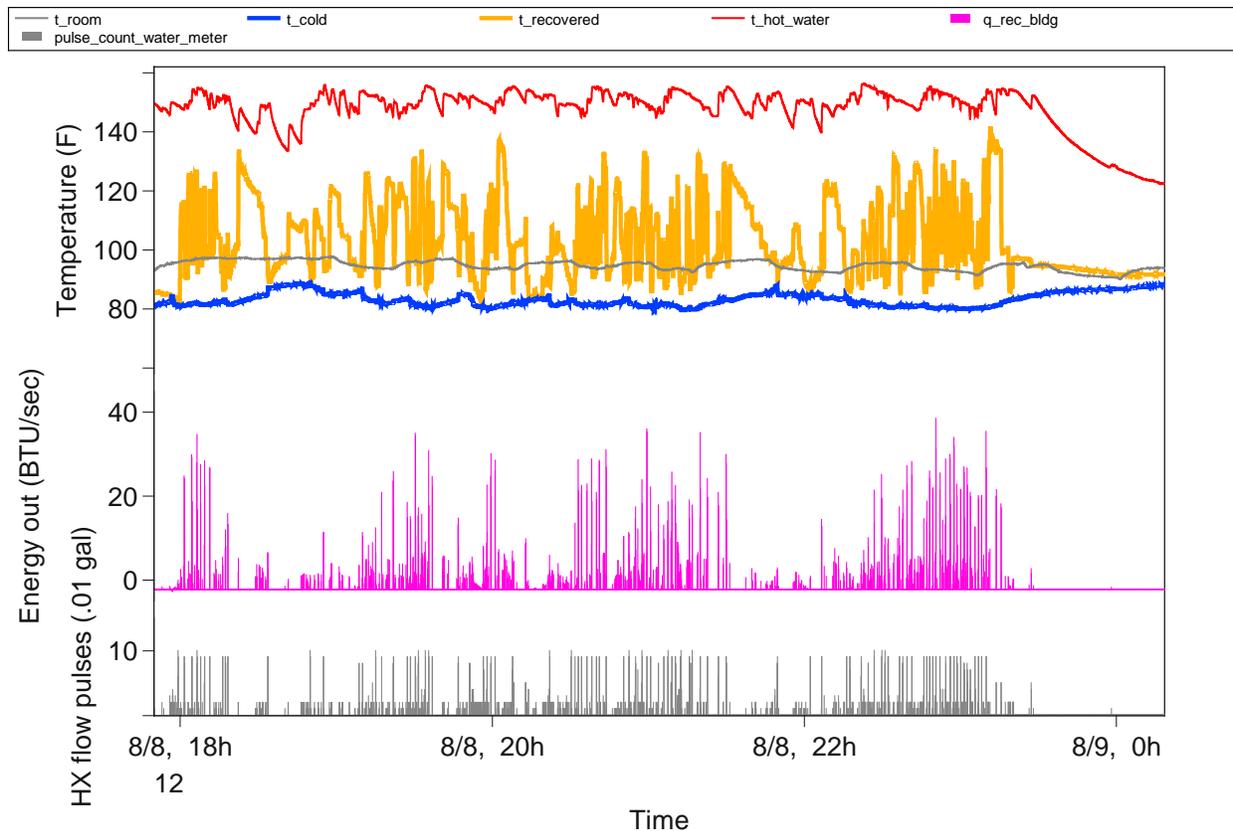

Figure 13 Typical operation of heat recovery system at restaurant over about 6 hours, August, 2012. 1-second resolution values. Grey bars at bottom represent water flow though the heat exchanger; 10 pulses per second is equivalent to 6 gpm.

Figure 14, results from a 15-minute period at the restaurant, shows the increase in recovery water temperature during times of little or no flow, indicating hot drain flow and heat storage in the heat exchanger. The occurrence of a dishwasher fill cycle after one of these storage episodes results in both a spike in recovered energy (as the preheated water leaves the heat exchanger), and a dramatic drop in recovered water temperature.
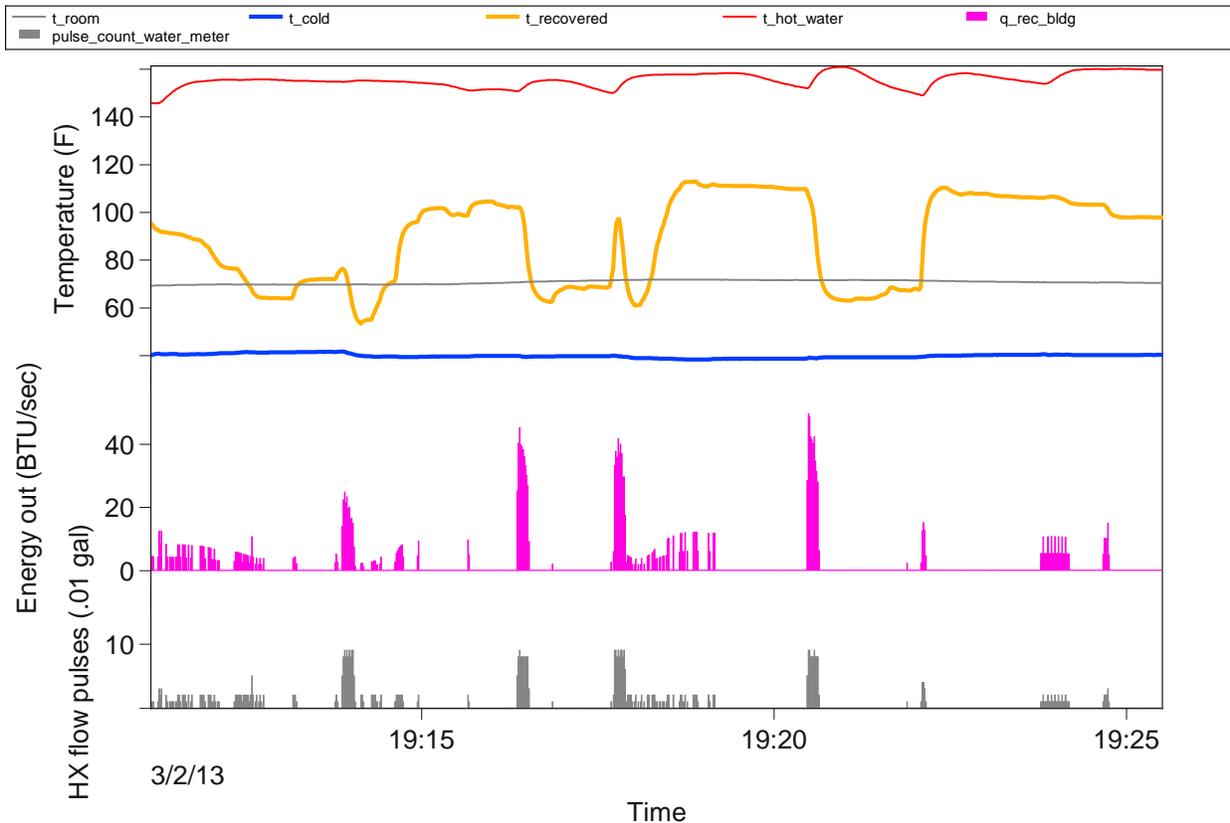

Figure 14 Restaurant, detail of performance over 15 minutes, showing evidence of heat storage in heat exchanger between flow episodes. 1-second resolution values.

We can use the thermal mass of the heat exchanger to explore the amount of energy that might be stored when there is hot drain water flow but no supply flow. Based on tubing sizes and thicknesses, the heat exchanger at the restaurant contains about 20 pounds of copper, with a heat capacity of about 1.8 Btu/F. This heat capacity is equivalent to about 0.22 gallons of water. With dishwasher cycles using about a gallon of water, the heat exchanger mass, starting at cold water temperature, could absorb a maximum of about 22 percent of the available energy in the drain water. In practice, this value will be limited by the heat transfer rate from drain water to copper (related to the heat exchanger effectiveness, discussed later).

The water content of the heat exchanger provides additional thermal mass, which we estimate at about 4.25 lbs, or 4.25 Btu/F of additional heat capacity. The water can't play a role equivalent to the copper, since heat transfer from the copper to stagnant water will be limited, but even if the water plays only a limited role, the total effective thermal mass of the heat exchanger is probably equivalent to a quarter gallon or more of water, and it may be able to absorb 10 to 20 percent of the energy passing through the drain, almost all of which can be recovered when supply flow begins. We believe the modest thermal mass of this heat exchanger, in a building where drain flow episodes are also usually small, plays a significant role in system performance.

The heat recovery system at the laundry (site 3) and student housing facility (site 4) both have pumped loop systems with single-speed pump controls, and supply-side flow through the heat exchanger is very nearly constant whenever these pumps operate (Figure 15 and Figure 16). Under this condition of constant supply flow, the rate of heat recovery, and recovered water temperature, vary with the temperature and flow rate of the drain water. The temperature rise across the heat exchangers at both these sites are far lower than at the restaurant site, a result of the higher typical supply side flow rates and less dynamic performance (i.e. active pump control means these heat exchangers never heat up as much as the restaurant system between draws), but also of lower drain water temperatures. (Both externally measured drain temperatures, and the maximum recovery temperatures show that typical drain water temperature at the restaurant was far higher than at the other sites).

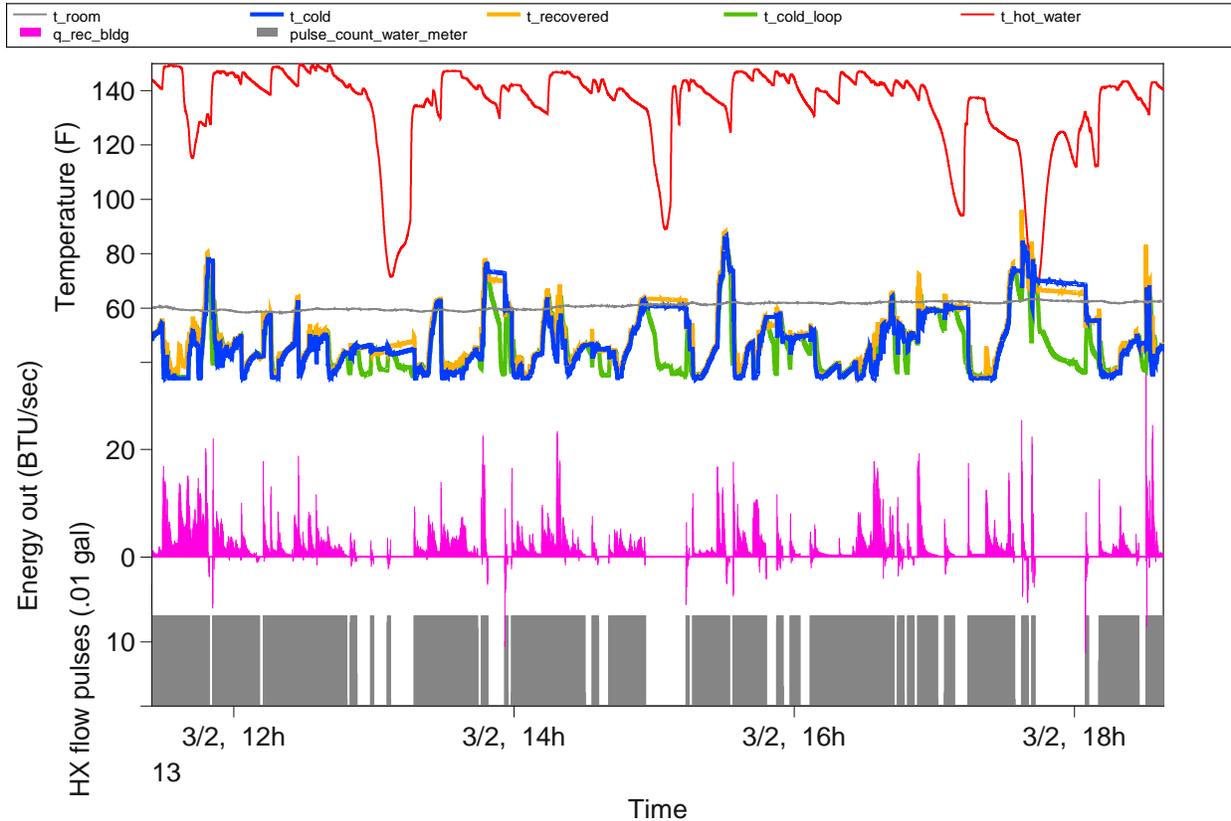**Figure 15 Typical operation of heat recovery system at laundry over about 6 hours, March, 2013. 1-second resolution values.**

Data for both sites also show numerous cases of sharp drops in energy recovery rates during pump cycles, which we take as evidence of cold water flows through the heat exchanger.

The pumped loop flow rate was usually about 8.4 gpm at the laundry, and about 6.6 gpm at the student housing facility.
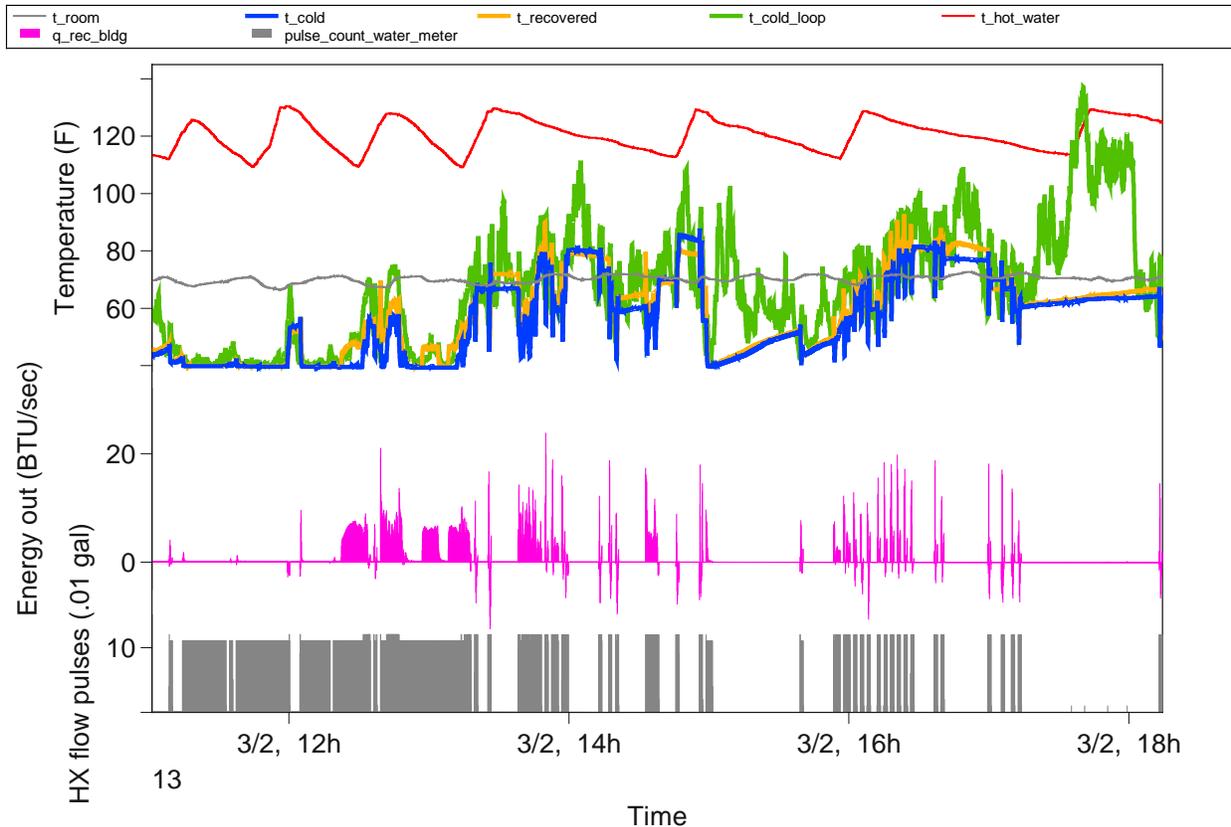
Figure 16 Typical operation of heat recovery system at student housing facility over about 6 hours, March, 2013. 1-second resolution values.

The cold loop temperature, measured on the section of piping shared by the pumped loop and the cold water feed to the water heating system, is also shown on these graphs. When the pump is operating, we expect the entire loop to become mixed, and cold loop temperature to track closely with cold water temperature (temperature of water entering the heat exchanger). This generally appears to be the case at the laundry, but not at the student housing facility. This is due to differences in installation of the systems.

Both the laundry and student facility have overhead cold water piping that drops down vertically as it enters the hot water storage tank (as shown in Figure 11). Early observation of system operation at the laundry verified that the cold loop section of piping was affected by thermosiphoning, and we had a check valve installed to correct it.

The cold loop piping at the student housing facility is affected by a combination of thermosiphoning and by the introduction of warm recirculation return water in the vertical section of pipe entering the storage tank. It wasn't practical to install a check valve at this site, and this warm water affects temperatures at the cold loop, especially when the heat recovery pump is off.

The laundry and student housing sites both show negative rates of heat recovery at times. This often appears in a characteristic pattern in which heat recovery cycles between positive and negative over a couple of minutes as water circulates through the pumped loop. The pattern starts when pump operation is triggered by the entry of cold water into the cold loop section of piping (when hot water is drawn). With very cold water in the cold loop, even a moderate heat exchanger temperature will provide the

difference needed to start the pump. Under these conditions, energy previously stored in the loop piping may be lost back to the drain.

For example, consider the case in which most of the pumped loop has been heated to 80°F during prior drain flows, after which cool drain water reduces the temperature of the heat exchanger to 70 °F. Water entering the cold loop at a temperature of 55 °F will trigger the differential controller and start pump operation. The 80 °F water in the loop will lose heat at the heat exchanger, while the colder 55 °F water will gain energy, creating the cyclical pattern of positive and negative heat recovery. This pattern doesn't appear to represent a critical problem, and most pump operating cycles result in a net heat gain.

The two systems with pumped loops also experienced operating cycles for periods of up to perhaps 30 minutes in which there was very little heat recovery. This implies that control settings were less than optimal, and that the temperature difference at which the pump is turned off should be increased from 3 to perhaps 4 or 5 °F. The position and mounting of temperature sensors at the heat exchanger and cold loop may also play a role. The use of variable speed pumping is another strategy to reduce pumping power when little heat is being recovered.

SHORT TERM TESTING AND RESULTS

We performed short-term testing of heat recovery system performance at three sites (no short term testing was performed at site 1). The intent of this procedure was to establish the performance of the heat recovery system under steady state conditions.

The performance of a heat exchanger can be characterized by "effectiveness." Effectiveness represents the amount of heat exchanged as a ratio to the maximum amount that could possibly be exchanged. When two fluid streams of equal specific heat and flow rate enter a heat exchanger, the cooler fluid can in theory be heated to the temperature of the incoming warm fluid.[10] A heat exchanger in which this occurs would have an effectiveness of 1.0. Practical heat exchangers will transfer less than the maximum possible amount of heat, and effectiveness levels in operation are always less than 1.0. Heat exchange effectiveness depends on flow rate. Effectiveness testing may be done at several different flow rates typical of the expected application, but generally with equal flow on the two sides of a heat exchanger. Effectiveness values are not intended to capture dynamic or heat storage effects, and effectiveness tests are run at steady state.

In practical operation, with constantly changing and often unequal flow rates in the two fluid streams, effectiveness is constantly changing.

Effectiveness values provided by manufacturers of heat exchangers are measured in lab settings, and apply to the heat exchanger alone, isolated from other components. When drain water heat exchangers are installed in real buildings, heat loss from piping and at appliances reduces the amount of energy available at the heat exchanger to less than the amount delivered by the water heating system (Figure 17).

The tests we performed are analogous to lab tests of heat exchanger effectiveness, but were performed on the systems as installed, and include the effects of building piping. We use the term "system effectiveness" for the results of this testing. This system effectiveness will be somewhat lower than the

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[10] This applies only to "counterflow" heat exchanger designs, in which the fluids flow past each other in opposite directions. Heat exchangers in DWHR systems normally use a counterflow design.

heat exchanger effectiveness as measured in a lab setting, and represents the practical upper boundary for heat recovery in the tested system.[11]
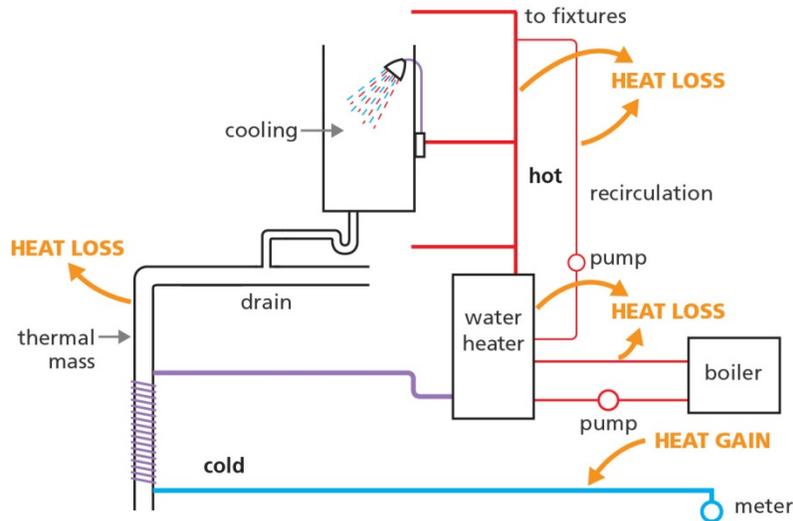

Figure 17 System effects in drain water heat recovery. Recoverable energy is limited by losses from piping and loads.

The procedure for this testing was essentially to draw water at a fixed flow rate for a period long enough for the heat exchange process to reach steady state. Heat recovery was measured in each case via the installed monitoring systems.

At the restaurant (site 2), a hand sink was used for testing at a low flow rate, and a spray sink for testing at a higher rate. Delivered hot water energy was calculated from the monitored hot water delivery temperature and monitored hot water flow rate.

At the laundry, water was drawn through hoses normally connected to washing machines. Drain water from the washing machines normally collects in a drain pan before flowing to the drain pipe system, but for consistency in this test we directed water into the mouth of the drain piping. Delivered hot water energy was calculated from the monitored hot water delivery temperature and the flow rate as observed at the building water meter.

We used two shower stalls and a lavatory sink for water draws at the student housing facility (site 4). Shower water temperature was controlled to about 103 °F by automatic mixing valves, and we used the mixed water temperature in calculating hot water energy delivered.

In each case, hot water energy delivered was calculated based on the temperature difference of hot water less the average cold water temperature at the heat exchanger at the time of the test. When the flow rates on the two sides of a heat exchanger are unequal, the general definition of effectiveness is the ratio of heat recovery to the maximum possible heat transfer to or from the fluid stream with the lower flow rate.[12].

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[11] System effectiveness, like conventionally defined heat exchanger effectiveness, varies with flow rate on both sides of the heat exchanger, so this upper bound is not a single value but an envelope of flow-dependent values.   Note also that short-term heat recovery rates under non-steady-state conditions (such as observed at the restaurant) can appear to exceed the steady state effectiveness limit.

[12] Technically, the heat capacity rate (flow rate x specific heat) is the relevant parameter, but if the specific heat is constant throughout the system, this is proportional to flow rate.

Applying this principle to the pumped loop systems at sites 3 and 4, with supply side flow rates of about 8.4 and 6.6 gpm, the flow rate on the drain side was the lesser flow, and was used in calculating system effectiveness. We ran each test to the point approximating steady state performance, as judged by watching temperature changes in real time.

One striking result of this testing is the demonstration of thermal mass effects. Each of the systems takes a noticeable amount of time and water volume from the start of flow to reach steady state. Results from the restaurant show this effect in terms of the instantaneous system effectiveness and average or cumulative system effectiveness from the start of the draw episode (Figure 18). The draw starts with falling effectiveness (in fact heat recovery briefly goes into negative values) because the heat exchanger was cooled, before this test, to a temperature below the typical temperature of cold water in the system piping. Allowing for this perhaps unusual startup condition, it takes about 4 gallons of flow for the instantaneous effectiveness to reach a near-steady state value. The average system effectiveness over the first 4 gallons of flow is only about 0.20, or about half the steady state effectiveness at that flow rate.
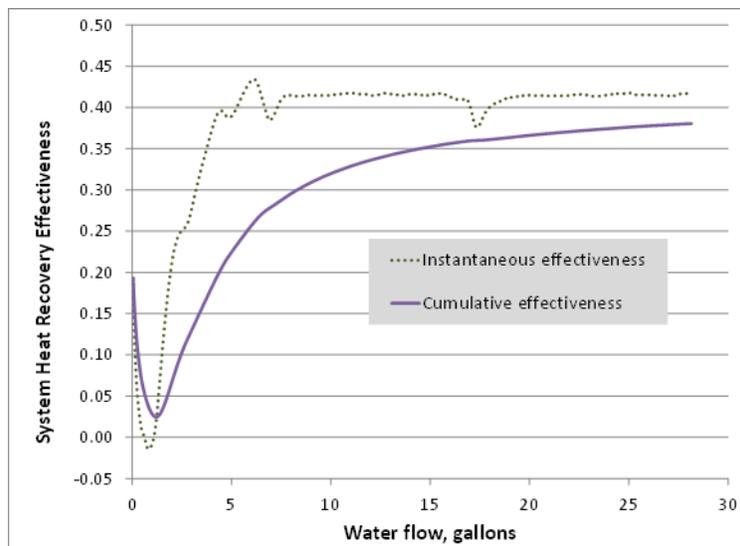

Figure 18 Development of steady state performance at restaurant

This mass effect may represent a major penalty on heat recovery system performance, but how much of a penalty depends on typical use conditions. If flows are short and the time between flows is long, losses of drain water energy to the room air will tend to be a larger fraction of the total energy available. Long sustained flows, and short time between flow episodes, allow performance closer to that measured at steady state.

Results for all the tests we performed are shown in Table 2. The table includes a ratio of system effectiveness based on these tests to nominal heat exchanger effectiveness, based on the results testing performed for the manufacturer.[13] Heat exchanger effectiveness values were based on the flow rate of the draw (i.e. the rate of flow through the drain), which is lower than the supply-side flow in the pumped loop systems at sites 3 and 4. The higher supply-side flow rates in our tests would tend to increase heat exchanger effectiveness above the nominal values, but probably not by a large margin.

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[13] PowerPipe™ Drain Water Heat Recovery Systems: Effectiveness Testing of Commercial Units, Michael R. Collins, University of Waterloo, Waterloo, Ontario, March 16, 2011. We used curve fit formulas for heat exchanger effectiveness as a function of flow rate as presented in this report to calculate effectiveness at the flow rates measured in our testing.

Effectiveness values are generally expected to decrease as flow rates increase.[14] This pattern doesn't hold for the second test at the laundry, where the observed system effectiveness increases as compared to that at a lower flow rate, and in fact exceeds the manufacturer's value for stand-alone heat exchange effectiveness. Based on these factors, we question the results of this second test.

The ratio of our observed system effectiveness to the heat exchanger effectiveness is relatively low in the tests at the student housing facility. Two factors likely contribute to this result. First, the use of showers in the testing means there was evaporative heat loss at the point of use, and second, the two stories of vertical cast iron drains probably resulted in relatively greater heat loss between the load and the heat exchanger than occurred at the other sites.

The lower ratio of observed system effectiveness to heat exchanger effectiveness in the second test at the restaurant may be due to the use of a spray sink for that test. The spray sink is about eight feet farther from the heat exchanger than the hand sink used for the first test, and use of the spray valve would lead to greater evaporative heat loss.

Table 2 System effectiveness test results

	Restaurant	**Restaurant**	**Laundry**	**Laundry**	**Laundry**	**Student housing**	**Student housing**
Flow rate to load (gpm)[15]	2.842	3.750	0.655	2.220	5.025	1.498	2.990
Hot water energy delivered to load (Btu/hr)	139,372	158,040	33,716	112,585	248,717	45,680	91,177
Heat recovery rate (Btu/hr)	58,039	53,028	15,619	59,195	66,331	16,054	31,815
System effectiveness	0.416	.336	0.463	0.526	0.267	0.351	0.349
Nominal effectiveness rating for heat exchanger	.5051	.4651	0.5848	0.4463	0.3036	0.4966	0.4661
Ratio: observed system effectiveness to manufacturer's heat exchanger effectiveness	0.82	0.72	0.79	1.18	0.88	0.71	0.75

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[14] In the case of system effectiveness testing as discussed here, there is at least one factor working in the opposite direction: Increasing the flow rate reduces residence time of water passing through the drain line, which will tend to decrease per-gallon heat loss to ambient air.

[15] Flow rates to loads – consider approximate for site 4: measured with cup and watch.

LONG TERM MONITORING RESULTS

We monitored sites 1, 2, and 3 each for more than 12 months. Site 4, the student housing facility, was identified much later, and we have about six months of usable data from that site. The performance of the three properly-performing systems is summarized in Table 3. [16] Projected annual energy recovery is an extrapolation over brief periods of missing data to the total expected energy recovery over a full year of 365 days. The value of recovered energy is based on natural gas priced at $8.00/million Btu and water heating system thermal efficiency of 75%, for an overall marginal cost of delivered energy of $10.67/million Btu.

Table 3 Summary of performance of installed drain water heat recovery systems

	Site 2 Restaurant	Site 3 Laundry	Site 4 Dormitory (student housing)
Projected annual energy recovery (Million Btu) Note 1	43.1	18.7	7.6[17]
Value of energy recovered annually, $ Note 2	460	200	81
Estimated system-specific annual delivered water heating energy (Million Btu)	150.5	211	28.9
Heat recovery as percent of estimated system-specific delivered water heating energy	29	8.9	26

The estimated system-specific annual delivered water heating energy is the amount of energy we estimate is delivered to fixtures connected to the installed heat exchanger. This amount, less losses at the fixtures and in the piping system, is the amount of energy that passes through the heat exchanger. These values should be considered rough estimates. For the restaurant, the value is based on measured hot water delivery volume and temperature, adjusted upwards for electrical heating at the water heater to meet operating temperature requirements.[18]

For the laundry, we estimated the water heating energy based on the nominal input of the water heating boiler, an assumed overall efficiency of 70 percent (including standby losses), and the monitored operating time of the gas valve. We did not have water heater operating data for the student housing facility, and in any case the loads we want to estimate are a fraction of the overall building load. In this case, we estimated total hot water use at 10 gallons per person per day, and used the monitored delivery temperature to calculate energy.

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[16] The apartment building, site 1, performed very poorly due to lack of proper adjustment of the balance valve controlling heat exchanger flow, and is not included in results summaries.

[17] This value is based on the very conservative approach of a linear extrapolation from the available data, nearly half of which is for a largely unoccupied period of the summer. If we extrapolate from performance during the occupied spring period (which includes a low-output spring break period) to a full year, the system might produce about 12 million Btu annually or about 60 percent more energy than shown in the table.

[18] We estimated the electrical energy added from the difference in temperature required at the dishwasher less the temperature of hot water leaving the water heating system.

In terms of total energy recovered, the restaurant system outperforms the other systems by a large margin. We believe this is due to the combination of very hot drain water (unmixed hot water, primarily from a dishwasher), no appreciable cold water flow through the drain, and the frequent flow of hot drain water that keep the drain system heated, even though the flows are intermittent. The laundry and student housing facility, by contrast, both have significant cold water loads that pass through the heat exchanger.

Heat recovery as a fraction of estimated delivered energy also suggests good performance at the restaurant. Values for the other sites must be considered rough approximations.

Daily total heat recovery over the monitoring period (Figure 19) shows the effects of occupancy at each site. The restaurant and laundry were clearly closed on Thanksgiving and Christmas Day, and the laundry also on New Year's Day. Heat recovery at the student housing facility drops off in the summer, when the facility is largely unoccupied. A second visible trend is that heat recovery at the restaurant and laundry is higher in the winter months. (Seasonal effects at the residence hall are hard to spot given the shorter monitoring period and low usage during the summer). This seasonal trend is a consequence of cold water temperature variation, which will be discussed further below.
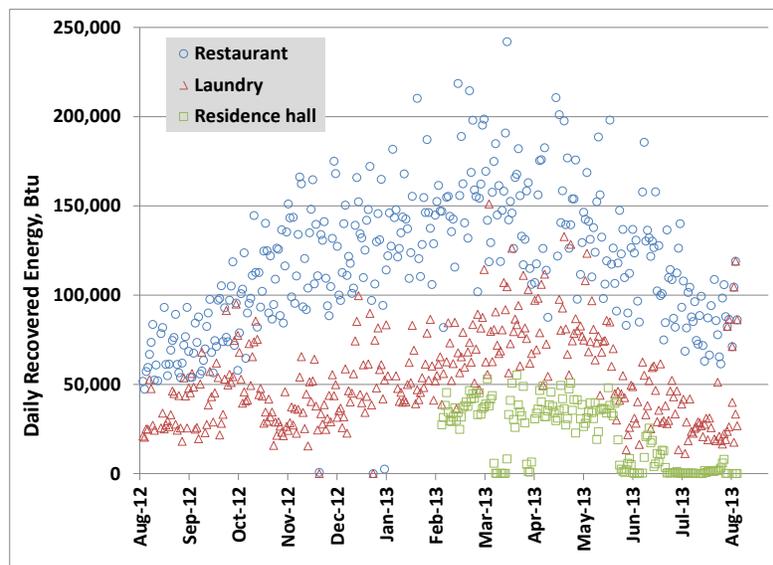

Figure 19 Daily total heat recovery

Figure 20 shows average heat recovery rates by hour of day corresponding to expected patterns of water usage. The restaurant has peaks during the morning, mid-day and evening dining and cleanup periods. The laundry has a less distinct peak around mid-day. The residence hall shows the highest heat recovery during morning hours, likely associated with showering. None of the sites show much activity between 1 AM and 5 AM.
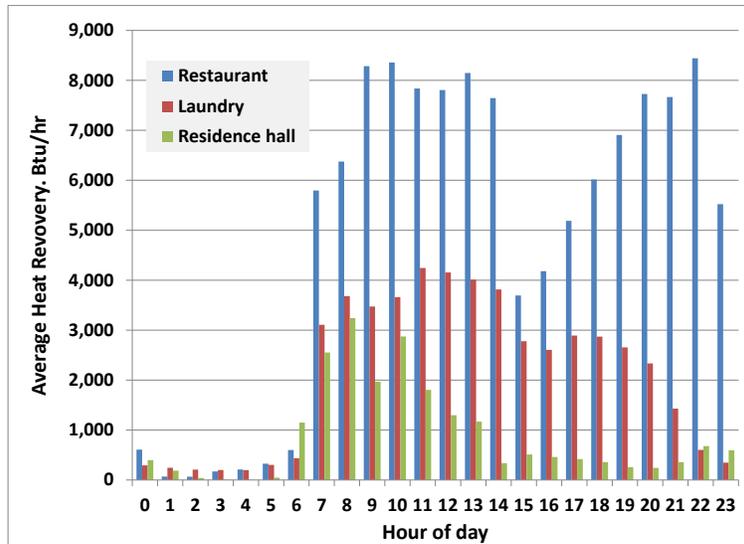
Figure 20 Average heat recovery by hour of day

Average heat recovery by day of week (Figure 21) shows increased weekend activity at the restaurant, with less distinct patterns at the other sites.
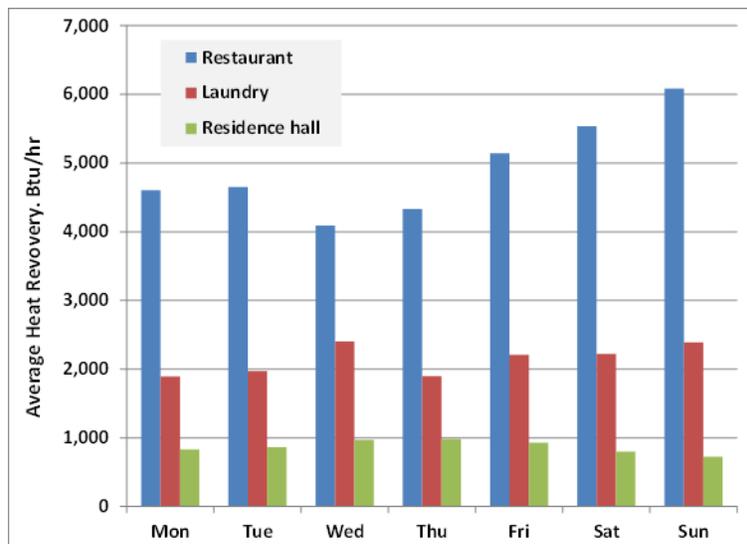

Figure 21 Average heat recovery by day of week

The distribution of heat recovery rates provides some additional insight into the differences between the systems (Figure 22). The values used comprised heat recovery rates during active flow through the heat exchanger, and don't include values of zero heat recovery when there was no flow. Typical heat recovery rates at the restaurant (site 2) are about 24,000 Btu/hr, with peak values well over 100,000 Btu/hr, and a small fraction of negative values.

The systems at sites 3 and 4 both have a typical heat recovery rate of less than 1,000 Btu/hr. This low typical rate is due in part to the lower typical temperature of drain water: the drain system at the laundry carries a mixture of hot, warm and cold water from washing machines, while the student housing drain carries water from showers, toilets, and lavatory sinks. A larger factor, however, may be the "tails" of

operation when the pump, once operation has been initiated, often continues to run for a period of time with very low heat recovery. Heat recovery rates at sites 3 and 4 rarely exceed about 40,000 Btu/hr, as compared to rates that frequently exceed 50,000 Btu/hr at site 2.
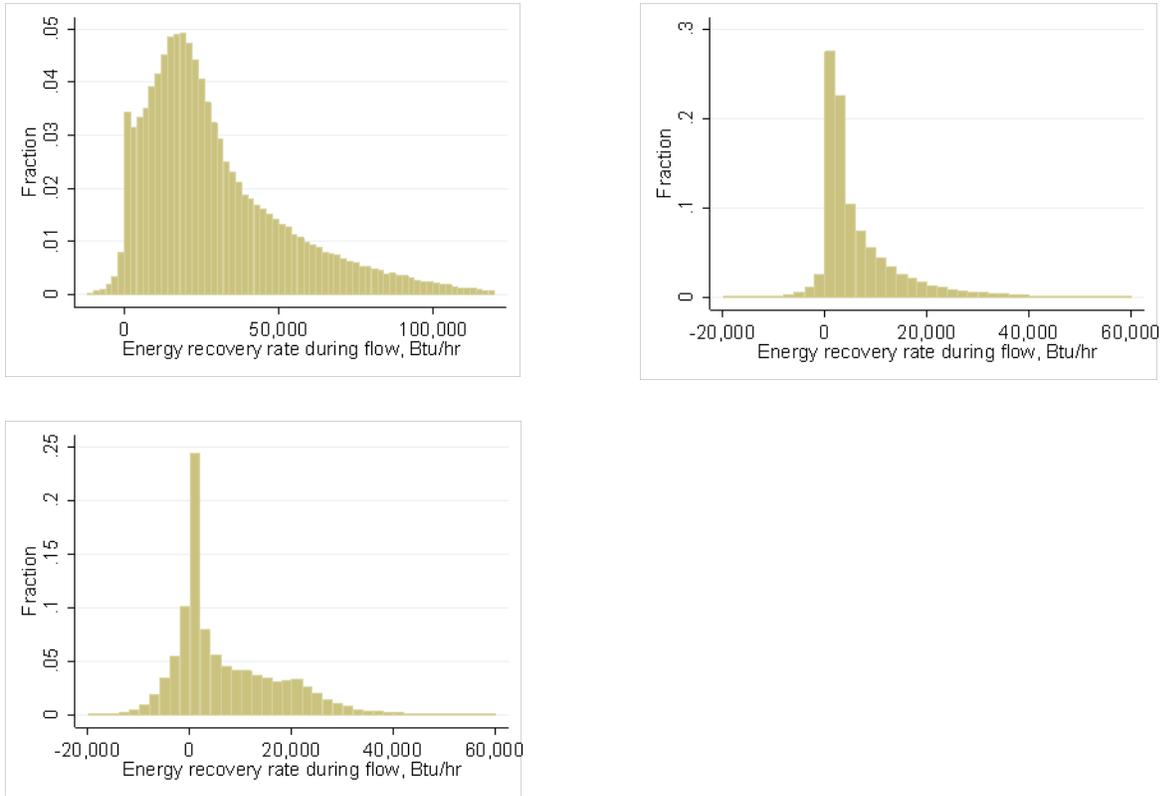

Figure 22 Distribution of heat recovery rate during active flow at sites 2, 3, and 4. Width of bins 2000 Btu/hr.

AMBIENT HEATING

As mentioned earlier, a combination of high ambient air temperatures and long plumbing runs in the restaurant mechanical space resulted in significant heating of the cold water from room air during parts of the monitoring period. We did not monitor cold water temperature entering the building, but assume the daily minimum cold water temperature observed at the heat exchanger is representative of the cold water temperature entering the building for that day. Using the difference between this assumed cold water temperature and the temperature measured when the water enters the heat exchanger, and the flow measured at the heat exchanger, allow estimation of the amount of energy gained from the room air. Daily estimates of this ambient energy gain are compared to recovered energy in Figure 23. The estimated annual energy gain from the ambient air heating at the restaurant is 11.6 million Btu, or about 27 percent as much as is recovered from the drain water.
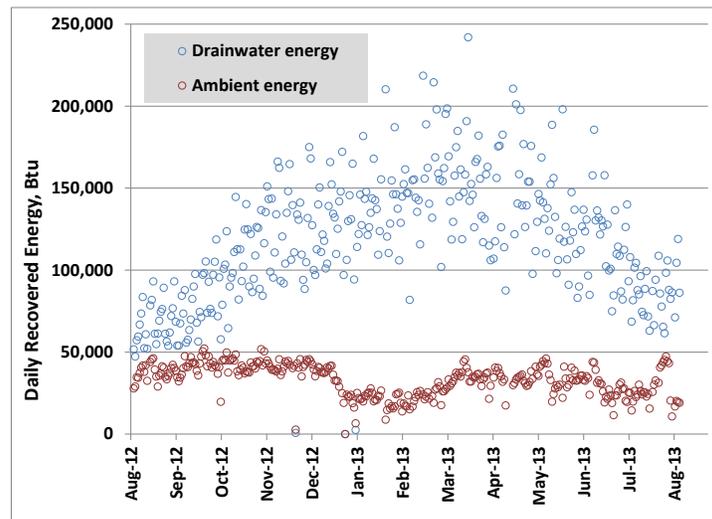

Figure 23 Estimated ambient air heating effect at restaurant

EXPLANATORY FACTORS

We used regression analysis to explore the relationship between system performance and the key factors of cold water temperature and for site 2, heat exchanger flow rate. We tested regressions using data averaged over one-minute and one-hour periods, and settled on one-minute values as providing the most useful results. At the laundry and student housing facility (sites 3 and 4), the temperature lags inherent in the system mean the pump often continues to operate for some minutes after useful energy recovery has ended. These periods of near-zero heat recovery tend to mask the effects being studied, and to reduce this effect, we dropped data for these two sites when the heat recovery rate was between -0.2 and +0.2 Btu/sec (+/- 720 Btu/hr). This has an effect on the results for site 4 in particular, increasing the estimated impact of cold water temperature, and increasing the R^2 (coefficient of determination) value.

This analysis is based on the assumption of an approximately linear relationship between cold water temperature and heat recovery. This assumption seems reasonable for the restaurant, where water flow through the heat exchanger depends entirely on draw patterns, and is independent of cold water and drain temperature. We know that heat exchange at any given flow conditions is approximately proportional to temperature difference across the heat exchanger (this is inherent in the definition of effectiveness).

Assuming flow rates and effectiveness are distributed independently of temperature, then average heat recovery rate should vary up or down in a roughly linear relationship with cold water temperature.

For the sites with pumped loop systems, we don't believe a linear relationship is likely. At these sites, the pump operates and heat exchange is specifically not independent of temperatures, but rather dependent on the differential controller to determine when positive energy is available. At any given cold water temperature, the amount of energy available depends on the distribution of drain water temperature (and flow), and there's no reason to think this availability will change in a linear way with cold water temperature.[19] In any case, our regression results are system-specific, and we don't have a basis for extending the results to other sites or heat exchangers.

The results of these regressions are shown in Table 4. The entries for "Cold water temperature effect" list regression coefficients for total recovered energy each minute against weighted average cold water temperature (temperature weighted in proportion to flow) for the same period. The negative values of the slope of energy recovery per degree increase in cold water temperature make sense; we expect energy recovery to decrease as cold water temperature increases. The modest R^2 values suggest, not surprisingly, that factors in addition to cold water temperature play a significant role in the amount of heat recovered.

The regression slope value for the restaurant appears reasonable, and suggests a change in performance of about 3 percent per degree F change in average cold water temperature. The values for the other sites suggest very large changes in performance with cold water temperature, on the order of 6 percent per degree F for the laundry, and over 35 percent for the student housing facility. Since we question the assumption of linearity between cold water temperature and performance for the pumped loop systems, we don't think the regressions for sites 3 and 4 have much value.

Table 4 Regression results using cold water temperature as an explanatory variable.

	Site 2 Restaurant	Site 3 Laundry	Site 4 Student housing
Cold water temperature effect: Change in recovered energy vs weighted cold water temperature (Btu/min per degree F)	-2.595	-2.042	-5.245
R^2 (coefficient of determination)	0.126	0.049	0.253
Additional expected annual energy recovery with a cold water temperature decrease of 1 degree F (Btu)	1.36 million	1.07 million	2.76 million

Using data for site 2, we also ran regressions of energy recovery against the combined variables of cold water temperature and measured flow rate through the heat exchanger. This yields a slightly different value for the cold water temperature coefficient, -2.26 Btu/min F. The coefficient of heat recovery versus flow rate is 30.2 Btu/min per gpm of flow[20], and the R^2 is 0.32.

PREDICTION OF HEAT RECOVERY

A common challenge in the decision to invest in energy efficiency technology is estimating the available savings in a particular application. This is very true in the case of drain water heat recovery, where there

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[19] Calculation of degree days against a variable base temperature provides an analogy. Changes in base temperature can be expected to yield changes in degree days that remain proportional over a small range in either direction, but larger changes in the base will yield non-proportional and asymmetrical changes in degree days.
[20] We used the average flow only when flow was greater than zero for this regression.

are to our knowledge no recognized procedures for estimating or measuring the amount of recoverable energy flowing through a drain system. One objective of our project was exploration of the use of exterior drain line measurements for prediction of recoverable energy.

To this end, we installed a combination heat flux sensor and temperature sensor on the exterior of the drain line of each system. These sensors were installed on the bottom of a horizontal section of drain line upstream of the heat exchanger, where they would be unaffected by heat transfer at the heat exchanger. They were held in place with a few wraps of electrical tape, allowing heat to pass through the sensors to and from room air. The heat flux sensors have a nominal sensitivity of 3 uV/Btu/hr sq ft. In two cases, they were mounted so a negative output reflects heat flow from the drain pipe to room air; in the third case the sensor was mounted in the reverse orientation.

Viewed graphically, these measurements suggest that exterior drain line measurements correlate at least roughly with recoverable energy. Data for the restaurant shows a general relationship between exterior drain temperature and recovered water temperature (Figure 24). Note that exterior drain line temperatures reach as high as 140°F, consistent with usage temperatures of 150°F to 180°F after electrical heating at the dishwasher.

The spikes in the heat flux sensor output at this site appear to track the rate of change of the drain temperature. We believe this is due to the thermal mass of the heat flux sensor. When the drain temperature changes quickly, the thermal mass and finite conductivity of the sensor itself means the hot side approaches steady state faster than the cold side, adding an output component related to the speed of temperature change. The heat flux sensor also responds more subtly to steady state heat flow as expected, with a negative voltage output with heat flow from the drain line to the room.
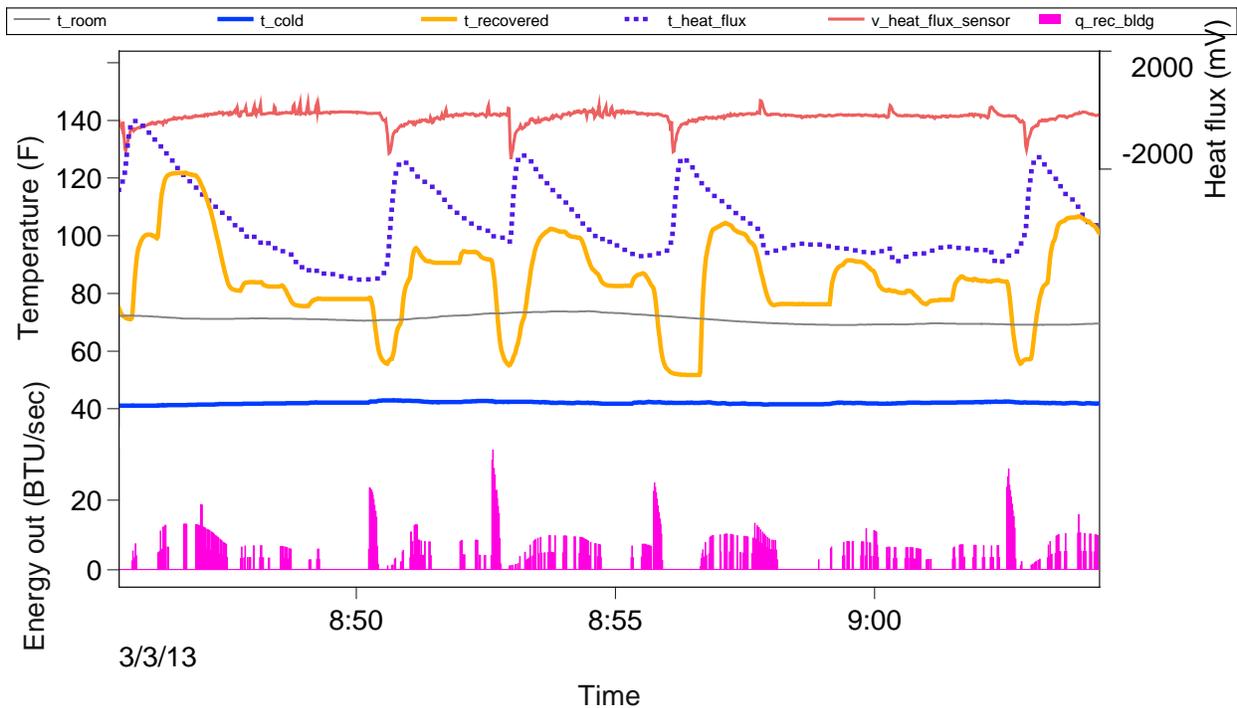

Figure 24 Exterior drain temperature and heat flux at restaurant. t-heat_flux is the tempearture at the heat flux sensor, v_heat_flux is the voltage output proportional to heat flow. 1-second values.

External drain temperatures at the laundry (site 3) include "t_drain1," the sensor attached to the top of the heat exchanger itself, and "t_heat_flux," attached to the bottom of the main PVC drain line approaching the heat exchanger (Figure 25). The t_drain1 sensor appears to track recovery temperature, as intended.
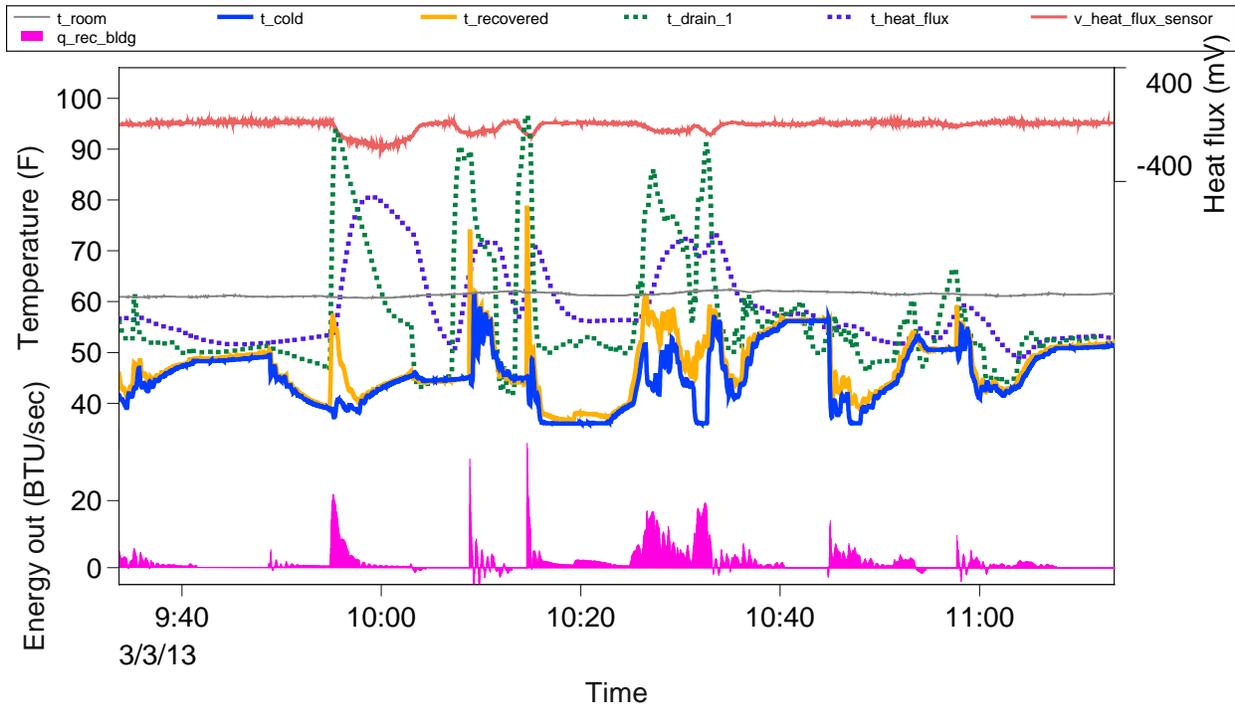

Figure 25 Exterior drain temperature and heat flux at laundry. t-heat_flux is the tempearture at the heat flux sensor, v_heat_flux is the voltage output proportional to heat flow. 1-second values.

Since this temperature is influenced by heat exchanger operation, it doesn't have value as an independent measure for predicting performance.

The t_heat_flux sensor appears to respond more slowly than t_drain1, as expected considering that it's mounted on PVC pipe rather than copper tubing. It also appears to track recovery temperature and energy in a general way, with a time lag.

Output of the heat flux sensor appears to mirror the temperature measured by t_heat_flux. The fact that it appears to follow the trend of temperature rather than a derivative of the trend (as noted for site 2 above) can be explained by the damping effect of the PVC pipe; the slower change in external pipe temperature means the sensor operates more closely to steady state, and the thermal mass of the sensor itself has a smaller effect.

Similar to the laundry, the student housing facility (site 4) includes a sensor at the top of the heat exchanger (t_drain2 in this case). It appears to track recovery temperature, as expected (Figure 26).

The response of t_heat_flux again appears to correlate in a general way with recovery temperature and energy, with a time lag. The voltage output of the heat flux sensor likewise appears to track the general trend in energy recovery, though in this case the sensor was installed in the reverse orientation and its output is positive when the drain temperature is elevated.

We installed an additional external drain line sensor at this site (t_drain1). Like the heat flux sensor, it was installed on the bottom of the horizontal cast iron drain line on the approach to the heat exchanger, but unlike the heat flux sensor, was insulated from the room air. Its response is very similar to that of t_heat_flux.
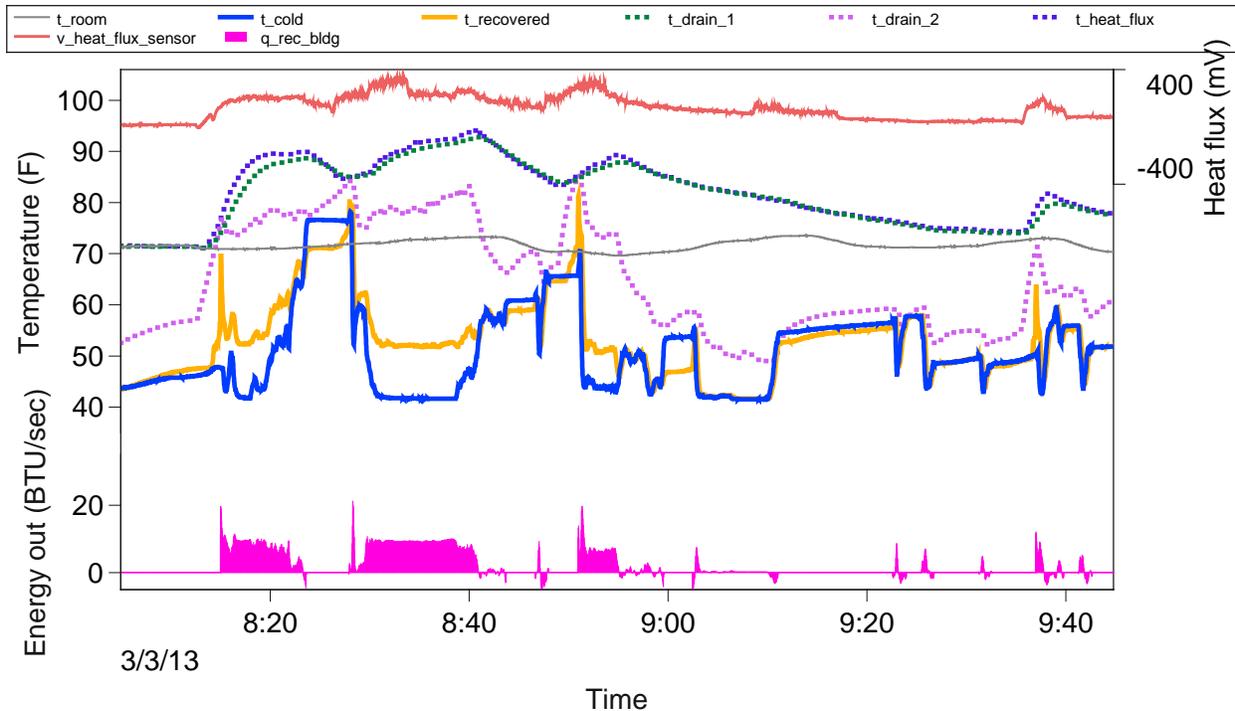

Figure 26 Exterior drain temperature and heat flux at student housing. t-heat_flux is the tempearture at the heat flux sensor, v_heat_flux is the voltage output proportional to heat flow. 1-second values.

Using exterior drain temperatures as a general indicator of drain water temperatures and flow, the difference between the sites is striking: the annual average temperature at the heat flux sensor at the restaurant was 110.7°F, while it was only 71.5°F at the laundry and 76.6°F at the student housing facility. Using room temperature as a base (since drain lines will settle at ambient temperature when there is no flow), the average exterior drain temperature at the restaurant was about 18°F above room temperature, but only about 1°F at the laundry and student housing facility.

We used regression analysis in an attempt to quantify relationships between external drain temperatures (or heat flux) and heat recovery.

We did regressions using values averaged over one minute and over one hour. We tried using some time lags between the drain temperature and recovered energy in regressions based on one-minute values, but didn't find an overall improvement in results. The one-hour regressions were expected to remove most of the effects of time lags between observed drain temperature and heat recovery (which appear to occur over periods of a few minutes), and produce the best results. As mentioned earlier, we dropped data records for sites 3 and 4 with heat recovery rates between -0.2 and +0.2 Btu/sec to reduce the impact of pump run time beyond the point of useful heat recovery. Including cold water temperature and drain temperature together as independent variables improved the results as compared to the use of a single independent variable.

Results of the regressions using drain temperature and cold water temperature together are shown in Table 5. The coefficient of determination (R^2) for these results are far higher than for the prior regression results, suggesting that adding the variable of drain temperature (and by implication, drain water temperature) goes a long way toward explaining the variation in heat recovery over time in the systems studied.

Table 5 Regression results showing relationship of heat recovery to combined effect of external drain temperature and cold water temperature. Regressions performed using 1-hour average values.

	Site 2 Restaurant	Site 3 Laundry	Site 4 Student housing
Drain temperature predictive effect: Change in recovered energy vs average external drain temperature (Btu/hr per degree F)	209.2	372.1	401.6
Cold water temperature effect: Change in recovered energy vs weighted cold water temperature (Btu/hr per degree F)	-147.2	-362.1	-117.8
R^2 (coefficient of determination)	0.819	0.538	0.691
Additional expected annual energy recovery with a 1 degree F increase in exterior measured drain temperature (Btu)	1.83 million	3.26 million	3.52 million

Regressions using the voltage output of the heat flux sensors have high R^2 values for sites 2 and 4, but generally don't appear to offer any advantage over drain temperature measurements as an indicator of energy availability (Table 6).

Table 6 Regression results – relationship of heat recovery to combined effects of heat flux from drain line and cold water temperature. Regressions performed using 1-hour values.

	Site 2 Restaurant	Site 3 Laundry	Site 4 Student housing
Change in recovered energy vs average drain line heat flux output (Btu/hr per volt)	-36,118.0	-21,275.4	39,433.2
Change in recovered energy vs weighted cold water temperature (Btu/hr per degree F)	-7.18	-100.3	-52.3
R^2 (coefficient of determination)	0.820	0.226	0.746

These results are intriguing, especially given the relatively high R^2 values in some cases, and suggest that measured external drain line temperatures together with knowledge of cold water temperatures could form the basis of a method for estimating recoverable energy in specific facilities.

The regression results alone, however, do not constitute a predictive method. At best, the regression slopes might predict the relationship between recoverable energy and average drain temperature over a modest range. More work with a number of similar systems and/or controlled testing might extend this idea into the area of useful predictive methods.

DISCUSSION

COST EFFECTIVENESS

The heat exchangers purchased for this project cost between $1,000 and $1,300 each. The costs we incurred in installation can't be considered typical because of the added cost of installing monitoring equipment. Based on our experience and discussion with plumbers, we believe the typical cost of installation materials and labor for retrofit DWHR systems in commercial facilities could range from under $1,000 in some cases where piping sizes are small and no pump is required, to $1,500 as a typical value. Costs could run much higher, of course, with long runs and large pipe sizes being major factors. Installation costs in new construction should be substantially less than in retrofitting.

Using a total installed cost of $2,500, and the savings as discussed earlier, the systems installed at sites 2, 3, and 4 would produce payback times of about 5.4, 12, and 31 years respectively. Selection of facilities with significant recoverable energy is a major consideration in cost effectiveness.

At the time this project was performed, two pricing trends worked significantly against the cost effectiveness of this technology: high copper prices, and decreasing natural gas costs. The price of copper in 2013 has floated around $3.25 per pound, as compared to typical prices of $1.00 per pound during the period 1989 to 2004.[21] This has a direct impact on the price of heat exchangers and on the cost of installations where copper piping is used. Natural gas, on the other hand, has been on a downward trend since about 2008, with prices comparable to those of 10 years earlier.[22]

The ultimate economic attractiveness of DWHR depends on using it in facilities where it will perform well and can be installed at a reasonable cost. Installations in facilities with high heat recovery potential, in new construction or retrofits where costs can be kept relatively low, could often produce payback times on the order of five years.

SELECTING COMMERCIAL APPLICATIONS FOR DWHR

The best applications for DWHR will combine many of the following characteristics:

- High volume of hot water usage.
- High water temperature as delivered to the drain under consideration.
- Low volume of cold water delivered to the drain under consideration.
- Long periods of continuous supply and drain water flow. Intermittent drain flows that are generally warm or hot, with frequent cold water supply flows, can also provide good performance.
- Low cold water temperatures. Higher cold water temperatures simply mean lower water heating energy use and reduced potential savings from heat recovery.
- An accessible drain line, carrying a substantial volume of warm or hot drain water.

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[21] Historical copper prices can be accessed on the InvestmentMine website.
[22] The price of natural gas can be accessed on the Energy Information Administration website.

- Drain line 2 inches to 4 inches in size, with an accessible unbroken length of at least 4 feet and preferably 6 feet or longer.
- Reasonably close proximity of the drain line to the cold water line supplying the water heating system (40 to 50 feet might be a reasonable limit). No major barriers to running pipe from cold supply to heat exchanger location and back.

Examples of occupancies that may offer good opportunities include:

- Health clubs, gyms, exercise and sports facilities on campuses, and any facilities with banks of showers that see heavy use.
- Restaurants and food service operations with heavy dishwasher use, and with dishwashers and other hot water loads on separate drains from cold water loads.
- Laundry operations (depending on the volume of hot water use).
- Vehicle washing (depending on the volume of hot water use).

New construction applications of drain water heat recovery systems can offer distinct benefits as compared to retrofit installation:

- *Reduced installation costs (and headaches).* The cost of cutting into existing plumbing is eliminated. Issues related to scheduling interruptions in plumbing service are eliminated.
- *Separation of drains.* Warm and hot water loads may be segregated on separate drain lines from cold water. This approach can be used in multi-family residences, where bath and shower fixtures can be attached to drains separate from toilets.
- *Plumbing optimization.* Drain lines and water heating systems may be located to allow shorter pipe runs and more practical installation of heat recovery systems. Heat exchangers may be placed in areas that are difficult to access in retrofits, e.g. within the walls of finished areas of multifamily buildings. Facilities such as health clubs located on upper floors of a building may represent excellent applications for the technology if the heat exchanger can be placed to capture water from shower stalls before it is mixed with drain water from other fixtures.

Finally, there are many other ways to reduce hot water energy consumption in commercial buildings. The following measures should be evaluated in conjunction with consideration of a DWHR installation:

- In indirect water heating systems, insulation of the loop piping between boiler and storage tank.
- In indirect water heating systems, control of the loop pump between boiler and storage tank.
- Efficiency of boiler or water heater
- Recirculation pump control
- Pipe insulation
- Control of thermosiphoning through the use of check valves or piping loops that create local high points

APPENDIX: DRAIN WATER HEAT RECOVERY EQUIPMENT MANUFACTURERS

Following is a list of drain water heat recovery equipment manufacturers identified through web searches in 2012 and 2013. The firms are listed alphabetically. Inclusion of a company in this list does not constitute a recommendation or endorsement on the part of the authors of this report.

EcoDrain
(horizontal applications)
Montreal, Quebec, Canada
Phone: 514.448.4798

RenewABILITY Energy Inc.
Kitchener, Ontario, Canada
Phone: 877.606.5559

ReTherm Energy Systems Inc.
Summerside, PEI, Canada
Phone: 902.436.6529

Swing Green, Inc.
Colorado Springs, CO, USA
Phone: 855.439.7446

Watercycles Energy Recovery Inc.
Edenwold, Saskatchewan, Canada
Phone: 306.531.9478