Multifamily Central Heat Pump Water Heating: Optimization and Energy Savings Persistence

Bonneville Power Administration
Emerging Energy Efficient Technologies Program

Final Report

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Executive Summary

Over the last several years the Bonneville Power Administration has funded research projects on the use of central heat pump water heating systems for mid-rise multifamily buildings. With any new technology questions arise regarding how the systems perform over time; do the systems continue to function, can maintenance personnel be found to manage the equipment, do the initial perceived savings persist over time or do they degrade? This project was a look back at the first pilot projects using Reverse Cycle Chillers (RCC) in below grade parking garages in Seattle mid-rise multifamily buildings and a review of the system design changes that have been incorporated at one of the most recent applications of this technology.

Ecotope conducted long-term performance monitoring of RCC domestic hot water systems and interviews with maintenance staff at two midrise multifamily buildings in Seattle: Stream Uptown and Sunset Electric. We also collected measurement and verification (M&V) data during commissioning at Batik, another midrise multifamily building with an updated RCC hot water system design.

We encountered issues at both Sunset Electric and Stream Uptown with the RCC systems’ performance and maintenance. Both systems had at least one compressor fail in just a few years of operation, an expensive problem that can offset the reduced energy costs of the RCC system over simpler systems. In addition, the systems at times relied largely or entirely on backup electric resistance heat or failed to meet demand for hot water. We attribute these issues to a combination of factors, including high head pressures resulting from suboptimal temperature maintenance strategies, improper maintenance and system reconfigurations by technicians, and a lack of effective defrost controls included in the RCCs themselves. While the system at Stream
Uptown has continued to experience a range of maintenance and operational issues, the system at Sunset Electric has proven to be reliable and high-performing with maintenance by knowledgeable service contractors and minor design changes.

A more recent RCC system design, installed at Batik, incorporated lessons from these earlier designs and has performed much more reliably as the building reaches full occupancy. We credit the improved performance to design and controls changes. Pending continued monitoring of this system, the design fundamentals that culminated in this design should be considered as a basis for a design standard. These design fundamentals include:

- Storage and RCCs should be sized per ASHRAE 2015 “Low water usage” methodology.
- RCCs should be installed in buffered spaces (such as parking garages) to moderate intake air temperature in climates with cold winters.
- Storage and controls should be configured such that main RCCs, when in an active heating cycle, always have ample cold water, which allows for higher COP and lower refrigerant head pressures.
- Manage defrost cycles to prevent frost build-up on coils.
- Treat the recirculation loop with a separate heat pump water heater configured to accept warm incoming water.
- Include monitoring equipment to measure flows, temperatures, and energy use to allow for troubleshooting, optimization, and long-term maintenance and performance tracking.
- Maintenance and operations of these systems must be overseen by a trained maintenance technician with experience with heat pump systems to guarantee long term performance.

With the latest RCC system design, which Ecotope refers to as the “version 3” design, we have the basis for a reliable, efficient solution for multifamily heat pump water heating in cool climates. However, the state of the technology still requires custom-engineered systems, equipment sourced from multiple manufacturers, and technicians with specialized knowledge of RCCs. If RCC technology is to become widespread, it is essential that manufacturers and designers collaborate to create an integrated platform for central heat pump water heating so that customers can trust they are purchasing a well-understood, reliable system. This should come in the form of a pre-packaged system, sold as a unit or series of modules that would include RCCs, storage, resistance backup, piping, controls, and monitoring equipment and be based upon the “version 3” design principles above.

At full maturation RCCs will become more of a “plug and play” technology. Designers should be able to provide input information such as number of apartments, expected peak occupancy, or occupancy type, and a manufacturer could provide a recommended package of components with recommended installation instructions such that much of the need for specialized knowledge and custom design is eliminated (along with much of the risk associated with a new technology). The technology positioned in this way would have the potential to reduce energy use for multifamily water heating by approximately a factor of 3.
1. Introduction

This report presents research funded by the Bonneville Power Administration (BPA) on the use of Reverse Cycle Chillers (RCCs) for domestic water heating in multifamily residential buildings. We will present and discuss results from long-term performance monitoring of RCC systems at two buildings in Seattle, WA as well as from interviews with maintenance staff and building management at these buildings. We will also discuss the commissioning of an RCC system at a third building in Seattle that represents an improved design for RCC hot water systems, drawing from lessons learned in the previous two projects.

1.1. Background

In 2009 Ecotope completed a feasibility study for the BPA Emerging Energy Efficient Technology program. The study examined the use of RCCs to produce domestic hot water for multifamily buildings in the Pacific Northwest. An RCC is essentially a commercial chiller set up to operate in reverse as a heat pump water heater and equipped with a double-walled copper heat exchanger so that it can process potable water directly. The RCCs use R-134a refrigerant whose physical properties limit the operating range to supply air temperatures above ~40F. The RCCs are therefore placed in below-grade parking garages to take advantage of the thermal buffering effects and allow year-round operation in the Pacific Northwest climate.

Following the feasibility study, two multifamily building projects in Seattle were recruited for pilot projects. The first project, Stream Uptown, is a 118-apartment mid-rise multifamily building, completed in 2013, in Seattle’s Uptown neighborhood. The hot water system at Stream Uptown was the first RCC to be designed and built by Ecotope. The second project was Sunset Electric, a 92-unit mixed-use multifamily building in Seattle’s Capitol Hill. This building’s hot water system was designed around the same time as Stream but was installed after, and therefore reflects some lessons learned from the first system. In addition to support for the pre-design work carried out in the feasibility study, BPA provided funding for system commissioning, coordination with the local utility (Seattle City Light) for conservation incentives, and for a Measurement and Verification (M&V) study. With support from BPA, Ecotope has continued to record M&V data throughout the life of both projects in order to investigate the effects of the RCC system design changes implemented at Sunset Electric, and to establish the long-term reliability of these systems.

BPA also granted funding for an M&V study at Batik, a 194-unit mixed-use multifamily building in Seattle’s Yesler Terrace, to optimize and monitor hot water system performance throughout commissioning and assess the impact of the design changes implemented since

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Sunset Electric’s system was installed. Batik’s RCC system can be thought of as “version 3” of Ecotope’s RCC design.

This report presents the findings from Ecotope’s investigation including analysis of long-term M&V data and interviews with maintenance staff at Stream Uptown and Sunset Electric. It also presents the M&V data collected during commissioning at Batik and discusses how this data was used in optimizing system performance.

1.2. RCC Fundamentals

A fundamental takeaway from this report should be that heat pumps are not boilers. RCCs cannot be simply substituted for gas or oil boilers in traditional hot water system designs and expected to perform reliably and save energy. Their successful operation and performance are strongly influenced by the temperatures of the source and load fluids (the garage air and city water).

The key lessons learned in these projects have related to proper management of these simple fundamentals:

- Heat pump water heaters function best with cold incoming water temperatures. If the incoming water temperature is too high, the refrigerant pressures get too high, and the heat pump cannot function. This requires careful design and management of the building hot water circulation system and an effective strategy for stratifying water storage in order to feed cold water to heat pumps while still delivering usable hot water.

- Heat pump water heaters function best with warm incoming air temperature. If the air temperature gets too cold the capacity and performance drop dramatically. This requires the heat pumps to be installed in an area that will stay within their refrigerant’s reasonable operating range throughout the winter.

- Heat pumps must be able to manage frost build-up on the air coils. When the source air is cool and moist, ice will develop on the coils and impede airflow and heat transfer. If the ice is not removed effectively, the heat pump cannot function properly and may sustain damage if it continues to run. Effective frost management requires controls to sense or predict when ice is forming and manage the heat pump cycles and defrost times.

- Hot water recirculation systems will typically use a very large amount of energy in multifamily buildings with central hot water systems (about a third of the total thermal energy). Depending on how recirculation systems are designed they can disrupt temperature stratification in the storage and feed hot water back to the heat pumps. The temperature maintenance system design is critical to overall hot water energy use.

1.3. RCC Design Development

The designs for Stream’s and Sunset Electric’s RCC systems were developed by Ecotope in conjunction with Colmac Industries, the RCC manufacturer, based on Colmac’s experience in the field. However, their equipment had previously mainly been deployed in hot, humid climates. Even with the thermal buffering added by locating the systems below grade, Seattle’s relatively cold winter climate led to operational issues that required different design considerations. This
mostly has to do with the performance degradation and derating needed due to defrost cycles at lower temperatures. When frost is present on the coils due to low temperature operation the equipment must be run in fan-only mode to melt the frost. While this is happening, the equipment expends energy without producing any hot water so available capacity and effective COP is reduced. The graphics below show the general performance of the equipment without taking into account further deratings associated with the defrost cycles.

Figure 2: RCC Manufacturer’s Performance Curves

The performance graphics above are for entering water temperatures of 70F. As can be seen, the capacity and efficiency drop off significantly at higher outgoing water temperatures and at lower entering air temperatures. The performance curves are not shown much below 50F entering air temperature because the defrost cycles begin to dominate more at these low temperatures.

The first pilot projects were sized using the pre-2015 ASHRAE sizing methodology which was developed assuming higher standard flow plumbing fixtures. Water use in typical new multifamily buildings has been dramatically reduced with low flow plumbing fixtures and efficient appliances. Measurement and Verification (M&V) data from the pilots revealed that the more conservative older sizing methodology resulted in heat pumps with at least twice the necessary output capacity.

These RCC systems used two parallel RCCs, each with a separate bank of storage tanks. The equipment was configured as a “single pass” system with constant capacity compressor output and variable water flow through the RCC. This means that the water leaving the RCC is always at or near the target temperature of 130F and delivered to the top of the stratified water storage tanks so that hot water is always available to the building without reheating. This strategy is in contrast to a “multi-pass” system where water flow rate through the heat pump is constant and is raised typically 8-12F on each pass. A multi-pass system will always rely on a gas or electric back-up or “finishing” tank that can bring the water up to usable temperature during or after high use events. The graphics below demonstrate the differences between the two approaches.
Figure 3: Multi-Pass vs. Single-Pass Heat Pump Control and Piping Strategy
Temperature maintenance on the recirculation loop or “ring main” presented an issue. Initially, the system at Stream was designed to have temperature maintenance in the recirculation loop provided by electric resistance. However, after initial monitoring it was discovered that the heat loss in the recirculation loop accounted for 1/3 of the heat demand of the entire system. The recirculation loop was then piped to return water to the storage tanks to be heated by the more efficient RCCs, rather than the electric resistance tank. This change, however, resulted in the RCCs taking in relatively hot water from the recirculation loop and caused issues with high head pressure as the RCC’s had been “critically charged” with refrigerant to optimize performance with cold incoming water. Refrigerant charge was reduced, and operations stabilized.

Sunset Electric’s RCC system was installed after Stream’s system, which allowed Ecotope to implement minor changes to piping and storage tank configuration to reduce reliance on resistance heating of the ring main and avoid high head pressures at the RCCs. The controls were altered to force longer heat pump cycles and use the RCCs in a “lead-lag” pattern. The “lead” RCC would operate as normal, engaging whenever hot water was needed. The “lag” RCC, however, would only engage when demand exceeded what the “lead” RCC could produce. Each week, the RCCs would switch roles in order to equalize wear on the equipment. In this design, temperature maintenance is handled entirely by the RCCs and the electric resistance tanks are in position as emergency back-up only.

The system at Batik, referred to by Ecotope as “version 3”, represented a more significant change in design. In this design, there is a separate RCC specifically for handling recirculation loop temperature maintenance. This RCC was configured as a multi-pass device in order to handle hotter incoming water without tripping out on high head pressure, allowing the main RCCs to process only relatively cold water at higher efficiencies. A storage tank with back-up electric elements serves as the final storage location for the water before it is supplied to the building through a mixing valve. That storage tank receives water, already at set point temperature from both the main RCCs and the RCC reheating the circulation loop water. Finally, a single bank of storage tanks (as opposed to parallel banks) now serve both of the main RCCs, which can be operated from a single point of control. The RCCs were configured to operate in tandem, which produces more hot water at once and allows more time, and reduced cycling losses and more temperature stratification in the storage tanks, between each cycle.
2. Methods

2.1. Long-term M&V Analysis

At both Stream Uptown and Sunset Electric, the M&V equipment that had been installed during commissioning remained in place and collected data continuously up to the present. There are significant differences in what parts of the system were monitored at each site, reflecting differences in the RCC system design as well as lessons learned from Stream Uptown about what was most important to monitor.

In early 2018, we compiled the data that had been collected since commissioning and reviewed all performance statistics over the life of the systems, flagging events where the systems were malfunctioning or where some measure had changed abruptly.

While there were adjustments made at both sites during the commissioning and start-up period, Stream Uptown’s RCC system underwent major changes in response to poor performance. These changes altered how certain measurements should be interpreted during different phases of the project. For example, the system was re-piped such that temperature maintenance in the recirculation loop was handled by the RCCs rather than an electric resistance tank. Therefore, the metering of the electric resistance tank no longer represented temperature maintenance, but instead represented backup resistance heating only. While this complicates interpretation of our results somewhat, it also lets us investigate different design alternatives.

The full M&V at these sites was described in detail in Ecotope’s 2015 RCC Pilot Project Report.

2.2. Coefficient of Performance

A central goal in this analysis is to estimate the real-world performance of RCC equipment. However, we also recognize that RCC equipment is often combined with other equipment to form the entire water heating system. In this report we have therefore defined two different Coefficient of Performance (COP) metrics:

- The “Equipment COP” evaluates the performance of a single piece of water heating equipment. Equipment COP is defined as the heat energy added to the water divided by the electrical energy input to the piece of equipment. As an annual average number this will take into account the cycling losses, the defrost cycles, and the variation in performance through the entire range of incoming water and air temperatures seen over the course of the average year.

- “System COP” recognizes that many RCCs will be installed along with a back-up system of some kind or a “finishing tank” or separate system to maintain temperature in the distribution system. The design of those other energy using systems will impact the overall efficiency of a water heating system using RCCs. The System COP is defined as the sum of heat added to the water system (including heat added to bring the incoming city water up to temperature and heat added to make-up the storage and distribution losses) divided by the total energy used by the system.
2.3. Follow-up Interviews

After reviewing M&V data, we reached out to the maintenance staff involved with the RCC systems at Sunset Electric and Stream Uptown. The interviews were intended to be open-format and free-flowing. However, we prepared a list of basic questions and the events we flagged during the M&V analysis. The main goals for each interview were to provide context for the events we saw in M&V data, to understand the challenges and cost involved in maintaining the systems, and to collect ideas on what resources would allow maintenance staff to work with RCC systems more effectively. Interviews lasted between 30 minutes and an hour each.

Sunset Electric and Stream Uptown are both operated by the same property management company. HVAC maintenance was handled by a single maintenance contractor throughout the life of the system at Sunset Electric. Stream Uptown was also contracted to that company in Fall 2017. We were able to speak with a technician and service manager at this maintenance contracting company, to a building maintenance technician at Sunset Electric, and the regional service manager at the property management company.

2.4. Commissioning M&V at Batik

Batik’s RCC system represented a significant revision in design and therefore required measurement at different points than either of the previous projects. Like both of the previous projects, however, it was built around an Obvius Acquisuite 8812 data logging platform. It incorporated flow and temperature measurements at strategic points as well as electricity usage for each RCC and electric resistance water heater.

M&V data was used to assess and fine tune the control and operation of the RCC system during commissioning. We set up an online tool\(^3\) to view raw data and hourly and daily averages for each of the monitored points on the RCC system, as well as calculated values like COP and heat output. This data was automatically updated every night, allowing the engineers and installers commissioning the project to quickly receive feedback on changes they made to the system.

The M&V at Batik is described in detail in Appendix B.

\(^3\) Available at http://www.ecotope.shinyapps.io/RCCViewer
3. Results

3.1. Monitoring and Verification

We present here the results of our M&V review for Stream Uptown and Sunset Electric. In reviewing the data, we plotted a subset of the M&V data over time (see Appendix A), and investigated additional measurements as needed to describe the events and develop hypotheses about their causes. We also asked maintenance staff about some of these events during the interview portion of the study. Where relevant, their explanations are also included here.

3.1.1. Stream Uptown Performance

Review of the Stream Uptown data and interviews with the property manager have revealed that the RCC system at Stream has had operational problems throughout its existence. At the end of the first pilot project, in 2014, when the system was re-piped and refrigerant charge reduced to allow the RCCs to handle higher incoming water temperatures for temperature maintenance, operations were stable and efficient with an Equipment COP of 2.4, but it did not last. A number of piping and controls changes have been made over the years that have not improved operations. In particular, the maintenance contractor at Stream Uptown re-piped the system, without input from designers, to again use an electric resistance storage water heater for temperature maintenance. Over the last several years, there have been long periods of purely electric resistance water heating with both RCCs not functioning, and there have been intermittent periods where the building runs out of hot water, indicating the controls are not adequately managing the back-up electric resistance heat. At least one of the compressors is currently broken and needing replacement. We cannot calculate the COP of the equipment directly because changes in the system’s configuration since the M&V was designed prevent us from separating primary water heating from temperature maintenance.

Currently, a service firm more experienced in refrigeration and heat pump technology is taking over the maintenance contract (the same firm and service technician providing service at Sunset Electric). Hopefully the lessons learned can be implemented at Stream Uptown to significantly improve operations. Our observations at this site points to the fact that the design and operation of these systems must be done properly and managed by experienced technicians if we are to expect dependable operations.

3.1.2. Sunset Electric Performance

The M&V data from Sunset Electric indicate discrete events and system operational characteristics that indicate issues with the RCC system there. Below is a synthesis of our findings both from analyzing the M&V data from Sunset Electric and from our discussions with maintenance staff. We were able to confirm and get explanations for all the events we found in the M&V analysis.
### Table 1: Sunset Electric Events

<table>
<thead>
<tr>
<th>Event</th>
<th>Year</th>
<th>Month</th>
<th>M&amp;V Observation</th>
<th>Event Cause</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>2015</td>
<td>Nov.</td>
<td>System does not operate for over a day after a power outage causing large runout.</td>
<td>Neighborhood-wide power outage</td>
<td>Reset equipment (turned main power switch off and on again)</td>
</tr>
<tr>
<td>S2</td>
<td>2016</td>
<td>March</td>
<td>RCC1 was producing increasingly hotter outlet water over the course of months.</td>
<td>Compressor failure</td>
<td>Replaced compressor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>2016</td>
<td>June – Nov.</td>
<td>System delivering overheated water to circulation loop (up to 140F) whenever RCC2 is running.</td>
<td>Failed mixing valve</td>
<td>Replaced mixing valve</td>
</tr>
<tr>
<td>S4</td>
<td>2017</td>
<td>Jan.</td>
<td>RCC1 again producing hotter and hotter water, then returns to normal.</td>
<td>High refrigerant pressure</td>
<td>Removed refrigerant</td>
</tr>
<tr>
<td>S5</td>
<td>2017</td>
<td>Jan. – April</td>
<td>Frequent runouts</td>
<td>Software update in controls causing overly-aggressive defrost cycle</td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>2017</td>
<td>April</td>
<td>System stabilizes</td>
<td>Experienced technician balanced flow through storage tanks and adjusted setpoints and control points for RCCs.</td>
<td></td>
</tr>
</tbody>
</table>

A number of the events warrant more explanation as they help to reveal themes about the system design and operation:

**Event S1.** In November 2015, we saw the system shut off completely (using no power) following a windstorm and brief power outage. We saw in the M&V data that the stored hot water was drawn for several hours until there was no more available, at which point the mechanical contractor was apparently called. They informed us during our interview that they manually reset the system and it came back online.

**Event S2.** In early 2016, Ecotope serendipitously observed a compressor failing over the course of several months, identifiable by the increasingly hot outlet water temperatures at the outlet of RCC1. When we found this, we were between projects and had no regular plan to examine the data. Interestingly, this is the opposite of what we saw at Stream Uptown where outlet temperatures fell as the compressor failed. In this case, Ecotope notified building management, and the maintenance contractor identified the cause of the issue as a failing compressor. It should be noted that this was detected by chance. If Ecotope had not looked in on the M&V data, it is likely the problem would not have been noticed until complete compressor failure.
Event S3. Another interesting observation from the M&V at Sunset Electric was the regular pattern of overheated water delivered to tenants between June and November 2016. A close examination of the data revealed that the overheated water was being delivered whenever RCC2 was running. The maintenance contractor later informed us that it was a case of a faulty mixing valve. The system had thrown an alarm when the issue started, but the building maintenance apparently ignored it and it was detected during a schedule visit by the maintenance contractor.

Event S6. A major finding from the M&V at Sunset Electric is the marked improvement in performance in Spring of 2017. This was the result of major control system changes by the new maintenance contractor and appears to have been a complete success in terms of reliability. As of May 2018, the system has been running for over a year with no operational changes, minimal electric resistance usage, and no runouts detectable by M&V. Interviews with both the maintenance contractor and property management indicated that they are very satisfied with the system’s performance over this period.

The last three events discussed here combined with the events at Stream Uptown point to the need for more training, familiarity, and experience with the equipment by both building staff and service technicians. In the case of the faulty mixing valve, the on-site maintenance staff elected to ignore the alarm. It wasn’t until a service visit by an experienced technician that the issue was remedied. Likewise, the marked improvement in performance at Event S06 points to the critical role to be played by an experienced service technician. Since this is still an emerging industry there are fewer of these people and that is a key factor holding the market back from rapidly expanding the use of this technology.

An important metric of performance is the overall average equipment COP. After full occupancy, we see an average equipment COP for the RCCs of 2.3. However, looking only at the data after April 2017, when the last major changes were made to the system, we see an equipment COP of 2.4. This accounts for the operation of the RCCs both for heating incoming water and for reheating the recirculation loop.

Although COP should change with incoming air and water temperature, we can remove the effects of temperature to some approximation by regressing COP on outdoor temperature and examining the residual (or the deviation from the expected COP given temperature). In Figure 4, two major changes in COP are clearly visible. The first shows a degradation in COP followed by a sudden increase corresponding to the compressor failure and replacement (subsequently identified as Event S02). The second (subsequently identified as event S06) shows a very inconsistent COP followed by a change to a stable COP that was higher than was seen before. This corresponds to a problematic control software update in January 2017 followed by the reconfiguration done by the maintenance contractor in April 2017.
3.1.3. Batik Commissioning

As of the writing of this report, Batik is not yet fully occupied. However, our M&V data proved valuable right away, as Ecotope was able to detect an incorrect piping arrangement remotely, and later used the data in deciding to change the setpoint on the trim tank in order to minimize electric resistance heating. Though the building is only beginning to reach full capacity at the time of the writing of this report, our M&V data suggests that the main RCCs are operating with a COP around 3.

On another occasion, the commissioning team viewed the M&V data in the online tool and found that the recirculation loop RCC had turned off. The commissioning team contacted the plumbing contractor of this issue and found that the RCC’s diagnostic program had not sent an alarm as intended. The M&V system therefore alerted Ecotope to two issues: overly sensitive overvoltage detection that had shut off the RCC automatically and an improperly configured alarm.

Ecotope was also able to detect less obvious issues using the M&V data. Figure 5: Batik Recirc RCC COP Trend is a screenshot from the online tool showing that the recirc RCC’s COP was slowly falling over time. This loss in performance will not necessarily lead to equipment failure or system alarms, and so it might have evaded notice without detailed system measurement.
These incidents highlight the importance of M&V equipment on new technology installations. M&V allows for early diagnosis of problems potentially before expensive equipment replacement is needed. Analysis of M&V data leads to learning that can be used to improve system performance or make changes in future designs.

See Figure 6 in Appendix A: for a timeline of M&V data during startup.

3.2. Follow-up Interviews

3.2.1. HVAC Maintenance Contractor

We spoke with a Renton, WA based service contractor specializing in mechanical, plumbing, and control systems. The firm made available both a field service technician and a service manager by phone. As the main service contractor for Sunset Electric, they were able to provide explanations for many of the M&V events discussed above. However, they had only recently begun working at Stream Uptown and therefore could not speak to many of the M&V events we recorded there. They did provide us information about the current state of the system at Stream.

The contractor did credit their success in working with RCC systems to their service tech’s extensive hydronics and HVAC experience, and noted that the typical maintenance technician for a domestic hot water system would not be expected to have this background. They suggested that better training for installers and maintenance staff is needed, either by the RCC manufacturers or system designers.

An important takeaway from this discussion was how the contractor was able to bring Sunset Electric’s hot water system into stable, efficient performance. As outlined above, this was
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achieved by lowering the refrigerant charge (below the manufacturer recommended charge), changing the system controls, and balancing flow between the two RCCs. Based upon their experience with these systems, the contractor believes that the recommended refrigerant charge in Colmac systems is too high for the mild Pacific Northwest climate. Additionally, they made the change to controls after realizing that both RCCs were on an overly aggressive defrost cycle.

3.2.2. Sunset Electric Building Engineer

The maintenance staff person at Sunset Electric was not directly responsible for servicing the RCC system but was often responsible for recognizing issues with the system and calling in a maintenance contractor. The person we spoke with had only been in the position since Fall of 2016, and therefore was not present during system startup. It appears that the system was alarming frequently from the time the building maintenance person had started, and so these alarms were not taken as seriously as they might have been. Building maintenance sometimes did not call the plumbing maintenance contractor even when refrigerant leaks or system alarms were evident, only when the problems resulted in tenant complaints. Often, they would simply reset the system (essentially cycling power off and on) rather than calling in the maintenance contractor, likely because of concerns about cost.

Given that building maintenance is responsible for a wide variety of building systems and that even plumbing and HVAC specialists are often unfamiliar with RCC systems, it should be expected that building maintenance people would not know much about RCCs. The staff person said that it would have been helpful to have a less technical description of the system.

3.2.3. Property Management Regional Service Manager

The property management company was able to provide feedback from the perspective of dealing with cost and tenant complaints about hot water issues. We spoke to the regional service manager, who handles both Sunset Electric and Stream Uptown. Since we had already spoken to the maintenance contractor and building maintenance about Sunset Electric, we focused this interview mainly on Stream Uptown.

Interesting takeaways from this interview include the high cost of maintenance at Stream Uptown: the service manager provided service records that showed they had spent more than $30,000 on maintenance in the past two years, not including an anticipated upcoming compressor replacement and re-piping. They also noted that water heating energy costs are billed back to tenants, so building owners and management actually do not benefit directly from the system’s increased efficiency while still being responsible for repair costs. They did acknowledge that, insofar as the RCC system led to LEED or other “green” certifications, the technology did help them market their building to potential tenants.

In general, the service manager was frustrated with the high upkeep costs and difficulty finding service technicians who could reliably fix problems. They had a different maintenance contractor provide service at this building until Fall 2017 and suspected that they had modified the system to the point where it was no longer operating as designed. However, they seemed to trust the maintenance contractor we had spoken to, who took over in Fall 2017, and expected that they would be able to get the system operating correctly, albeit at significant additional cost. They felt
that, while they understood the importance of developing new technology, they were bearing the burden of maintaining a complex and unfamiliar system without receiving adequate support or benefiting directly from the system’s increased efficiency.

The property management company also manages another Seattle building with an RCC system called Stack House. This RCC system was also designed by Ecotope and is similar to Sunset Electric in design. Though there was not M&V at Stack House, the service manager indicated that they had not had significant performance issues at that building. The Stack House RCC system, however, had also required a compressor replacement.
4. Discussion

Our results demonstrate that RCCs are a promising strategy for significantly reducing the energy usage of hot water systems in multifamily buildings in cool climates. We observed that, with knowledgeable staff and careful attention to design, the systems can perform reliably and efficiently. However, our results also suggest that at this stage in their development, RCC systems are not yet a turnkey solution to hot water heating and can be unreliable and expensive to maintain unless designed by engineers with experience in such systems and maintained by knowledgeable service contractors. Our results also suggest that an effective defrost strategy, possibly beyond the capabilities of existing commercially available RCCs, is essential for reliable operation of these systems.

4.1. Technician Training

The last year of stable, efficient performance at Sunset Electric suggests that, with experienced technicians maintaining a well-designed system, RCCs can perform quite well. We observed a high Equipment COP of 2.4 from the M&V data, and both the service contractor and building management were happy with the system’s performance and reliability. One should probably not conclude that design differences at Sunset Electric are the sole reason for its success. While it was designed and installed incorporating lessons learned from Stream Uptown, the designs are very similar, and in fact Sunset Electric did experience similar issues to Stream after initial commissioning. Instead, the improved performance at this building demonstrates that knowledgeable service contractors are essential for the smooth operation of these systems. The service contractor at Sunset Electric had experience in refrigeration and was able to apply this expertise in diagnosing issues such as overcharged refrigerant levels, as well as make helpful controls changes.

We saw an entirely different situation at Stream Uptown. Frequent use of the backup electric resistance heater dramatically lowered the COP of the system, especially in the winter months. The system was unreliable and often unable to meet peak loads, even with backup resistance. As the backup resistance tank was sized to be completely redundant, and as the building actually uses less hot water than was predicted, this implicates changes made to the system by the maintenance contractor. Building management told us that their maintenance contractor had recommended and carried out re-piping the system without input from system designers after RCCs stopped operating in early 2017, likely due to a failed compressor. We see in the M&V data that the changes they made placed a constant load on the electric resistance tank (likely temperature maintenance for the recirculation loop as with the initial design), but we cannot tell remotely how the system is configured. building management’s plan is to bring in the same experienced contractor that serves Sunset Electric and restore the system to its designed configuration.

Certainly, the varying approaches and experience of maintenance at the two buildings made a large difference. As discussed previously, Stack House Apartments, which has an RCC system with a similar design to Sunset Electric and is serviced by the same maintenance contractor as Sunset Electric, is also performing well according to the property management. This all lends support to the idea that maintenance contractors must understand the unique challenges of RCC
systems in order to keep them running properly. Experience with traditional hot water heaters is not sufficient. In order for this technology to become more widely adopted, technicians will need to be trained in the specifics of heat pump water heating technology. We recommend developing training and documentation for use by technicians and building management in order to increase understanding of these systems.

4.2. Defrost Controls

The RCC systems at both Sunset Electric and Stream Uptown, in addition to the previously mentioned Stack House Apartments and another Ecotope project, Augusta, all had compressors fail in fewer than 5 years of operation. Compressor replacement is expensive and, in this study, we saw failing compressors lead to poor system operation for months before they were replaced. Compounding the issue, the manufacturer of the heat pumps in this study offers only a one-year warranty on compressors, meaning that a new building may not even be fully occupied by the time the warranty has expired.

The unreliability of compressors in RCCs is likely due to defrost control issues. These products have previously been used in warm climates where frost buildup was not a concern. In cooler regions like the Pacific Northwest, however, ambient air is often humid and only a few degrees above freezing. In these conditions, it is easy for ice to build up on the cold evaporator coils, effectively insulating them and preventing heat transfer. This leads to high refrigerant pressure, an issue that occurred repeatedly at both sites.

The RCCs used in these buildings do not have the capability to detect ice on their evaporator coils, so engineers and technicians are limited to simple timer- and temperature-based control strategies. For example, in ambient temperatures under 55°F, the system may run for a maximum of 90 minutes and then blow air over its coils for 30 minutes before resuming operation. However, there is no way to detect whether defrosting was finished after 5 minutes or if ice buildup remained after the 30-minute cycle. Determining the parameters for this defrost strategy essentially requires an educated guess, and this situation incentivizes using an extremely conservative strategy since it is much more expensive to burn out compressors than to turn off the heat pump intermittently, even if doing so requires the system to use backup resistance heat. Regardless, some of the time, this simple control strategy will not allow enough defrost time and will cause high head pressures and damage the compressors.

Considering the performance impact and expense of compressor failure, this issue will need to be addressed if RCCs are to become widely adopted in cool climates. It is essential that manufacturers implement frost detection and effective frost control strategies in order to protect compressors.

4.3. Integrated Systems

At present, RCC systems must be custom engineered for every application, as there is no pre-configured kit, or even established, off-the-shelf designs available. If these systems are to be widely adopted, there will need to be some standard approach developed so that developers can trust they are purchasing a well-understood, reliable system without going through the process of developing their own designs through trial-and-error. This could come in the form of a pre-
packaged system, sold as a unit or series of modules that would include RCCs, storage, resistance backup, and piping. This model has been successful in the single-family residential market, where integrated heat pump water heaters and split systems can be installed by contractors without engineering support.

Integrated systems should be tested in laboratory conditions to ensure and quantify their performance under a variety of conditions, similar to the current testing standards for residential heat pumps.

4.4. Establishment of Standards

BPA has supported research that has led to an improved, more reliable RCC hot water system design that can serve as a repeatable basis for future designs. Other firms have also been developing their own designs for RCC systems. Some of those designs may prove valuable in developing a standardized approach, whereas some are not likely to produce good results, such as those locating RCC equipment outdoors with no temperature buffering or defrost controls. If RCC systems are to become widespread and actually deliver improved energy efficiency, it will be important to develop standards that draw on designs that are proven to work and discourage those that will not perform as expected. These standards will be essential for developing building codes and policies that promote efficient, reliable RCC systems.

With the latest generation of RCC systems, manufacturers, engineers, and other stakeholders now have the opportunity to compare mature designs and to develop a series of standards for use in a variety of multifamily residential and commercial applications.

Some of the key design principles that emerged out of Ecotope’s progression to “version 3” of the RCC design are as follows:

- **Sizing** – Storage and RCCs should be sized per ASHRAE 2015 “Low water usage” methodology.
- **Source air temperature** – In cool climates, RCCs must be installed in buffered space and discharge cold air to outside in order to maintain appropriate source air temperatures.
- **Source water temperature** – Storage and controls must be configured to allow a large volume of cold water to be stored before turning on heat pumps. Doing so allows for a longer cycle length without having too-hot water enter the heat pump, which could result in low efficiency and possible high head pressure.
- **Manage defrost cycles to prevent frost build-up on coils** – An effective strategy to defrost condenser coils is essential to the reliability of RCC systems. Ideally, manufacturers would make frost detection available on their RCC products.
- **Treat recirculation loop with separate heat pump water heater** – Temperature maintenance is a significant part of the system’s energy usage, and so using electric resistance will result in a major decrease in efficiency. However, a large volume of warm water returning to the RCCs from the recirculation loop also results in lower
performance. An effective strategy has been to use a separate RCC, which can be configured to accept higher incoming water temperatures, for temperature maintenance.
5. Conclusions

Our results demonstrate that RCCs are a promising strategy for significantly reducing the energy usage of hot water systems in multifamily buildings in cool climates. We observed that, with knowledgeable staff and careful attention to design, the systems can perform reliably and efficiently. However, our results also suggest that at this stage in their development, RCC systems are not yet a turnkey solution to hot water heating and can be unreliable and expensive without the attention of experienced professionals at each stage of design, installation, commissioning, and maintenance.

Monitoring each system was vital in commissioning each system and diagnosing performance issues, and it provided us valuable insight into how the systems are maintained after commissioning. From our M&V data and the interviews we conducted, we identified three main opportunities to make this technology ready for widespread use.

First, we saw that effective maintenance by knowledgeable contractors was a crucial factor in these systems performing efficiently and reliably. RCC water heaters are an emerging technology that is very different from traditional water heating equipment, so there are not yet many technicians experienced in working with them. When RCCs are not maintained properly, their efficiency advantages can be greatly diminished, and they can even become damaged. In particular, improper configuration and adjustment can result in the RCC’s compressor failing, an expensive problem that, if it happens frequently enough, will entirely offset the cost savings gained from increased energy efficiency. We recommend developing training for maintenance technicians focused on heat pump technology, to be developed in conjunction with designers and technicians.

Second, we believe there is opportunity to improve the reliability of commercially available RCCs. We saw at least one compressor failure at both sites we investigated, and incidentally learned of two other RCC systems that had compressors fail. Both the M&V data and previous experience suggest that effective condenser defrosting is essential in protecting compressors from burnout. Yet the current generation of RCCs do not offer any frost detection features. Instead, engineers and technicians have implemented timer based defrost cycles based on a best guess about how long it will take to defrost the coil. This method is suboptimal because it will almost always either spend more time than necessary in defrost mode (continuing to defrost after the coil is dry) or end defrost mode prematurely (since there is no way to detect whether ice buildup remains). Implementing frost detection would be a relatively simple improvement to commercially available RCCs that would have a large impact on reliability. As Ecotope found that using a separate RCC for temperature maintenance was desirable, it would further improve compressor reliability to provide equipment configured specifically for the hotter incoming water temperatures encountered by the recirculation loop RCC.

Finally, RCC hot water system development is still at a stage where each system must be custom-engineered. The availability of integrated systems would greatly reduce the barrier to implementing these systems more broadly. We see that the latest generation of RCC hot water system, installed at Batik, has improved operation over the previous designs. Pending continued
monitoring of this system, the design fundamentals that culminated in this design should be considered as a basis for future integrated systems. These design fundamentals include:

- Storage and RCCs should be sized per ASHRAE 2015 “Low water usage” methodology.
- RCCs should be installed in buffered spaces (such as parking garages) to moderate intake air temperature in climates with cold winters.
- Storage and controls should be configured such that main RCCs, when in an active heating cycle, always have ample cold water, which allows for higher COP and lower refrigerant head pressures.
- Manage defrost cycles to prevent frost build-up on coils.
- Treat the recirculation loop with a separate heat pump water heater configured to accept warm incoming water.
- Include monitoring equipment to measure flows, temperatures, and energy use to allow for troubleshooting, optimization, and long-term maintenance and performance tracking.
- Maintenance and operations of these systems must be overseen by a trained maintenance technician with experience with heat pump systems to guarantee long term performance.

These integrated systems should be subject to standardized performance testing procedures, similar to single family residential water heaters, so that developers and policy makers can be confident that the systems will reliably produce energy savings.

If these issues are addressed, RCCs would become a very attractive option for developers. Widespread adoption of this technology in cool climates would have a major impact on overall energy use for water heating in multifamily buildings.
Appendix A: Figure 6: Batik Selected Measurements Timeline (Startup)
Appendix B: Batik M&V Design

Figure 7: Simplified Energy Balance of Batik Water Heating System
Figure 8 presents a simplified energy balance diagram of the Batik hot water system with flow and temperature measurement points labeled. The thermal energy flow of the incoming city mains water is represented by $\dot{Q}_{CW}$. The thermal energy flow of the incoming/outgoing garage exhaust air are represented by $\dot{Q}_{GA1}$ and $\dot{Q}_{GA2}$, respectively. The thermal energy flow of the outgoing and recirculated hot water is represented by $\dot{Q}_{hot1}$ and $\dot{Q}_{hot2}$, respectively, referenced at the points where the energy leaves/enters the system.

Of course, the heat pumps themselves add heat to the system ($\dot{Q}_{motor}$) as well as the electric water heaters ($\dot{Q}_{WH}$). Assuming the electric water heaters run minimally, and the heat pumps operate with a COP of 3, this implies that approximately one third of the thermal energy added to the water comes from the input electricity of the RCCs, and the other two thirds come from heat stored in the garage air.\(^4\)

Outside energy enters the system principally via three sources: (1) the energy used to power both the motors that drive the compressors and the electric resistance elements, (2) the “cold” city mains inlet water, and (3) the exhausted garage air. The general energy balance of the system is described by the following equation:

$$\dot{Q}_{hot1} = \Delta \dot{Q}_{GA} + \dot{Q}_{motors} + \dot{Q}_{CW} + \dot{Q}_{hot2} + \dot{Q}_{WH}$$

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<td>RCC-1 Current Transformer</td>
<td>Dent 50A/100A Small Split-Core CT</td>
<td>1&quot; Opening</td>
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</table>

\(^4\) The majority of the heat generated by the action of the compressor ($Q_{motor}$) ends up as heat in the refrigeration fluid. However, some fraction of that energy not shown in the simplified diagram is lost as heat from the compressor case to the surrounding air. Similarly, the simplified diagram neglects the heat lost from the insulated storage tanks and incidental piping to the surroundings.
<table>
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Figure 8: Measurement Points for Batik RCC System
Appendix C: Usage Patterns

There was a significant difference in the hot water usage at the two pilot buildings. Stream Uptown averaged 20 gallons per day per unit, while Sunset Electric averaged only 16 gallons per unit per day. These are both rather small demands—consider that with a low-flow, 1.5 GPM showerhead, those usages could be accounted for by just 13 and 11 minutes of daily showering at Stream Uptown and Sunset Electric, respectively. These are smaller units in vibrant urban neighborhoods, and they are largely occupied by single tenants who spend relatively little time at home. Both buildings have an average of about 1.2 occupants per apartment. Consequently, we might expect that the hot water systems at both buildings are effectively oversized for the unexpectedly low demand.

Despite relatively low hot water usage, we are able to see interesting patterns in the data. Figure 9 shows hourly average demand in GPM by the hour of the day, by building, and by weekend or weekday. Individual days are shown in light gray. Colored lines indicate percentile of all data, with green (50%) being the median. On weekdays, we see the expected draw pattern with a morning “shower spike”, a low demand during the day, and moderate demand in the evening. On weekends, when tenants might sleep in and remain in their unit throughout the day, we see a later morning spike in demand, followed by a more even demand throughout the day.

**Figure 9: Water Demand (GPM) by Hour of Day**

![Water Demand Graph](image)
Appendix D: Ambient Conditions

The RCC systems draw heat from garage air in order to provide thermal buffering from the outdoor air which is sometimes too cold to supply the heat pumps. By comparing the daily average garage temperatures to NOAA weather data (see Figure 10), we can see that at both pilot sites the daily average garage temperature was almost always warmer than the outdoor temperature. We see this effect attenuate at higher ambient temperatures as should be expected since the building above would not be using space heating and therefore not leaking heat into the garage. This attenuation was less pronounced at Sunset Electric, where the garage temperatures benefit from the year-round waste heat from a large refrigeration system in the restaurant located in the building’s first floor.

At Stream Uptown, we do see a cluster of data in Figure 10 near the 1:1 line, indicating that garage and ambient temperatures were nearly equal. We know that in June – September of 2017, the garage door was mostly left open due to a mechanical issue, which likely accounts for the higher temperature cluster along the 1:1 line. The lower temperature observations at near the 1:1 line are from early in 2018 and may result from a similar situation.

Figure 10: Daily Average Outdoor Temperatures vs. Garage Temperature