Gas Absorption Heat Pump Performance Analysis

EXECUTIVE SUMMARY

Gas-driven absorption heat pumps (GHPs) can achieve a heating efficiency that is beyond 100% where traditional gas-driven heating equipment, like boilers, cannot. This means that they have potential to reduce energy consumption, operating costs, and carbon emissions in buildings. This white paper summarizes data monitoring results from a pilot in a Toronto multi-unit residential building where a Vicot GHP was used to supplement an existing boiler to provide domestic hot water (DHW) for the building. The GHP was interfaced with the existing DHW circuit via a heat exchanger in a system design that sought simple integration rather than fully optimized performance.

The Sustainable Technologies Evaluation Program (STEP) of the Toronto and Region Conservation Authority (TRCA) was contracted by The Atmospheric Fund to analyze the performance of the GHP based on monitoring data collected by a third party from January to June 2023. STEP determined that the GHP provided approximately one third of the heating for DHW during the monitoring period, with the boiler providing the remaining two thirds. There was a decreasing trend for the GHP from the beginning to the end of the monitoring period. The GHP started off providing approximately 55% of the heating load at the beginning of the monitoring period but this reduced to 30% by the end. The data was not sufficient to determine the main cause of this trend.

The total GHP efficiency for the monitoring period was calculated to be 113%, but it ranged daily from more than 140% to as low as 80%. The total system efficiency including both boiler and GHP was calculated at 90%, but daily it varied from 80% to 110%. The key factors negatively impacting efficiency were high return temperatures to the GHP and short on-cycle times. These factors were more important than the outdoor temperature for the GHP efficiency and were related to the hydronic design of the system.

The heat exchanger may have acted as pinch-point for heat energy, with the glycol loop heating up faster than it could reject heat to the DHW circuit. This may have been exacerbated by the heat exchanger having been installed in a parallel flow configuration, which has poorer heat transfer than the standard cross flow configuration. Furthermore, cold city water was mixed with continuously circulating warm recirc water from the building before having a single pass through the heat exchanger

of the GHP loop. This likely reduced heat transfer from the GHP loop and caused higher glycol temperatures.

Hydronic design and controls that fosters longer on-cycle times, cooler glycol return temperatures, and greater overall GHP utilization may result in better overall performance than was achieved in this installation. However, this could result in increased installations costs. A hydronic design that sought optimized performance for the GHP might consider a preheat tank. The system as it is currently designed may benefit from improved recirc control, reconnection of the heat exchanged in cross-flow configuration, and control parameter changes like an increase in the on/off deadband to promote longer on-cycle times.

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1 INTRODUCTION

1.1 Overview

Gas-driven absorption heat pumps (GHPs) can achieve a heating efficiency that is beyond 100% where traditional gas-driven heating equipment, like boilers, cannot. This means that they have potential to reduce energy consumption, operating costs, and carbon emissions in buildings.
This white paper summarizes data monitoring results from a pilot in a Toronto multi-unit residential building (MURB) where a GHP from the manufacturer Vicot was used to supplement an existing boiler to provide domestic hot water (DHW) for the building.

1.2 System Design

The GHP absorbed heat energy from cold outdoor air and heated a glycol antifreeze loop. The glycol loop was interfaced with the existing DHW circuit via a heat exchanger (HX) in a system design that sought simple integration rather than fully optimized performance. The HX was installed in series with the boiler, and upstream of it. Water from the DHW tanks was constantly circulating through both the HX and the boiler before being supplied back to the tanks. Upstream of the HX was the supply of cold city water and the return of warm recirc water from the building. When the water entering the HX decreased below 45°C, the GHP turned on to provide heating. This would occur when cold city water entered the loop due to hot water draws from the building. The GHP was then effectively preheating the city water but it only allowed one pass across the HX before the city water was fully mixed into the DHW tanks.

1.3 Monitoring and Analysis

The Sustainable Technologies Evaluation Program (STEP) of the Toronto and Region Conservation Authority (TRCA), was contracted by The Atmospheric Fund to analyze the performance of the GHP based on monitoring data collected by a third party from January to June 2023. The key monitored parameters are included (i) the boiler and GHP gas consumption, (ii) the flow of water through the boiler and GHP on the water side of the system, and (iii) the entering and leaving temperatures of water through the boiler, as well as on both sides of the HX. Efficiency, capacity, and other parameters were calculated from these data points.

2 GHP EFFICIENCY

STEP calculated that the total efficiency of the heat pump for the monitoring period was 113%, but there was substantial seasonal variation. Figure 1 shows aggregated daily efficiency of the GHP through the monitoring period. Efficiency reaches beyond 140% on some days, and as low as 80% on others. There is also a clear seasonal trend with the lowest efficiencies being obtained in the spring. The seasonal trend is not related to the outdoor temperature since the opposite would have been expected; i.e. a higher efficiency in spring than in winter. The outdoor temperature dependence of the GHP efficiency is plotted in Figure 2. It is not a clear increasing trend as the outdoor temperature increases, as might be expected. This is because the GHP efficiency is more strongly impacted by other parameters, specifically its cycling behaviour, discussed shortly.

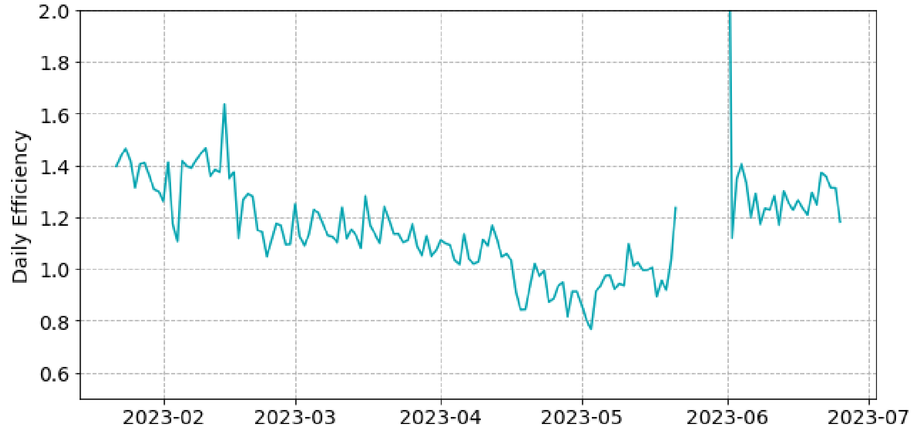

Figure 1. On a daily basis, the efficiency of the GHP exceeded 140% and dropped to as low as 80%. There are also gradually changing seasonal trends with efficiency decreasing from winter to spring and then increasing again moving into the summer.

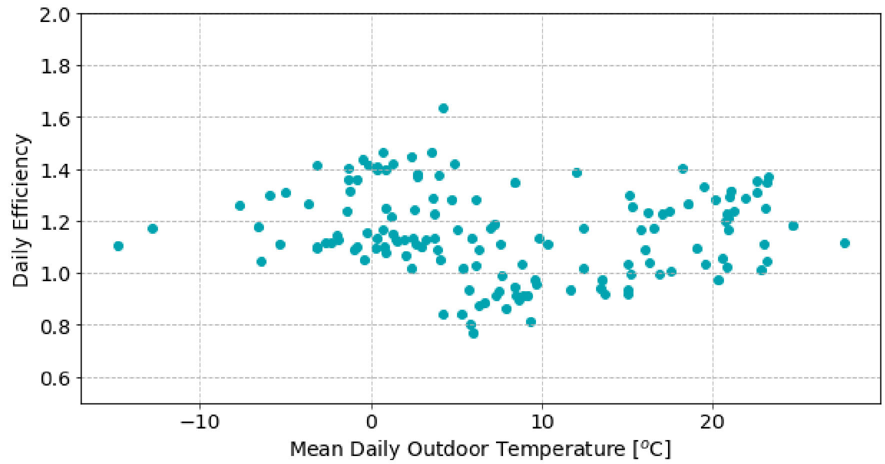

Figure 2. There is not a clear trend showing the impact of outdoor temperatures on GHP performance. This is because other factors (like the return glycol temperature to the GHP, and the GHP cycling) are more impactful on performance.

3 FRACTION OF DHW HEATING FROM THE GHP

Based on the calculated heat delivered by the GHP and boiler, STEP determined that the GHP delivered approximately one third of the total heating provided to the DHW, with the boiler providing the remaining two thirds. This is illustrated in Figure 3.

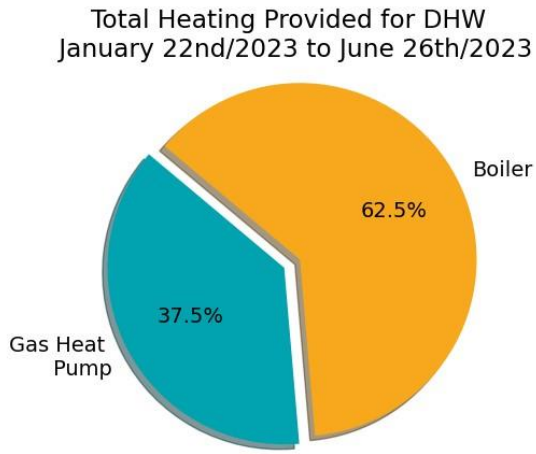

Figure 3. The GHP provided approximately one third of the DHW heating and the boiler provided the remaining two thirds.

The daily fraction of heating from the GHP is shown in Figure 4. Initially, it averaged near 55% of the total DHW from the GHP but then decreased to near 30% at the end of the monitoring. In addition to the steady decrease, there was also a stepwise drop in February. The stepwise drop was directly proceeded by what appears to be an event with the boiler and GHP, where both were taken offline for the majority of February 14th, 2023. This shows up as the downwards spike in Figure 4.

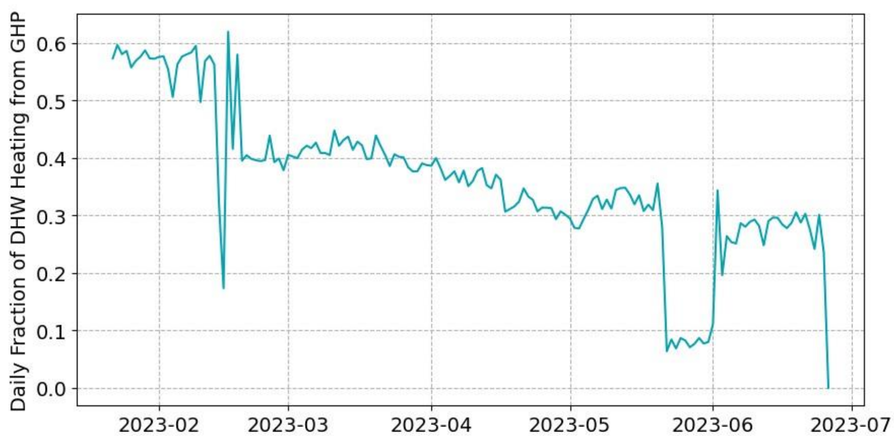

Figure 4. There is a gradual decrease in GHP utilization and a stepwise decrease that occurred on February 14th, 2023.

The stepwise drop also corresponds directly to an increase in the mean return water temperature entering the heat exchanger (and also to a sharp decrease in the amount of time the return temperature is below 45ºC). This is shown in Figure 5 and Figure 6. The instantaneous gas input to the boiler also had a corresponding stepwise increase (Figure 7). Previously it tended to settle near 60 kW, but afterwards, near 140 kW. Given the sharpness of the transitions seen across each of these parameters, and also the fact that it corresponds with an event with the boiler and GHP, it appears that something changed regarding the boiler or controls that then precipitated the stepwise change in the heat pump utilization. However, the specific change was not identified.

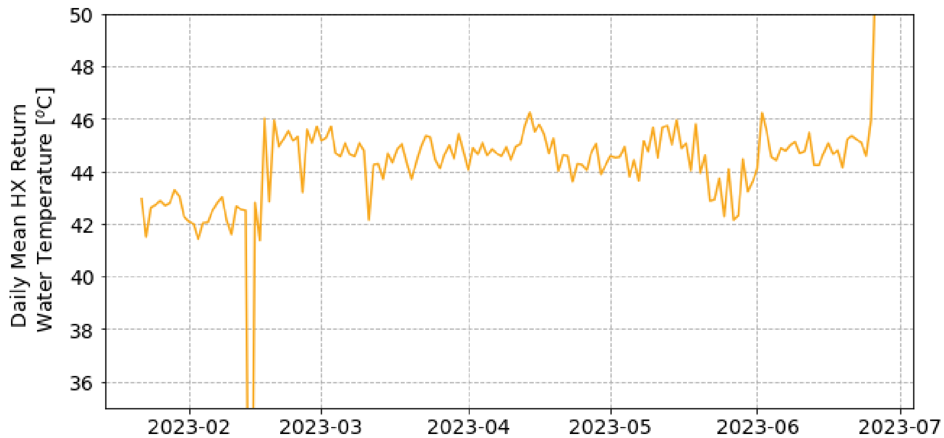

Figure 5. The mean water temperature entering the heat exchanger had a stepwise jump on the same day that the GHP utilization had a stepwise drop.

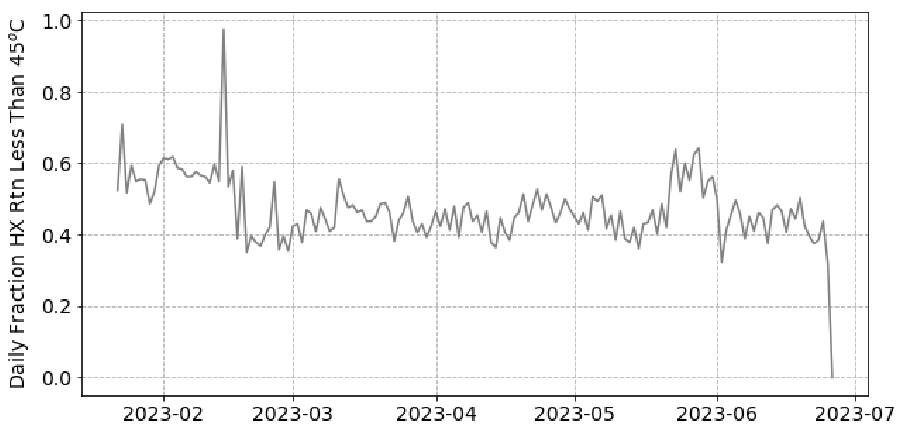

Figure 6. The fraction of time that the water temperature entering the GHP spends below 45°C (triggering the GHP on) sharply decreased on the same day the GHP utilization had a stepwise drop.

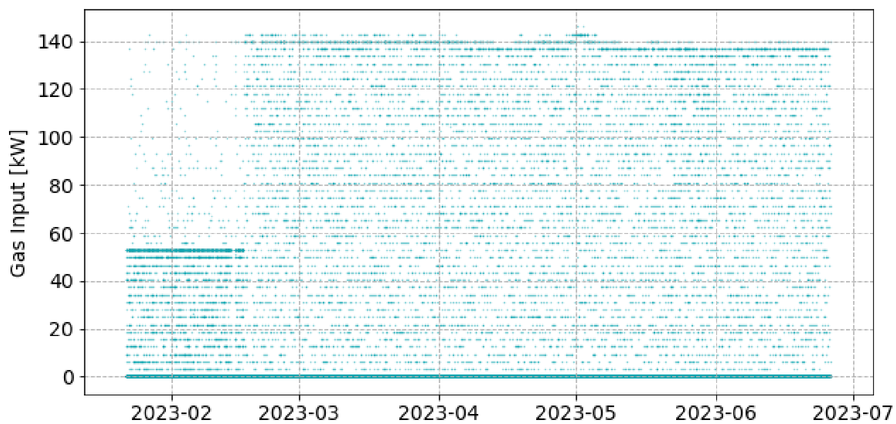

Figure 7. The boiler was on at maximum capacity more frequently after the stepwise change in GHP utilization. Previously it tended to settle on a value less than 60 kW and seldom reached above 140 kW. STEP did not verify why it had previously been settling below 60 kW.

The gradual decrease in the heat pump utilization initially appears correlated with the decreasing GHP efficiency seen in Figure 1, and this makes physical sense. If the heat pump efficiency decreases, then it would be expected to produce a lesser share of the heating. However, the efficiency begins to recover moving into the summer while the GHP utilization did not. It continued a gradual decrease. The only correlation identified in the data with that trend was with the overall heating energy delivered for DHW. This is shown in Figure 8.

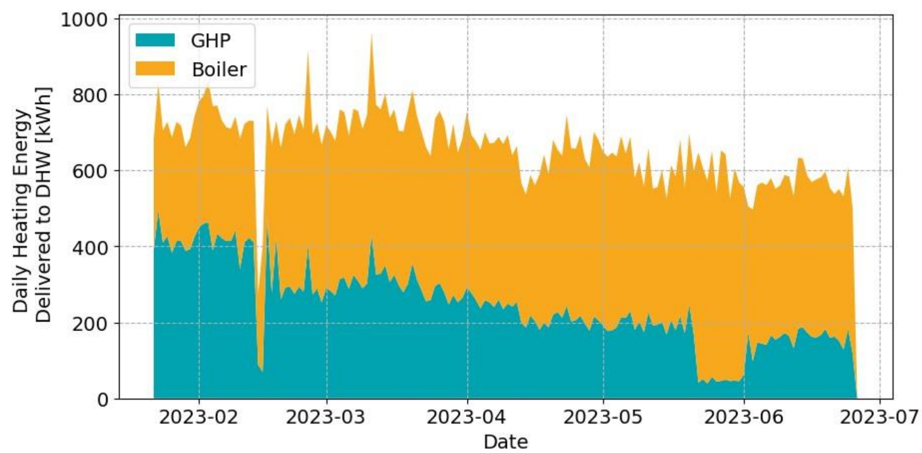

Figure 8. The overall DHW load slowly decreased from the beginning to the end of the monitoring period, and along with it, so did the fraction of heating provided by the GHP.

The DHW slowly decreased (on average) moving from the beginning to the end of the monitoring period, and as it decreased, the heat pump utilization decreased as well. STEP was not able to identify a causal relationship behind this correlation. More data, a full year, would be helpful in further diagnosing this issue. In summary, the major factors that appear to be reducing the heat pump utilization were:

1) the control set-points of the boiler/system (there was no confirmation on what changed, but something clearly did change in February);
2) the decreasing efficiency of the heat pump; and
3) the decreasing DHW load of the building.

4 EFFICIENCY OF THE FULL DHW SYSTEM

The total full system efficiency for the monitoring period was calculated at 90%. The daily aggregated efficiency is plotted in Figure 9. It ranges from 80% to 110%.

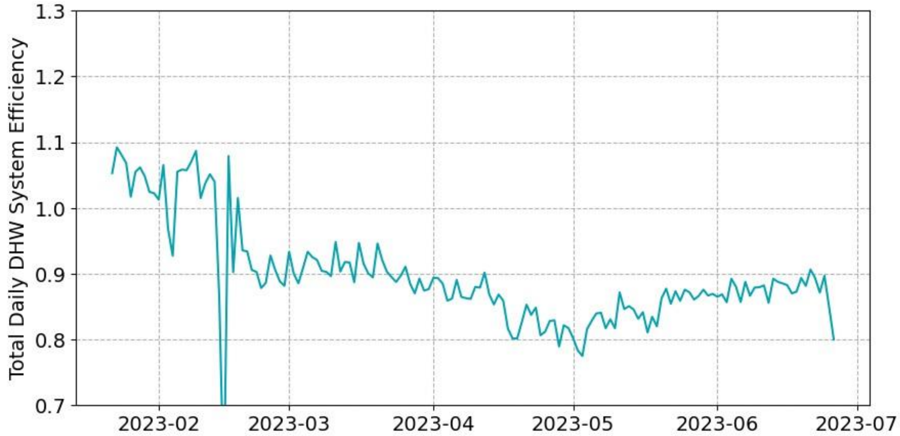

Figure 9. Daily efficiency of the full system (GHP + boiler) varies from 80% to 110%.

5 CONTROL STRATEGY

The GHP was intended to provide heating whenever the water temperature entering the building side of the heat exchanger was below 45^{o}C. STEP did not confirm if there was a deadband or hysteresis for this value. STEP directly evaluated how frequently the heat pump was on for different building-side HX return temperatures. This is shown in Figure 10. Below a temperature return temperature of 40^{o}C, the heat pump is on (i.e. consuming some level of gas) approximately 80% of the time. Above 50^{o}C, it is on 20% of the time, or less.

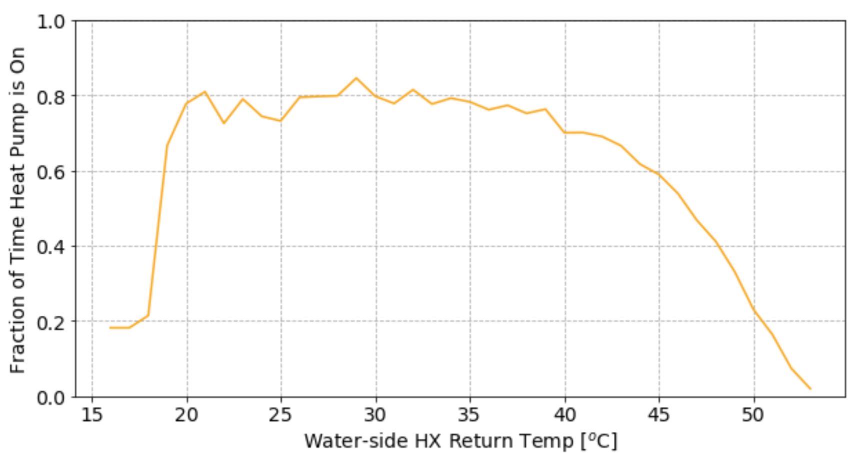

Figure 10. When the water temperature entering the heat exchanger is below 40^{o}C, the GHP is typically on near 80% of the time. When it is above 50^{o}C it is on 20% of the time or less, and above 52^{o}C it is off entirely.

While there was not a sharp transition at 45^{o}C, the heat pump *did* appear to generally be on when it is expected to be on. The analysis continued to determine why it was not on close to 100% of the time (rather than 80% of the time) when the building-side HX return temperatures were cool. For approximately a third of the data points where the GHP was “incorrectly” off (when it was expected to have been on) it was for a duration longer than 5 minutes. Conversely, $2/3^{rds}$ of the time the GHP was “incorrectly” off are short 5-minute “blips” that are likely not indicative of an issue. Time series plots of the longer duration off-intervals are shown in Figure 11 – including a period lasting several hours, approximately a day, and also several days. No explanation was obtained for these occurrences.

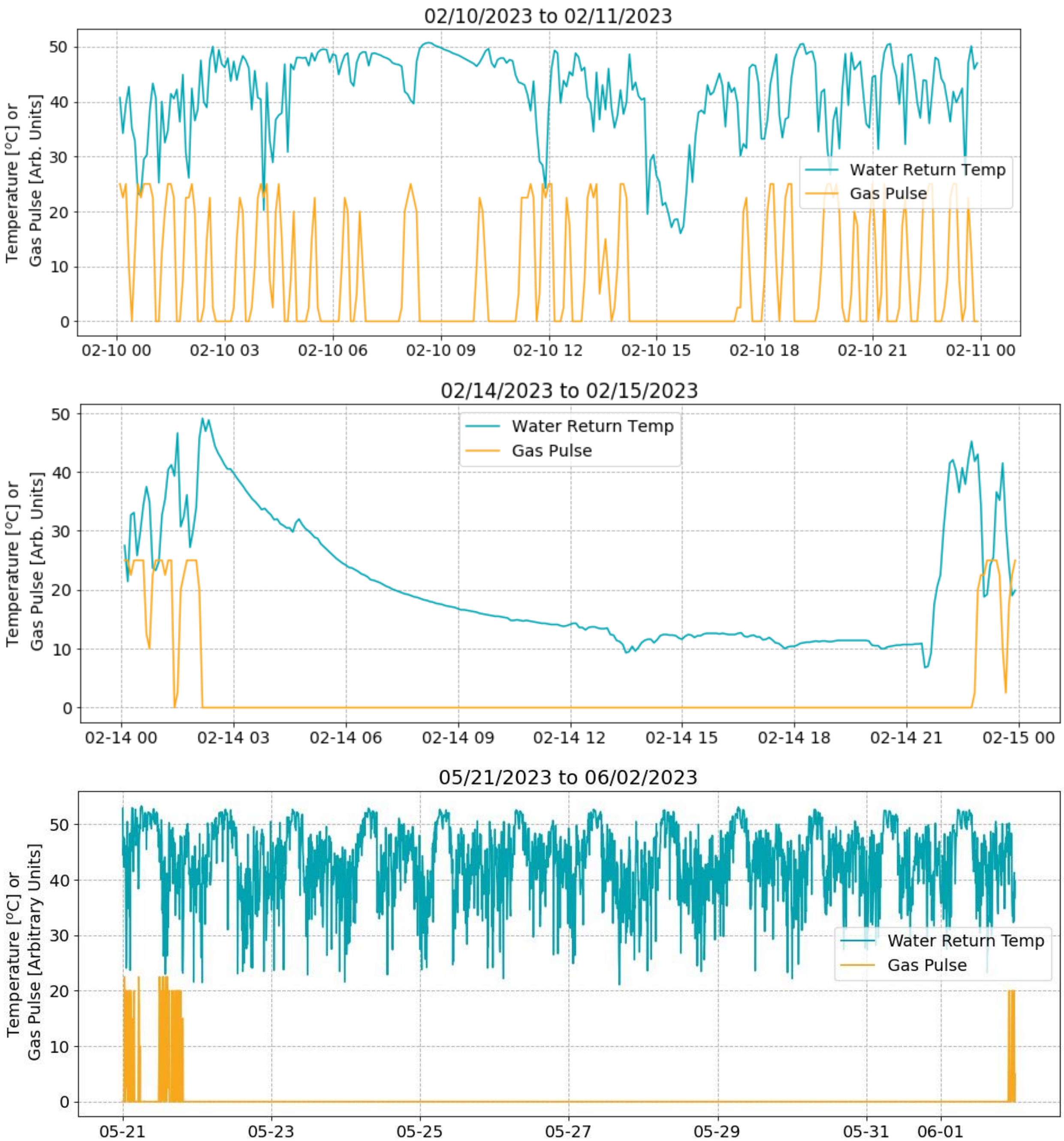

Figure 11. Time series data from different days were evaluated to determine why the GHP was not on for 100% of the time whenever it was expected to be on (rather than 80%). The top plot shows a window of time starting at 15:00 and lasting a few hours, where it looks like both the boiler and GHP were offline (i.e. the tanks dropped below 20°C). The middle plot shows, that both GHP and boiler were offline for the majority of February 14th. The bottom plot shows that from May 21st to June 1st, only the GHP was off and the boiler was still on.

Overall, the GHP operated largely according to the intended controls strategy and generally was on or off according to expectations. However, for a small fraction of the data, the GHP is off for longer durations when it was expected to be on. This reduced the utilization of the GHP by a small amount.

6 KEY FACTORS IMPACTING EFFICIENCY

6.1 Cycle Time

The most important factor impacting efficiency was the time the GHP stayed on once it turned on, referred to in this document as the fully on cycle time. "Fully on" here means a gas consumption at 80% of the rated input, or greater. The daily average fully on cycle time is shown in Figure 12. The heat pump tended to stay fully on for nearly 15 minutes per cycle in the winter months and has trended towards 5 minutes in the spring and then again above 10 minutes in the summer. Short operating cycles are known to negatively impact heat pump performance. When a heat pump turns on, it takes time to reach the maximal steady-state efficiency and capacity. Overall efficiency is diminished when it is not able to reach a steady-state efficiency (or only achieves it for a short period of time) due to short on cycles.

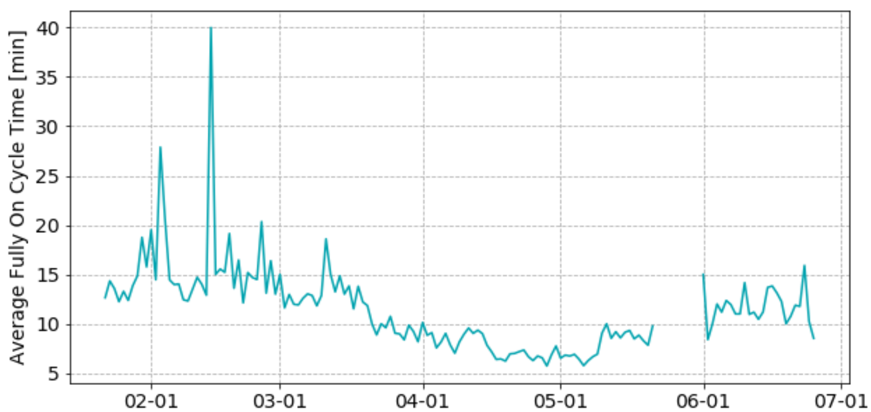

Figure 12. The fully on cycle time is typically near 15 minutes in the winter, trends down to above 5 minutes in the spring, and is typically above 10 minutes in the early summer.

Figure 13 shows time series gas consumption data from one day in the winter and Figure 14 shows data from one day in the late spring. The shorter on cycle time in the spring is clear from the “spikes” in the data, where it is only fully on for 5 minutes or less before ramping down. The flatter tops in the winter data shows that the heat pump tended to stay on for longer periods once fully on.

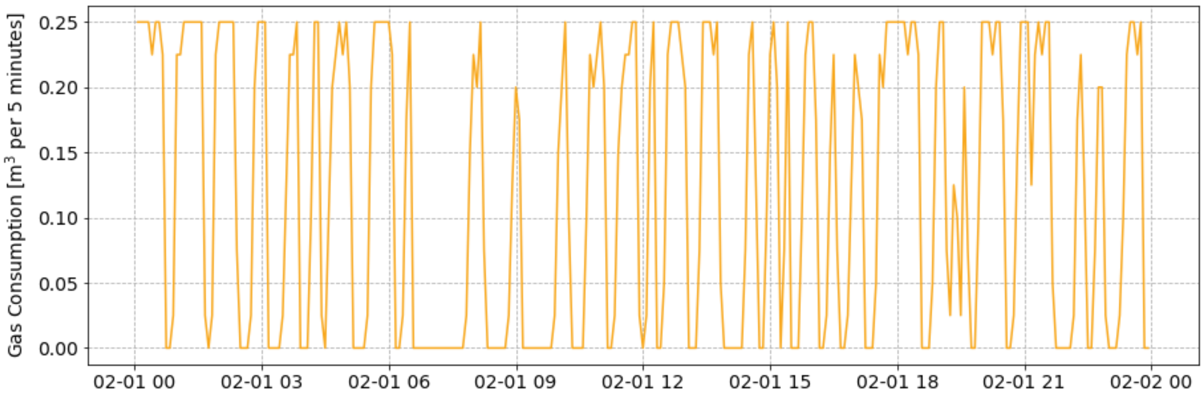

Figure 13. Heat pump on cycles are visualized for February 1st, 2023. Note the flatter tops to many of the peaks, indicating that the heat pump has stayed for more than one 5-minute monitoring interval once it turns on in response to a heating call.

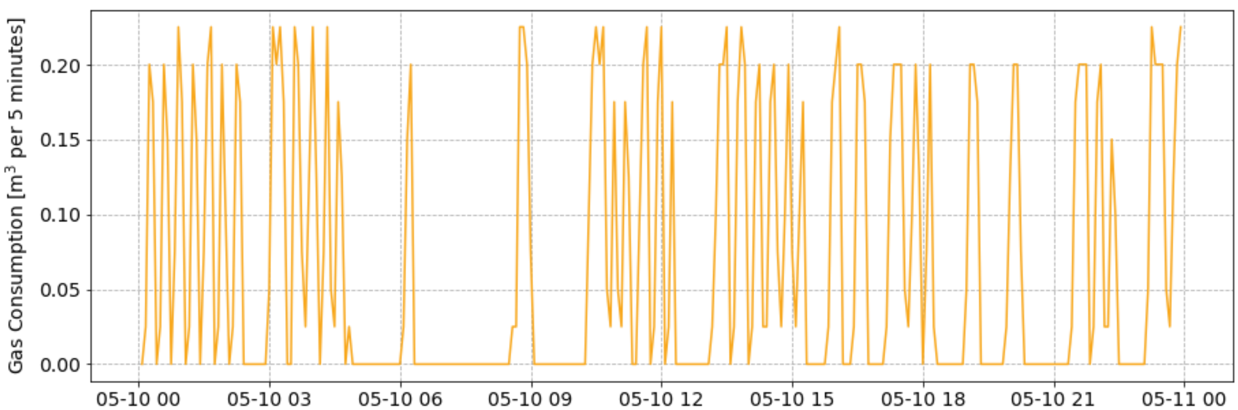

Figure 14. Heat pump on cycles are visualized for May 10th, 2023. Note that, in contrast to the previous figure, the on cycles take on much more peaked profile where the heat pump is only fully on for one 5-minute monitoring interval.

The strong negative relationship that short cycle times have on the heat pump efficiency is clear in Figure 15. There wasn't a physical explanation for why it decreased from winter into spring and then recovered moving into the summer. STEP initially theorized that the increasing water temperatures from the city mains may be allowing the tanks to recover quicker in the spring than in the winter, and that this could result in shorter cycle times for the GHP. However, since the cycle time begins increasing into the summer again, this explanation was not sufficient.

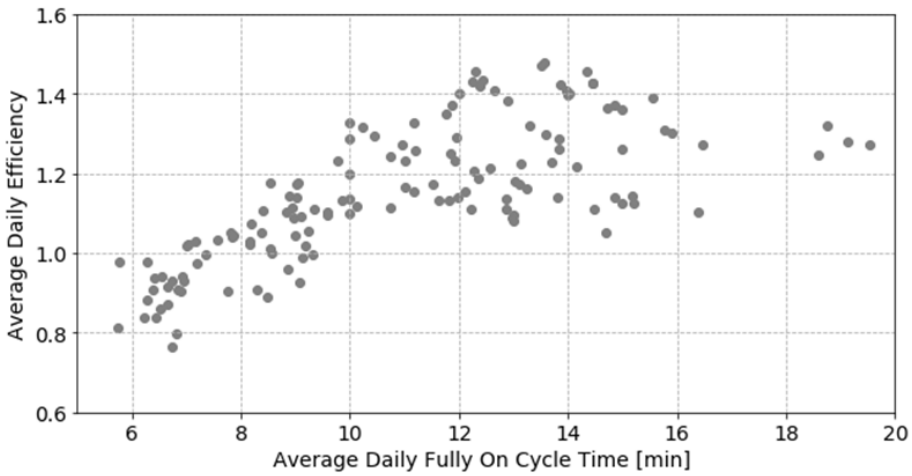

Figure 15. There is a clear relationship between the fully on cycle time and the average daily efficiency, such that efficiency is drastically diminished when the heat pump is only able to operate with short on cycles.

6.2 Return Temperature

With any heat pump, the efficiency decreases when it must pump heat across larger temperature gradients between the outdoor temperature and the return temperature to the heat pump. The 4-hr aggregated GHP efficiency is plotted against the 4-hr aggregated mean return glycol temperature in Figure 16. A histogram of glycol return temperatures is provided in Figure 17. The impact of the return glycol temperature on efficiency is pronounced, with a rapid decline occurring above return temperatures of 48°C.

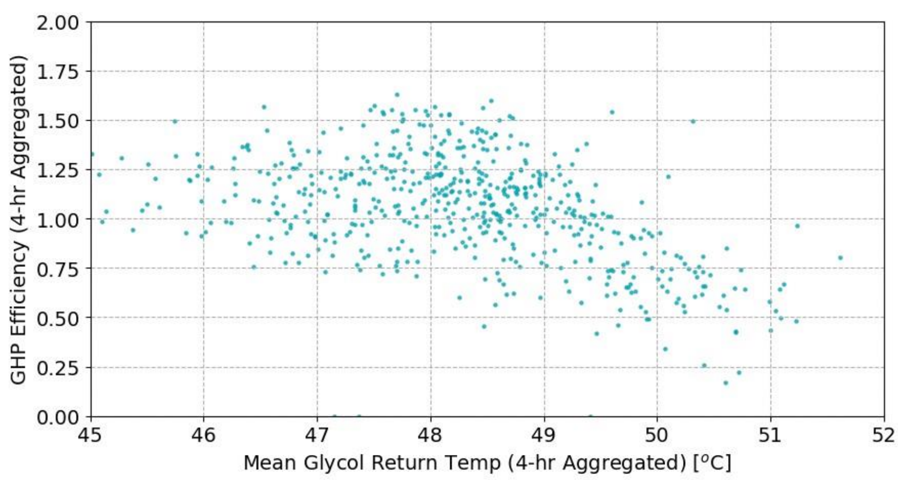

Figure 16. The heat pump efficiency decreases with increasing return glycol temperatures.

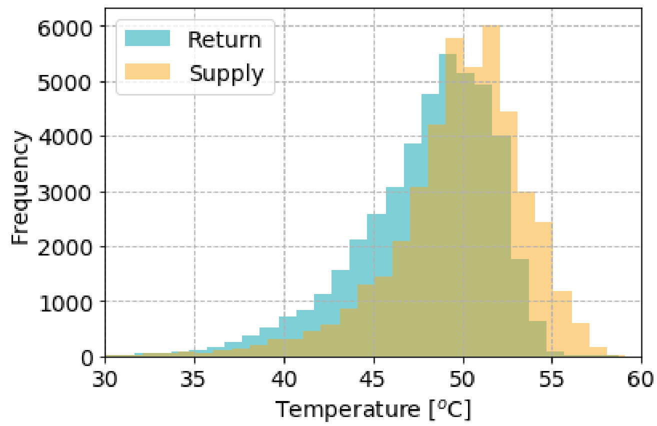

Figure 17. The return glycol temperatures to the GHP are very warm. This is an issue because the GHP performance is drastically lowered for warmer return temperatures.

7 SYSTEM IMPROVEMENTS

The key factors that are decreasing efficiency in this installation are the high return temperatures and short fully on cycle times. The high return temperatures are largely a result of the hydronic design of the system but other installation-specific factors are likely contributing as well. From a design perspective, the cold water from the city mixes with the hot water from the tanks and the hot water from the recirc loop *prior* to passing through the heat exchanger and being heated by the GHP. The GHP will see warmer temperatures and have a lower efficiency than if the design allowed the GHP to heat the cold water from the city more directly (for example, a design utilizing a preheat tank heated exclusively by the GHP).

The recirc loop was operating continuously and this is unnecessary. Smarter recirculation control would cause less mixing of hot recirculation water into the heat exchanger and ultimately result in lower return temperatures for the GHP. Return temperatures may also be reduced by changing the connections to the heat exchanger. It was connected in a parallel flow configuration, but better heat exchange can be had with counterflow and this is the how the heat exchanger's specifications state it should be installed. The current configuration may result in the heat exchanger being a pinch point where there is not sufficient heat transfer and there is additional warming in the glycol loop of the GHP.

STEP wase not able to identify the root cause of the short on cycle times. However, regardless of the cause, this issue may have a potential fix in that this parameter may partly be influenced by the control setpoints of the system. For example, if the deadband or hysteresis of the GHP controller can be increased, it may help promote greater cycle times. As an example, the heat pump may turn on to start heating when the temperature drops below 45^{o}C but continue to stay on until it reaches 50^{o}C. STEP did not confirm the current deadband of the controller. It may be the case that this has already been implemented and that shorter cycle times are unavoidable with this hydronic system design. A feature of this design is that the city water only gets one pass across the heat exchanger before being fully mixed into the tanks. Again, an alternative system design which utilized a preheat tank would be able to promote longer cycle times.

There are limitations to how much the deadband could be increased. As the turn-off threshold increases (50ºC in the above example), it will push the GHP to operate with greater return temperatures where it is less efficient and may also begin approaching the high-temperature cut-off limits of the heat pump. It is recommended that any changes to the control be implemented with care and that data monitoring continue after these changes to identify if performance has improved.

One of the main factors impact the GHP overall utilization is the efficiency of the GHP, if efficiency can be improved using the approaches listed above, then the heat pump utilization would improve as well. STEP was not able to fully identify why the utilization decreased steadily over the monitoring period, apart from the impacts of a decreasing efficiency, but saw a correlation with the steadily decreasing DHW load from winter to summer. In future projects, a full year of monitoring is recommended where possible to help fully understand these seasonal trends.

One of the positive aspects of this monitoring project is that the data showed that a high efficiency (>140%) was possible from this heat pump when it was allowed to operate for longer cycles. Note that these efficiencies were obtained after considering the losses from the heat exchanger, and also with high return temperatures. Hydronic system designs and control strategies which took special care to mitigate high return temperatures and foster long operating cycles, would see higher efficiencies then were observed on average in this installation, but that may come at increased costs.