Minimizing Auxiliary Heat Use for Cold Climate Operation of Air Source Heat Pumps

Preprint

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Minimizing Auxiliary Heat Use for Cold Climate Operation of Air-Source Heat Pumps

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ABSTRACT

This paper investigates the auxiliary heat use for air-source heat pumps (ASHPs) operating in cold climates. Twelve variable-capacity, central ducted ASHPs installed in single-family homes in cold climate regions (eleven in the northwest United States and one in a Denver suburb) were monitored for an entire winter season to collect data at cold temperatures. The methodology employed airside and power measurements that were taken every five seconds, to calculate the heat pump's capacity, coefficient of performance (COP), and auxiliary heat energy consumption. This paper provides insights into the practical implications of auxiliary heat utilization in centrally ducted ASHPs and suggests opportunities to mitigate the usage of auxiliary heat, improving overall system efficiency during cold climate operation.

INTRODUCTION

Historically, air-source heat pumps (ASHPs) have faced challenges in cold climates due to their reduced efficiency in extremely low outdoor temperatures. With recent advancements in cold climate ASHP technology, leveraging inverter-driven, variable-speed compressors and fans, low-temperature performance has been improved significantly, making them a viable energy-saving option for many homes in colder regions. Despite the widespread adoption of inverter-driven central heat pump systems, there are still concerns about the in-field performance of these systems when installed in cold climates, particularly with the utilization of auxiliary heat.

Even though the cold temperature coefficient of performance (COP) of ASHPs has been steadily improving over recent years due to enhanced compressor technology, larger heat exchangers, and inverter-driven systems, auxiliary heat usage can significantly decrease installed seasonal efficiency. Auxiliary heat, often in the form of electric resistance heating, serves as a backup heating source when the heat pump alone cannot meet the heating demand during extremely cold weather or rapid temperature drops. Auxiliary heat is typically activated based on outdoor temperature thresholds, when the heat pump's output capacity is insufficient to maintain indoor comfort levels, or to temper the indoor supply air during reverse-cycle defrost. However, the overall system efficiency of heat pumps drastically decreases when auxiliary heat is activated. Factors that influence the activation of auxiliary heat include low outdoor temperatures and temperature lockout settings, indoor heating demand, building characteristics, heat pump sizing mismatch, defrost cycles, system malfunction or maintenance, and user behavior. Understanding when and why auxiliary heat is activated will provide opportunities to develop control strategies and optimization techniques that can effectively minimize auxiliary heat usage and improve the overall energy efficiency of heat pump systems.

Field testing and monitoring can be used to evaluate the heat pump performance with auxiliary heat in actual operating environments, under different weather conditions, building occupancies, and usage patterns capturing the complexities and variations present in real-world conditions. A few field studies have been conducted on variable-speed central heat pumps in

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various climates (Schoenbauer et al. 2017; Larson et al. 2013; Munk et al. 2014; Kegal et al. 2017) that focused on evaluating heat pump performance for meeting home heating and cooling loads and estimated energy savings. However, more investigation is required, especially on auxiliary heat use in centrally ducted ASHPs and factors influencing their operation, to reduce the dependence on auxiliary heat at low outdoor temperatures. The National Renewable Energy Laboratory (NREL) conducted a field study monitoring 12 centrally ducted, variable-speed heat pumps installed in single-family homes located in a cold climate for an entire winter season in 2021–2022. Given the interest in cold temperature heat pump performance, 6 of 12 instrumented heat pumps were monitored for one additional winter during 2022–2023 to collect more data at cold temperatures. The study focused on evaluating heat pump performance at cold temperatures by measuring the in-field performance of centrally ducted, variable-capacity ASHPs and analyzed energy consumption at different operating modes.

This paper investigates auxiliary heat use for ASHPs operating in cold climate conditions. From the field data, the following questions are addressed:

a. In comparison to compressor-based heating, how much energy is used by the electric resistance auxiliary heater?

b. In cold weather, what percentage of the home's heating load is met by the compressor compared to electric resistance backup heat?

c. How frequently is the auxiliary heat activated, and what factors influence its operation, such as outdoor air temperature, indoor heating demand, building characteristics, fault detection, user behavior, or defrost mode?

d. Why right sizing is important? How can we better match the heating load with the capacity of the heat pump and auxiliary heat sources to minimize the need for auxiliary heat during cold weather operation?

This paper provides insights into the practical implications of auxiliary heat utilization in centrally ducted ASHPs and suggests opportunities to mitigate the usage of auxiliary heat, improving the overall system efficiency during cold climate operation.

FIELD TESTING

The NREL field study monitored 12 centrally ducted, variable-speed heat pump systems over the course of the 2021–2022 winter season. One site was near NREL outside Denver, Colorado, and the other 11 sites were located in the northwestern United States (Washington and Montana). All the sites in Washington and Colorado were in International Energy Conservation Code (IECC) Climate Zone 5 (PNNL 2022). Site 10, which was in Montana, was in IECC Climate Zone 6. Most sites had a high-efficiency, fully electric, variable-capacity central heat pump system already installed prior to the study. The only variable-speed dual fuel heat pump in the study was located at the site in Colorado, and it was equipped with a natural gas furnace for backup heating. Due to the interest in assessing heat pump performance in cold temperatures, 6 of the 12 instrumented heat pumps (Sites 2, 3, 5, 6, 8 and 10) were monitored for an extra winter during 2022–2023 aiming to gather more data, specifically at colder temperatures.

At each site, two independent, stand-alone data loggers were employed, one positioned near the indoor unit (IDU) and the other near the heat pump outdoor unit (ODU). A weather station was integrated into the ODU data logger to record the outdoor air dry-bulb temperature and relative humidity. Airside and power measurements were collected at five-second intervals to assess the heat pump performance including heat pump capacity, COP, and auxiliary heater energy consumption. We developed algorithms to automatically identify the heat pump operating mode including defrost and auxiliary heating operation. We temporarily installed an air handler flow plate or Duct Blaster® to measure the indoor airflow at various blower speeds during the initial site visit to establish a correlation between the IDU airflow rate and the blower power consumption. Throughout the duration of the study, blower power was continuously monitored to estimate the indoor airflow rate. Additionally, an extensive thermal and duct audit of the entire house was conducted during the initial site visit to evaluate the winter heating requirements and heat pump sizing. In order to determine the appropriate heat pump size for each site, heating design loads for the entire home were calculated using ASHRAE 99% design temperatures (ASHRAE 2017) and compared against the maximum capacities reported by the manufacturer. A full description of the methodology can be found in Winkler and Ramaraj (2023).

Winkler and Ramaraj (2023) documented site information, house characteristics, heat pump and auxiliary heat specification for 12 monitored heat pumps, field monitoring and data analysis methodologies, and measured heating and cooling field performance for winter 2021–2022. The site numbers used throughout this paper are consistent with the site numbers used by Winkler and Ramaraj (2023).

To make sure we recorded every hour with heating operation throughout the winter season, we defined the winter period as running from October 1 to March 30. Given the study's primary focus on assessing cold temperature performance, it is valuable to compare the measured temperature data with the typical weather conditions at each site. Based on the heating design temperatures for each location, it was observed that winter 2022–2023 had significantly more hours with cold temperatures compared to winter 2021–2022. Because there were more hours at cold temperatures during the second winter, we were able to investigate the heat pump operation at temperatures close to the compressor lockout temperature recorded from the communicating thermostat.

AUXILIARY HEAT USE PERFORMANCE RESULTS AND DISCUSSION

Prior to discussing auxiliary heat use from the study, we summarize the heat pump performance for 5 of the 6 sites monitored during winter 2022-2023. It is important to note that all systems, apart from Site 3, were equipped with auxiliary electric resistance heaters. Site 3, instead, had a natural gas furnace for backup heating. The focus of this paper is limited to analyzing the heat pump performance when using electric resistance auxiliary heat, so Site 3 results are not included here. Table 1 lists the percentage of time the heat pump was either completely off, operating in fan-only mode, running with only compressor-based heating, utilizing the auxiliary heat, or in defrost mode, as well as the energy use for each mode during the monitoring period, similar to Table 11 from Winkler and Ramaraj (2023), which includes the summary of heating data for winter 2021–2022. The percentage of time with auxiliary heat on includes time periods of auxiliary-only heating, combined compressor with auxiliary heating and auxiliary heating during defrost cycles. When comparing performance across the two winters, it is important to remember that temperatures were noticeably colder during winter 2022–2023 compared to winter 2021–2022.

In the case of all-electric homes employing electric-resistance auxiliary heating elements, it is interesting to investigate the auxiliary usage, particularly at cold outdoor temperatures to understand the frequency with which the system relies solely on auxiliary heat or uses it to supplement compressor-based heating. The electric resistance auxiliary heating elements were configured in multiple stages with a lockout temperature above which the auxiliary heater should not have operated.

Table 1. Summary of Heating Data for Winter 2022–2023

	Site 2	Site 5	Site 6	Site 8	Site 10
Hours of data	4,368	4,368	4,368	4,368	4,262
Percent of time system off [%]	14.3	24.7	1.0	32.3	40.4
Percent of time with fan-only operation [%]	24.3	6.3	33.3	11.8	4.6
Percent of time with compressor operation [%]	55.4	57.6	61.2	39.0	49.5
Percent of time with auxiliary heat on [%]	5.0	9.8	3.6	16.8	5.6
Percent of time in defrost [%]	1.7	2.7	0.4	1.8	1.5
Compressor-based heating energy [kWh]	5,211	4,332	5,340	3,520	3,734
Blower energy (season) [kWh]	576	635	282	849	306
Auxiliary heater energy (heating) [kWh]	1,078	2,270	1,657	6,715	824
Defrost cycle [kWh]	815	1,151	120	1,156	412
Compressor-based heating season COP	2.6	2.5	1.7	3.2	2.6
Fraction of load served by compressor	0.93	0.84	0.85	0.73	0.92
System heating season COP	2.3	2.1	1.5	2.0	2.3

The auxiliary heat energy use reported in Table 1 (above) and Table 11 from Winkler and Ramaraj (2023) was calculated by aggregating the auxiliary heater energy consumption during time periods of auxiliary-only heating and combined compressor with auxiliary heating, excluding defrost cycles from the calculation. Based on the summary data in Table 11 from Winkler and Ramaraj (2023) for winter 2021–2022, the auxiliary heat energy usage exceeded 35% of the compressor-based heating energy for Sites 2, 5, 8, 11, and 12. Notably, for Sites 2 and 8, auxiliary heat energy consumption exceeded the compressor-based heating energy during winter 2021–2022. The final two rows of both the tables present the estimated fraction of the building's heating load served by the compressor and the overall system COP, which takes auxiliary heating into consideration. The sites with the highest fractions of load served by the compressor typically had lower auxiliary heating usage. Based on the data in Table 11 from Winkler and Ramaraj (2023) for winter 2021–2022, the overall seasonal system heating COP decreased for several sites accounting for auxiliary heat energy consumption. Specifically at Sites 2 and 8, the auxiliary heat lowered the overall system COP by more than 30% during winter 2021–2022. Six sites (Sites 1, 4, 6, 7, 10, and 13) had relatively minimal auxiliary heater usage, resulting in a less than 7% reduction in system heating COP for winter 2021–2022.

Because there were more hours at cold temperatures during the second winter, we were clearly able to see the increase in auxiliary heating usage compared to winter 2021–2022. The compressor-based heating COP decreased slightly for all six monitored sites for the second winter due to the colder temperatures, and the system heating COP also decreased for all sites except for Site 2, which had a compressor lockout fault during winter 2021–2022, resulting in increased auxiliary heat usage. Site 8 consumed the most auxiliary heating energy during winter 2022–2023 and operated the auxiliary heater for nearly 17% of the winter, as shown in Table 1. The auxiliary heat use for Site 5 exceeded 50% of compressor-based heating energy, while Sites 2, 6, and 10 had relatively less auxiliary heater usage during winter 2022–2023.

The auxiliary heat was activated due to several factors, which included low outdoor temperatures and temperature lockouts, undetected system faults, heat pump sizing mismatch, defrost cycles, and thermostat setback recovery. These auxiliary heat drivers are discussed in detail in the following sections.

Low Outdoor and Lockout Temperatures

The compressor lockout temperature refers to the minimum outdoor temperature below which the heat pump compressor operation is disabled. The auxiliary heat lockout temperature is defined as the maximum outdoor temperature above which the auxiliary heat source is disabled (unless the heat pump is in defrost mode). The compressor and electric resistance auxiliary heater should be able to run simultaneously when the outdoor temperature is above the compressor lockout temperature and below the auxiliary lockout temperature. Table 2 compares the compressor lockout temperatures to the minimum observed temperature with consistent compressor operation, and the auxiliary heat lockout temperature to the maximum observed temperature when the auxiliary heat is turned on. For most of the sites, the observed temperatures aligned close to the lockout temperature settings.

It was observed that little energy was consumed in the warmer bin adjacent to the auxiliary heat lockout temperature and auxiliary heating runtime increased at colder temperature bins. For sites with an enabled compressor lockout temperature, consistent compressor operation was observed at temperatures colder than the lockout temperature. For Sites 1, 2, and 10 with a disabled compressor lockout temperature, onboard controls lockout the compressor when outdoor air temperatures were below 0°F or 2°F, depending on the site. For Sites 5, 6, and 8, the compressor consistently operated at colder temperatures below the set compressor lockout temperature on the unit's thermostat.

Table 2. Lockout Temperatures Compared to the Minimum Observed Temperature with Compressor Operation and Maximum Observed Temperature with Auxiliary Operation (Defrost Excluded)

Site	Compressor Lockout Temp.	Min. Obs. Comp. Temp.	Min. Obs. Temp.	Auxiliary Heat Lockout Temp.	Max. Obs. Aux. Temp.
1	Disabled	0°F	-2°F	35°F	35°F
2	Disabled	0°F	0°F	25°F	28°F
4	N/A	0°F	0°F	N/A	35°F
5	5°F	0°F	-6°F	35°F	38°F
6	6°F	4°F	-6°F	35°F	~35°F
7	0°F	4°F	0°F	40°F	45°F
8	5°F	-2°F	-6°F	35°F	45°F
10	Disabled	2°F	-20°F	30°F	34°F
11	N/A	4°F	0°F	N/A	40°F
12	5°F	8°F	8°F	35°F	38°F

The maximum observed temperature when the auxiliary heat is turned on aligns well with the auxiliary heat lockout temperature for all sites except Site 8. We notice that the auxiliary heater started operating when the outdoor air temperature was below 45°F despite an auxiliary lockout temperature of 35°F. This is also one of the reasons for higher auxiliary energy consumption for Site 8.

Undetected System Faults

In cases of system malfunctions, auxiliary heat is activated if the heat pump is temporarily disabled or unable to operate efficiently. When comparing winter 2022–2023 to winter 2021–2022, the system heating COP decreased for all sites except for Site 2. Winkler and Ramaraj (2023) reported that an unexplained and undetected fault occurred at Site 2 with the controls or the onboard outdoor temperature sensor from February 16, 2022, through April 11, 2022, causing the heat pump to exclusively use the electric resistance auxiliary heater to heat the home. This fault did not occur during winter 2022–2023, which can explain the difference in performance between the two winters. Despite the colder winter, the auxiliary heat energy consumption decreased by 69%. The compressor-based heating energy at Site 2 increased 56% because of the increased compressor-based heating operation (2,420 hours during winter 2022–2023 compared to 1,764 hours in winter 2021–2022, a 37% increase) and the colder winter. Despite the colder winter, the system heating COP at Site 2 increased 21% from 1.9 to 2.3 because of the compressor lockout fault that occurred during winter 2021–2022. Figure 1 shows the decrease in auxiliary heating energy for winter 2022–2023 compared to winter 2021–2022.

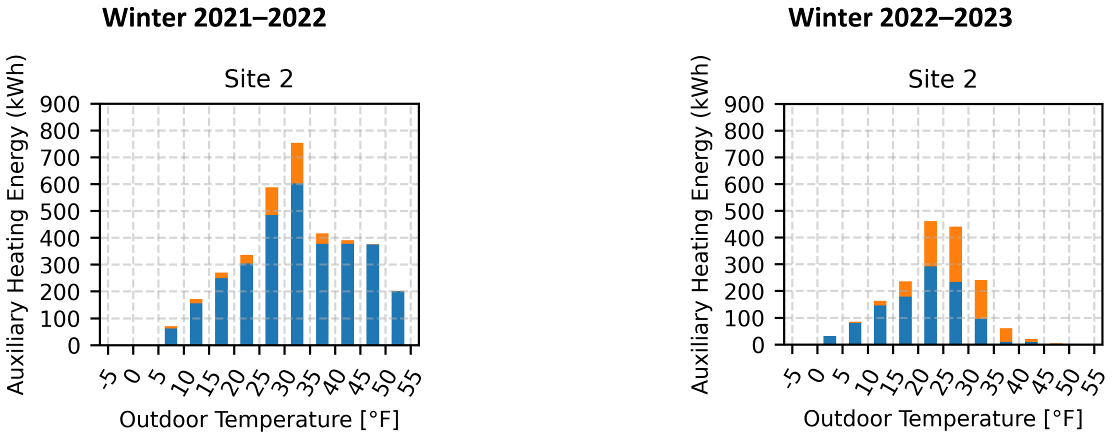

Figure 1 Auxiliary heater energy in heating (blue) and defrost (orange) modes during winter 2021–2022 (left) and winter 2022–2023 (right) for Site 2.

Heat Pump Sizing Mismatch

Figure 2 illustrates the comparison between the estimated fraction of the building's heating load fulfilled by compressor-based heating and the sizing of the heat pump for winter 2021–2022. In this comparison, a value of 100% indicates that the heat pump has been perfectly sized to meet the building's design heating load at the 99% design temperature. Based on this criterion, several heat pumps in the study were found to be undersized. The portion of the heating load served by the compressor is influenced by various factors, including heat pump sizing, winter weather conditions, occupant thermostat settings and schedule, heat pump control settings, and heat pump capacity retention in cold temperatures.

Auxiliary heat is needed to meet the building's heating load at temperatures below the balance point. The heat pump at Site 8 proved to be undersized for the heating load of the house, with a balance point temperature of approximately 39°F due to an inefficient distribution system. As a result, the system depended on an electric resistance auxiliary heater to satisfy ~20% of the building's heating load during winter 2021–2022 and ~27% during the subsequent winter of 2022–2023. Furthermore, the heat pump at Site 8 activated the auxiliary heater for roughly six minutes after each defrost cycle and occasionally relied on the auxiliary heater to recover from thermostat setback periods. Site 8 consumed the most auxiliary heating energy during winter 2022–2023 and operated the auxiliary heater for nearly 17% of the winter, as shown in Table 1. The auxiliary heater was used more during winter 2022–2023 to compensate for the reduced heat pump capacity because the compressor was operating at a lower frequency at moderate temperatures compared to winter 2021-22. From Table 2, we noticed that the auxiliary heater started operating when the outdoor air temperature was below 45°F despite an auxiliary lockout temperature of 35°F. All these factors significantly decreased the overall performance of the heat pump.

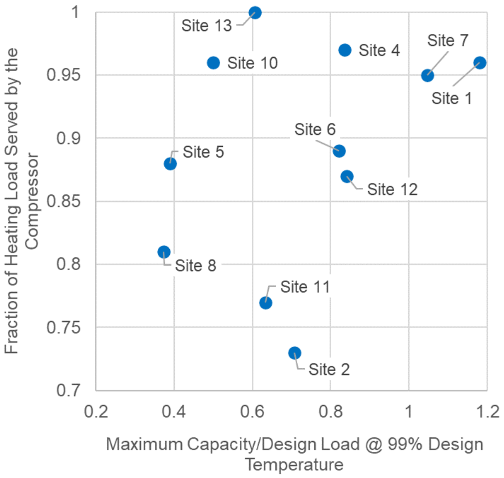

Figure 2 Fraction of the building heating load served by the compressor compared to the heat pump sizing percentage at the 99% heating design temperature for winter 2021–2022.

In contrast, Sites 10 and 13 met most of the building's heating load by compressor-based heating and used less auxiliary heat despite being undersized mainly due to warmer than normal winter weather when compared to the heating design temperature. Because the winter weather at Site 11 was colder than usual, the compressor was able to meet roughly 80% of the heating load even when the heat pump was sized to meet 63% of the design heating load. Notably, the heat pumps at Sites 1 and 7 were the only two heat pumps in the study sized with excess heating capacity. Consequently, both sites predominantly utilized the compressor to meet over 95% of the season's heating load, as anticipated.

Defrost Cycles

During defrost cycles, the heat pump activates auxiliary heat to maintain indoor comfort while the outdoor coil is defrosted. Across all sites, the auxiliary heater was in operation during and/or immediately after the defrost cycle. Sites 1, 8, and 13 ran auxiliary heat during a recovery period following the defrost cycle, whereas most other sites turned off the auxiliary heat immediately following the defrost cycle, as shown in Table 13 (Auxiliary Heat Use Following a Defrost Cycle During Winter 2021–2022) from Winkler and Ramaraj (2023). In certain cases, depending on the building's heating load, the auxiliary heat continued to run for extended periods following a defrost cycle. Figure 3 shows an example winter day for Site 8 with auxiliary heat running after a defrost cycle. Each point in the figure represents the operating mode for each 30-second sample data. From the indoor power in Figure 4, we can see that the auxiliary heater was activated during the defrost cycle and several minutes following the cycle.

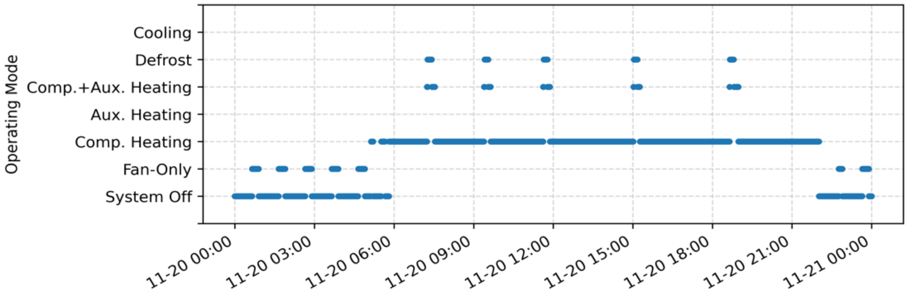

Figure 3 An example day with auxiliary heat running after defrost cycle for Site 8.

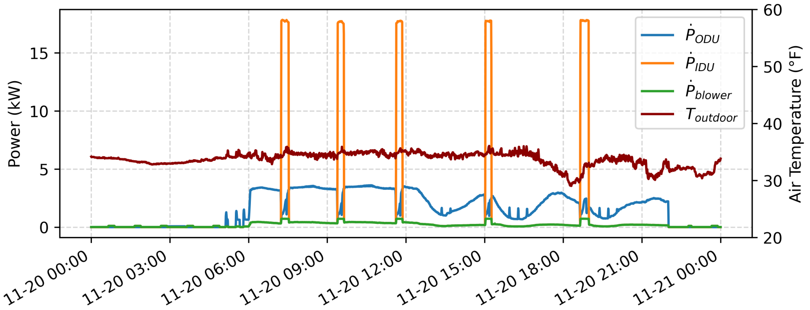

Figure 4 Corresponding power during a defrost cycle and auxiliary heating after defrost cycle for Site 8.

Although all the systems spent only a minor portion of their operating hours in defrost mode, the energy consumed during defrost operations surpassed 20% of the compressor-based heating energy for Sites 5, 7, 8, and 11, primarily because the auxiliary heater was activated during defrost. At 3 out of the 11 sites, defrost operation was the main user of auxiliary heating.

Setback Recovery

Auxiliary heating can provide rapid heating to restore indoor temperatures to the setpoint during setback recovery, especially in colder conditions when the indoor temperature has dropped significantly. However, this is not an optimal control and can negate the energy savings achieved during the setback. Auxiliary heating supplements the heat pump's heating capacity during setback recovery, especially if the heat pump alone is unable to meet the heating demand within the desired timeframe. Site 8 occasionally relied on the auxiliary heater to recover from thermostat setback periods. Figure 5, Figure 6, and Figure 7 show the operating mode, power, and air temperatures, respectively, for Site 8 during a setback period on a particular winter day. We can observe that after 6 a.m., the auxiliary heater was activated to recover from the setback period even though the outdoor temperature was above 40°F. The auxiliary lockout temperature for Site 8 is 35°F.

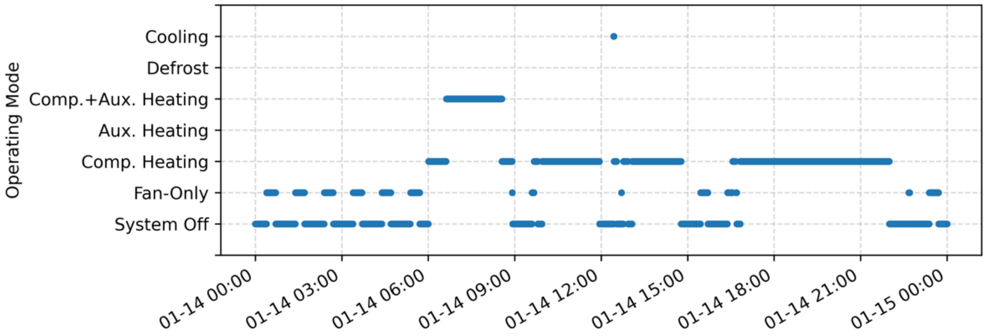

Figure 5 An example day using auxiliary heating for setback recovery at Site 8.

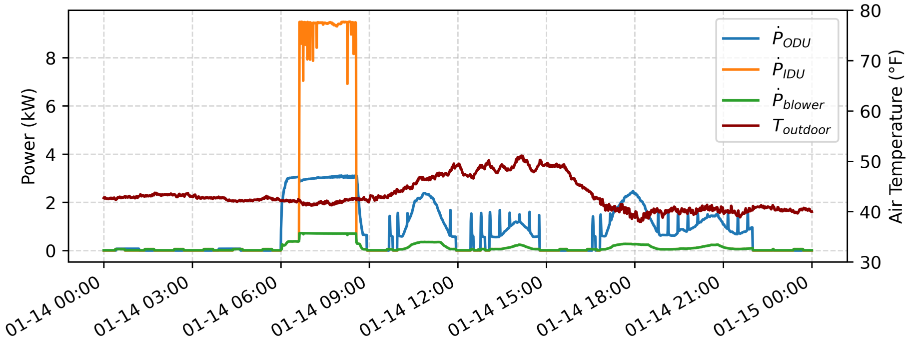

Figure 6 ODU and IDU power during setback recovery period at Site 8.

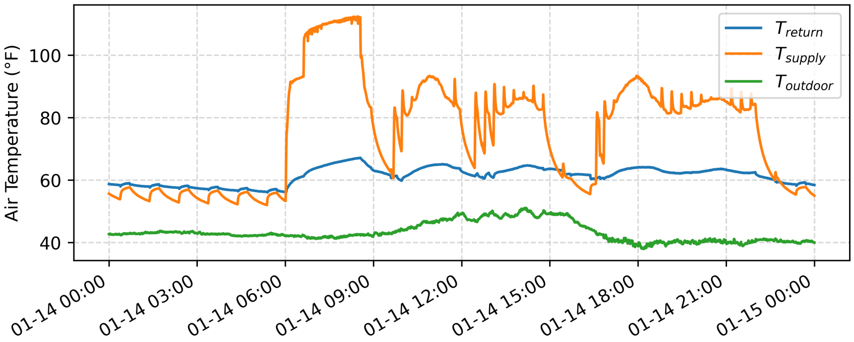

Figure 7 Air temperatures during setback recovery period at Site 8.

SUMMARY AND CONCLUSIONS

Excessive use of electric resistance auxiliary heat in ASHPs can reduce the overall efficiency of the heating system, especially if it is triggered too often. This can result in considerable energy waste and undermine the energy-saving benefits of ASHPs. To minimize this, it is important to choose the right size heat pump and use appropriate control settings. Mitigating the need for auxiliary heat in cold climates involves addressing several factors that trigger its activation.

- **Low Outdoor Temperatures**: Utilize ASHPs designed specifically for cold climates that maintain capacity at lower temperatures. These units can operate effectively without relying on auxiliary heat, even in colder conditions.
- **Temperature Lockouts**: Minimize compressor lockout temperature settings to ensure the heat pump operates as long as possible before auxiliary heat is engaged.
- **Undetected System Faults**: Regular maintenance and monitoring can detect faults early, preventing unnecessary activation of auxiliary heat. Installing advanced diagnostic tools can help identify issues such as refrigerant leaks or airflow obstructions that may cause the system to default to auxiliary heat.
- **Heat Pump Sizing Mismatches**: Ensure proper sizing of the ASHP during installation. An undersized system may struggle to meet heating demands and rely excessively on auxiliary heat, while an oversized system may cycle on and off too frequently, reducing efficiency.
- **Defrost Cycles**: Minimize the impact of defrost cycles by choosing heat pumps with advanced defrost technology. Some systems can optimize defrost frequency and duration, reducing the need for auxiliary heat during these cycles.
- **Setback Recovery**: Optimize thermostat setback strategies to avoid triggering auxiliary heat during recovery periods and rely on compressor-based heating capacity when feasible. Gradual temperature adjustments and utilizing smart recovery features can help maintain comfort without overreliance on auxiliary heat.

By addressing these factors, the activation of auxiliary heat can be significantly reduced and the overall efficiency of centrally ducted ASHPs in cold climates can be maximized.

NOMENCLATURE

ASHP	air-source heat pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
COP	coefficient of performance
IECC	International Energy Conservation Code
IDU	indoor unit
NREL	National Renewable Energy Laboratory
ODU	outdoor unit

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