Efficient Heating for High Altitude Housing in Peru

Ajay Dalal[1], Walter Daniel Leon-Salas[1], William Hutzel[1], Pedro Flores Larico[2], Miguel Angel Vizcardo Cornejo[2], Mauricio Postigo Malaga[2], Miguel Angel Ocharan Pichu[2]

[1] Purdue University, West Lafayette (United States of America)

[2] Universidad Nacional De San Agustin De Arequipa, Arequipa (Peru)

Abstract

The global push for decarbonization has highlighted the need for sustainable heating solutions, particularly in geographically challenging and remote locations such as the Peruvian Andes, where traditional heating methods are inefficient and pollute the environment. Air source heat pumps are a viable solution but come with their own challenges, including cost, access to electricity, and performance degradation at high altitudes. A project is underway to install and evaluate an air-source heat pump at a research station located at an altitude of 4,128 m in Sumbay, Peru. The primary goal of this research is to evaluate and expand existing models that predict the heating performance of air-source heat pumps at high altitudes, resulting in improved designs and enhanced customer satisfaction.

Keywords: high altitude performance, air-source heat pump, altitude correction factor, decarbonization, peru

1. Introduction

Peru is a geographically varied country with a significant portion of its population living near the Andes mountains, at high elevations with a challenging climate. Heating in these areas has traditionally used biomass fuels like wood, feces, or crop residues, which not only create greenhouse gas emissions but also pose indoor environmental quality problems like respiratory disease due to smoke inhalation (World Health Organization, 2021).

To address these challenges, there are cleaner and more efficient heating technologies that provide heating and reduce dependence on polluting fuels. Transitioning away from conventional biomass not only safeguards human health but also minimizes environmental degradation resulting from deforestation as well as black carbon emissions (Bond et al., 2013). Defining heating solutions as both a health and ecological intervention necessarily shifts the focus towards sustainable approaches that serve populations that live at high altitudes. The decarbonization of heating is therefore a climate and public health necessity.

Decarbonization is the process of reducing or eliminating carbon dioxide emissions from human activities, most specifically those relating to energy generation and consumption. The challenge to reduce climate change worldwide has brought decarbonization as a central theme in public policy as well as technological innovations. With regards to heating, decarbonization means a switch from combustion-based heating, where carbon is released into the atmosphere, to electrified and lower-carbon technologies such as heat pumps. This not only reduces the impact of climate change, but it also improves local air quality, which is specifically of importance for the indoor environment when switching from biomass and fossil fuel heating approaches (Edenhofer et al., 2014).

Like most of Latin America, natural gas and biomass are the most used heating fuels in Peru. According to the International Energy Agency (IEA, 2024), approximately 90% of rural households in Latin America still rely on biomass. Natural gas infrastructure is expanding, but many remote communities remain disconnected from piped networks. While natural gas heating is familiar and emits less CO_2 when compared to biomass it is still a significant source of carbon emissions compared to an air source heat pump (IEA, 2025).

10.18086/swc.2025.05.04 Available at http://proceedings.ises.org

Since 2017, a partnership between the Universidad Nacional de San Agustín (UNSA) in Arequipa, Peru, and Purdue University in West Lafayette, IN, USA has pursued research projects tied to the overarching theme of sustainability. One recent project is the Centro Internacional de Biociencias e Innovación (CIBCI), which serves as a testbed for a variety of agricultural and business opportunities. One promising idea is leveraging the natural beauty of the landscape to encourage eco-tourism. Eco-tourists will stay in a cabin that is being renovated to accommodate overnight guests. An important part of that renovation is providing a sustainable method of heating the cabin during cold weather.

The CIBCI research station is located near the Sumbay caves at an altitude of 4,128m and ~100km from the nearest major city and where UNSA resides, Arequipa. The research station shown in Figure 1 is designed as a fully self-sustaining facility with solar panels, wind turbines, and a greenhouse. The site also includes a trout farm and a biodigester to support food production and waste management. The station also features an unheated cabin where personnel stay while working at this remote location. A long-term goal is to upgrade the cabin to a place where eco-tourists stay while visiting.

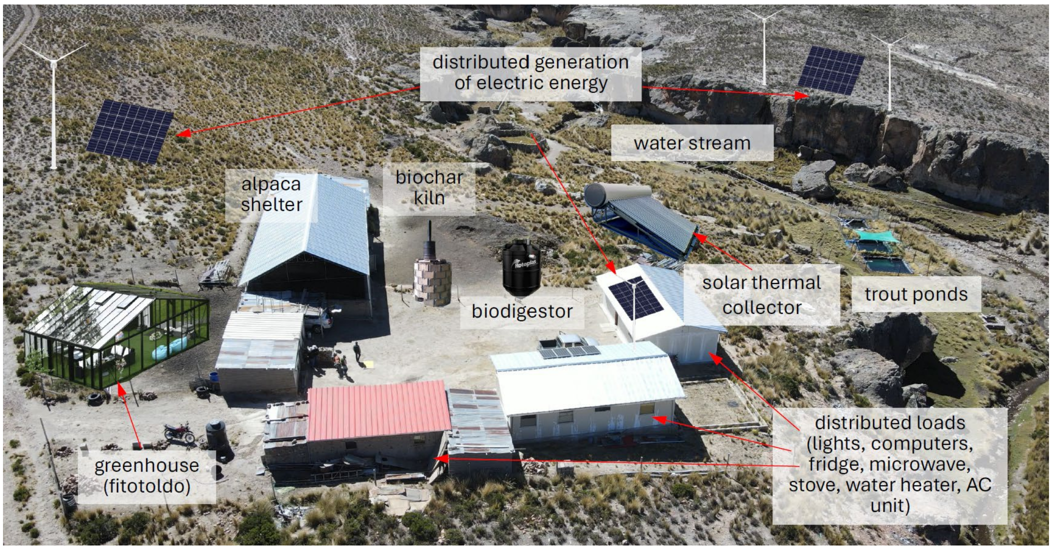

Figure 1. The CIBCI research station showcasing a variety of installed and planned sustainable technologies.

The research station cabin, as well as other homes in the region, require heating nearly year-round due to the cold climate, and it must be delivered efficiently and sustainably. The cabin is roughly 11 by 6.5 meters with two three-by-three-meter bedrooms. The method chosen to increase thermal comfort for the cabin must be simple, reliable, and cost effective so that it can be replicated for other homes in the Andes region.

There are several steps for improving thermal comfort in a home. These steps should be pursued in a sequence, starting from the simplest and least expensive and progressing to the more difficult and more expensive options. Following this logic, the first step is sealing air gaps to prevent conditioned air from escaping. The next step is adding insulation to keep the heat inside the home. After insulating and air sealing, the heating source within the home can be swapped for a better alternative.

Air source heat pumps (ASHP) are one viable option for sustainable heating. They are highly efficient, do not rely on piped fossil-fuel resources, and only need electricity to operate. These features make them an attractive option for heating homes in the indigenous Peruvian region. ASHPs are a particularly good option if distributed electricity sources from wind or solar photovoltaics are available. Using an ASHP for the cabin at the CIBCI research station would decrease carbon emissions and not require utility infrastructure like natural gas. Even if an ASHP is too expensive for individual homes, it could be an option for community gathering spaces.

Air-source heat pumps are widely known for their energy efficiency, especially compared to electric resistance heaters and natural gas heaters. ASHPs function by transferring heat from the outdoor air into a building's interior. They operate using electricity, but the ratio of the heating provided as compared to the electricity to run the equipment, known as the Coefficient of Performance (COP), can be three or higher. A COP of three means that for every unit of electricity supplied, three units of heat will be moved into the building. The large

COP is what makes heat pumps an attractive option compared to other forms of heating.

One key challenge with heat pumps is that their performance degrades at higher altitudes. Manufacturers rate ASHPs at sea-level conditions, but their performance degrades with elevation because air pressure and density are inversely related to altitude. With lower air pressure and air density, ASHPs extract less thermal energy per unit of airflow compared to at sea level. If this drop in performance is not properly accounted for, the ASHP may be compromised and unable to meet the heating demand.

Even if an ASHP has degradation in its performance, it can still be a better option than using biomass fuel, as biomass fuel is also inefficient when used at high altitudes due to the thinning air (Zhang B. et al., 2022). More research is needed to identify altitude-based correction factors for air source heat pumps and provide "best practice" recommendations for future ASHP installations.

Electrification of heating is a central strategy for reducing reliance on biomass and fossil fuels in remote communities. However, there are few alternatives when there is a lack of utility infrastructure. The increased use of renewable resources, like wind and solar photovoltaics, creates new options by providing electricity in places where it did not exist before.

2. High Altitude Heat Pumps

Air-source heat pumps have been engineered and optimized mostly for performance at or near sea level, where atmospheric conditions are well understood and relatively constant. High-elevation operation presents site-specific challenges that impact efficiency, capacity, and reliability. Reduced barometric pressures, decreased air densities, and site-specific climatic conditions act in combination to degrade mechanical performance and thermodynamic processes. The elevation-based effects have the potential to compromise heat transfer, modify refrigerant performance, increase energy consumption, and create operating problems such as frosting. Measurement and interpretation of these losses of performance have strategic value for precise system performance prediction in remote, high-installation sites and for providing insight into how to improve test standards.

Operating an ASHP at a high altitude introduces challenges that reduce the effectiveness of the ASHP. As shown in Figure 2, air density is inversely related to altitude. The inverse relationship between the density of air and altitude is exponential, causing air to be significantly less dense as altitude increases. Lower atmospheric pressure, lower air density, and lower average temperatures all contribute to the reduction in ASHP efficiency as well as capacity, which can be critical in remote installations where system performance must be reliable and consistent.

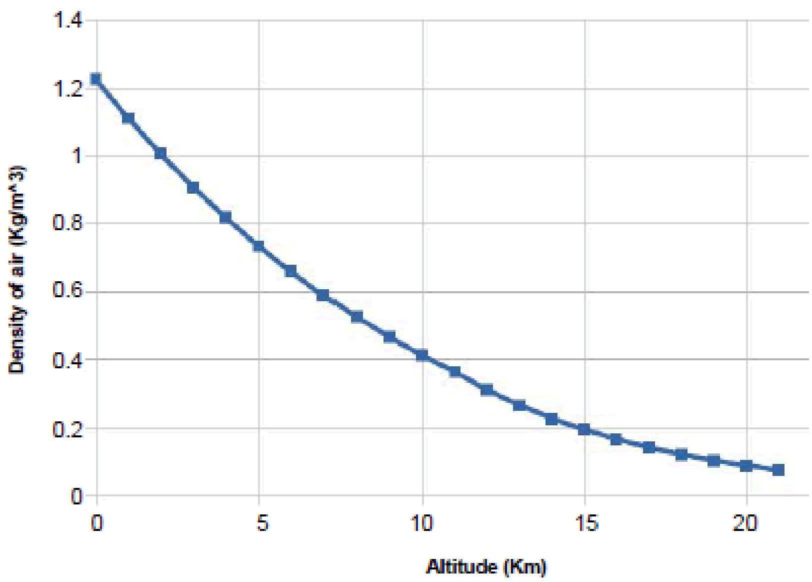

Figure 2: Density of Air Compared to Altitude (Osmanaj, 2018)

Reduced air density at higher altitudes results in a lower air mass flow rate through the evaporator, which limits the thermal energy absorption from the ambient air. The limited energy absorption is heightened by a decline in the convective heat transfer coefficient, which relies on both air properties and flow dynamics (Di et al., 2023). Refrigerant saturation temperatures are also affected by low barometric pressure, which lowers the evaporation pressure and increases the work required by the compressor. (Riffat & Ma, 2004).

Li et al. (2017) demonstrated that the behavior of refrigerants changes significantly at reduced ambient pressures. The volumetric efficiency of the compressor declines, while the mass flow of the refrigerant decreases for fixed-speed units. Due to this decline, the heating capacity not only declines but also puts additional stress on other mechanical components, such as the fan motors, which must compensate by increasing their speed to deliver adequate airflow (Xu et al., 2020). The increased fan speed raises power consumption and wear on the fan.

Due to the growing potential of using ASHPs at higher altitudes, researchers have developed theoretical models to estimate the performance degradation of ASHPs at higher elevations. Two models relevant to altitude ASHP output deficiency were created, one by Li et al. (2019) and one by Lyu et al. (2024), which builds upon Li et al.'s model. Both models offer different approaches to quantifying the effects of elevation on an ASHP but are still complementary.

Li et al. (2017) constructed an integrated theory and numerical model based on the performance of an ASHP in Xizang, which is located in a Tibetan area with an average elevation of exactly 4,000 meters. Li et al.'s (2017) integrated model involves heat transfer equations, thermodynamic property state transitions, and meteorological information to simulate ASHP performance at elevations ranging from 3,000 to 5,000 meters.

Frost formation on the evaporator is discussed, but it is determined to be a non-issue as Xizang has low relative humidity, especially when the outdoor temperature is freezing. Li et al.'s model incorporates every part of the ASHP separately. The compressor, expansion valve, finned tube evaporator, and condenser are all sub-models. The model is simulated with a total energy balance for all important ASHP components, dynamic compressor action, refrigerant performance at low pressures, and frosting systems. The model shows that low air pressure as well as low ambient temperature, have a great impact on the performance of the ASHP.

Compared with the simplified model later proposed by Lyu et al. (2024), Li et al.'s model offers time-varying performance simulation capability rather than a single average correction factor. Li et al. experimentally verified their simulation and concluded that their capacity for heating was diminished by 16-20% above 4,000 meters, which agreed well with their measurements taken in the field.

Although more precise, Li et al.'s model is also computationally complicated and requires extensive local climatic data, system design, and simulation programs such as TRNSYS or MATLAB. It is more appropriate for overall design and feasibility studies than real-time control or quick surveys.

Lyu et al. (2024) developed a simplified correction model for ASHP heating capacity in high-altitude environments by first running detailed thermodynamic simulations across various altitudes, outdoor temperatures, and operating pressures. From this simulation dataset, they isolated the relationship between local barometric pressure and capacity loss. They then fitted a pressure-based correction coefficient that adjusts the rated sea-level capacity of a heat pump. This coefficient directly links reduced atmospheric pressure to diminished evaporator heat transfer and altered refrigerant cycle performance.

To create the final equation, Lyu et al. (2024) combined the pressure correction term with manufacturer-rated heating capacity values, producing a formula that can be applied without repeating complex simulations. The model was validated using measured field data from four high-altitude installations on the Tibetan Plateau, covering altitudes from near sea level to roughly 4,000 meters and outdoor temperatures from −20 to 10 °C. From these cases, the model consistently estimated ASHP heating capacity losses to be about 4-5% per 1,000 meters. Outdoor temperature heightened the altitude factor, with warmer temperatures creating a lower altitude factor, as shown in Figure 3. Based on the figure, an ASHP installed at 2000m would output roughly 92% of its rated capacity at outdoor temperatures around -20 °C but only about 90% of its rated capacity at 10 °C.

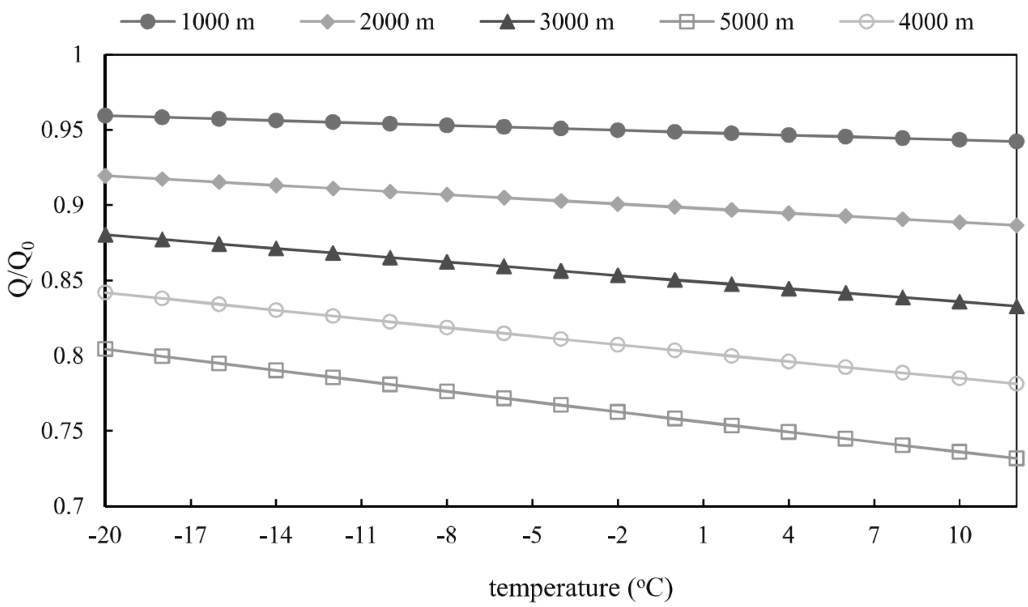

Figure 3: Altitude Correction Factor Variation with Outdoor Temperature (Lyu et al., 2024)

The process required minimal calibration, with only a few measured operating points from a given ASHP being needed to fit the local correction factor. By using barometric pressure instead of relying on elevation to create the altitude factor, the model should be able to accommodate regional atmospheric differences as barometric pressure is not uniform across the world, even at identical elevations (Vaia, 2025). This would be important for the ASHP to be installed at the CIBCI station, as the temperature and humidity profiles would vary, likely leading to slightly different barometric pressure than in the Tibet region, even at similar elevations.

3. Testing Standards for ASHP Systems

ASHRAE 37 (2017) is the standard for Methods of Testing for Rating Electrically Driven Unitary Air-Conditioning and Heat Pump Equipment. The standard specifies test methods and calculations to determine performance ratings for various types of unitary air-conditioning and heat pump systems in both steady-state and part-load conditions. The standard ensures that performance ratings are standardized and consistent across the board, no matter the industry.

AHRI 210/240 (2024) is the standard for Performance Rating of Unitary Air-Conditioning and Air-Source Heat Pump Equipment created by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). The standard applies to commercially available heat pumps that have capacities less than 20 kW. Similar to ASHRAE 37, AHRI 210/240 specifies how to determine performance metrics for ASHPs, such as Seasonal Energy Efficiency Ratio (SEER), Energy Efficiency Ratio (EER), and Heating Seasonal Performance Factor (HSPF2).

To maintain consistency, the testing procedures in both ASHRAE 37 and AHRI 210/240 align with each other. Within both standards, the indoor-side air enthalpy test is discussed as a certified method for determining an ASHP's actual heat capacity. This method requires enthalpy to be measured at the inlet and outlet of the indoor coil, as well as the mass flow rate of dry air passing through the coil, to calculate the unit's heating capacity.

High altitude regions, such as in Sumbay, have relatively low humidity levels, which means that the humidity remains constant between the inlet and outlet of the indoor coil. Enthalpy is a function of temperature, humidity, and specific heat of air (which is typically constant), so if humidity is constant, enthalpy would be linearly related to temperature (ASHRAE, 2025). Due to the heating process being primarily sensible, heating capacity can be determined using a simpler process that uses the mass flow rate of air passing through the indoor coil, the temperature of the inlet and outlet of the coil, and the specific heat of the air in the region.

4. ASHP Selection and Installation

An ASHP was selected using a steady-state analysis that determined the heating requirements for the cabin at the CIBCI station. This steady-state analysis was conducted for a reasonable worst-case scenario using the coldest recorded temperature in Sumbay in 2022 (NSRDB, 2022). The analysis made reasonable assumptions for the heat transfer coefficients of the fiberglass-insulated walls, ceiling, and floor. The ventilation rate for infiltration was assumed to be two air changes per hour. The indoor temperature setpoint is assumed to be 23°C. These factors, alongside dimensions of the cabin, can be used to run the calculation to achieve a rudimentary ASHP capacity requirement.

The heat loss through the walls, floor, ceiling, and windows was calculated using Equation 1 with U being the U-factor of the material, and T being the temperature. The heat loss through air gaps (ventilation loss) was calculated using Equation 2, with $\dot{m}$ being the mass flow rate, c_p being the specific heat capacity of the air, and T being the temperature. All the heat losses were added together to determine the capacity requirement for the ASHP.

$$Q = U * Area * (T_{indoor} - T_{outdoor}) \quad \text{(eq. 1)}$$

$$Q_{ventilation} = \dot{m} * c_p * (T_{indoor} - T_{outdoor}) \quad \text{(eq. 2)}$$

Using 2022 weather data for Sumbay, the worst-case outdoor temperature was found to be -4°C (NSRDB, 2022). Applying equations 1 and 2, it can be shown that the cabin would require a heat pump rated at approximately 7 kW, assuming a COP of 4.0 when operating at sea level. However, Figure 4 shows the impacts of altitude-induced derating. The lower line of Figure 4 shows that 7 kW of heating is needed at sea level, but that increases to 8.5 kW of heating at an elevation of 4128 m.

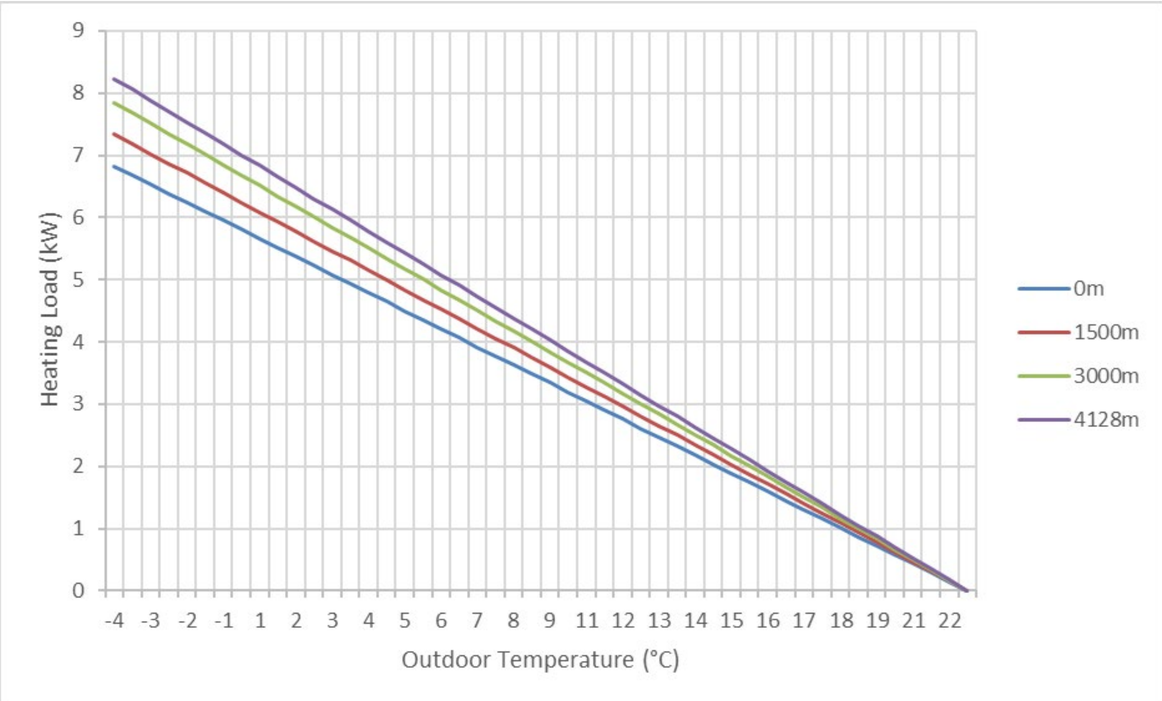

Figure 4: Heating Load Requirement Adjustment Due to Altitude Effects at Sumbay's Elevation

Local vendors have been identified to find an ASHP that is suitable based on the sizing calculations. The ASHP had to meet capacity requirements and have an integrated sensor for tracking its power consumption while in operation. The chosen ASHP will be installed and properly charged by contractors. One key part is installing the outdoor unit so that it is level and elevated above where snow and debris can accumulate on the ground.

5. ASHP Data Collection and Analysis

A variety of sensors have been installed at the research station to gather data for evaluating the heat pump performance over time. The following data will be monitored at 15-minute intervals to capture a variety of outdoor weather conditions.

- Outdoor Conditions, including temperature, humidity, and barometric pressure
- Indoor Conditions, including temperature and humidity inside the cabin
- Heat Pump Performance, including power use and air temperature differential for heating

The volumetric air flow across the indoor coil of the ASHP will be established by a direct measurement once the unit is installed and operating correctly. The volumetric air flow rate ($\dot{Q}_{air}$) will be constant over time. However, mass flow of air ($\dot{m}_{air}$) will vary based on weather conditions. The mass flow of air will be computed in real time using the volumetric flow and the ideal gas relationship shown in equation 3. In equation 3, p is barometric pressure, R is the ideal gas constant for air, and T is absolute temperature.

$$\dot{m}_{air} = \frac{p\dot{Q}_{air}}{RT} \quad \text{(eq. 3)}$$

AHRI Standard 210/240 will be used to compute air-source heat pump performance. This test procedure defines laboratory methods for determining heating capacity and coefficient of performance (AHRI, 2024). While originally intended for laboratory certification, these procedures provide a methodological foundation that can be adapted for field testing in remote, high-altitude locations such as Sumbay.

Within AHRI 210/240, the Indoor Air Enthalpy Method will be used for this field study. Equation 4 is an equation for the sensible heat output, where $\dot{m}_{air}$ is the mass flow rate of air passing through the indoor coil, c_p is the specific heat of the air, and T_{out} and T_{in} are the outlet and inlet temperatures of the air passing across the coil.

$$Q_{ASHP} = \dot{m}_{air} * c_p * (T_{out} - T_{in}) \quad \text{(eq.4)}$$

Lyu et al. determined an altitude factor by using the ratio of expected ASHP heat output versus actual heat output. For the ASHP installed at the CIBCI station, the expected heat output from the ASHP will be unknown unless a full capacity test is conducted, in which case the expected output would be the rated capacity of the ASHP. Therefore, a ratio of the rated COP and actual COP will be used to determine an altitude factor to then be applied to Lyu et al.'s model. The electrical power input W_{in} (kW) to the heat pump will be used to calculate COP according to Equation 5.

$$COP = \frac{Q_{ASHP}}{W_{in}} \quad \text{(eq.5)}$$

Following AHRI's data acquisition and calculation methodology while integrating site-specific parameters, such as measured barometric pressure, the data points collected at the CIBCI station can produce performance data directly comparable to that of the model by Lyu et al. (2024). The altitude factor can be determined by the ratio of the actual field COP to the manufacturer-rated COP. Comparisons can then be made with Lyu et al.'s findings across various outdoor temperature bins to evaluate consistency or variability of altitude effects. Appropriate statistical methods will be used to complete the comparison. In the scenario that the altitude factors differ, further investigation will be done using already collected data to correlate why the altitude factors varied and what could be done in future work.

6. Conclusion

The decarbonization of heating in high-altitude regions like the Peruvian Andes presents a significant challenge, requiring solutions that are both sustainable and effective in demanding environmental conditions. ASHPs offer a promising alternative to traditional biomass fuels, reducing greenhouse gas emissions and harmful indoor air pollution. However, their performance is known to degrade with increasing altitude, and existing models for this derating effect have not yet been validated in the climatic context of the Andes.

This paper outlines the methodology to directly address this knowledge gap. Through the installation, instrumentation, and ongoing monitoring of an ASHP system at the CIBCI research station, this study is designed to generate a crucial performance dataset for the region. The subsequent analysis, which will be grounded in established AHRI and ASHRAE testing standards, is intended to evaluate and refine existing altitude correction factor models, such as the one proposed by Lyu et al. (2024).

The anticipated findings from this research will have significant practical implications. A validated performance model would enable engineers and installers to more accurately size and specify ASHP systems for high-altitude applications, preventing underperformance and ensuring occupant comfort. Ultimately, this work aims to support the broader adoption of clean electric heating technologies, contributing to improved public health and energy sustainability in remote mountain communities in Peru and around the world.

7. References

AHRI. (2024). AHRI Standard 210/240-2024: Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment (I-P). Air-Conditioning, Heating, and Refrigeration Institute.

ASHRAE. (2017). *ANSI/ASHRAE Standard 37-2017: Methods of Testing for Rating Unitary Air-Conditioning and Heat Pump Equipment.* American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

ASHRAE. (2025). *ASHRAE handbook—Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., . . . Zender, C. S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research Atmospheres*, *118*(11), 5380–5552. https://doi.org/10.1002/jgrd.50171

Di, Y., Zhao, C., Lian, X., Li, X., Bao, D., & Liu, J. (2023). Study on the performance of a new Ultra-Low Temperature Air Source Heat Pump (ASHP) unit in cold regions. *Buildings*, *13*(8), 2107. https://doi.org/10.3390/buildings13082107

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., & Zwickel, T. (2014). Climate Change 2014: Mitigation. Technical Summary. *ResearchGate*. https://www.researchgate.net/publication/262048938_Climate_Change_2014_Mitigation_Technical_Summary

International Energy Agency IEA. (2024). The last-mile push to reach universal clean cooking access in Latin America and the Caribbean. (2024, December 16). IEA. https://www.iea.org/commentaries/the-last-mile-push-to-reach-universal-clean-cooking-access-in-latin-america-and-the-caribbean

International Energy Agency IEA. (2025). CO2 emissions – Global Energy Review 2025. IEA. https://www.iea.org/reports/global-energy-review-2025/co2-emissions

Li, Y., Li, W., Liu, Z., Lu, J., Zeng, L., & Yang, L. (2017). Theoretical and numerical study on performance of the air-source heat pump system in Xizang. Renewable Energy, 114, 489–501. https://doi.org/10.1016/j.renene.2017.07.033

Lyu, W., Wang, Z., Li, X., Xu, Z., Pu, Z., & Zhao, W. (2024). A simplified model for correcting the heating capacity of air source heat pumps in high-altitude plateau areas. *Energy, 305*, 132173. https://doi.org/10.1016/j.energy.2024.132173

Osmanaj, S. (2018). An experimental study of Wind Data of a Wind Farm in Kosovo. *PRZEGLĄD ELEKTROTECHNICZNY*, *1*(7), 23–27. https://doi.org/10.15199/48.2018.07.05

NSRDB. (2022). https://nsrdb.nrel.gov/data-viewer

Riffat, S. B., & Ma, X. (2004). Improving the coefficient of performance of thermoelectric cooling systems: a review. *International Journal of Energy Research*, *28*(9), 753–768. https://doi.org/10.1002/er.991

World Health Organization. (2021). *Household air pollution and health*. WHO. https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

Xu, F., Chen, X., Zhang, H., & Shi, Y. (2020). Field study on winter heating performance of the air source heat pump system in cold regions. *International Journal of Heat and Technology*, *38*(1), 213–222. https://doi.org/10.18280/ijht.380123

Zhang, B., Shen, Z., Sun, J., He, K., Zou, H., Zhang, Q., Li, J., Xu, H., Liu, S., Ho, K., & Cao, J. (2022). County-level of particle and gases emission inventory for animal dung burning in the Qinghai–Tibetan Plateau, China. *Journal of Cleaner Production*, *367*, 133051. https://doi.org/10.1016/j.jclepro.2022.133051

Zhang, M., Yang, Z., Ma, J., Zhang, X., Xiao, H., Wang, R., Shi, W., & Wang, B. (2021). Standard rating conditions based on two-side multi-grade method: summary and analysis on the Chinese standards for air source heat pumps. International Journal of Refrigeration, 131, 394–406. https://doi.org/10.1016/j.ijrefrig.2021.07.005