Single-Family Residential Thermal Energy Storage

New Mexico

Supercomputing Challenge

Final Report

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Executive Summary

Current single-family heating in the United States uses a lot of carbon. Carbon-intensive gas furnaces can be replaced with heat pump technology. Several of the shortcomings of heat pumps, such as cost and versatility, might be addressed by using thermal energy storage to load-shift and run the heat pump when it is more efficient or at least possible to do so. The system analyzed consists of a 2000 square-foot home with hydronic heating, an outdoor water storage tank, an air-source water heating heat pump with performance equations and data taken from the literature, and hourly weather records from various climates across the U.S. The conclusion is that while load-shifting with thermal energy storage is possible, recently released air-source heat pumps with backup heating are adequate for the continental U.S.

Problem statement

Residential energy infrastructure is highly carbon intensive. Residential natural gas usage contributes around 15% of total U.S. natural gas consumption [EIA, 2023]. Over 90% of the natural gas used in homes is for space heating and water heating [EIA, 2024]. The total energy consumption for space and water heating from natural gas, propane, and fuel oil in homes is approximately the same as the total residential electrical energy usage [EIA, 2024]. This indicates that the electrical grid would need to provide twice what it currently does annually to replace fossil fuel heating with electric resistance heating. Heat pumps could help mitigate this need, as they can be 2-5 times more energy efficient in space heating than electric resistance heating [NEEP].

Technology	Cost to replace existing furnace	Concerns	Positives
Gas Furnace	$5k	Carbon intensive	Low cost
Air-Source Heat Pump	$10k	Limited by air temperature	Low carbon
Ground-Source Heat Pump	$5-60k	Limited by local geology, high cost	High COP

Table 1: Summary of currently available alternatives to electric resistance heating.

Air-source heat pumps (ASHP) are less energy efficient the colder the outside air is, and there is a temperature below which an ASHP cannot operate. For cold climate air source heat pumps, this is currently around -13°F. It currently costs about $10,000 to install an ASHP in place of other heating systems, and resistance or gas heating backup can be integrated with ASHP models where necessary [Mitchell & Kaluza]. Ground-source heat pumps (GSHP) are affected by the viability of local geology for drilling or digging. It costs $5,000-60,000 to install a GSHP depending on the case, and they have a ratio of heat output to energy input, called a coefficient of performance (COP), of 3-5 [Maday]. Because of the geological limitations on GSHPs and the air temperature limitations on ASHPs, it may make sense to have a system that stores heat with thermal energy storage (TES) to use in conditions where an air source heat pump is regularly non-functional due to low air temperature or where ground source heat pumps are inapplicable.

The type of TES technology is limited by several factors. Most important is personal and environmental safety in a single-family residential (SFR) setting, which eliminates most chemical batteries, fuel cells, and organic phase change materials. The temperature range of molten silicon, molten salts, sand, and most inorganic phase change materials is incompatible with safety or SFR heating equipment. Water is promising as a storage medium due to its abundance, non-toxicity, high volumetric heat capacity, and compatibility with air to water ASHPs. The readily available complex solutions for large multifamily and commercial buildings rely on excess heat generation by the housed activities and often rely on industrial scale ice generation for TES, conditions which do not occur in a SFR [CALMAC]. This leaves utilizing the temperature differential of a water tank at higher temperatures for consideration.

Model

Single-Family Residence Demand

Three locations are modeled to evaluate SFR TES: Albuquerque, NM; Los Alamos, NM; and Bismarck, ND. The model uses average hourly temperature data for each location [NREL]. The heat demand in each case is of a 2000 ft^2 house of the same dimensions—30x66.7x8.5 ft—with an 85/15 wall to window ratio using the various insulation levels for different locations [ENERGY STAR] (See table 2).

Location	Walls (1400 ft^2)	Doors/windows (250 ft^2)	Roof (2000 ft^2)	Floor (2000 ft^2)
Albuquerque	R11	R2	R60	R19
Los Alamos	R15	R2	R60	R30
Bismarck	R15	R2	R60	R30

Table 2: R-values used to model well-insulated homes.

The heat loss of a surface, measured in Btu/hour, is given by the following [Pisupati]:

$$Heat\ Loss = \frac{Area\ \cdot\ \Delta T}{R - value}$$

The heat demand is met with a hot-water heating system that requires water with a temperature of at least 120°F to be pumped through it [King Electric].

Heat Pump

The heat pump modeled is a 1-stage air to water ASHP rated up to 75°C (167°F) output and that uses R410 as a refrigerant [Le et al.]. The approximately linear data of the COP and maximum electrical input relative to outside temperature allows interpolation or extrapolation of these values for winter temperatures. When multiplied together, these values give the output rate for the heat pump.

Tank

The tank is modeled as a cylinder with a height to diameter ratio of 1.0. The final volume of the tanks is approximately 2500 gallons in Albuquerque, 3000 gallons in Los Alamos, and 6000 gallons in Bismarck, to meet most of the heating demand of a typical year. These tanks cost $5,000-10,000 [Tank Depot]. The heat loss of the tank is modeled using R-value 10 for the bottom of the tank and R-value 60 for the other surfaces. The change in temperature is calculated on an average hourly basis using the following equations, with q as heat, ΔT as the change in temperature between the inside and outside of the tank, m as mass, and C_p as specific heat:

$$\Delta Q = q_{in} - q_{out} = q_{HP} - q_{house} - q_{loss}$$

$$\Delta T = \frac{\Delta Q}{m \cdot C_p}$$

Control Algorithm

The control logic has four primary factors deciding whether the heat pump is active or not in descending order of precedence. Several of these factors are tied to the local weather forecast. The forecast indicates when any hourly outdoor temperature in the short future period is below a target threshold. This period is approximately the length of the charge/discharge cycle.

The first factor is the temperature inside the tank. The controller aims to keep the temperature inside the tank between high and low target temperatures. The high target temperature is always 160°F to stay at a reasonable output pulled from the heat pump. The low target temperature is 130°F by default, but it is raised to 150°F if the forecast shows temperatures outdoor temperatures below 20°F. This action decreases the likelihood of hitting a cold period when near 130°F, which could cause the tank temperature to fall below the minimum 120°F.

The second factor is the outside air temperature. There is a preferred low temperature below which the heat pump is turned off for efficiency. This is set at a high threshold by default, but if the forecast shows the temperature falls below the low threshold, the low temperature is the low threshold instead (See table 3).

Location	High threshold (°F)	Low threshold (°F)
Albuquerque	30	20
Los Alamos	20	10
Bismarck	10	0

Table 3: Selected low temperature limits for heat pump operation.

The third factor is that if the tank temperature drops below 120°F and it is possible for the heat pump to run, it engages the heat pump. This reduces periods when the tank may go below the minimum temperature of 120°F necessary for heating the house.

The final factor is that when the forecast doesn’t show any temperature below 62°F, it disables the heat pump, as any heat demand at that point is likely short transient summer demand that need not be met.

This combination of factors is sufficient to determine the feasibility questions about SFR TES. The best available heat pumps are variable-speed, which allows for smooth rather than on-off control. Unfortunately, the technical data for performance modeling of these heat pumps is not readily available. The model is coded in Python using pandas to manage the data and matplotlib to visualize the results.

Verification

I verified the model using a manual calculation for a single timestep and comparing it to the values given by the model, getting the same answers. I also used a spreadsheet to calculate the volume of tank needed to supply the heat demand of a house for 7 days based on heating degree day data from 2020 [NOAA]. I used the result as an upper limit to the size of tank considered in the model, which was about 10,000 gallons.

The control logic is demonstrated by a graph of February 2022 in Albuquerque, as it shows the tank temperature cycling and the external operating temperature control influenced by the forecast (See Figure 1).

Results

The results of the model show that for the 2022 data all the three cases have a tank temperature above 120°F for the duration of the year (See Figures 2-4). This confirms that it is feasible for a tank to load-shift heat for residential heating. I also did a manual plot of the output of a 36,000 Btu/hr rated Mitsubishi cold climate ASHP and the house heat demand against outside temperature [AWS] (See Figure 5). It shows that all the way down to -13°F, the output of the heat pump is higher than the demand. This means that the house can be heated using only the ASHP down to the minimum operating temperature of the heat pump. There are cold-rated heat pumps with outputs from 9,000-48,000 Btu/hr available to heat any size residence.

The model predicts the power needed for supplementary electric resistance heating to heat the house when the heat pump is unable and the amount of power the heat pump or a resistance heater would consume over the course of the year when heat pump operation is feasible. The supplementary heating took about 300 kWh per year in Bismarck and was negligible in Albuquerque and Los Alamos. This is insignificant compared to the 13,000 kWh per year needed to operate the heat pump for the year. The annualized cost ($10,000/25 years) of the water tank is likely more than the cost of using backup gas or electricity instead. Although it is physically possible to load-shift using thermal energy storage, it appears economically infeasible compared to the cost of using an ASHP with supplementary heating instead.

Most Significant Achievement

I think that my most significant achievement over the course of the project were my attempts at optimizing code performance. Most of the code related to my project was written in Python, with data management usually being done with pandas or NumPy. The early versions of 2-D plate conductivity models and the system model were very inefficient with memory usage, often including unnecessary copying to temporary variables. This caused the code to run slower and use more memory, which became obvious and hindered debugging with larger datasets. To fix this, I learned methods in NumPy, pandas, and utilities built for these libraries that avoid unnecessary copying without changing the way the underlying logic functions. I also found and applied methods that placed work inside efficient libraries instead of in loops of my own code.

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Figures

Figure 1: February 2022 simulation in Albuquerque with a 2500-gallon tank

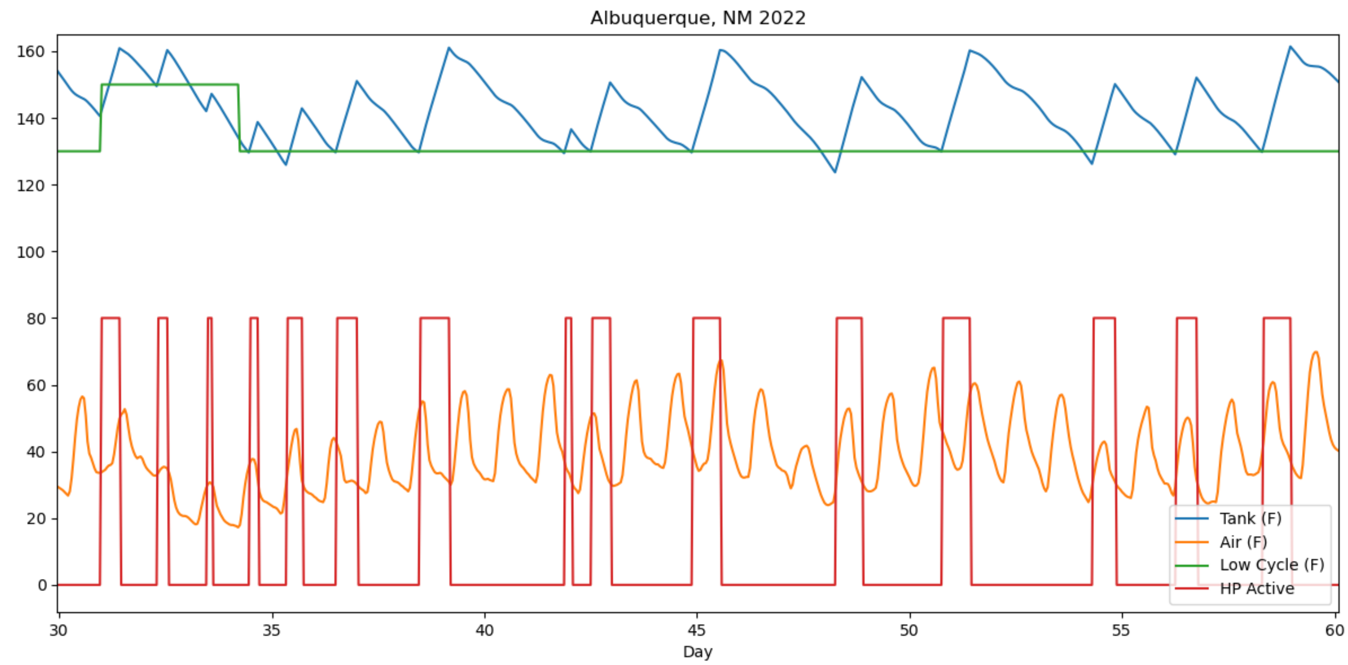


Figure 2: January to December 2022 simulation in Albuquerque with a 2500-gallon tank

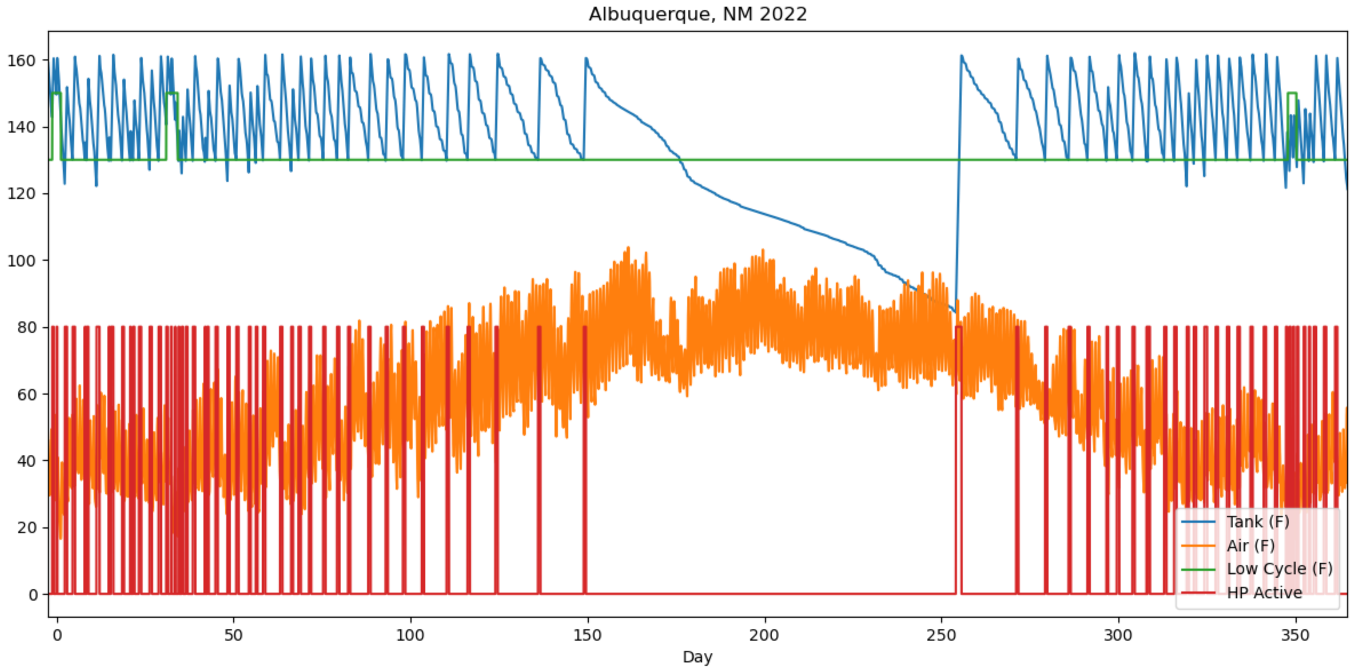


Figure 3: January to December 2022 simulation in Los Alamos with a 3000-gallon tank

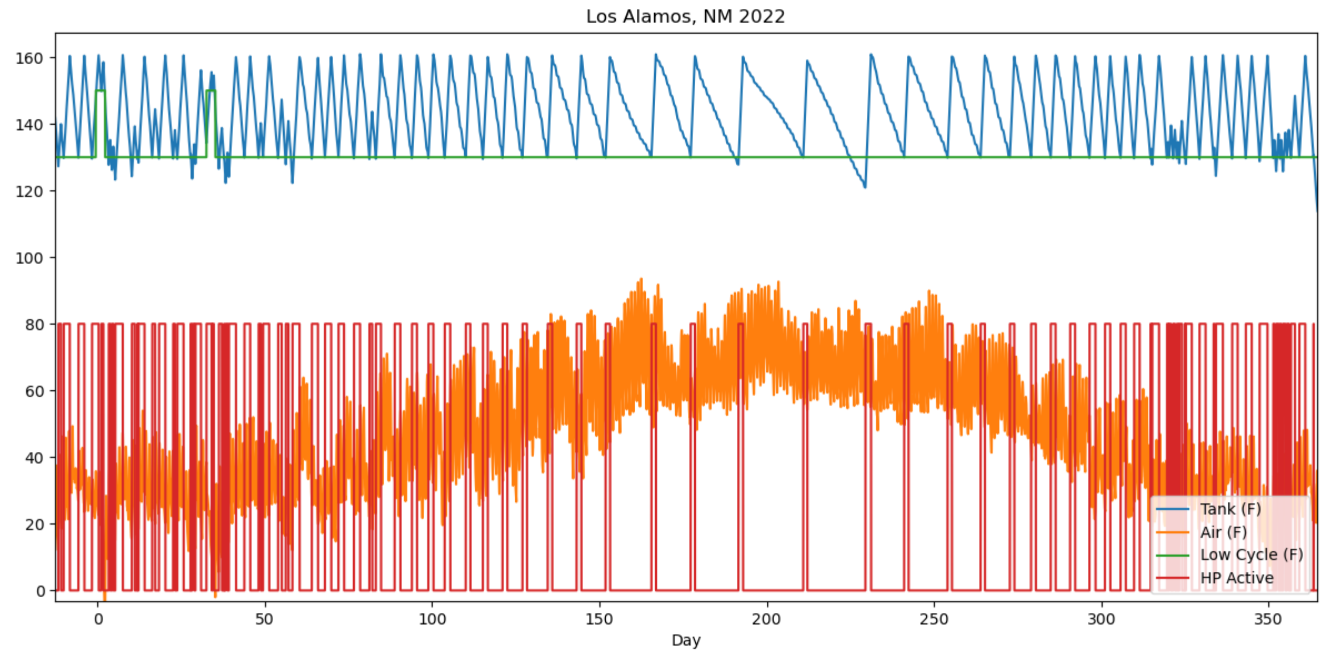


Figure 4: January to December 2022 simulation in Bismarck with a 6000-gallon tank

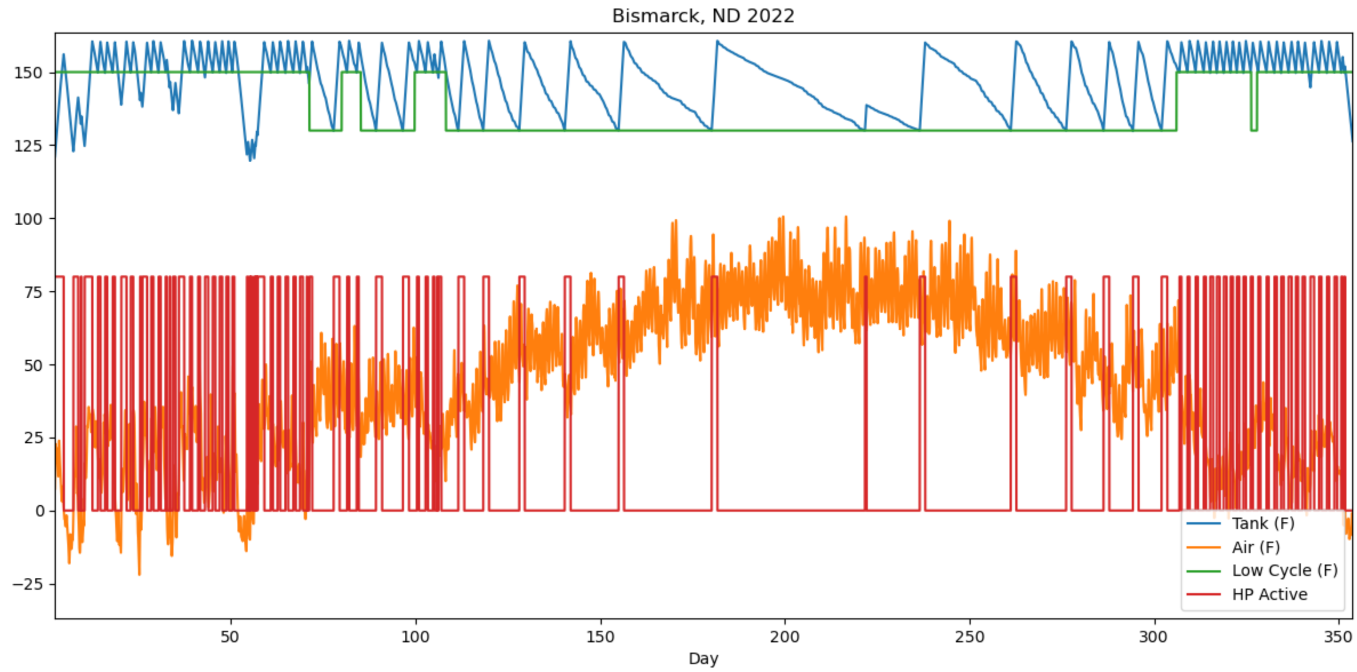
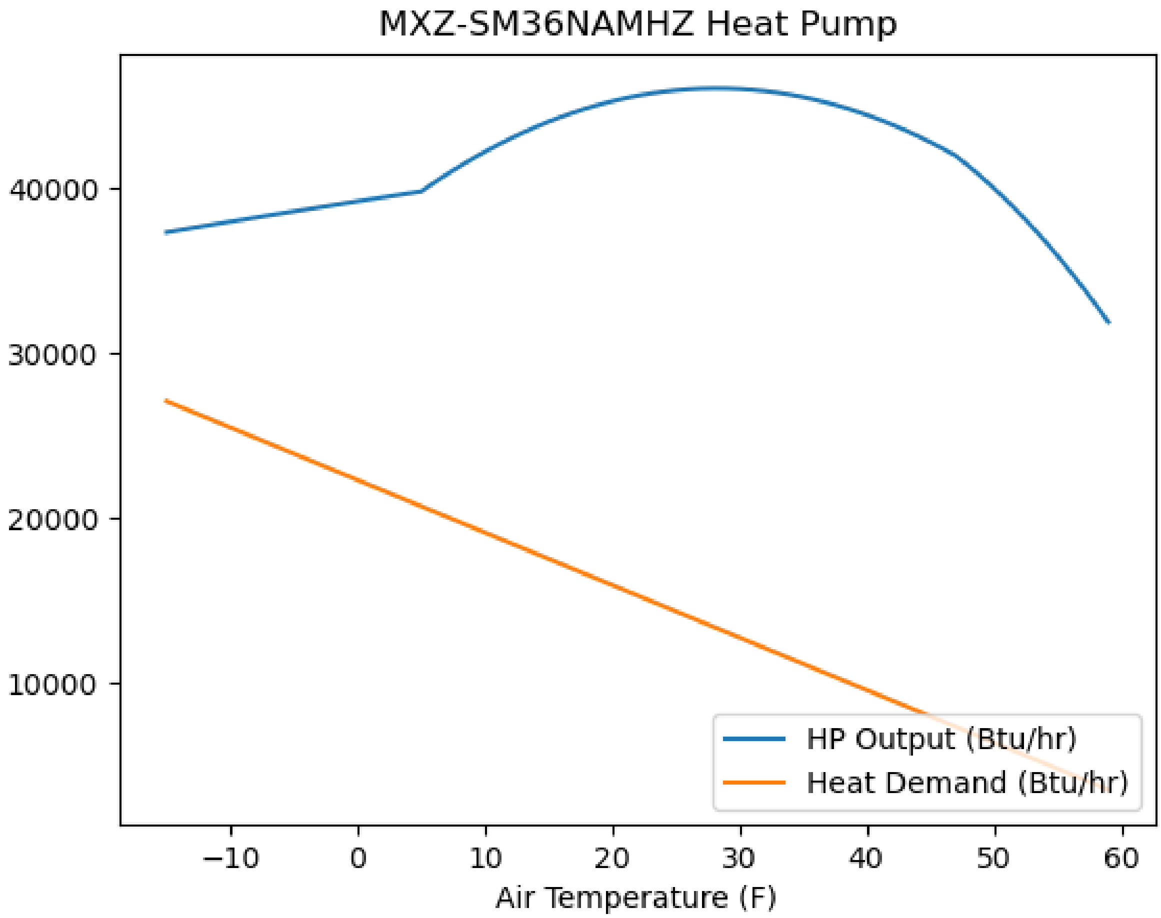


Figure 5: Output of a 36K Mitsubishi cold climate ASHP and demand vs. air temperature



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