A Dynamic Modeling Framework for High-Performance Heat Pumps and Controls Evaluations

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ABSTRACT

High performance HVAC equipment such as cold climate heat pumps is crucial to the nation's building electrification goals. The operation of HVAC systems is dynamic, subject to ambient conditions, controls and occupants' interactions via thermostats. Moreover, a wider adoption of heat pumps relies on customers' satisfaction on both energy efficiencies and thermal comfort. We developed a Modelica-based modeling framework that can simulate the dynamic operation and occupant's thermal comfort of residential HVAC equipment, including air conditioners, furnace, heat pumps, fans and thermostats, in realistic house environment. The framework leverages multiple latest development from DOE Building Energy Modeling Program including Modelica Buildings Library, Spawn of EnergyPlus, ResStock and BOPTEST, from which high-fidelity and computationally efficient component models are applied in the framework to be used for evaluating various smart thermostat algorithms. These can include, for example, basic functions such as occupant-sensing based and/or schedule-based setpoint setbacks.
We utilized the framework to conduct annual energy consumptions and thermal comfort simulations for over 250 houses across the United States and its climate zones. Our preliminary analysis shows different thermostat setback strategies may lead to energy savings range from 2% to more than 20%. In this paper, we focus on demonstrating the details of various HVAC equipment models and their operating modes such as controls of auxiliary heaters, frost and defrost operations and speed controls of double-speed and variable speed heat pumps. We believe the framework could be a useful virtual testbed for studying equipment impacts to building electrification.

1. INTRODUCTION

Heat pumps are a crucial piece of building equipment to reduce energy consumptions and accelerate the use of clean and renewable energy. However, predicting the energy use of heat pumps in realistic housing environment can be an intricate task especially when we consider each building is unique regarding the envelop, location, occupants' behaviors and the resulting equipment controls. In the field, the actual operation of heat pumps may deviate significantly from their lab test conditions and underlying assumptions of efficiency ratings. To improve the prediction without incurring a high cost from field measurements, one viable solution is to develop a simulation-based framework for evaluating heat pumps' dynamic operation in realistic housing environment and accounting for the abovementioned field factors. The creation of such a framework not only produces a realistic indoor load profile but also offers an opportunity to integrate occupant-building interactions, such as a time series of thermostat setpoints, so that it is possible to capture the cyclic operation of heat pumps.

To establish such a framework, we must simultaneously model both heat pumps' dynamic operation and the response from the thermal zone such as the resulting change of indoor temperature from the dynamic operation. Although there are various software packages capable of conducting these two simulations, additional features such as the computational efficiency of executing such co-simulations between equipment and building, and a pathway of scaling up any analyses to a large region, e.g., a national level, are desired to make the simulations impactful. Given all these considerations, we selected a set of building energy modeling software packages, namely, Spawn of

EnergyPlus, Modelica Buildings Library, ResStock, and BOPTEST, all of which are under the active development and maintenance by the US Department of Energy, Building Technologies Office. Spawn of EnergyPlus (Spawn, 2014) is a next-generation engine intended to bridge the worlds of BEM and control workflows. Spawn reuses the EnergyPlus modules for lighting, building envelope, and loads but re-implements the HVAC and controls modules in the equation-based modeling language Modelica. The selection of Spawn as the primary engine for building load simulation enabled a smooth integration with components available in Modelica Buildings Library (MBL) (Modelica Budlings Library, 2024). Various HVAC components available in the MBL can be connected to the Spawn building model to investigate cyclic operations of equipment in response to time variant indoor thermal load, which also enables modeling of thermostats' functionalities such as setpoint scheduling. By using BOPTEST (Building Operations Testing Framework) (BOPTEST, 2023), control points such as indoor air temperature, occupancy schedule, can be exposed to third party control algorithms developed for smart thermostats which then return control signals (on/off, mode switch, compressor speed and so on) to HVAC equipment. In addition, BOPTEST is used to compute key performance indicators (KPIs) such as HVAC power consumptions and occupant thermal comfort index. As we mentioned earlier, since each building and its installed HVAC system operation are unique, it is important to consider an ensemble of buildings that can be statistically representable to US housing stock, so the simulation results can be an impactful reference to the nation's building electrifications. In light of this, ResStock (ResStock Analysis Tool, 2024) is used as a database to provide a large and diverse housing samples in a way that Spawn can readily use.

The framework has been utilized to evaluate the energy savings and thermal comfort of smart thermostats in 52 representative houses across the nation by *Benne et. al* (2024). In this paper, we focus on introducing the HVAC equipment modeling methodologies. We will next examine the component models such as thermal zones and two speed heat pumps as well as controls that are typical to HVAC products such as ones for defrosting operations of heat pumps, backup heater and others. Benne et. al. studied three types of equipment: air conditioners plus furnaces, single speed heat pumps, and two speed heat pumps. To delve into the details of the equipment modeling using a limited number of pages, the authors decided to focus on one type of equipment, two speed heat pumps, because their modeling requires more controls than any other two types.

2. METHODOLOGY

To model various HVAC equipment including heat pumps, we utilize models available in the MBL of which two main ones are Spawn (MBL path: Buildings.ThermalZones.EnergyPlus_9_6_0.ThermalZone) and HVAC equipment, e.g., heat pumps (MBL package path: Buildings.Fluid.HeatPumps) and electric backup heaters (Buildings.Fluid.HeatExchangers.HeaterCooler_u). For the sake of brevity, the detailed implementations of these models can be found in the Modelica Budlings Library (2024). Additional functionalities were added to the systems to account for important features, namely, air infiltration, baseline thermostat controls, heat pump defrost controls, fan operation controls and backup heater controls.

Air infiltration needs to be added to Spawn thermal zone model due to the way Spawn was implemented that removed the infiltration flow rates from the original EnergyPlus file. Air infiltration is the unintended flow of air from the outdoor directly into a thermal zone, which among many implications, will impact the indoor thermal load. The calculation of air infiltration uses the following equation that assumes temperature difference between indoor and outdoor temperature and windspeed are the driving forces. The equation (Sherman and Grimsrud, 1980) also requires an estimation of effective leakage area.

$$Infiltration\ (volumetric\ rate) = \frac{A_L}{1000} * \sqrt{C_s|\Delta T| + C_w(WindSpeed)^2} \quad (1)$$

Where
A_L is the effective air leakage area, "good" insulation is assumed in the simulations
C_s and C_w are stack coefficient and wind coefficient, respectively. 0.000145 and 0.000174 are assumed in the simulations, respectively.
ΔT is the average indoor-outdoor temperature difference and *WindSpeed* is the average local wind speed. Both parameters were obtained from the simulations.

Baseline thermostat controls utilize the Hysteresis block from the MBL (Buildings.Controls. OBC.CDL.Continuous.Hysteresis) which allows users to set lower and higher temperature thresholds of a thermostat. As an example, if 22.3°C and 24.3°C are set as the lower and higher thresholds, respectively, the thermostat will not turn on a heat pump until the indoor temperature exceeds 24.3°C and will not turn off the heat pump until the indoor temperature is below 22.3°C. When the indoor air temperature falls in the region of 22.3°C and 24.3°C, no action is taken by the heat pump, i.e., no action in a dead band. Among many advantages of using a hysteresis control, avoiding a chattering behavior from the HVAC equipment is a major concern. Two speed units require a more complicated thermostat control so that the thermostat can send not only the on and off signal but also a speed signal. In this case, a state graph was utilized to determine the heat pump's operation status. The transition criteria of the thermostat from one state to another may require the consideration of both T_air (indoor air temperature) and the derivative of the indoor air temperature, indicating whether the temperature moves towards the desired direction or not. Figure 1 shows an example of such implementation for two speed heat pumps in the heating operation. Advanced thermostat algorithm may include additional features such as occupancy thermostat and night thermostat as shown in Figure 2.

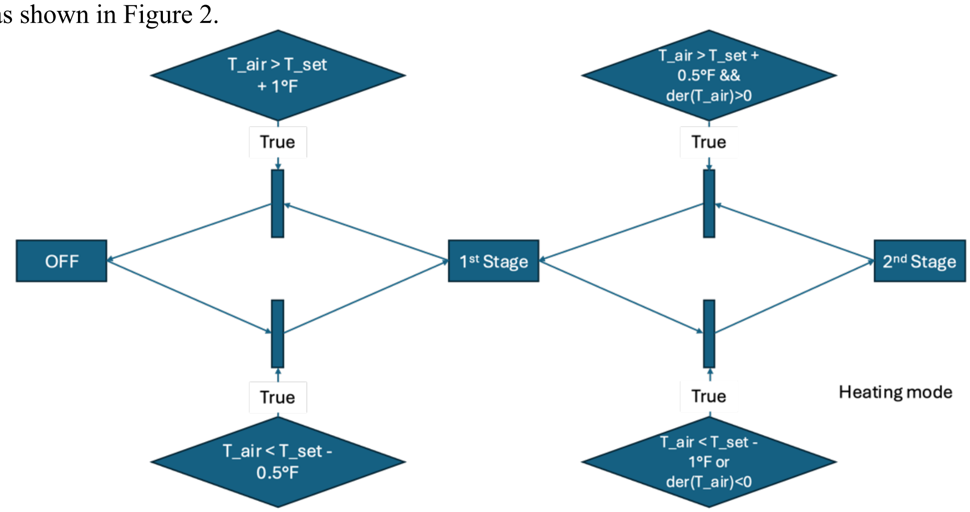


Figure 1: Compressor speed control for a two-speed heat pump under heating operation

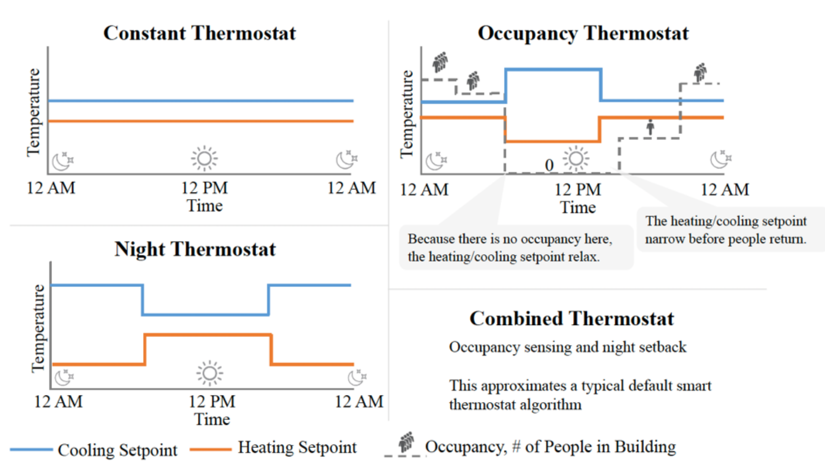


Figure 2: Various smart thermostat settings [5]

Heat pumps may undergo defrosting cycles from time to time in a winter when frost frequently accumulates on the outdoor coil. Via defrosting, heat pumps reset the coil surface condition so that its heat transfer with the ambient air is recovered. There are several options for heat pumps to defrost the outdoor coil and the paper only considers the use of reverse cycles. Many state-of-the-art heat pumps adopt a combined time-based and temperature sensor-based approach to determine the onset and cessation of defrosting cycles. However, the air conditioner and heat pump components we adopted in this study do not include the modeling of refrigerant pressure and temperature, and as a result, defrosting controls presented in this paper only consider a time-based approach. As Figure 3 shows, the heat pump will start defrosting when the accumulated time reaches 30 min. for counting both conditions regarding ambient temperature and heat pump status are true. This logic reflects our thought that when both conditions are true, frost can build up on the coil, and when either one is false, no frost is generated at the instance. The defrost time will be set to 20 min. without interruption and after that, both timers will be reset to zero.

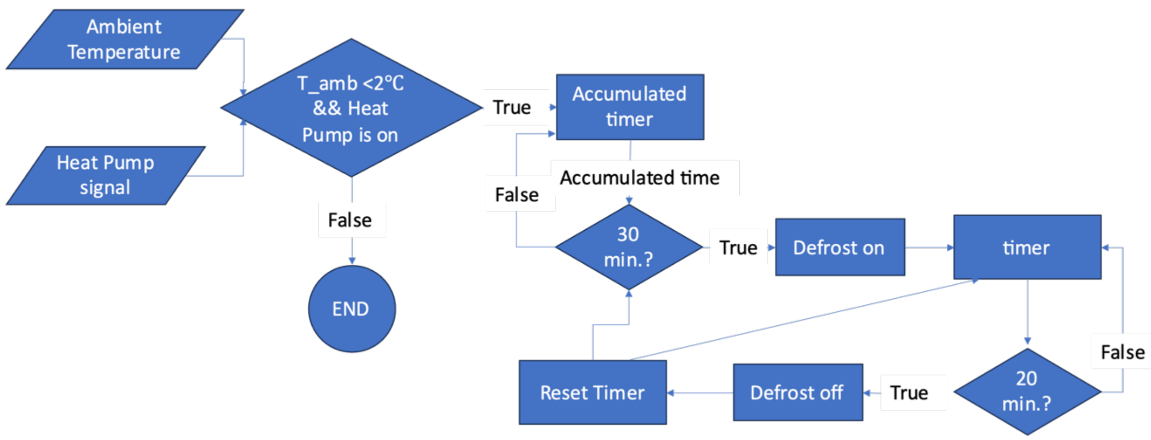


Figure 3: Heat pump defrost control logic

To protect HVAC equipment, indoor fans were modelled to be on 30 seconds before HVAC turns on and to be off 30 seconds after the HVAC equipment turns off. A fixed delay block (Modelica.Blocks.Nonlinear.FixedDelay) is used to implement the 30 seconds delay on the HVAC equipment when a thermostat sends the ON signal to the HVAC equipment and, vice versa, the 30 seconds delay will be implemented on the fan when thermostat sends the OFF signal to the HVAC equipment.

Backup heaters were modeled along with all heat pumps and the heater turns on when the ambient temperature becomes too low for the heat pump to operate (e.g., -5°C in the paper). For simplicities, the backup heater, in this paper, functions like an emergency heater, i.e., it will not work in parallel with the heat pump, and the heater will only have one stage of power inputs. When the heater is on, the accumulated timer mentioned above in the defrost control will not accumulate time because the heat pump is off. We acknowledge, in the field, there are products which can turn on both heaters and heat pumps the same time, e.g., A heater functions like a supplement to the heat pump.

3. RESULTS AND DISCUSSIONS

We will start this section by reviewing the implementation of previously mentioned customized controls, followed by presenting the annual heat pump operation. The simulations were conducted under typical climate conditions of Baltimore, MD (Wilcox and Marion, 2008). The house under the study is a two story, single thermostat zone, detached house with an indoor area of 1600 sq. ft.
It should be noted that we conducted annual simulations of the two speed heat pump operation, but some plots are zoomed in to a couple of days or even hours in a day so that readers can better examine the proper control implementations.
Figure 4 shows the annual infiltration flow rate of the house using Eqn. 1. The air flow rate ranges from 0.00171 kg/s to 0.174 kg/s, with an average of 0.0614 kg/s. As the equation suggests, the infiltration flow rate shows a strong correlation with the temperature difference between indoor air and outdoor air which is larger in winter and smaller in summer. The windspeed does not vary too much in the location to make an impact to the infiltration.

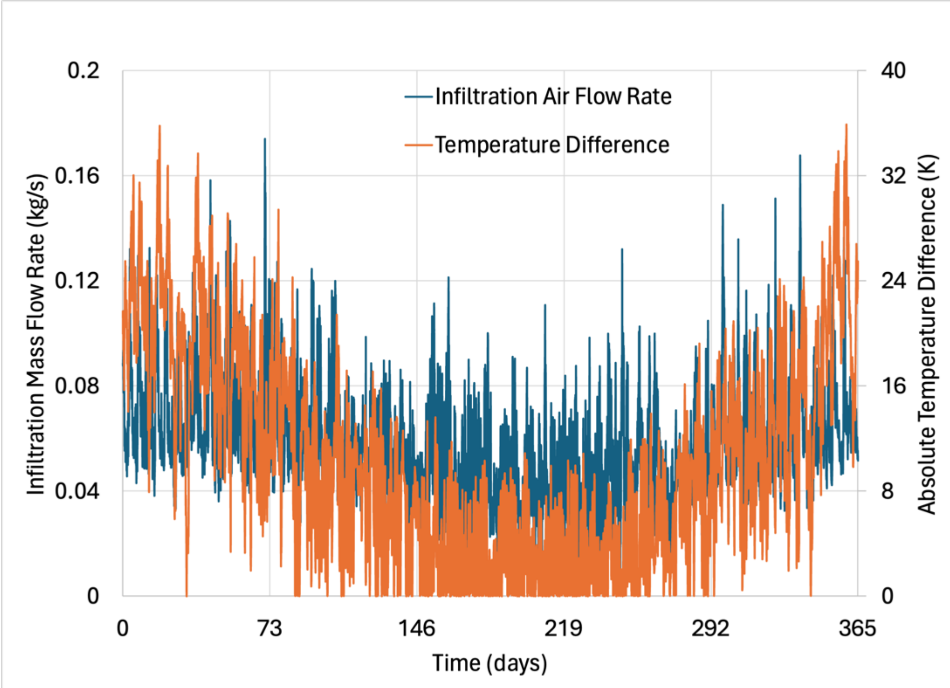


Figure 4: Annual infiltration flow rate compared to indoor/outdoor temperature difference

As we mentioned earlier, the baseline thermostat has two temperature settings in heating and cooling modes, respectively. Figure 5 shows the annual indoor air temperature which is generally kept well controlled within the dead band of cooling and heating setpoints. The temperature does swing in a wider range during shoulder seasons and this leads to early cooling in March and late heating in early September as the Time (days) indicated. We acknowledge the fact that in the field, occupants may have to manually switch the heat pump modes and as a result, the indoor air temperature may show a different profile. In addition, there are days in summer when the temperature exceeds the upper threshold of the dead band. This is due to the sizing (EnergyPlus Input Output References, 2021) of the equipment leads to unmet hours, not noises from control signals.

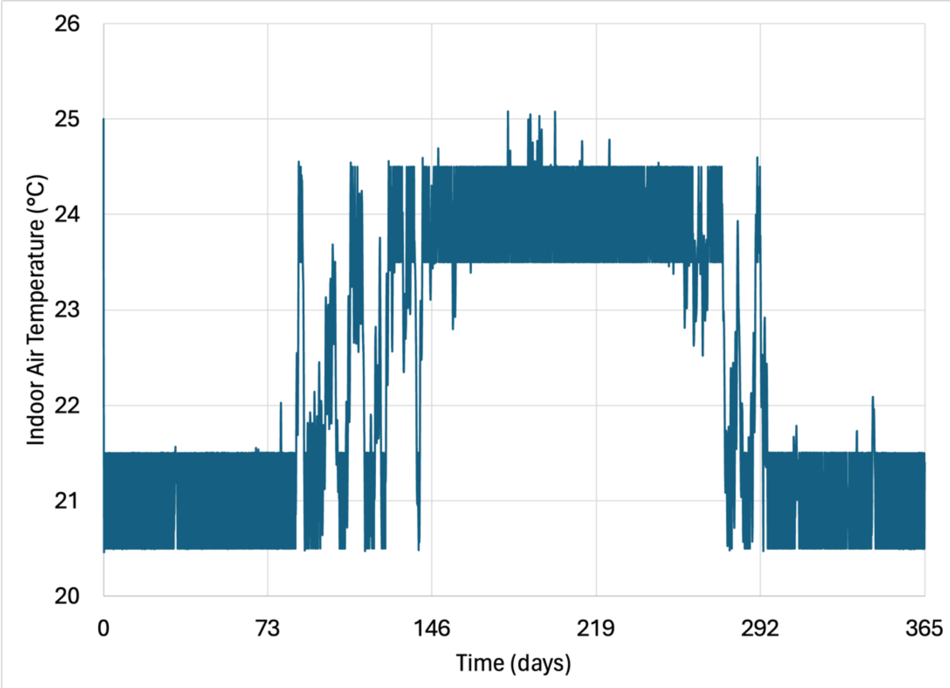


Figure 5: Annual indoor air temperature profile

Figure 6 shows a zoom in view of the first 2 days in year, so readers can conveniently examine the defrost control implemented to the heat pump model. The accumulated timer only adds minutes when the heat pump is in operation and the ambient temperature is below 2°C. This explains the lack of defrost operation in the middle of day 1 when the ambient temperature is higher than the threshold. In the remaining time, the defrost starts after almost every heat pump's operation which appear to require a longer run period of 30 min. if not cut short by the defrost.

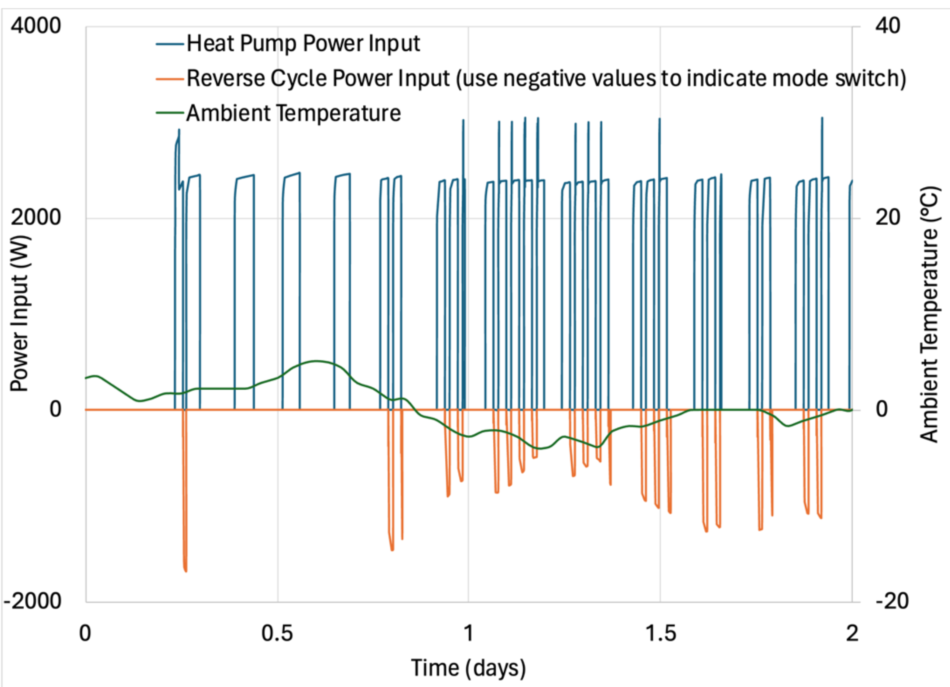


Figure 6: Zoom in view to examine defrost control

We next examine the control of fan and heat pump operation sequence. We intend to protect the heat pump during start up so the fan turns on in advance to provide enough air flow through the coil and we intend to utilize free cooling/heating on the coil so we keep the fan on for 30 seconds after the equipment is off. Figure 7 shows the cooling operation is in sync with the indoor air flow circulation and the sequential operation of fan and the equipment is correctly implemented.

We next examine the compressor speed control for a two-speed heat pump (Figure 8). As we described in the early section, in heating mode, the compressor steps up from a lower speed setting to a higher speed setting when either of two condition becomes true: 1) the indoor air temperature falls more than 1°F below the setpoint; 2) the derivative of the indoor temperature is smaller than zero, meaning the air temperature deviates away from the correct direction. The heating operation is also complicated by the defrost operation and therefore we plotted the defrost power, heat pumping power and indoor air temperature altogether to better review the implemented control. The zoom in period starts with a time when the heat pump is OFF and the room temperature gradually falls towards the lower threshold (20.5°F). Once the indoor temperature reaches it, the heat pump turns on at the lower speed setting and the room temperature increases for 30 min. and then the defrost starts. During the defrost period, due to the indoor thermal inertia, the room temperature still increases but the derivative of the temperature becomes closer to zero. As the defrost period ends, the heat pump returns to the lower speed setting but the derivative of the room temperature turns to negative, so the heat pump steps up to the higher speed setting to correct the indoor temperature trend, even though temperature wise, the high speed setting threshold of indoor temperature has not been met. The high speed setting provides the heat pump enough capacity to quickly correct the trend of indoor air temperature and since the temperature threshold has not yet been met, the equipment falls back to the low speed setting very shortly.

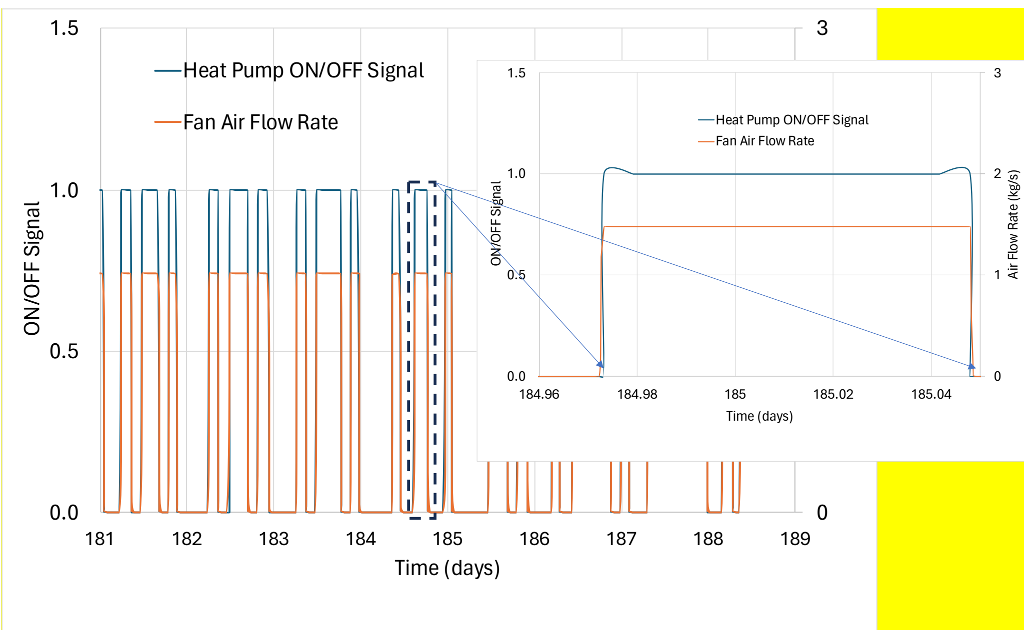


Figure 7: Zoom in view to examine fan control sequence

We last review our implementation of the backup heater control. There are two aspects of the implementation to be examined: the backup heater turns on when the ambient temperature is below -5°C and once the heater is on, the heat pump turns off. Figure 9 demonstrates that the control is correctly implemented.

With all the controls being examined, we present the overall annual power consumptions from various modes of the two-speed heat pump (Figure 10). We use different colors to distinguish the heat pump operation modes: heat pumping, air conditioning, defrosting and heating via the backup heater. We also overlay the ambient temperature to the power consumptions so that it is clear to the readers when the heat pump has to change the operating modes. Figure 11 *(Benne et. al, 2024)* presents the energy use intensity and thermal comfort of 52 houses across the United States using the two-speed heat pump model. Different colors represent different smart thermostat settings and the large circles indicate the average value of the 52 houses. Occupancy is predicted to save the least energy on average of 2-3%, Night saves about 4-6%, and Combined 5-8%. As the paper focuses on presenting the equipment modeling details, we will not discuss the savings due to different thermostat settings. Instead, we encourage readers to refer to the paper by *Benne et. al.* (2024) for more information regarding other HVAC equipment type and detailed smart thermostat control implementations.

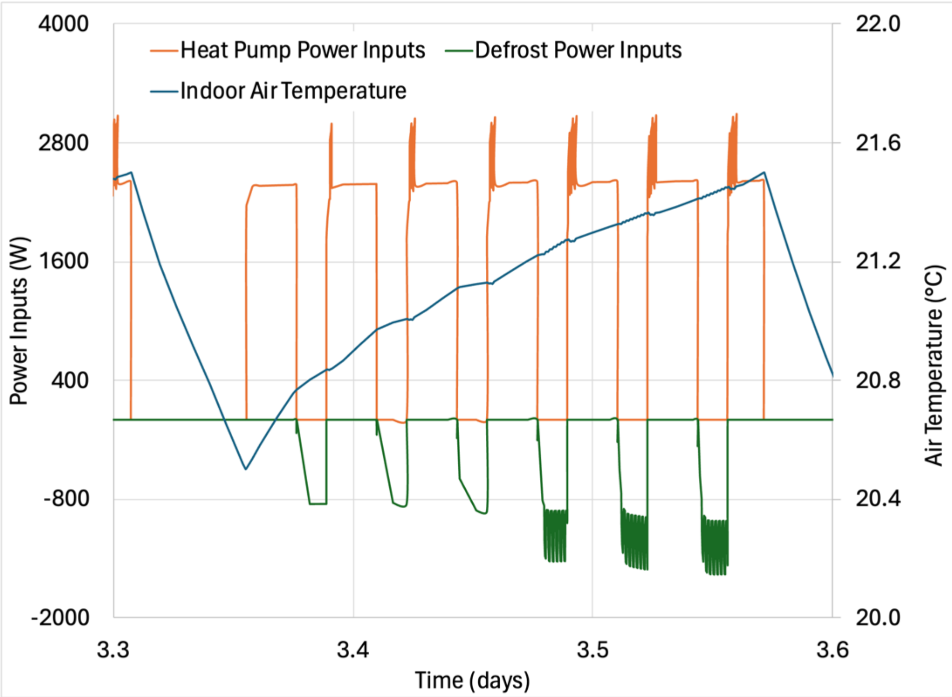


Figure 8: Zoom in view to examine compressor speed control

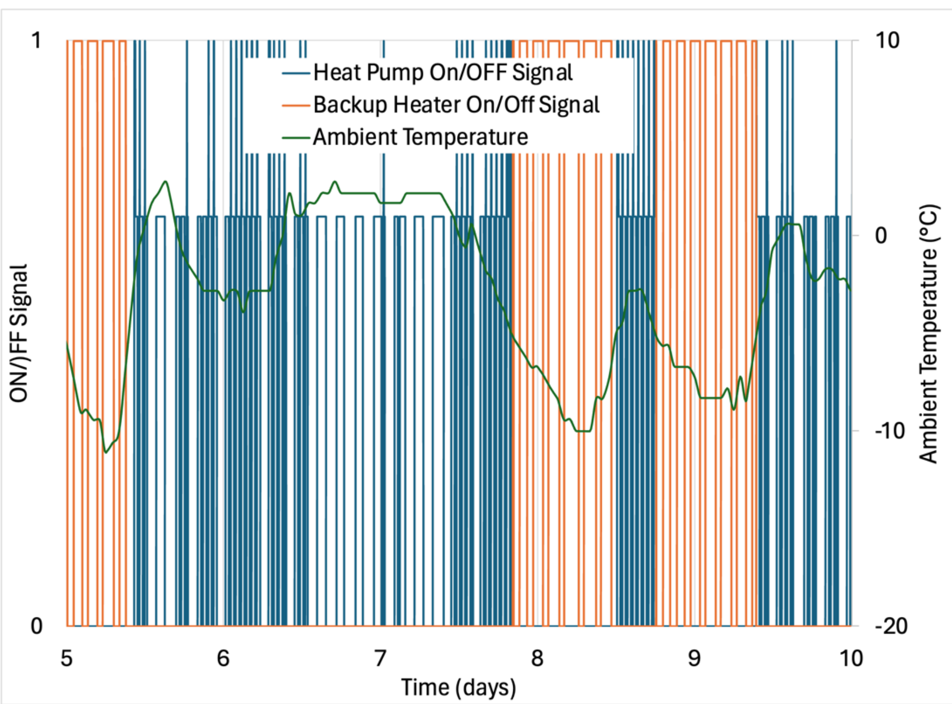


Figure 9: Zoom in view to examine back up heater control

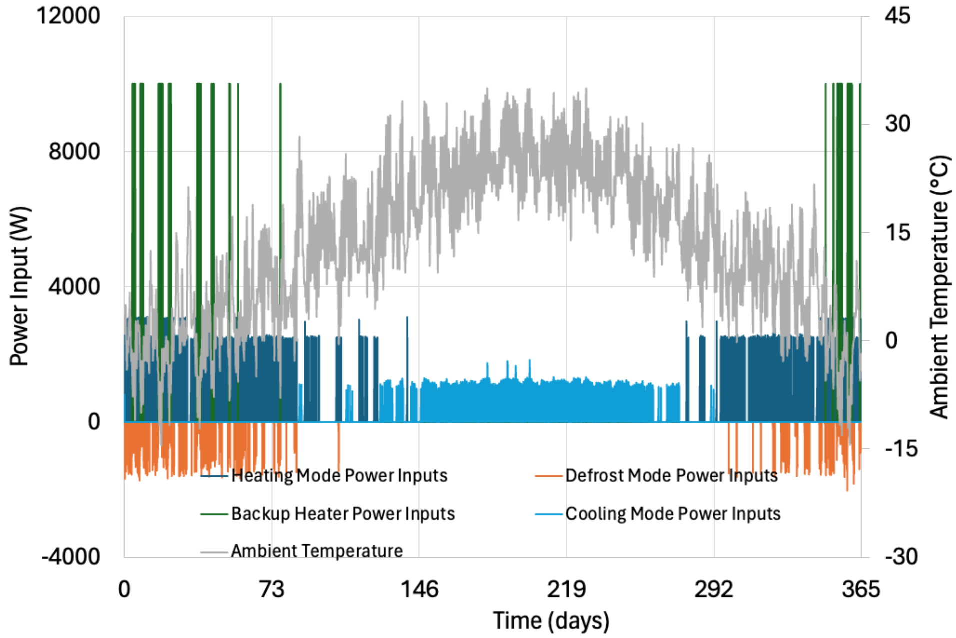
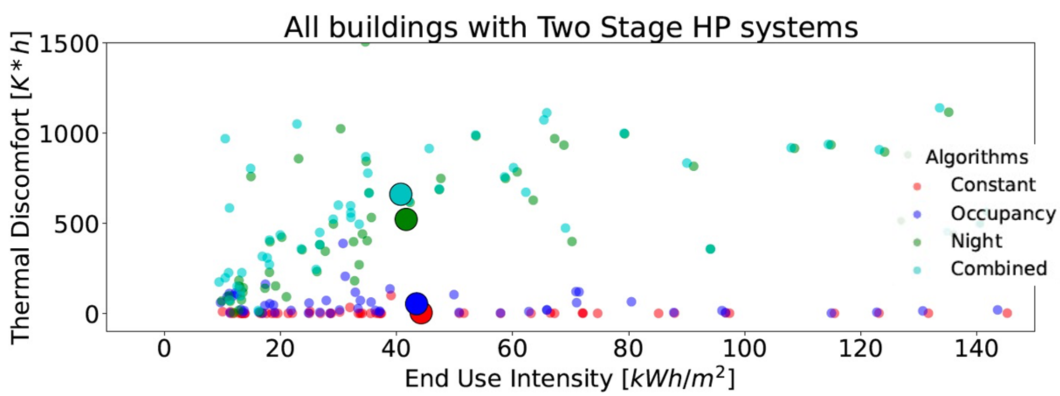


Figure 10: Heat pump annual operation profile



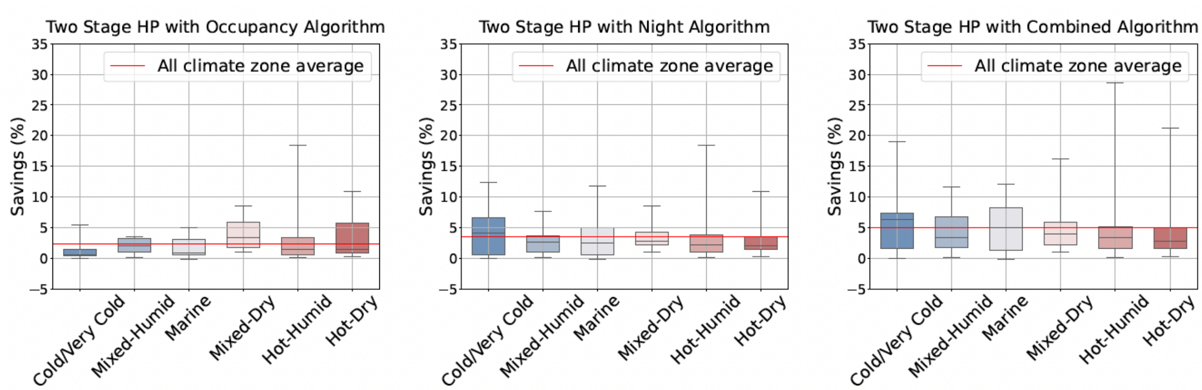


Figure 11: Thermal discomfort and energy use intensity for the three HVAC system types.[5]

4. CONCLUSIONS

We introduce a modeling framework to evaluate the dynamic operation of heat pumps in realistic housing environment. The framework includes two important components: an HVAC equipment component and a thermal zone component. To further account for the field factors that may impact the heat pump operation, we developed a model to account for air infiltration and controls to regulate the backup heater, fan operation sequence, defrosting operation and compressor speeds. In this paper, we applied the framework to a single thermal zone detached house in Baltimore and examined the implementation of each control. We concluded the controls were correctly implemented and therefore the annual operation of the heat pump was later presented. The framework has been utilized to investigate the energy saving and thermal comfort from various smart thermostat algorithms in 52 houses across the United States.

REFERENCES

[1] Buildings-Spawn-of-EnergyPlus (Spawn), 2014, Retrieved June 17, 2024, from https://www.energy.gov/eere/buildings/articles/spawn-energyplus-spawn

[2] Modelica Buildings Library, 2024, Retrieved June 17, 2024, from https://simulationresearch.lbl.gov/modelica/

[3] BOPTEST: Building Operations Testing Framework, 2023, Retrieved June 17, 2024, from https://www.energy.gov/eere/buildings/boptest-building-operations-testing-framework

[4] ResStock Analysis tool, 2024, Retrieved June 17, 2024, https://www.nrel.gov/buildings/resstock.html

[5] Benne K., Thomas J., Ling J., Blum D., Roth A., 2024, *Simulation-Driven Rating of Smart Thermostats, SimBuild 2024, Eleventh National Conference of IBPSA-USA, Denver, Colorado, May 21 – 23, 2024*

[6] Sherman, M.H., and Grimsrud, D.T.. 1980. Infiltration-pressurization correlation: Simplified physical modeling. ASHRAE Transactions 86(2): 778. Paper DV-80-09-3.

[7] Wilcox S., Marion W., 2008, User Manual for TMY 3 Data Sets, Technical Report, NREL/TP-581-43156 Revised May 2008

[8] EnergyPlus Input Output References, 2021, Chapter 1.18.1 Input for Design Calculations and Component Autosizing, EnergyPlus Version 9.6.0 Documentation

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