Title

Towards a Techno-Economic Analysis of PCM Integrated Hybrid HVAC Systems

Authors

Helmns, Dre
Blum, David
Casillas, Armando
et al.

Publication Date

2024-01-21

Peer reviewed

Building Technologies & Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory

Towards a Techno-Economic Analysis of PCM-Integrated Hybrid HVAC Systems

Dre Helmns[1], David Blum[1], Armando Casillas[1], Anand Prakash[1], Jonathan Woolley[2], David Vernon[3], Caton Mande[3], Michael Woodcox[4], Spencer Dutton[1]

[1] Lawrence Berkeley National Laboratory, Berkeley, CA
[2] Emanant Systems LLC, Northampton, MA
[3] Western Cooling Efficiency Center, Davis, CA
[4] NestWorks LLC, Orinda, CA

Energy Technologies Area
May 2021

D. Helmns, D. H. Blum, A. Casillas, A. Prakash, J. Woolley, D. Vernon, C. Mande, M. Woodcox, S. Dutton (2021). "Towards a techno-economic analysis of PCM-integrated hybrid HVAC systems." In Proc. of the 6th International High Performance Buildings Conference at Purdue, May 24-28.

This work was supported by the e Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies of the U.S. Department of Energy under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Towards a Techno-Economic Analysis of PCM-Integrated Hybrid HVAC Systems

Dre HELMNS[1*], David BLUM[1], Armando CASILLAS[1], Anand PRAKASH[1], Jonathan WOOLLEY[2], David VERNON[3], Caton MANDE[3], Michael WOODCOX[4], Spencer DUTTON[1]

[1] Lawrence Berkeley National Laboratory, Berkeley, CA, USA

[2] Emanant Systems LLC, Northampton, MA, USA

[3] Western Cooling Efficiency Center, Davis, CA, USA

[4] NestWorks LLC, Orinda, CA, USA

* Corresponding Author: drehelmns@lbl.gov

ABSTRACT

Thermal end uses dominate building energy consumption and are a major driver of peak demand. As heating is electrified, peak electrical power required will surge, prompting a need for innovative HVAC system designs and controls. These designs must incorporate novel technologies at the component level and new integration techniques at the system level. One such possibility involves the addition of thermal energy storage (TES) in heating and cooling equipment using a phase change material (PCM) heat exchanger. Here, thermal energy storage via phase change can be used to shift the HVAC system loads to times of lower electricity cost, reduced carbon intensity, and greater energy efficiency. Most of the current utilization of PCM in buildings involves passive components. By actively controlling when heat is stored and released from PCM, we can optimize the building HVAC system to cost-effectively meet consumer needs with the flexibility to draw on renewable energy resources when they are abundant and available.

While this combination of technologies is promising in theory, simulation-based evaluation of a prototype can be difficult due to the modeling requirements at the component level and the large number of possible configurations and operating modes at the system level. To conduct this evaluation, we use the Modelica language for modeling and simulation because it enables users to represent the important physics of the problem, interchange and rearrange components in an efficient manner, and implement a range of control configurations. In this work, we considered three case studies: a portable building, a large commercial retail store, and a multifamily residential apartment unit. Each of these employs a different system design, ranging from a single package vertical unit incorporating PCM to a central plant with independent heat pump, evaporative cooling, and thermal energy storage components. This paper describes the technologies in question, presents modeling at the component and system levels, and demonstrates building energy and demand charge cost savings with local time-of-use tariffs in a hot-dry climate.

1. INTRODUCTION

Many researchers and policy makers have proposed shifting away from on-site combustion of fossil fuels for all types of heating, ventilation, and air conditioning (HVAC) and domestic hot water (DHW) equipment. Supplied by renewable electricity generation, all-electric HVAC systems could reduce direct greenhouse gas emissions attributed to the buildings sector by 8.6% (Leung, 2018). However, transitioning new and existing buildings to all-electric HVAC and DHW systems is a monumental challenge. US buildings use 8.52 trillion cubic feet of natural gas on-site annually with the vast majority of this natural gas consumption used to provide space heating (58%) and water heating (21%) (*Natural Gas Consumption by Sector*, 2020). Electrification of HVAC and DHW will increase the existing portion of electricity contribution attributed to buildings by 73% (*Electricity End Use*, 2020). All-electric systems will impact regional and seasonal electricity loads, necessitating adaptation of how we design and operate to support the grid. One promising strategy is to reduce and shift loads on the demand side to better match available energy on the supply side.

To address this challenge, we developed and modeled several all-electric so-called "hybrid" HVAC system designs with local energy storage in three distinct building applications (large commercial retail, portable buildings, and multifamily residential). Our technology strategies to improve efficiency and provide energy storage include: high performance variable capacity heat pumps, indirect evaporative cooling, ventilation heat recovery, sub-wet bulb evaporative water cooling, and PCM thermal energy storage. Each of the systems and components modeled are described in Section 2. The hybrid systems, as well as comparative baseline gas and all-electric systems, were modeled using the Modelica language (Mattsson & Elmqvist, 1997). Modelica's object-oriented specification and excellence in multi-domain physical system modeling allows for component models to be combined into system models that serve as an explicit representation of the proposed system architectures and control concepts. This study leverages an international effort to develop and share component models (Wetter et al., 2019), specifically the Modelica Buildings Library (GitHub commit 0ef82ef) and the IDEAS Building Energy Simulation Library (GitHub commit a91fd24) (Wetter, Zuo, Nouidui, & Pang, 2014; Jorissen et al., 2018), and develops new or enhances existing models where necessary.

In this paper, we describe our evaluation of the impact of new load shifting systems for three building types against their respective comparative baselines. We share our designs for the different architectures and describe how we've modeled the building envelope, loads, air delivery, hydronic plant, and control systems. The goal of our models is to accurately represent physical component configurations and explore opportunities to improve HVAC and DHW systems for energy efficiency and load shifting. To test our models in different climates with local tariffs, we created a parametric simulation framework to easily run a set of case studies. The tool outputs time series data for visualization of system operation and associated energy, demand, and cost savings. We provide sample results for summer and winter peak days and summarize annual operation costs and equipment sizing for a case study in Albuquerque, New Mexico. We aim to ultimately make these models available to others so that users have access to a simulation tool that can support the implementation of novel energy technologies for grid-interactive efficient buildings.

2. METHODS

We designed and modeled all-electric hybrid mechanical systems for three buildings. Each system incorporated similar components, in different configurations, as appropriate for the building type, size, loads and occupancy profiles.

The large commercial retail system, shown at the top of Figure 1, utilizes a central air-water heat pump with both a sub-wetbulb evaporative cooler (SWEC) and evaporative condenser air pre-cooler to increase efficiency and cooling capacity. The heat pump provides heated or cooled water to PCM thermal energy storage, and/or to a distributed array of hydronic air handlers. Ventilation is provided to the building by a dedicated outdoor air system (DOAS) using a heat exchanger that performs heat recovery ventilation (HRV) and indirect evaporative cooling (IEC). The system includes hot (43°C) and cold (11°C) PCM thermal energy storage for load shifting, peak shaving, and additional capacity.

The portable building system, shown in the middle of Figure 1, is similar in concept to the large commercial retail system except it is designed to have all components packaged in a vertical wall-mounted unit, similar to equipment typically used in these buildings. From bottom to top, this system includes: hot (43°C) and cold (11°C) PCM thermal energy storage, an air-to-water heat pump with evaporative condenser air pre-cooling, an air handling module that includes IEC and HRV, a water-to-air heat exchanger, and a pair of fans (and dampers) to manage ventilation, exhaust, and recirculated air flow. Since all system components are connected together in a packaged wall-mount unit, this system has some operating modes that are different from the large commercial retail system. For example, ventilation air from the IEC may mix with return air and be cooled further through the water-to-air heat exchanger.

The multifamily residential system, shown in the bottom of Figure 1, is designed to provide all heating, cooling, and DHW with a single heat pump that replaces the split system and tank water heater commonly used in residential buildings. The system consists of an air-to-water heat pump paired with PCM thermal energy storage and a hydronic air handler (or fan coil units). This system includes PCM TES with two hot phase change temperatures (43°C and 58°C), used for heating and DHW respectively. Ventilation for the residence is provided separately.

2.1 Models for Building Envelopes and Loads

Each system is modeled using a single thermal zone, whose envelope construction properties and whose convective, radiant, and latent internal load design values and annual schedules (except holidays) are defined based on a corresponding Department of Energy Reference Building with New Construction (Deru et al., 2011). New Construction models comply with the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 (ASHRAE 2004a). For all systems, *Buildings.ThermalZones.Detailed.MixedAir* is used to model the dynamic room heat balance and the floor sits on 2 meters of soil. The large commercial retail model is based on the "Stand Alone Retail Store" Core Retail

Zone. It has a floor area of 1600 m^2, two external walls with no windows, two internal walls modeled as adiabatic on the outside boundary, and a roof that is exposed to the environment. The portable building model is based on the "Primary School Building" Corner Classroom. It has a floor area of 99 m^2, made modular with four external walls and a double-pane window with air gap facing south, with a roof that is exposed to the environment. The multifamily residential model is based on the "Mid-rise Apartment Building" Bottom Floor North-Facing Apartment. It has a floor area of 88 m^2, one external wall with a double-pane window with air gap, and three internal walls and a ceiling modeled as adiabatic on the outside boundary. Weather data for a given climate is represented by TMY3 files using *Buildings.BoundaryConditions.WeatherData.ReaderTMY3*. Design heating and cooling loads for a given climate for the corresponding reference building zones are used as sizing parameters for the system components.

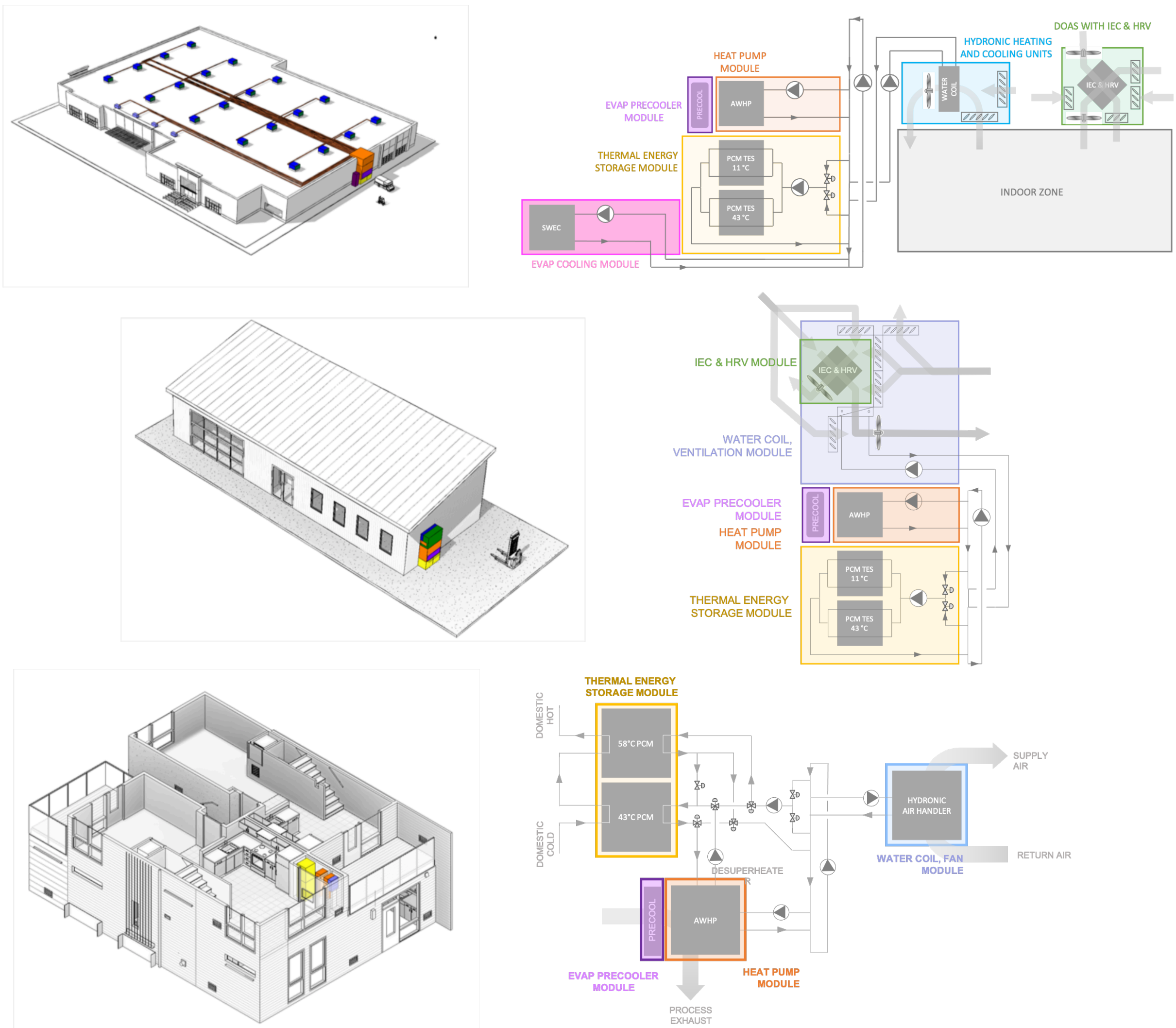


Figure 1: Large commercial retail (top), portable building (middle), and multifamily residential (bottom) schematics

The multifamily residential model also defines DHW loads using an annual schedule of endpoint water flowrate demand and domestic cold water temperature from a publicly available stochastic DHW event generator (Hendron, Burch, & Barker, 2010). In the multifamily residential model, a thermostatic mixing valve is used to control the ratio of domestic cold and hot water flow rates to an outlet temperature set point of 43°C modeled using a PI feedback controller. The DHW temperature is determined according to the hydronic plant models described in the following sections.

2.2 Models for Air Delivery Systems

The air delivery system for each building type is modeled with a similar structure of component models, though their exact definition and corresponding controls determine which system is instantiated. This model design choice was made to provide efficient, yet flexible, means of modeling the large number of system configurations for all building types and associated baseline and hybrid systems. The air delivery system is made up of a supply and return duct, supply fan, heating coil, cooling coil, mixing box with economizer, and an IEC/HRV unit enabling heat exchange between the exhaust and outside air streams. For all systems, the supply fan uses *Buildings.Fluid.Movers.FlowControlled_m_flow*, the mixing box with economizer ideally mixes two air streams according to an input signal between 0 and 1, and the IEC/HRV unit uses *IDEAS.Fluid.HeatExchangers.IndirectEvaporativeHex* with constant heat exchanger effectiveness in dry and wet mode equal to 0.80. All pressure drops are lumped into a single resistance downstream of the supply fan equal to the design pressure rise of the fan. Taken from the corresponding Reference Building model, for the large commercial retail system, the pressure drop is 1100 Pa, hydraulic efficiency is 0.59, and motor efficiency is 0.91. For the portable building and multifamily residential systems, the pressure drop is 622 Pa, hydraulic efficiency is 0.65, and motor efficiency is 0.86.

The differentiating factor for each system model is based on the selection of the heating and cooling coil model. For the baseline systems, the heating coil is modeled as a direct-fire gas furnace using *Buildings.Fluid.HeatExchangers.HeaterCooler_u* with efficiency of 0.80 and the cooling coil is modeled as a wet direct-expansion unit with *Buildings.Fluid.HeatExchangers.DXCoils.AirCooled.VariableSpeed* with the cooling equipment COP calculated as a function of the difference between the source-side entering and load-side leaving temperatures (Staffell, Brett, Brandon, & Hawkes, 2012). For the baseline all-electric systems, the heating and cooling coils are modeled as the condenser and evaporator of the same reversible air-to-air heat pump using the same component models as the baseline system, except with the COP for both heating and cooling calculated as a function of the difference between the source-side entering and load-side leaving temperatures (Staffell et al., 2012). For the hybrid systems, the heating coil is modeled as a dry hydronic coil using *Buildings.Fluid.HeatExchangers.DryCoilEffectivenessNTU* and the cooling coil is modeled as a wet hydronic coil using *Buildings.Fluid.HeatExchangers.WetCoilCounterFlow*.

2.3 Models for Hydronic Plant Systems

Hydronic plant models are only needed for the new hybrid system designs. The models for the large commercial retail and portable building systems are structured in the same way to promote efficiency in the ability to model the large number of system configurations, while the model for the multifamily residential system is significantly different. For the large commercial retail and portable building systems, the hydronic plant system is modeled separately for heating and cooling, though both do not run at the same time to enforce an assumption of a single heat pump. Their structures are the same except inclusion of the SWEC in the large commercial retail system.

The air-to-water heat pumps are modeled using *Buildings.Fluid.HeatExchangers.SensibleCooler_T* and *Buildings.Fluid.HeatExchangers.Heater_T*, with COPs calculated as a function of the difference between the source-side entering and load-side leaving temperatures (Staffell et al., 2012). The heat pump heating capacity is assumed to be equal to the cooling capacity and the remainder of required heating capacity is assumed to be met by an auxiliary electric resistance heater with a COP of 1. The associated circulation water pump is modeled using *Buildings.Fluid.Movers.FlowControlled_m_flow*. Evaporative condenser precooling is modeled in each cooling heat pump model by using the outside air wetbulb temperature, assuming a wetbulb effectiveness of 1.0, instead of the drybulb temperature in the determination of COP. The control signal inputs to the model are the set point for the water leaving the heat pump and the fraction of nominal water mass flowrate for the pump. For the multifamily residential model, the cooling heat pump model also includes a desuperheater model that recovers a fraction of the condenser heat flow in a secondary circuit as a function of the entering water temperature, with an associated enable/disable control input signal (*In-Floor Warming Module: external desuperheater*, 2015; Yrjölä & Laaksonen, 2015). For the large commercial retail system, the SWEC is modeled similarly to the air-to-water heat pump, except that the COP is approximated at a constant 10.5 and the leaving water temperature is approximated as equal to the outside air wetbulb temperature.

The PCM TES heat exchanger for each building type is based on a design that includes two circuits that each interact with the same PCM. The model represents 1-D heat transfer from one fluid circuit to the PCM through convection at the pipe boundary and resistance by the copper pipe wall and aluminum fins protruding into the PCM. The resistances and PCM itself are modeled with the component *Buildings.HeatTransfer.Conduction.SingleLayer*. To produce the two-circuit model, the 1-D heat transfer circuit is repeated with symmetry around the PCM. Each circuit utilizes a mixing volume *Buildings.Fluid.MixingVolumes.BaseClasses.MixingVolumeHeatPort* to calculate the fluid outlet temperature given the inlet temperature and heat transfer with the PCM cell. Three different PCMs were utilized to produce TES heat exchangers at three different temperatures: 11°C for cooling, 43°C for space heating, and 58°C for domestic hot water. Their material properties are found in Table 1, based on three commercially available thermal batteries.

Table 1: Average solid-liquid phase change material thermal properties used in hydronic plant models

Melt temperature, T_m	Latent heat, h_{ls}	Specific heat, c	Density, ρ	Thermal conductivity, k
11°C	126 kJ/kg	2050 kJ/kg·K	1125 kg/m^3	0.200 W/m·K
43°C	153 kJ/kg	1550 kJ/kg·K	1675 kg/m^3	0.584 W/m·K
58°C	226 kJ/kg	3150 kJ/kg·K	1360 kg/m^3	0.584 W/m·K

For the large commercial retail and portable building, the TES was sized by analyzing time series load data for the baseline all-electric systems. First, for each day, the thermal load was integrated over the peak tariff times. Then, the maximum value was chosen for each month and the TES size was set equal to the average of these 12 values. For multifamily residential, which also includes DHW loads, we first calculated the amount of PCM TES needed solely to serve DHW loads. To do so, we determined the minimum PCM capacity to maintain the first hour rating (FHR) for an apartment unit that would traditionally be served by a 60 gallon hot water tank at 60°C. For an equivalent TES size, we calculated the amount of thermal energy required to raise that volume of water from the inlet mains temperature to the storage tank temperature, using a “70% rule”. This rule is commonly applied to storage tank water heaters to represent the degree of mixing within the tank. While it is not directly applicable to sizing PCM TES in the same way, it is an appropriate first pass at generating the same ratio of heat pump size to nominal storage capacity. The relative sizes of 43°C and 58°C PCM were determined based on the DHW temperature lift required of each. Additional capacity was then added to the 43°C PCM thermal battery to serve half of the integrated space heating load on the peak day.

For the multifamily residential systems, DHW is provided to the building by heating the domestic cold water inlet to a temperature set point of 60°C. The baseline system does this with a natural gas-fired tankless water heater, modeled using *Buildings.Fluid.HeatExchangers.Heater_T* with an efficiency of 0.80. The baseline all-electric does this with a heat pump water heater tank using *Buildings.Fluid.Storage.StratifiedEnhanced* with five stratification levels and the total heat provided by the heat pump assumed to equally distribute among them. A PI feedback controller controls the heat pump heat output to ensure the second highest stratification level maintains the hot water temperature set point. The COP of the heat pump is calculated as a function of the difference between the source-side entering and load-side leaving temperatures (Staffell et al., 2012). The heat pump heating capacity is such that the ratio of total heating capacity to heat pump heating capacity is equal to 1.3, with the remaining heating capacity provided by an auxiliary electric resistance heater with COP of 1. The source temperature is assumed to be the inside room air temperature and the load temperature is assumed to be the average temperature of all stratification levels in the tank. For the hybrid system, the domestic cold water passes first through the 43°C and then through the 58°C PCM heat exchangers. There is no active control for the outlet temperature. Instead, the high melting temperature of 58°C is assumed to produce hot enough water for the thermostatic mixing valve to meet the appropriate fixture water temperature set point.

For all hydronic models, circulation pump power is not calculated and circulation pumps are assumed to operate as ideal flow movers. Three-way valves control fractional flow in different branches served by the same pump.

2.4 Models for Controls

For the large commercial retail and portable building systems, a thermostat provides feedback control on zone air temperature between occupancy schedule-based heating and cooling set points, indicated by dashed lines in the top panels of Figure 3. The fan operates at heating, cooling, ventilation, or setback speeds according to the thermostat feedback and occupancy schedule. For cooling and heating, the thermostat control signal is used as an input to the rate of gas burn in the furnace, compressor speed in the DX unit and air-to-air heat pump, and water valve positions as applied to each system type. The minimum outside air damper position is set based on system mode. When unoccupied, the minimum position is closed; while in occupied mode, it is set to provide minimum outside air flow at the corresponding heating, cooling, or ventilation fan speed. Economizer control of the outside air damper via the thermostat control signal is enabled if the outside air dry bulb temperature is less than the return air temperature and the system is in cooling mode. If the outside air damper is saturated open, then the cooling coil is modulated on. In the hybrid systems, the IEC/HRV is on in wet heat recovery mode if the system is cooling and the wetbulb temperature of the return air is less than the outside air dry bulb temperature. It is on in dry heat recovery mode if the system is heating and the return air dry bulb temperature is greater than the outside air dry bulb temperature. If the system is not heating or cooling , the IEC/HRV is in dry mode if it was previously enabled on (either as wet or dry). Otherwise, it is turned off.

The portable building and large commercial retail hybrid hydronic systems are in cooling mode if the air system is cooling or if the cold TES is in charging mode. The system is heating if the air system is in heating mode, the air system is in freeze protection mode, or if the hot TES is in charging mode. The heating/cooling supply water temperature set point is 43.5/10.0°C normally, and 50.5/6.0°C if in TES charging. A feedback controller generates a PI control signal based on supply water temperature and is used first to modulate return water flow through the TES to maintain the supply water temperature at set point if the TES is in discharge mode. Then, the control signal is used to modulate return water flow from the TES through the SWEC to maintain the supply water temperature. This occurs if the system is in cooling mode and if the SWEC is present in the system and enabled, based on comparing the temperature of the water that would enter the SWEC to the outside wetbulb temperature. Finally, the control signal is used to modulate return water flow from the SWEC through the ASHP to meet the supply water temperature set point of the system. The evaporative condenser pre-cooler is enabled if the heat pump is in cooling mode. The TES is in charging or discharging mode according to a schedule, based on the electricity tariff, and on whether the TES is detected to be fully charged or fully discharged, determined by the outlet water temperature. To limit heat pump peak demand during charging, the control signal for the TES pump is set based on estimating the SOC at the start of the period and calculating the constant flowrate needed to have the TES fully charged by the end of the scheduled period. As a general rule, the TES discharge window overlaps with all, or some portion of, the peak time-of-use tariff periods.

For multifamily residential, the control of the fan, heating, and cooling coils are the same as for large commercial retail and portable building systems, except the ventilation air flowrate is zero and there is no economizer nor IEC/HRV. The hydronic system is heating if the air system is heating, if the high temperature PCM is in charging mode and the air system is not cooling, or if the low temperature PCM is in charging mode and the air system is not cooling. If the air system is cooling, the hydronic system is cooling. The heating supply water temperature set point is 52°C normally, and 64°C if the low or high temperature TES are in charging mode. A control signal is generated via PI feedback on supply water temperature and used first to modulate return water flow through the low temperature TES to maintain the supply water temperature at setpoint if the TES is in discharge mode. Otherwise, the low temperature TES is bypassed. The control signal is used to modulate return water flow through the heat pump to meet the supply water temperature setpoint. The evaporative condenser pre-cooler is enabled if the heat pump is in cooling mode.

The low and high temperature TES are in charging or discharging (low only) mode according to a schedule, determined based on the electricity tariff, on whether the TES is detected to be fully charged or fully discharged by the outlet water temperature of water flowing through the TES, and on if the system is not in cooling mode. During a scheduled charging period, the TES pump control signal is set to be constant, tuned to ensure DHW demand can be met and the low temperature PCM can be adequately recharged each day without causing too much electricity demand. The bypass valve is opened only if the high temperature PCM is charging, allowing the outlet water from the high temperature PCM to also charge the low temperature PCM. The modulation valve directs water flow from the circulation pump to the high temperature PCM only if it is in charging mode, since it is not discharged for space heating. Finally, the desuperheater valve and pump direct water at constant flow to the low temperature PCM when the heat pump is cooling.

2.5 Parametric Simulations

The performance and cost evaluations of the different integrated systems in this paper were done using a parametric simulation framework that was developed for easily configuring the different scenarios to enable running simulations at scale. Additionally, the framework was developed using the open-source and free JModelica tool (Åkesson, Årzén, Gäfvert, Bergdahl, & Tummescheit, 2010) and publicly available docker environment (https://github.com/lbl-srg/docker-ubuntu-jmodelica). Use of this docker container enhanced portability by allowing team members to run simulations irrespective of host operating systems. Figure 2 is a graphical representation of the framework.

In the configuration step, a user populates a configuration file with a matrix of simulation settings including climate zones, system types, building types, and energy storage charging and discharging times. With this information, one (or more) Modelica record files are automatically written and saved to disk to be used for parameterization of the appropriate system model upon simulation. In the simulation phase, using JModelica, the system models defined by the configuration are compiled into Functional Mockup Units (FMU) and simulated with the CVODE variable timestep solver and tolerance of 1e-6 for the duration of a whole year. The simulation step results in the generation of one result .mat file for each configured simulation. Using the BuildingsPy package (https://simulationresearch.lbl.gov/modelica/-buildingspy/) and tariff information from the configuration, the system performance time series data are extracted from the .mat files and used for final cost and performance analysis.

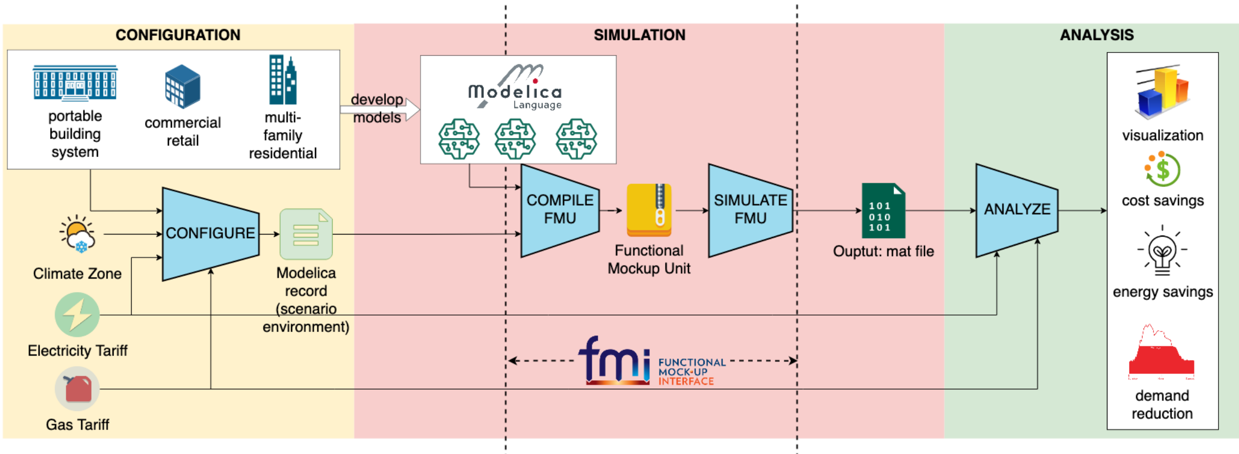


Figure 2: Parametric simulation framework consisting of case study configuration, simulation, and analysis

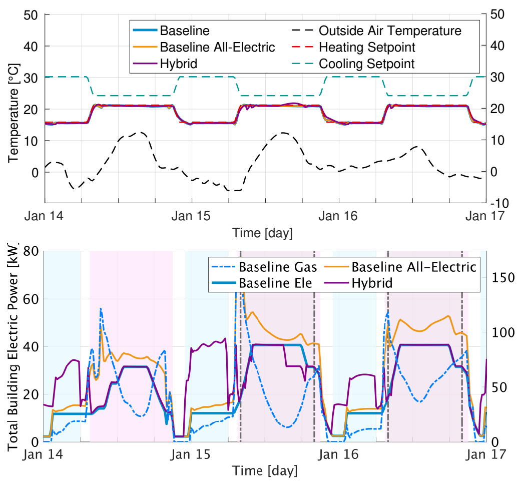
3. RESULTS

Equipped with designs, models, and a parametric simulation framework, we present results for the three building types in Albuquerque, New Mexico with two different tariffs applied in post-processing. Public Service Company of New Mexico Rate NO. 3B, with peak hours from 8 am - 8 pm, was used for the large commercial retail and portable building systems and Central New Mexico Electric Cooperative Rate NO. 25, with peak hours from 6:30 am - 9 am (winter only) and 4:30 pm - 10:30 pm (all year), was applied to the multifamily residential system. Time series simulation outputs are post-processed and re-sampled to 15 minutes. Figure 3 shows zone air temperature (top), whole building electric power and gas power (bottom) for each building type and system type for winter (left) and summer (right). Zone temperature setpoints, outside air temperature, tariff peak periods, and TES charging and discharging periods are also presented.

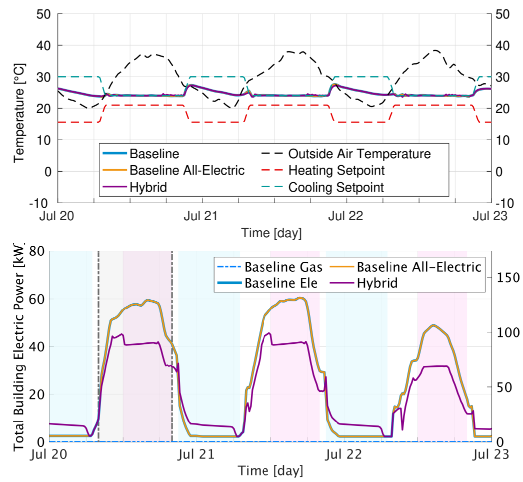
In the top panels of Figure 3, we see that zone air temperature was properly maintained for each system and building type. In addition, we see the baseline (gas) system often has the lowest electrical demand in winter. Gas use for space heating and hot water is also captured on the right axis of this lower panel plot in subfigures 3a, 3c, and 3e. In winter, we can see that gas demand tends to coincide with baseline all-electric peaks. On average, HVAC electric demand is roughly half of the whole building electric demand, reflecting the importance of targeting heating and cooling systems for load shifting. These plots reveal that the dispatch of stored thermal energy during peak periods effectively flattens electric demand for space conditioning and water heating. During off-peak hours, electric demand is necessarily higher for the hybrid HVAC system in order to charge the PCM TES for the following discharge period. Charging control is better for some building types and seasons than others. Across all building types and seasons, discharging the TES results in lower peak electric demand for HVAC and DHW than the baseline all-electric system. The results reveal that the new hybrid HVAC system accomplishes thermal load shifting throughout the year but could be further optimized on several fronts, including PCM TES sizing and transient operation. In future simulations, model predictive control (MPC) could optimize these systems.

4. DISCUSSION

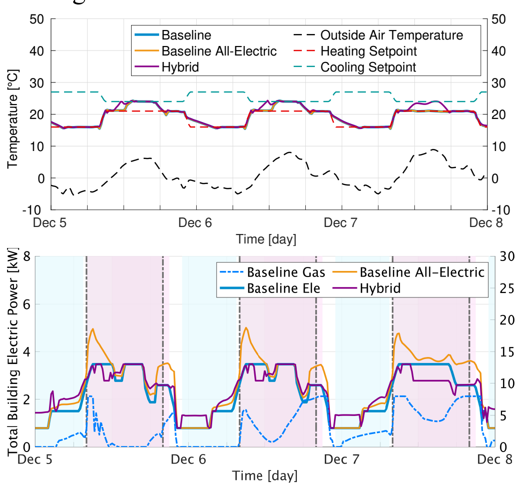
Table 2 presents the simulated annual costs for total energy, electrical energy, electrical demand, and natural gas, as well as cost savings for each system compared to the corresponding baseline system. It can be seen that when peak demand of the baseline and baseline all-electric systems occurs in the summer, the hybrid HVAC systems are able to generate savings. When the peak occurs in the winter (due to heating), the all-electric systems incurs very high demand charges resulting in increased total costs. Note that for the large commercial retail building and the portable building, the demand charges contribute to more than 50% of the total annual costs, emphasizing the importance of peak load reduction in these commercial buildings. The hybrid system generates total cost savings compared to both baseline and baseline all-electric in both large commercial retail (around $4,500) and the portable building (around $500), but performs worse than the baseline system in the multifamily residential building. The baseline all-electric system is more costly than the baseline in all cases except the portable building, highlighting the benefit of integrated



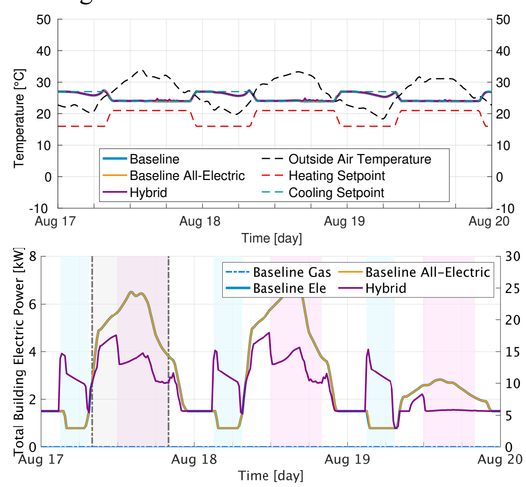
a: Large commercial retail in winter



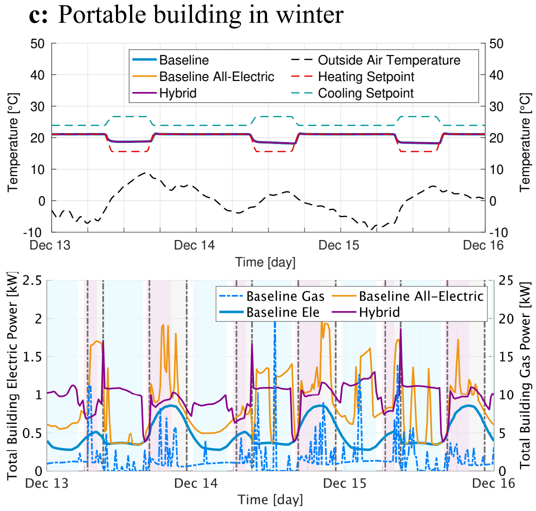
b: Large commercial retail in summer



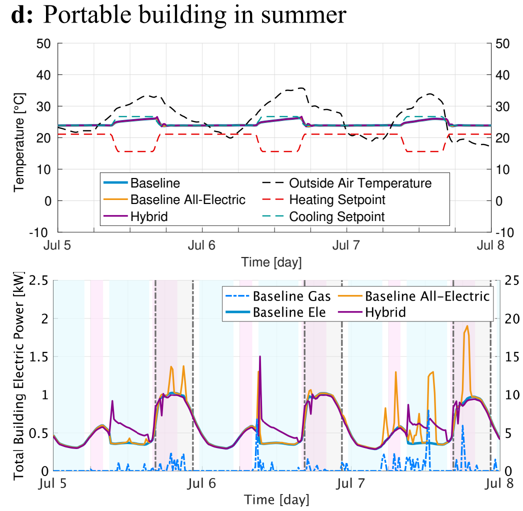
c: Portable building in winter



d: Portable building in summer



e: Multifamily residential in winter



f: Multifamily residential in summer

Figure 3: Three systems in winter and summer where grey vertical lines enclose peak tariff periods, blue shaded regions correspond to TES charge windows, and pink shaded regions correspond to TES discharge windows

storage in all-electric systems. The relevance is also evident in the large commercial retail building, where the baseline all-electric system has its maximum demand in winter (79.80kW) whereas the hybrid peaks in summer (only

48.08kW). Such results reveal successful shifting of hot thermal loads in the winter and accompanying reduction in peak demands.

Table 2: Costs incurred in the different buildings with baseline, baseline all-electric, and hybrid HVAC systems

	Electricity: Energy Costs	**Electricity: Demand Costs (Peak Demand)**	**Natural Gas: Energy Costs**	**Total Costs**	**Total Cost Savings (Demand Cost Savings)**
Large Commercial Retail					
Baseline	\$4,624.41	\$12,225.48 (60.67kW in Jun)	\$2,759.79	\$19,609.68	0.00 % (0.00 %)
Baseline All-Electric	\$5,094.07	\$15,459.87 (79.80kW in Feb)	\$0.00	\$20,553.94	-4.82 % (-26.46 %)
Hybrid	\$4,446.77	\$10,700.27 (48.08kW in Jul)	\$0.00	\$15,147.04	22.76 % (12.48 %)
Portable Building					
Baseline	\$474.33	\$1,369.14 (7.13kW in Jun)	\$98.61	\$1,942.08	0.00 % (0.00 %)
Baseline All-Electric	\$489.68	\$1,439.15 (7.13kW in Jun)	\$0.00	\$1,928.83	0.68 % (-5.11 %)
Hybrid	\$436.10	\$1,043.38 (4.79kW in Aug)	\$0.00	\$1,479.48	23.82 % (23.79 %)
Multifamily Residential					
Baseline	\$425.40	\$273.22 (1.05kW in Jul)	\$131.24	\$829.86	0.00 % (0.00 %)
Baseline All-Electric	\$537.27	\$572.52 (2.01kW in Dec)	\$0.00	\$1,109.79	-33.73 % (-109.55 %)
Hybrid	\$537.67	\$321.46 (2.00kW in Jan)	\$0.00	\$859.13	-3.53 % (-17.66 %)

In addition to the demand and cost reductions provided by the hybrid systems, secondary benefits are in the form of peak thermal load reduction for the heat pump and coils, which create additional potential capital cost savings on component sizing and electrical infrastructure. Peak heat pump loads are significantly reduced by the ability of the thermal energy storage to shift demand to off-peak hours, while coil loads in some systems (retail and portable) are reduced via the IEC/HRV providing conditioning before the air reaches the system's air-side coil. Compared to the baseline all-electric system, peak summer/winter heat pump load reductions for the hybrid system in the portable building are 7/8% and large commercial retail are 21/40%. Similarly, peak coil loads are reduced 34/42% and 53/40% respectively. The multifamily residential system actually sees an increased peak winter load of 46% due to DHW load being shifted from the heat pump water heater to a single heat pump, and negligible change in peak summer load.

In order to verify the validity of results for all three systems, the energy use intensity (EUI) of the baseline systems in all building types were compared to typical average EUI values in real buildings. The reference data was obtained via the Buildings Performance Database, the largest publicly-available source of building energy data in the US (*Building Performance Database*, 2020). The EUI across the three building types provided by the database were found to be comparable with simulation results for buildings of similar use-type and square footage, with large commercial retail building's reference annual site EUI of 173 kWh/m^2, matching closely to simulated annual site EUI of 195 kWh/m^2. As mentioned in Section 2, the portable building used a primary school as its reference. Similar buildings of this type have an annual site EUI of 191 kWh/m^2, while our simulation predicts 249 kWh/m^2. We attribute this larger deviation to the building's exposure as a modular classroom. Finally, the simulated multifamily residential building reference annual site EUI is 72 kWh/m^2 compared to a ~50% higher simulated prediction of 111 kWh/m^2. The full multifamily reference building includes unconditioned hallways and lobbies that are often unoccupied, in contrast to the single unit that we modeled. We hypothesize that another contributing factor to all three simulations predicting higher EUI than the references cases is that we modeled primary occupancy zones with appropriately larger loads.

5. CONCLUSIONS

In this paper, we explored the impact of new load shifting systems for three building types. We simulated our models in a hot-dry climate with local time-of-use tariffs and generated time series data for visualization of system operation on peak days in winter and summer. Compared to baseline and baseline all-electric systems, we found that the hybrid HVAC systems we developed were able to reduce annual operation costs and equipment sizing for two of the configurations, large commercial retail and portable buildings, in this specific case study scenario.

Even though the results section presented significant cost savings by using a PCM-integrated hybrid HVAC system, this evaluation and the corresponding results are preliminary. We are currently working on adding a life cycle cost (LCC) analysis application to the parametric simulation framework. The LCC analysis, along with studying how this system would fare in different climate zones with different tariffs, would provide a more holistic evaluation of the new architectures presented in this paper. Development is underway to achieve these goals.

REFERENCES

Åkesson, J., Årzén, K.-E., Gäfvert, M., Bergdahl, T., & Tummescheit, H. (2010). Modeling and optimization with optimica and jmodelica. org—languages and tools for solving large-scale dynamic optimization problems. *Computers & Chemical Engineering*, *34*(11), 1737–1749.

Building performance database. (2020). Retrieved from `https://buildings.lbl.gov/cbs/bpd`

Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., … others (2011). Us department of energy commercial reference building models of the national building stock.

Electricity end use. (2020, Dec). Retrieved from `https://www.eia.gov/totalenergy/data/monthly/pdf/sec7_19.pdf`

Hendron, B., Burch, J., & Barker, G. (2010). *Tool for generating realistic residential hot water event schedules* (Tech. Rep.). National Renewable Energy Lab.(NREL), Golden, CO (United States).

In-floor warming module: external desuperheater. (2015). Maritime Geothermal Ltd. Retrieved from `https://www.nordicghp.com/product/nordic-products/external-desuperheater/`

Jorissen, F., Reynders, G., Baetens, R., Picard, D., Saelens, D., & Helsen, L. (2018). Implementation and verification of the ideas building energy simulation library. *Journal of Building Performance Simulation*, *11*(6), 669–688.

Leung, J. (2018). Decarbonizing us buildings. *Center for Climate and Energy Solutions*.

Mattsson, S. E., & Elmqvist, H. (1997). Modelica-an international effort to design the next generation modeling language. *IFAC Proceedings Volumes*, *30*(4), 151–155.

Natural gas consumption by sector. (2020, Dec). Retrieved from `https://www.eia.gov/totalenergy/data/monthly/pdf/sec4_5.pdf`

Staffell, I., Brett, D., Brandon, N., & Hawkes, A. (2012). A review of domestic heat pumps. *Energy & Environmental Science*, *5*(11), 9291–9306.

Wetter, M., van Treeck, C., Helsen, L., Maccarini, A., Saelens, D., Robinson, D., & Schweiger, G. (2019). Ibpsa project 1: Bim/gis and modelica framework for building and community energy system design and operation–ongoing developments, lessons learned and challenges. In *Iop conference series: Earth and environmental science* (Vol. 323, p. 012114).

Wetter, M., Zuo, W., Nouidui, T. S., & Pang, X. (2014). Modelica buildings library. *Journal of Building Performance Simulation*, *7*(4), 253–270.

Yrjölä, J., & Laaksonen, E. (2015). Domestic hot water production with ground source heat pump in apartment buildings. *Energies*, *8*(8), 8447–8466.

ACKNOWLEDGMENT

This research was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.