Implementation of a reconfigurable heat recovery heat pump and control plant template and its use for performance evaluation

Karthik Devaprasad
Associate Member

Junke Wang, PhD
Associate Member

Lingzhe Wang, PhD
Associate Member

Xing Lu, PhD
Associate Member

Yan Chen, PhD
Member

Michael Wetter, PhD
Member

Paul Ehrlich, PE
Member

ABSTRACT

With the increasing use of electric heat pumps for HVAC and water-heating applications, making them compatible with and responsive to a grid with time-varying electrical capacity is crucial. However, the application of electric heat pumps is complex and requires practitioners to make multiple design and operational decisions to manage trade-offs between competing priorities like energy efficiency and power demand. Additional strategies, like thermal energy storage, provide options for better management but add complexity to design and operations. Hence, there is a need for a simulation platform and templates that empowers designers to make these decisions.

This manuscript describes the development of such a simulation template in the Modelica modeling language that allows users to pick templated configurations of heat pump plants and adapt them to their specific project needs, and then evaluate them with tested control algorithms to identify capacity requirements. They can then further customize these algorithms to meet their project requirements and validate them on the same platform. Firstly, the simulation platform consists of templates that can be configured with various options for a heat recovery system that exchanges energy between a hot-water loop and a chilled-water loop. It is combined with external energy loop templates for energy conversion, consisting of components like air-to-water heat pumps and cooling towers for heat injection and rejection, respectively. Secondly, the control algorithms consist of modules for determining the various required operation modes for the plant based on the heating and cooling loads, and then managing the staging processes for the plant. This platform is then used to conduct a case-study to evaluate the energy efficiency of the implemented control sequences.

Karthik Devaprasad is a staff engineer at Pacific Northwest National Laboratory. **Junke Wang** is an engineer at Pacific Northwest National Laboratory. **Lingzhe Wang** is a former post-doctoral researcher at Pacific Northwest National Laboratory. **Xing Lu** is an engineer at Pacific Northwest National Laboratory. **Yan Chen** is a senior research engineer at Pacific Northwest National Laboratory. **Michael Wetter** is a senior scientist at Lawrence Berkeley National Laboratory. **Paul Ehrlich** is the founder and President of Building Intelligence Group LLC.

INTRODUCTION

Broad use of commercial heat pumps is relatively new in the market, but is increasing in prominence recently. They have the benefit of serving both heating and cooling applications, since they can interact with any hot or cold thermal energy storage, and either discharge energy from it or charge it to meet heating and cooling loads.

Past projects have highlighted the difficulty in appropriately sizing heat pump plants, and then designing control systems to operate them efficiently and reliably [1][2][3]. To facilitate the process, various organizations have released design guides and created webtools. ASHRAE has previously released design guides for district heating and cooling systems. However, not all the information there is directly transferable to commercial building heat pump plants [4]. The city of Zurich, Switzerland, has previously released comprehensive design and control guides for heat pump plants [5]. While this is a valuable resource, it may not be directly applicable to use cases in the United States which see higher ratios of cooling versus heating loads. Certain manufacturers have made available design guides [6] and control sequences for storage-source heat pump plants on an interactive web tool [7]. However, the performance of heat pump plants varies greatly with external weather conditions and operating parameters. Other operational issues include an inability to supply water at the correct temperature. Therefore, there is a need for a reliable simulation platform where designers can iteratively simulate and size heat pump plants under varying loads and weather conditions, and test configurable implementations of control systems with the system model under the same conditions.

There has been progress made towards meeting this need for a high-fidelity simulation solution that also allows for control validation. [8] details an energy analysis that was executed using Modelica simulation models for a heat pump plant with a water-cooled chiller combined with a district energy system and a borefield for meeting both the heating and cooling loads. Also, the Modelica Buildings Library [9] has existing capabilities for templates [10] that allow users to configure HVAC system models and pair them with the required control modules to test them, which provides an advantage over conventional tools like EnergyPlus with load-based operation of HVAC equipment [11]. The Modelica Buildings Library also allows implementing the control logic using the proposed ASHRAE Standard 231P (Control Description Language) [12, 13] and adding semantic information for use of proposed ASHRAE Standard 223P [14], therefore enabling a digitialized design-build-operate workflow as described in [15]. Providing a set of configureable template heat pump systems will allow designers to compare their performance and test the integration of different thermal energy storage technologies.

This paper addresses these gaps by adding to the existing capability on the Modelica Buildings Library that allows users to automatically set up a custom plant using predefined subsystem templates, and then use them to test system sizing and validate controls. We first present the new subsystem templates we are implementing to cover the required mechanical functionality. We then describe new control modules we have implemented to operate these new functional subsystems. A designer can customize and use these as required and test them out on the above generated system simulation model. The paper then presents a demo of the same capabilities for designing a cascading heat pump plant with an external energy loop for heat injection and rejection, and then testing its performance in a simulation study that covers various weather conditions experienced by a location in a year.

APPROACH

This section describes the design of the various heat pump plant subsystem templates, the implementation of the various control modules for local and supervisory control, and finally the integration of these templates and control modules to form a complete system model, before sizing it.

Existing heat pump plant templates

The existing heat pump plant template in the Modelica Buildings Library is for an air-source heat pump plant for heating and cooling applications with optional heat recovery chiller. Apart from the overall system template that represents a complete air-source heat pump plant, with a schematic as seen in Figure 1, it also contains subsystem templates for functional subsystems like the heat pump group and isolation valve groups (used for scaling the capacity of the plant, if required).

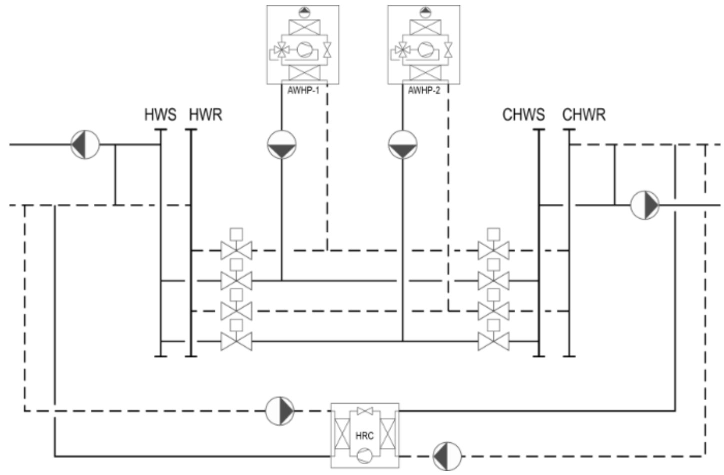


Figure 1 Schematic for the air-source heat pump plant template currently available in the Modelica Buildings Library. Image re-used from https://simulationresearch.lbl.gov/modelica/..

Additional subsystem template-based heat pump plant model

While the air-source heat pump plant may meet many heating and cooling requirements in moderate climes, it may not be suitable in more severe climates due to the high lift required between the outdoor air temperature and the heating supply or cooling supply water temperature. Apart from that, there are various other strategies designers are interested to test the performance of, such as thermal energy storage technologies and energy sources like ground-source thermal energy and waste-water heat recovery, as seen in the literature, e.g., [6], [7] and [8]. These systems are inherently complex to design, given the variable performance of heat pump systems under changing weather and system operation conditions.

To facilitate the design of these complex systems, the heat pump plant template package needs to be extended to cover systems that are classified as “cascading heat pump plants” in the industry, with an “external energy loop” that can be used to exchange energy with external energy sources such as geothermal sources. This loop can be operated at a moderate temperature between the chilled water and hot water loop supply temperatures and can be used to store heating energy or cooling energy. The external energy loop can also be tapped into at periods when one of the heating or cooling loads is dominant, to moderate the return temperature on the non-dominant side and reduce the lift across the heat pump. The schematic for such a complete plant system is seen in Figure 2.

The new subsystem templates will not be packaged in a single system template that can be automatically generated, as is the case for the system shown in Figure 1. Instead, the system model is assembled manually to reduce the potential number of configuration options the user must pick. Future releases of the Modelica Buildings Library will contain multiple examples of such complex heat pump plant systems that users can directly use, with the possibility for the user to implement custom configurations.

Design of new subsystem templates

Depending on whether the external energy loop has heat injection or heat rejection components, it can be thermally coupled with one of or both the hot water loop and the chilled water loop. For this specific demo, the external energy loop is thermally linked to both the hot water loop and the chilled water loop using heat exchangers. This is preferred because the loops can transmit heat while preventing any fluid mixing. The plant is divided into the following templates: a central heat recovery heat pump group, an isolation valve group that diverts the hot water and chilled water flows from the heat pump to the corresponding loops, and an external energy loop template. The external energy loop template further includes a cooling tower template, in which a cooling tower is paired with a condenser pump and a heat exchanger that connects it to the external energy loop.

Figure 2 also shows the schematic for the external energy loop template which contains the heat rejection components, including the cooling tower with heat exchanger, and the heat injection components, including the air-source heat pump and an electric trickle heater for managing unmet loads.

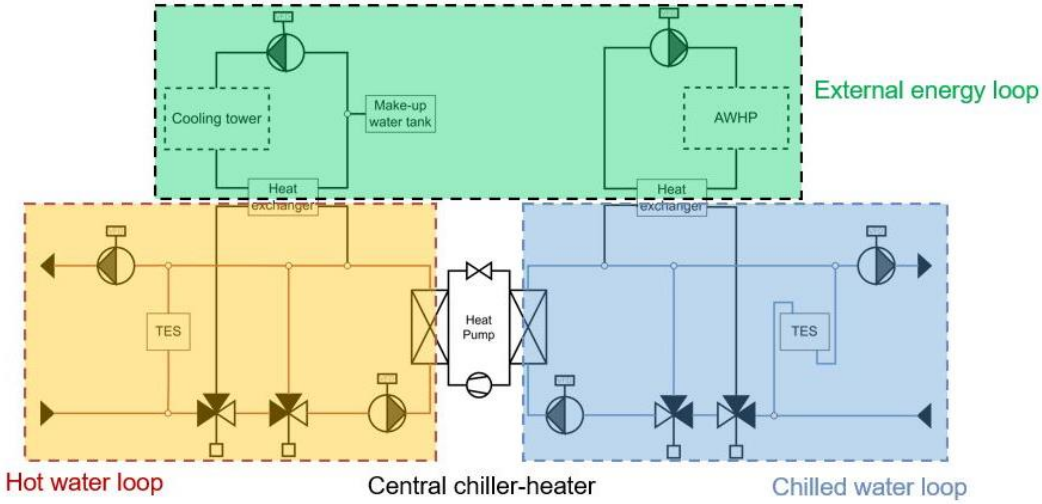


Figure 2 Schematic for the heat pump plant indicating the various subsystems, including the external energy loop, the central heat recovery, the hot water loop and the chilled water loop.

The templates for the heat pump group and the isolation valve group have been adapted from the latest release of the Modelica Buildings Library.

Once the various templates have been individually developed and tested, they are all combined, as seen in Figure 3, to form a complete heat pump plant model. In addition to the subsystem templates, pumps are added on both the hot water and chilled water loops. A minimum flow bypass valve is also added to provide minimum fluid flow to the central heat pump. Heat exchangers are added to thermodynamically couple the external energy loop to the hot water and chilled water loops. Finally, ideal heating and cooling components are added to the ends of the hot water and chilled water loops for recreating precalculated end loads. That will be achieved by exactly enforcing the measured flowrate and measured temperature differential between the supply and return water temperatures from the precalculated simulations, which will in turn lead to the same end loads. The valves used to enforce the measured flowrate also generate the requests for enabling the plant and resetting the setpoints.

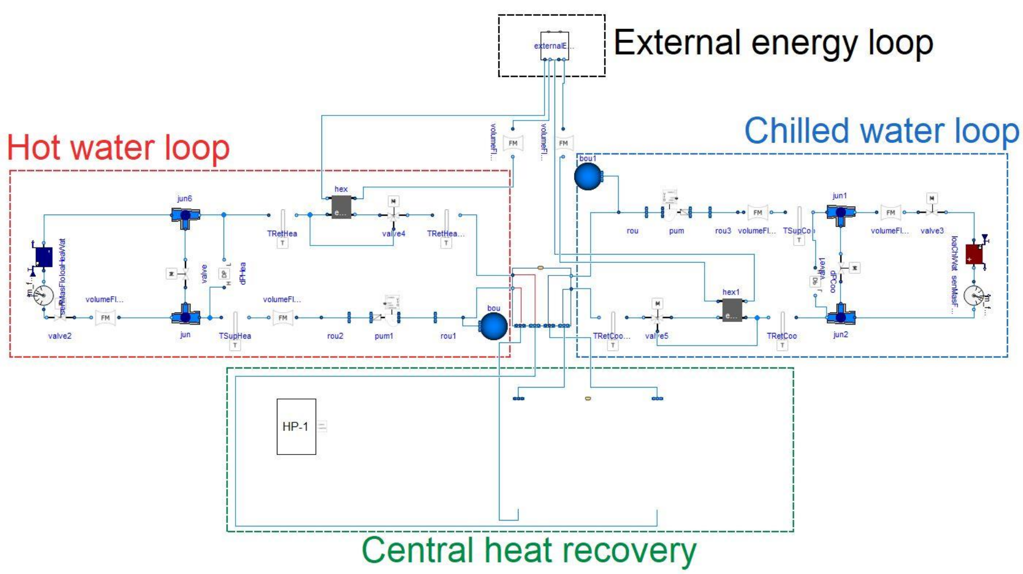


Figure 3 Modelica implementation for the overall heat pump plant system.

Control sequence proposal and module development

Most of the control modules for the local and supervisory control of simpler air-source heat pump plants, including the plant enable, the differential pressure setpoint reset and the temperature setpoint reset, as well as the modules for controlling the staging process, have been previously implemented and released as a part of the Modelica Buildings Library. However, for our specific configuration, an additional supervisory control module in the form of an operation mode controller is required. Also, the new templates require a new set of controllers to operate the various components in them.

The operation mode control decides whether to operate in the heating mode, cooling mode or heating-cooling mode, and whether to use the external energy loop for heat injection or heat rejection. The implemented logic for the module is seen in the Finite State Machine in Figure 4. The figure also shows the initial implementation of the same in Modelica using blocks from the Controls Description Library (CDL) in the Modelica Buildings Library.

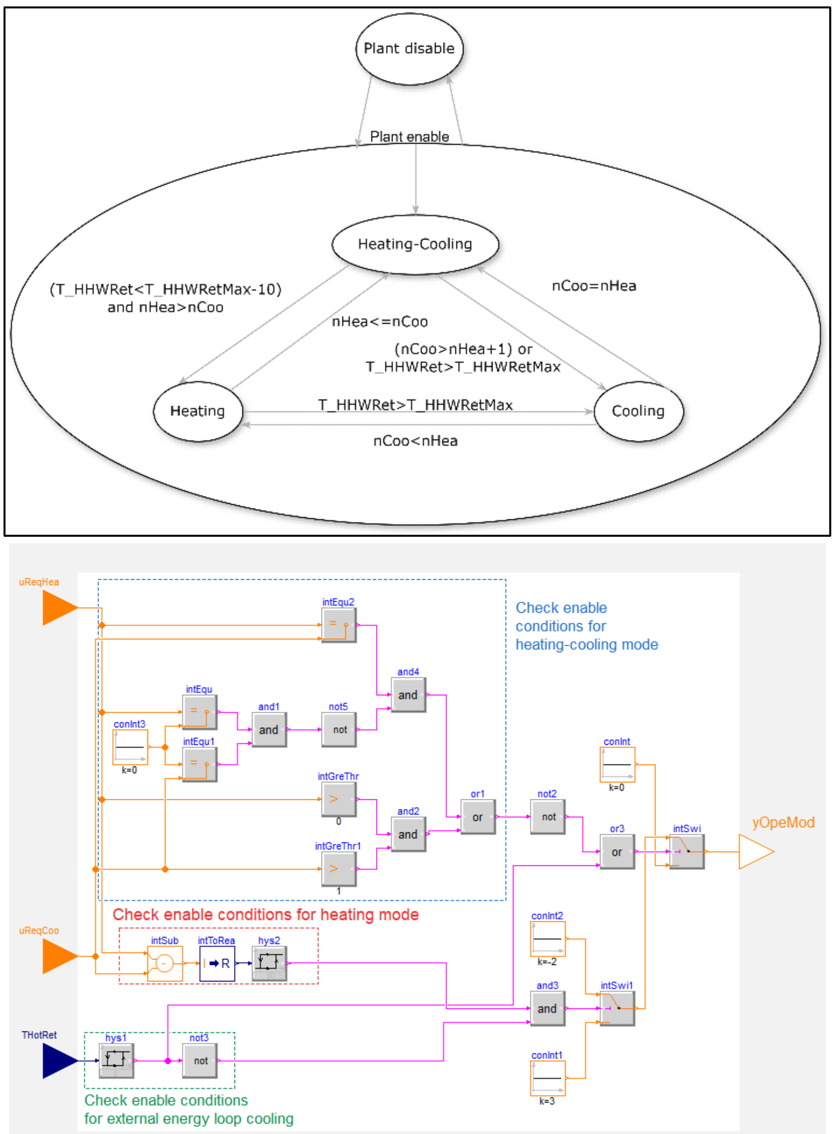


Figure 4 Finite State Machine depicting the logic for the operation mode (left), and the implementation in CDL (right).

In the Finite State Machine, *T_HHWRet* is the hot water return temperature, *T_HHWRetMax* is the maximum allowed return temperature, *nHea* is the number of heating supply requests from the loads, and *nCoo* is the number of cooling supply requests from the loads. *Heating-cooling* represents the mode when the plant is serving both heating and cooling loads with the use of the central heat pump, *Heating* is the operation mode when the plant is serving a dominant heating load by engaging the central heat pump and the external energy loop for heat injection on the evaporator coil of heat recovery system, and *Cooling* represents the mode when serving a dominant cooling load with the use of the central heat pump and the external energy loop on the condenser coil for heat rejection. The logic is also designed to switch to the Cooling mode when the hot water return temperature exceeds a maximum limit as a failsafe.

An external energy loop controller is implemented that receives a unique integer signal for each operation mode and activates the corresponding components. Instances of the previously implemented control modules for the safe operation of heating and cooling components are used to manage the corresponding valves and pumps for the cooling tower and the air-source heat pump. These modules ensure that the isolation valves are opened and pumps are enabled first, and only activate the heating or cooling component when water flow has been established.

A cooling tower control module is implemented to regulate the hot water return temperature at a user-specified temperature by modulating the three-way valve on the heat exchanger in the cooling tower subsystem. The condenser pump is enabled when the plant is enabled, the plant is in Cooling mode, and the outdoor air temperature is above a lockout temperature. The cooling tower is enabled when the three-way valve on the heat exchanger is at an opening greater than 80% continuously for 5 minutes.

EXPERIMENT

This section delves into the sizing and validation of the system model when integrated with the implemented control modules, before setting up a comparison to study the effectiveness of the energy-efficiency measures when combined with the newly implemented sequences for the specific configuration.

System set-up and boundary conditions

The implemented control modules are integrated with the system model shown in Figure 3. In addition to the modules described in the previous section, modules readily available in the Modelica Buildings Library for functions like plant enable, temperature setpoint and static pressure setpoint reset are also integrated into the model. The loads for the system are calculated using the DOE prototype EnergyPlus model for a large office building (90.1-2022) [16] located in Buffalo, NY (climate zone 5A). The cooling load is acquired by measuring the total mass flow rate and the temperature differential between the supply and return legs of the plant loop *CoolSys1_Demand* in the EnergyPlus model. Similarly, the heating loads are acquired by making the corresponding measurements in the loop *HeatSys1* in the EnergyPlus model.

The autosized component parameters from the EnergyPlus model are used to nominally size the components in the Modelica model. Some of the important parameters are listed in Table 1. Once the parameters have been assigned, the model is also manually verified to ensure the required setpoints and flowrates are being successfully achieved. The power consumption values, especially for the pumps, are also examined and tuned to be as close as possible to the EnergyPlus reference model, by manually adjusting the pump performance curves.

Table 1. Heat pump plant rated capacity

Parameter	Value	Parameter	Value
Central heat pump – Heating capacity	1.2 MW	External energy loop – Heating capacity	8.2 MW
Central heat pump – Cooling capacity	2.5 MW	External energy loop – Heating flowrate	0.053 m3/s
Hot water loop nominal flowrate	0.12 m3/s	External energy loop – Cooling capacity	21 MW
Chilled water loop nominal flowrate	0.12 m3/s	External energy loop – Cooling flowrate	0.9 m3/s

Experimental set-up

For the energy-efficiency measure-integration comparison, two different controllers, a baseline (controller-1) and a controller with measures integrated (controller-2), are set up. The difference between the two is seen in Table 2.

The system model is simulated for three different representative seasons using the weather file for Buffalo, NY. The three representative seasons are as follows: Winter (Jan 1st – Jan 31st), Spring (Apr 1st – Apr 30th) and Summer (July 1st – July 31st). The simulations are run on the Dymola 2023 IDE set up on a Windows system with 16 cores and 32 GB of RAM. The results are stored at equal intervals of 60s, and the average simulation runtime is about 400 seconds long.

Table 2. Comparison of baseline and energy-efficiency measure-integrated control

Feature	Controller-1	Controller-2
Differential pressure setpoint control	Constant differential pressure setpoint	Differential pressure setpoint is reset from minimum pressure to maximum pressure when the trim-and-respond output based on heating and cooling requests varies from 0% to 50%.
Supply water temperature setpoint control	Constant supply water temperature setpoint	Supply water temperature setpoint is reset from minimum load value to nominal setpoint value when the trim-and-respond output based on heating and cooling requests varies from 50% to 100%.

PRELIMINARY RESULT

Dynamic performance

Heating mode operation: The heating mode simulation results are shown in Figure 5 a). From it, we can see that the plant is enabled and enters Heating mode (-2) when heating load requests are generated due to the applied heating load. The plant is repeatedly cycled at low load levels and is enabled for longer durations during the early morning and late afternoon hours. The longer duration cycles allow the supply temperature setpoint to be reset, with the hot water (HHW) supply temperature closely tracking it. The return water to the evaporator coil in the chilled water (CHW) loop is heated to about 23ºC, which reduces the temperature difference of the lift between the evaporator and condenser coils.

Cooling mode operation: The cooling mode simulation results are seen in Figure 5 b). As in the heating mode results, the plant repeatedly cycles at low load conditions and operates for a longer duration of time continuously during the early afternoon hours, which affords it an opportunity to reset the CHW supply temperature setpoint. The CHW supply temperature closely tracks that setpoint. On the condenser coil in the hot-water loop, the HHW return temperature to the condenser coil is cooled down when viable to a setpoint temperature of 18º C by the cooling tower in the external energy loop.

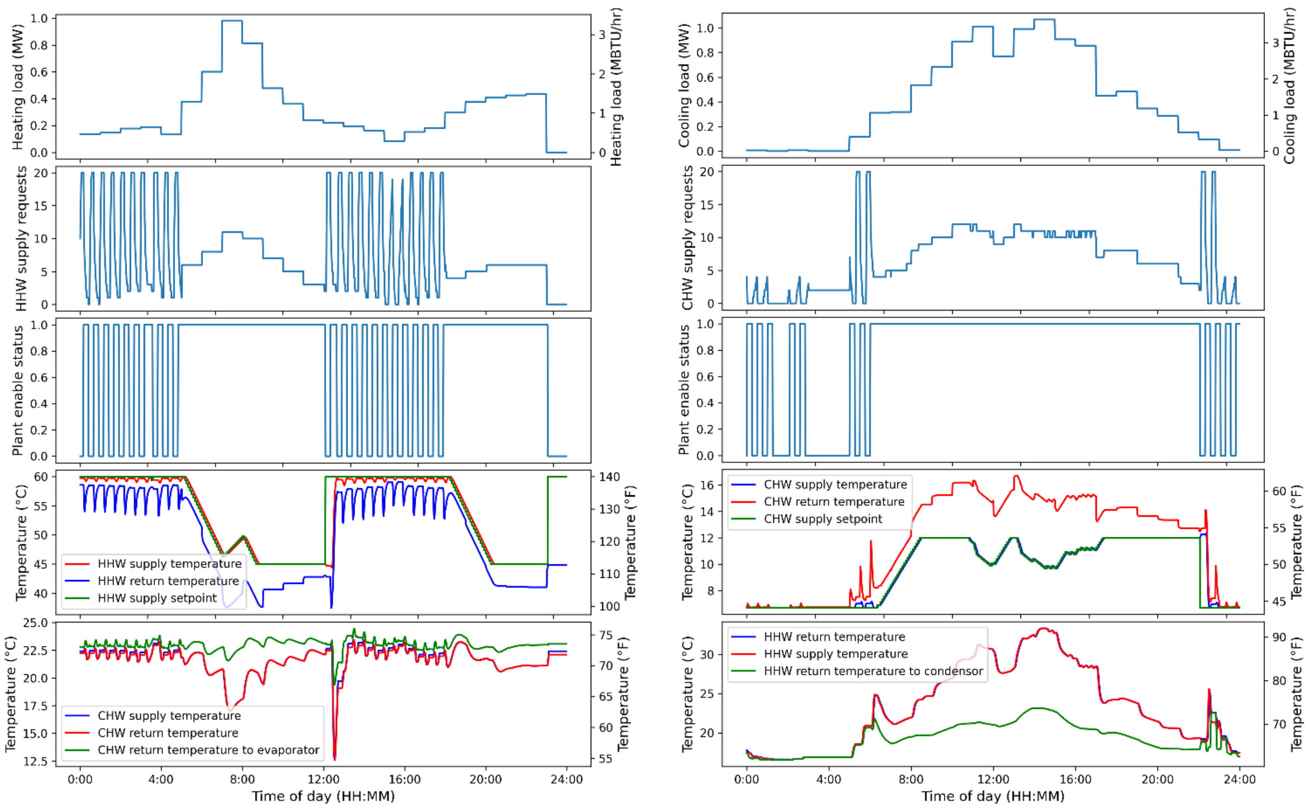
Comparison of energy consumption

Figure 6 provides a quantitative comparison of the energy consumption of the components for the various simulation periods with controller-1 and controller-2. The simulation results reveal that controller-2 is able to achieve energy reduction in the Winter and Summer simulation periods, with no savings achieved in the Spring season. This is primarily due to the longer cycle duration in the Winter and Summer, with an average cycle time of 25 minutes and 70 minutes respectively, which gives the plant more opportunities to reset the supply temperature setpoint. In the Spring period, the energy savings are much smaller since the average cycle time is just above 16 minutes, which is not sufficient time for the reset to trigger, with a default initial delay of 15 minutes.

SUMMARY

The simulation model for cascading heat pump plants was developed using existing and newly developed templates within the Modelica Buildings Library. Additional control modules were developed to operate the newly implemented templates, and then tested in a closed loop with the complete system model. The results were used to validate the operation of the system model, and to also study the effectiveness of energy-efficiency measure integration. The study revealed energy reduction as expected with the controller-2 in instances where the cycle times were long enough to trigger the setpoint reset.

It was successfully demonstrated how the developed capability enables virtual control testing, and can therefore support a design-build-operate process with end-to-end quality control, such as introduced in [15] and now based on standardized control description via ASHRAE Standard 231P [13], to ensure that operational performance conforms to the design specification and is not impacted by control simplification when programming the building automation system.



a) b)

Figure 5 a) Heating mode validation results for a single day (January 9th), and b) cooling mode validation results for a single day (July 8th).

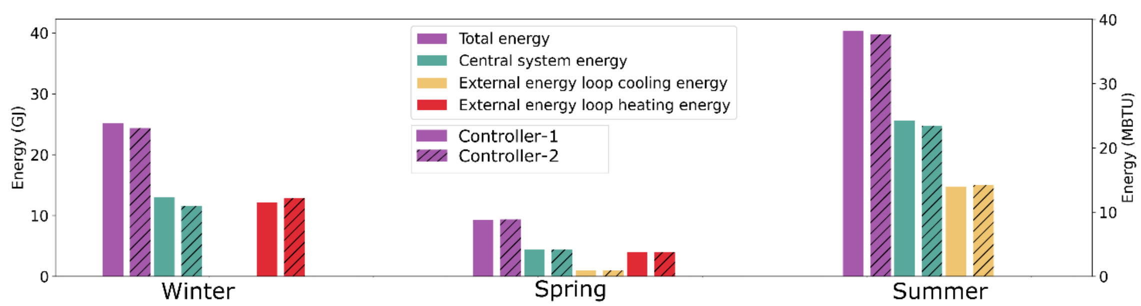


Figure 6 Quantitative comparison of electric energy consumption by end use for controller-1 and controller-2.

REFERENCES

[1] Oram, S. 2019. *Central Heat Pump Water Heating with 3 Case Studies*, ACEEE Hot Water Forum, Nashville, TN
[2] Oram, S. 2018. *Heat Pumps Are Not Boilers*, ACEEE Hot Water Forum – 2018, Portland, OR
[3] Carano, C, Jacques, E, Pierrot, H, Kotula, L, Singer, M. 2023. *Heat pumps and high-rise homes: Case studies from across Europe*, European Heat Pump Association.
[4] ASHRAE. 2013. *ASHRAE District Heating and Cooling Design Guides*

[5] Zurich. 2014. Stadt Zurich. *Waermepumpen fuer die Instandsetzung, Systemevaluation fuer die Instandsetzung. Schlussbericht. Amt fuer Hochbauten, Fachstelle Energie- und Gebaeudetechnik*. August 2014. German version URL: https://tinyurl.com/2dcetf8c, English auto-translation URL: https://tinyurl.com/55hz35ue.

[6] Trane. 2023. *Trane application guide for Thermal Battery Storage Source Heat Pump Systems*, March 2023

[7] Trane, *Trane design assist*, URL: https://tranedesignassist.com/

[8] Wetter, M, Hu, J. 2019. *Quayside Energy Systems Analysis*, Lawrence Berkeley National Laboratory, LBNL-2001197, March 2019

[9] Wetter, M, Zuo, W, Nouidui, TS, Pang, X. 2014. *Modelica Buildings library*. Journal of Building Performance Simulation, 7(4):253-270, 2014. https://dx.doi.org/10.1080/19401493.2013.765506

[10] Gautier, A, Wetter, M, Hu, J, Tummescheit, H. 2023. *HVAC and Control Templates for the Modelica Buildings Library*, 15th International Modelica Conference 2023, Aachen, Germany, https://doi.org/10.3384/ecp204

[11] *EnergyPlus™*. 2017. Computer software. Version 00. September 30, 2017. https://www.osti.gov//servlets/purl/1395882.

[12] Wetter, M, Milica, G, Hu, J. 2018. *Control Description Language*. 1st American Modelica Conference, Cambridge, MA, USA, August 2018. https://dx.doi.org/10.3384/ecp1815417

[13] ASHRAE, *ASHRAE Standard 231P "Control Description Language"*.

[14] ASHRAE, *ASHRAE Standard 223P "Semantic Interoperability"*.

[15] Wetter, M, Ehrlich, P, Gautier, A, Grahovac, M, Haves, P, Hu, J, Prakash, A, Robin, D, Zhang, K. 2022. *OpenBuildingControl: Digitizing the control delivery from building energy modeling to specification, implementation and formal verification*. Energy, Volume 238, Part A, January 2022. https://doi.org/10.1016/j.energy.2021.121501

[16] DOE and PNNL. 2023. *Commercial Prototype Building Models*, Richland, WA, Pacific Northwest National Laboratory. Available at https://www.energycodes.gov/development/commercial/prototype_models