5^{th} Generation District Heating and Cooling Modelica Models for Prosumer Interaction Analysis

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Abstract

5th Generation District Heating and Cooling (5GDHC) provides a promising pathway for decarbonising the thermal sector. To quantify the synergies between heating, cooling, and electricity, complex thermofluid models are required. Modelica offers a potential solution for developing such models but despite recent research efforts, there is a lack of bespoke 5GDHC component models in literature. This paper addresses this gap by presenting a comprehensive set of Modelica models for key elements of 5GDHC systems and their interactions: prosumers, balancing units, and hydraulic interfaces. The models comprise some commercial libraries. To facilitate accessibility, Functional Mock-up Units (FMU) are generated for these models, which can be opened by any Modelica environment using Functional Mock-up Interface (FMI). Component design, relevant controls, and the applicability of Power Hardware-in-the-Loop (PHIL) setups are discussed. A theoretical use case exemplifies hardware minimisation, using only heat exchangers to investigate prosumer behaviour. The paper concludes with a discussion on the potential use of these models, opportunities for improvement, and the need for further research and experimental investigations in understanding 5GDHC systems.

Keywords: 5th Generation District Heating and Cooling, Power Hardware-in-the-Loop, Energy Systems

1 Introduction

Among the efforts to limit the impact of climate breakdown and rise of global temperature levels, the decarbonisation of thermal networks represents a crucial challenge, especially while trying to maintain security of supply and low costs (IEA 2021). A system that is attracting increasing attention is 5th Generation District Heating and Cooling (5GDHC) which offers opportunities for synergies between heating and cooling loads, low temperature waste heat utilisation and sector coupling with the electricity grid through the use of heat pumps (Gjoka, Rismanchi, and Crawford 2023). This system utilises an ambient network for meeting both heating and cooling demands with decentralised energy stations. They feature water source heat pumps, boosting the temperature for meeting heating or cooling needs and thus commonly referred to as Booster Heat Pumps (BHP), Thermal Energy Storage (TES) and hydraulic pumps. Since buildings are feeding heat/coolth into the ambient network while they are using coolth/heat, they are referred to as prosumers. The thermal and hydraulic balance is provided to the system by a balancing unit, which adds heat or coolth depending on the demand requirement of the network (Buffa et al. 2019).

However, this pumping and energy unit decentralisation leads to a bidirectional flow regime in the network when heating and cooling demands are present. This may in turn cause thermodynamic subcycles, hydraulic misbalances such as “pump hunting” depending on the topology of the network and the transient behaviour of the network medium (Angelidis et al. 2023). To capture the operational complexity of such systems, it is key to accurately model thermofluid behaviour. Detailing the hydraulic and energy flow interaction coupled with overarching controls is a challenge that fits the multi-engineering scope of the Modelica simulation language (Abugabbara 2021). Modelica allows for accurate simulation of the system dynamics including bidirectionality of flow, pressure constraints, flow characteristics and energy interactions between heating and cooling. It is recognised by the International Energy Agency as one of the key computational tools for building system modelling (Wetter and Treeck 2017). Modelica features multiple open access libraries with validated components for buildings and community heating and cooling energy systems, including the Buildings (Wetter et al. 2014) and AixLib (Mueller et al. 2016) libraries, summarised in one library under BESMod (Wüllhorst et al. 2022).

Regarding 5GDHC systems, publications have focused on describing modelling methodologies and subcomponent development, aimed mainly at studying particular elements (Blacha et al. 2019; Abugabbara, Javed, and Johansson 2022; van der Heijde et al. 2017). However, these studies have limitations. The developed models are not provided for reuse, nor include a comprehensive explanation of the interplay between control regimes and prosumer, balancing unit, and decentralised pumping station interaction. Furthermore, they have been mostly case-specific, with only some Buildings library components providing limited insights on BHP and TES interaction and overarching control. Finally, prosumer interaction, the function of the balancing unit and the effects of decentralised pumping to system performance has not been experimentally validated. This is mainly due to the large number of units and hardware components required to study such interactions. Power Hardware-in-the-Loop (PHIL) provides a method for combining simulation tools with real hardware, interfacing through digital and analogue input/output signals, that could facilitate system-wide experiments with the use of minimal hardware. Facilitating such experiments through the provision of bespoke Modelica models for 5GDHC would be a step forward in understanding and quantifying the complex behaviour of such systems.

The aim of this paper is to present a set of comprehensive Modelica models, including experimentally validated subcomponents from the ProHMo library[1] for prosumers, hydraulic interface, and balancing unit to accurately simulate 5GDHC systems. The models have been developed to facilitate PHIL implementations, enabling experimental analyses of prosumer interactions in 5GDHC. A methodology for utilising only a heat exchanger (HEX) to replicate prosumer behaviour is presented along with a discussion on usability of the models using Functional Mock Up Interface (FMI). This feature allows the presented components to be used in any Modelica environment or in combination with Energy Management Systems (EMS) from other coding environments such as Python.

The library design is discussed in section 2, with a detailed investigation of the system components along with rule-based control strategies implemented. Section 3 includes an exemplary use case of the components for a simple 5GDHC system with two prosumers and a balancing unit. In section 4, the methodology for PHIL setups is discussed for experimental analysis of prosumer interaction or developed digital twins with minimal hardware use. Section 5 includes a discussion on strengths and limitations of the presented models along with the areas for further research. Finally, section 6 concludes with future use cases and research options.

2 Component Design

The development of the Modelica components is guided by five key guiding principles, namely usability, scalability, accuracy, flexibility & validity (Wetter and Treeck 2017). The prosumer and balancing unit models were based on equipment from the thermal Prosumer House Model (ProHMo) library (Zinsmeister and Perić 2022). The ProHMo library includes experimentally validated components from the Center for Combined Smart Energy Systems (CoSES) lab that are scalable. It is based on the Green city library from the commercial Modelica environment Simulation X (Zinsmeister and Perić 2022). The library uses a thermal only approach to simplify the models and shorten simulation time, where pressure influences are neglected. This simplification is valid for heating systems within houses (Zinsmeister and Perić 2022; Zinsmeister et al. 2023).

To model the interaction of prosumers in a district heating network with several prosumers, it is important to represent the network in detail, including pressure losses and bidirectionality of flow. For this purpose, the building models of ProHMo are coupled with hydraulic components through a communication interface submodel, referred to in this paper as hydraulic interface. The hydraulic interface serves as an accurate and comprehensive representation of the hydraulic components within the system, their behaviour and interaction. It comprises interconnected hydraulic elements (pumps, valves, sensors, pipes and elements of hydraulic resistance), facilitated by hydraulic connectors, and replicates all relevant elements encountered in real-world applications.

Furthermore, fitting control strategies are needed for all components for different grid operations. In this section, the development of bespoke components for 5GDHC is presented, allowing the setup for creating digital twins, an example of which is shown in Figure 1. In this figure, two prosumers are connected with a balancing unit through a thermal grid. The hydraulic interfaces allow for the hydraulic connection of the only thermal connector models. The prosumer and balancing unit models, as well as the hydraulic interfaces, are discussed below.

2.1 Prosumers

The prosumer model includes energy transformation units, thermal stores and demands. It can represent both Space Heating (SH) and Space Cooling (SC) demand along with Domestic Hot Water (DHW). The Modelica model is shown in Figure 2.

2.1.1 Model Description

The operation of the BHP and a Direct Cooling Heat Exchanger (HEX_{DC}) is the focal point in the prosumer component. HEX_{DC} allows for direct utilisation of the coolth from the network's cold pipe (if low enough) without upscaling it via a BHP. It has been shown that their use in 5GDHC is instrumental to the system's efficient operation (Wirtz et al. 2021). For SH and DHW, the load is to be supplied mainly from the BHP with any additional loads supplied by an auxiliary heater (electric resistance) placed within the BHP unit. For heating, the energy transformation units are connected in series with the TES which is discharged by the heat sinks. Cooling is directly supplied by the energy transformation units (HEX_{DC} or BHP) without going through the TES.

The BHP model is based on measurements of a commercial BHP found in the CoSES lab, reproducing its efficiency and dynamics. The TES model has also been experimentally validated (Zinsmeister and Perić 2022) and is represented by a one dimensional stratified model, where the TES is split into multiple layers of constant size. 10 temperature layers are used in the ProHMo library to match the number of temperature sensors in the physical unit in the lab. The maximum temperature, seen at level

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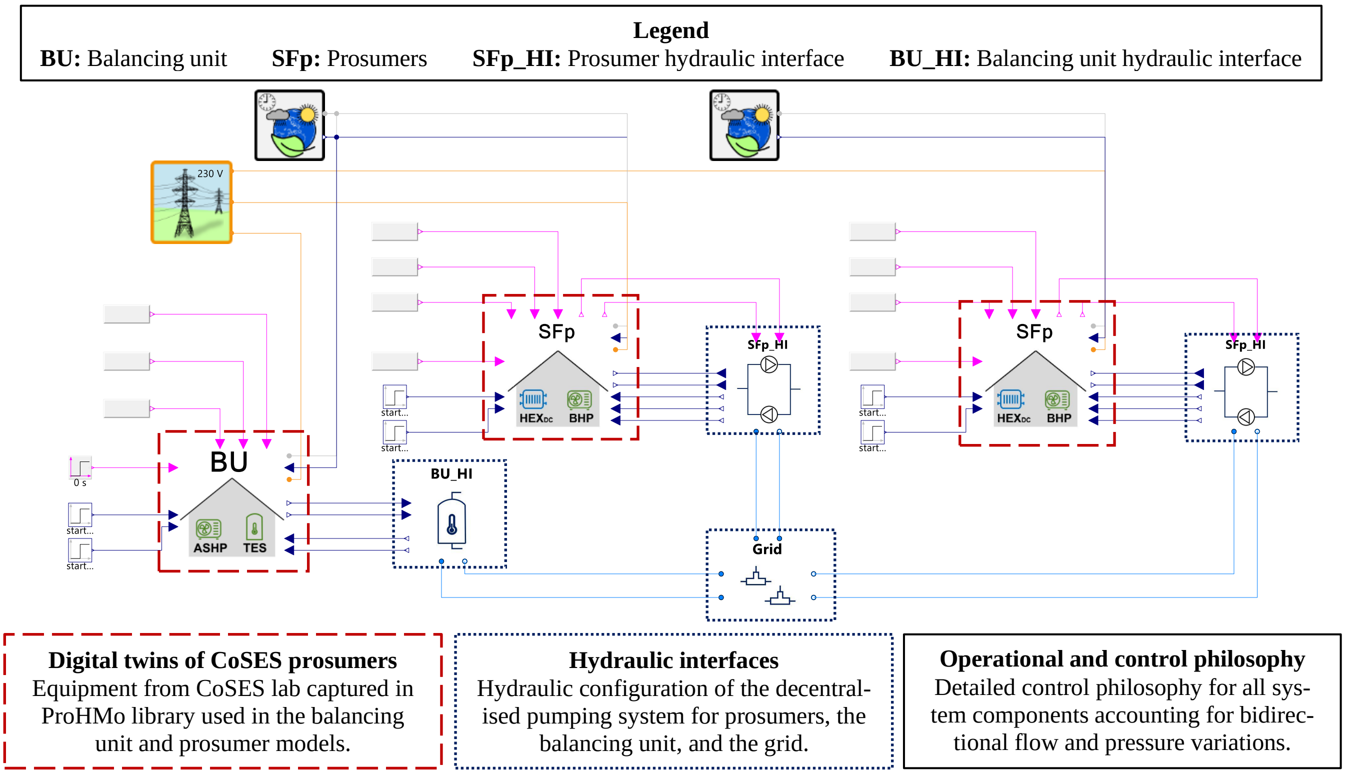
[1] Available online at: https://gitlab.lrz.de/energy-management-technologies-public/coses_prohmo


Legend
BU: Balancing unit **SFp:** Prosumers **SFp_HI:** Prosumer hydraulic interface **BU_HI:** Balancing unit hydraulic interface

Digital twins of CoSES prosumers
Equipment from CoSES lab captured in ProHMo library used in the balancing unit and prosumer models.

Hydraulic interfaces
Hydraulic configuration of the decentralised pumping system for prosumers, the balancing unit, and the grid.

Operational and control philosophy
Detailed control philosophy for all system components accounting for bidirectional flow and pressure variations.

Figure 1. Library components used for 5GDHC system development.

10, is set to 60°C. This value satisfies both DHW supply and legionella avoidance requirements (Chartered Institution of Building Services Engineers (CIBSE) 2020). A hydraulic switch, namely a 3-Way Valve (3WV), can change the charging levels based on temperature in the TES. Discharching for SH is from layers 5 (Flow) and 1 (Return) since there is a low temperature heating system (underfloor heating) and layer 10 (Flow) and 1 (Return) for DHW. The discharge of the TES is modulated by a pump valve setup based on temperature and flow requirements from the heat sinks.

The SH and SC demands are captured by adapted Green City library models which allow for different number of residents, construction characteristics, building type and terminal units. The default is set to new buildings with underfloor heating/cooling systems which is most relevant for 5GDHC prosumers with heating and cooling demands (Angelidis et al. 2023). The flow and return temperature depend on the flowrate supplied by the tertiary pumps (variable flowrate pumps in the building) but are designed for 40-30°C for heating and 15-20°C for cooling. Both SH and SC are modulating around a temperature setpoint (21°C for heating and 23°C for cooling) by varying the request inlet flowrate. Similarly, DHW is modelled, requiring a temperature of 60°C and, based on the consumption, returning a cooled down water at varying flowrates. There is a heat exchanger between the end DHW consumption and the water from the TES. DHW is dependent on the number of residents and can be switched off during

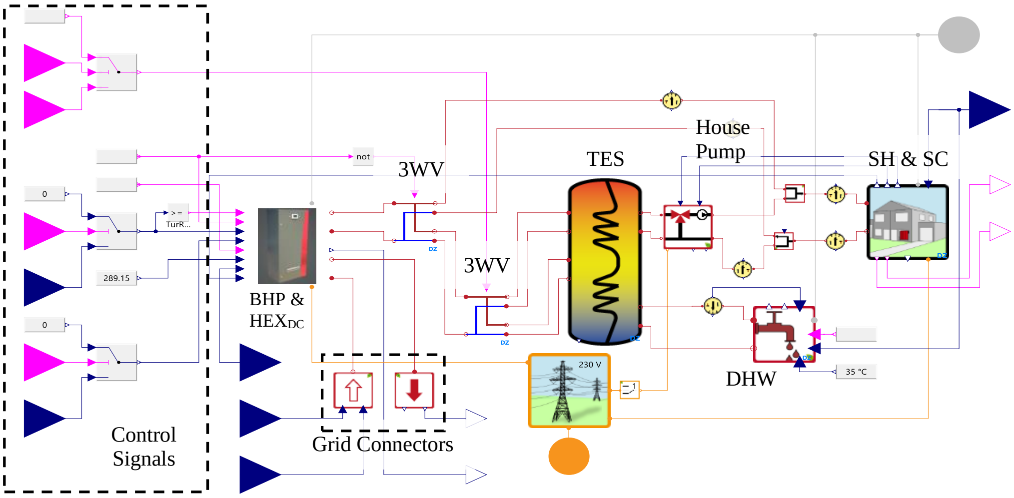


Figure 2. Prosumer Modelica Model

cooling operation (if no DHW is required during cooling periods). At each time step, there can only be heating or cooling demands with a 3WV alternating between BHP or HEX_{DC} when in cooling mode.

2.1.2 Control Strategy

The control strategy for modulating the BHP in heating mode is built around the discharging rate of the TES. The goal for the control is to keep a stratified TES, minimise the starts and stops of the BHP, keep a minimum temperature of 55°C on the TES at layer 9 and maximise system efficiency. Based on these objectives, the control uses a 3WV to charge the top or middle of the TES, with priority given to charging the top layer. To avoid on/off control with hysteresis (system lagging to the input signal), a novel control method is proposed with the modulation of the BHP as a function of the reference TES temperature layer. Equation 1 shows how the modulation factor is determined by the ratio between the actual and maximum temperature difference for the TES temperature layer against set maximum and minimum values.

$$mf = (((\max(0, \min(1, (1 - \frac{T_{reference} - T_{sup,minT}}{T_{sup,maxT} - T_{sup,minT}})))) \qquad (1)$$

where mf is the modulation factor for the BHP, $T_{reference}$ is the reference temperature layer, $T_{sup,minT}$ is the minimum temperature value for the reference temperature layer and $T_{sup,maxT}$ the maximum temperature value for the layer. When the reference temperature is equal to the maximum allowed temperature, the modulation factor is zero. Conversely, when the temperature matches the minimum allowed temperature, the modulation factor is 1. To ensure the modulation factor stays within the bounds of 0 and 1, a max-min definition is applied. This approach accounts for cases that the temperature levels in the TES exceed the upper limit (e.g., on start-up).

To maintain TES stratification, the prosumer component utilizes two modulation factors: one for the top for DHW and one for the middle for SH, as shown in Figure 3. Depending on the setting of the 3WV, the respective modulating factor is used, with the reference temperature layer set to layer 7 for charging of the top of the TES and layer 4 for the middle. These layers are chosen to limit hysteresis and the impact of water inflow to/outflow from the TES.

It is seen that the higher layer modulation factor mf_h is utilising a temperature band between the start and stop temperature setpoints, $T_{StartHP,h}$ and $T_{StopHP,h}$ respectively. In a similar manner, the lower layer modulation factor mf_l is determined by a lower temperature range $T_{StartHP,l}$ and $T_{StopHP,l}$. This control strategy allows for a stratified TES, maximisation of BHP operation and abiding to top level minimum temperature requirements. An operation example for 1 day is shown in Figure 4. The difference between layer 5 and 6 occurs due to the water outflow from the TES for SH demands occurring at layer 5.

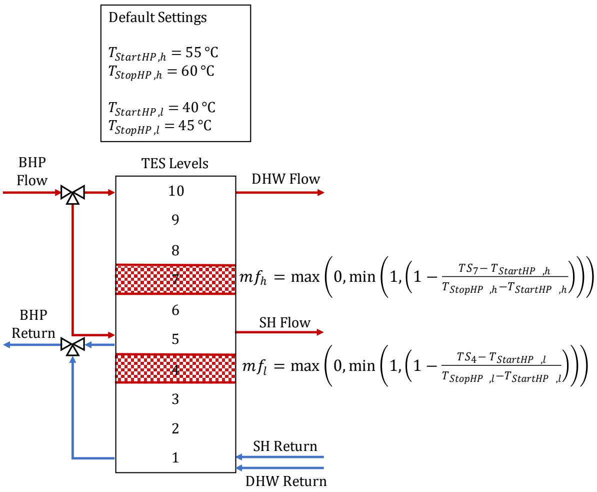


Figure 3. Schematic of control methodology for BHP.

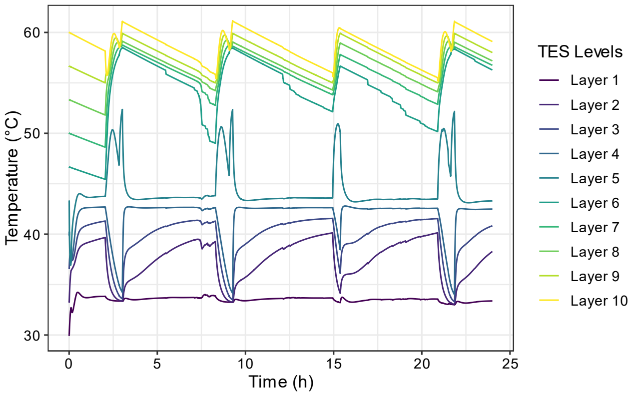


Figure 4. TES operation under modulation of the BHP

For SC, at default settings, priority is given to HEX_{DC} over the BHP (in cooling mode). The choice of switching to the use of the BHP if the room is not cooled after a designated time (defined by the user) is also provided.

Finally, a further control option has been added for the operation of the BHP. This allows for operation of the evaporator and/or the compressor under constant temperature difference or flowrate, both of which are available for commercial BHP units. Depending on the operation, the power modulation is achieved by varying the non-fixed variable within limits set by the user. The equations governing these behaviours have been modified in the models utilizing conditional functions ("if" statements) to adapt their operation accordingly. By implementing these adjustments, the BHP and grid inlets can be dynamically controlled, enabling greater flexibility in their operation. This adaptability allows for improved system performance and optimization tailored to the specific use case, with due consideration given to external factors such as flowrate and temperature differences.

2.2 Balancing unit

The balancing unit is responsible for providing thermal and hydraulic balance to the network. The Modelica model is captured in Figure 5 and described in the following sections.

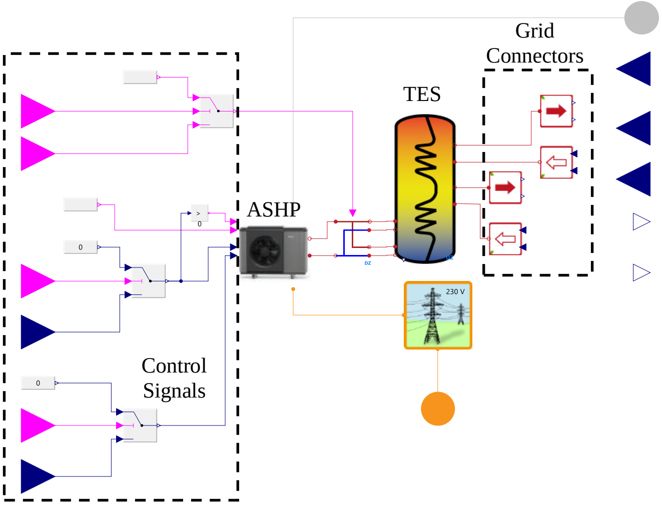


Figure 5. Balancing Unit Modelica Model

2.2.1 Model Description

An Air Source Heat Pump (ASHP) is connected in series with a TES that acts as a passive interface between the hot and cold pipes. This setup with the TES directly connected to the hot and cold pipe of the network (hot grid pipe at the top of the TES and cold grid pipe at the bottom), provides a passive hydraulic balance, critical for the operational integrity of the system featuring decentralised pumps and energy transformation units. The TES is therefore suppling heat or cold depending on the energy misbalance. The hot grid pipe is connected to the top of the TES (layer 10) while the cold pipe to the bottom (layer 1), allowing for a stratified TES with the hot pipe temperature at the top (e.g., 20°C) and the cold pipe temperature at the bottom (e.g., 15°C). Depending on the thermal balance needed by the network, the TES is cooling down (during heating balance needed) or heating up (during cooling balance needed). The ASHP needs to keep the TES temperature within the operational limits by recharging the top or bottom of the TES with heat or coolth respectively.

2.2.2 Control Strategy

To achieve this operational strategy, the ASHP is connected in series with the TES where a 3WV can change the TES charging levels based on mode of operation of the ASHP. Therefore, charging for heating uses level 9-6 for flow and return and level 2-5 for flow and return for cooling operation. This setup allows for unidirectional flow through the ASHP while keeping a stratified TES without mixing when variations between heating to cooling dominant system operation occurs. The mode of the ASHP depends on the flow direction of the grid, with cooling activated when the flow leaves the bottom of the TES, and heating when the flow leaves from the top.

The ASHP operation is following the same rule-based control for the modulation factor as the one described in equation (1). The operation of the balancing unit is captured in Figure 6, with an explanation of operation during heating and cooling dominant network operations described in the following paragraphs.

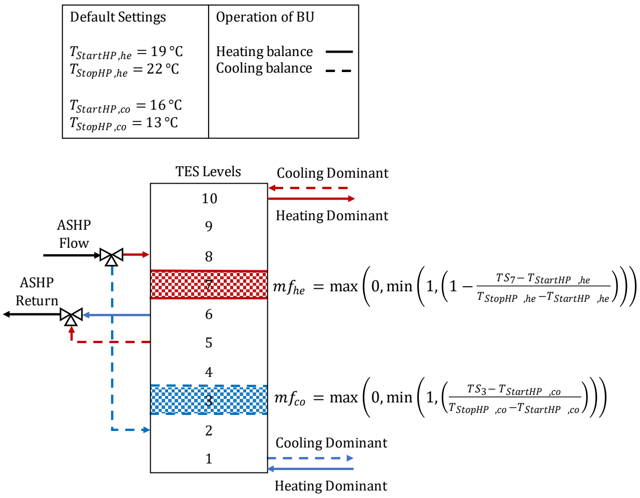


Figure 6. Balancing unit setup and connection schematic

Like the BHP heating setup, there are two modulation factors for the ASHP, in this case depending on the operation mode (heating or cooling). During heating, the flow going through the TES is from the bottom to the top with the ASHP in heating mode. The heating modulation factor mf_{he} is used which is calculated based on equation (1) with the upper and lower temperature bands being $T_{StartHP,he}$ and $T_{StopHP,he}$. For cooling, flow is reversed in the grid, with hot water coming in at the top of the TES and cold one coming out at the bottom. Therefore, the ASHP is in cooling mode, cooling down the lower half of the TES. For the modulation factor during cooling mf_{co} there is no need to subtract the ratio of the reference temperature from 1 since it directly responds to the cooling power requirements. This operation also allows for a stratified TES that can respond to dynamic changes in heating/cooling balance requirements.

2.3 Hydraulic Interface

The hydraulic interface is needed for the connection of Modelica components with thermal connectors to a system with hydraulic connectors that can capture bidirectional flow as well as pressure variations.

The hydraulic interface can avoid utilising library components that are only available in Simulation X, therefore open access Modelica standard library components are preferred. The functionality of the interface follows the methodology presented in the ProsNet library (Elizarov and Licklederer 2021), where the primary and secondary side communicate through a set of input/output signals. The key novelty in the approach developed in this paper, is the introduction of a thermal volume to represent the prosumer, considering thermal inertia and pressure variations of the system. Therefore, we can combine the benefits of utilising thermal only connectors in the prosumer and balancing unit components (low computational times and lower complexity) without compromising the hydraulic performance of the system. At the same time, this setup allows for a clear separation between the thermal only models utilising Simulation X components that can be turned into Functional Mock-Up units (FMU) as discussed in Section 2.4. The hydraulic interfaces for the prosumer, the balancing unit, and the grid model are illustrated in Figure 7.

For the prosumer hydraulic interface unit, the key inputs and outputs from the hydraulic interface are temperature [°C] and flowrate [l/min]. Signals for the set flowrate $\dot{V}_{g,set}$ asked by the prosumer and the output temperature $T_{p,out}$ from the prosumer are sent to a volume representing the prosumer, allowing for thermal inertia to be accounted for, resulting in the temperature the grid actually sees from the prosumer, $T_{g,out}$. Depending on the instantaneous demand mode (heating or cooling), the respective pump from the interface becomes active and flow is thus changing direction respectively. We use a PI controller to

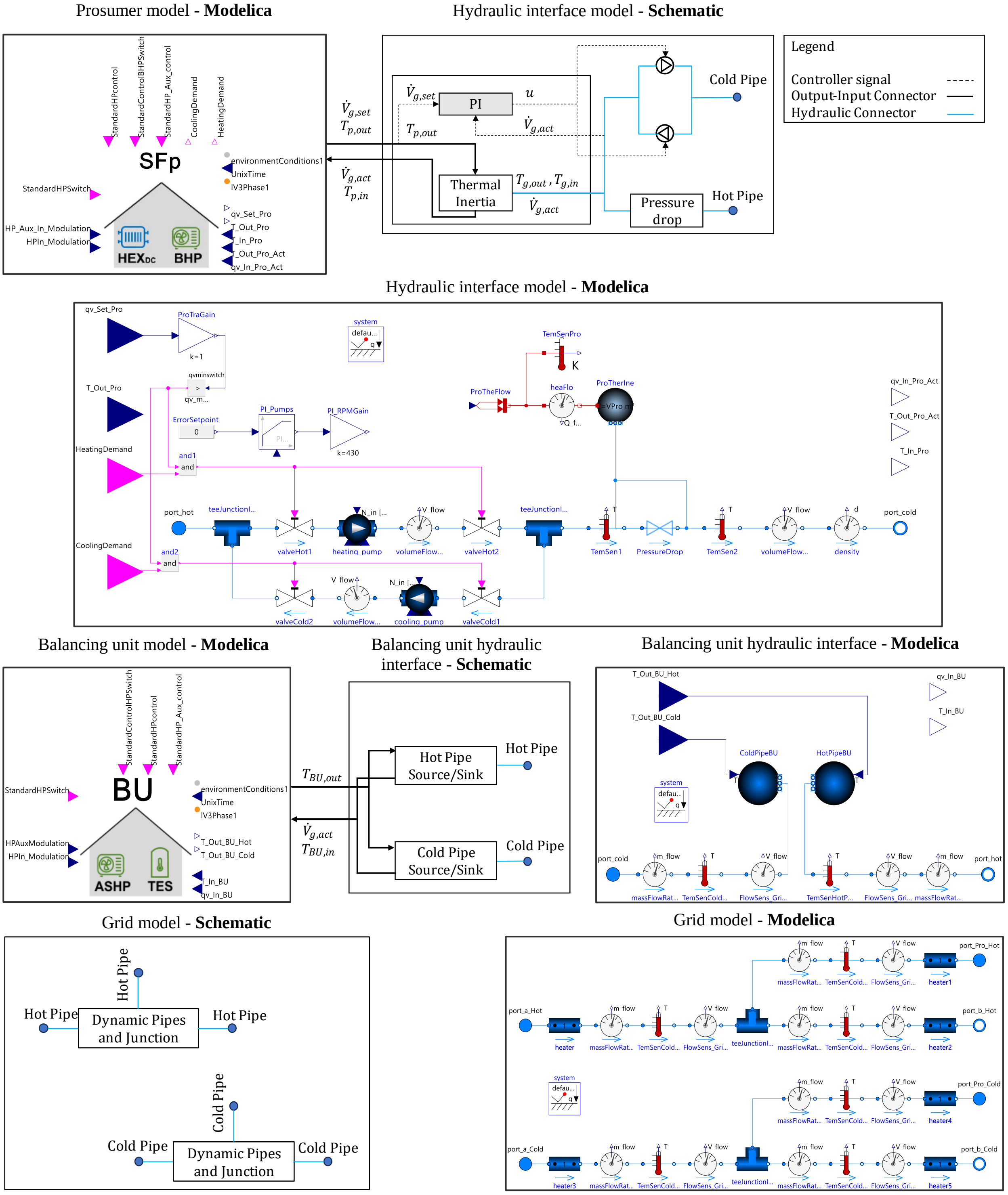


Figure 7. Hydraulic interfaces for prosumer and balancing unit as well as hydraulic model of the grid

give the setpoint u to the respective pump, considering the actual $\dot{V}_{g,act}$ and set flowrate $\dot{V}_{g,set}$. Then, $\dot{V}_{g,act}$ and $T_{g,in}$ are fed back to the prosumer as inputs.

For the balancing unit's hydraulic interface, the key input is the temperature from the balancing unit. The temperature corresponds to the top or bottom of the TES, depending on the flow direction, namely the sign of $\dot{V}_{g,act}$ as described in Section 2.2.2. If $\dot{V}_{g,act}$ is positive, which means there is dominant heating demands in the grid (flow from cold to hot port), then the hot pipe volume acts as a source with $T_{BU,out}$ being equal to the temperature at the top of the TES. $T_{BU,in}$ equal to the temperature of the cold pipe flows at the bottom of the TES. The opposite happens when there is cooling dominant operation and thus a negative $\dot{V}_{g,act}$, with the cold pipe volume becoming a source and the hot pipe volume becoming a sink.

The pipe network, namely the grid model, comprises dynamic pipes, sensors and junctions to allow for the connection of the prosumers and the BU. The grid model allows for parallel connection between loads, and includes ports for both the hot and cold pipes.

2.4 FMUs of Prosumers and Balancing Unit

To further increase the usability of the model, both prosumer and balancing unit models are developed so that they can be exported to FMUs, allowing for their use through the FMI standard for application in all Modelica environments (The Modelica Association 2023). With FMUs for these components, an arbitrary size of network can be built, with varying topologies and design and operational characteristics in any Modelica environment. However, the benefits from using a FMU come at a cost of transparency and editability. The components become "black boxes" that have specific elements that can be edited, significantly limiting the flexibility of the models to change. To maximise their usability, a set of key parameters have been made editable in the FMU. These follow the ProHMo library methodology as described in (Zinsmeister and Perić 2022), and include:

- Inputs for individual control setpoints
- Weather files
- Consumption parameters
- Energy generator unit capacities
- TES dimensions

3 Exemplary Use Case

To showcase the usability of the produced models, a simple system is used. It involves a heating and cooling prosumer as well as a balancing unit connected through a grid element in parallel. This setup is the one shown in Figure 1, Section 2. A constant temperature difference is kept between the cold and the hot pipe, and the grid pipes are modulated based on variable flowrate. HEX_{DC} is used for the cooling prosumer while the BHP for the heating prosumer (connected in series to the TES).

The simulation is performed for one day, with an aim to observe the behaviour of the system and qualitatively verify its operation. Figure 8 displays key outputs, namely the temperature levels of the top and bottom layers of the BU TES, the temperature in the living zones of the prosumers as well as the temperature and flowrate values on the grid's junction.

Plot A indicates the fluctuations of the temperature levels in the TES of the balancing unit, responding to heating and cooling requirements in the grid while keeping the upper (22°C) and lower (13°C) temperature limits. The spikes observed occur during ASHP start-up, with a momentary large intake. Plot B shows that the temperatures in both prosumer's living areas are maintained at the target reference temperatures (21°C for heating and 23°C for cooling). Larger deviations are observed during cooling due to the controller setting, underfloor cooling system behavior and the house pump's flowrate capacity.

Graphs C and D present temperature levels at both the hot and cold pipes. In plots E and F, flow halts for the cooling prosumer after hour 13, causing the respective pipe temperatures to track ambient temperatures and those of the segment preceding it. During the flow interruption

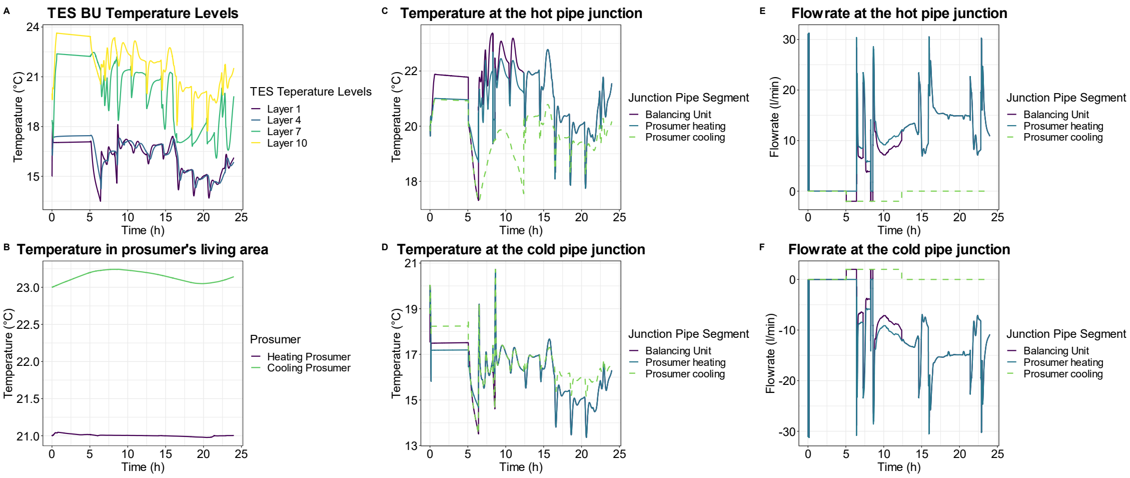


Figure 8. Exemplary case study outputs

until hour 5, the balancing unit remains idle, with the TES temperature slightly decreasing due to energy losses.

Overall, hydraulic and thermodynamic balances are kept in the system. The temperatures are maintained in the prosumer houses and bidirectionality of flow is captured. The balancing unit can operate both in heating and cooling mode ensuring that the top and bottom temperature levels are kept. It is shown that the components provide a working basis for investigations of different design cases and operation strategies. The next section describes how such designs can be validated with minimal hardware utilising PHIL approaches.

4 Power Hardware-in-the-Loop

Prosumer behaviour and interaction under different design conditions and control methodologies is one of the key gaps in research of 5GDHC systems. Experimentally validating models would require multiple BHP and buildings with both heating and cooling demand as well as the ancillary equipment (valves, pipes etc.) for developing a thermal network. To facilitate experimental validation of generated system models or the experimental assessment of prosumer interaction under varying control and design philosophies, the components are designed in such a way as to be able to utilise PHIL with minimal hardware requirements. Figure 9 illustrates how PHIL can be used for experimentally simulating a prosumer with only a HEX.

The HEX is sending metered signals to the prosumer simulation model for the flowrate and temperature present both on the primary and secondary side of the HEX. These are converted to standard unit values via a conversion module and fed to Modelica, which in turn sends back control signals. For the conversion & control modules, various software/hardware interaction methodologies are available. For example, the CoSES lab utilises Industrial Controllers for the hardware, communicating in real time with NI VeriStand for the conversion of logged data and control setpoints, as thoroughly explained in (Zinsmeister et al. 2023). Regarding hardware, other than the HEX, a heating and/or cooling unit are required to raise/drop the temperature for both the prosumer and grid side.

Prosumers' BHP and $\mathrm{HEX_{DC}}$ can be emulated with a PHIL setup. As mentioned in Section 2.1, the prosumer model features a BHP and $\mathrm{HEX_{DC}}$, controlled in either constant flowrate or temperature difference. For the $\mathrm{HEX_{DC}}$ operation, based on the measured flowrate and temperature, the set return temperature of the house $T_{h,set}$ is calculated based on the heating/cooling system of the building and the building and outdoor temperature. The 3WV mixes water from the supply side to reach $T_{h,set}$. A signal is also provided for the grid pump $\dot{V}_{g,set}$, as explained in Figure 7 found in Section 2.3. For the BHP emulation, the grid pump is still operated according to the control signal $\dot{V}_{g,set}$ but the house side operates differently. The 3WV is closed, so that it doesn't mix water from the supply into the return line and the pump on the building side is operated to supply $\dot{V}_{h,set}$ to achieve the outlet temperature of the heat pump on the grid side.

Further implementations are possible that follow the same principles as the ones mentioned above. These could include multiple HEX connected in series or in parallel to study the interaction of various prosumers. In addition, the balancing unit could be connected in a similar approach to study its characteristics. Even an entire network with multiple prosumers and balancing units could be included as a simulation model on the grid side which would allow for investigating the impact of single/multiple prosumers on larger grids.

5 Discussion

This paper presents a set of models for the development of 5GDHC systems. The models have been developed with a focus on usability, scalability, accuracy, flexibility, and validity. The following sections provide some insight on strengths and limitations as well as a discussion on potential applications of the models.

5.1 Strengths

These components utilise validated models from the ProHMo library that are modular and can provide a detailed representation of component operation and building behaviour. They provide a good rule-based control allowing for BHP operation with low number of starts and stops for a longer component lifetime and a stratified TES. Start up and slew times are included as well as solutions for hysteresis. Computational time is kept low since we are using hydraulic equations only for the network, significantly reducing the complexity of the model. The models are made open access and have platform independent

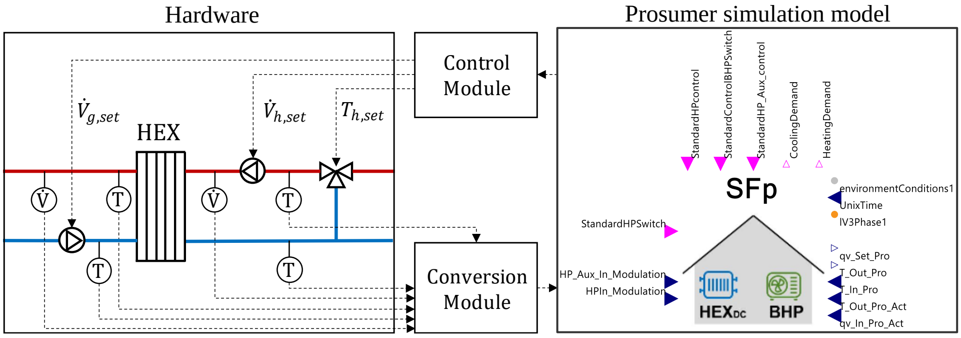


Figure 9. PHIL for a prosumer using a heat exchanger.

FMUs where commercial components are used. They can be coupled with various grid models and elements such as seasonal thermal storage.

Another key benefit that is arising from these models, is the capacity for PHIL experimentations with minimal hardware to study prosumer interaction. The models can be used to emulate both building and BHP/HEX$_{DC}$ behaviour. Different levels of detail for PHIL experiments allow a detailed analysis of grid behaviour and component interaction with low costs, space requirements and overall complexity.

5.2 Limitations

The key limitations of the components come from the use of the ProHMo library. It is built in Simulation X which is not an open access tool. This limits the capacity to freely edit the components. FMU provision has been presented as a workaround, but it does not fully open the “black box” of the component and does not allow for simple drag and drop of the individual components for use on any Modelica environment. The prosumer and balancing unit component models could be integrated into other libraries which are using open access components, while keeping the methodology of their operation intact.

The building models are focused on residential properties and may not accurately represent different consumer classes such as office blocks or retail properties. Moreover, the operational behaviors of the energy transformation components are tied to the units used in the CoSES lab, which are designed for household-scale applications. Consequently, when attempting to model much larger units or units with different technical specifications (e.g., refrigerants), the scalability and accuracy of the models may be compromised.

5.3 Potential Applications

The main benefit of this work is the provision of bespoke models and methodologies that facilitate the studying and analysis of 5GDHC systems. They can act as a basis for the creation of research cases on the impact of several parameters on the overall performance of the system. For example, they could be used to investigate different network topologies and the effect that network behaviour has on the hydraulic operation. The effect of including different consumer classes as prosumers as well as the seasonal co-occurrence of their heating/cooling demands could also be studied. The models could be used to replicate bespoke networks for industrial applications with given building schedules. Detailed operational strategies could also be investigated, identifying the effect of the hydraulic setup on the creation of thermodynamic subcycles and pump hunting phenomena. By developing relevant network and ground models, the effect of the ground type on the network performance can be studied for different insulation levels of the pipework, with a focus on the capacity for thermal losses under different network temperature regimes, insulation series and pipe materials. The impact on the number and location of balancing units as well as the introduction of passive balancing units such as seasonal energy storage (e.g., aquifers) can be quantified. The level of centralisation can also be studied, by changing the consumption parameters, allowing for a deeper investigation of the thermal zoning effect and combination of 4GDH with 4GDC and 5GDHC networks.

6 Conclusions

This paper presents a comprehensive set of Modelica models for the key components of 5GDHC, namely prosumers, balancing units, and hydraulic interfaces.

The component design and assessment, including their interconnections and control strategies, have been discussed and demonstrated through an exemplary use case. The paper has also demonstrated the applicability of PHIL setups for experimental analysis of prosumer interactions with the use of minimal hardware requirements, exemplified through a theoretical case study setup utilizing only a HEX to model a prosumer.

The presented models and methodologies provide an advancement in the understanding and analysis of 5GDHC systems. The provision of FMU models allows for their utilization in various coding environments through FMI, promoting open access as part of the ProHMo library.

Overall, this work contributes to the development of tools and methodologies for the analysis and study of 5GDHC systems, offering potential avenues for future research and application. By further refining and expanding the accessibility of the models, the understanding and adoption of 5GDHC systems can be advanced in a more open and collaborative manner.

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Nomenclature

Abbreviation	*Meaning*
5GDHC	5th Generation District Heating and Cooling
3WV	3-Way Valve
ASHP	Air Source Heat Pump
BHP	Booster Heat Pump
DHW	Domestic Hot Water
EMS	Energy Management System
FMI	Functional Mock-Up Interface

Abbreviation	*Meaning*
FMU	Functional Mock-Up Unit
HEX	Heat Exchanger
HEX_{DC}	Direct Cooling Heat Exchanger
PHIL	Power Hardware In the Loop
SC	Space Cooling
SH	Space Heating
TES	Thermal Energy Storage

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