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Implementation of a Digital Twin of the CoSES District Heating Prosumer Laboratory#

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ABSTRACT

This paper presents a digital twin for the district heating prosumer laboratory at the Center for Combined Smart Energy Systems (CoSES) consisting of heat generators, thermal storages and heat consumption. It is developed using a newly created, Modelica-based simulation library named CoSES ProHMo. Existing simulation models often fail to accurately represent the behavior of commercial hardware components. Therefore, the digital twin features new, accurate heat generator models and tuned models for thermal storage units and heat consumption. The component models are parametrized using measurements from the CoSES laboratory. It can be exported and used in other programs via the Functional Mock-up Interface (FMI). This allows the digital twin to be used platform-independently to design control strategies for realistic heating systems. If desired, the control strategies can be ported to an embedded controller and further tested in the CoSES laboratory. A case study with multiple heat generators, thermal storages and a heat sink was designed to demonstrate the utility of the library. The analysis of the results shows previously unanticipated interactions between different heat generators and the internal controllers of commercial hardware. Based on these findings, the proposed digital twin library can be used by the research community to create realistic scenarios for testing novel control strategies for heating systems and prosumers in district heating grids.

Keywords: Digital Twin, Simulation, Modelica, Power Hardware in the Loop, Prosumer, District Heating

1. INTRODUCTION

Smart Energy Systems are a cost-effective way to accelerate the energy transition by combining electricity, heat, transport and gas sectors to exploit synergies between them [1]. In this context, the introduction of thermal prosumers in district heating grids can further drive sector coupling between electricity and heat by combining several buildings to a larger system with more flexibility. Thermal prosumers are houses that can extract or provide heat from/to the grid. With prosumers being integrated into district heating grids, new control concepts for buildings and grids have to be designed.

These concepts are developed using simulation models and can be further improved in laboratories with commercial hardware and under close to real-world conditions. For laboratories, Power-Hardware-in-the-Loop (PHIL) is a powerful tool to emulate elements that cannot be integrated, such as consumer behavior. In a PHIL setup, part of the system is simulated and sends setpoints to a test environment, where they are converted into a real power flow whose measurements are sent back to the simulation model. This PHIL concept is the basis of the Center for Combined Smart Energy Systems (CoSES) laboratory at the Technical University of Munich (TUM), which was designed to investigate control concepts for smart energy systems [2]. The laboratory consists of five connected houses with different generators, storages and loads on electric and heat side. Several components of the CoSES laboratory have already been characterized and can be used to validate simulation models [3, 4].

When testing new control strategies in laboratories, it is important that simulations and experiments provide comparable results. Most simulation libraries for heating systems are based on generic simulation models which allow the qualitative analysis of heating systems. However, these simulation models often fail to accurately represent the behavior of commercial hardware components. Therefore, a digital twin of the CoSES laboratory is developed based on the newly created simulation library named CoSES ProHMo to develop and tune control strategies prior to experiments. It features accurate heat generator models and tuned models for thermal storage units and heat consumption, which are parametrized using measurements from the CoSES laboratory. The main contribution of this paper is the digital twin library that can be used by the research community to develop novel control strategies in realistic scenarios for heating systems and prosumers in district heating grids.

The remainder of this papers arranged as follows. Section 2 presents the CoSES ProHMo library as the basis of the digital twin and options to export the models to other programs. These models are used to generate dynamic PHIL setpoints for the CoSES laboratory (section 3). In section 4, a case study compares the simulation results with the results of a PHIL experiment.

2. SIMULATION MODELS

The digital twin of the CoSES laboratory should mimic the behavior of its components in detail, ideally with a short simulation time. It should further be conductive to development work where the implementer is changing strategies or parameters. This enables the development and testing of suitable control strategies.

To implement the digital twin, the CoSES ProHMo simulation library is used. It is created in Modelica, an object-oriented modelling language for cyber-physical systems [6]. The structure is shown in Fig. 1. Since the Green City library [5] already provides accurate, predefined simulation models for building energy systems, it serves as a basis for the heat consumption, thermal storages and environment. These models are adapted and parametrized to replicate the behavior of the CoSES laboratory. Heat generator models are created from scratch to accurately mimic the behavior of the commercial components in the CoSES laboratory. The CoSES ProHMo library can be exported via the Functional Mock-up Interface (FMI) to other programs or used in NI VeriStand for PHIL or Software in the Loop (SiL) experiments. It is described in the following section and published on github [7].

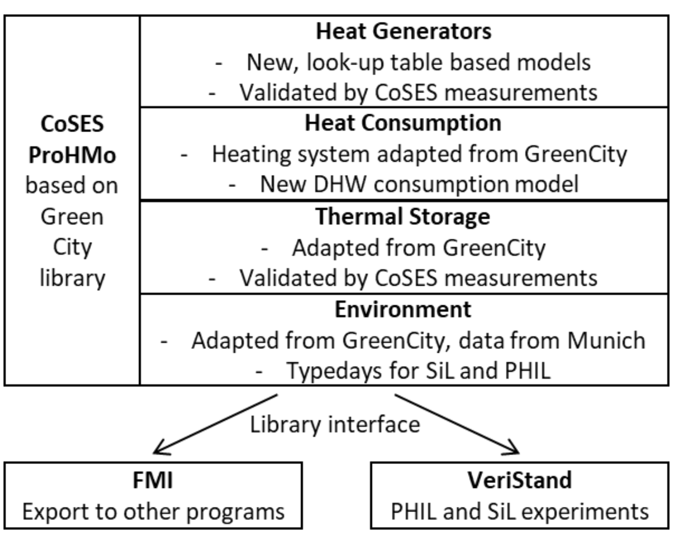

Fig. 1: Structure of the CoSES ProHMo simulation library

The models of the CoSES ProHMo library neglect pressure constraints and pressure losses within the system, which reduces the simulation time. This simplification is valid under the assumption that the system has a unidirectional flow and that pumps can provide the desired flow rate at any time, which is the case for heating systems under normal heating conditions. It replicates the behavior of the commercial components of the CoSES laboratory, including their internal control and specific behavior. Since internal control strategies vary among manufacturers, other equipment might behave differently.

2.1 Heat generators

Each house of the CoSES laboratory is equipped with one or more heat generators. Despite adjustments, generic heat generator models of various simulation libraries could not adequately replicate the behavior of the components. Generic models are good for qualitative analysis, but in this case not sufficient to represent the behavior of specific heat generators in detail. Therefore, heat generator models of the CoSES ProHMo library are based on look-up tables that provide data on dynamic behavior and efficiency. These look-up tables are derived from measurements in the CoSES laboratory. All models use Modelica Standard Library (MSL) objects and can be imported directly in other Modelica based simulation programs. The library so far consists of models of condensing boilers, air-source and ground-source heat pumps and combined heat and power units (CHPs). All models are similar in design and documented in detail in the Modelica documentation.

The behavior of the CHP is described here as an example and based on experimental characterizations [3]. It is divided into four sections as illustrated in Fig. 2:

- Start-up and cool-down process: The start-up and cool-down behavior are provided by a time dependent look-up table.
- Warm-up process: Energy required to warm up the CHP is subtracted from the steady-state efficiency and decreases linearly during the warm-up phase. The warm-up energy and time depends on the downtime.
- Steady-state: Two-dimensional look-up table provide the efficiency, which depends on the return temperature and power modulation. Load changes during steady-state are modeled with a rising or falling flank.

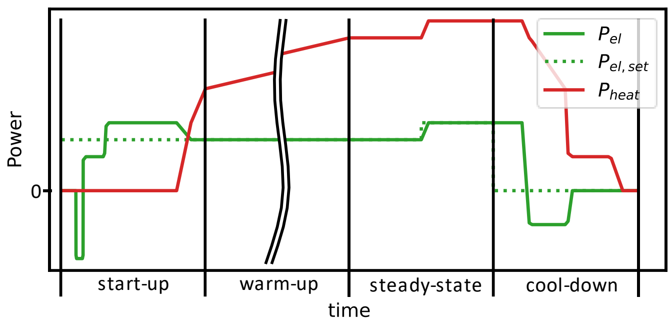

Fig. 2: Schematic of the four operation sections of the CHP

2.2 Heat consumption

The space heating system and domestic hot water (DHW) consumption constitute the heat consumption of a house. The Green City library already provides a detailed model of the consumption of space heating systems. This model was adapted in parts to better represent the desired characteristics of the heating system:

- The area specific heating power is adaptable so that the return temperature can be influenced.
- Electric consumption and presence profiles can be specified to better reflect their impact on heating consumption. Electric consumption profiles are implemented from [8].
- The set room temperature is variable, depending on presence and night time reduction settings.

For the DHW consumption, a new model was created that contains consumption profiles as a time series based on [9]. The model further checks if the DHW temperature is within the desired temperature range.

2.3 Thermal storages and heat distribution

The simulation library uses a slightly adapted version of Green City's stratified thermal storage model. It was calibrated using measurement data of the CoSES laboratory [4] and has additional inlet and outlet ports.

Depending on the type of heat generator, it is useful to position the thermal storage tank in different ways between the heat generation and consumption [10]. The different heat distribution systems are modeled and can connect the thermal storage with the heat generators, heat consumption and bidirectional district heating substation according to the requirements.

2.4 Environment Data

The Green City library includes a model for weather data from various locations. In order to integrate individual weather data and type day analysis, this model was extended. For the case study of this paper, weather data of the year 2021 in Munich was used, which is available on github [7]. For real-time simulations and PHIL experiments, type days were derived based on VDI 4655 [11].

2.5 Library interface

SimulationX and Modelica offer various ways to use simulation models in other programs. If only elements of the MSL are used, they can be used in all Modelica-based simulation programs without further adjustments, as for example in the case of the heat generators from section 2.1. To use the library outside of SimulationX, different interfaces are available to export the code, among others code export via FMI or creating .dll files for NI VeriStand.

FMI is a free standard to exchange dynamic models using a combination of XML files, binaries and C code and is supported by many tools [12]. The file can be unzipped and modified if necessary. FMI model export has the advantage that well-designed libraries can be integrated into other programs, e.g. the SimulationX based CoSES ProHMo models of this paper are used in the ProsNet library for bidirectional district heating grids in Dymola [13].

In the CoSES laboratory .dll files are used to import models into NI VeriStand for SiL and PHIL applications. When importing the digital twin in NI VeriStand for SiL tests, controllers and communication interfaces can be tested in real time prior to the experiment to find errors, saving time and money.

3. POWER HARDWARE IN THE LOOP SETUP IN THE COSES LABORATORY

PHIL combines a physical and a simulated system. It can integrate environmental conditions and user behavior in experiments that are difficult to be accounted for. The setpoints are specified by the simulation model and converted into power flows in the laboratory, whose measured values are in turn sent back to the simulation model. In addition to the more realistic representation of the environment and user behavior, the results are better reproducible since the experiments can be performed independently of ambient conditions.

The PHIL setup of the space heating system in the CoSES laboratory is shown as an example in Fig. 3. The heating controller defines the set water flow through the heating system (V_{set}) and the supply temperature ($T_{sup,set}$) based on the current room and outdoor temperature. The simulation model of the space heating system further calculates the return temperature ($T_{ret,set}$) using the measured supply temperature (T_{sup}) and water flow ($\dot{V}_{sup}$) from the testbed.

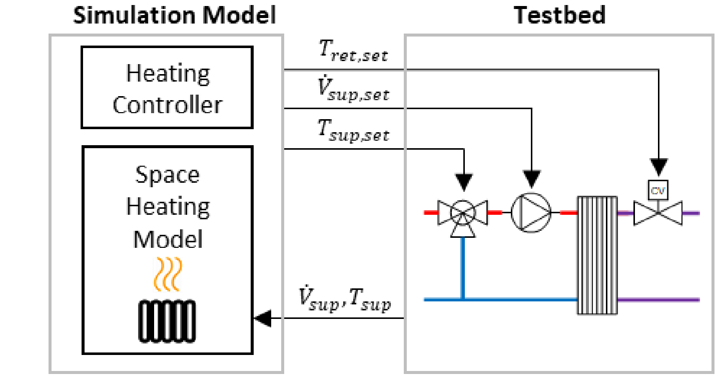

Fig. 3: Setup and data exchange of the PHIL experiment for the space heating system

The testbed consists of a commercial mixing station with a 3-way mixing valve and a pump to control the supply temperature and water flow of the heating system. If the inlet temperature into the mixing station is higher than the set supply temperature, the 3-way mixing valve injects cold water from the return pipe. The heat is extracted by a heat exchanger. A control valve on the cooling water side regulates the cooling water flow and thus the heat extraction and the return temperature of the heating system.

Other PHIL applications in the CoSES laboratory are domestic hot water consumption, solar thermal heat generators, the environment of air source and ground heat pumps and the district heating grid.

4. CASE STUDY AND RESULTS

A case study was conducted on one of the emulated houses in the CoSES laboratory to compare simulation and experimental results. Fig. 4 and Fig. 5 show the panoramic view and configuration of the testbed. It consists of a CHP unit (A) and a condensing boiler (B) with a nominal heat output of 6 and 20 kW, respectively. The condensing boiler operates at a constant water flow and temperature difference of 10 K between supply and return pipe, while the CHP produces heat at a constant supply temperature of 80 °C, adjusting the water flow depending on the return temperature. The consumption is emulated for a building with 6 inhabitants and a heated area of 300 m² (C). Two thermal storages are used for heating (D) and to provide DHW (E).

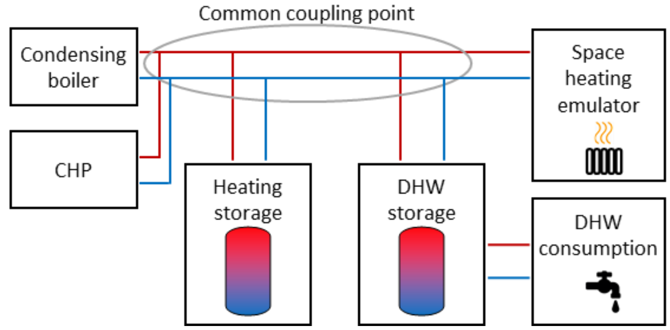

Fig. 5: Configuration of house 1 for the case study

A rule-based controller is used in this case study. The on/off conditions are:

- CHP / Condensing boiler:
  On condition: $T_{Sto,heat,top} < 65\,°C$ / $60\,°C$
  Off condition: $T_{Sto,heat,bottom} > 70\,°C$
- DHW storage charging
  On condition: $T_{Sto,DHW,top} < 50\,°C$ and $T_{Sto,DHW,top} < T_{Sto,heat,top}$
  Off condition: $T_{Sto,DHW,top} > 65\,°C$

4.1 Power Hardware in the Loop results

Fig. 6 shows the set and measured values of the PHIL testbed of the space heating system. The graph shows that the values, especially the return temperature, can be followed accurately.

The slow oscillation of the supply temperature and flow rate is caused by the controller of the mixing station and the missing thermal inertia of the heating system. These deviations are measured and sent to the simulation model. The same applies if the set supply temperature is higher than the inlet temperature of the mixing station or the volume flow is higher than the maximum volume flow of the pump and therefore the desired values cannot be achieved. These discrepancies

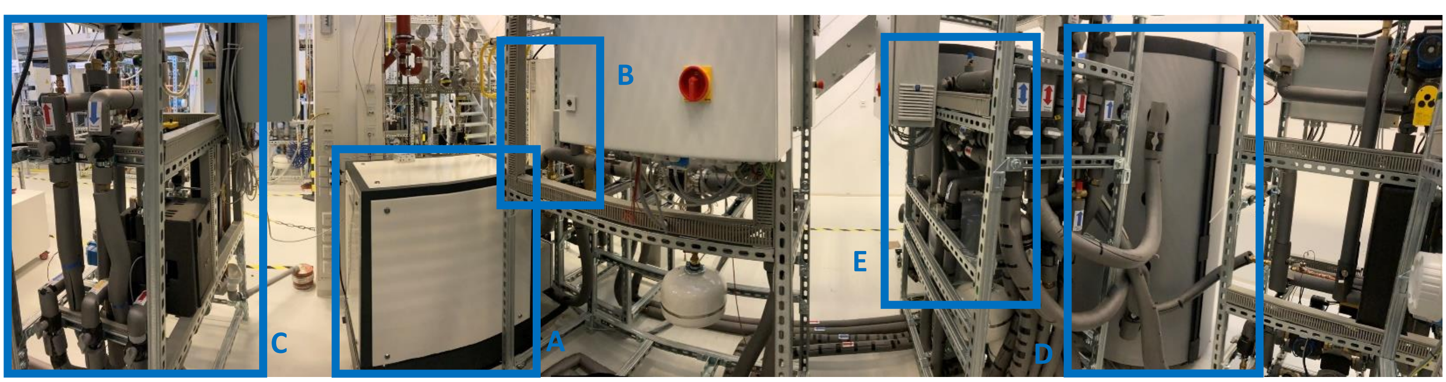

Fig. 4: Panorama picture of house 1

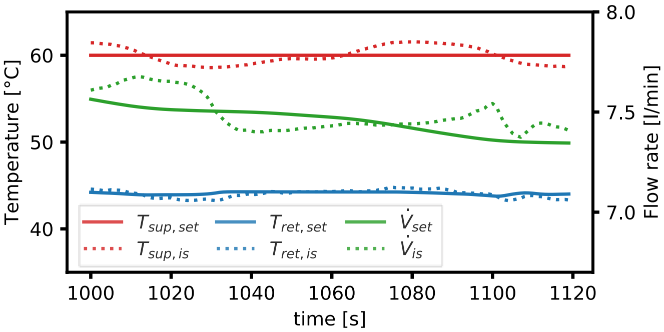

Fig. 6: Set and measured value of the PHIL testbed for space heating consumption

lead to a change in the room temperature and must be compensated for at a later time when the heating system provides the desired values again. The response to previous deviations is one of the advantages when using PHIL for the heating system.

The difference between the consumed heat of the simulation model and the PHIL testbed is $< 0.1\,\%$, which shows that the emulator works as planned.

4.2 Comparison of simulation and experimental results

Since the thermal storage is the balancing element between heat consumption and generation, it represents the behavior of the whole system very well and can be used to compare the results.

Fig. 7 shows the temperatures in the thermal storage and its state of charge (SOC) for the experiment and the simulation. The SOC and thus the energy content of the thermal storage is very accurately reproduced by the simulation model. The temperature plots of the different layers show that the temperatures in the simulation model reflect the internal temperature distribution less accurately and that the temperature stratification is less prominent in the simulation model. This is due to a too high heat exchange between the different levels, which cannot be further reduced in the simulation model due to numerical problems. However, the overall behavior is close enough to the measured values, especially at higher layers.

The inlet and outlet temperature of the thermal storage are shown in Fig. 8. During the charging process, the behavior is not exactly reproduced due to the previously mentioned discrepancy in the stratification of the thermal storage. The shape of the "temperature waves" is flatter in the simulation results, what results in a slightly different efficiency. Since the condensing boiler is active and operates at a constant temperature difference, this leads to a different inlet temperature at the top of the storage. The oscillating inlet temperature at the top is caused by the CHP and described below. During discharging, the experimental and simulation results match well.

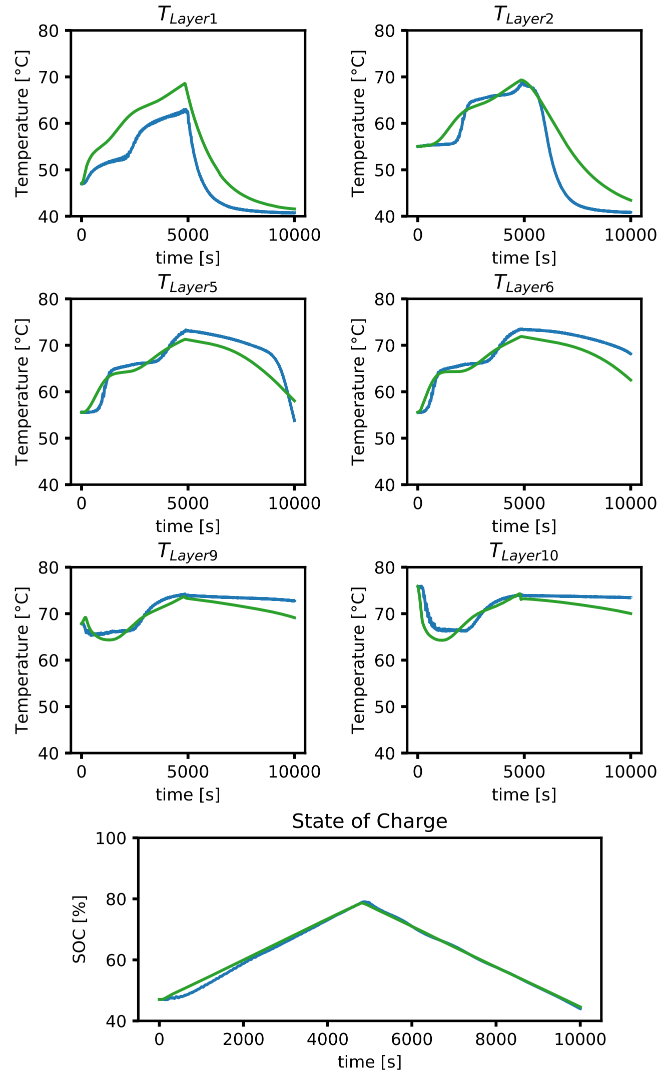

Fig. 7: Simulation (green) and experimental (blue) results during charging and discharging of the thermal storage

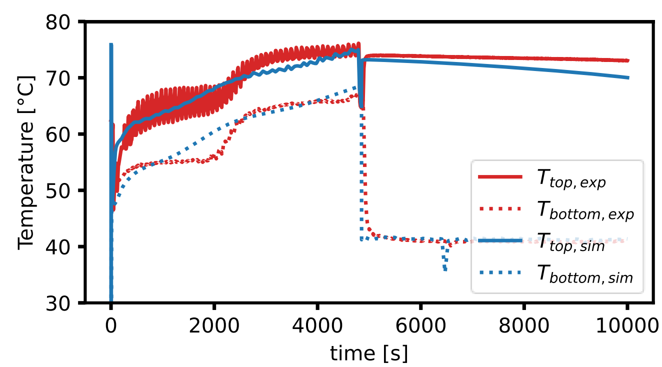

Fig. 8: Storage inlet and outlet temperatures

The different temperatures in the storage would lead to slightly different control signals and would make the comparability difficult. Therefore, the same setpoints for the heat generators are used in the simulation model as in the experiment.

If the condensing boiler and the CHP are active at the same time, the water flow through the CHP is influenced by the suction effect of the higher water flow of the condensing boiler. The control of the pump in the CHP cannot compensate for this, resulting in too high a flow through the CHP when the pump is active. Because of this, more heat is withdrawn from the CHP than produced, which results in the pump being switched off after a while. Hence, the periodic on and off behavior of the pump shown in Fig. 9 and the fluctuating supply temperature into the thermal storage in Fig. 8. This effect was unexpected and can probably be observed often in houses with multiple heat generators. It slightly affects the overall heat generation but has no influence on the electric power generation.

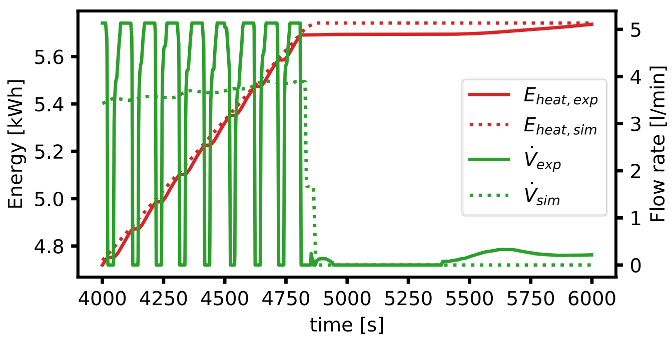

Fig. 9: Deviating flow through the CHP when affected by other components

The difference in heat generated by the condensing boiler and the CHP between simulation and experiment is $< 1\,\%$ and $5.9\,\%$, respectively. The higher deviation of the CHP is caused by an unexpected flow when it is deactivated as illustrated in Fig. 9. If this effect is ignored, the difference between simulation and experiment of the CHP is $< 1\,\%$.

The flow through the deactivated heat generator is caused by the space heating pump. Heat generators, space heating system and thermal storage are connected via a common coupling point. Therefore, part of the water flow is unintentionally drawn through the deactivated heat generators instead of being taken from the thermal storage. This is not considered in the simulation model and leads to a higher heat extraction from the CHP, because it extracts heat from its thermal inertia while being switched off. However, it also reduces the supply temperature of the space heating system once the heat generator is too cold.

This unwanted effect can be prevented by installing an automatic valve at the heat generator, which is open when it is active. Another option would be to connect the thermal storage so that it decouples heat generators and the heating system. However, this would increase the return temperature to the heat generators and thus reduce their efficiency [10].

5. CONCLUSION

This paper presents a digital twin of the CoSES laboratory to investigate prosumers in district heating systems. Existing models of heating systems in generic software often fail to accurately represent the behavior of commercial hardware components. This requires the development of specific models for an accurate analysis and control design of particular systems. Therefore, the CoSES ProHMo library was created for the digital twin, which consists of validated models of heat generator, heat consumers and thermal storages. The models can be exported and used in other programs via FMI. Researchers can use the proposed digital twin library to develop control strategies for realistic heating systems with commercial equipment. If desired, the designed control strategies can be ported to an embedded controller for commercial hardware in the PHIL testbed at the CoSES laboratory to gain further insights.

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