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"Validation of a mosaik-based Python simulation framework for smart district energy plants with a large heat pump share"

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Abstract

Integrating heat pumps into smart district energy plants (DEP) is a key strategy for decarbonizing residential heating systems, but it introduces substantial modeling and operational challenges, particularly when combined with 4th generation district heating networks and multi-source heat pump configurations. To address these challenges, we developed *DES.sim*, a modular, object-oriented, and open-source simulation framework based on the *mosaik* co-simulation framework. The framework provides parameter-driven long-term simulations of heat pump (HP) centered district energy systems (DES) and includes low-complexity component and controller models, support for multiple DHN topologies, and flexible integration of custom components.
We validated *DES.sim* using one year of measurement data from an operational DES in Karlsruhe-Durlach, Germany, that contains a hybrid HP and gas boiler system. The system-wide energy balance shows very good agreement between simulation and measurement: the simulated shares of HP and gas boiler generation closely match the measured shares (72.0 % simulated vs. 71.7 % measured HP share). The thermal outputs to domestic hot water and space heating are reproduced almost exactly. Only slight deviations occur in the HP performance indicators, with the simulated seasonal performance factor (SPF) 1.2 % lower than measured. This difference results from model simplifications, including the representation of two parallel heat pumps as a single aggregated unit.
Overall, the validation confirms that *DES.sim* reliably reproduces the system-level behavior of the real DEP and is suitable for strategic design studies and operational analyses. Its parameter-based setup and modular structure make it well suited for future work on multi-parameter optimization and sensitivity analyses under varying technological and scenario assumptions.

Keywords: District energy systems; Heat pump integration; Co-simulation; Energy system validation; Smart energy systems

1. Introduction

Heat pump (HP) centered District Energy Plants (DEP) represent a promising approach to transforming the heat supply of residential districts toward low-carbon and fossil-free solutions. They enable integration into 4th Generation District Heating systems, which are defined as systems "that provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems" [1]. In this paper, the combination of HP-centered DEPs and District Heating Networks (DHN) is referred to as a District Energy System (DES).

The effective integration of HPs into DESs poses specific technical and operational challenges. Supplying domestic hot water requires high temperatures for hygienic reasons, which HPs often cannot provide. As a result, additional heating components such as combined heat and power (CHP) units or gas boilers are required. To achieve economic efficiency, smart operation of the DEP is necessary to ensure synergies with local energy sources such as CHP and photovoltaic (PV) systems. At the same time, maximizing the HP share is essential to minimize carbon emissions. Planners and operators must therefore balance the trade-off between economic performance and environmental impact.

To support this task, we developed a modular and generalizable simulation framework suitable for long-term simulations. This open-source tool enables strategic simulations of DESs with varying design parameters, thereby supporting lifespan-level optimization for cost efficiency and carbon reduction. Additionally, it can be used to evaluate the effectiveness of smart control strategies in further improving economic performance and reducing carbon emissions. This paper presents the development of the simulation framework, including its component models, and its validation using a real HP-centered DEP located in Karlsruhe Durlach, Germany.

2. Methodology

The following chapter outlines the methodology applied to develop the simulation framework and to establish its validation. First, the *mosaik* framework, which serves as the foundational framework, is introduced. Subsequently, the *DES.sim* framework developed on this basis is described in detail. Finally, the setup and parameterization of the model used for the validation of the Durlach district are presented.

2.1. mosaik Framework

In energy system simulations, the components comprising the energy system are quite commonly developed as stand-alone models, with an exchange of information between these models being necessary for simulations to progress. The open-source framework *mosaik* [2], developed in the context of smart grids, handles the information flows between models in such co-simulations. The models must be implemented with the provided component application programming interface (API) to allow coupling with *mosaik*. The scenario API provided by *mosaik* can then be used to specify data flows between the coupled models in the scenario definition and execute the co-simulation. The *mosaik* APIs offer the flexibility to couple models from multiple programming languages and easily set up multiple entities in large scale simulation scenarios, which can then be used as a test bed for different control strategies.

In addition to these APIs, the *mosaik* ecosystem provides a database of existing simulators and adapters for key components (both electrical and thermal) of the energy system, and tools that help in building and analyzing scenarios, thereby simplifying the setup of the simulations. *mosaik-heatpump*, one of the available packages, provides models for the simulation of heating systems - consisting HPs, hot water tanks, and controllers – and adapters for co-simulation in *mosaik*. The HP model, first developed for co-simulation with user behaviour in households in a socio-technical analysis [3], has been significantly extended for a work on co-simulation with PV-T collector systems to analyse performance improvements [4]. The model provides the possibility to simulate HPs with different heat sources and heating capacities, while taking operational limits on temperatures and capacity into consideration. Furthermore, the model allows the simulation of HP performance at varying levels of complexity, through the different calculation modes based on the open-source *hplib* [5] and *TESPy* [6] libraries.

2.2. DES.sim framework architecture

The simulation framework *DES.sim* presented in this paper is based on the *mosaik* framework, specifically on models provided within the *mosaik-components* package. In particular, the HP and hot water tank models are reused, the latter representing a thermal energy storage (TES) unit with an integrated electric heating rod. The goal of the framework is to offer a generalized and easily parameterizable solution for simulating DEPs.

Simulation input parameters are defined in a single JSON file that contains all component and controller configurations. This setup also allows the selection of different DHN topologies, namely 2-pipe, 3-pipe, or 4-pipe systems. In a 2-pipe system, a single supply and return line are used to provide both space heating (SH) and domestic hot water (DHW). In contrast, a 3-pipe system separates DHW and SH in the supply line but shares a common return, while a 4-pipe system fully separates DHW and SH with dedicated supply and return lines for each.

As input data, the framework requires weather profiles (ambient temperature and global irradiance) provided as CSV files, as well as heat demand profiles (separated into DHW and SH in the case of 3- or 4-pipe systems) and electricity demand profiles for the households.

To achieve this, the framework provides low-complexity component models and a generic controller model operating based on a temperature setpoint control logic. The controller also allows configuration of the DHN topology by selecting between 2-, 3-, and 4-pipe systems. Table 1 provides an overview of all models included in the *DES.sim* framework. For a more detailed description of the models, the reader is referred to the GitHub documentation [7].

Table 1. Description of all models contained in *DES.sim*

Model	Parent class	Parameters	Outputs	Principle	Framework
Energy Transformer	-	Nominal power, operation stages, set temperatures or set flow rate	Mass flow rate and temperature	Energy balance	*DES.sim*
Gas boiler	Energy Transformer	Startup coefficients and startup time	Mass flow rate and temperature	Energy balance + Empirical regression	*DES.sim*
CHP	Energy Transformer	Electrical efficiency	Mass flow rate, temperature and electric power	Energy balance + Empirical regression	*DES.sim*
Controller	-	Temperature setpoints, heating curve, supply configuration, tank interconnections	Consumer flow rates, tank balancing flows, inbuilt heating rod power, Generator control signals	Rule based	*DES.sim*
HP (TesPy, fast mode)	-	Operation limits, heating capacities and COP table.	Mass flow rate, temperature and Electric power required	Steady-state Thermodynamics	*mosaik-components*
Hot water tank (TES)	-	Connection ports, dimensions, heat transfer coefficient, heating rod power stages	Layer temperatures, port temperatures	Mass and energy conversion	*mosaik-components*

2.3. Validation setup

To demonstrate the fidelity of the introduced simulation framework *DES_sim*, a system-level validation was carried out for a hybrid HP-centered DEP (2 HPs + gas boiler) and a CHP-centered DEP (CHP + gas boiler) including TES. Monitoring data from the "*Smartes Quartier Karlsruhe Durlach II*" project was used. In this project, a smart and innovative energy concept for a small district of 5 multi-family buildings (see Fig. 1) was designed in 2019, built in 2021 and has been in operation since February 2022: Buildings 2 and 4 are supplied by bivalent HP systems, the remaining three buildings 1, 3 and 5 are connected to a CHP-centered district heating network, supported by gas boilers for peak demand (see Fig. 2). Additionally, PV plants are installed on the roof of the buildings. All components are integrated into a local grid and monitored. A detailed description of the DES can be found in [8], [9].

The hybrid HP subsystem under investigation supplies a building with 30 apartments and a heated living area of 2107 m². It consists of a HP cascade with a total thermal capacity of 71 kW_{th} connected to a multi-source hydraulic (borehole (BHX) and air-to-brine heat-exchanger (AHX)). A 100 kW_{th} gas boiler is installed to support DHW production at temperatures above 65 °C and SH for outdoor temperatures below -5 °C. Three thermal storage tanks are incorporated to buffer peak loads. More details can be found in [10].

Figure 1. Aerial shot of the residential district in Karlsruhe-Durlach, Germany [11]

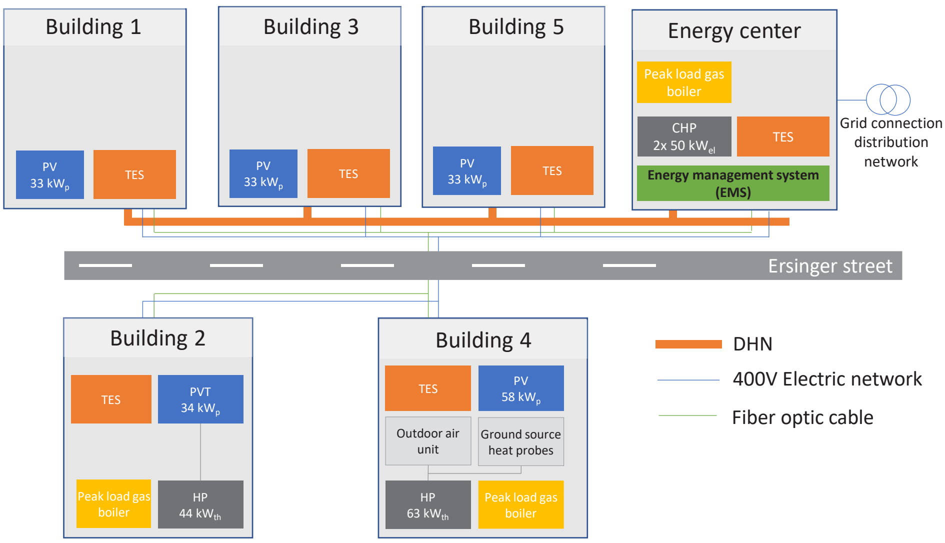

Figure 2. Schematic of the DES in Karlsruhe-Durlach, Germany containing the HP DEP in building 4 and the CHP DEP in the energy center

For the purpose of this validation, we analyzed data from the entire year 2024. We used heat meter data to determine the thermal power that each generator supplied to the storage tank and the power delivered to the consumers. We also used temperature sensor data to evaluate the supply and return temperature time series on the evaporator side of the HP. Since the actual district consists of three subsystems that are not physically connected, we modeled the HP-centered DEP in Building 4 and the CHP-centered DEP for Buildings 1, 3, and 5 in two separate simulation scripts and evaluated the overall energy balance during post-processing. We excluded the subsystem in Building 2 due to a HP failure during the observation period and because its configuration is nearly identical to that of Building 4.

To model the Durlach district in the *DES.sim* framework, we defined the system boundaries to include only the heating components and the TES (see Fig. 3 and Fig. 4). Therefore, only storage losses were considered in the energy balance, not losses in the DHN. We represented the heat source of the HP and the heat consumers (DHW and SH) as time series profiles derived from the measured data. We treated the gas supply and the electrical grid as infinite sources. For the heat source profile, we used the temperature data from the source connected to HP 1, since the HP 2 operated during less than 5% of the observation period. For the heat demand, which consists of DHW and SH, we used the two measured thermal power time series directly.

Modeling the hydraulic layout of the Durlach district required several simplifications. The real system uses multiple switching valves that enable highly flexible operation, allowing each of the three storage tanks to be charged individually. In the simulated layout, we omitted these valves because their influence on the overall energy balance was considered negligible.

In the simulated layout, the HP charges Tank 2 (middle tank) while drawing its condenser inlet supply from Tank 3. The space heating demand is primarily supplied from Tank 2. When the temperature in this tank falls below the required supply temperature defined by the heating curve, the controller mixes in a portion of the flow from the hotter Tank 1. To achieve this, we implemented a temperature-regulated mixing valve, as shown in Fig. 3, in the controller model. Tank 1 supplies the DHW demand. A peak-load boiler charges this tank to maintain the hot water supply temperature above the legally required setpoint of 65 °C.

We modeled the dual HPs as a single air-to-water HP with the combined capacities of both units. To this end, we summed the thermal capacities from the datasheets of the two HPs, and averaged the COPs. For the gas boiler, we applied the datasheet thermal efficiency of 98% and multiplied it by a factor of 0.9 to account for startup and shutdown phases as well as operation at non-optimal conditions. The control logic is derived from the measurement data and implemented as a temperature setpoint control logic with heuristic rules. We also parameterized the heating curve based on the measured data of ambient temperature and supply temperature. Table 2 below lists all model parameters used for the validation.

Table 2. Model parametrization for the Durlach district

Model	Parameter	Value
Gas boiler	Power stages	0 kW_{th}, 50 kW_{th}, 100 kW_{th}
	Supply temperature	70 °C
	Thermal efficiency	88 %
Controller (for HP DEP)	Supply configuration	4-pipe
	Boiler turn on condition	TES 1 (top layer) < 60 °C
	Boiler turn-off condition	TES 1 (top layer) > 65 °C
	HP turn-on condition	TES 2 (middle layer) < 50 °C
	HP turn-off condition	TES 2 (middle layer) > 55 °C
	Heating curve - max supply temperature	60 °C at 0 °C ambient temperature
	Heating curve - min supply temperature	52 °C at 10 °C ambient temperature
Controller (for CHP DEP)	Supply configuration	2-pipe
	CHP turn on condition	TES (top layer) < 65 °C
	CHP turn-off condition	TES (top layer) > 78 °C
	Boiler turn-on condition	CHP runtime > 20 minutes and TES (top layer) < 80°C
	Boiler turn-off condition	TES (top layer) > 85
Heat pump (HP)	HP model	Vitocal350 (self-configured)
	Calculation mode	fast
	Heat source medium	air
Combined heat and power (CHP)	Thermal power stages	0 kW, 92 kW
	Supply temperature	93 °C
	Electrical power	50 kW

Thermal energy storage (TES)	Height (HP DEP / CHP DEP)	1930 / 2450 mm
	Volume (HP DEP / CHP DEP)	2500 / 6000 liters
	Heat transfer coefficient of walls	0.5 $W/m^2 \cdot K$
	Number of layers	3
	Heating rod power stages	0 kW_{th}
	Heating rod position	1900 mm

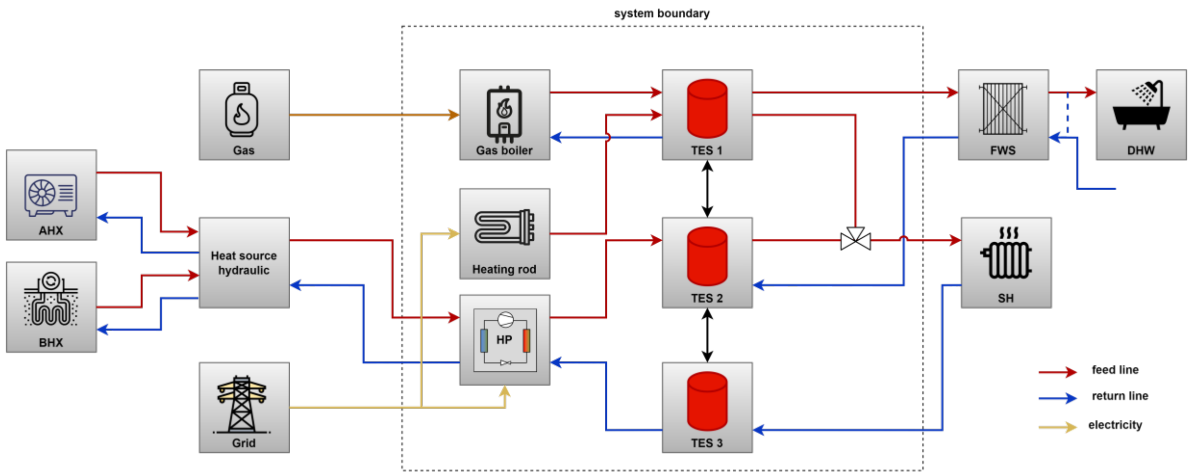

Figure 3. Simulation setup for the validation of the HP-centered DEP with the system boundary. Only the components inside the boundary are modelled.

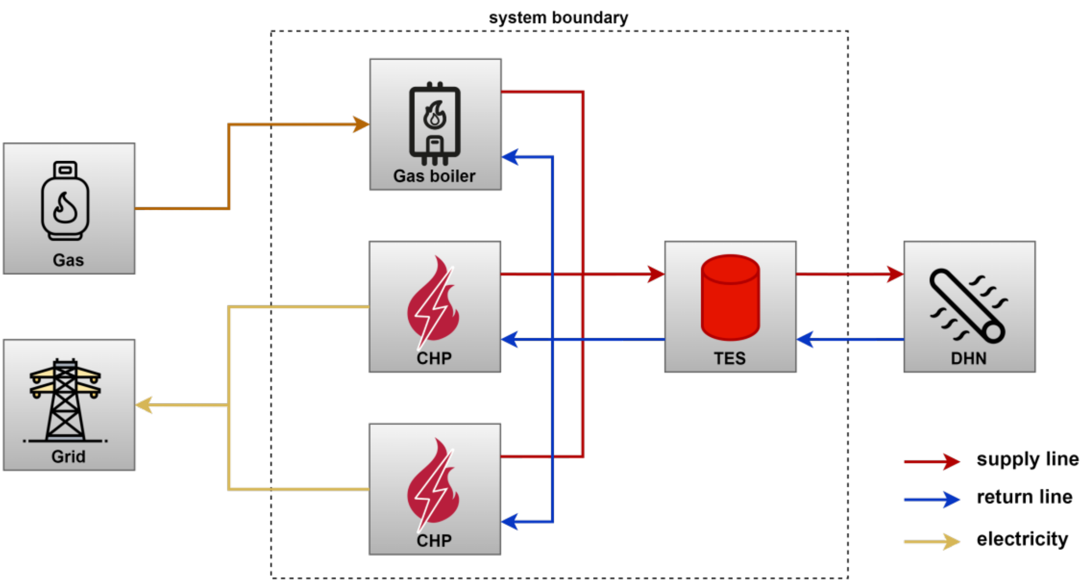

Figure 4. Simulation setup for the validation of the CHP-centered DEP with the system boundary. Only the components inside the boundary are modelled.

3. Results and Discussion

3.1. Simulation results

The simulation of the Durlach district, as described in Chapter 2.3, has a runtime of 9 minutes for a simulation period of one year in 5-minute steps. Fig. 5 shows the overall energy balance of this simulation, consisting of the HP-centered DEP and the CHP-centered DEP. The energy balance shows a CHP generation of 620.5 MWh, a HP generation of 130.6 MWh, a gas boiler generation of 50.7 MWh in the HP DEP and 0.2 MWh in the CHP DEP, a DHW supply of 57.5 MWh and an SH supply of 115.2 MWh, resulting in a HP share of 72.0 % and a gas boiler share of 28.0 % of the total heat generation in the HP-centered DEP.

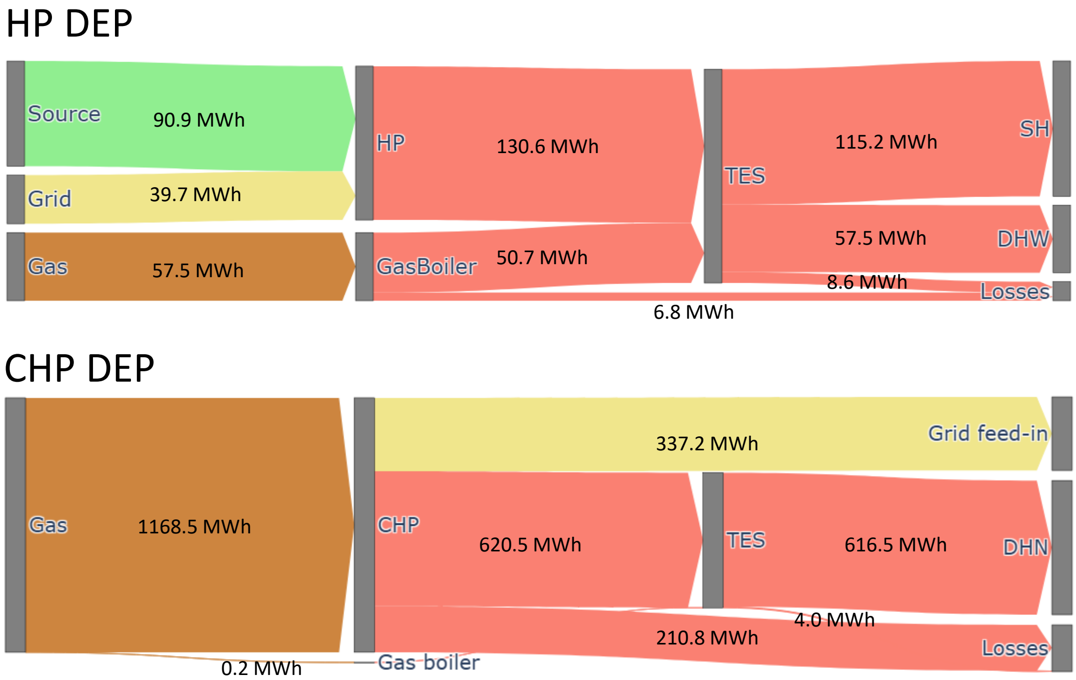

Figure 5. Sankey diagram of the simulation energy balance for one year including losses

3.2. Validation results

Framework validation is performed on the basis of the energy balance for one year. The validation criterion is therefore the consistency of the overall system energy balance.

3.2.1. Heat Pump District Energy Plant

Table 3 below shows the aggregated energy values for the simulation of the HP DES in building 4 and the comparison to the measured values. The comparison is also depicted as a bar plot in Fig. 6. The measured data shows an HP share of 71.7 % and a gas boiler share of 28.3 % of the total heat generation. As Table 3 shows the energy balance of the simulation deviates only slightly from the measured one. The significant differences are noticeable only in the HP and gas boiler performance. The gas boiler discrepancy can be explained by the assumed thermal efficiency for the simulation, which is derived from a combination of data sheet information and empirical values based on experience.

Table 3. Aggregated yearly energy values for the HP-centered DEP

	Aggregated energy value in MWh		Relative deviation from measurement
Energy flow (source → sink)	Measurement	Simulation	
Source → HP	92.4	90.9	- 1.6 %
Grid → HP	37.2	39.7	+ 6.7 %
HP → TES	129.6	130.6	+ 0.8 %
Gas → Gas boiler	58.1	57.5	- 1.1 %
Gas boiler → TES	51.1	50.7	- 0.8 %
Gas boiler → Losses	7.0	6.8	+ 2.9 %

Heating rod → TES	0.0	0.0	0.0 %
TES → DHW	57.5	57.5	0.0 %
TES → SH	115.2	115.2	0.0 %
TES → Losses	8.0	8.6	+ 7.5 %

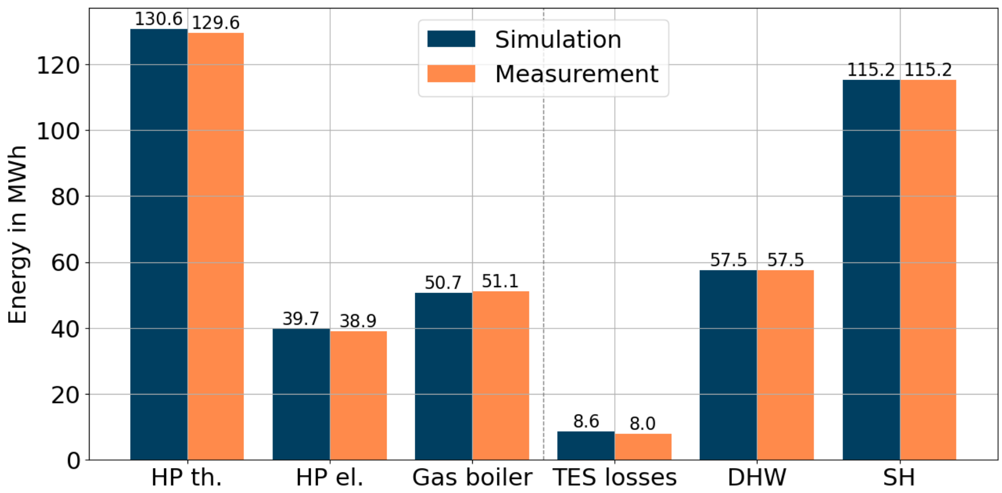

Figure 6. Bar plot of aggregated yearly energy values for the HP-centered DEP

Comparing the HP operation gives insight into the slight differences in the HP performance. The seasonal performance factor (SPF) comparison in Fig. 7 shows that the largest deviation in the HP efficiency was during the summer months, when there was exclusively DHW demand present. As the HP mainly serves the SH demand and only the low temperature of the DHW demand, its thermal output is much lower in these months, 3.6 MWh in July compared to 19 MWh in February (measured data). This lower load leads to more frequent on/off cycling of the HP, which reduces the efficiency in real operation. The simulation model, however, is not capable of capturing the effects of increased switching frequency, and the modelled performance therefore remains unaffected. Over the entire year the simulated HP has a SPF of 3.29, which is slightly lower than the measured SPF of 3.33.

The analysis of the evaporator and condenser temperatures in Fig. 8 shows that the operating range of the simulated HP matches that of the measured HP very well. The comparison of the COP over the temperature lift in Fig. 9 shows a qualitative difference in HP performance between simulated and measured operation. This can be explained by the fact that the simulation does not explicitly model part load operation; it assumes the HP operates at nominal conditions, which leads to a more linear relationship between temperature lift and COP in the simulation.

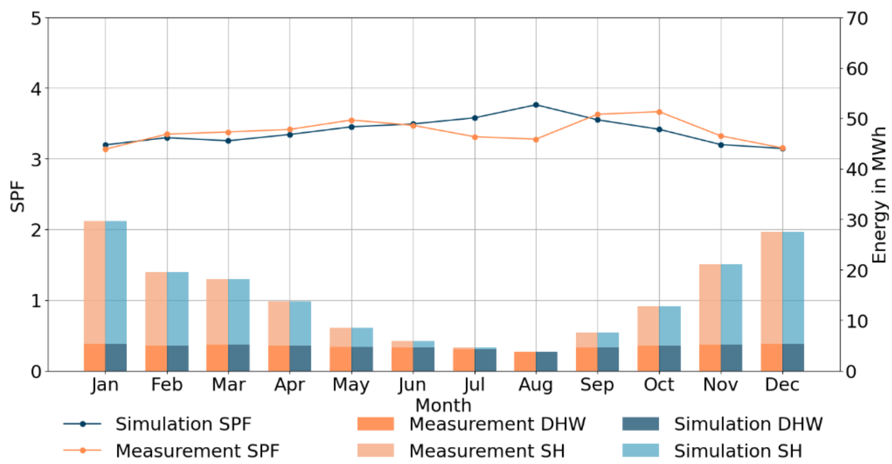

Figure 7. Comparison of the monthly SPF and the aggregated energy values of DHW and SH for the simulated and measured HP

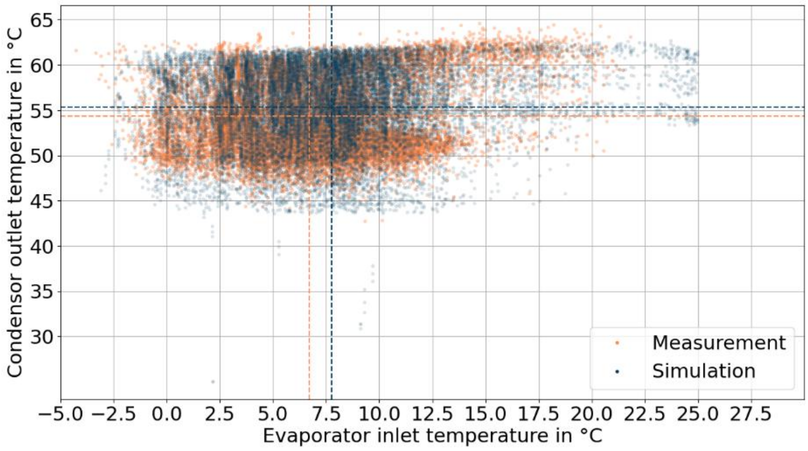

Figure 8. Scatter plot of HP evaporator inlet and condenser outlet temperatures with weighted averages on energy output (dotted lines)

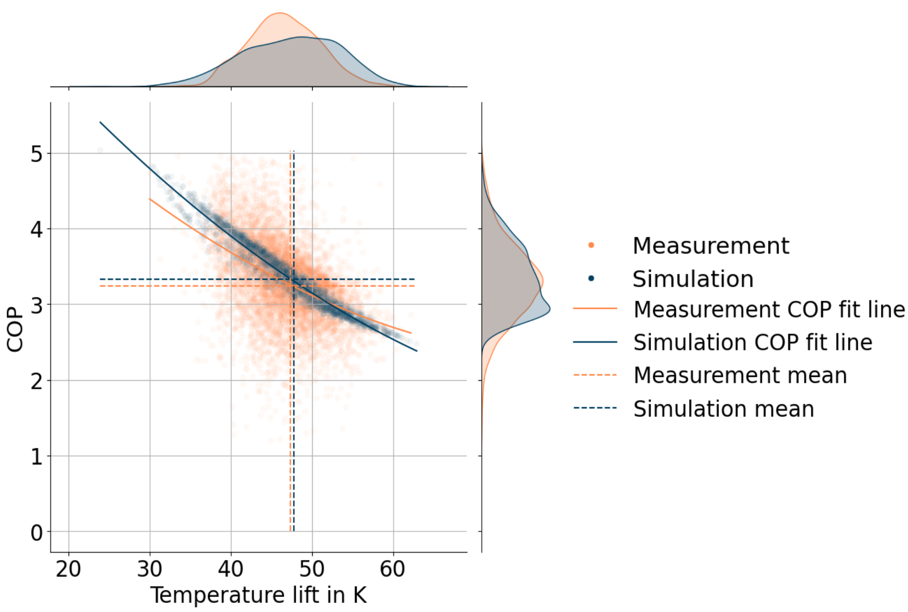

Figure 9. COP vs. temperature lift for simulated and measured HP operation (in hourly data) with the respective frequency distribution

The *DES.sim* simulation framework is validated for the HP, gas boiler and controller model on the energy balance of the system. The HP shows some deviations in its model dynamics, which can be attributed to model simplifications and operational variability. Many of the necessary modeling assumptions were straightforward to make because we already possess practical and operational experience with this DES. In the planning phase, however, one typically does not have this advantage or such detailed knowledge of the system.

3.2.2. Combined Heat and Power District Energy Plant

The bar plot in Fig. 10 depicts the energy balance of the CHP-centered DEP. The simulated and measured CHP results show very good agreement. In this system, the gas boiler operates only as a redundancy unit and runs exclusively in manual mode; therefore, it is not relevant for the validation. It should also be noted that the gas boiler can feed directly into the DHN and thus does not contribute to the TES losses. Table 4 compares the aggregated annual energy values from the measurements and the simulation.

Table 4. Aggregated yearly energy values for the CHP-centered DEP

Energy flow (source → sink)	Aggregated energy value in MWh		Relative deviation from measurement
	Measurement	Simulation	
Gas → CHP	1155.5	1168.5	+ 1.1 %
CHP → TES	621.6	620.5	- 0.2 %
CHP → Grid	332.8	337.2	+ 1.3 %
Gas boiler → TES	5.1	0.2	- 96.1 %
TES → DHN	616.5	616.5	0.0 %
TES → TES Losses	5.4	4.1	- 24.1 %

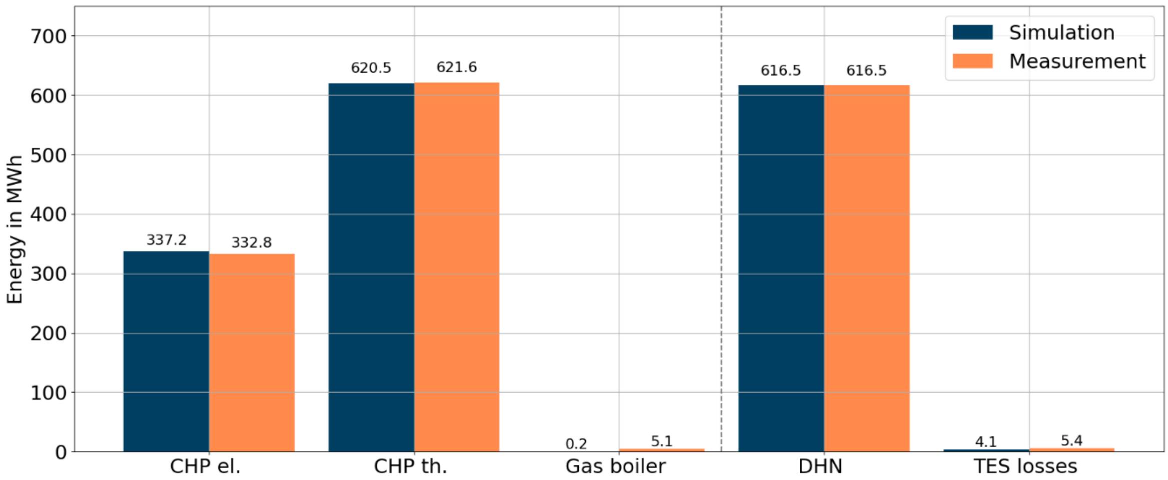

Figure 10. Bar plot of aggregated yearly energy values for the CHP-centered DEP

3.3. Discussion

The validation with a real HP-centered DEP demonstrates a comparable energy generation share, thereby confirming the validity of the *DES.sim* simulation framework. During the validation process, we encountered common challenges associated with simulating real systems. Despite the availability of extensive measurement data, certain assumptions and simplifications were necessary to model the system and reduce hydraulic complexity.

Specifically, the complex HP setup, comprising two sources capable of supplying two HPs, was simplified to a single source supplying only one HP. Although this reduces some of the operational advantages of multiple HPs and sources, such as the ability to switch to more favorable source temperatures or to access three distinct heat outputs (HP1, HP2, and HP1+HP2), the resulting energy balance supports the validity of the *mosaik* HP model and the overall *DES.sim* simulation setup.

Furthermore, the component-specific control of a real energy system is not as simple as is assumed in the controller model of the DES.sim. The operation of a real DEP can result in unexpected behavior, that cannot be modeled properly. But by focusing the results on the overall system energy balance the influence of the control strategy is minimized.

4. Conclusion

We successfully developed and validated *DES.sim*, a simulation framework for HP-centered DEPs, based on *mosaik*. The framework has been made available on GitHub (https://github.com/ltomas1/DES.sim), and the validation setup code is provided in the "validation" folder. The validation on the system energy balance of a real DES in Karlsruhe-Durlach confirms the fidelity of the *DES.sim* framework and its component models.

DES.sim brings the advantages of an object-oriented, open-source modelling approach and supports the integration of custom component models, including those implemented in other programming languages. It enables a fully parameter-based setup, allowing users to configure the entire simulation through a single input JSON file. This structure makes the framework well suited for parameter optimization studies, as it also includes a post-processing script that computes the yearly annuity and CO_2-emissions from the simulation results. The validation indicates that *DES.sim* can be applied to other district configurations with minimal adaptation, due to its parameter-based setup and modular architecture.

In further work, we are going to use this framework in a multi parameter optimization study to identify optimal design configurations. We will also conduct a sensitivity analysis to investigate the influence of future scenario uncertainties on DES performance.

Acknowledgements

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