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Comparison of Component-Oriented and System-Oriented Modeling in the Context of Operational Energy System Analysis

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Abstract: Simulation based studies for operational energy system analysis play a significant role in evaluation of various new age technologies and concepts in the energy grid. Various modelling approaches already exist and in this original paper, four models representing these approaches are compared in two real-world hybrid energy system scenarios. The models, namely TransiEnt, μGRiDS, and OpSim (including pandaprosumer and mosaic) are classified into component-oriented or system-oriented approaches as deduced from the literature research. The methodology section describes their differences under standard conditions and the necessary parameterization for the purpose of creating a framework facilitating a closest possible comparison. A novel methodology for scenario generation is also explained. The results help to quantify primary differences in these approaches that are also identified in literature and qualify the influence of the accuracy of the models for application in a system-wide analysis. It is shown that a simplified model may be sufficient for the system-oriented approach especially when the objective is an optimization-based control or planning. However, from a field level operational point of view, the differences in the time series signify the importance of the component-oriented approaches.

Keywords: operational energy system analysis; model comparison; component-oriented; system-oriented; chp simulation; heat pump simulation

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1. Introduction

1.1. Background and Motivation

Reducing greenhouse gas emissions is a fundamental building block for achieving the targeted climate goals, and conversion of fossil fuel-based energy-consumption to cleaner renewables is necessary to facilitate this. However, most renewable sources are subject to natural fluctuations. Sector coupling (SC) is a critical tool to balance such fluctuations. SC gives the possibility to utilize the surpluses from renewable sources or to buffer slack periods by using relevant storage capacities and energy from other sectors [1].

Operational energy system analysis examines technical aspects such as storage levels, circuit temperatures, and dynamic changes in component operations over the entire energy system. At the low-voltage level, two coupling technologies of electricity and heat are predominantly found—combined heat and power (CHP) plants and heat pump (HP) systems. In addition, heat storage systems play an important role at the low-voltage level in balancing out fluctuations on both the load and the supply side.

There are many models to represent energy systems, but modeling approaches vary. Accordingly, this paper evaluates the different modeling approaches for such technologies, aiming to highlight the necessary accuracy of a model to simulate the various aspects needed for an operational energy system analysis. In the scope of this work, the typical approaches are classified as system-oriented or component-oriented approaches. With the system-oriented approach, the focus is clearly on an entire energy system or at least large parts of it (e.g., distributed neighborhoods or low-voltage grids), and less on the individual components forming this system. The goal of such models generally is to obtain an accurate estimate of the overall system behavior with minimal parameterization and complexity of the component models. Both, the achieved accuracy, and also the required accuracy for a specific use-case of the system-oriented approach are difficult to quantify. Therefore, reductions and simplifications on the components are often made with regards to simulation time optimization without exact knowledge of the impacts of the introduced error on the overall results. With the component-oriented approach the focus is on the investigation of the exact behavior of a single component in the system and it generally leads to a single energy plant level analysis. The states of the overall system usually are considered only as framework boundary conditions.

The state of research and the contribution of this paper are described in Section 1, followed by Section 2 which begins by describing the structure of the model comparison and briefly introduces the models involved. This is followed by a detailed description of the model types to which the previously presented models can be assigned. At the end of this section, the adjustments for the model comparison are described. Section 3 presents the results of the model comparison. Section 4 then discusses the results before summarizing and concluding in Section 5.

1.2. State of Research

A large number of models with varying levels of accuracy and complexity exist in literature on the modeling of hybrid energy systems. The optimal choice of models with the necessary accuracy-complexity balance is a field of science of its own and is specific to the application of each model. The individual component models are mostly either static, linear power flow models, or grey-box models combining physical laws of mass and energy conservation with data mining techniques to capture part-load behavior or operational dynamics. For instance, cogeneration models of the former type are used in literature for control analysis and control optimization of energy systems (Table 1 Part I) whereas the latter, more complex models are used for energy performance analysis and system optimization (Table 1 Part II).

Similarly, simplified grey-box models for simulating HP as part of an energy plant, as well as more complex models with refrigerant circuit calculations are both well established in the literature (Table 1 Part III–IV). The complex models can be parameterized for various types of refrigerants, evaporator-condenser combinations, and control logic and are often published in software libraries with their simulation results typically implemented in component level operational analysis of the plant.

Thermal storage modeling varies significantly, based on the level of details required in the simulation. For the simulation of a geographically spread energy system with many plants and storages, an energy balance based mixed linear storage tank can be implemented A similar model can also be used in energy system design and optimization problems to reduce the complexity of the optimization problem (Table 1 Part V). However, for component-oriented operational analysis, stratified storage tanks are the standard. Here, spatially discretized tank volumes with either energy balance models using ordinary differential equations or 2-D laminar flow models using partial differential equation models are used (Table 1 Part VI). Some of these models are part of published libraries or software packages such as TRNSYS, EnergyPlus, HVACSIM+, or Modelica Building Systems while others are created by authors in simulation environments of their choice.

Table 1. Selected literature review on cogeneration, HP and storage tank models and comparison of energy system models.

References	Focus
I: System-oriented cogeneration models for control analysis and control optimization of energy systems	
[2]	Linear energy balance CHP models with a constant part-load factor implemented for Model Predictive Control (MPC) of multiple units in a Microgrid
[3]	Nonlinear energy balance CHP model with a polynomial fit for part-load behavior implemented for MPC of a single building energy system
[4]	Linear energy balance CHP (gas turbine) models with calculation of CO_2 emissions and part-load behavior based on ambient temperature. Implemented in evaluation of different performance indicators to be used in optimal control of a microgrid
[5]	Linear energy balance CHP models without part-load consideration implemented in operation strategy optimization of a trigeneration system
II: Component-oriented cogeneration models for energy performance analysis and system optimization	
[6]	Nonlinear energy balance CHP model with first order lag describing the CHP start-up dynamics and no part-load behavior. Implemented for voltage regulating operation of a mini CHP plant
[7]	Nonlinear CHP models with both mass and energy balance over internal components of the unit. Part-load behavior and start-up dynamics represented using curve fits for most commonly used micro-CHP units in building sector
[8]	Isochronous governor control strategy implemented in a transfer-function based model for a turbine-generator CHP system with ambient temperature-based part-load simulation. Aim of study was performance analysis of a microgrid controller
III: Data-driven simplified HP models	
[9]	For use in building simulation programs, a steady-state simulation model for a HP (water-to-water) with reciprocal vapor compression is presented
[10]	Data-driven parameter estimation of a water-to-water HP model to implement curve fits for part-load operation is carried out and the model is implemented in the IDA-ICE simulation environment
IV: Component-oriented complex HP models	
[11]	For building HVAC systems, a freely available Modelica library is presented. The individual parts of a typical HP system (e.g., compressor, expansion valve) is simulated using physical principles
[12]	Differential equations representing the mass and energy balance in a refrigeration cycle are modelled in a state-space system. The model is used to investigate the dynamic behaviors of a single compression chiller (reverse HP)
V: Mixed storages	
[13]	Energy balance based mixed tank model including losses for calculating energy stored in tank but without representation of temperature. Implemented in energy cost-based operation optimization.
[14]	Generic single temperature storage model with energy balance and no losses implemented in an MINLP for analyzing effect of long-term heat storages on CHP operation in a district heating network
VI: Stratified storages	
[15]	A Fourier's equation based 1-D stratification model implemented in simulation of a building solar-thermal system
[16]	Comparison of a 1-D mass and energy balance model with a 2-D laminar flow model for describing thermal stratification in a heat storage tank.
VII: Comprehensive study of the typical models and methods used for simulation of energy systems especially for buildings and microgrids	
[17]	Overview of heating, ventilation and air conditioning (HVAC) modeling and simulation, including categorization.
[18]	Critical overview of HVAC systems modeling techniques in terms of their applicability, acceptability, strengths, weaknesses, applications, and performance.
VIII: Model comparison on modeling of hybrid energy systems	
[19]	Comparison of two models for the analysis of the energy system (methodical and result-oriented)
[20]	Four approaches to modeling stratification in thermal energy storage (TES) systems with mixed-integer linear programs are presented and compared with the capacity model
[21]	The relationship between model complexity and the accuracy of the results is investigated in a case study with 160 models

A comprehensive study of the typical models and methods used for simulation of energy systems, especially for buildings and microgrids, can be found in the works of Trčka and Hensen and Afroz et al. (Table 1 Part VII). Some of those modeling approaches are implemented in the current work to simulate hybrid energy systems with realistic load profiles and parameters to partly quantify the differences and partly qualify their implementation for operative energy system analysis.

For the model comparison for simulation of hybrid energy systems especially on the operational level, only a few publications can be found (Table 1 Part VIII). Lund et al. [19] perform a comparison of two power system models focusing on an islanded grid to show the advantages and improvements of the models. In the work of Schütz et al. [20], the comparisons are limited to different energy storage models and whole hybrid energy systems are not considered. The work of Priesmann et al. [21] provides an overview of many models with the focus on implementations of power system optimization for dispatch and investment. It was noticed that studies considering power and heat/gas networks simultaneously are lacking.

1.3. Contribution of This Paper

Building on previous literature, this work classifies and compares typical approaches to modeling energy systems in a novel manner, using two real-world scenarios for hybrid energy systems and identifying the advantages and limitations of these approaches. Unlike previous studies the models used in this work represent all common methodologies for simulating electricity, heat, and gas grids, are open source, and allow tuning of parameters such that the comparisons can be made in a closest possible framework. Additionally, a novel methodology for creating consistent thermal and electrical loads for a local grid is implemented since this is one of the main inputs for such comparative studies.

The results show variances of different output indicators such as the mean tank temperature or the thermal output of the CHP and HP. A detailed analysis makes it possible to state how well different types of modeling are suited to answer questions in operational energy system analysis. Since the results of the four representative models are very similar, they can potentially be used as benchmarks for other models.

2. Models and Scenario Set-Up

2.1. Set-Up of the Model Comparison

In order to examine the different modeling approaches for the operational analysis of SC technologies/systems that are expected to have high implementation rates in the near and far future, two scenarios are simulated: one scenario focuses on a CHP unit and the other analyzes a HP system. Simplifying assumptions were made in order to achieve a balance in implementation complexity and a high comparability of the models while using default settings of the different participating models whenever possible. However, the same input data had to be used, some of the model parameters had to be harmonized and controller tuning was necessary as discussed in Section 2.4.

2.1.1. CHP Scenario

Various model configurations are possible to represent a CHP system, depending on multiple factors such as the technologies and sizes of the individual components, detailed simulation of the energy grids and the heating network. However, for the set-up of the model comparison we consider only a gas engine CHP unit as shown in the block flow diagram in Figure 1. The CHP converts final energy from gas to heat and power (electricity). The heat is supplied to a distribution network via a hot thermal energy storage tank (HTES) that acts as both a hydraulic and energy-buffer. The electricity is used to satisfy the local electrical loads (EL) and the excess is fed back into the power grid. For the sake of scenario organization, the energy grids are not simulated in the scope of this work. Therefore, the space heating and domestic hot water requirements are combined into a single heating load profile (HL). A brief description of the generation of the load profiles is given in

Section 2.4.1 For the remaining heating load that cannot be supplied by the CHP due to the limited power of the plant, a gas-fueled back-up heater is implemented, also supplying heat to the HTES.

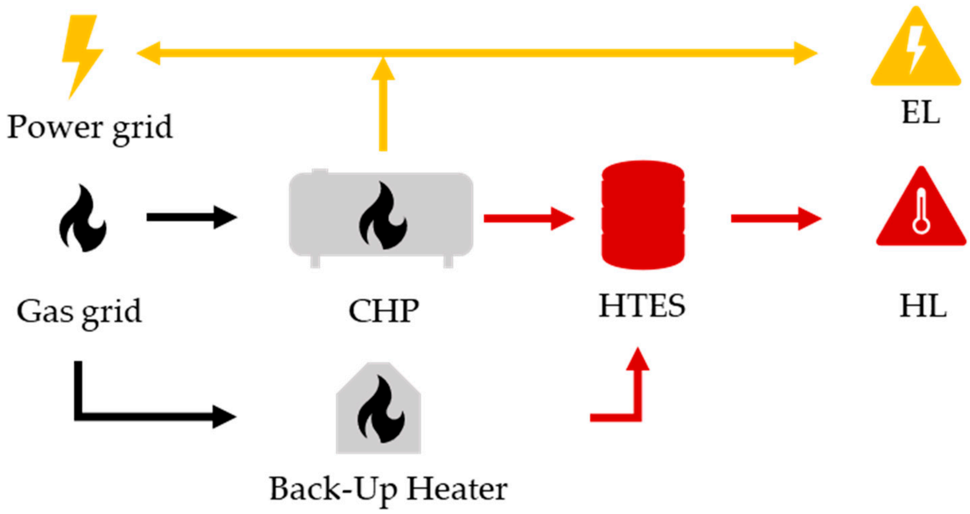

Figure 1. Schematic representation of the CHP scenario set-up.

2.1.2. HP Scenario

For HPs, a variety of HP systems and models exist but a standard air-source HP and a set-up similar to the CHP scenario is simulated in this work as shown in Figure 2. Analogous to the previous scenario, a HTES is implemented but it is assumed that this tank only satisfies the space heating requirement, while the higher temperature domestic hot water requirements are separated from the thermal analysis due to limited hot temperature supply by HPs. These are covered by an electric boiler within the HL network. There is no bidirectional flow of electricity to the grid and the energy grids are also not simulated in detail. Consequently, only one HP system is simulated. Unlike the previous scenario only a single building profile corresponding to that HP is used instead of aggregating the load profiles for various buildings. It is assumed that the HP is located directly in one household.

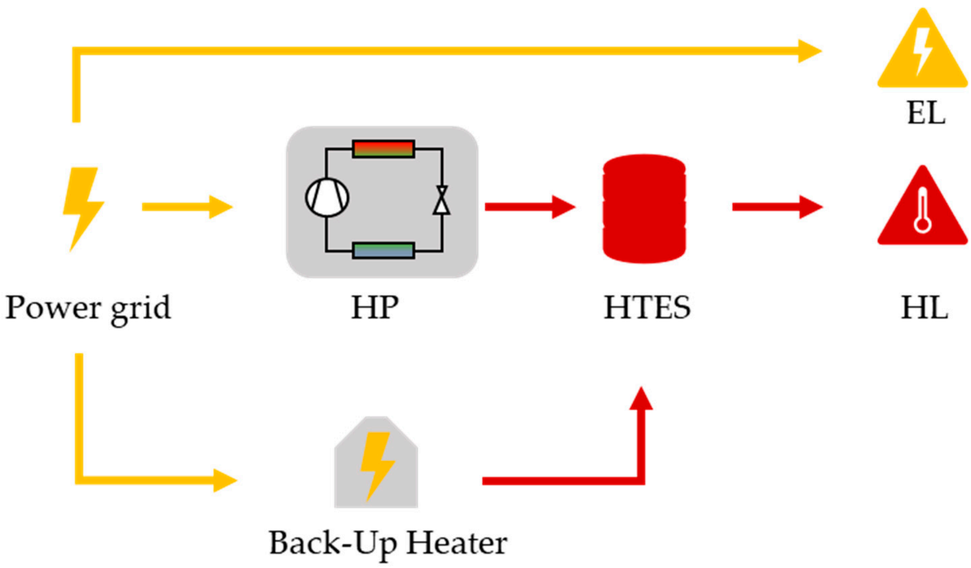

Figure 2. Schematic representation of the HP scenario set-up.

A following thermal load conventional control strategy with parallel operation of an auxiliary back-up heater is implemented in both scenarios. The back-up heater is simulated as a static model with constant efficiencies under the assumption that most back-up heaters are either electric coils or high-efficiency gas boilers with extremely fast dynamic responses. In the CHP scenario, a gas boiler is implemented with modulated power output providing exactly the residual thermal energy whereas in the HP scenario, an electrical coil with nominal thermal output and On/Off control is considered. The tuning parameters for the controllers were harmonized to minimize differences in the control implementation methods and are discussed in detail in Sections 2.3 and 2.4.

2.2. Contributing Models and Their Classification

The four participating models are described below. There are component-oriented as well as system-oriented approaches. In addition, libraries, stand-alone models and also co-simulation frameworks are compared here. Section 2.3 will then describe how well the models are suited to represent the general model landscape in power system analysis.

2.2.1. TransiEnt

The TransiEnt library is an open-source model library for the integrated simulation of coupled energy systems within the simulation environment Dymola using the declarative modeling language Modelica [22]. It enables a combined assessment of electricity, gas, and heat within one integrated tool while considering transient effects. The library also includes components to allow easy modeling and simulation of complex grid structures on the distribution grid level, developed within the project IntegraNet [23].

2.2.2. µGRiDS

The simulation model Microscale Grid Reactive Decentralized Energy Systems (µGRiDS) is a tool for operational analysis of various building energy systems with a focus on component level interactions for improving the operational efficiency of the plant [24]. The basis of µGRiDS is a grey-box methodology using step-response analysis, regression fits of experimental- and manufacturer's-data, and mass and energy balance implemented in the OpenModelica environment.

2.2.3. OpSim Incl. Pandaprosumer

OpSim is a co-simulation framework, based on a client-proxy architecture programmed in Java and Python [25]. OpSim sets its focus on testing and simulating complex energy systems and its control strategies (i.e., users can test simple controllers on an isolated power system model or simulate highly complex smart grid scenarios with multiple control strategies acting in parallel on the same grid model) [26–28]. OpSim is, thereby, able to investigate scenarios across different voltage and sector levels [26,29].

Pandaprosumer (ppros) on the other side focuses on the simulation of consumer and storage time series. The architecture of ppros is similar to pandapower and pandapipes.

2.2.4. Mosaik

The Python-based co-simulation framework mosaik focuses on providing high usability and flexibility for the integrated simulation of diverse simulation components [30]. Thus, already existing simulation models and tools developed in different programming languages and based on different modeling approaches can be re-used and coupled into an integrated co-simulation with mosaik. The focus is on the investigation of smart grid scenarios (e.g., to test different control strategies such as centralized or agent-based control). For the model comparison, some already coupled models were used [31,32].

2.2.5. Classification

Table 2 provides an overview of the contributing models. The table lists the modeling languages and the scope of application. The goals of the model and the focus of the current projects are compared. In addition, the underlying approaches are shown, and open-source and documentation are referenced.

Table 2. Overview of the contributing models.

	TransiEnt	µGRiDS	Opsim/Ppros	Mosaik
Modeling language	Modelica	Modelica	Any modeling language can be integrated/python	Any modeling language can be integrated
Time resolution	continuous	continuous	discrete	discrete
Application *	HVAC, BES, GLS	HVAC, BES	HVAC, BES, GLS	HVAC, BES, GLS
Focus	Simulation of coupled energy systems	Plant level analysis and optimal control	Test-/simulation environment for smart grid applications	Simulation of smart grid scenarios
Approach **	s-o/c-o	c-o	s-o/c-o	s-o/c-o
Open Source	yes	yes	no	yes
Documentation	[23,33]	[24,34]	[25–29,35]	[36]

* BES, building energy system; GLS, energy grid level systems. ** s-o, system-oriented; c-o, component-oriented.

2.3. Technology Modeling Differences under Standard Condition

The two-primary modeling approaches evaluated in this work are the system-oriented linear energy-balance models and the component-oriented nonlinear process models, which also simulate the circuit temperatures and volume flows. Under standard implementation conditions the component-oriented models focus on simulating the operational dynamics and variable efficiencies of the components that are also observed in reality. The system-oriented models on the other hand focus on evaluating the energy-economic performance of an entire system which typically would include a variety of energy plants. The following subsections describe in further detail the approaches in the context of the main components that are involved in forming the hybrid systems described in Section 2.1. Although many more characteristic differences may exist in the details of the large number of models in literature, for sake of brevity only the significant differences in the models used within this work are highlighted with reference to the models commonly used in the field of operational energy system analysis. The characteristics of the participating models are also summarized in Table 3 at the end of the section.

Table 3. Overview of the approaches used in the CHP and HP scenario.

	TransiEnt	µGRiDS	OpSim/Ppros	Mosaik
CHP	c-o	c-o	s-o	s-o
HP	s-o	c-o	s-o	c-o

s-o: system-oriented, c-o: component-oriented.

2.3.1. Primary Heating Sources

In the component-oriented approach, the part-load behavior of the CHP and HP is simulated using regression polynomials with inlet temperatures of the components as the independent variables and power outputs or coefficient of performance (COP) the components as the dependent variables. The order (first order or higher) of these polynomials dictates if the models are linear or nonlinear. The dynamic response of these components, especially their thermal outputs, is described using the manipulated variable step-response which is characterized by a time-constant and transfer coefficient or gain. These parameters are used in a differential equation describing a first order lag with the on/off switch of the CHP or HP as the manipulated variable. Additionally, some models in this class simulate a modulated power output of the heating sources while others work with only the nominal power output when the device/piece of equipment is on. The fuel consumption and energy balances are calculated using regular practices of mass and energy balance. The nominal capacities, efficiencies, and volumetric flows along with the coefficients of regression are typical parameters necessary to specify such models.

In the system-oriented approach, either the nominal efficiency of a component is used as a constant parameter, or in the case of the HP the Carnot efficiency is applied. The thermal and electrical output are calculated by static models. Since the calculation of the hydraulic circuit temperatures is not in the focus of this approach, a mass balance is not necessary but energy balance models are applied. Both modulating and constant thermal and electrical power calculations based on the loads are possible.

The thermal dynamics of CHP are included in the μGRiDS and TransiEnt models but the HP is simulated as a static system. The Carnot efficiency calculation of HP is included in OpSim/ppros and TransiEnt whereas a regression-based efficiency calculation is used in μGRiDS and mosaik. The electrical dynamics and modulating power output of the primary components are not included in this work.

2.3.2. Thermal Storages

In the component-oriented approach, the water thermal storage tanks are simulated as stratified storage tanks with the temperature of a specific layer being the system-state calculated using a differential equation. Thus, with increasing discretization, the temperature distribution in the tank could be simulated more accurately. However, the model complexity increases with increasing system-states. A balance must be found according to the necessary accuracy of the simulation results. Depending on the detail of the models the discretization in space and flow of water/heat is simulated in 1-D or 2-D, leading to system of ordinary differential equation or partial differential equation respectively. In this work, a 1-D multilayer model using Fourier's law for determining heat flow between layers and losses to the environment is considered in the μGRiDS, TransiEnt, and mosaik (HP scenario) models. These models summarize the complex convective and conductive flow using an effective vertical heat conductivity. The dimensional and material parameters (e.g., diameter, number of layers, and conductivity coefficients) along with operational parameters such as initial temperature are typical parameters of this storage model. In accordance with accepted norms, the hotter source feed (discharge supply) is fed into (removed from) the top of the tank and colder water enters or leaves at the bottom of the tank. The discharge layer feeding the HL circuit can also be defined separately. In the μGRiDS model, this is by default one layer below the top layer, for representing a dead volume on top of the tank and in the TransiEnt model, this is defined as the top layer by default. For models using the stratified tanks, the thermal energy of the back-up heater is input at a set temperature at top of the tank. The volume flow in this circuit is calculated based on the temperature difference and heating output of the back-up heater in the CHP or HP scenario (see Section 2.1)

The simplified system-oriented approach to model thermal storages uses a simple energy balance without spatial discretization and discretized heat flows within the storage. Here, the current heat demand and production are used to calculate the mean temperature or the energy level in the tank and consequently, the state-of-charge (SOC) is calculated as a percentage of the maximum energy levels. This approach is implemented in the OpSim/ppros and mosaik (CHP scenario) models. The back-up heater energy in this approach is directly used in the energy balance over the tank model.

2.3.3. Control Strategy

In terms of the control strategy, we distinguish between the component- and the system-oriented control strategy. The thermal load following/heat driven strategy is implemented using a hysteresis switching differential controller in both approaches but the parameters or system-states chosen for tuning are different. In the component-oriented approach, stratified tank temperatures (e.g., the top and bottom temperature are generally used to implement the switching differential for the CHP and HP). Here, the entire tank capacity can be used to achieve longer run times for the components since the devices switch on when the top of the tank is below a minimum temperature and they turn off when the bottom of the tank heats up to a maximum temperature limit. Thus, the top of the tank can also be maintained at a temperature relevant to the heating distribution circuit. The control of the back-up heater is implemented so that it turns on when the primary heating source cannot cover the heating load and the tank temperature is below a minimum limit. It then follows the hysteresis before turning off.

In comparison, the system-oriented approach simplifies the control strategy by reducing the complexity of the storage model. Instead of modeling several temperature layers, the system-oriented approach assumes that the storage consists of solely one homogeneous unit. This unit is represented by one temperature or energy level (i.e., SOC). The control strategy acts similarly to the component-oriented approach following a hysteresis controller. The main drawback of this approach is that the technological limits of the different components are insufficiently modelled. In reality, for example, HPs often cannot reach the temperature required, especially in terms of domestic hot water supply. An additional heater usually compensates for the target/actual temperature level. A purely average-temperature or energy control could make an additional heater obsolete and thus under-estimate the system impact. The big advantage of this approach, however, is its computational performance boost necessary for a system-wide investigation.

2.3.4. Implementation Tools/Software

For the component-oriented models the control signal and return-line temperatures are primary inputs and the feed-line temperatures, volume flows, actual power outputs and fuel consumption are the primary outputs. By exchanging the information on circuit temperatures and volume flows between the individual component models their interactions are established and the system-states are simulated. An equations-based approach is typically implemented to develop such component models and connect their hydraulic circuits for developing a simulation model with high focus on a single plant. For instance, the equations-based approach in the Modelica environment is represented in this work by μGRiDS (both for simulating the CHP and the HP) in OpenModelica and TransiEnt in Dymola for simulating the CHP plant.

The system-oriented models use a reduced complexity. OpSim/ppros and mosaik are not modeling the continuous behavior of the component, but calculate state and outputs in discrete steps. Thus, the calculations are less complex, which can significantly improve calculation time. Due to this loss in temporal detail, the results might be less accurate, but for the system-oriented use case this is usually unproblematic. Especially, when large numbers of components are simulated to investigate the effects on the system-level, the performance might be more important than the accuracy of the results. The HP model from TransiEnt is also classified as system-oriented, as similar to OpSim/ppros it uses a simplified efficiency calculation based on Carnot efficiency, although on a temporal level, transient effects are still considered. On the other hand, the HP model from mosaik is classified as rather component-oriented, since a more detailed modeling of the HP and the storage are implemented based on the TESPy library [37]. Thus, classification is based both—on temporal resolution, as well as level of detail of the implementation. The general classification of the participating models is shown in Table 3.

While OpSim/ppros has a focus on the system-level and μGRiDS on component-level, TransiEnt and mosaik can represent both types of models depending on the investigated use case. To give an example for this flexibility, each of them uses a system-oriented model in one scenario and a component-oriented in the other. The assignment to the approaches depends on the components used within the models for the specific use case. For instance, the level of detail of the hot water tank of mosaik and TransiEnt is different for each scenario: For the system-oriented implementation a simplified tank with one temperature was chosen, while for the component-oriented implementation a more detailed tank model with multiple layers was used. In general, for each scenario two system- and two component-oriented approaches are analyzed.

A more detailed summary of the significant characteristics that further differentiate the participating models is presented in Table 4 below. The shown characteristics describe for each scenario how the dynamic behavior of the component is modeled (e.g., whether the efficiency is constant or variable and depending on other parameters) or with which level of detail the hydraulic circuit is modeled. Additionally, it is compared which types of HTES, hydraulic circuits, and controllers are available and which programming environment is used for the different models.

Table 4. Main characteristics of the models used for the simulation of CHP and HP scenario.

	TransiEnt	μGRiDS	OpSim/Ppros	Mosaik
CHP Dynamics	No	Thermal	No	No
CHP Efficiency	Constant	Regression	Constant	Constant
CHP Hydraulic Circuit	Yes	Yes	No	No
HP Dynamics	No	No	No	No
HP Efficiency	Carnot	Regression	Carnot	Regression
HP Hydraulic Circuit	No	Yes	No	No
HTES (a) 1-D Stratified (b) Mixed	a, b	a	b	a, b
HL Hydraulic Circuit (a) Mixing valve logic (b) Energy Balance	a, b	a	b	b
Hysteresis Controller (a) Stratified Temp. (b) Mean Temp. (c) SOC	a, b	a	(b), c	a, b
Implementation	Dymola	OpenModelica	Python	Python

With reference to the literature research from Section 1.2 it is evident that the models participating in this study represent if not all, then at least the primary characteristics necessary for operational system analysis across both approaches. However, since the participating models have different foci in their default settings and frameworks, a significant effort for harmonization of the model inputs and parameters was necessary for developing the scenarios defined in Section 2.1. This process is described in the following section.

2.4. Technology Modeling Harmonized for Model Comparison

The following subsections describe the steps taken to harmonize the main input data for the scenarios in terms of the thermal and electrical load profiles and the model parameters in terms of component specifications, hydraulic circuits, controller tuning, and model initialization.

2.4.1. Input Data

A major challenge for operational analysis of SC technologies is the generation of consistent and realistic thermal and electric load profiles. As described in Section 2.1, the EL and HL blocks represent the thermal and electric loads of a distribution grid. That low-voltage grid consists of 118 building units. Each unit was assigned a priori one electric load profile representing real measured data from the SimBench datasets [38]. A novel methodology was implemented in this work to create thermal load profiles consistent with these electricity profiles and yet dependent on the ambient conditions, building class, and user profile.

In this method, firstly the total area of a building unit and its total number of residents was estimated based on the annual electricity demand for that building. Here, the assumptions in the SimBench dataset regarding specific electricity demand of 0.0125 kWh/(m^2a) and an average space requirement per inhabitant of 46.7 m^2 were used. The residential buildings were classified as single-family houses (less than five inhabitants) or multiple-family houses (five to seven inhabitants) based on the number of residents whereas larger buildings (>seven inhabitants) were classified as commercial complexes. In the next step, five space heating profiles were generated using technical standards such as DIN EN ISO 13790 [39] and DIN 4108 [40] and included information on user profile, weather conditions, and building class. These 5 profiles were imposed onto the 118 units using a classification algorithm based on building age/class developed by the authors in a previous project [23]. Similarly, five different domestic hot water profiles were imposed onto the 118 units such that simultaneity of the profiles both within one household and between the different buildings is avoided and therefore the occurrence of unrealistically high demand peaks is prevented.

2.4.2. Model Parameters

The first set of model parameters to be fixed were the nominal capacities, nominal efficiencies, and dimensions of the components. The CHP sizing was carried out based on the duration-curve analysis of the thermal load profile and a full-load operation of ca. 4500 h was assumed. A technical data sheet for a market-ready CHP was then used to configure the nominal capacity and efficiency. Similarly, the data sheet of a standard HP for such application scenarios was used to fix the nominal heating capacity and power input. The system-oriented approach used the Carnot efficency to calculate a reference COP for a working temperature of 7°/35 °C in the HP circuit. For the CHP scenario, the volumetric capacity of the storage tank was dimensioned for three hours of CHP operation assuming a temperature difference of 30 K and for the HP scenario, the storage tank as well as the HP were dimensioned based on VDI 4645 [41]. In addition to the volumetric capacity of the storages required by all the models, the component-oriented models specifically needed further physical dimensions such as height and diameter to simulate the stratifications. Also, the number of layers (discretization) in the tank was fixed for these models. Thermal losses from the tank were assumed negligible for sake of simplicity by setting the heat transfer coefficient through the tank walls to zero.

Subsequently, it was necessary to define the hydraulic circuits of the component-oriented models. In this case, parameters such as feed-line temperatures for the heating circuit, CHP output, and back-up heater and volume flows in the HP and HL circuits were harmonized. In the component-oriented approach, these parameters were necessary for the mass and energy balance in the HP-HTES circuit and for calculating the HP output temperature. Whereas, in the system-oriented approach a constant setpoint temperature was estimated based on the expected operating temperature differential for the HP under the hydraulic circuit parameters. The expected operating temperature differential was also applied to calculate the nominal COP and capacity as described earlier.

A significant challenge was in tuning the thermal hysteresis controller for the different approaches since the stratification models use top and bottom temperatures in the tank and the mixed tank models use either SOC or the mean temperature of the tank. Eventually, the mean temperature of the tank was decided on as the parameter for the controller in both scenarios. Here the switching differential in both scenarios was estimated keeping in mind the setpoint temperature for the HL circuit and operating temperature differential of the heating sources. For instance, with the CHP operating at a temperature differential of ca. 50 K, a feed-line temperature of 90 °C, and the set-point for HL circuit at 80 °C a hysteresis of 85 °C/75 °C was used. Similarly, the hysteresis for the back-up heater was implemented to maintain a minimum temperature of 75 °C in the tank. The SOC based models reverse-calculated their SOC parameters using the temperature values. For instance, OpSim/ppros assumed 90 °C as 100% SOC and 70 °C as 0% SOC.

For initialization, all components were considered to be turned off and an initial temperature of the tank of 85 °C for the CHP scenario and 46.55 °C for the HP scenario was defined for all models. The main parameters for the model harmonization are summarized in Tables 5 and 6 below.

Table 5. Main parameters used for the simulation of CHP scenario. "X" denotes a check mark when the parameter is implemented in the corresponding model.

	Value	**TransiEnt**	**µGRiDS**	**OpSim/Ppros**	**Mosaik**
CHP-electrical power	134 kW_{el}	X	X	X	X
-thermal power	202 kW_{th}	X	X	X	X
-electrical efficiency	36%	X	X	X	X

Table 5. *Cont.*

	Value	TransiEnt	μGRiDS	OpSim/Ppros	Mosaik
-thermal efficiency	54.5%	X	X	X	X
-feedline temperature	90 °C	X	X	-	-
Back-up feedline temperature	90 °C	X	X	-	-
HTES-Volume	18 m^3	X	X	X	X
-Diameter	2 m	X	X	-	-
-Height	6 m	X	X	-	-
-number of layers	10	X	X	-	-
-heat transfer coefficient	0 kW/(m^2K)	X	X	X	X
-initial tank temperature/SOC	85 °C/75%	X	X	X	X
HL-feedline temperature	80 °C	X	X	-	-
-volume flow	51 m^3/h	X	X	-	-
Hysteresis controller Temp. set-point	85 °C/75 °C	X	X	-	X
Hysteresis controller SOC set-point	25%/75%	-	-	X	-
Back-up controller set-point	75 °C	-	-	X	X
Back-up controller hysteresis set-point	75 °C/76 °C	X	X	-	-

Table 6. Main parameters used for the simulation of HP scenario. "X" denotes a check mark when the parameter is implemented in the corresponding model.

	Value	TransiEnt	μGRiDS	OpSim/Ppros	Mosaik
HP-electrical power	3.8 kW_{el}	X	X	X	X
-thermal power	17.2 kW_{th}	X	X	X	X
-reference COP	4.7	X	-	X	-
-feedline temperature	45 °C	X	-	X	-
Back-up nominal power	4.15 kW_{el}	X	X	X	X
-efficiency	98%	X	X	X	X
HTES-Volume	0.77 m^3	X	X	X	X
-Diameter	0.72 m	-	X		X
-Height	1.8 m	-	X	-	X
-number of layers	n	-	10	-	3
-heat transfer coefficient	0 kW/(m^2K)	X	X	X	X
-initial tank temperature/SOC	46.55 °C/85%	X	X	X	X
HL-feedline temperature	40 °C	-	X	-	-
-volume flow	2.79 m^3/h	-	X	-	-
Hysteresis controller Temp. set-point	32.75 °C/47.55 °C	X	X	-	X
Hysteresis controller SOC set-point	25%/89.35%	-	-	X	-
Back-up controller Temp. set-point	30.45 °C/46.55 °C	X	X	-	X
Back-up controller SOC set-point	15%/85%	-	-	X	-

3. Results

The two scenarios were simulated for an entire year in 15-min resolution and the main output indicators were used for an operational analysis and an energy balance analysis. The operational analysis primarily involves the behavior of the tank temperatures, and power output of the heat sources. For a better comprehension of the results, the operational analysis is presented for 96 h of operation in each summer, transition, and winter season. These representative time periods were selected to cover all possible ambient temperature conditions, plant dynamics, and control states. The energy balance analysis involves data for the whole year and represents not only capacities of the heating sources but also the residual electrical and thermal loads. The start-up/shut-down cycles of the components over an entire year are also considered. The results of these analyses are presented in the following sections.

3.1. CHP Scenario Operational Analysis

The mean tank temperatures for all four models are shown in Figure 3. During all three seasons, the behavior of the mean temperature for all the models is very close with a few deviations especially the higher mean temperature for µGRiDS. The cyclic jigsaw pattern typical for a hysteresis controller can also be seen. Here, the CHP switches off when the mean temperature reaches 85 °C and switches on when the tank cools down to 75 °C as described in the control logic earlier. A small lag in the behavior of the mosaik results is observed (e.g., highlighted section in Figure 3) wherein the temperature exceeds both limits by a few degrees Kelvin before switching direction. This lag is caused by the way of handling cyclic dependencies between simulators in version 2.6 of mosaik, which leads to a delay of one simulation step of 15 min for the controller. For new implementations, this delay could be avoided by using the same time loop feature, which was introduced after the implementation of this scenario in version 3.0 of mosaik and is described in [30]. On the other hand, results with TransiEnt display turning on/off of the CHP slightly before reaching the 75 °C/85 °C limits respectively. This is obvious in the winter scenario where the CHP is switched off only for TransiEnt. Two main reasons can be identified for this behavior. Within the hysteresis used in this scenario, events between the integration time steps are also considered as the continuous behavior of the system can be taken into account in the Modelica-based approaches (compare Section 2.3.4). Furthermore, the hysteresis switching differential is already activated, when limits are about to be reached, instead of after they crossed (Boolean operator ">" and "<", instead of ">=" and "<="). An effect of this implementation is also the higher number of start-ups of the CHP as shown in Table 7 later. For all models, a higher number of cycles is observed in summer due to the lower heating load.

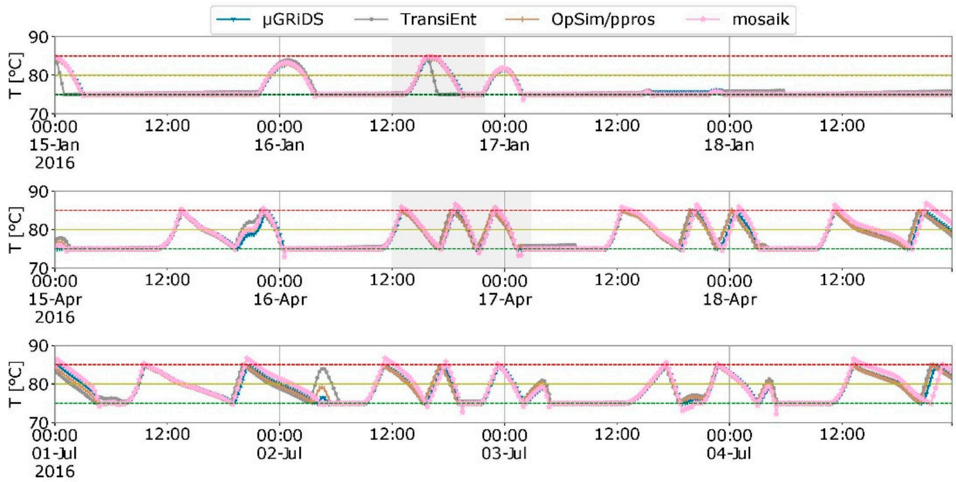

Figure 3. Mean tank temperature for the different models in winter (**top**), transition (**mid**), and summer (**bottom**) seasons.

Table 7. Output indicators for the models under study. Significant deviations are highlighted.

	µGRiDS	TransiEnt	OpSim/Ppros	Mosaik
Total Thermal Load [MWh]	3045	3045	3045	3045
Thermal Output CHP [MWh]	**1151**	1139	1138	1132
Thermal Output Back-up [MWh]	1914	1910	1907	1913
Thermal Storage [MWh]	0.02	0.02	**0.01**	0.02
Mean Temperature [°C]	**78.5**	77.6	77.5	77.7
Total Electrical Load [MWh]	349	349	349	349
Electrical Output CHP [MWh]	764	756	754	751
Grid Feed-in [MWh]	415	404	406	402
No. of CHP Start-Ups	620	**650**	622	**596**

To obtain a generalized view of the temperature behavior a boxplot of the entire year is shown in Figure 4. Here, the similarity of the results is even more significant. The median temperature for stratification models is higher than for mixed models. The minimum and maximum temperature for the TransiEnt and OpSim/ppros models represent well the control temperature set-points. The mosaik model deviates due to the integration step lag as described earlier in this section.

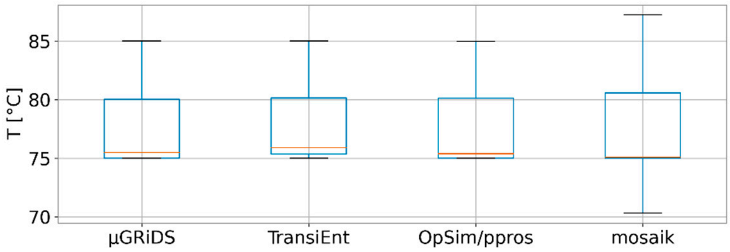

Figure 4. Mean temperature distribution of the different models for whole year.

The similarity in the mean temperature behavior and representation of the controller behavior is in part due to the harmonization in the parameters wherein the stratified tank models used also the mean temperature instead of other layers for the control action. However, as seen in Figure 3 the mean temperature or mixed tank temperature is not completely representative of the operation of a real stratified tank. Here, the tank temperature is often and especially in winter colder than the necessary set-point temperature of 80 °C for the heating circuit. A more accurate representation of the tank stratifications for the μGRiDS and Transient models is shown in Figure 5 below.

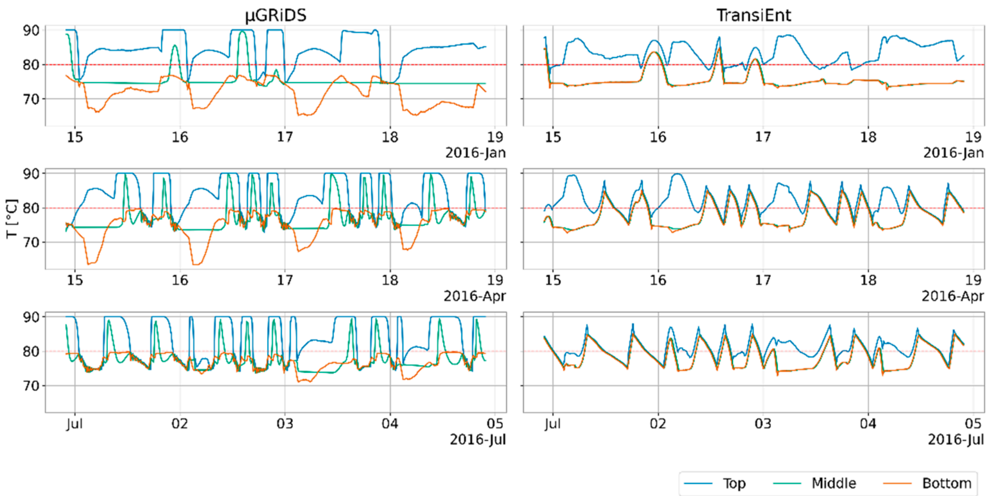

Figure 5. Temperature stratification for the μGRiDS and TransiEnt models in winter, transition, and summer seasons.

For the same time periods during the three seasons the top, middle, and bottom temperature out of the 10 layers from the simulation of the HTES are displayed. A significant observation is that the top temperature of the tank which is used to feed the HL circuit is often hotter than the required temperature of 80 °C. Thus, although it may seem that the mean temperature of the tank is unable to satisfy the HL circuit, the necessary temperature is available due to the stratification behavior. Here, a characteristic difference in the simulation of the temperature stratifications between the two models is noticed especially for the bottom layer in the winter and transition season when the thermal load is higher. In the TransiEnt approach no real stratification occurs between the middle and the bottom layer of the tank during most of the time. This is due to the optimal control of the back-up heater. The sum of the heat generated from the CHP and the back-up heater matches always nearly exactly the heat load requirement. As both the inlet and outlet are at the same stage in the tank, the heat enters and leaves the tank within the same time stamp. Therefore, almost none of the heat is conducted to the lower layers, leading to a heat equilibrium between those layers. When the return temperature drops below the set-point mean temperature of 75 °C as in winter and transition seasons, a clear stratification is also visible for the TransiEnt model.

Analogous to the temperature behavior, the behavior of thermal output of the CHP was also evaluated during the operational analysis. The Figure 6 shows the CHP's thermal power for the four different models during the three different seasons. As expected, in winter the CHP was continuously in operation and producing its nominal output of 202 kWth due to the higher thermal loads. In the transition and summer seasons switching sequences of the CHP are observed corresponding to the control logic based on the tank temperature in Figure 5 above. Although the cyclic patterns appear very similar at first sight, careful observation reveals the dynamic behavior of the CHP in the µGRiDS results. The CHP output in this model requires almost 1 h after start-up to reach its nominal value since the thermal dynamics are simulated with a time constant of ca. 560 s.

Figure 6. CHP thermal output for the different models in winter (**top**), transition (**mid**), and summer (**bottom**) seasons.

3.2. CHP Scenario Energy Balance Analysis

With simulation data for the entire year, an energy balance analysis reveals the total output of the CHP and back-up heater. Also, the residual energy required to satisfy the HL and EL is calculated. This analysis is additionally a cross-check of the individual model results to assure the energy balance (i.e., heating or electrical generation, storage, and load requirements are balanced). The results are summarized in Table 7 below.

As expected, the total thermal and electrical load is the same for all models (i.e., the same input load profiles were applied). The thermal balance can be drawn by comparing the heat produced by the CHP and the back-up heater along with the energy stored and the thermal load. Similarly, the electrical balance is seen in the electrical energy produced by the CHP and the surplus above the required electrical load that is fed into the grid. There are no significant differences in the overall energy balances and the mean tank temperature amongst the four models but a closer observation reveals higher thermal (and consequently also electrical) energy generation in the µGRiDS results. This is primarily due to the implementation of the tank model in µGRiDS with an unavoidable dead volume (thermal loss) as discussed in Section 2.3. The thermal losses in this case are ca. 20 MWh or 1.7% and accounting for almost 99 h of longer CHP operation. This is also represented in the lower number of CHP start-ups for the µGRiDS results. A lower number of CHP start-ups is also seen in the mosaik results which may arise due to the integration time step lag and a higher number of start-ups in TransiEnt due to the sensitivity of the hysteresis controller as described in Section 3.1. However, a further parameter analysis will be necessary to quantify these effects along with the implementation of temperature stratifications on the CHP start-ups for the different models.

3.3. HP Scenario Operational Analysis

In the following two subsections, we compare the results obtained by the different models involved in the HP scenario. For this purpose, an operational as well as an energy balance analysis is conducted, similar to the CHP scenario.

Different to the CHP scenario, big operation differences can be identified during the entire year. As seen in Figure 7, especially in winter the profiles are diverging significantly. In transition season, the results seem to be quite similar, whereas, in summer, the starting point between the four different models diverge. One reason can be found in the hysteresis control. In summer, as there is almost no space heating demand, it can take quite long till the lower control limit is reached, as happening in the water storage (see Figure 8). Therefore, the starting point of the HP is different between the models, even though the temperature before the HP control kicks in, is almost the same.

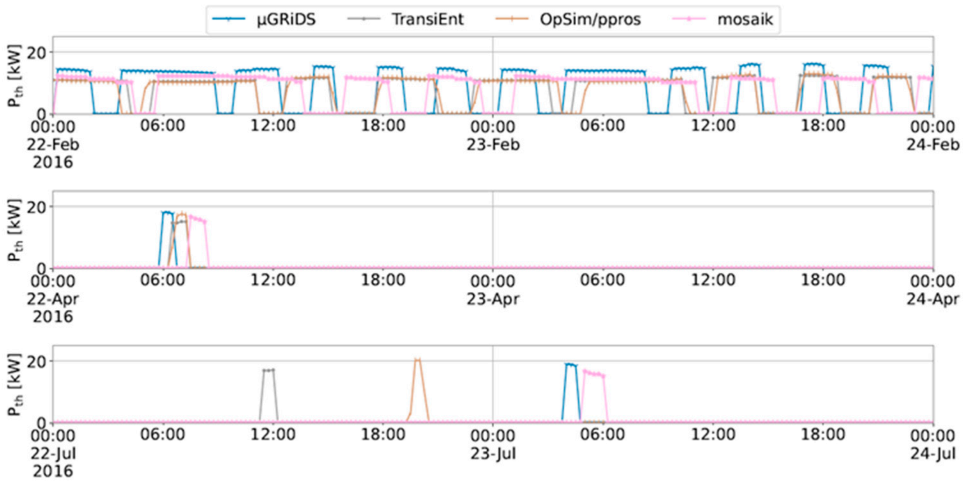

Figure 7. Thermal output of the HP for two days in February (winter), April (transition) and July (summer). Compared are the different results among the four models involved.

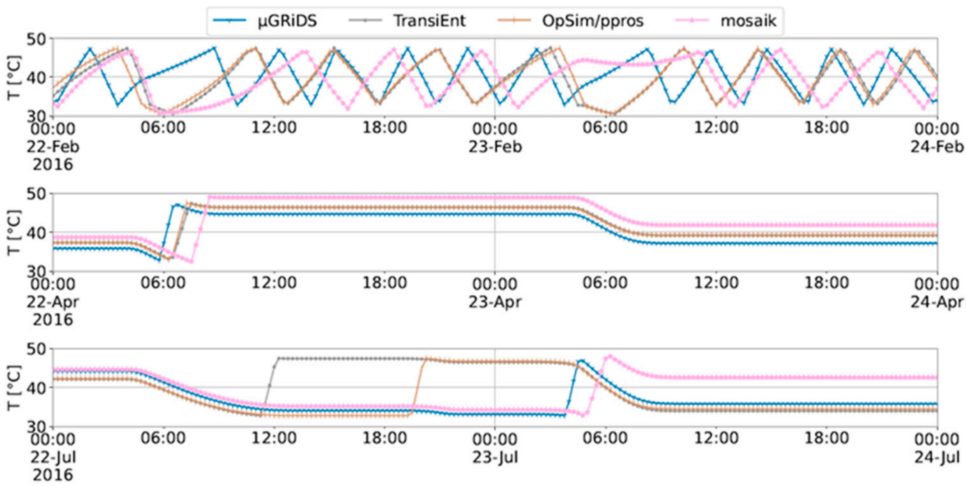

Figure 8. Mean temperature of the hot water storage for two days in February (winter), April (transition) and July (summer). Compared are the different results among the four models involved.

Another interesting result can be seen in terms of the back-up heater. In Figure 9 the additional heater switches on only twice a year (both in February).

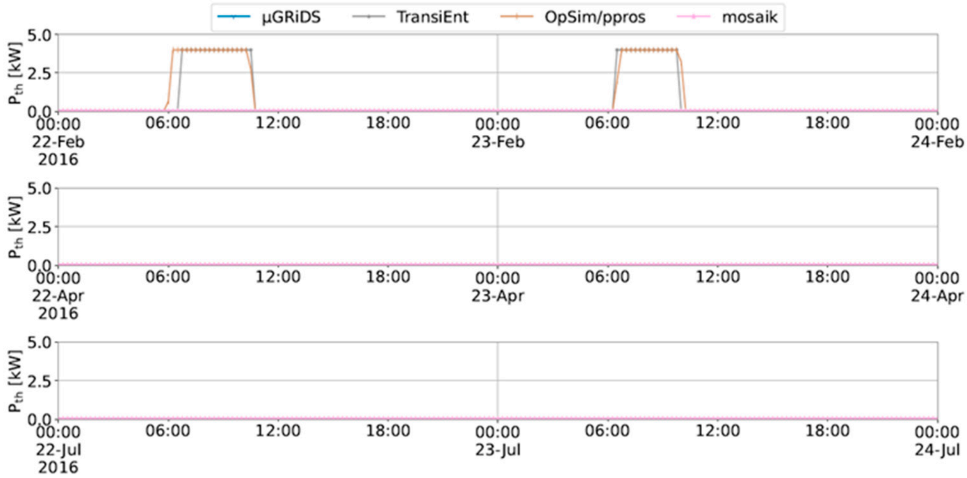

Figure 9. Thermal output of the heaters for two days in February (winter), April (transition) and July (summer). Compared are the different results among the four models involved.

However, this is not the case in all four models. Only in case of the models using the Carnot-COP an additional heater is needed. With the other two models, an additional heater is never required during the entire year. One reason for the deviation is the slight higher thermal power of the two models µGRiDS and mosaik compared to TransiEnt and OpSim/ppros as seen in Figure 7. The different control strategy implementations in case of the stratified in comparison to the simple energy storage are a second explanation for the difference caused.

3.4. HP Scenario Energy Balance Analysis

In comparison to the operational analysis, the differences in results fluctuate massively. While on the thermal system side the differences are quite small, on the electrical side severe deviations can be identified. Table 8 illustrates these findings.

Table 8. Output indicators for the models under study. Significant deviations are highlighted.

	µGRiDS	TransiEnt	OpSim/Ppros	Mosaik
Electrical Input HP [kWh]	5871	6442	5985	**7701**
Thermal Output HP [kWh]	21,748	21,756	21,735	21,737
Electrical Input Heater [kWh]	0	32	33	0
Thermal Output Heater [kWh]	0	31	32	0
Electrical Input Water Heater [kWh]	1447	1447	1447	1447
Thermal Output Water Heater [kWh]	1447	1447	1447	1447
Sum electric loads [kWh]	7318	7920	7464	**9148**
Mean Temperature [°C]	40.4	40.9	40.4	40.9
No. of HP Start-Ups	**1135**	933	952	831

Comparing the difference of the thermal output of the HPs, the maximum relative difference in reference to the mean is 0.06%. Also, the difference of the mean temperature in the hot water storage is negligible. However, on the electrical system side the relative deviation sway extremely. In case of the three models µGRiDS, TransiEnt, OpSim/ppros the maximum difference in reference to the mean is 4.66%. Taking also mosaik into account, mosaik show a difference in reference to the mean of 14.89%. This deviation can be traced back on the different COP calculation methods. While µGRiDS and mosaik base their calculations on HP fact sheets, TransiEnt and OpSim/ppros use a variation of the Carnot degree of efficiency. µGRiDS uses a more generic approach and the mosaik model can currently only simulate certain HP models for which the datasheets are prepared. Thus, the used HP system seems to be not optimally sized and has a higher electrical demand than the other models.

A closer look at the distribution of the electrical HP load and the storage temperature manifests this statement.

While in Figure 10 there is almost no difference in case of TransiEnt and OpSim/ppros, mosaik's results differ totally. This is caused by the different fact sheets used by µGRiDS and mosaik.

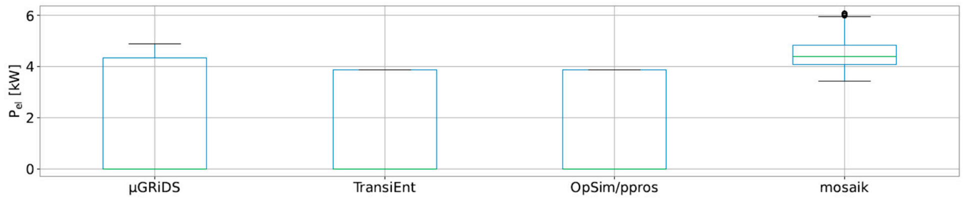

Figure 10. Boxplot of the HP electrical demand.

In comparison, there is almost no difference in terms of the mean temperature in all three models, as seen in Figure 11.

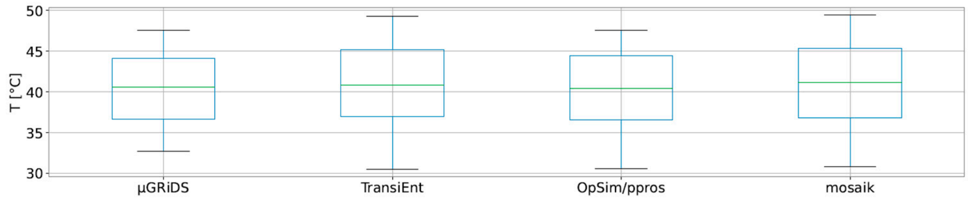

Figure 11. Boxplot of the mean temperature in the hot water storage.

4. Discussion

Based on the simulation results of the CHP and HP scenarios shown in the previous section, the advantages and disadvantages of the types of models compared earlier are presented in this section. The component-oriented models provide the possibility to simulate complex plant dynamics and represent control and operation knowledge of the components within the simulation environment. This level of detail can be used to simulate control approaches, transient processes, and component behaviors in a single local gas or heat grid comprehensively. But this approach reaches the limits of its applicability in the simulation and optimization of a large grid or network with multiple plants and storages, since increased complexity also leads to increased computational costs.

As seen in the simulation of the CHP and the HP scenarios, the differences between system- and component-oriented models in the energy balance over a longer period are not significant. For instance, there are maximum deviations of only 1% from arithmetic mean values for the four models. In the HP scenario larger differences in the results occurred but they were caused by individual characteristics of the models and could not be assigned to a specific type, as explained in Section 3.4. Thus, application of detailed description of the plant level dynamics may not be necessary in optimization of a grid-wide operation as the interaction of various plants and existence of multiple storage elements may provide a tolerance for both spatial and dynamic accuracy.

For investigations with focus on the dynamic behavior and control of units, the component-oriented models are needed as the temperatures and mass flows are important on a building level. Also, the run time and number of start-ups of the heating system can be relevant, for example, for the sizing of a system. Additionally, detailed calculations can be important for a correct simulation of SC, in which the exact temporal occurrence of events can have a large impact on the balancing between sectors. In this context, future studies might extend the model comparison in this paper regarding the control strategy. For the comparison at hand, the controllers were harmonized and used the mean tank temperatures as base for the hysteresis controller. A comparison of this approach using mean temperatures and an approach with stratified layers for control would yield further information on the applicability of detailed component-based models for plant level operational analysis.

The flexibility of co-simulation allows to also couple other models depending on the relevant use case. Thus, it is also possible to integrate the other models of the comparison into co-simulation. For example, the μGRiDS HP model can be exported as Functional Mockup Unit (FMU), which is a standard format for exchange of co-simulation models based on the Functional Mockup Interface (FMI) standard [42,43] and integrated in a co-simulation. This way, the limitations of mosaik's and OpSim/ppros' HP models could be mitigated for use cases that need more detailed simulations. Additionally, the integration with the co-simulation frameworks allows to instantiate the HP model multiple times with minimal effort compared to direct implementation in μGRiDS and to investigate its effect on a grid. This can also be extended to other use cases such as hardware-in-the-loop simulations, tests of grid control strategies as well as virtual power plant operation strategies. On the contrary, one major drawback is the additional complexity and computation overhead being induced using co-simulations compared to a fixed set of models in an integrated simulation environment.

As the system-oriented models usually consider a smaller number of parameters and in- and outputs to simulate a certain component/technology (e.g., turbine CHP or engine CHP), the technology types are easily interchangeable. On the other hand, component-oriented models consider more details like temperatures and mass flows, which makes the data exchange and implementation of various technologies more complicated. Especially when detailed parameters of a system are unknown, it can be advantageous to use a system-oriented approach. The influence of differently set parameters potentially outweighs the influence by simplification of the models.

5. Conclusions

The various modelling approaches for energy system analyses, presented in literature were classified as system-oriented and component-oriented approaches. These approaches were representatively investigated in two real-world hybrid energy system scenarios using the TransiEnt library, μGRiDS, and OpSim (including pandaprosumer and mosaik libraries/models). A significant effort was necessary for identifying all model parameters, generating input data, and creating a simulation framework so as to compare these models in a harmonized set-up. Primary concluding remarks are listed below:

- The qualitative classification in Section 2.3 show that a clear boundary between the two approaches is not practical. Some models are able to represent both approaches, depending on choice of the individual component model from within a library or coupling of component models in a co-simulation framework.
- Critical analyses of simulation results often pointed at certain model features necessary to capture a particular technical aspect relevant to that model's field of application as the reason for discrepancies.
- The simulation results show that for questions concerning network planning and design, where the focus is on simultaneity, system-oriented models such as a simple energy storage model, would be sufficient for valid results. For system design and operation using model predictive control as an example, detailed component-oriented models maybe necessary.
- Distribution grid expansion measures are expensive and the complexity keeps increasing due to an increasing number of decentralized plants. The separation of systems is no longer clear-cut and for operational energy system analysis, all energy grids (power, heat, and gas) along with storage systems have to be analyzed together. It is therefore important to further investigate the effects of different approaches and match them to their appropriate problem statements.

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