Sector Coupling and Multi-Domain Systems Validation

E. Widl, G. Silano, O. Gehrke, and T. Zerihun

Abstract The transition to a decarbonized energy system requires integrating multiple energy carriers (e.g., power, heat, gas) and engineering domains (e.g., control, ICT) to optimise resource use and enhance resilience. The increasing share of non-programmable renewables, such as solar and wind, introduces grid stability challenges, including voltage fluctuations and congestion, necessitating advanced flexibility solutions. Multi-energy and multi-domain systems address these challenges. This chapter showcases innovative methods and approaches for assessing sector coupling and multi-energy systems in the context of the energy transition.

1 Technical Assessment of Integrated Energy Solutions

Sector coupling and multi-energy systems are expected to become crucial for the energy transition as they have the potential to enhance energy efficiency and integrate renewable energy sources more effectively by linking electricity, heating, cooling, and transport sectors [4]. This interconnected approach can leverage a more flexible use of energy, reducing reliance on fossil fuels and enabling higher shares of renewables, such as wind and solar. However, the assessments of the impact on the related technical infrastructure—such as the electrical grid, district heating system, and gas networks—is a relatively recent subject [3, 9]. For instance,

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power-to-heat technologies, combined with thermal storage and flexible loads, enable surplus renewable electricity to be converted into thermal energy, supporting grid balancing and congestion management [5].

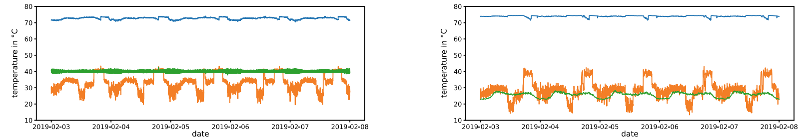
ERIGrid 2.0 has supported research on sector coupling and multi-energy systems by providing researchers with access to advanced laboratories and simulation tools for testing integrated energy solutions. This research and development performed in ERIGrid 2.0 (as described in chapters "Holistic Smart Energy System Validation"–"Laboratory Infrastructure Integration and Automation") has advanced innovative methods for assessing sector coupling and multi-energy systems in the context of the energy transition. This enables the validation of cross-sector energy applications—such as power-to-heat, hybrid energy networks, and smart control via ICT networks—ensuring efficient renewable integration and system flexibility.

The following sections provide examples of technical assessments of sector coupling and multi-energy systems. These examples cover different types of systems (multi-energy, cross-sector) and approaches (simulation, laboratory testing). Together, they demonstrate what insights may be gained using the tools and methodologies established in ERIGrid 2.0, showcasing the potential of integrated testing, validation, and simulation tools, enabling more efficient and reliable system integration for a broad spectrum of applications.

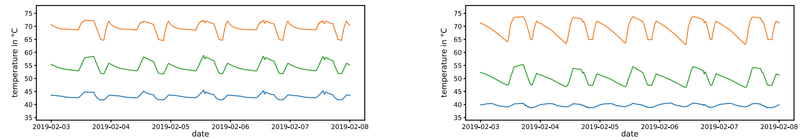
2 Co-Simulation of a Multi-energy Network

The Multi-Energy Networks benchmark (see section "Multi-Energy Network Benchmark") provides a reference setup for multi-energy sector coupling, where a power-to-heat facility connects a low-voltage electrical grid to a local heating network. The intention behind this benchmark scenario is to showcase the feasibility of using simulations for assessing multi-energy systems. However, simulation-based technical evaluations of multi-energy grids, primarily concentrating on operation and control, remain a challenge with the majority of available tools. This is because existing simulation tools generally focus on a single technical domain (e.g., thermal or electrical grids), having either emerged from extensive research in their particular scientific community or driven by a need from the industry to solve specific objectives. Hence, the co-simulation approaches developed as part of ERIGrid 2.0 (see section "Heat Networks and Power System") have been used to demonstrate the maturity of available simulation tools for the assessment of multi-energy grids.

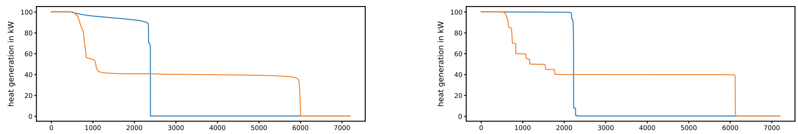
Two implementations of the simulation benchmark have been created, relying on the mosaik co-simulation framework [6]. Both utilize pandapower [10] for simulating the electrical subsystem and employ independent implementations of the controllers' logic. Nonetheless, the implementations vary in their representation of the thermal domain. The first implementation uses the pandapipes package [2] for modeling the heat network, whereas the second implementation uses the DisHeatLib library [1] to simulate the complete thermal subsystem, including the heat network and the power-to-heat facility.



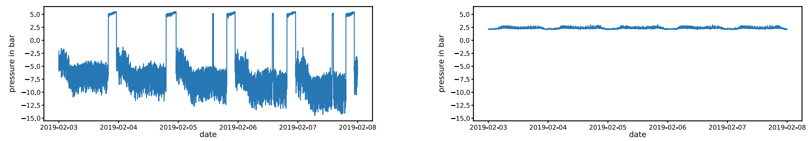
(a) Temperature profiles at supply line inlet (blue) and return line outlet (green) of *consumer_1* and network return line (orange).



(b) Temperature profiles in storage tank from top (orange), center (green) and bottom (blue) of the volume.



(c) Duration plot of heat pump power consumption with (orange) and without (blue) voltage control.



(d) Pressure profiles at return line outlet of *consumer_1*.

Fig. 1 Comparison of simulation benchmark results for pandapipes (left) and the DisHeatLib (right) [11]

Figure 1 shows a selection of results from the co-simulation setup using pandapipes (left column) and the DisHeatLib (right column), respectively [11]. Figure 1a compares the temperature profiles at the supply line inlet (blue) and the return line outlet (green) of *consumer_1* as well as the network return line (orange). This shows that both implementations differ considerably in how they model the consumer (i.e., the temperature of the returned mass flow), but the resulting network dynamics are comparable both qualitatively and quantitatively. The same argument holds for the operation of the storage tank (cf. Fig. 1b) and the heat pump (cf. Fig. 1c). In contrast, Fig. 1d shows that the computation of the pressure distribution fails with pandapipes in case more than one source feeds the network (i.e., when both the external thermal grid and the storage tank feed into the network's supply line). Wherever the pressure calculation does not fail, the comparison shows that the two approaches do not produce similar results due to different assumptions regarding the pressure drop in the consumer models.

This provides an interesting comparison between the distinct simulation approaches used by the two implementations. The pandapipes package provides a (quasi-)static analysis of balanced fluid systems, useful for the computation of temperature, pressure and velocity distributions in pipe networks. The DisHeatLib library is designed for the analysis of thermo-hydraulic transients in fluid systems, which is useful for the assessment of flow reversals and time-delayed propagation of fluid properties in pipe systems. Nevertheless, for the operation of the power-to-heat facility, both implementations give compatible results. This suggests that both approaches are suitable for adequately representing the dynamics of the coupled system and generating plausible results.

3 Multi-RTI Lab Tests of Multi-Energy District Flexibility

The Multi-Energy District Flexibility demonstration was designed to assess the feasibility and technical performance of power-to-heat technologies within a local multi-energy district. In contrast to the approach chosen in section "Heat Networks and Power System", this demonstration relied on laboratory infrastructure available within the ERIGrid 2.0 consortium. The demonstration focused on evaluating their impact on both the electrical and thermal networks, testing their ability to support grid operations through congestion management and balancing power provision. As part of ERIGrid 2.0, this experiment played a pivotal role in validating cross-domain energy system integration methodologies (see chapters "Holistic Smart Energy System Validation"–"Laboratory Infrastructure Integration and Automation"), leveraging geographically distributed RTIs and real-time control strategies to address key challenges of the energy transition.

The experiment was conducted across multiple RTIs, each contributing specific resources and expertise. As illustrated in Fig. 2, the setup included a district heating network at DTU, a CHP system at RSE, a heat pump with thermal storage at CRES, a BESS at SINTEF, and a real-time simulation of the distribution grid at TUD. The

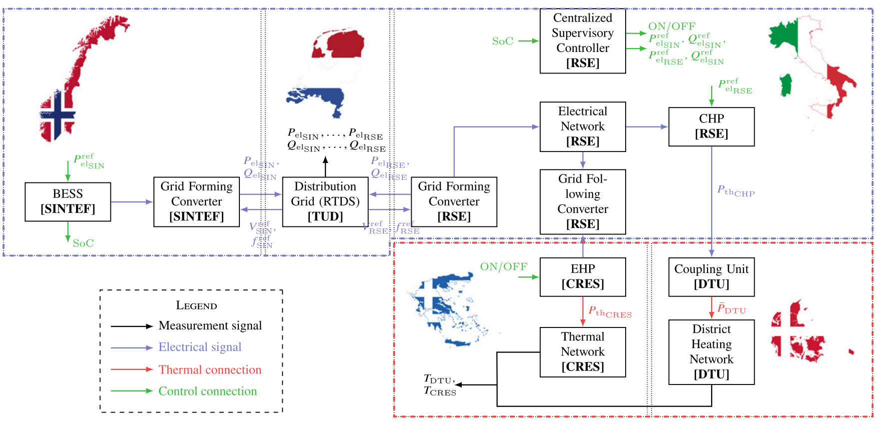


Fig. 2 Representation of the multi-energy district case study, with the electrical and thermal subsystems highlighted by blue and red dashed boxes, respectively [8]

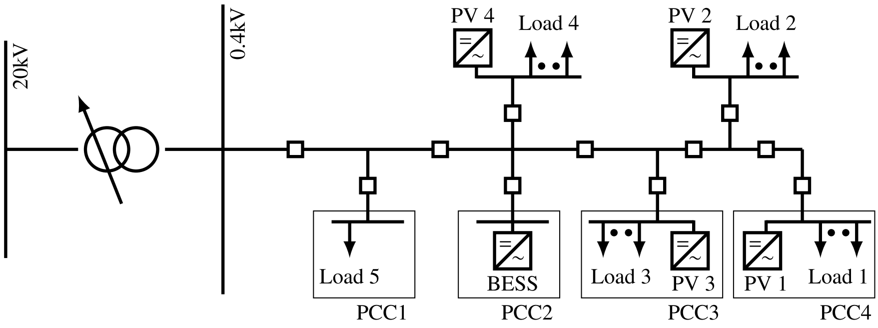


Fig. 3 Schematic representation of the CIGRE LV-distribution benchmark grid along with the PCCs [8]

electrical network was based on the CIGRE LV-distribution benchmark (see Fig. 3), emulated through DRTS, while the thermal system consisted of a double-pipe heating network interfaced with controllable heat sources and loads [7, 8].

The experimental infrastructure was designed to replicate the operation of a real multi-energy district by coupling electrical and thermal networks across geographically distributed RTIs. Data exchange was enabled through ERiGrid 2.0-developed tools, including JaNDER and uAPI (see chapter "Laboratory Infrastructure Integration and Automation"), ensuring reliable real-time communication between laboratories. As shown in Table 1, a diverse set of electrical and thermal parameters was exchanged among the RTIs, facilitating coordinated control of active and reactive power, voltage regulation, and thermal energy management. The integration of these technologies allowed for HIL testing and GDS, enabling the validation of advanced control strategies for multi-energy systems.

The demonstration focused on two key operational scenarios: Overvoltage management and undervoltage management. The first scenario, depicted in Fig. 4, addressed voltage rise due to high photovoltaic generation and low demand by increasing power consumption through heat pumps and BESS charging. The second scenario, shown in Fig. 5, examined voltage drops caused by low PV generation and high demand, requiring additional power generation from the CHP unit and thermal storage activation. The experimental results, illustrated in Figs. 6 and 7, confirmed

Table 1 Signals exchanged among RTIs, including their symbols and operational ranges [8]

Symbols	Unit	Min	Max	Symbols	Unit	Min	Max
$P_{el_{SIN}}$	kW	−40	40	$Q_{el_{SIN}}$	$kVAr$	−5	5
$P_{th_{CHP}}$	kW	46	81	$P^{ref}_{el_{SIN}}$	kW	−40	40
$\bar{P}_{DTU}$	kW	0	25	SoC	%	0	100
V^{ref}_{SIN}	V	150	400	f^{ref}_{SIN}	Hz	48	52
$P_{el_{RSE}}$	kW	−100	100	$Q_{el_{RSE}}$	$kVAr$	−50	50
V^{ref}_{RSE}	V	150	400	f^{ref}_{RSE}	Hz	48	52
$P_{th_{CRES}}$	kW	0	30	T_{DTU}	°C	0	100

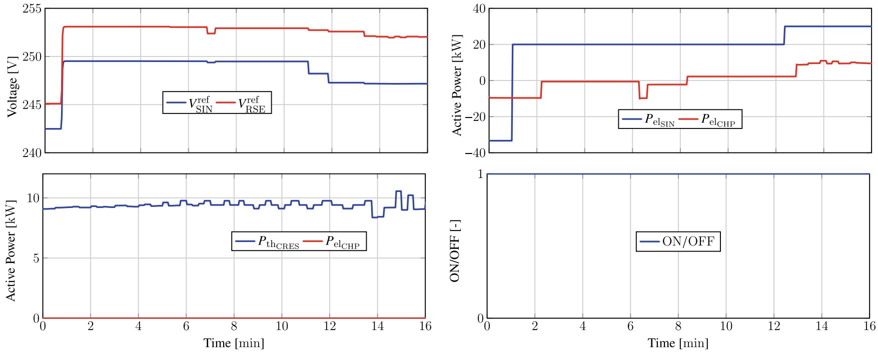


Fig. 4 Reference voltage sent from the distribution grid (TUD) to the grid-forming converters (SINTEF and RSE), along with the active power generated by the BESS and CHP and enable signals of the EHP in the overvoltage scenario [8]

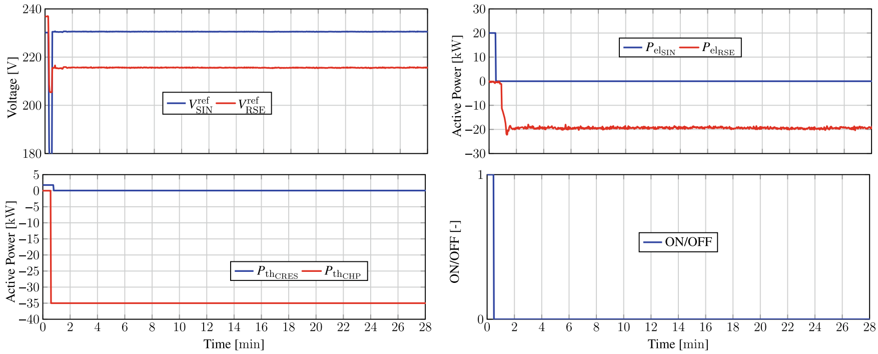


Fig. 5 Reference voltage sent from the distribution grid (TUD) to the converters (SINTEF and RSE), along with the active power generated by the BESS and CHP, and the enable signals of the EHP, in the undervoltage scenario [8]

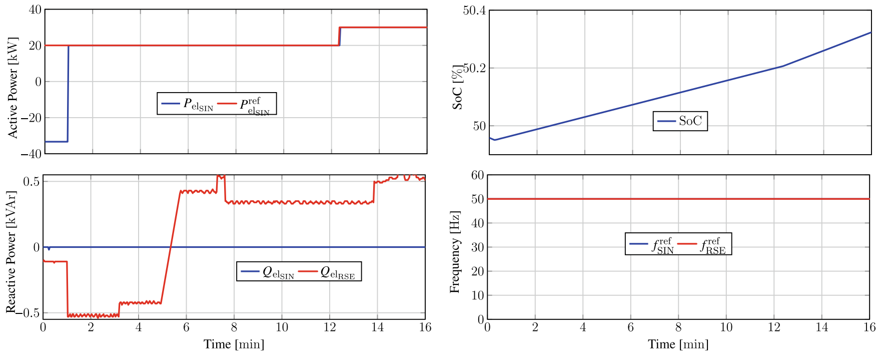


Fig. 6 Reference and actual active power profiles at the SINTEF facility, along with the SoC of the BESS, during the overvoltage scenario experiment. Additionally, reactive power and frequency data are included [8]

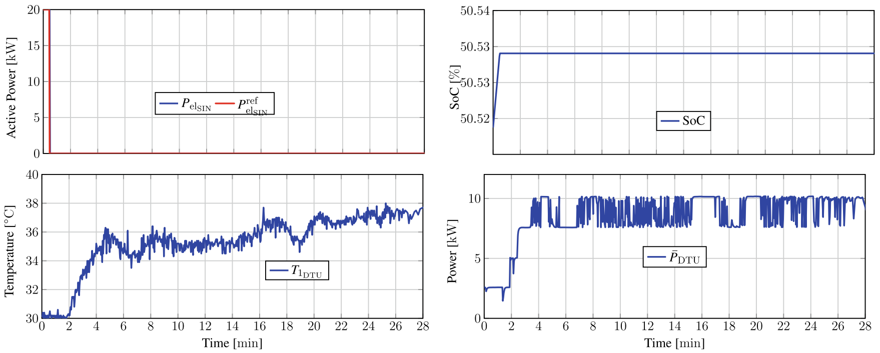


Fig. 7 Power and SoC of the BESS at SINTEF, alongside the temperature of the heat source buffer tank, and the power of heat sent to the buffer, in the undervoltage scenario [8]

that power-to-heat solutions effectively mitigated voltage deviations, demonstrating their potential as grid flexibility resources. Further details can be found in [7]. For the sake of brevity, plots and tabulated data are not included in this section.

The control strategy employed in the demonstration prioritized active power adjustments, while other parameters such as temperature control remained secondary considerations. The dynamic response of the thermal system, as shown in Fig. 8, highlighted the significantly slower time scales of thermal processes compared

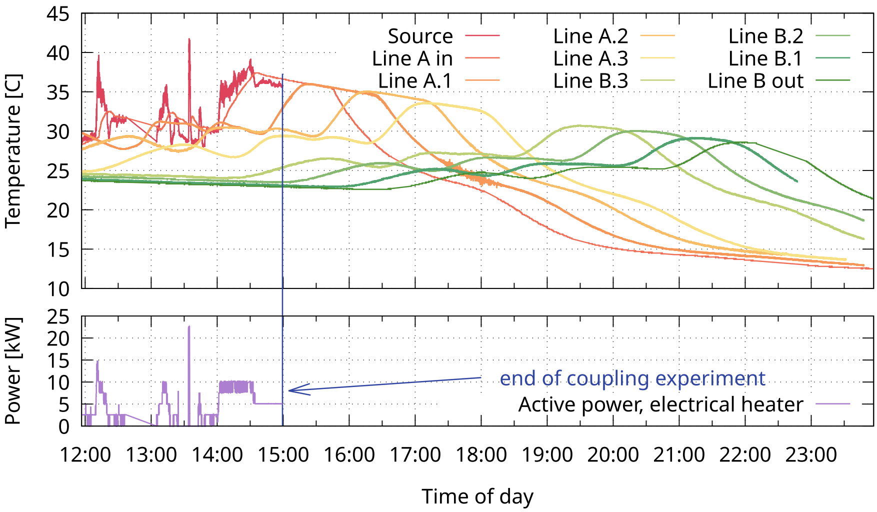


Fig. 8 Dynamic response of the thermal network. Bottom graph: Power consumption of the heat source, tracking the CHP's heat output. Top graph: Heat propagation through the network, measured at various points along the forward pipe [8]

to electrical systems, emphasizing the need for integrated control approaches that account for these differences.

By successfully integrating power-to-heat solutions within a distributed experimental framework, this demonstration validated the effectiveness of ERiGrid 2.0 methodologies, including the uAPI for RI data exchange, the JaNDER middleware for RTI communication (see chapter "Laboratory Infrastructure Integration and Automation"), and holistic test case descriptions for multi-energy system coordination (see chapters "Holistic Smart Energy System Validation"–"Enhanced Validation Methods and Benchmark"). The results confirmed that sector coupling can enhance grid flexibility, supporting both real-time operational stability and long-term energy transition goals. Furthermore, the use of advanced data exchange and synchronization tools facilitated seamless multi-laboratory collaboration, reinforcing the feasibility of cross-border experimental validation for emerging energy technologies.

4 Co-Simulation of an AC Grid and ICT Network

This demonstration was designed to characterize and validate co-simulation tools for multi-domain systems that combine an electrical grid and a networked ICT system, where the ICT infrastructure is used to monitor and control aspects of the electrical grid. In such systems, the performance of the ICT network directly affects the performance of the electrical grid, making it crucial that the modeling of the energy system accurately captures the interactions between the two subsystems. Currently, there are no established tool chains or validation approaches for comprehensively evaluating such cyber-physical power systems. To validate the proof-of-concept simulation developed within ERIGrid 2.0 (see section "Co-Simulation of Power Systems and ICT Networks"), a direct validation method was devised which compares the co-simulation results to experimental results from an emulated power-ICT system as well as from a physical laboratory.

The demonstration scenario considers the coordination between a Distribution System Operator (DSO) and an Aggregator for activating flexibility resources for voltage regulation. The test case assumes a section of an electrical distribution grid with two aggregators operating independently. Each aggregator manages a portfolio of flexible DERs which provide load reduction on demand. The primary customer for these grid services is the local DSO, which monitors the grid and submits service activation requests to the aggregators. A heterogeneous communication network facilitates data transfer between DSO, measurement equipment, flexibility assets, and aggregators. The test system is stimulated in two ways: through events within the communication network (equipment failure) or within the electrical network (sudden changes in load).

5 Summary and Implications

The access to state-of-the-art laboratories and simulation tools in ERIGrid 2.0 has enabled research and development dedicated to the evaluation of integrated energy solutions, enhancing the understanding of sector coupling and multi-domain systems. As a consequence of this research conducted as part of ERIGrid 2.0, new tools and methods have been developed for the validation of energy applications across multiple sectors. This is relevant for a variety of subjects of high importance for the energy transition–including power-to-heat, smart control, and hybrid energy networks–enabling the successful integration of renewable energy sources and improvement of system adaptability.

The sector coupling and multi-energy system examples presented here encompass a diverse set of systems and evaluation methods. Together, they showcase the capabilities of ERIGrid 2.0's methodologies and tools for integrated testing, validation, and simulation, illustrating how these tools can enhance system integration across multiple domains.

References

1. Leitner B, Widl E et al (2019) A method for technical assessment of power-to-heat use cases to couple local district heating and electrical distribution grids. Energy 182:729–738. https://doi.org/10.1016/j.energy.2019.06.016
2. Lohmeier D, Cronbach D et al (2020) Pandapipes: an open-source piping grid calculation package for multi-energy grid simulations. Sustainability 12(23). https://doi.org/10.3390/su12239899
3. Lund H (2018) Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach. Energy 151:94–102. https://doi.org/10.1016/j.energy.2018.03.010
4. Mancarella P (2014) MES (multi-energy systems): an overview of concepts and evaluation models. Energy 65:1–17. https://doi.org/10.1016/j.energy.2013.10.041
5. Manco G, Tesio U, Guelpa E, Verda V (2024) A review on multi energy systems modelling and optimization. Appl Thermal Eng 236:121871. https://doi.org/10.1016/j.applthermaleng.2023.121871
6. Ofenloch A, Schwarz JS, Tolk D, Brandt T, Eilers R, Ramirez R, Raub T, Lehnhoff S (2022) MOSAIK 3.0: combining time stepped and discrete event simulation. In: 2022 open source modelling and simulation of energy systems (OSMSES). Aachen (2022)
7. Silano G, Paludetto G, Rodio C, Lazzari R, Feng Z, Kontou A, Paspatis A, Kotsampopoulos P, Gehrke O, Zerihun T, Acosta A, Rikos E, Subramaniam Rajkumar V (2024) D-JRA4.3 Demonstration of the extended research infrastructure. https://doi.org/10.5281/zenodo.12796352
8. Silano G, Rikos E, Rajkumar V, Gehrke O, Zerihun TA, Rodio C, Lazzari R (2024) Integrating power-to-heat services in geographically distributed multi-energy systems: a case study from the ERIGrid 2.0 project. In: 2024 open source modelling and simulation of energy systems (OSMSES), pp 1–6. https://doi.org/10.1109/OSMSES62085.2024.10668976
9. Sorknæs P, Lund H, Andersen AN (2015) Future power market and sustainable energy solutions—the treatment of uncertainties in the daily operation of combined heat and power plants. Appl Energy 144:129–138. https://doi.org/10.1016/j.apenergy.2015.02.041

10. Thurner L, Scheidler A et al (2018) Pandapower-An open-source python tool for convenient modeling, analysis, and optimization of electric power systems. IEEE Trans Power Syst 33(6):6510–6521. https://doi.org/10.1109/TPWRS.2018.2829021
11. Widl E, Wild C, Heussen K, Rikos E, Hoang TT (2022) Comparison of two approaches for modeling the thermal domain of multi-energy networks. In: 2022 open source modelling and simulation of energy systems (OSMSES), pp 1–6. https://doi.org/10.1109/OSMSES54027.2022.9769129