Test Case 12

Author Benedikt Leitner, Edmund Widl
Project SmILES, ERIGrid 2.0
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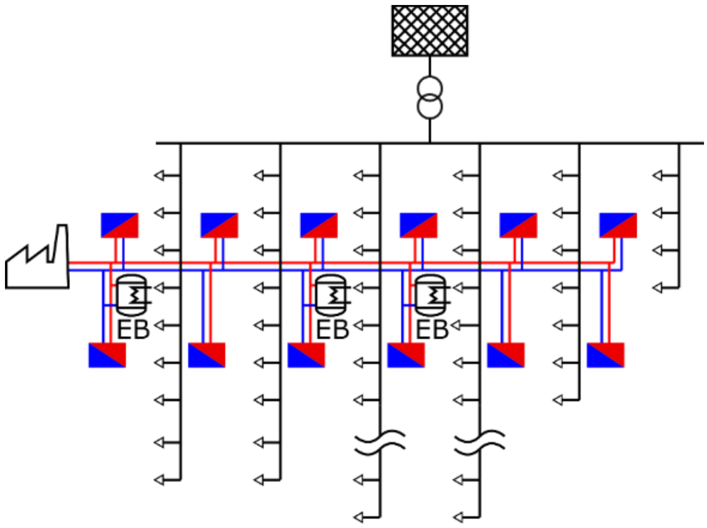
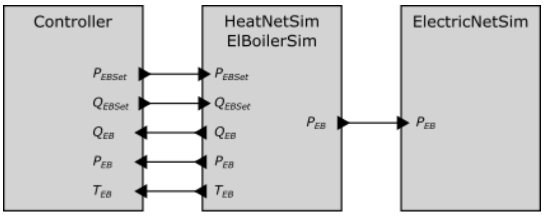
Name of the Test Case	Verification of improved self-consumption of RES in a coupled heat & power network using power-to-heat
Narrative	This test case is used to verify that the self-consumption of renewable energy sources in a coupled heat and power network improves when using distributed power-to-heat appliances compared to a base scenario without power-to-heat. Different control schemes can be applied to reach this goal, which can be assessed in the context of this test case.
Function(s) under Investigation (*FuI*) “the referenced specification of a function realized (operationalized) by the object under investigation”	Control function(s) of power-to-heat appliances Note: The actual control schemes (and the corresponding control functions) are defined in the test specifications.
Object under Investigation (*OuI*) "the component(s) (1..n) that are to be qualified by the test”	External electric grid: • power flows (to and from) Gas heating boiler (for base load): • heat generation Local heating network: • supply temperatures at thermal substations • differential pressures at thermal substations Low voltage distribution network: • voltages at consumer connection points
Domain under Investigation (*DuI*): “the relevant domains or sub-domains of test parameters and connectivity.”	• electric (low voltage distribution network) • heat (local heating network)
Purpose of Investigation *(PoI)* The test purpose in terms of Characterization, Verification, or Validation	Verification of reduction of energy flows flowing out of the network. At the same time energy imports should not increase and the operational parameters of both networks must remain within acceptable ranges.
System under Test (*SuT*): Systems, subsystems, components included in the test case or test setup.	The SuT comprises a coupled low-voltage distribution network and local heating network (sub-urban district), which host residential homes, offices and workshops. A high share of the building stock is connected to the heating network, which is supplied by a central gas-fired boiler. Generation from rooftop photovoltaic power plants covers a significant part of the annual electric energy demand. Electric boilers are installed in the heating network with the aim to further increase the self-consumption of photovoltaic generation at a network scale.

	
Functions under Test (*FuT*) Functions relevant to the operation of the system under test, including FuI and relevant interactions btw. OuI and SuT.	• energy flows (in and out of the networks) • effort variables of both networks (bus voltages, supply temperatures, differential pressures) • loading of the transformer
<u>Test criteria</u> *(TCR)* Formulation of criteria for each PoI based on properties of SuT; encompasses properties of test signals and output measures.	
Target Metrics *(TM)* Measures required to quantify each identified test criteria	• total power flow from external electric grid in MWh • total heat flow from base district heating boiler in MWh • voltages at consumer connection points in p.u. • transformer loading in % • differential pressures at substations in bar • supply temperatures at substations in °C
Variability Attributes *(VA)* controllable or uncontrollable factors and the required variability; ref. to PoI.	Controllable factors: • electric boiler activation • gas boiler activation Uncontrollable factors: • demand (electrical and thermal) • PV generation
Quality Attributes *(QA)* threshold levels for test result quality as well as pass/fail criteria.	The power flow to the external grid and the heat flow from the base district heating boiler are reduced compared to a scenario without power-to-heat appliances. Thus, self-consumption of RES is improved. At the same time, the power flow from the external grid is not allowed to increase more than 1%. Moreover, the following technical criteria must be met: • voltages at consumer connection points within 0.95 p.u. and 1.05 p.u. for 99% of time • differential pressures at substations within 0.9 bar and

		5 bar for 99% of time • supply temperatures at substations above 65°C for 99% of time • transformer loading never goes above 100%

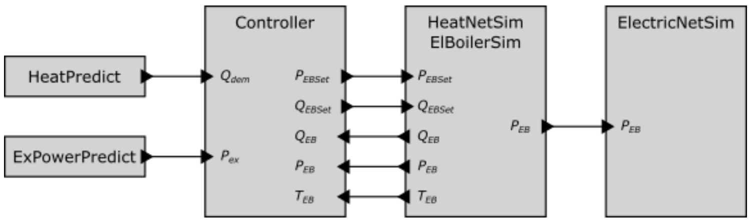
Qualification Strategy

Test Specification TC12.TS01

Reference to Test Case	TC12
Title of Test	Electric Boiler Activation for Excess Power Consumption with Proportional Controllers
Test Rationale	This test aims at self-consumption of excess power generated from distributed renewable power generators (i.e., the rooftop PV generators). The excess power is fed into the local heating network. The local use of excess power helps mitigate problems in the electric distribution network, such as reversed power flows, high loading of equipment and voltage band violations. On the other side, distributed infeed into the local heating network might cause problems due to reversed mass flows, fluctuating supply temperatures or differential pressure problems. Electric boilers are used as power-to-heat appliances. They consist of an electric heater, for the conversion of power to heat, and a thermal energy storage, for the (short-term) storage of generated heat. The operation of the electric boilers and storage units are governed by simple proportional controllers.
Specific Test System (graphical)	This test case uses simple proportional controllers with fixed operational parameters (e.g., temperature thresholds) to calculate new setpoints for the electric boilers. The district heating network/electric boiler simulation send actual power consumption of electric boilers to the electric network simulation. A detailed description of the controller scheme is given in: https://doi.org/10.1016/j.energy.2020.118540 
Target measures	The test is successfully passed if power flows to the external network are reduced compared to a scenario without power-to-heat. Simultaneously, power import into the network is not allowed to increase by more than 1%. Moreover, relevant network constraints need to be met.
Input and output parameters	• P_{EBSet} … electric boiler setpoint for nominal heat flow • Q_{EBSet} … electric boiler setpoint for nominal power consumption • Q_{EB} … electric boiler heat flow • P_{EB} … electric boiler power consumption • T_{EB} … thermal storage temperature
Test Design	This test needs to run for an entire year to account for the

	daily/seasonal variations of loads/generators and the impact of the predictive control, as it usually plans ahead several hours/days.
Initial system state	• district heating pipes have nominal temperatures • thermal storages are empty, i.e., have nominal return temperature of district heating network • electric boilers not running
Evolution of system state and test signals	• Every 15 minutes the electric boiler controllers receive current heat generation and heat discharge from respective electric boilers, based on which new setpoints are calculated. • Every 15 minutes the electric network receives current power consumption from electric boilers • Except for the previous, subsystems are independent from each other.
Other parameters	None
Temporal resolution	Local heating and electric boilers: • dynamic, variable step size (typically order of seconds) Electric network and predictive controllers: • 15 minutes
Source of uncertainty	None
Suspension criteria / Stopping criteria	• critical violation of network operation constraints (freezing/boiling water in any part of district heating network, etc.) • predictive controller unable to predict next step (infeasible model)

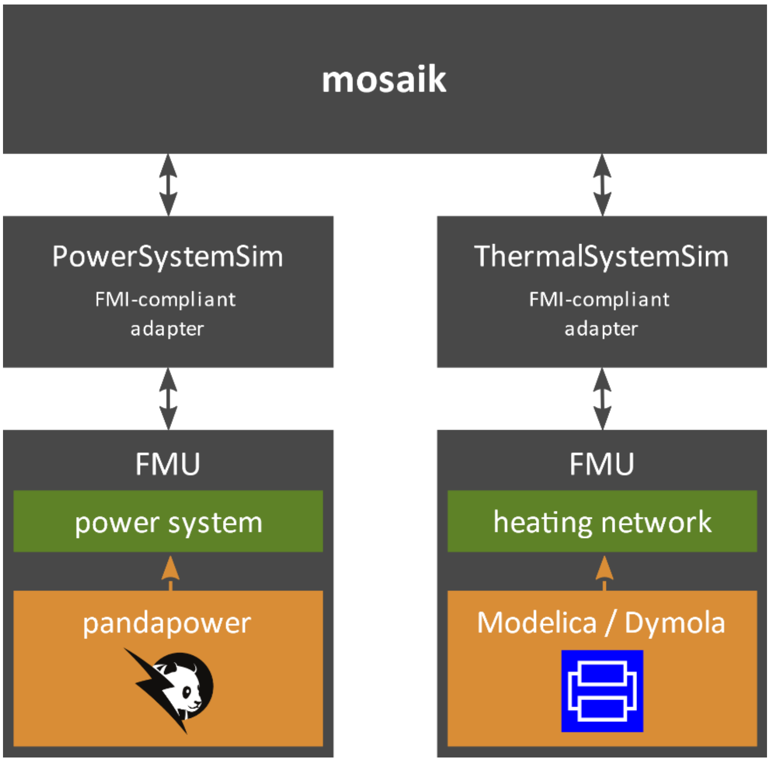
Test Specification TC12.TS02

Reference to Test Case	TC12
Title of Test	Electric Boiler Activation for Excess Power Consumption with Model-predictive Control
Test Rationale	This test is conceptionally similar to TC12.TS01. The difference is that for planning the operation of the storage units and the electric heaters a predictive controller is used. The aim of the controller is to minimize negative residual load of the electric network. To enable this planning, negative residual load in the electric as well as heat demand in the heat network need to be known/predicted. This test assumes perfect knowledge of these time-series data and, thus, does not focus on the quality of predictions.
Specific Test System (graphical)	The controller uses heat demand and excess power predictions together with current storage temperatures, electric boiler power consumption and heat discharge to calculate new setpoints for the electric boilers. The district heating network/electric boiler simulation send actual power consumption of electric boilers to electric network simulation. This test case uses an advanced model-predictive control scheme for activating the electric boilers and storage units. A detailed description of the controller scheme is given in: https://doi.org/10.1016/j.energy.2020.118540 
Target measures	same as TC12.TS01

Input and output parameters	• Q_{dem} … predicted heat demand • P_{ex} … predicted power demand • otherwise same as TC12.TS01
Test Design	The electric boilers are activated with the help of a predictive control approach, which enables a planning of discharging and charging the thermal storage units with regards to excess power availability. For instance, thermal storages can be emptied before times with high excess power but low heat demand and thus makes the use of the electric heater still possible. This test needs to run for an entire year to cover the daily/seasonal variations of loads/generators and the impact of the predictive control, as it usually has planning horizons of multiple hours/days.
Initial system state	same as TC12.TS01
Evolution of system state and test signals	• Every 15 minutes the electric boiler controllers receive current heat generation and heat discharge from respective electric boilers together with predicted residual load of electric network and heat demand of district heating network. Thus, electric boilers receive new setpoints for heat generation & heat discharge from model predictive controllers. • Every 15 minutes electric network receives current power consumption from electric boilers • Otherwise subsystems are independent from each other.
Other parameters	None
Temporal resolution	same as TC12.TS01
Source of uncertainty	None
Suspension criteria / Stopping criteria	same as TC12.TS01

Mapping to Research Infrastructure

Experiment Specification TC12.TS01.ES01

Reference to Test Specification	TC12.TS01
Title of Experiment	Co-Simulation of Electric Boiler Activation for Excess Power Consumption with Proportional Controllers
Research Infrastructure	N/A
Experiment Realisation	The experiment is implemented as co-simulation using mosaik with a simulator synchronization step size of 15 minutes. 
Experiment Setup (concrete lab equipment)	Dedicated simulation components are implemented as FMUs for Co-Simulation: • power system simulation: the power system is implemented as pandapower model, using consecutive power flow calculations to simulate the power system; the electric boilers are represented as PQ loads; • thermal network simulation: the local heating network and the electric boilers are modelled with Modelica and compiled with Dymola; this model includes the proportional controllers that actuate the boilers;
Experimental Design and Justification	This is a basic co-simulation setup using the mosaik environment with FMUs.
Precision of equipment and measurement uncertainty	N/A
Storage of experiment data	The output from the individual simulation components is stored as time series data (HDF5 data format).

Experiment Specification TC12.TS02.ES01

<table>
<tr><td>Reference to Test Specification</td><td>TC12.TS02</td></tr>
<tr><td>Title of Experiment</td><td>Co-Simulation of Electric Boiler Activation for Excess Power Consumption with Model-predictive Control</td></tr>
<tr><td>Research Infra-structure</td><td>N/A</td></tr>
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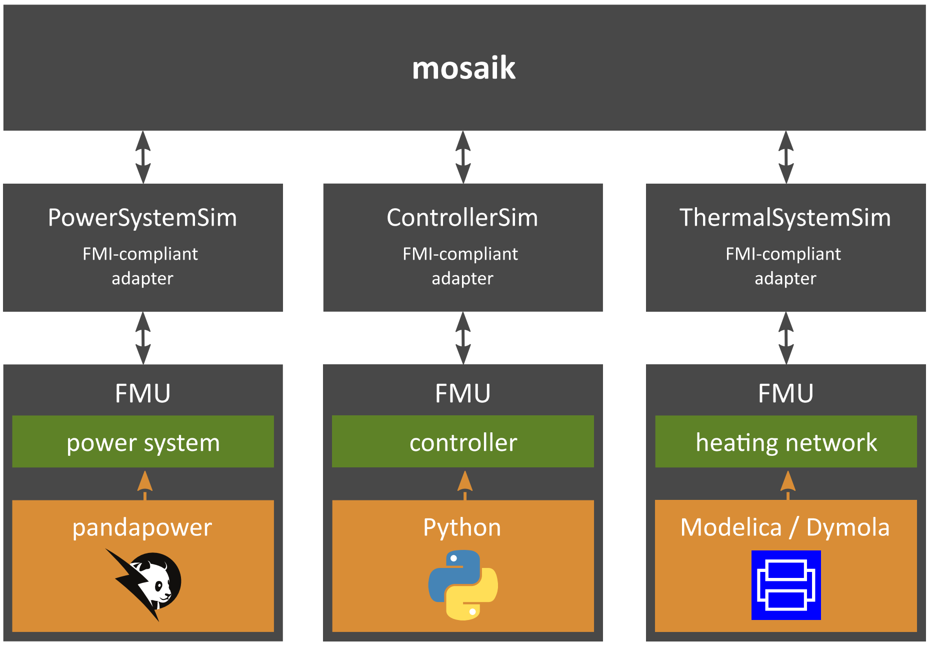
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- power system simulation: the power system is implemented as pan-dapower model, using consecutive power flow calculations to simulate the power system; the electric boilers are represented as PQ loads;
- thermal network simulation: the local heating network and the electric boilers are modelled with Modelica (and compiled with Dymola); this model includes the proportional controllers that actuate the boilers;
- model-predictive controller: the controller logic is implemented in Python</td></tr>
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<tr><td>Precision of equip-ment and measure-ment uncertainty</td><td>N/A</td></tr>
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