1. Document History

Date	Version	Description	Author
2021-03-23	0.1	First draft version	Edmund Widl (AIT)
2021-05-17	0.2	Add quasi-static thermal network system configuration	Christopher Wild (DTU)
2021-09-01	0.3	Add additional information for the electric network configuration	Tran The Hoang (CEA)
2021-11-19	0.4	Update system configuration to the final implemented benchmark setup	Edmund Widl (AIT)

2. General description

2.1 System configuration identification

ID	Name
MENB-SC	System configuration for the multi-energy network benchmark

2.2 Short description of context

Context description
The system configuration described in this document has been developed as part of a reference setup for multi-domain energy network simulations. This reference setup intends to inspire the use of co-simulation for the assessment of multi-energy systems. The level of detail was chosen in a way that allows to apply different modelling approaches for the individual subsystems. For instance, the thermal network could be implemented either in a quasi-static model (series of equilibrium states) or a dynamic model (hydraulic transients).
Key figures
• electrical network: 2 consecutive lines (0.3 km each), connected to external grid • thermal network: 3 main consecutive pipes (supply and return, 0.5 km each), connected to external grid • power-to-heat facility: 1 heat pump (max. 100 kW_{el}) connected to a thermal tank (100 m^3) feeding into the thermal network • consumption: 2 consumers, each representing the aggregated loads (electrical and thermal) of an urban quarter and connected to both networks • generation: 2 PV systems (one of 150 $kW_{el, peak}$ and one of 50 $kW_{el, peak}$)
Key words
• local consumption of high PV generation • decentralized heat generation • heat pumps • coupled heat and electric networks

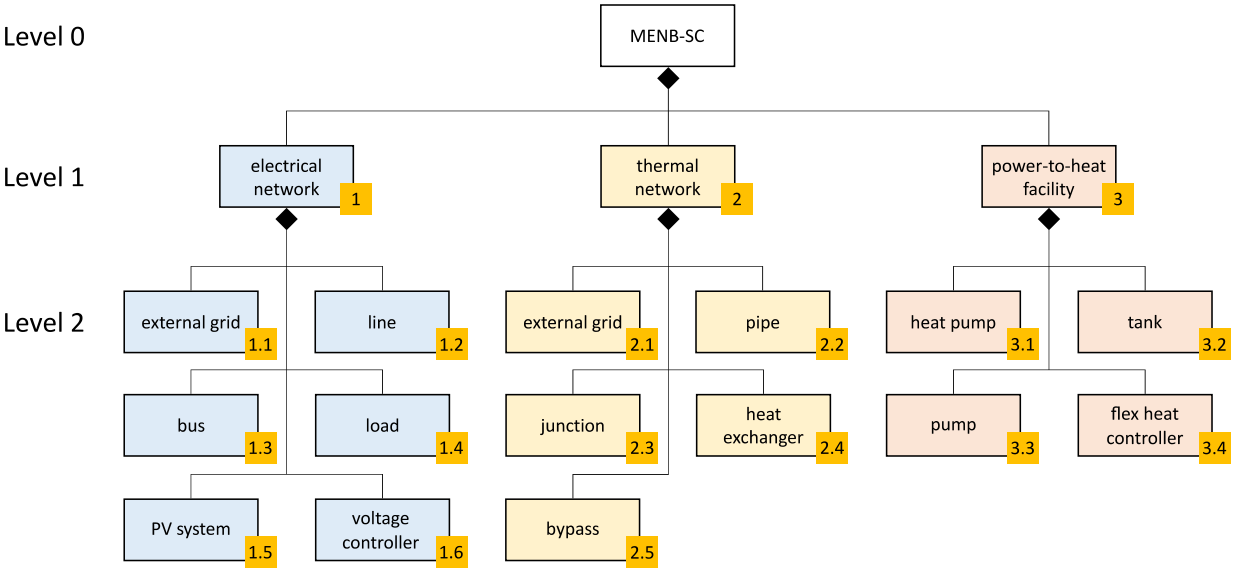
2.3 Climate

Climate conditions
Climate is typical for Central Europe with its moderately warm summers and cold winters. Solar irradiation ranges between 800 and 1200 kWh/m².
Ambient ground temperature is constant 8°C.

2.4 Geographical features

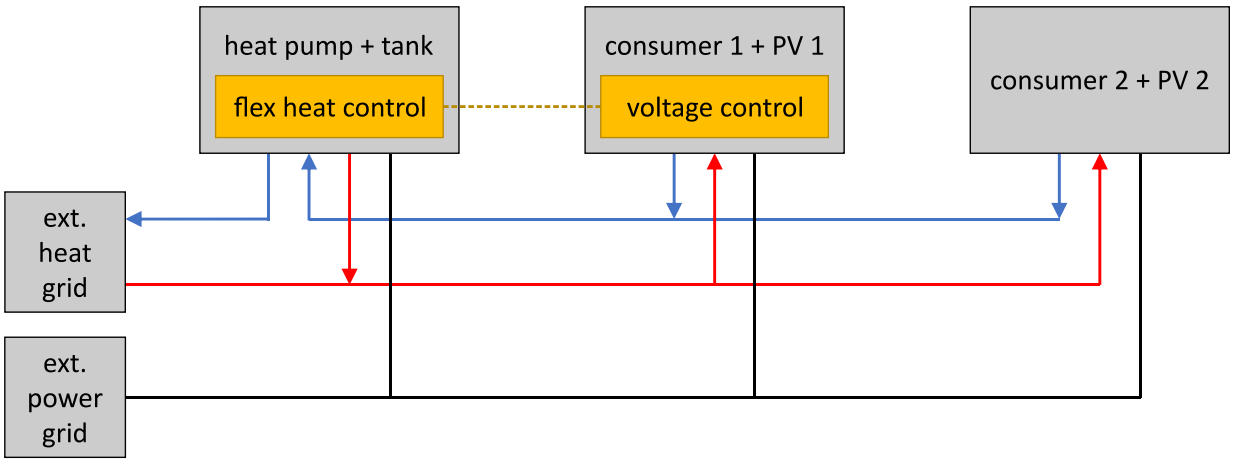
Geographical features
The system configuration resembles part of the sub-urban area of a typical Central European city.

3. System breakdown (SBD)

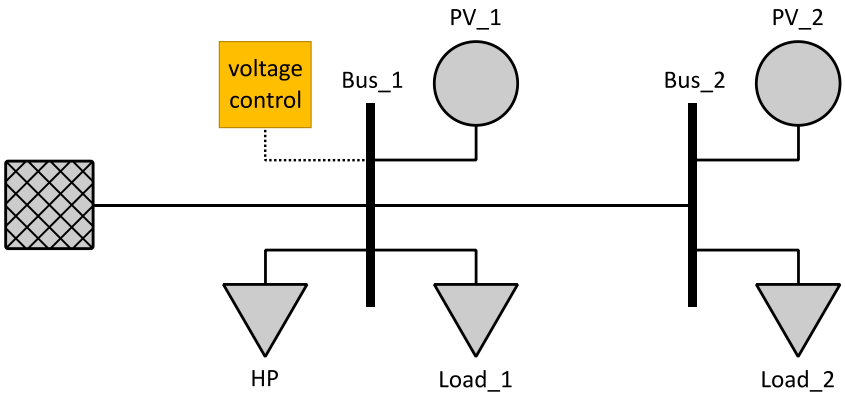


4. Graphical representations of SC

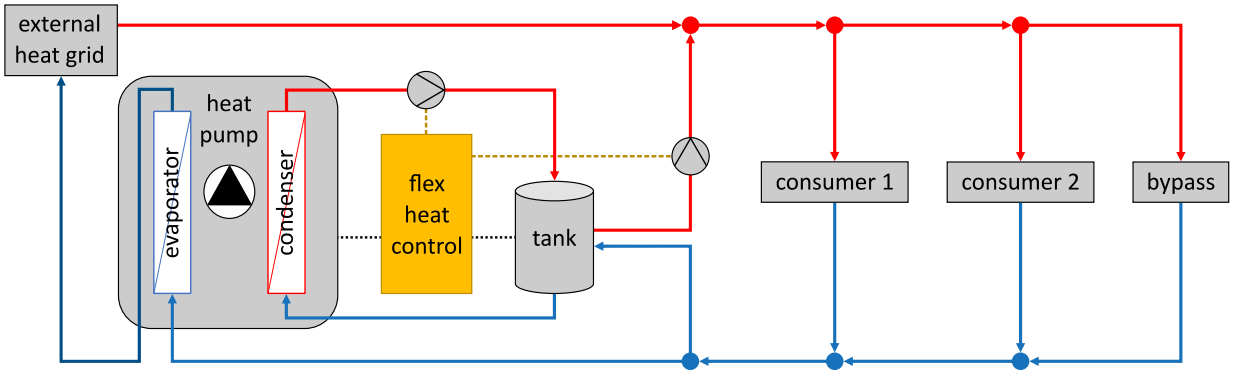
4.1 Overview



4.2 Electrical grid (detailed view)



4.3 Thermal grid (detailed view)



5. Element interface description

Name	ID	Type of exchange	Types of classes connected	Comment
Heat connector	Heat-Connection	heat flow (water mass flow)	`ExternalElectricGrid`, `Line`, `Busbar`, `Load`, `PVSystem`, `HeatPump`	connects components of the thermal network
Electric power connector	Electric-Connection	electric power flow (electric current)	`ExternalThermalGrid`, `Pipe`, `Junction`, `Bypass`, `HeatExchanger`, `Tank`, `HeatPump`, `Pump`	connects components of the electrical network
Measurement connector	Measure-Connection	measurement exchange (communication signal)	`Bus`, `Tank`, `HeatPump`, `VoltageController`, `FlexHeatController`	connects sensors with controllers via a communication link
Control connector	Ctrl-Connection	control signal exchange (communication signal)	`Pump`, `HeatPump`, `VoltageController`, `FlexHeatController`	connects controllers with actuators via a communication link

6. Element descriptions

6.1 Electrical network

About	
ID in SBD	1
Level in SBD	1
Class name	`ElectricNetwork`
Parent class	-
Contained in	`MENB-SC`
Description	This element represents an electric distribution network. It contains interconnected components with the purpose of delivering electricity to the consumers.
Number of elements in SC	1
Attributes	
Functionality	The electrical network's actual functionality is determined by its components. This class serves as logical unit containing these components and has itself no functionality.
Physical characteristics	-
Instances characterization	
Interfaces	-
ID in simulation	`el_net`

About	
ID in SBD	1.1
Level in SBD	2
Class name	`ExternalElectricGrid`
Parent class	-
Contained in	`el_net`
Description	This element represents a connection to an external electrical grid supplying the local electrical distribution network.
Number of elements in SC	1
Attributes	
Functionality	The external grid controls the voltage and the phase angle of the busbar to which it is connected.
Physical characteristics	• `f` (float) - Nominal frequency [Hz] • `vn` (float) - Nominal voltage [kV]
Instances characterization	

Interfaces	• plug_ext (ElectricConnection): connection point of the electrical distribution network to the external grid		
Instance parameterization	Element ID	f [Hz]	vn [kV]
	ext_el_grid	220	0.4

About						
ID in SBD	1.2					
Level in SBD	2					
Class name	Line					
Parent class	-					
Contained in	el_net					
Description	This element represents a power line of an electrical distribution network.					
Number of elements in SC	2					
Attributes						
Functionality	The power lines transport electricity between the busbars of an electrical network.					
Physical characteristics	• l (float): line length [km] • r (float): resistance [Ω/km] • x (float): reactance [Ω/km] • c (float): capacitance [nF/km] • max_i (float): rated current [kA]					
Instances characterization						
Interfaces	• plug_line_a (ElectricConnection): connection to a bus of the electrical distribution network on one side of the power line • plug_line_b (ElectricConnection): connection to a bus of the electrical distribution network on other side of the power line					
Instance parameterization	Element ID	l [km]	r [Ω/km]	x [Ω/km]	c [nF/km]	max_i [kA]
	line_1	0.3	0.306	0.29	13.2	0.35
	line_2	0.3	0.306	0.29	13.2	0.35

About	
ID in SBD	1.3
Level in SBD	2
Class name	Busbar
Parent class	-

Contained in	el_net		
Description	This element represents an electrical busbar used in substations for local power distribution.		
Number of elements in SC	2		
Attributes			
Functionality	The electrical busbars connect the components of the electrical network (lines, loads, PV systems).		
Physical characteristics	• vn (float) - nominal voltage [kV]		
Instances characterization			
Interfaces	• plug_bus (ElectricConnection): connection point to other components (lines, loads, PV systems) of the electrical distribution network • meas_voltage_pu (MeasureConnection): voltage measurement (for the voltage controller) [p.u.]		
Instance parameterization	Element ID	vn [kV]	
	bus_1	0.4	
	bus_2	0.4	

About			
ID in SBD	1.4		
Level in SBD	2		
Class name	Load		
Parent class	-		
Contained in	el_net		
Description	This element represents a component of the electrical network that consumes (active) electric power.		
Number of elements in SC	3		
Attributes			
Functionality	Each load represents an aggregation of the (active) power consumption of several consumers (e.g., households connected to an LV feeder).		
Physical characteristics	• vn (float): nominal voltage [kV] • p (float): nominal active power consumption [kW]		
Instances characterization			
Interfaces	• plug_load (ElectricConnection): connection to a bus of the electrical distribution network through which power is consumed		
	Element ID	vn [kV]	p [kW]

Instance parameterization	load_1	0.4	0.12
	load_2	0.4	0.045

About		
ID in SBD	1.5	
Level in SBD	2	
Class name	PVSystem	
Parent class	-	
Contained in	el_net	
Description	This element represents a PV system comprising several PV panels.	
Number of elements in SC	2	
Attributes		
Functionality	The PV systems generates electrical power and supplies it to the electrical distribution network via a busbar connection. Its generation profile is independent of the network conditions.	
Physical characteristics	• P_peak (float): peak production [kW]	
Instances characterization		
Interfaces	• plug_pv (ElectricConnection): connection to a bus of the electrical distribution network through which the generated power is delivered to the electrical network	
Instance parameterization	Element ID	P_peak [kW]
	pv_1	150
	pv_2	50

About	
ID in SBD	1.6
Level in SBD	2
Class name	VoltageController
Parent class	-
Contained in	el_net
Description	This element represents a voltage controller in the electrical distribution network.
Number of elements in SC	2
Attributes	

<table>
<tr><td>Functionality</td><td colspan="3">This controller monitors the voltage at bus_1 and proposes a power consumption setpoint for the heat pump (controllable/flexible load) to keep the voltage within acceptable limits.</td></tr>
<tr><td>Physical characteristics</td><td colspan="3">• delta_vm_up (float): upper threshold for turning off the heat pump [p.u.]
• delta_vm_low_hp_on (float): lower threshold for turning on the heat pump [p.u.]
• delta_vm_low_hp_off (float): lower threshold for turning off the heat pump [p.u.]
• delta_vm_deadband (float): deadband size [p.u.]
• hp_p_el_mw_min (float): minimum operating point (minimal allowed power consumption) of heat pump [MWe]
• k_p (float): the controller's proportional term [-]</td></tr>
<tr><td colspan="4">Instances characterization</td></tr>
<tr><td>Interfaces</td><td colspan="3">• meas_voltage_pu (MeasureConnection): voltage measurement at bus_1 [p.u.]
• setpoint_hp_p_el (CtrlConnection): proposed heat pump setpoint for electrical consumption [MW$_{el}$]</td></tr>
<tr><td rowspan="5">Instance parameterization</td><td>Element ID</td><td>delta_vm_up [p.u.]</td><td>delta_vm_low_hp_on [p.u.]</td></tr>
<tr><td rowspan="4">voltage_ctrl</td><td>0.1</td><td>– 0.1</td></tr>
<tr><td>k_p [-]</td><td>delta_vm_low_hp_off [p.u.]</td></tr>
<tr><td>0.15</td><td>– 0.08</td></tr>
<tr><td>hp_p_el_mw_min [kW$_{el}$]</td><td>delta_vm_deadband [p.u.]</td></tr>
<tr><td></td><td>35</td><td>0.03</td></tr>
</table>

6.2 Thermal network

About	
ID in SBD	2
Level in SBD	1
Class name	ThermalNetwork
Parent class	-
Contained in	MENB-SC
Description	This element represents the thermal network that delivers a mass flow of hot water to satisfy the heat demand of the connected consumers.
Number of elements in SC	1

Attributes	
Functionality	The thermal network's actual functionality is mostly determined by its components. This class serves as logical unit containing these components and has itself no functionality.
Physical characteristics	-
Instances characterization	
Interfaces	-
ID in simulation	`th_net`

About	
ID in SBD	2.1
Level in SBD	2
Class name	`ExternalThermalGrid`
Parent class	-
Contained in	`th_net`
Description	This element represents a connection to an external higher-level thermal network supplying the local thermal network.
Number of elements in SC	1
Attributes	
Functionality	The external thermal network acts as a pressure source with a prescribed supply temperature. It is considered an ideal heating unit without any constraints regarding mass flow or ramp rates.
Physical characteristics	• `p_ext` (float): pressure of the external thermal network [bar] • `T_supply_ext` (float): nominal supply temperature [°C]
Instances characterization	
Interfaces	• `flange_supply` (HeatConnection Junction): supply line connection to external thermal grid • `flange_return` (HeatConnection Junction): return line connection to external thermal grid

Instance parameterization	Element ID	`p_ext` [bar]	`T_supply_ext` [°C]
	`ext_th_grid`	6	75

About	
ID in SBD	2.2
Level in SBD	2
Class name	`Pipe`

Parent class	-
Contained in	`th_net`
Description	This element represents a straight pipe with constant cross section used to transport water within the thermal network.
Number of elements in SC	14 (7x supply, 7x return)
Attributes	
Functionality	Determines the transport effects (pressure drop, flow delays, etc.) for a mass flow based on hydraulic principles. Depending on the insulation of the pipe and the surrounding temperature, the temperature of the water transported through the pipe changes.
Physical characteristics	• `l` (float): pipe length [km] • `d` (float): pipe diameter [m] • `alpha` (float): heat transfer coefficient [$Wm^{-2}K^{-1}$] • `k` (float): roughness of pipe material [mm]
Instances characterization	
Interfaces	• `flange_a` (HeatConnection): connection to another component of the thermal network on one side of the pipe • `flange_b` (HeatConnection): connection to another component of the thermal network on other side of the pipe

Instance parameterization

Element ID	`l` [km]	`d` [m]	`alpha` [$Wm^{-2}K^{-1}$]	`k` [mm]
`pipe_1_supply` / `pipe_1_return`	0.5	0.1	1.5	0.0
`pipe_tank_supply` / `pipe_tank_return`	0.01	0.1	1.5	0.01
`pipe_2_supply` / `pipe_2_return`	0.5	0.1	1.5	0.01
`pipe_3_supply` / `pipe_3_return`	0.01	0.1	1.5	0.01
`pipe_4_supply` / `pipe_4_return`	0.5	0.1	1.5	0.01
`pipe_5_supply` / `pipe_5_return`	0.01	0.1	1.5	0.01
`pipe_6_supply` / `pipe_6_return`	0.01	0.1	1.5	0.01

About	
ID in SBD	2.3
Level in SBD	2

Class name	`Junction`
Parent class	-
Contained in	`th_net`
Description	This element represents a tee junction for connecting three pipes.
Number of elements in SC	6
Attributes	
Functionality	Used either for splitting the mass flow from a single pipe into separate mass flows of two pipes of or joining mass flows from two separate pipes into a single mass flow for one pipe. Splitting/joining follows basic hydraulic rules (e.g., mass conservation).
Physical characteristics	-
Instances characterization	
Interfaces	• `flange_1` (HeatConnection): connection to pipe 1 • `flange_2` (HeatConnection): connection to pipe 2 • `flange_3` (HeatConnection): connection to pipe 3
ID in simulation	• `junction_<1-2>_supply` (branch-off from supply line to consumers) • `junction_<1-2>_return` (branch-off from return line to consumers) • `junction_tank_supply` (branch-off from supply line to tank) • `junction_tank_return` (branch-off from return line to tank)

About	
ID in SBD	2.4
Level in SBD	2
Class name	`HeatExchanger`
Parent class	-
Contained in	`th_net`
Description	This element represents a heat exchanger acting as an aggregated heat consumer in the thermal network.
Number of elements in SC	2
Attributes	
Functionality	The heat exchanger is fed with hot water from the thermal network's supply line. The mass flow through the heat exchanger is adjusted to reach a pre-defined return temperature, depending on the current heat demand from the aggregated consumer.
Physical characteristics	• `T_return_target` (float): set-point for return temperature [°C]

Instances characterization		
Interfaces	• `flange_supply` (HeatConnection): inlet of heat exchanger from supply line • `flange_return` (HeatConnection): outlet of heat exchanger to return line	
Instance parameterization	Element ID	`T_return_target` [°C]
	`hex_1`	40
	`hex_2`	40

About	
ID in SBD	2.5
Level in SBD	2
Class name	`Bypass`
Parent class	-
Contained in	`th_net`
Description	This element represents the bypass of the thermal network.
Number of elements in SC	1
Attributes	
Functionality	Ideal valve that allows to regulate the water mass flow from the supply line to the return line independently of the consumers.
Physical characteristics	-
Instances characterization	
Interfaces	• `flange_supply` (HeatConnection): inlet of bypass from supply line • `flange_return` (HeatConnection): outlet of bypass to return line
ID in simulation	`bypass`

6.3 Power-to-heat facility

About	
ID in SBD	3
Level in SBD	1
Class name	`PowerToHeatFacility`
Parent class	-
Contained in	`MENB-SC`

Description	This element represents a power-to-heat facility comprising a heat pump connected to a thermal tank, which feeds into the thermal network's supply line to support its operation. By consuming local excess PV generation, the power-to-heat facility can be used at the same time to improve the stability of the electrical network and support the supply of the thermal network. Its components are actuated by the flex heat controller.
Number of elements in SC	1
Attributes	
Functionality	The power-to-heat facility's actual functionality is determined by its components. This class serves as logical unit containing these components and has itself no functionality.
Physical characteristics	-
Instances characterization	
Interfaces	-
ID in simulation	`p2h`

About	
ID in SBD	3.1
Level in SBD	2
Class name	`HeatPump`
Parent class	-
Contained in	`p2h`
Description	This element represents a heat pump with constant condenser output temperature.
Number of elements in SC	1
Attributes	
Functionality	The source for the evaporator is the thermal network's return line. The condenser's output is fed to the thermal storage tank.
Physical characteristics	• `P_rated_max` (float): electrical power rating of compressor [kW_{el}] • `P_rated_min` (float): minimal electrical power consumption for operating the compressor [kW_{el}] • `P_0` (float): electrical stand-by power consumption [kW_{el}] • `T_evap_min` (float): minimal evaporator outlet temperature [°C] • `T_cond_max` (float): maximum condenser outlet temperature [°C]

<table>
<tr><td></td><td colspan="4">

T_cond_target (float): condenser outlet temperature setpoint [°C]
eta_sys (float): ratio between work provided by the pump and available thermodynamic work [-]
eta_comp (float): compressor efficiency [-]
lambda_comp (float): compressor time constant [s^{-1}]

</td></tr>
<tr><td colspan="5">Instances characterization</td></tr>
<tr><td>Interfaces</td><td colspan="4">

plug_load (ElectricConnection): connection to a bus of the electrical distribution network through which power is consumed
flange_evap_in (HeatConnection): inlet of heat pump evaporator from return line
flange_evap_out (HeatConnection): outlet of heat pump evaporator to return line
flange_cond_in (HeatConnection): inlet of heat pump condenser from tank
flange_cond_out (HeatConnection): outlet of heat pump condenser to tank
meas_p_el (MeasureConnection): measurement of electrical power consumption (for flex heat controller) [kW_{el}]

</td></tr>
<tr><td rowspan="6">Instance parameterization</td><td>Element ID</td><td>P_rated [kW_{el}]</td><td colspan="2">P_0 [kW_{el}]</td></tr>
<tr><td rowspan="5">hp</td><td>100</td><td colspan="2">0.3</td></tr>
<tr><td>T_evap_min [°C]</td><td>T_cond_max [°C]</td><td>T_cond_target [°C]</td></tr>
<tr><td>20</td><td>85</td><td>75</td></tr>
<tr><td>eta_sys [-]</td><td>eta_comp [-]</td><td>lambda_comp [s^{-1}]</td></tr>
<tr><td>0.5</td><td>0.7</td><td>0.2</td></tr>
</table>

About	
ID in SBD	3.2
Level in SBD	2
Class name	Tank
Parent class	-
Contained in	p2h
Description	This element represents a stratified hot water storage tank.
Number of elements in SC	1
Attributes	
Functionality	The tank has two hydraulic loops (also see pumps below):

	• cold water is drawn from the bottom of the tank, heated up by the heat pump and fed back at the top of the tank • hot water is drawn from the top of the tank and fed to the heating network's supply line; simultaneously an equal amount of cold water is drawn from the heating network's return line to refill the tank
Physical characteristics	• V (float): tank volume [m^3] • h (float): height of tank (without insulation) [m] • d (float): thickness of insulation [m] • k (float): specific heat conductivity of insulation [$Wm^{-1}K^{-1}$] • N (int): number of volume segments [-]
Instances characterization	
Interfaces	• flange_tank_supply (HeatConnection): hot water outlet of tank to supply line • flange_tank_return (HeatConnection): cold water inlet from return line to tank • flange_hp_out (HeatConnection): cold water outlet from tank to heat pump condenser • flange_hp_in (HeatConnection): hot water inlet from heat pump condenser to tank • meas_temp (MeasureConnection): tank temperature measurement (for flex heat controller) [°C]

Instance parameterization	Element ID	V [m^3]	h [m]	d [m]	k [$Wm^{-1}K^{-1}$]	N [-]
	tank	100	9.2	0.1	0.03	10

About	
ID in SBD	3.3
Level in SBD	2
Class name	Pump
Parent class	-
Contained in	p2h
Description	This element represents a water pump with prescribed mass flow rate.
Number of elements in SC	2
Attributes	
Functionality	Ideal water pump that generates a mass flow according to the setpoint. Moves the water in the following loops of the power-to-heat facility: • condenser loop: pump hot water from the heat pump condenser to the tank

	• network support loop: pump hot water from the tank to the supply line
Physical characteristics	-
Instances characterization	
Interfaces	• `flange_in` (HeatConnection): pump inlet • `flange_out` (HeatConnection): pump outlet • `setpoint_mflow` (CtrlConnection): set-point for pump mass flow (from flex heat controller)
ID in simulation	• `pump_cond` (pump for tank charging loop) • `pump_tank` (pump for tank discharging loop)

About	
ID in SBD	3.4
Level in SBD	2
Class name	`FlexHeatController`
Parent class	-
Contained in	`p2h`
Description	This element represents a dedicated controller for operating the power-to-heat facility.
Number of elements in SC	1
Attributes	
Functionality	The flex heat controller decides whether the heat supply is covered entirely through the external grid or whether the power-to-heat facility supports by discharging the tank. If required, the heat pump is used to charge the tank, taking into account the power consumption threshold from the voltage controller (i.e., the power consumption never exceeds the setpoint, but may be less).
Physical characteristics	• `T_tank_max` (float): maximum tank temperature [°C] • `T_tank_min` (float): minimum tank temperature [°C] • `mdot_tank_out_setpoint` (float): setpoint for tank discharge mass flow rate [kg/s]
Instances characterization	
Interfaces	• `meas_tank_temp` (MeasureConnection): measurement of tank temperature [°C] • `meas_hp_p_el` (MeasureConnection): measurement of electrical power consumption of heat pump [kW_{el}] • `setpoint_hp_p_el`: (CtrlConnection): setpoint for power consumption of heat pump from voltage controller [MW_{el}]

	• setpoint_tank_mflow (CtrlConnection): setpoint for tank discharge mass flow [kg/s] • setpoint_cond_mflow (CtrlConnection): setpoint for heat pump condenser mass flow [kg/s]		
Instance parameterization	Element ID	T_tank_max [°C]	T_tank_min [°C]
	flex_heat_ctrl	72	65

7. Element connections

From		To	
Element ID	Interface ID	Element ID	Interface ID
ext_el_grid	plug_ext	line_1	plug_line_a
bus_1	plug_bus	line_1	plug_line_b
bus_1	plug_bus	line_2	plug_line_a
bus_1	plug_bus	load_1	plug_load
bus_1	plug_bus	hp	plug_load
bus_1	plug_bus	pv_1	plug_pv
bus_2	plug_bus	line_2	plug_line_b
bus_2	plug_bus	load_2	plug_load
bus_2	plug_bus	pv_2	plug_pv
ext_th_grid	flange_supply	pipe_1_supply	flange_a
ext_th_grid	flange_return	pipe_1_return	flange_b
junction_tank_supply	flange_1	pipe_1_supply	flange_b
junction_tank_supply	flange_2	pipe_tank_supply	flange_b
junction_tank_supply	flange_3	pipe_2_supply	flange_a
junction_tank_return	flange_1	pipe_2_return	flange_b
junction_tank_return	flange_2	pipe_tank_return	flange_a
junction_tank_return	flange_3	hp	flange_evap_in
junction_1_supply	flange_1	pipe_2_supply	flange_b
junction_1_supply	flange_2	pipe_3_supply	flange_a
junction_1_supply	flange_3	pipe_4_supply	flange_a

junction_1_return	flange_1	pipe_4_return	flange_b
junction_1_return	flange_2	pipe_3_return	flange_b
junction_1_return	flange_3	pipe_2_return	flange_a
junction_2_supply	flange_1	pipe_4_supply	flange_b
junction_2_supply	flange_2	pipe_5_supply	flange_a
junction_2_supply	flange_3	pipe_6_supply	flange_a
junction_2_return	flange_1	pipe_6_return	flange_b
junction_2_return	flange_2	pipe_5_return	flange_b
junction_2_return	flange_3	pipe_4_return	flange_a
hex_1	flange_supply	pipe_3_supply	flange_b
hex_1	flange_return	pipe_3_return	flange_a
hex_2	flange_supply	pipe_5_supply	flange_b
hex_2	flange_return	pipe_5_return	flange_a
hp	flange_evap_out	pipe_1_return	flange_a
hp	flange_cond_in	pump_cond	flange_out
hp	flange_cond_out	tank	flange_hp_in
hp	meas_p_el	flex_heat_ctrl	meas_hp_p_el
tank	meas_temp	flex_heat_ctrl	meas_tank_temp
tank	flange_hp_out	pump_cond	flange_in
tank	flange_tank_return	pipe_tank_return	flange_b
tank	flange_tank_supply	pump_tank	flange_in
pump_tank	flange_out	pipe_tank_supply	flange_a
bypass	flange_supply	pipe_6_supply	flange_b
bypass	flange_return	pipe_6_return	flange_a
voltage_ctrl	meas_voltage_pu	bus_1	meas_voltage_pu
voltage_ctrl	setpoint_hp_p_el	flex_heat_ctrl	setpoint_hp_p_el
flex_heat_ctrl	setpoint_tank_mflow	pump_tank	setpoint_mflow
flex_heat_ctrl	setpoint_cond_mflow	pump_cond	setpoint_mflow