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Hybrid System simulator description

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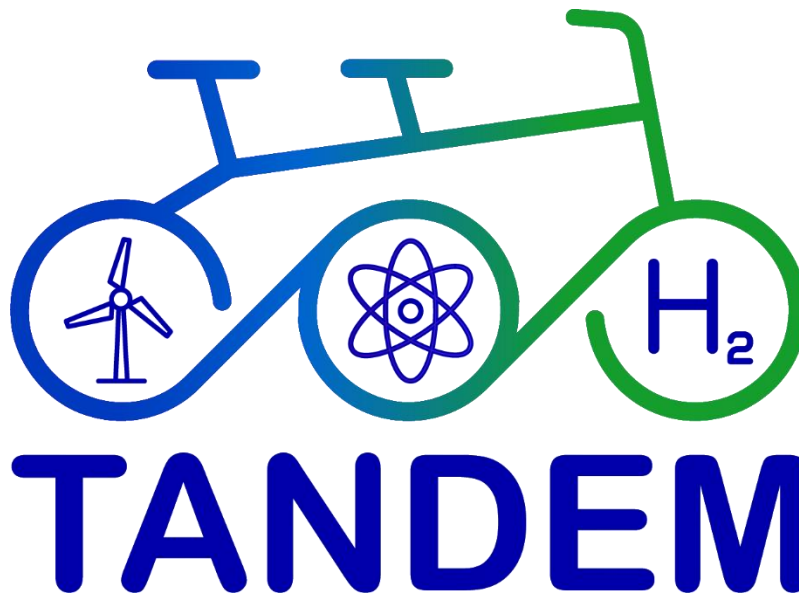
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Summary

Description of the implementation of a first version of the hybrid system simulator to represent the energy study cases selected

Approval

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D2.5 – Hybrid System Simulator Description

WP2 - Task 2.3

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History

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Abbreviations and Acronyms

Acronym	Description
BOP	Balance Of Plant
CCGT	Combined Cycle Gas Turbine
CEA	Alternatives Energies and Atomic Energy Commission
CR	Czech Republic
CHP	Combined Heat and Power plant
DH	District Heating
EDF	Électricité de France
E-SMR	European Small Modular Reactor
HES	Hybrid Energy System
HTSE	High Temperature Steam Electrolyzer
LTE	Low Temperature Electrolyzer
LTI	Linear-Time-Invariant
NPP	Nuclear Power Plant
NSSS	Nuclear Steam Supply System
RO	Reverse Osmosis



Acronym	Description
SG	Steam Generator
SMR	Small Modular Reactor
SOC	State Of Charge
SOEC	Solid Oxide Electrolyzer Cell
TES	Thermal Energy Storage
WP	Work Package
WPP	Wind Power Plant



Executive Summary

This deliverable, Deliverable 2.5 (D2.5) presents the results of Task 2.3, concerning the implementation of the first version of hybrid system simulators, based on the three case studies described in Deliverable 1.4, as well as additional information presented in Deliverable 3.2. These case studies explore the possibility of integrating nuclear energy, implemented via Small Modular Reactors (SMRs), with various electrical and thermal consumers, such as district heating networks or hydrogen production plants.

The simulators are developed by CIRTEN-Politecnico di Milano using the open-source TANDEM library, built in the object-oriented modelling language Modelica, within the framework of Work Package 2 of the project. In line with the project scope, two distinct simulators have been created and tested by CIRTEN-Politecnico di Milano and Empresarios Agrupados.

The District Heating Simulator is based on the configuration of the Northern European case study located in Southern Finland. This simulator allows for the study of the thermal behaviour of district heating networks powered by various energy sources, including two Small Modular Reactors (SMRs) or thermal energy storage (TES) systems. This simulator has been implemented for future coupling to the Backbone optimisation tool, alongside a series of assumptions outlined in this deliverable.

The Energy Hub Simulator is based on the configuration of the Southern European case study located in Fos-sur-Mer. This simulator enables the analysis of the combined behaviour of multiple energy sources, with the goal of producing hydrogen via a high-temperature electrolyser. Two distinct configurations of this simulator have been developed: one featuring an intermediate oil loop and the other incorporating a TES system, allowing for a comparison of which setup is more favourable for implementation. As with the previous simulator, this model has been designed with future integration into the PERSEE optimisation tool in mind, based on a set of assumptions also detailed in this deliverable.

The main results of Task 2.3, as presented in Deliverable 2.5, include the capabilities of the various simulators, their limitations, risk detection capabilities, and the results of the test cases generated to verify the correct functioning of the systems. These test cases are available in the Git repository of the project.

Additionally, this document provides recommendations for potential future improvements to the simulators and their components.

Keywords

Hybrid Energy System, Dynamic model, Simulator, Modelica, Energy Hub, District Heating, SMR, Hydrogen, High Temperature Steam Electrolyzer



1 Introduction and Objective

The EU TANDEM (Small Modular Reactor for a European Safe and Decarbonized Energy Mix) Project presents a conceptual design for a clean energy system that integrates heat and electrical energy production. This system has two primary objectives: supplying electricity and heat to district heating networks and generating hydrogen through electrolysis. The TANDEM Project leverages a combination of power generation plants to achieve hybrid energy production, with a primary focus on utilizing nuclear energy through Small Modular Reactors. Additionally, the project explores various scenarios to evaluate the integration of different energy production plants and to assess the overall feasibility of the system.

In this framework, the aim of this deliverable is to describe the dynamic model of the various configurations of the Hybrid Energy System (HES) simulators, one for a district heating use and one for the energy hub use with a focus on hydrogen production. It includes a discussion of its capabilities and limitations, as well as an explanation of the control philosophy implemented in the systems. These models will allow studying some aspects of the energy systems like:

- Possibility to keep the reactor at constant load varying the electrical power generation and heat cogeneration.
- Heat generation following the hydrogen demand.
- Transient evolution of the fluid temperature in District heating networks for different year seasons.
- State of charge of thermal energy storage systems and hydrogen storage, enabling the analysis of various charging and discharging scenarios.

For the model definition, the requirements and limitations of the individuals models have been taken into account. This information has been defined as per the deliverable D2.1 “Modelica models requirements for the ‘TANDEM’ library development” ([12]) as well as per the deliverable D2.3 “Modelica models description for the ‘TANDEM’ library” ([13]).

The model of the simulator has been built up in the simulation and modelling platform of Dymola® using some specific libraries for the simulation of thermal and power plants as ThermoPower, HTSE, Buildings, WindPowerPlants or ThermoSysPro. The model scope includes the following systems of the different plants:

- Nuclear Power Plant (NPP): Small Modular Reactor (SMR) and balance of plant (BOP)
- High Temperature Steam Electrolyzer (HTSE): Solid Oxide Electrolysis Cell (SOEC) stack and its BOP
- Energy storages: tanks for Thermal Energy Storages (TES)

- Renewable sources: Wind Power Plants (WPP) and photovoltaic plants (PV)
- District Heating (DH): fluid network, fluid storages and heat exchangers
- Other power sources as Combined Heat and Power plant (CHP) and Heat pumps

The objective of this deliverable is focused on showing a general overview of the dynamic simulation models including:

- Scope and topology of the models implemented in the HES simulators
- Boundary conditions for each simulator
- Control philosophy implemented in each simulator
- Assumptions and limitations of the simulators
- Test cases demonstrating the capabilities of the simulators

The most relevant simulation results generated by these models are included in this report.

2 Study cases description

The TANDEM project examines three different study cases, each representing a distinct scenario in various regions of the European Union. These cases include two configurations of hybrid energy systems designed for power supply and heat generation for district heating networks in Northern and Central Europe, and another hybrid energy system configuration corresponding to an energy hub including hydrogen generation in Southern Europe.

For this deliverable, only two different study cases will be created to ensure the feasibility of the system modeling, representing the Northern and Southern European cases, while the Central European case is omitted due to its similarities with the Northern case.

2.1 Northern European case

The objective of the TANDEM Northern European case is to supply electrical power and heat to the district heating network already established in Finland, connecting Helsinki, Espoo and Vantaa. Specifically, the entire heat network is divided into different sublines:

- NPP – Helsinki West transmission line
- Helsinki West heat network
- Helsinki East – Helsinki West transmission line
- Helsinki East heat network

To achieve this, various power sources are either planned or are already implemented in the system, as shown in the Figure 1.

More specifically, this region requires sufficient heat to supply two existing district heating networks: one interconnecting the cities of Orlová and Bohumín, and another linking the cities of Karviná and Havířov. These two district heating networks are further interconnected, forming a macro DH network.

For this case, the flow of heat and electricity comes from various energy sources:

- For the region of Orlová and Bohumín, the main source of heat is an SMR that would be installed in the city of Dětmorovice, with the potential use of heat pumps and boilers as additional sources. For electricity, energy generated by photovoltaic and wind power plants will be used, as well as electricity from batteries and the national grid.
- For the region of Karviná and Havířov, the main sources of heat of the DH network are two CHP plants, the CHP Karviná Heating Plant and the CHP ČSA Heating Plant, supported by heat pumps and boilers. The same sources as in the previous region will be used for the electricity.

This configuration is represented in the scheme shown in the Figure 2.

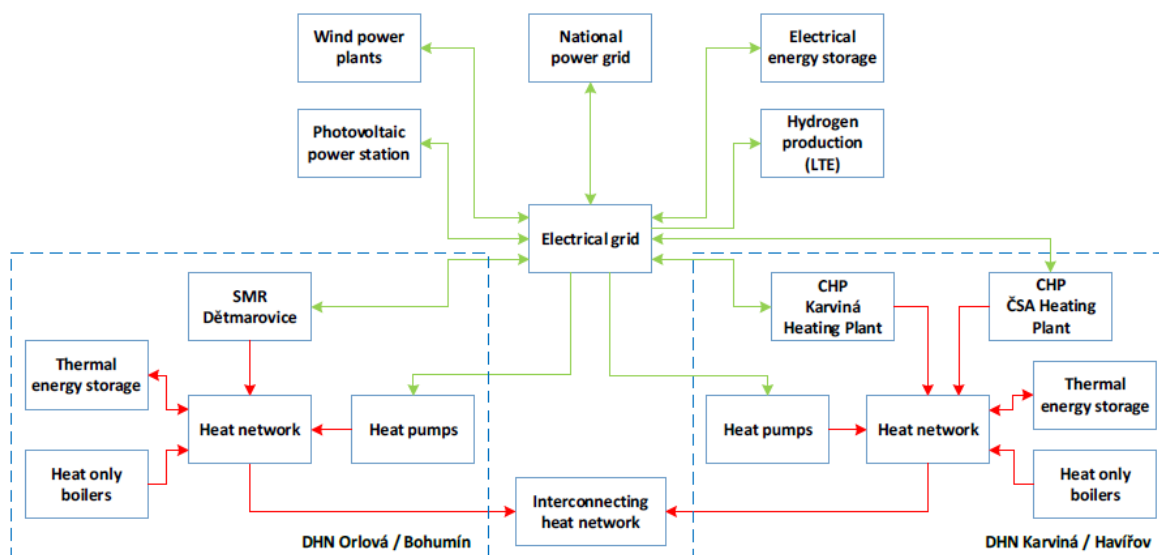


Figure 2: Scheme of the District Heating system configuration for the Central European case ([15]) - energy scenario corresponding to the start of SMR deployment in 2035

It is important to mention that this case has not been used for the development of the district heating simulator. However, it is included as a proposal for potential future implementation (for more information, see the section on Future improvements and enhancements).

2.3 Southern European case

The last study case refers to the Energy Hub configuration. The goal of this case is to study the feasibility of an energy hub with production units focused on hydrogen production. This case is located at For-sur-Mer, in the South of France. It is a virtual case that does not include real data.

This case shows a energy scenario corresponding to the start of SMR deployment in 2035, where any additional thermal or electrical energy produced could be used for other external applications like reverse osmosis or low-temperature electrolyzers. Some of the different possibilities can be seen in Figure 3. However, these cases are not considered in this deliverable, which focuses on PV, Wind Energy, CCGT and SMR as production units, and the HTSE as the main consumer.

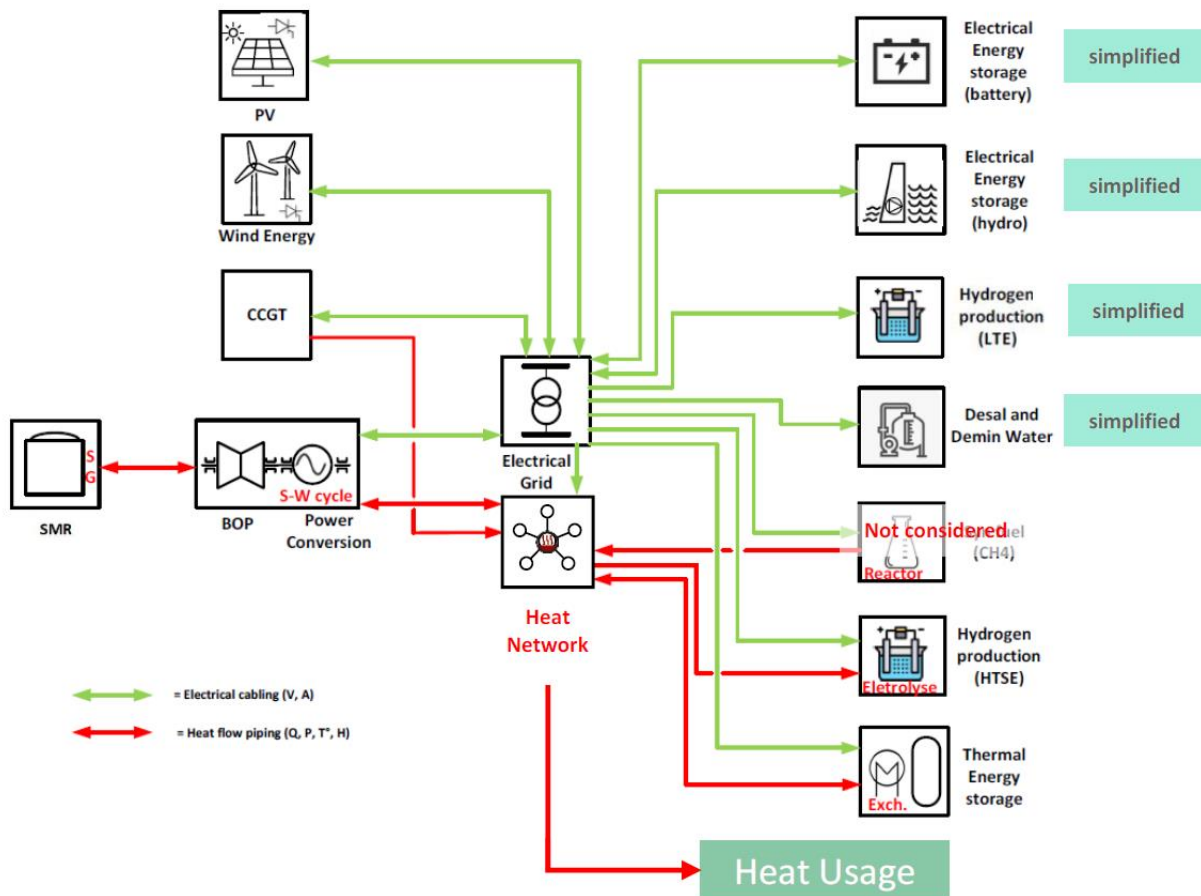


Figure 3: Configuration of the Hybrid Energy System for the Southern European case ([14]) - energy scenario corresponding to the start of SMR deployment in 2035

Instead, for this deliverable, a 2050 scenario (based on the mentioned 2035 case and the TANDEM/deliverable 3.2 'run7' case) is studied, where thermal power production relies on the

SMR, and electrical power production is based on the SMR, CCGT, and renewable sources. The main consumer is a HTSE producing H₂ and storing them in a Hydrogen system storage. The simplified scheme of this system can be seen in the Figure 4.

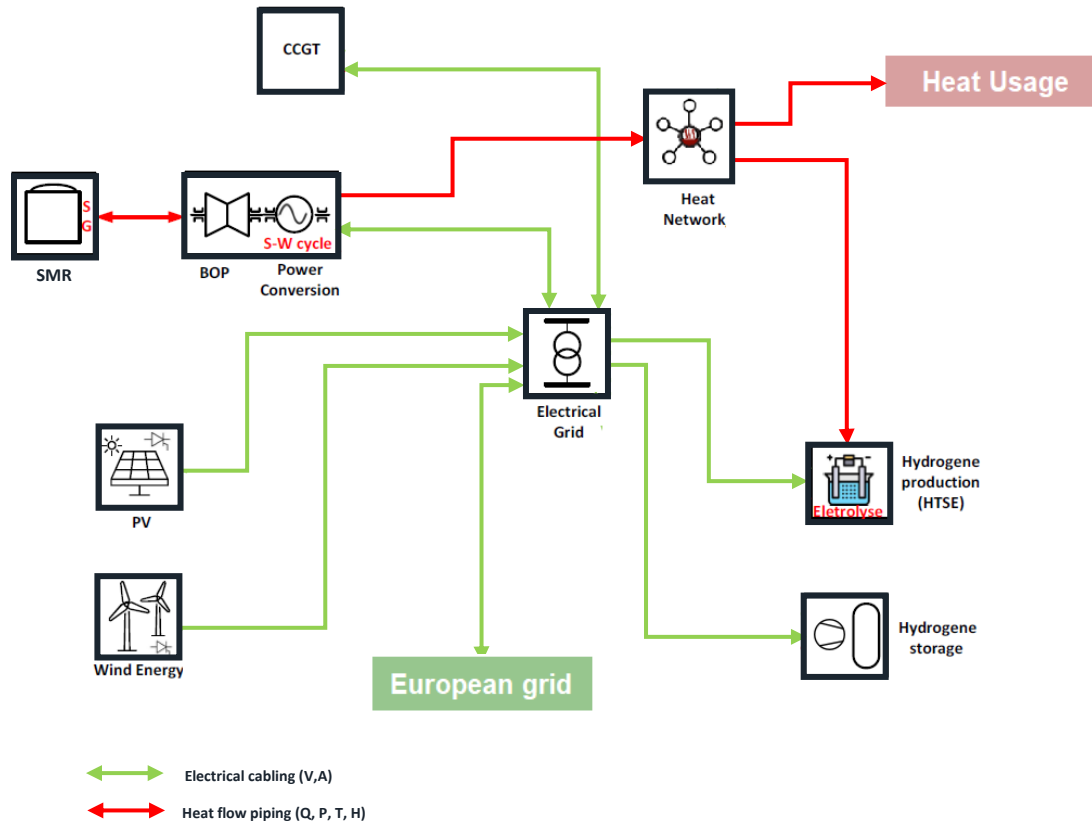


Figure 4. Simplified Southern Europe case scheme.

This configuration has been used as the basis for developing the Energy Hub simulator.

3 Overview of the dynamic simulation tool

The different models of the coupled TANDEM Hybrid Energy System have been developed using several existing libraries and developing other additional components for this purpose. These models have been created using the simulation and modelling platform Dymola®.

3.1 Dymola® Overview

Dymola® (Dynamic Modeling Laboratory) is a multidisciplinary modeling and simulation tool developed by Dassault Systèmes. It is widely used in various fields of engineering and research to model several systems such as mechanics, electronics, aeronautics, automotive, etc.

Dymola® allows the integration of different types of physical systems into a model, which is very important for applications where several components interact with each other.

This environment is based on the open Modelica modeling language, which permits the use of the models in other Modelica language based software. Additionally, several existing Modelica libraries can be used and implemented in Dymola in order to enhance the complexity or capability of the models.

A Dymola® model consists of a series of components associated with a set of equations representing their physical behaviour. The components are connected through the ports, which define a set of physical variables to be interchanged in the connections, i.e. pressure, temperature, enthalpy, flowrate, etc.

3.2 TANDEM library

The TANDEM library contains all the components that have been developed to assemble the simulator with the different configurations of the mentioned cases. This library has been created using components available in other Modelica libraries or components specifically created for the project. The libraries used are:

- ThermoPower: A library with components enabling dynamic studies of thermal power plants and energy conversion systems. This library was developed by the Politecnico di Milano (PoliMi).
- ThermoSysPro: A library containing components used for thermo-hydraulic systems and for instrumentation and control systems. This library was developed by Électricité de France (EDF).
- HTSE: A library that contains the open-source High Temperature Steam Electrolyser model used in the simulator. This library was developed by the Alternatives Energies and Atomic Energy Commission (CEA) using some components from the CEA_Energy_Process_Library, also developed by the CEA.



- **Modelica Buildings:** A library that allows for dynamic calculations related to the energy of buildings and districts, as well as their control systems. It is an open-source library generated by the Lawrence Berkeley National Laboratory.
- **Wind Power Plants:** A library used for the simulation of wind power plants. It is an open-source library developed during a Diploma project at the Technical Engineering College, TGM.

Moreover, some of the models available in the TANDEM library were applied for different preliminary analyses, such as the integration of the nuclear reactor with a district heating network in the Finnish context [17] and its coupling with a two-tank thermal energy storage system operated to perform electrical peaking, thereby increasing the electricity production flexibility [18].

To obtain more detailed information about the components included in the TANDEM library, refer to the Git repository [7] and to deliverable D2.3 [13].

4 Models description

The following is a description of the hybrid system simulators developed by CIRTEN-Politecnico di Milano, taking into account the different scenarios mentioned above: the energy hub and the district heating cases.

For these cases, the assumptions made in setting up the simulator will be detailed, along with the defined model boundaries and the control philosophy selected for the system. Finally, the computational capabilities of each system will be outlined.

It is important to note that the design and implementation of the simulators consider the trade-off between the convergence speed of the simulations and the accuracy or depth of the results obtained. Additionally, this design process has been guided by the goal of coupling the simulators with optimization tools: Backbone for the District Heating case and PERSEE for the Energy Hub.

4.1 Energy Hub Simulator

As a first approach to the Hybrid Energy System simulator of the Energy Hub configuration, it is necessary to establish some assumptions that will determine the operability of the system and its capabilities.

For this system, the configuration sized in the case study 'run7' (result of optimization studies PERSEE) from TANDEM/deliverable 3.2 [16] has been used as the basis, along with the schematic configuration from deliverable 1.4 [14]. In this case, a series of assumptions are made, which will be mentioned in the following sections.

4.1.1 Schematics

The simplified scheme of the district heating simulator is depicted in Figure 5. Three different loops can be distinguished in the scheme:

- Electrical flow between components is represented by a green line.
- Thermal flow between components is represented by a red line.
- Hydrogen flow between components is represented by a blue line.

For the simulator configuration, a distinction can be made between the electrical grid and the thermal grid. Considering the scope of this deliverable, the thermal grid is limited to the intermediate thermal loop between the SMR and the HTSE. On the other hand, the electrical grid is modeled in a simplified manner, assuming that both consumers and producers feed all the electrical energy into the grid. The schematic used is shown in Figure 5.

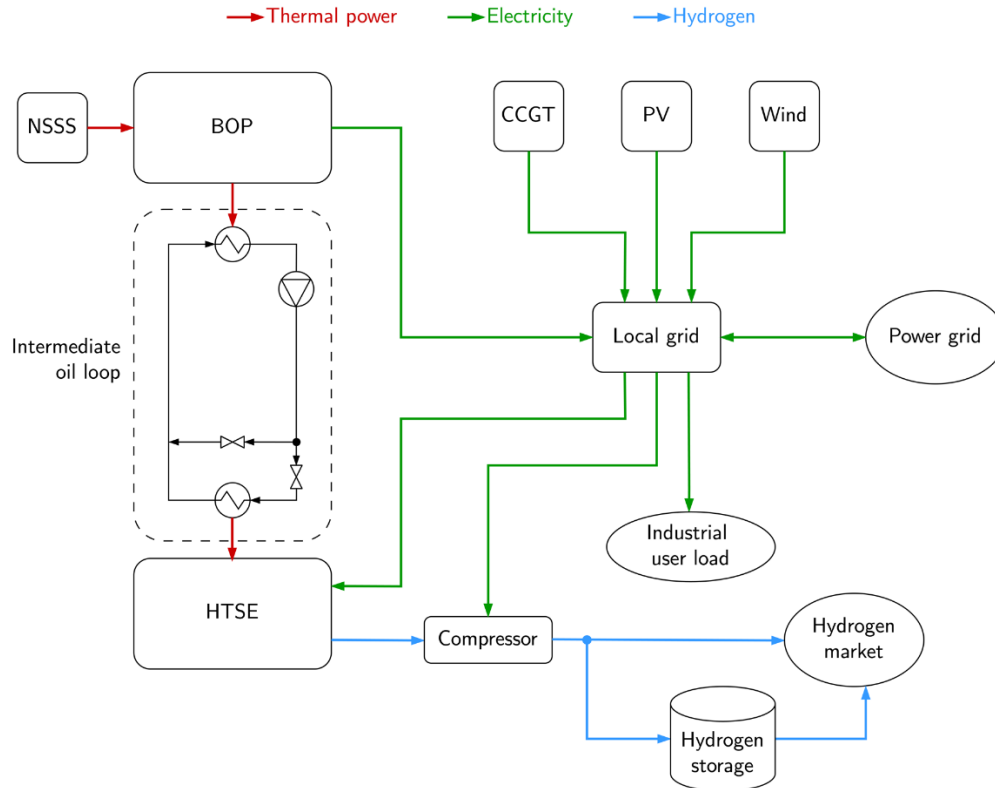


Figure 5. Energy Hub configuration scheme

Figure 5 illustrates the thermal connection between the SMR BOP and the HTSE. An intermediate oil loop has been implemented to account for fluid inertia between the two components, incorporating pressure loss calculations.

Additionally, to explore different possibilities related to the intermediate oil loop between the reactor and the electrolyzer, an alternative configuration has been created that includes a thermal storage system based on a two-tank configuration. This system decouples the operation of the reactor from the electrolyzer, providing greater flexibility for the entire system.

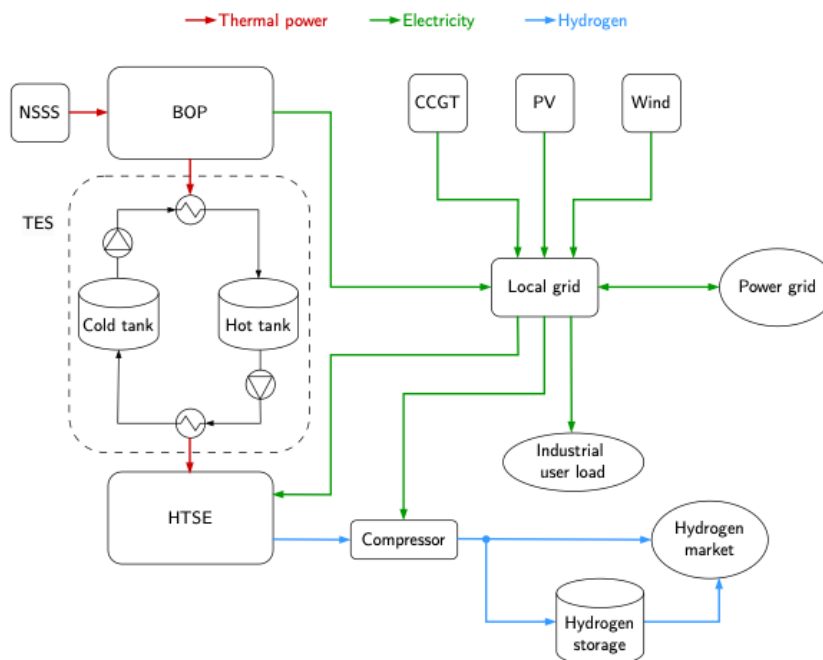


Figure 6. Energy Hub alternative configuration scheme

Both diagrams were utilized to develop the simulator schematic in Dymola, resulting in two distinct configurations, as illustrated in Figure 7 and Figure 8. These figures indicate the connectors available for adjusting the system's boundary conditions, as well as those necessary for obtaining the specified model results, which are essential for integration with the PERSEE optimization tool.

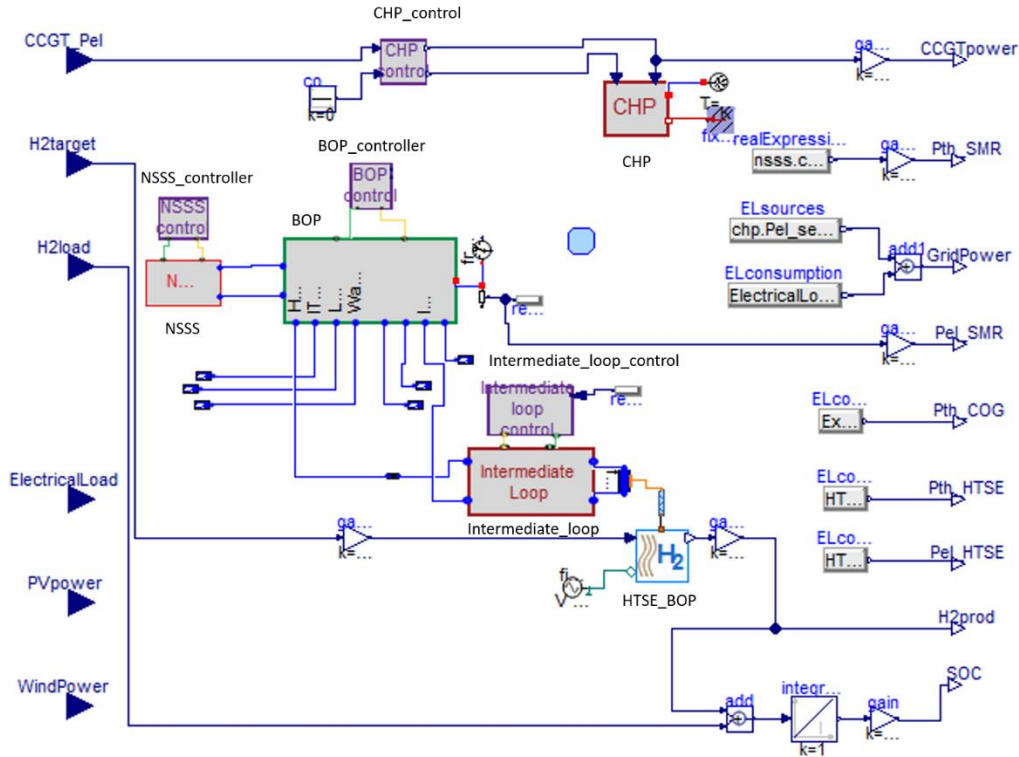


Figure 7. Schematic of the Energy Hub simulation model

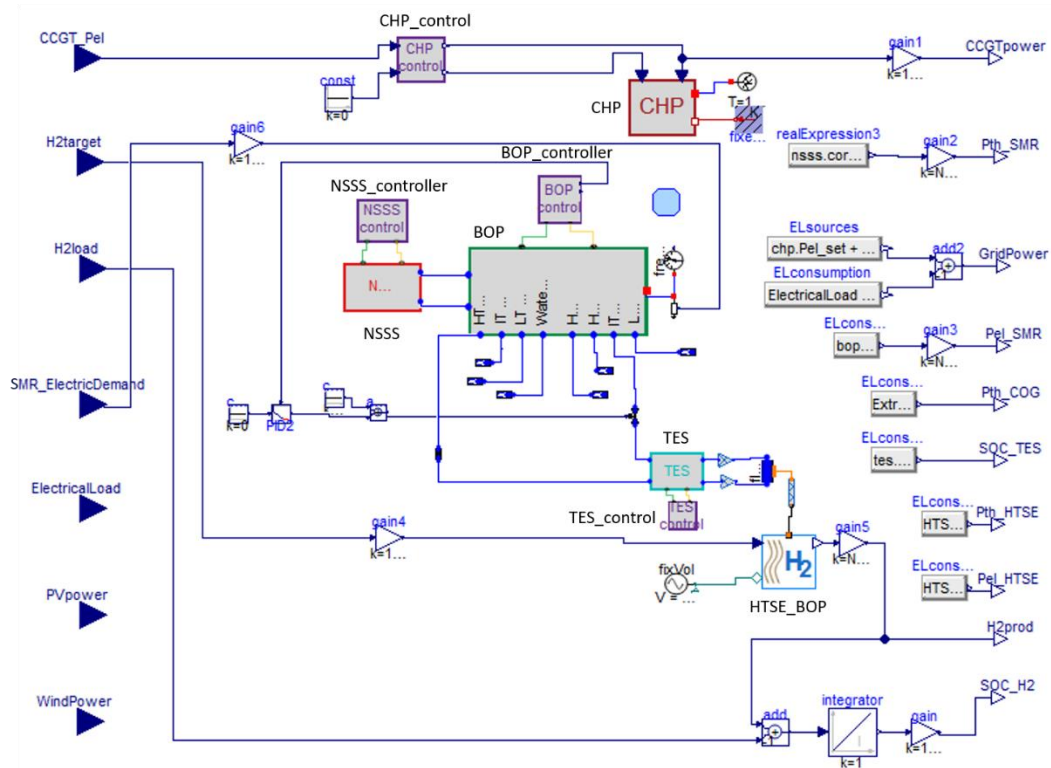


Figure 8. Schematic of the alternative Energy Hub simulation model

The following table lists the code names of the main components of the Energy Hub simulator. For more information on each component, please refer to the Git repository of the TANDEM library and to TANDEM/deliverable 2.3 [13].

Component Name	Component Type	Description
TES	TANDEM.EnergyStorage.ThermalStorage.SensibleLoop_HX1D_WaterOil_fluid_trans	Thermal Energy Storage system with two-tank oil-based storage system connecting the electrolyser with the NPP
Intermediate_loop	TANDEM.TestCases.EnergyHub.Components.IntermediateLoop	Intermediate oil loop connecting the electrolyser with the NPP
CHP	TANDEM.PowerSources.SimpleCHP	Combined Heat and Power plant as an additional source of electric power
HTSE_BOP	TANDEM.H2production.HTSE.HTSE_module_steam	Balance of plant for the HTSE, including the electrolyser stack
Module_splitter	TANDEM.Tools.OtherTools.ModuleSplitter	Gain to adjust the number of NPP and electrolyser modules present in the system
NSSS	TANDEM.SMR.NSSS.NSSS_ThermoPower.NSSSsimplified_fluid	Nuclear Steam Supply System (NSSS) based on the European Small Modular Reactor (E-SMR)
BOP	TANDEM.SMR.BOP.BOP_POLIMI.BOPdyn_fluid_v2	Balance of Plant of the Nuclear Power Plant, based on the TANDEM ThermoPower model

Table 1. Code names of the simulator of the TANDEM Energy Hub system

To explain the simulator in more detail, the schematics for the intermediate oil loop and the TES system are included below.

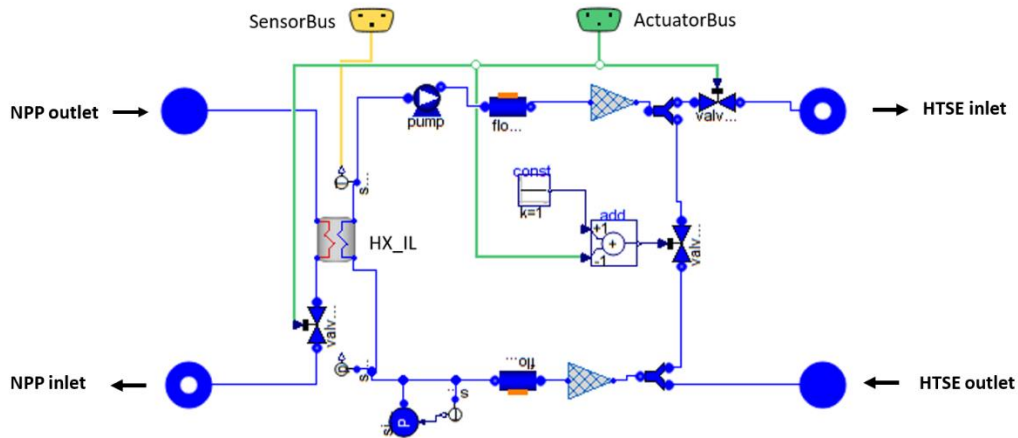


Figure 9. Schematic of the intermediate loop for the Energy Hub simulation model

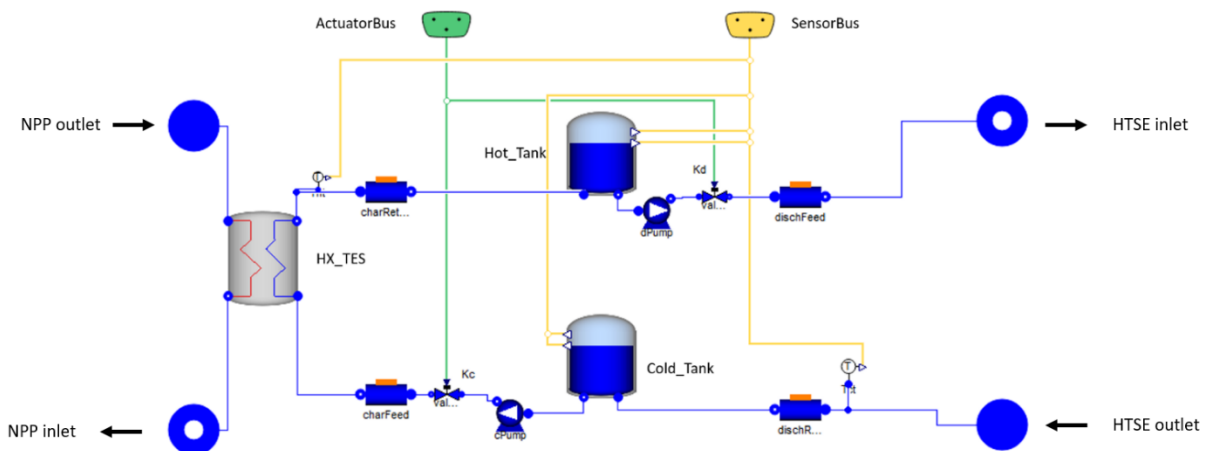


Figure 10. Schematic of the Thermal Energy Storage for the alternative Energy Hub simulation model

Figure 9 shows the schematic diagram of the intermediate oil loop used to connect the two main components of the system. This loop includes a bypass control system, a shell-and-tube heat exchanger, and a pumping system that facilitates the control of the oil flow. Additionally, two Module Splitters are included, allowing the system's behavior to be adjusted based on the number of existing electrolyzer modules, as well as pipes that account for the distances between the different systems and fluid dynamics.

Figure 10 displays the schematic of the two-tank oil-based system used as the TES system in the alternative case of the simulator. It also includes a shell-and-tube heat exchanger, two pumping systems (one for each tank), and pipes similar to those in the previous case.

In summary, the Table 2 presents the main components along with a brief description and the specific model used:

Component Name	Component Type	Description
HX_IL	TANDEM.EnergyStorage. ThermalStorage. Components.ShellAndTu be_WaterOil	Heat exchanger for transferring heat from the SMR – BOP to the HTSE – BOP via an intermediate oil loop
HX_TES	TANDEM.EnergyStorage. ThermalStorage. Components.ShellAndTu be_WaterOil	Heat exchanger for transferring heat from the SMR – BOP to the decoupled HTSE- BOP through the TES system
Hot_Tank	TANDEM.EnergyStorage. ThermalStorage. Components.Tank	Hot-side oil tank of the TES system.
Cold_Tank	TANDEM.EnergyStorage. ThermalStorage. Components.Tank	Cold-side oil tank of the TES system.

Table 2. Code names of the Intermediate Loop and TES System in the Energy Hub alternative Simulator

4.1.2 Assumptions

For both configurations, several assumptions were made. These assumptions are as follows:

- This simulator focuses on the dynamic behavior of the SMR and its BOP, the HTSE and its BOP, and the two thermal connection configurations between them, while treating the other components as simplified.
- Although the study case used as the basis of the simulator ('run7') includes two SMRs, each delivering 540 MWth, only one model of the nuclear island has been implemented. To simulate the thermal and electrical power of both reactors, a multiplicative gain has been incorporated, allowing the simulations to run as if there were two modules.
- There is only one hydrogen production component, which is the HTSE, as considered in case study run7 of deliverable 3.2.

- The sizing of the HTSE (number of modules) was performed to accommodate a maximum cogeneration power of 100 MWth. In this configuration, there are 27 modules per SMR unit.
- It is assumed that the system does not supply thermal power to the thermal grid; instead, all the thermal power released by the NSSS is delivered to the electrolyzer through the intermediate oil loop or the TES system. This causes the electrical energy produced by the reactor's BOP to vary according to the thermal energy required by the HTSE in the case of the intermediate oil loop. In the case of the TES system, the electrical energy produced is set externally as a boundary condition.
- The size of the hydrogen storage system and the initial charge have been set to 16,000 kg and 50%, respectively, with the option for the user to modify them.
- This configuration considers the CHP to deliver only electrical power, omitting any thermal power export. In this setup, the CHP operates with an efficiency of 0.53 and a rated electrical power of 80 MWe, with the option to adjust these values as needed.
- The electrical power consumed by the system includes the power used by the electrolyser, the electrical power load required externally, and the power consumption of the hydrogen compressor.
- The parameters assumed regarding the intermediate oil loop are as follows:
 - Distance: 1 km between SMR – BOP and HTSE.
 - Hot side temperature: 250 °C.
 - Fluid travel time: 6 minutes.
 - Working fluid: Therminol 66 thermal oil.
- The parameters assumed regarding the TES system are as follows:
 - Distance: 500 meters from the SMR – BOP to the TES and 500 meters from the TES to the HTSE.
 - Hot tank temperature: 250 °C.
 - Cold tank temperature: 200 °C.
 - TES capacity: 264 MWth.
 - Working fluid: Therminol 66 thermal oil.
- Renewable energy sources are included in the model but introduced via an input connector to the simulator, rather than as internal components.

4.1.3 Boundary conditions

The boundary conditions normally define the operating conditions of the system at the limit of the model's scope. In the case of the Energy Hub simulator, the boundary conditions depend on the hydrogen production needs of the system, as well as on the environmental conditions affecting the electricity generation of renewable energies. These boundary conditions can be

accessed and modified through the input connectors of the simulator, allowing for the simulation of different case studies using the same model.

The following table summarizes the boundary conditions of the system and the accessible connectors to modify them:

Boundary Condition	Connector
Setpoint of the CHP electrical power production [We]	CCGT_Pel
HTSE hydrogen production objective [kg/s]	H2target
Hydrogen externally required to the H ₂ storage [kg/s]	H2load
Electrical load required to the HES [We]	ElectricalLoad
Photovoltaic electrical power production [We]	PVpower
Wind farm electrical power production [We]	WindPower
Electrical power required to the SMR – BOP [We]	SMR_ElectricDemand

Table 3. Boundary Conditions in the Energy Hub simulator and Energy Hub alternative simulator

It is important to note that this last boundary condition (SMR_ElectricDemand) is only available in the simulator's alternative model, which includes the TES system. This is because, by decoupling the SMR and the HTSE, a boundary condition is introduced to regulate the amount of heat and electrical energy extracted from the BOP.

4.1.4 Control philosophy

The Energy Hub simulators includes various control loops that affect the NSSS, the heat extraction and electrical energy production of the SMR – BOP, the intermediate transmission loop or TES system connecting the SMR to the HTSE, as well as hydrogen production by the HTSE and the CHP.

For the design of the control system, it is necessary to consider the aforementioned assumptions, as they allow for determining which system parameters will be modified over time. The chosen

control philosophy will influence the simulator's final capabilities, limitations, and the types of case studies that can be carried out.

As mentioned in the assumptions section, a 'reactor follows hydrogen' control philosophy is implemented, where the amount of heat extracted from the SMR - BOP varies according to the thermal needs of the electrolyser. This philosophy is applied when the intermediate oil transmission loop is used.

In the case of the intermediate TES system, the amount of heat varies according to the user's electrical needs, with the extracted heat being adjusted as the surplus that is not required for electricity generation.

The following sections present the block diagrams of the control loops included in the simulator, along with a brief description of each.

Thermal Energy Storage system controller

This controller adjusts the position of the valves at the outlets of the hot and cold tanks, taking into account the temperatures at the inlets of the hot and cold sides, as well as the tank levels. Using a cascade of PI controllers, the valve opening is then adjusted to reach the target temperature. The components of these controllers come from the Modelica Standard Library.

Additionally, if the level of any tank rises above the maximum or falls below the minimum, the system opens or closes the valves to prevent further charging or discharging.

Figure 11 shows the block diagram of the TES system control loop, where green lines represent actuator signals, yellow lines indicate measured system signals, and pink lines represent boolean logic signals.

The following table shows the setpoint values established for the controller, which can be modified by the user:

Variable	Setpoint value
Hot side temperature [°C]	250
Cold side temperature [°C]	200
Minimum oil level in the tank [%]	5
Maximum oil level in the tank [%]	95

Table 4. Setpoints values of the TES system controller

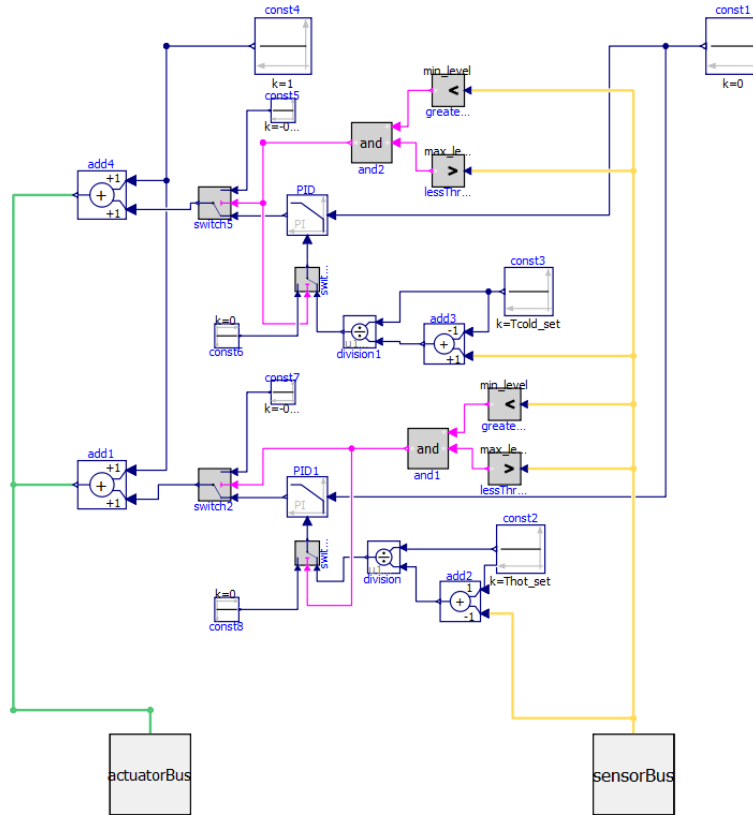


Figure 11. Energy Hub TES control loop

Legend:

Symbol	Description	Symbol	Description
	Gain component		Proportional & Integral Controller
	Real-to-Boolean signal transformer with comparison cases		Division input
	Constant analog source		Adder input
	Limiter of a signal range		Difference between commanded and feedback signal
	AND logic gate		Switch component

into the controller, which correspond to the power demands placed on the plant. The system sets the maximum and minimum electrical power values to 80 MWth and 0 MWth, respectively.

Additionally, the controller includes a gain that accounts for the amount of heat extracted from the plant, which impacts the electrical power generated. The user can adjust this gain. However, as the assumptions indicate, heat extraction from this plant is considered negligible in this case, so the gain has minimal significance.

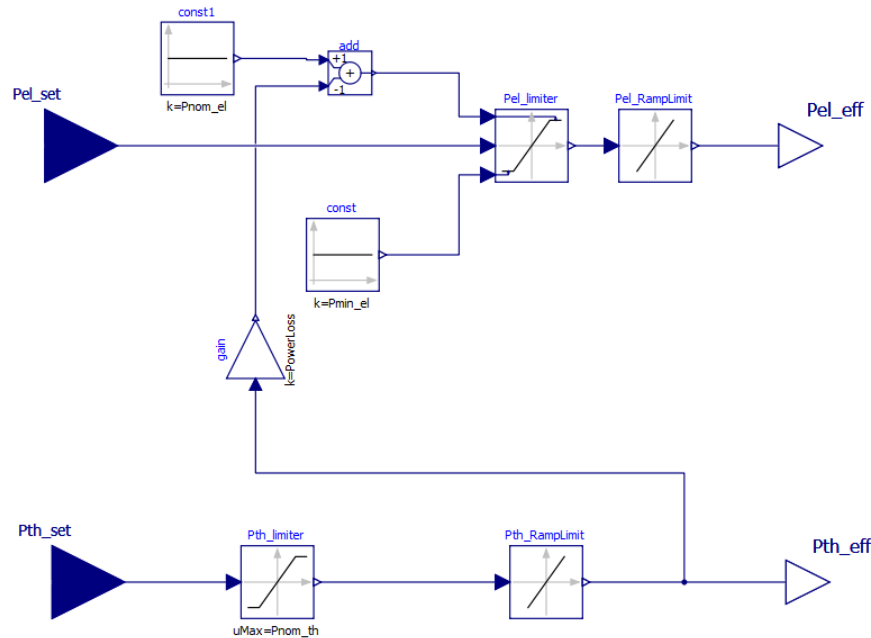


Figure 13. CHP control loop

HTSE – Balance of Plant controller

The control system for the electrolyser and its BOP is included within those components in the TANDEM library. This system aims to achieve the targeted H_2 production rate set as an input signal, factoring in the current production rate. To accomplish this, a cascade of PI controllers regulates the fuel mass flow by adjusting the opening of the steam intake valve. Additionally, a second PI controller manages the power supplied to the electric heater to reach the required inlet temperature for the stack.

For further details, refer to TANDEM/deliverable 2.3 [13] and the Git repository of the TANDEM library.

Nuclear Steam Supply System controller

The NSSS controller is responsible for minimizing pressure and temperature fluctuations in the reactor, considering the reactor pressure and the average core temperature. More detailed information about this control system can be found in TANDEM/deliverable D2.3 [13].

NSSS – Balance of Plant controller

This control loop uses a cascade of PI controllers to maintain pressure and temperature at their set values by adjusting the pumps' speed and valves' positions. These predefined values are shown in the Table 5.

Variable	Setpoint value
Pressure at the outlet of the High Pressure Pump [bar]	46.4
Pressure at the outlet of the Low Pressure Pump [bar]	7.647
Pressure at the outlet of the Steam Generator (SG) [bar]	45
Temperature at the outlet of the SG [°C]	300
Temperature at the inlet of the SG [°C]	163
Temperature at the inlet of the Low Pressure Turbine [°C]	260.44
Pressure at the inlet of the Low Pressure Turbine [bar]	7.547
Pressure at the inlet of the hot side of the Reheater [bar]	44.5
Pressure at the inlet of the Low Pressure Turbine second stage [bar]	0.801
Tank pressure [bar]	7.147

Table 5. Setpoint values of the BOP controller

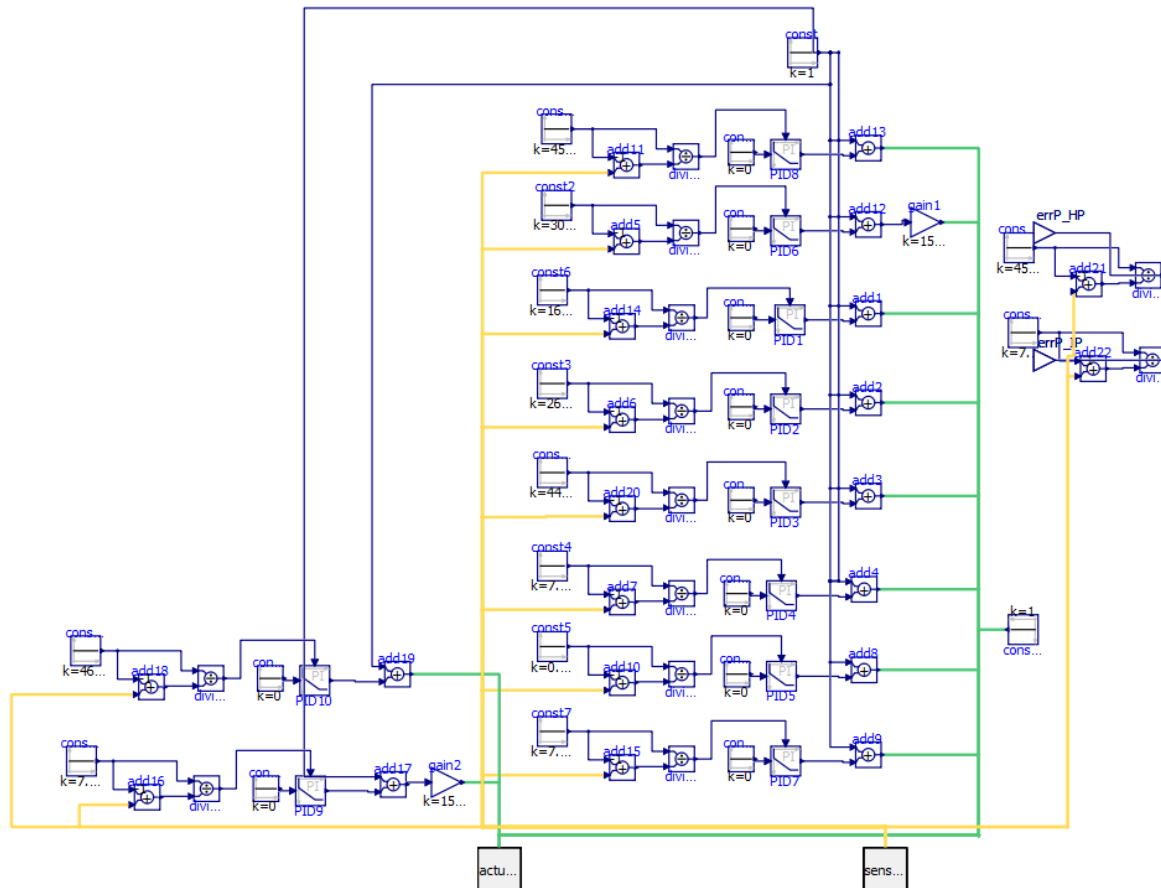


Figure 14. NPP – Control loop of the balance of plant in the energy hub simulator

In this way, and explained in a simplified manner, the relationship between the process variables shown in the table and the controlled variables is outlined below:

- The pressure at the outlet of the low-pressure pump is set by adjusting the speed of the pump, while the pressure at the outlet of the high-pressure pump is adjusted by varying the position of the valve at the outlet of the BOP.
- The remaining pressure values are obtained by adjusting the openings of the valves located immediately before or after the pressure sensor. For more detailed information, please refer to TANDEM/deliverable D2.3 [13].
- Regarding the temperature values, the temperature at the outlet of the steam generator is regulated by adjusting the speed of the high-pressure pump, while the temperature at the inlet of the steam generator is controlled by varying the position of the valve located in the reheater at the outlet of the BOP.
- The temperature at the inlet of the low-pressure turbine is regulated by adjusting the position of the valve at the outlet of the hot side of the reheater.
- Lastly, the grid frequency is controlled acting on the turbine admission valve.

4.1.5 Capabilities

Steady calculations

The Energy Hub simulator allows for the study of the system in a steady-state at specific operating points, enabling verification of the correct operation of the systems included in the full model. It is important to note that, in order to obtain consistent results in any simulation, it is essential to properly initialize the system's values.

Transient calculations

Regarding transient calculation capabilities, the simulator can run typical operational transients for these systems. Examples include variations in hydrogen production demand, aimed at studying the behaviour of other components, and changes in electrical demand, which directly affect hydrogen production in the case of the intermediate oil loop. On the other hand, the alternative configuration with the TES system allows for decoupling electrical demand from hydrogen production, enabling new study cases.

In this way, the two available configurations allow for evaluating which technology may be more suitable for implementation in the actual system. Different transient cases can be run to determine which situations favour one configuration over the other.

Expected outputs

The simulator design considers future integration with the PERSEE optimization tool. Based on this, connectors were introduced in the model to access the variables required by the optimization tool. Table 6 lists these output variables and the connectors through which their values can be accessed.

Variable description	Output connector
Electrical power produced by the CHP	CCGTpower
Thermal power delivered by the reactor	Pth_SMR
Net electrical power delivered to the grid	GridPower
Electrical power generated by the SMR – BOP	PeI_SMR
Thermal power extracted from the SMR – BOP	Pth_COG
Thermal power consumed by the HTSE	Pth_HTSE
Electrical power consumed by the HTSE	PeI_HTSE
Hydrogen production rate	H2prod
State of charge of the hydrogen storage	SOC/SOC_H2
State of charge of the intermediate TES system	SOC_TES

Table 6. Output variables of the Energy Hub simulator

For clarification, the state of charge of the hydrogen storage refers to two different connectors, depending on whether the system includes the intermediate oil loop (SOC) or the TES system (SOC_H2). Similarly, the connector for the state of charge of the intermediate TES system (SOC_TES) is only available in the simulator's alternative configuration, which includes the TES system.

4.2 District Heating Simulator

The TANDEM project includes two distinct study cases related to the HES configuration for district heating and electricity supply. However, only one model is developed, being capable of recreating each study case by setting some of the parameters and components of the different systems. In this case, the case developed in Northern Europe, specifically situated in the south of Finland, is studied.

As a first approach to the Hybrid Energy System simulator, it is necessary to establish some assumptions that will be taken to be able to create an initial configuration of the system. These assumptions fix some design parameters and define the control philosophy of the simulator. It is important to mention that certain assumptions have been made with the goal of coupling the simulator to the Backbone optimization tool.

4.2.1 Schematics

The basic layout of the hybrid simulator for district heating and electricity supply is shown in Figure 15. It distinguishes between the different distribution networks of Helsinki West and Helsinki East, as well as the transmission lines that interconnect these networks and the nuclear power plant. In this model, four main blocks of the district heating system under study can be distinguished:

- The transmission line between the nuclear plant and the Helsinki West distribution network, highlighted with an orange rectangle.
- The Helsinki West distribution network, marked with an ellipse labeled 'Helsinki W'
- The transmission line between the Helsinki West and Helsinki East district heating networks, highlighted with an orange rectangle.
- The Helsinki East district heating distribution network, marked with an ellipse labeled 'Helsinki E'

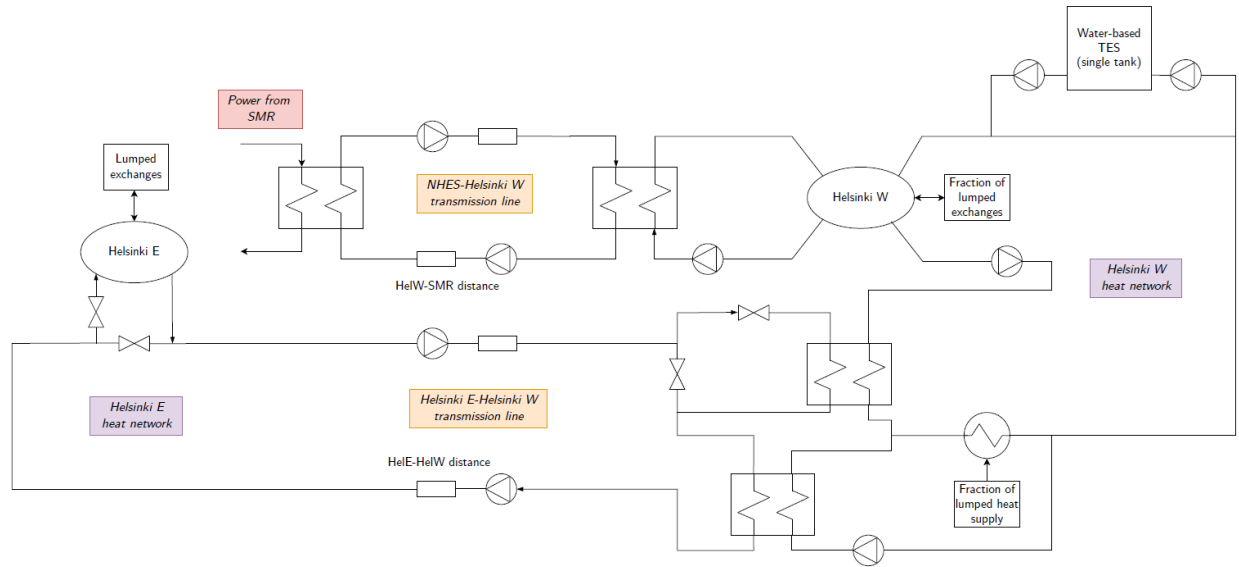


Figure 15. District Heating configuration scheme

This basic layout is translated into a schematic generated in Dymola that simulates the configuration of the system in more detail. This configuration can be seen in Figure 16.

The yellow lines that connect the components to the SensorBus represent control connections, specifically sensor measurement data. The green lines that connect the components to the ActuatorBus also represent control connections, but in this case, they are related to information flows from the controller to the actuators. Finally, the blue lines represent steam or water flow connections, and the red lines represent thermal couplings.

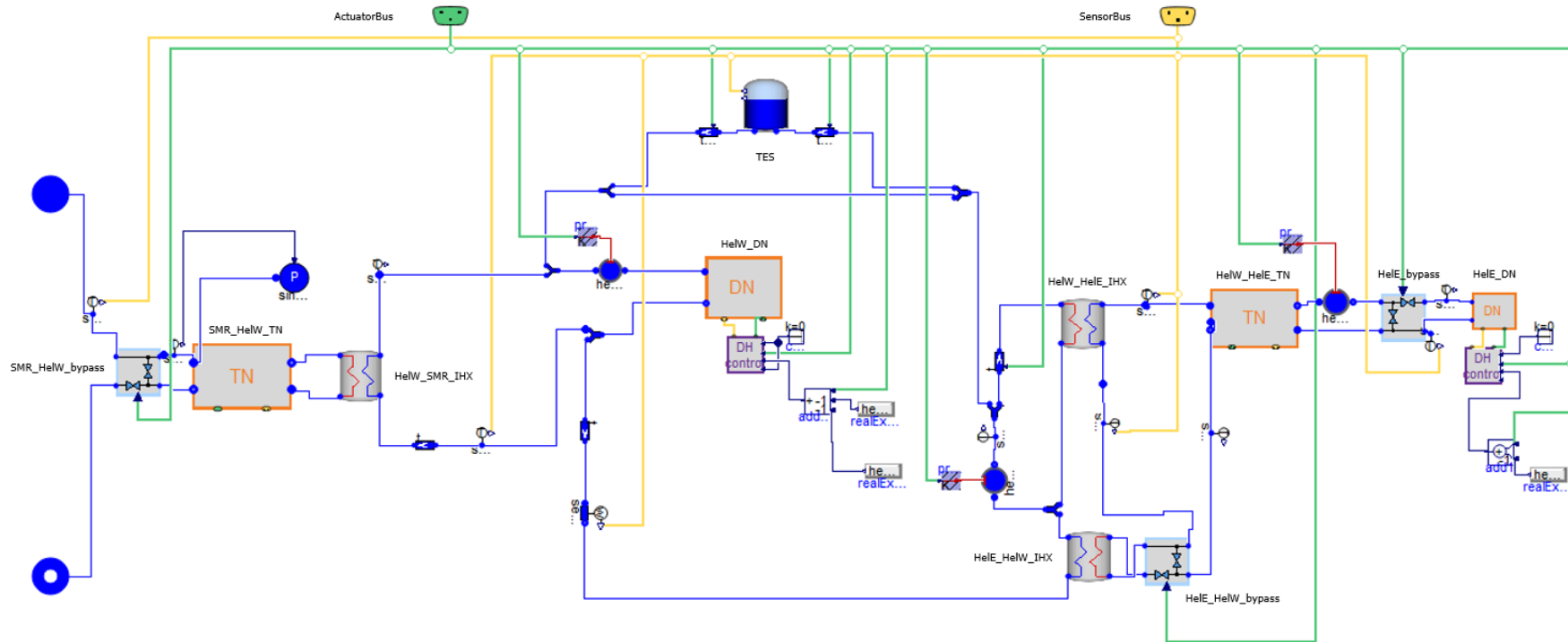


Figure 16. Schematic of the District Heating simulation model

The following table summarizes the code names of the main components of the district heating system. For further information on each individual component, please refer to the Git repository of the TANDEM library and to TANDEM/deliverable 2.3.

Component Name	Component Type	Description
TES	TANDEM.EnergyStorage.ThermalStorage.Components.Tank	Thermal Energy Storage of the complete District Heating system
HeIW_DN	TANDEM.DistrictHeating.Components.Distribution	Helsinki West DH distribution network
HeIE_DN	TANDEM.DistrictHeating.Components.Distribution	Helsinki East DH distribution network
SMR_HeIW_TN	TANDEM.DistrictHeating.Components.Transmission_n_sizing	Transmission line between the outer section of the NPP and the Helsinki West DH distribution network
HeIW_HeIE_TN	TANDEM.DistrictHeating.Components.Transmission_n_sizing	Transmission line between the Helsinki West and Helsinki East DH distribution networks
SMR_HeIW_bypass	TANDEM.DistrictHeating.Components.FluidDistribution	Bypass valve system between the outer section of the NPP and the Helsinki West DH distribution network
HeIE_HeIW_bypass	TANDEM.DistrictHeating.Components.FluidDistribution	Bypass valve system between the Helsinki West and Helsinki East DH distribution networks
HeIE_bypass	TANDEM.DistrictHeating.Components.FluidDistribution	Bypass valve system between the Helsinki East DH distribution network and the Helsinki East – West transmission line
HeIW_SMR_IHX	TANDEM.DistrictHeating.Components.HXOD_NTU	Internal heat exchanger to transfer heat from the Helsinki West DH system to the Helsinki West – SMR transmission line
HeIW_HeIE_IHX	TANDEM.DistrictHeating.Components.HXOD_NTU	Internal heat exchanger to transfer heat from the Helsinki West to the Helsinki East DH systems
HeIE_HeIW_IHX	TANDEM.DistrictHeating.Components.HXOD_NTU	Internal heat exchanger to transfer heat from the Helsinki East to the Helsinki West DH systems

Table 7. Code names of the main components of the District Heating network

Considering that the simulator also includes the nuclear plant model, it is necessary to integrate the displayed district heating model with the SMR and BOP models. Thus, the schematic of the complete model of the simulator is as follows:

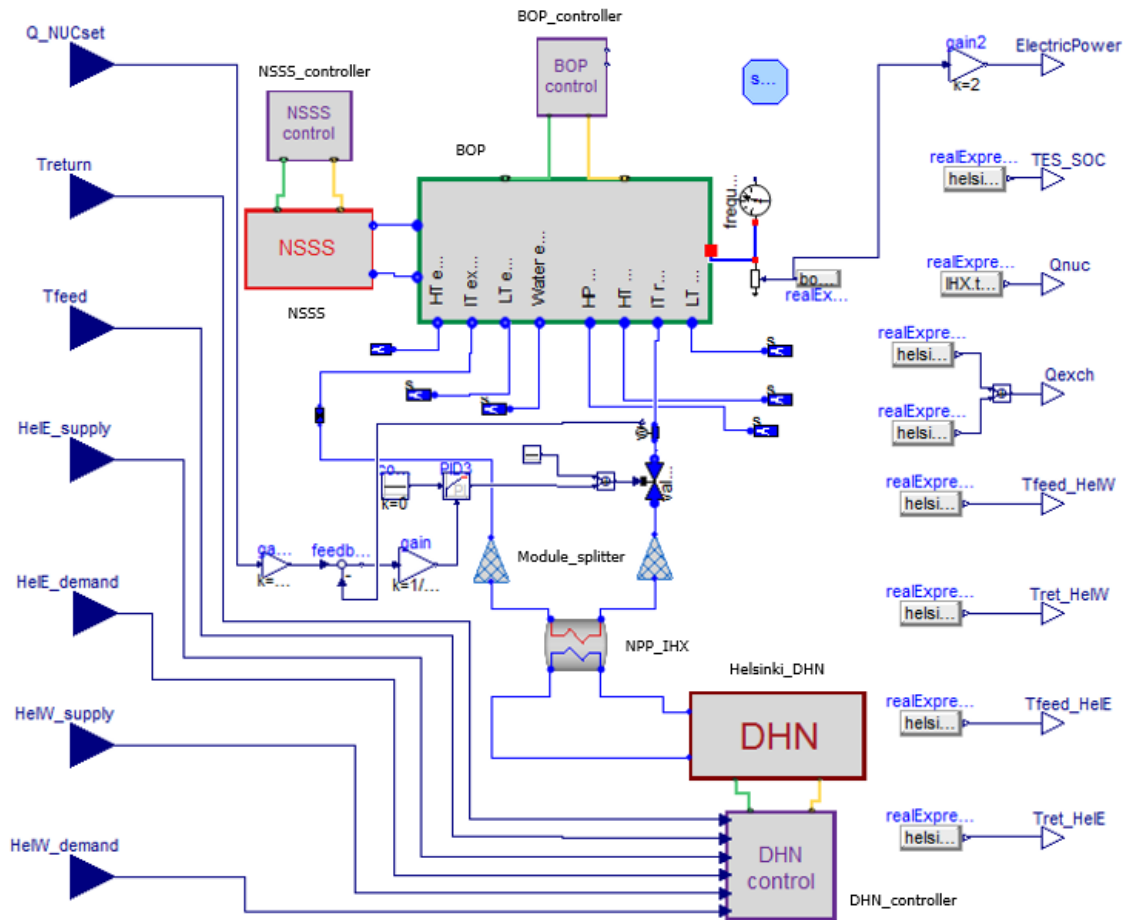


Figure 17. Schematic of the simulator of the TANDEM District Heating configuration

The code names of the main components included in the complete model of the District Heating simulator and a brief description of each component are provided in Table 8.

Figure 17 also shows the different connectors available to modify the boundary conditions of the system and obtain the significant parameters of the simulation (see the Boundary conditions section for more information about the boundary conditions of the system.)

Component Name	Component Type	Description
Helsinki_DHN	TANDEM.TestCases.DHN_Helsinki.Components.HelsinkiDHN	Helsinki district heating model shown in Figure 16
NPP_IHX	TANDEM.EnergyStorage.ThermalStorage.Components.ShellAndTube_WaterOil	Internal heat exchanger to transfer heat from the NPP to the Helsinki West – SMR transmission line
Module_splitter	TANDEM.Tools.OtherTools.ModuleSplitter	Gain to adjust the number of NPP modules present in the system
NSSS	TANDEM.SMR.NSSS.NSSS_ThermoPower.NSSSsimplified_fluid	Nuclear Steam Supply System based on the European Small Modular Reactor
BOP	TANDEM.SMR.BOP.BOP_POLIMI.BOPdyn_fluid_v2	Balance of Plant of the Nuclear Power Plant, based on the TANDEM ThermoPower model

Table 8. Code names of the simulator of the TANDEM District Heating configuration

4.2.2 Assumptions

For this configuration, different assumptions have been considered. These are as follow:

- The simulator focuses on the dynamic behavior of the NSSS and its BOP, the heat exchangers, the DH networks, and its water-based thermal energy storage system, while omitting or simplifying the other components.
- The components related with the heat exchange between different thermal networks or TES are sized considering the following rated operating conditions:

Design Operating Condition	Value
Thermal power exchange in the 'HelW_SMR_IHX' [MWth]	100
Thermal power exchange in the 'HelW_HeIE_IHX' [MWth]	140
Thermal power exchange in the 'HeIE_HelW_IHX' [MWth]	140
Temperature range in the 'SMR_HelW_TN' [°C]	140 – 95
Temperature range in the 'HelW_DN' [°C]	90 – 50
Temperature range in the 'HelW_HeIE_TN' [°C]	80 – 50
Temperature range in the 'HeIE_DN' [°C]	90 – 50

Table 9. Rated operating conditions of the District Heating network

- The reactor load is set constant, delivering 540 MWth. However, the electrical power generation and the heat cogeneration will vary depending on the heat demand needed by the district heating system.
- Heat supplied to the system by additional sources is split to be fed into the system through the feedwater line to meet temperature requirements, while the remaining heat is directly fed to the distribution network.
- The heat exchanger models are modeled as quasi-static (0D), simplifying the heat transfer phenomenon and increasing the speed of the model.
- Due to the unification of various thermal energy storage systems into a single system, thermal losses are considered negligible, as calculating parameters like thermal transmittance or other geometric factors was not feasible. However, the TES allows for adjustments to account for these thermal losses if needed.
- As an initial state, both TES systems are considered half-filled, which will be treated as a nominal condition, assuming steady-state conditions
- The heat exchange between 'HeIW_DN' and 'HeIW_HeIE_TN' is carried out using two heat exchangers, depending on the target flow direction, to facilitate system convergence.
- Although the study case includes two SMRs, to simplify the model, only a nuclear power plant model has been incorporated; however, a multiplicative gain for the extracted steam flow rate has been utilized to simulate the increase in thermal and electrical flow that would be produced by the two specified nuclear modules.
- The electrical component of the simulator has been simplified to meet the simulator's requirements. In this configuration, all electrical production is assumed to be fed directly into the electric grid. Additionally, certain components shown in Figure 1, which served solely for electricity generation, have been omitted.

4.2.3 Boundary conditions

In the case of the District Heating simulator, the boundary conditions largely depend on the parameters of the consumers in the thermal network related with the demand. Similarly to the Energy Hub simulator, these boundary conditions can be modified through the available connectors of the simulator, allowing the simulation of different study cases using the same model.

The following table summarizes the boundary conditions of the system and the accessible ports available for modifying them:

Boundary Condition	Connector
Thermal power extracted from SMR-BOP [Wth]	Q_NUCset
Return temperature from the DHN [K]	Treturn
Supply temperature to the DHN [K]	Tfeed
Helsinki East thermal power supply [Wth]	HelE_supply
Helsinki East thermal power demand [Wth]	HelE_demand
Helsinki West thermal power supply [Wth]	HelW_supply
Helsinki West thermal power demand [Wth]	HelW_demand

Table 10. Boundary Conditions of the District Heating simulator

4.2.4 Control philosophy

The District Heating simulator includes the main control system that affects the different distribution networks and transmission lines of the entire system, as well as the control system that manages the thermal extraction from the BOP of the SMR.

As a baseline, it is assumed that the system uses all the heat generated by the SMR and auxiliary systems (CHP and TES) to supply the district heating network, while electricity generation will play a secondary role, not requiring detailed control. This decision was made considering that the optimization tool did not account for the electrical part of the model.

In this way, and taking into account that the SMR – BOP operates in cogeneration mode, the control system will adjust the heat extracted from the BOP based on the existing demand in the district heating system, utilizing the total thermal power extracted and thereby considering a surplus heat of zero.

Table 11 lists the control variables and the process variables required to reach the established setpoint values. Process variables are the ones being monitored, while control variables are adjusted to achieve the desired values of the process variables.

Process variable	Controlled variable
Feed temperatures of the District Heating Network	Heat supply allocation
Extracted thermal power	Cogeneration valve
Helsinki West return temperature	Thermal Energy Storage operation
Helsinki East return temperature	Bypass system

Table 11. Main Control Loop Variables of the District Heating configuration

The following sections presents the block diagram of the simulator's main control loops included in the model and provides a brief description of each.

TES controller of the District Heating configuration

This control loop directly regulates the amount of water injected into or extracted from the TES of the district heating configuration. It uses a series of PID controllers that take into account the current state of charge (SOC) of the tank, the water flow introduced into the *HeIW_HeIE_IHX* heat exchanger, and the temperature difference between the return temperature setpoint and the measured return temperature at the inlet of the *HeIW_SMR_IHX* heat exchanger.

Figure 18 shows the block diagram of the control loop implemented in the simulator for this specific component. This control loop is integrated into the main controller of the district heating configuration, which is described below.

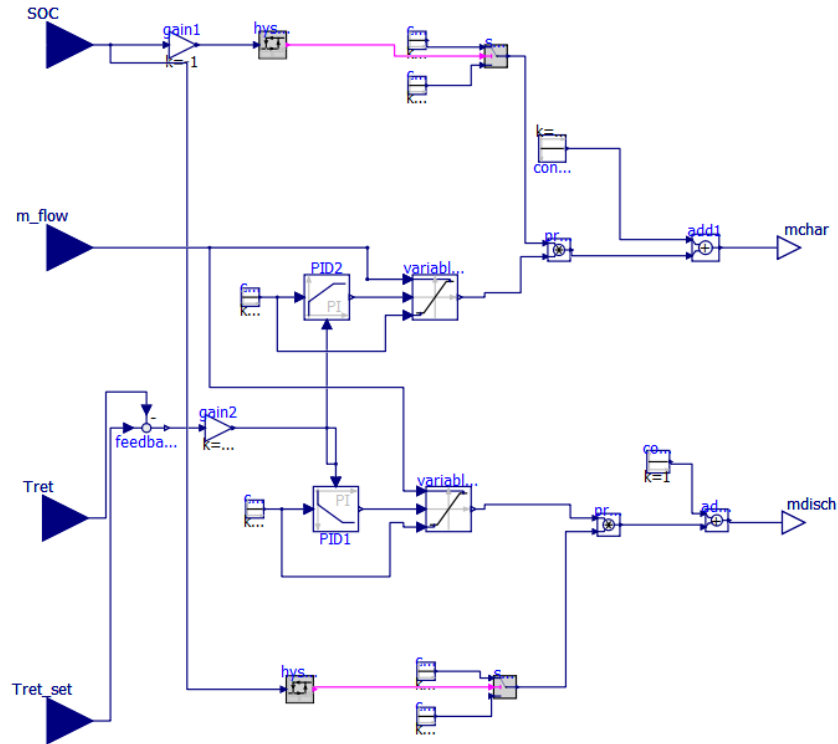


Figure 18. TES control loop in the District Heating simulator

Legend:

Symbol	Description	Symbol	Description
	Gain component		Proportional & Integral Controller
	Real-to-Boolean signal transformer with hysteresis		Product input
	Constant analog source		Adder input
	Limiter of a signal range		Difference between commanded and feedback signal

Main controller of the District Heating network

This control loop adjusts the temperatures throughout the district heating network by varying valve openings and setting the necessary flows. The block diagram of this controller is shown in Figure 19, where the green lines represent the actuator signals, and the yellow lines represent the measured signals in the system.

A brief description of the operation of the different loops integrated into the controller is provided below:

- **Bypass valve between the BOP of the nuclear power plant and the Helsinki West transmission line:** The valve opening is regulated by a PI controller based on the setpoint temperature of the fluid at the system inlet, set at 140°C, and the measured temperature at the district heating inlet.
- **Bypass valve between the Helsinki East distribution network and the transmission line:** The position of this valve is adjusted through a PI controller, using the return temperature of the Helsinki East distribution network as the measured value, and the return temperature setpoint defined in the boundary conditions as the target value.
- **Bypass valve between both heat exchanger between Helsinki West and Helsinki East:** The opening of the valve between these two heat exchangers is regulated using a PI controller that considers the set feed temperature and the temperature of the water entering the *HelW_HeE_IHX* heat exchanger.
- **Hot water flow entering the HelW_HeE_IHX exchanger:** the control loop that regulates the amount of hot water entering the exchanger is managed by a PI controller, which adjusts the flow based on the difference between the set feed temperature and the actual feed temperature measured at the inlet of the Helsinki East transmission line.

It is worth mentioning that the parameters of the PI controllers included in the simulator were designed through a tuning process using the Control System Toolbox of MATLAB. The procedure is straightforward: first, the Modelica models are linearised using the linearisation tool of Dymola to export the models as a Linear-Time-Invariant (LTI) system, as the MATLAB tool requires linear models. Then, the MATLAB tool is used to tune the PI parameters in terms of performance and robustness. Finally, these parameters are implemented in the PI controllers of Modelica.

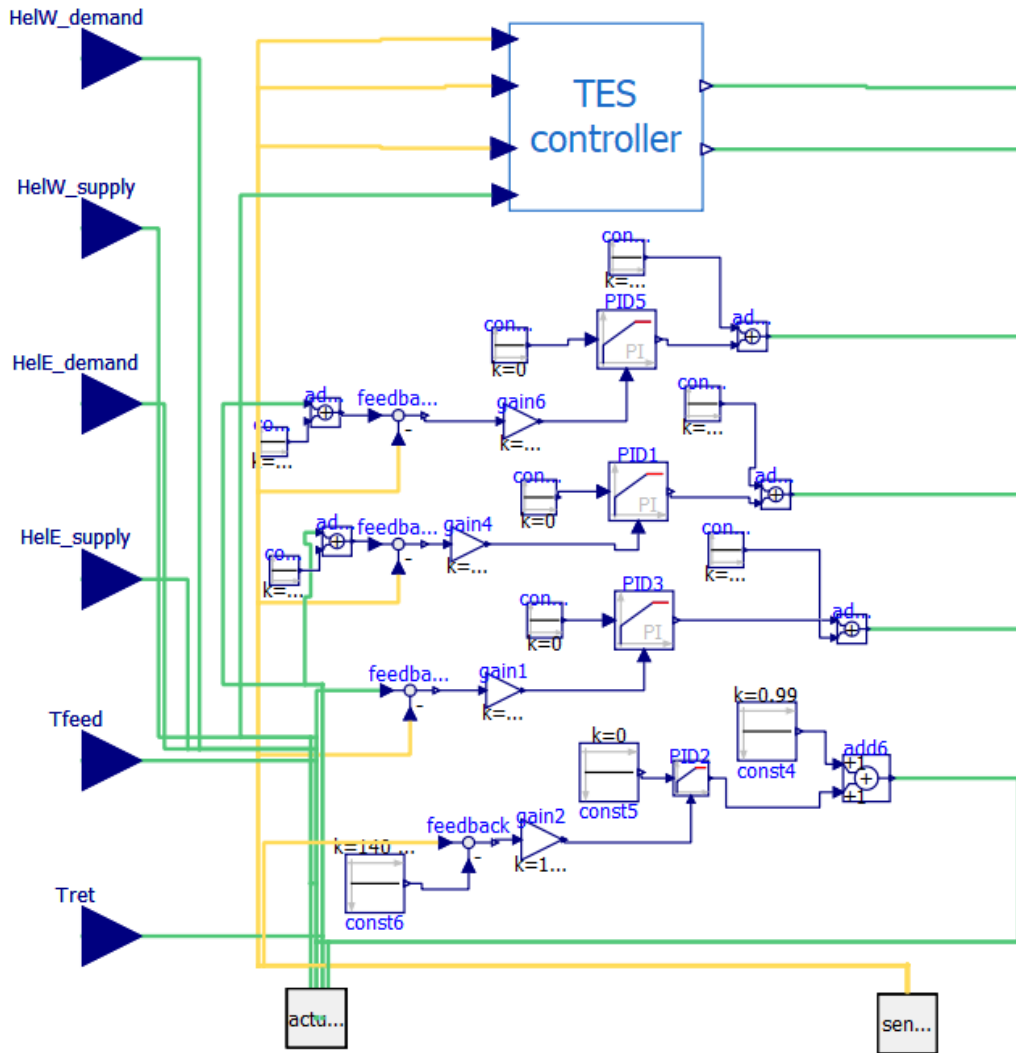


Figure 19 Control loop of the District Heating network

Distribution Network controller

This type of controller is used solely to convert the thermal power signals for demand, supply, and exchange in the corresponding distribution network, making these signals usable by the network.

Nuclear Steam Supply System controller

Similarly to the Energy Hub simulator, the steam generator controller is responsible for minimizing pressure and temperature fluctuations in the reactor, considering the reactor pressure and the average temperatures at the inlet and outlet of the reactor core. More detailed information about this control system can be found in TANDEM/deliverable 2.3 [13].

NSSS – Balance of Plant controller

This control loop is identical to the one used in the Energy Hub simulator. For further details, please refer to the Energy Hub Control philosophy section included in this deliverable.

4.2.5 Capabilities

Steady calculations

Similarly to the case of the Energy Hub, the simulator can perform steady-state calculations to analyze the system at specific operating points, enabling the study of the steady-state behavior of all its components.

Transient calculations

On the other hand, the simulator can perform transient simulations that are typical of the operation of such systems. These simulations include gradual variations in the heat demand of the distribution networks within the district heating configuration, which, in turn, adjust the demand on the reactor's BOP to optimize the parameters of electrical and thermal energy cogeneration.

Another type of transient of interest that the simulator can execute involves a deliberate reduction in heat extraction from the BOP to increase electrical production, thereby affecting the downstream district heating network. This is one of the example cases presented in the following sections.

Expected outputs

Both the structure of the simulator and the control system have been designed for future integration with the Backbone optimization tool. To achieve this, the simulator is configured to receive a set of input values as boundary conditions, yielding specific parameters to feed into the model generated by the optimization tool.

The following table presents the output variables provided by the simulator and the connector available to obtain externally the data from the model:

Variable description	Output connector
Electrical power generated by the reactor BOP	ElectricPower
State of charge of the Thermal Energy Storage of the District heating	TES_SOC
Thermal power extracted from the reactor BOP	Qnuc
Net thermal power exchanged between Helsinki East and Helsinki West	Qexch
Feed temperature of Helsinki East distribution network	Tfeed_HeE
Return temperature of Helsinki East distribution network	Tret_HeE
Feed temperature of Helsinki West distribution network	Tfeed_HelW
Return temperature of Helsinki West distribution network	Tret_HelW

Table 12. Output variables of the District Heating simulator

5 Models testing

This section provides a description and the results of the test cases conducted to evaluate the capabilities of the different simulators. First, the test cases are introduced, followed by their results, along with a brief analysis of the simulator's limitations and adaptability.

5.1 Energy Hub simulator

To assess the capabilities of the two different configurations of the Energy Hub simulator, one test case has been prepared for each. These cases are presented below.

5.1.1 Description of test cases

HTSE start-up and reduction to lower operational production levels.

In this case, the simulation begins with the electrolyzer start-up, setting it to its nominal hydrogen production level. Once this level is reached, production is reduced to the lower limit value used in the PERSEE optimization tool. This process serves to verify the simulator's correct operation before integration.

From a numerical perspective, the boundary conditions applied in this simulation are presented in Table 13. Hydrogen production is initially set at a nominal level of 5.4 kg/s, which is maintained for one hour before being reduced by 40%, resulting in a flow rate of 3.24 kg/s. In this case, hydrogen production is assumed to match hydrogen load.

Additionally, no external electrical energy input from other sources, such as CHP or renewables, is considered, and electrical demand is also assumed to be zero.

Boundary Condition	Variable	Value
Hydrogen load and production (during HTSE start-up)	Initial hydrogen production [kg/s]	0
	Final hydrogen production [kg/s]	5.4
	Transient start time [s]	500
	Transient duration [s]	500

Boundary Condition	Variable	Value
Hydrogen load and production (during HTSE decrease production)	Initial hydrogen production [kg/s]	5.4
	Final hydrogen production [kg/s]	3.24
	Transient start time [s]	5
	Transient duration [s]	500
CHP electrical power production	Electrical power [We]	0
PV electrical power production	Electrical power [We]	0
Wind power plant electrical production	Electrical power [We]	0
Electrical load	Electrical power [We]	0

Table 13. Parameters for Test Case 1 of the Energy Hub Simulator

TES charging and HTSE start-up and reduction

This case introduces an additional transient compared to the previous one, aimed at verifying the correct operation of the thermal energy storage (TES) system. Starting with full electrical generation from the BOP and with the electrolyzer off, the nominal electrical power of the SMR is reduced as thermal power extraction begins to charge the TES system.

After a charging period, steam extraction from the BOP stops, and the electrolyzer is turned on, replicating the same transient behavior as in the previous test case. However, in this case, the thermal power used to operate the electrolyzer comes directly from the TES system, instead of from the BOP as in the previous case. Similar to the previous case, Table 14 presents the boundary conditions used to replicate this test case.

Boundary Condition	Variable	Value
SMR electrical demand (during steam extraction increase)	Initial electrical power [We]	353e6
	Final electrical power [We]	307.2e6
	Transient start time [h]	2
	Transient duration [h]	2

Boundary Condition	Variable	Value
SMR electrical demand (during steam extraction decrease)	Initial electrical power [We]	307.2e6
	Final electrical power [We]	353e6
	Transient start time [h]	8
	Transient duration [h]	2
Hydrogen load and production (during HTSE start-up)	Initial hydrogen production [kg/s]	0
	Final hydrogen production [kg/s]	5.4
	Transient start time [h]	14
	Transient duration [h]	2
Hydrogen load and production (during HTSE decrease production)	Initial hydrogen production [kg/s]	5.4
	Final hydrogen production [kg/s]	3.24
	Transient start time [h]	20
	Transient duration [s]	2880
CHP electrical power production	Electrical power [We]	0
PV electrical power production	Electrical power [We]	0
Wind power plant electrical production	Electrical power [We]	0
Electrical load	Electrical power [We]	0

Table 14. Parameters for Test Case 2 in the Energy Hub Simulator

5.1.2 Results of the test cases

HTSE start-up and reduction to lower operational production levels.

As mentioned in previous sections, a significant part of the simulator's importance lies in hydrogen production. Therefore, the results presented below will focus on the behaviour of the electrolyser, as well as the SMR and its BOP.

Figure 20 includes six graphs that provide significant information for studying the most relevant components. These graphs allow the following conclusions to be drawn:

- When the electrolyzer starts up, steam extraction from the BOP increases to 100 MWth, causing a reduction in cogenerated electrical power by over 40 MWe. The opposite occurs when the electrolyzer's operating rate is reduced to 60%: the extracted heat decreases by 40 MWth, and electrical power increases by 15 MWe. This shows that thermal extraction does not linearly affect electrical generation in the BOP.
- The electrical power generated in the BOP of the two SMRs is insufficient to fully meet the electrolyzer's electrical demand. Therefore, the remaining required power is drawn from the grid. This insufficiency is due to the low efficiency of the electrolyzer, which has been optimized as part of Task 3.3 of the project, significantly reducing its electrical requirements.
- A delay of approximately 6 minutes is observed for the thermal power as it travels from the BOP to the electrolyzer. This delay is due to the existence of the intermediate oil loop with a distance of 1 km.
- Finally, it can be observed that the reactor experiences minor power fluctuations during variations in the BOP, caused by reactivity feedback. This is evident in the last graph, where no external reactivity insertions are shown.

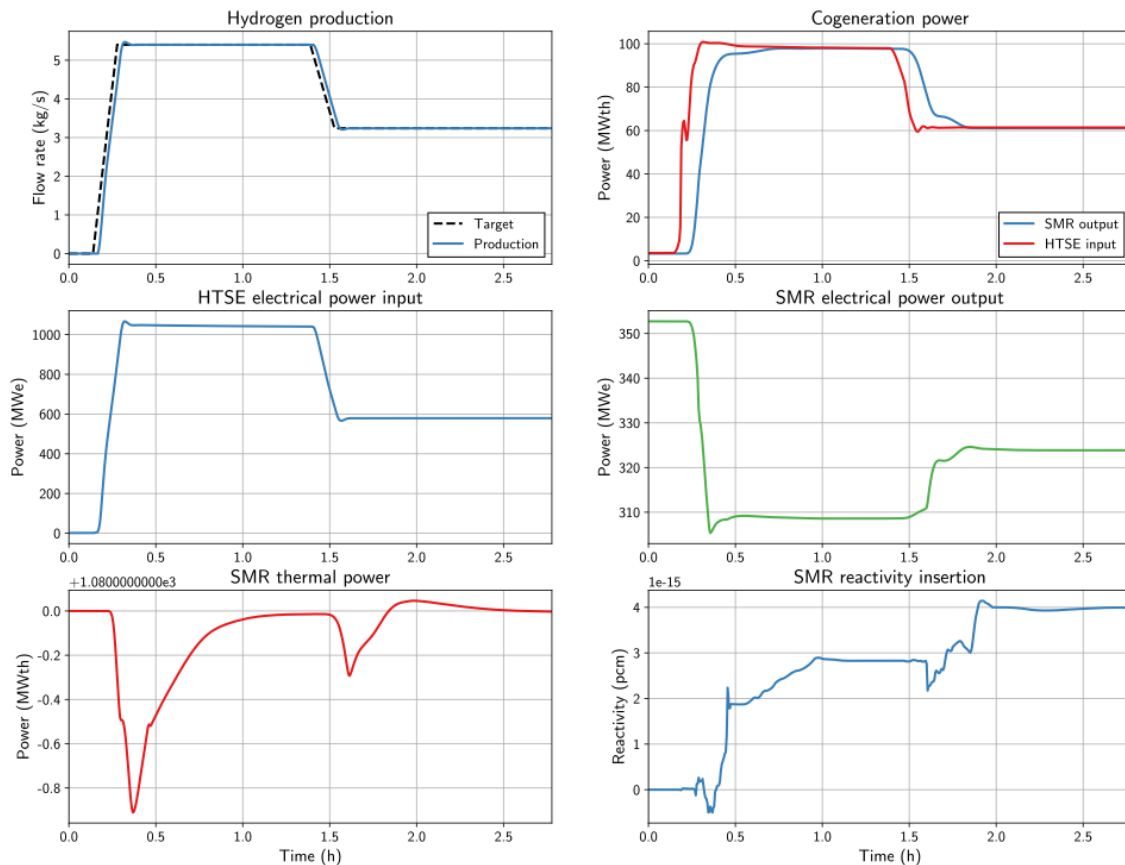


Figure 20. Results of the Energy Hub Test Case 1

TES charging and HTSE start-up and reduction

In the second test case, the simulation time is longer to observe the behavior of all the significant systems in the simulator. For this case, six significant graphs are presented again in Figure 21, which allow the study of the behavior during this transient analysis.

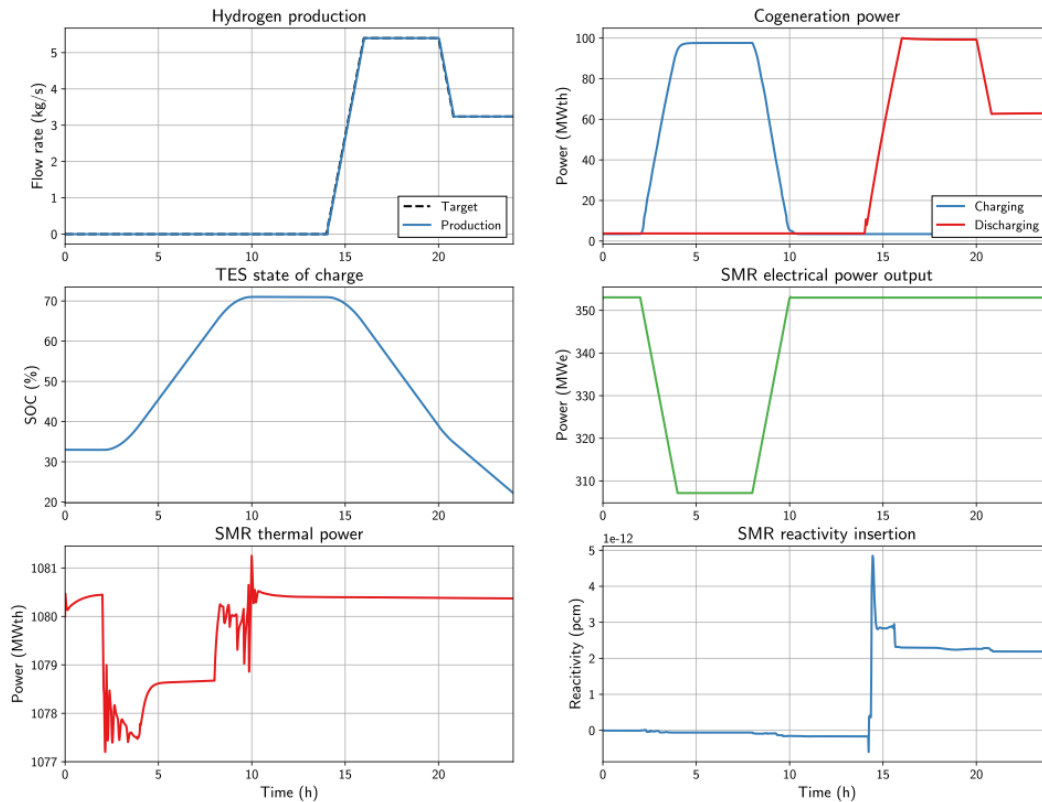


Figure 21. Results of the Energy Hub Test Case 2

The following conclusions can be drawn from the previous graphs:

- Due to having the electrolyzer off during the first 14 hours, when extracting 100 MW_{th} of thermal power (which corresponds to a decrease of about 13% in electrical power), the tank quickly increases its charge, surpassing 70% of its nominal value, increasing by approximately 40% over 8 hours.

On the other hand, when the electrolyzer is turned on, the discharge occurs at the same rate as during charging when it operates at the nominal production value. This is important because it allows for the study and optimization of the tank size to adjust its usage time.

- Although the rest of the results from the second part of the simulation are similar to the previous test case, it is important to highlight the reactor's behavior. Thanks to the decoupling of the BOP and HTSE, during the electrolyzer's operation period, there are no variations in the reactor core, enhancing its safety.

5.1.3 Functions evaluation

The Energy Hub simulator allows for the execution of a wide range of transient and steady-state scenarios, enabling the study of the behavior of the reactor and electrolyzer, as well as the hydrogen production of a future energy system to be implemented in a harbor-like infrastructure.

These simulations can be used to validate and test the proposed configuration of the hybrid system before implementation, allowing for the verification of the behavior of the components and assessing whether they are suitable for subsequent implementation. Additionally, they can also be used to estimate the electrical or fuel consumption required by these components.

Some of the key features of the simulator include:

- Simulate scenarios involving increases or decreases in hydrogen demand and production.
- Adjust the cogeneration of the BOP and CHP to meet the electrical load required by the system.
- Study different scenarios of electrical production from renewable energy sources to assess the system cogeneration needs.
- Analyze the reactor state in response to variations across the system, enabling the study of reactivity and thermal power.

5.1.4 Limitations

Due to the assumptions made and the capabilities of the components used in the simulator's assembly, there are a set of limitations that may affect its performance during certain transient simulations.

The most important limitations worth mentioning are:

- The reactor model cannot simulate sudden operational changes such as startups or emergency shutdowns.
- The electrical grid is not modeled. Instead, all the electrical power produced is fed directly into a fictitious ideal grid, with no control implemented. Similarly, the electrolyzer draws the required electrical power directly from this grid. This makes it impossible to study the impacts on the electrical grid, such as frequency changes or overloads.

- Hydrogen storage is considered ideal, without accounting for potential pressure losses at the inlet and outlet. This limitation prevents studies on certain dynamic aspects of the system. However, it does allow for analyzing the evolution of hydrogen stored in the tank, which is calculated as the difference between hydrogen load and hydrogen production.
- The control system is not optimized for a specific operational mode.

5.1.5 Adaptability of the hybrid energy system simulator

As mentioned in section 3 of this deliverable, the simulator was developed using libraries based on the Modelica modeling language. This choice, along with the inherent flexibility of Modelica, provides the system with a high degree of adaptability and scalability.

In this way, the parameters of the different components of the simulator can be modified to meet the user's requirements. These parameters range from more specific properties of each component, such as the geometry of the reactor or electrolyzer, to more general parameters, such as the number of electrolyzer modules or system controller settings, as well as their setpoint values.

Additionally, it is possible to incorporate new components into the system with small adjustments, which can improve the model's accuracy or expand its capabilities to study other technologies.

5.1.6 Capability of potential risks identification

As shown in the test cases, the simulator can be used to study the system behavior to verify its proper functioning or even identify potential safety risks to the plant. Thanks to the complexity of the main components, it is possible to assess the reactor state in response to normal operational variations. A clear example is presented in the test cases, where properties of the reactor core, such as reactivity (an indicative measure of operational stability) and the thermal power delivered, can be studied. These studies help detect the operational limits of the entire system before harmful values are reached in the SMR.

Additionally, the simulator can also be used to identify issues related to hydrogen production, such as insufficient or excessive reductions in electrical current, as well as temperature decreases in the intermediate loop.

5.1.7 Optimization capability

One of the additional goals of the task and the simulator is to add the capability of coupling the model with the PERSEE optimization tool, allowing for direct optimization of the simulation by considering the constraints introduced in the tool. This enables the system to be optimized

quickly while accounting for restrictive parameters not included in the Modelica model, such as costs or CO2 emissions.

5.2 District Heating simulator

To verify the correct functioning of the District Heating simulator, two test cases were prepared to demonstrate the capabilities outlined in the model description.

5.2.1 Description of test cases

Reduction of heat supplied by the E-SMR

In this case, beginning from a steady-state operating condition, a variation occurs in the cogeneration of the reactor's BOP, reducing the amount of thermal energy extracted and thereby increasing electrical energy production. Such variations allow for the study of potential fluctuations in the district heating network due to foreseeable events, such as an increase in electrical demand that may need to be met by the E-SMR.

At the parameter level, the boundary conditions have been set as outlined in Table 15 to achieve the desired variation in the system.

Boundary Condition	Variable	Value
Thermal power extracted from the reactor BOP	Initial output thermal power [Wth]	100e6
	Final output thermal power [Wth]	0
	Transient start time [s]	28800
	Transient duration [s]	7200
Return temperature from the DHN	Temperature setpoint [K]	323.15
Supply temperature to the DHN	Temperature setpoint [K]	368.15
Helsinki East thermal power supply	Thermal power [Wth]	60e6
Helsinki East thermal power demand	Thermal power [Wth]	200e6
Helsinki West thermal power supply	Thermal power [Wth]	240e6
Helsinki West thermal power demand	Thermal power [Wth]	200e6

Table 15. Parameters for Test Case 1 in the District Heating Simulator

For this purpose, it has been assumed that the reactor provides a steady 100 MWth of thermal power until, after 28,800 seconds of simulation (8 hours), a complete reduction in the heat extracted from the system is introduced. This reduction is applied proportionally as a ramp signal over a duration of 7,200 seconds (2 hours).

Reduction of heat demand in Helsinki East

For this test case, starting again from a steady-state condition, a reduction occurs in the heat demand of the Helsinki East district heating network. This variation allows for studying how the system evolves and how the heat not absorbed by one of the distribution networks is redistributed, enabling an assessment of the state of the transmission and distribution networks, as well as the thermal storage status of the system.

The values used this time for the boundary conditions are similar to those of the previous case, with the variation in reactor production removed and a variation introduced in the demand of the Helsinki East district heating system. Thus, the initial thermal demand of Helsinki East is considered to be 200 MWth, decreasing to 100 MWth after 28,800 seconds (8 hours) of simulation. This reduction, as before, occurs proportionally over 7,200 seconds (2 hours) of simulation.

Boundary Condition	Variable	Value
Thermal power extracted from the reactor BOP	Thermal power [Wth]	100e6
Return temperature from the DHN	Temperature setpoint [K]	323.15
Supply temperature to the DHN	Temperature setpoint [K]	368.15
Helsinki East thermal power supply	Thermal power [Wth]	60e6
Helsinki East thermal power demand	Initial thermal power [Wth]	200e6
	Final thermal power [Wth]	100e6
	Transient start time [s]	28800
	Transient duration [s]	7200
Helsinki West thermal power supply	Thermal power [Wth]	240e6
Helsinki West thermal power demand	Thermal power [Wth]	200e6

Table 16. Parameters for Test Case 2 in the District Heating Simulator

5.2.2 Results of the test cases

Reduction of heat supplied by the E-SMR

Once the simulation is completed, it is possible to observe the variation in the system due to the reduction in heat extracted from the BOP.

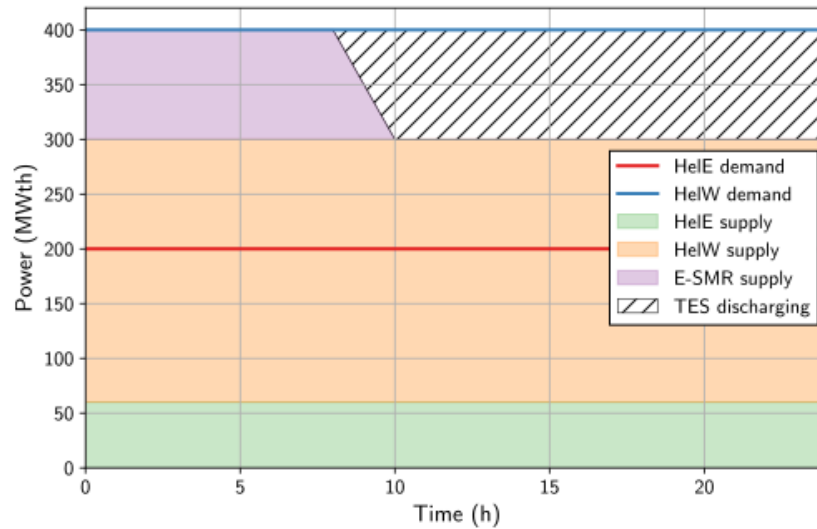


Figure 22. Heat Supply and Demand in District Heating Simulator - Test Case 1

Figure 22 shows the sum of the different sources of thermal energy, as well as the total demands in the distribution networks of the district heating system. It can be observed that after 8 hours of simulation, the thermal power from the reactor (E-SMR supply) decreases by 100 MWth, while the demands of both networks remain constant. Consequently, since it is necessary to meet this demand, the storage system discharges to provide the missing 100 MWth (TES discharging).

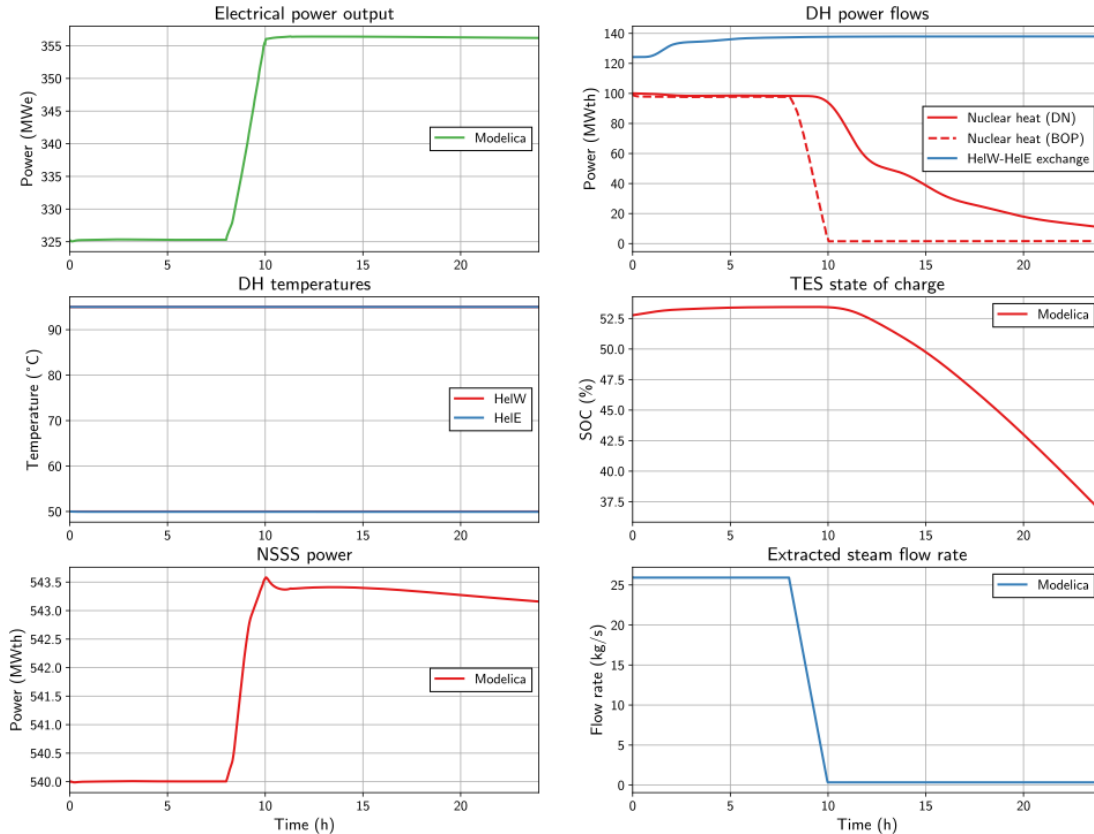


Figure 23. Results of the District Heating Simulator - Test Case 1

Figure 23 includes six different graphs that provide a comprehensive overview of the most important systems in the simulator. From these graphs, the following conclusions can be drawn:

- Thanks to the presence of the thermal energy storage system, which compensates for the decrease in heat extracted from the BOP, it is confirmed that the supply and return temperatures in the distribution networks of Helsinki West and Helsinki East are controlled at the set values of 95°C and 50°C, respectively.
- The load status of the TES decreases by more than 10% of its nominal capacity during the first 10 hours following the complete reduction of heat supplied by the reactor, indicating that the system could not sustain this operating mode for an extended period without additional heat input from another source.
- Due to the total reduction of heat extraction, the heat that is not extracted is utilized for electricity generation in the BOP, resulting in an increase of over 30 MWe in total electrical energy production.

Reduction of heat demand in Helsinki East

Similar to the previous case, the reduction in demand in Helsinki East affects the entire system, and its status can be assessed through simulation.

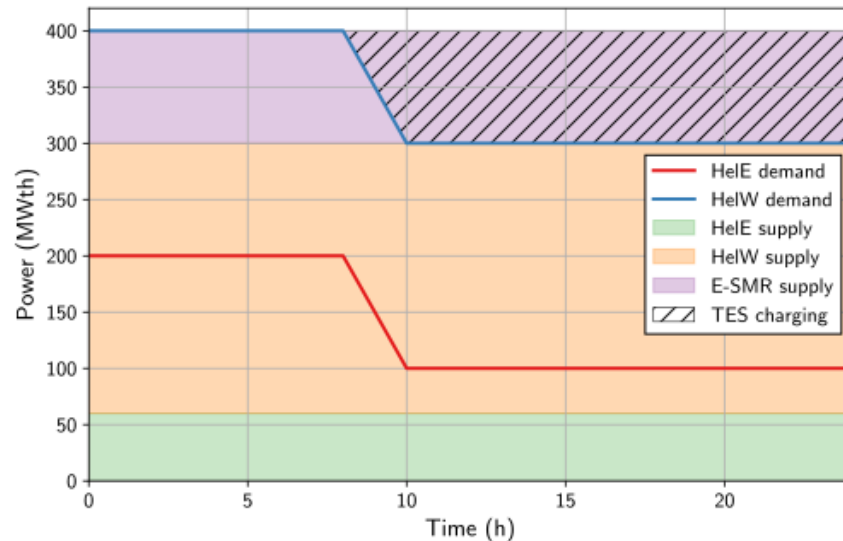


Figure 24. Heat Supply and Demand in District Heating Simulator - Test Case 2

By observing Figure 24, which displays the demands and sources of the system, it can be seen that, due to the reduction in demand in Helsinki East, the total power demand of the system decreases, reaching 300 MWth after 10 hours of simulation. Since the heat extraction from the BOP does not vary, there is an excess of thermal energy entering the district heating system. In this case, this excess energy is used to charge the TES, dynamically increasing the load from the moment the demand reduction begins (at 8 hours of simulation) until the end of the simulation.

On the other hand, Figure 25 presents the representative graphs for this case, allowing for an understanding of the state of the entire system during the simulation:

- The temperatures in the distribution networks of Helsinki West and East do not experience significant variations, remaining at the set values, with the latter showing a slight increase in return temperature.
- The excess heat not utilized by the Helsinki East network is used to charge the thermal energy storage system of the entire district heating network. It can be observed that, starting from 10 hours of simulation, the amount of water in the tank begins to grow proportionally, increasing the storage system load by over 20% during the next 14 hours.
- Since there is no increase in the steam extracted from the BOP, its electrical output remains practically constant.

- Finally, it can be observed that the reduction in incoming heat to the Helsinki East distribution network is due to the decrease in heat exchanged between the Helsinki East and West networks, dropping from about 140 MWth to around 40 MWth of exchanged heat.

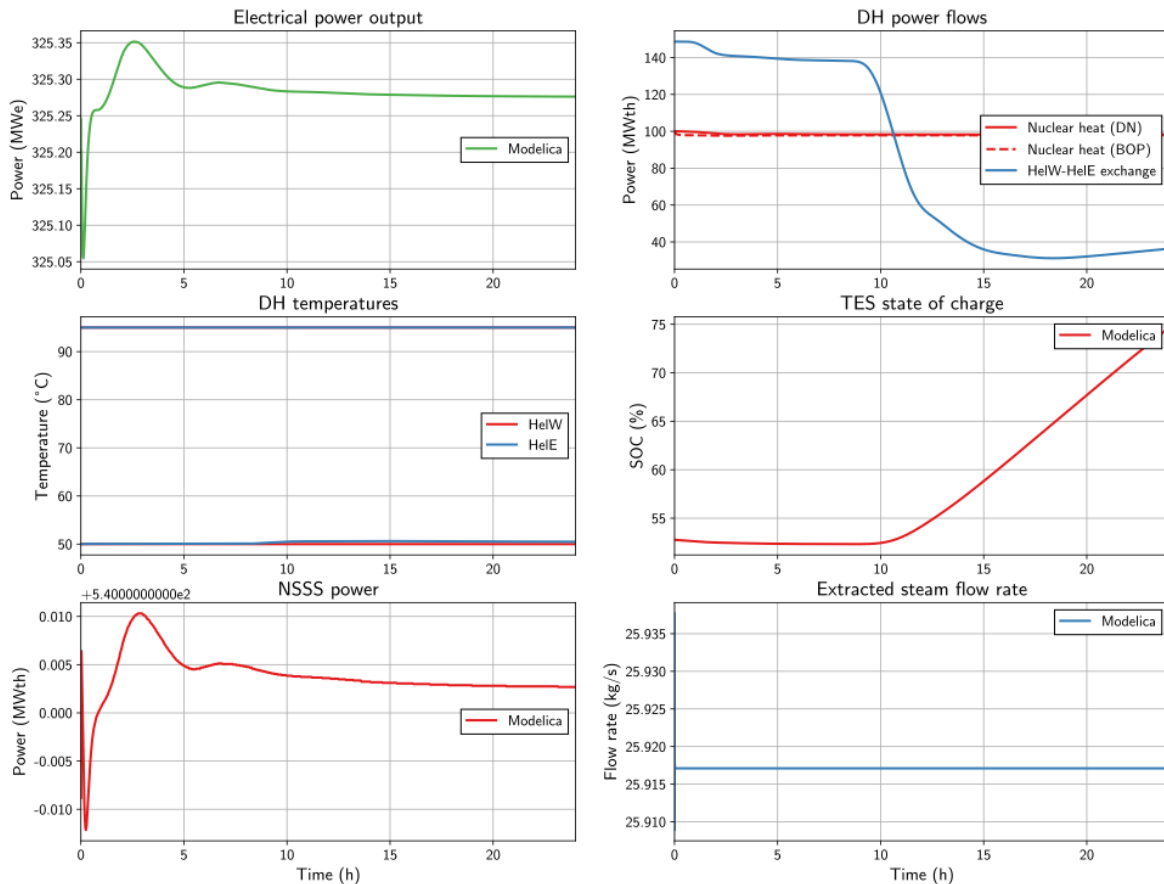


Figure 25. Results of the District Heating Simulator - Test Case 2

5.2.3 Functions evaluation

Similarly to the other simulator, the District Heating simulator can perform a range of transients and steady-state calculations that allow for the analysis of the distribution and transmission networks within the district heating system of the Northern European Case. Additionally, it enables SMR and BOP status to be assessed.

These calculations facilitate forecasting the condition of specific system components, evaluating the impact of anticipated demand changes, and quickly experimenting with adjustments to the control system and its setpoint values, thereby optimizing overall system control.

Some of the simulator's key functions include:

- Simulating scenarios of increased or decreased thermal power demand by the district heating network.
- Adjusting the extraction of electrical power from the system to fine-tune the cogeneration operations of the BOP plant.
- Modifying control system setpoint values that directly impact the district heating system, such as the supply or return temperatures of distribution networks.
- Analyzing reactor status in response to system-wide variations, enabling the study of the neutronic state of the reactor core, temperature, and the total thermal power delivered by the SMR.

5.2.4 Limitations

This simulator has a series of limitations that may affect the results in specific simulation scenarios. Some of these limitations are mentioned in the assumptions section due to the simplification of certain components or systems, while other limitations directly impact the simulator's capabilities.

The most important limitations are:

- It is not possible to simulate abrupt changes in reactor operation, such as startup or emergency shutdown procedures.
- A control system for the electrical part of the simulator has not been defined. This means that all electrical power generated by the reactor BOP is fed directly into the electrical grid, preventing the study of electrical phenomena caused by overloads or grid frequency variations due to excess power output.
- The system has been sized for typical winter operating temperatures. Therefore, if the simulator is used at other temperature levels, a series of adjustments will be required.
- The control system is not optimized for a specific operational mode.

5.2.5 Adaptability of the hybrid energy system simulator

Similarly to the Energy Hub simulator, the District Heating simulator allows modifications by adjusting various component parameters, such as the geometric properties of the nuclear island, heat exchangers, or internal parameters of the Helsinki district heating network.

Additionally, new components can be added easily, including other sources of heat or electricity, enabling the simulation of different case studies, such as those included in the TANDEM/deliverable 3.2. In this regard, the TANDEM library provides a wide range of components to facilitate more in-depth studies with the simulator.

5.2.6 Capability of potential risks identification

Thanks to the capabilities of the simulator, it is possible to conduct a series of transient simulations to study risk situations across the entire system. While the behavior of the reactor core cannot be analyzed during emergency shutdowns or startups, variations within the core—such as operating temperatures, neutronic state, and coolant condition—can still be assessed.

Additionally, given the importance of the district heating network in the simulator, it is possible to detect drops in the temperatures of the district heating distribution networks, which can affect the heat supply to the district heating system in Helsinki. Furthermore, by examining the load status of the thermal energy storage (TES) network, it is feasible to identify situations of thermal overload that could subsequently impact the state of the BOP and the reactor upstream.

5.2.7 Optimization capability

Similar to the other simulator, one of the objectives of this simulator is its ability to be coupled with the Backbone optimization tool, with the aim of optimizing various system parameters, such as the setpoint values of the control system.

Therefore, the simulator is designed to both receive and provide the necessary information to the tool, making it a highly adaptable system for optimization.

6 Future improvements and enhancements

The described simulators allow for complex steady-state and transient calculations, as mentioned earlier. However, there are certain limitations or simplifications that open the door to the implementation of a series of improvements. Although these improvements are not within the project scope, they are outlined in this section to facilitate possible next steps for further development of the simulators:

- **Improve the electrical component of the district heating simulator:** to enable an adequate study of the system electrical grid, it is recommended to include components from the Buildings library, available in the Modelica repository of the project, to simulate the electrical state at various electrical nodes as well as the loads. Additionally, it is suggested to incorporate new electric power generation systems, such as photovoltaic or wind power plants. Furthermore, a more complex control system for the electrical grid of the simulator would also be necessary.
- **Enhance the Energy Hub simulator to replicate all cases studied in TANDEM/deliverable 3.2:** this improvement would involve including those components that, while not considered in the run7 case study, are present in the other cases. Some of these components include: LTE, SMGR, among others.
- **Create a simulator for the Central European case for the district heating network of the Czech Republic:** this would require modifying the components of the Finnish district heating simulator, generating a new model that includes the distribution and transmission networks of the region.
- **Improve the simulators by reducing the number of simplified components:** this proposed improvement should be carried out with consideration of the trade-off between the convergence speed of the current simulators and the accuracy or depth of the results. As an initial proposal, it is suggested to begin by modifying or replacing the hydrogen storage tank of the Energy Hub simulator, as well as the upstream compressor, since these changes could add an interesting depth of study to this type of simulator.

7 Conclusions

The simulators designed and assembled as part of Task 2.3 demonstrate the practical functionality and capabilities of the TANDEM library components when integrated into a complex Hybrid Energy System.

These simulators allow for the study of hybrid system behavior in the project Northern and Southern European cases and can be adapted for the Central European Case with some adjustments and modifications to the Northern case. Key features of these simulators include their ability to analyze SMR behavior, enabling examination of parameters such as reactivity and thermal power over different simulation periods, as well as to study the district heating network and the electrolyzer, depending on the simulator.

Although this is an initial version, the simulators are designed for integration with the PERSEE and Backbone optimization tools, enabling combined techno-economic and operational studies and optimization analyses to identify the most suitable values and sizing for the entire system.

These simulators are publicly available in the GitLab repository of the TANDEM library [7], allowing users to run the included test cases, add new cases, or even enhance the simulators based on the proposals in this deliverable.

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