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Cross-comparison of simulation results between PERSEE, the modelica simulator and ECOSIMPRO for the energy hub configuration

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Summary

TANDEM project will perform a technical study that includes the development of a EcosimPro® simulation model, and a comparative analysis of the results obtained with it and the abovementioned codes to: - Ensure the predictivity of the hybrid energy system models implemented in the energy hub studies in TANDEM/WP3, - Assess the impact of the lump models of PERSEE against the Modelica-based simulator on the techno-economics optimization results, using EcosimPro® model. - Identify the issues that may arise due to potential discrepancies due to system?s sizing, operating points, boundary conditions and additional aspect to be studied.

Approval

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D3.5 - Cross-comparison of simulation results between PERSEE, the modelica simulator and ECOSIMPRO for the energy hub configuration

WP3 - Task 3.3

April 01, 2025 [M32]

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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 Commision
CHP	Combined Heat and Power plant
EAI	Empresarios Agrupados Internacional
HES	Hybrid Energy System
HTSE	High Temperature Steam Electrolyser
HX	Heat exchanger
MILP	Mixed Integer Linear Programming
NPP	Nuclear Power Plant
NSSS	Nuclear Steam Supply System
SMR	Small Modular Reactor
SOC	State Of Charge
SOEC	Solid Oxide Electrolyser Cell
WP	Work Package
WPP	Wind Power Plant

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Executive Summary

This deliverable, Deliverable 3.5 (D3.5), presents the results of Task 3.3, which focuses on the technical study of the optimized Energy Hub architecture using the EcosimPro® modeling and simulation tool. This architecture is based on the Energy hub configuration, as described in Deliverable 1.4, along with additional information provided in Deliverable 3.2 (sizing of a low-carbon solution). The case study explores the potential of nuclear energy (SMRs) integration in hybrid energy systems.

The simulator and the subsequent technical study have been conducted by Empresarios Agrupados Internacional (EAI) using various EcosimPro® libraries, supported by POLIMI and CEA. Additionally, new components have been developed and modified to align with the expected scope of the task. The technical study includes a comparative analysis of the results obtained using different simulation and optimization tools within the project, including the Modelica-based simulator developed in Deliverable 2.5 and the PERSEE optimization tool. Note that the the level of the model implemeted in the PERSEE optimization tool came from a compromise between computing time and accuracy. It is not expected that the PERSEE model can reach the same level of performance as the Modelica-based and EcosimPro® models. Further studies have been conducted in the project to assess the impact of the lump models of PERSEE against the Modelica-based simulator on the techno-economics optimisation results (see TANDEM/Deliverable 3.4).

The objective of this study was to give first elements to ensure the predictivity of the hybrid energy system models implemented in the energy hub studies in TANDEM/WP3.

Keywords

Energy Hub, Simulator, PERSEE, Modelica, EcosimPro, Small Modular Reactor, SMR, HTSE, Electrolyser, Hydrogen Production, TANDEM, Renewable energy sources

1 Introduction

The EU TANDEM (Small Modular Reactor for a European Safe and Decarbonized Energy Mix) project presents an illustration to size an Energy Hub configuration to produce heat, electricity and hydrogen. The sizing, resulting from an optimization process (minimization of total cost taking into account constraints on CO2 emissions) has been carried out with the PERSEE tool [3]. The analysis will be completed with operational studies with the coupling between PERSEE and the Modelica-based simulator developed with the TANDEM Modelica library.

Within this framework, the aim of this deliverable is to conduct a technical study to assess the consistency of the results obtained using the PERSEE optimization tool and the TANDEM Modelica-based simulator with the EcosimPro® simulation tool. PERSEE is a tool designed for conducting techno-economic and enviromental studies based on Mixed Integer Linear Programming (MILP), enabling optimization simulations [1][3]. The Modelica-based simulator used in this study was developed in Task 2.3 of the project, utilising the TANDEM Modelica library created within the scope of the project [5].

To perform this technical study, an Energy Hub simulator is developed within the scope of TANDEM, according to the Southern European Case [2], using EcosimPro®. Subsequently, various simulations are performed to compare the physical behavor of the various components in the hybrid energy system and analyze multiple aspects of their performance. This study includes:

- Analysis of possible differences on the key simulated parameters characterizing each component.
- Investigation of potential causes for inconsistencies between models.

Additionally, this deliverable includes a discussion of the EcosimPro® simulator capabilities and limitations, as well as an explanation of the control philosophy implemented in the system. Similarly to the simulators developed in Modelica, the requirements and limitations of the individual models have been considered during the development of the simulator.

The simulator model has been built using the EcosimPro® modeling and simulation tool, leveraging available libraries within the software for various components. In this case, the FLUIDAPRO library is used for modelling the Thermal Energy Storage (TES) system, the THERMAL_BALANCE library for the Nuclear Power Plant (NPP), the HVAC library for fluid calculations in the electrolyser balance of plant as well as the hydrogen compressor and storage, and the SMART_GRID library for modelling renewable energy sources. Additionally, custom components, such as the High Temperature Steam Electrolyser, have been developed as needed to simulate the different system modules according to the model scope. This scope includes the following subsystems:

- Nuclear Power Plant: Small Modular Reactor (SMR) and its balance of plant (BOP).
- High Temperature Steam Electrolyzer (HTSE): Solid Oxide Electrolysis Cell (SOEC) stack and its BOP.
- Energy storage: tanks for Thermal Energy Storages.
- Hydrogen storage: Hydrogen compressor and storage system.
- Renewable sources: Wind Power Plants (WPP) and photovoltaic plants (PV).
- Additional power sources as a Combined Heat and Power plant (CHP) .

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

2 TANDEM Energy Hub System Description

The Energy Hub system of the TANDEM project is designed for electricity and hydrogen production, aiming to enhance operational flexibility to meet a demand of 8.257 ton/h H_2 and 657GWhe per year [3], while also studying the reduction of energy dependence on fossil sources. The system is studied for implementation in Southern Europe, specifically in Fos-sur-Mer, France.

For this task, the study is conducted in accordance with the specifications of the case study “run7” from deliverable D3.2. The "run7" case study corresponds to one possible configuration of the low-carbon energy hub and focuses on a 2050 energy scenario with a high penetration of Small Modular Reactors, reducing dependence on fossil energy sources without completely eliminating it.

In this scenario, thermal production is centered on a set of two SMRs, each with a nominal thermal power of 540 MWth. Through their respective Balance of Plant systems, they achieve a nominal electrical power output of 170 MWe when no thermal extraction occurs and 155 MWe when operating at the maximum designed thermal extraction of 50 MWth.

Additionally, there are three other electrical energy sources: a photovoltaic plant with a nominal capacity of 200 MWe, a wind farm with 33 MWe, and a gas-fired combined cycle plant with 88 MWe.

The primary consumer of the generated energy is a High Temperature Steam Electrolyser with a nominal consumption of 367 MWe, complemented by a hydrogen storage system.

All these components are electrically interconnected through a grid operating at 380 kV, while the thermal connection is exclusively between the SMR system and the High Temperature Steam Electrolyser plant via a network of pipelines.

This structure is illustrated in Figure 1. For further information regarding the case study “run7”, please refer to TANDEM/Deliverable 3.2 [3].

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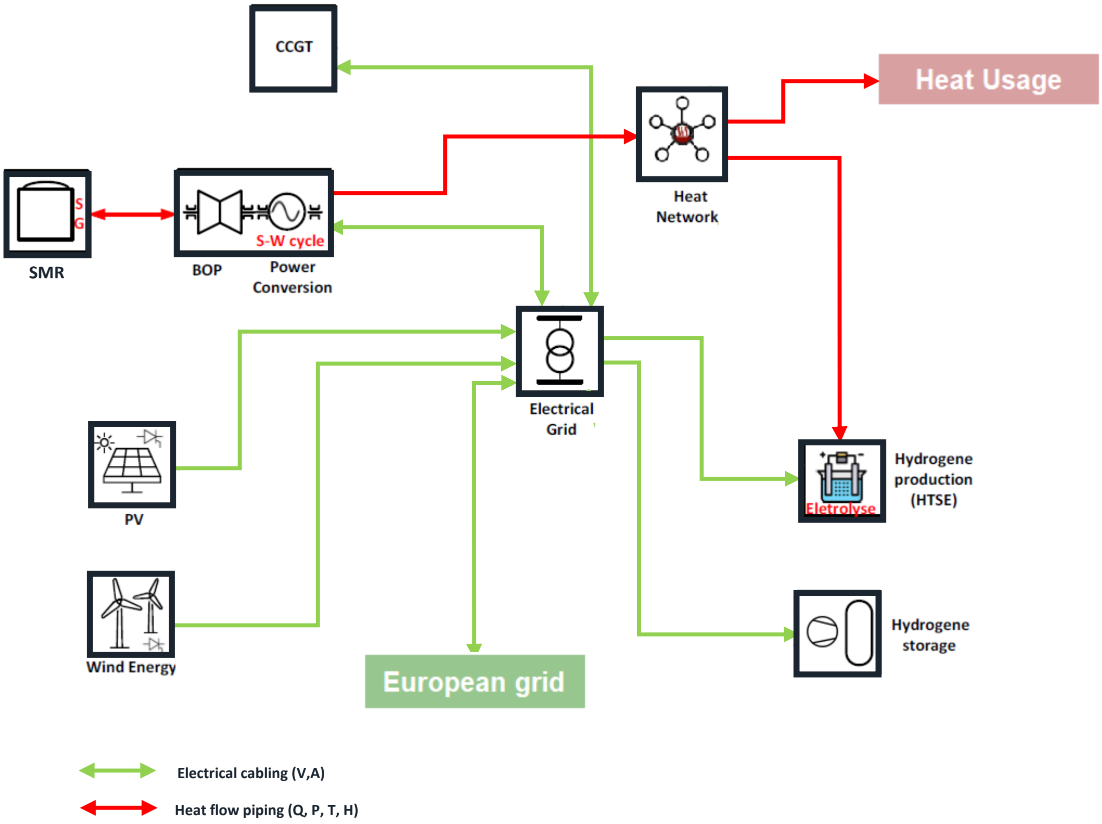

Figure 1: Case "run7" scenario scheme ([6]).

The diagram shown in the previous figure has been used as the basis for the development of the various models in the Energy Hub system simulator.

3 Model Scope

The simulation model of the Energy Hub system has been designed and sized to achieve the nominal values described in the previous section. It takes into account the development and scope of the models created in the TANDEM Modelica library [4] and the model developed with the PERSEE optimization tool [1], allowing for a technical comparison between them.

The scope of the Energy Hub system simulator includes:

- Nuclear Steam Suply System: The dynamic model of the nuclear plant includes the SMR as a thermal source and the BOP that allows the electricity generation and the thermal extraction required by the system.
- High Temperature Steam Electrolyser: The simulator contains the dynamic model of the electrolyser, as well as the BOP model that allows thermal exchange with the heat extracted from the nuclear plant.
- Renewable Energy Sources: The dynamic models of the wind and solar plants are included.
- Thermal Energy Storage System: The system includes the dynamic model of a thermal energy storage system based on two tanks, placed between the nuclear plant and the electrolyzer, thus increasing the flexibility of the entire system.
- Combined Cycle Gas Turbine: The scope of this system is limited to a simplified model of a CCGT.
- Hydrogen Storage System: This system contains a dynamic model of a three-stage compressor, as well as a hydrogen storage tank.

The coupling of all these models allows the evaluation of the system's performance at different operating points, thus enabling the analysis of the following aspects:

- Maintaining the reactor at a constant load while varying the thermal power extracted from its BOP.
- Varying the hydrogen demand of the system and its production, allowing the study of different optimal operating points.
- Studying the electrical production from the included renewable sources, thereby reducing reliance on fossil sources.
- Analyzing the electrical consumption of different components in the system, such as the HTSE or the hydrogen storage compressor, among others.

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4 Overview of the Dynamic Simulation Tool

The Energy Hub system model of TANDEM has been developed using a set of proprietary libraries from the EcosimPro® simulation and modeling platform (version 7.0), along with the implementation of various components required to simulate specific aspects of the system.

Specifically, the toolkits THERMAL_BALANCE, HVAC, FLUIDAPRO, and SMART_GRID were utilized in this system and will be described in the following sections.

EcosimPro® enables a modular organization of the different subsystems and components within the models, enhancing the readability of schematics and data while also facilitating future modifications and improvements.

4.1 EcosimPro® Overview

EcosimPro® [7] is a multidisciplinary simulation tool that has been developed by EAI (Empresarios Agrupados Internacional) under partial ESA funding. EcosimPro® development started in 1989 within the framework of the Environmental Control and Life Support Systems (ECLSS) to assist for its modelling in the Hermes and Columbus ESA projects.

EcosimPro® is a powerful mathematical tool, which is capable of modelling any type of dynamic system that can be represented by equations (differential, algebraic, linear and non-linear) and by discrete events. It is an intuitive tool as it has a very powerful graphical user interface similar to other modern Microsoft work environments.

EcosimPro® can be used to carry out multiple types of studies: stationary, transient, parametric, optimization, design, etc. The modeller only has to create or reuse the basic components (turbine, compressor, etc.) and EcosimPro® handles the complexity of extracting, sorting and solving all the equations numerically.

This software has its own modelling language, called EL (EcosimPro® Language). It is based on more than 30 years of experience of many engineers working in simulation in the energy and aerospace sectors.

An EcosimPro® 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, flow, etc.

Each library component has an associated symbol and each symbol can be configured for different cases modifying the values of the set of input data. That means the components can be reused as often as the user requires. This concept of modelling gives the user considerable flexibility for building models.

The main features of EcosimPro® are as follows:

- Powerful algebraic-differential equation solvers that can work simultaneously with thousands of equations.
- A highly intuitive graphics tool to build systems by dragging and connecting multidisciplinary component icons in a workspace.
- Object graphics editor to initialise the data of each component.
- Display of results using graphs, histograms, etc.
- Post-processing capability through the generation of a binary file with the simulation results.
- Multidisciplinary use of libraries, making it possible to create components that mix disciplines such as mechanical, electrical, fluids, control, etc.
- Easy-to-learn modelling language for programming the basic components of a library. These are some of the advantages:
- Object oriented (inheritance, aggregation, etc.).
- Existing C/C++ and FORTRAN functions can be called from the EL language.
- Support causal and non-causal modelling approaches.
- Discrete events and state machines can be modelled..
- Intelligent connection ports to simplify the modelling of variables between components.
- Highly versatile experiment language.
- Connectivity with other engineering tools: Matlab/SIMULINK, MS-Excel, ISIGHT, MS-Visual Basic etc.). Additionally EcosimPro models can also be translated into C++ code, which can be reused in other C++ applications.
- Export models as black box. Models and calculations can be encapsulated and encrypted in a standalone application (deck) with user defined accessible input/output variables.
- HIL and OPC standard: A model can also be exported ready to be used in a HIL (Hardware In the Loop) system through Simulink. It can be connected to SCADAs, other models or hardware using OPC standard as well.

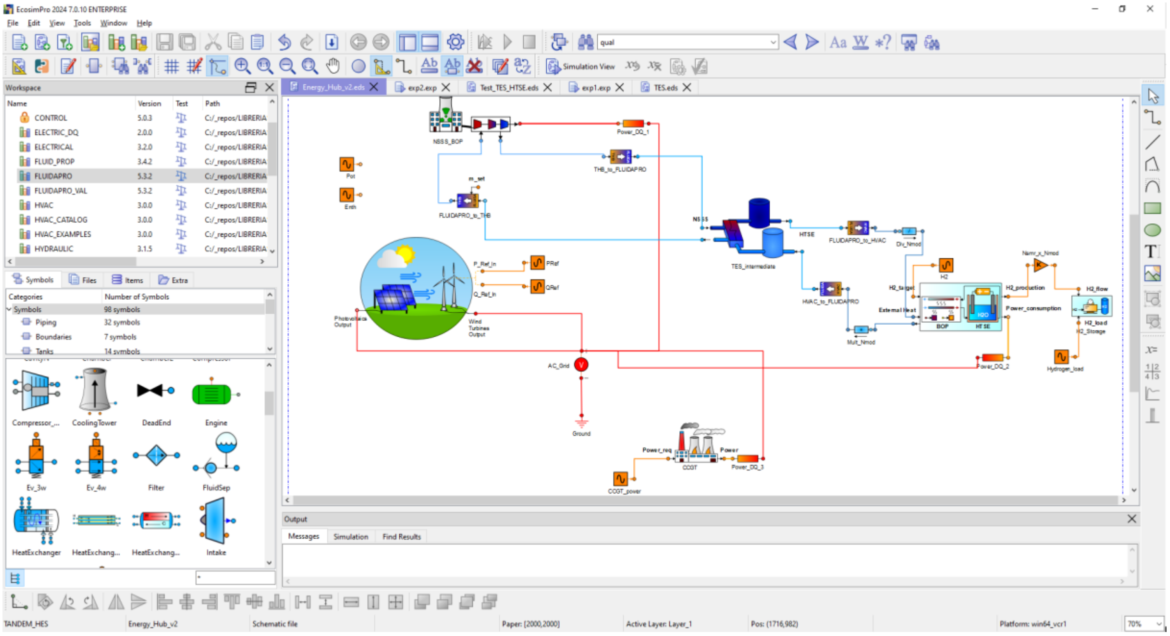

Figure 2: Graphical User Interface of EcosimPro®

4.2 THERMAL_BALANCE toolkit

The THERMAL-BALANCE toolkit is used to carry out steady state thermal balance studies in typical power generating plants (Coal, Combined Cycle, Nuclear, Thermosolar, etc). The toolkit also enables performing studies with slow dynamics where model boundary conditions change with time.

The main features of this toolkit are the following:

- The schematics generated with EcosimPro/PROOSIS are similar to the layout of the plant, which allows the user to easily identify any part of the model.
- Component formulation according to accepted codes, such as the American Society of Mechanical Engineers (ASME) code and the Heat Exchange Institute (HEI) code, among others, including steady state and some dynamic behaviour and controls.
- The toolkit contains a wide range of ready-modeled components which cover all modelling needs of these types of systems, ie, pumps, compressors, valves, pipes, motors, heat exchangers, condensers, turbines, evaporators, electric generators, cooling towers, etc.
- The toolkit is prepared to work not only with water, but also with air, oxygen, carbon dioxide, carbon monoxide, helium, argon, methane, propane, butane and sulphur dioxide. Users will also find it easy to add new fluids.

The palette of the components included in the THERMAL_BALANCE toolkit is shown in Figure 3.

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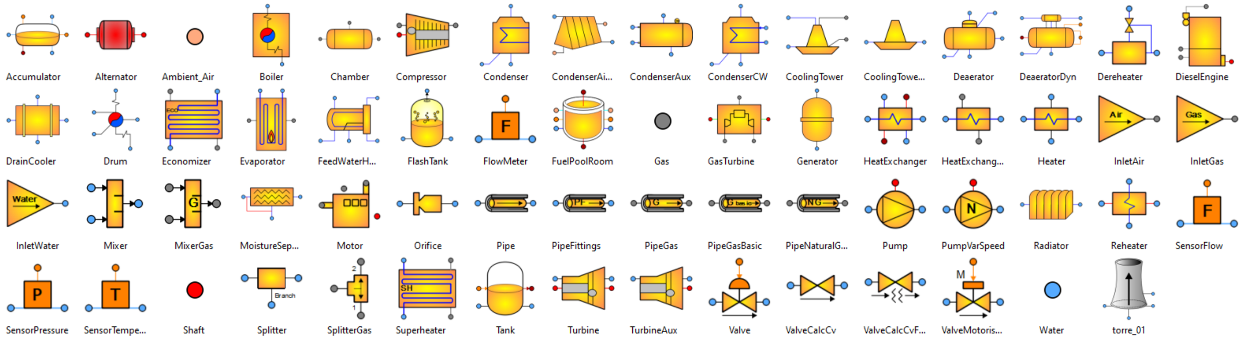

Figure 3: Palette of the THERMAL_BALANCE library

For the TANDEM project, this toolkit has been used for modeling the SMR and the BOP of the nuclear power plant, as detailed in the following sections.

4.3 HVAC toolkit

The HVAC toolkit is designed with consideration for the influence of human presence within heating, cooling, and ventilation systems. This toolkit enables transient simulations of fluid systems containing a gas mixture with a vaporizing liquid, combustion processes, or Heating, Ventilation, and Air Conditioning (HVAC) system analysis.

This toolkit comprises multiple libraries that allow for the design of simple fluid networks as well as complete, complex buildings with their associated control systems. The included libraries are:

- HVAC Library: Contains all the fundamental components required for complex transient calculations of fluid characteristics in duct and piping networks. Additionally, these serve as the foundation for developing more complex components included in the BUILDINGS library.
- BUILDINGS Library: Includes components related to building envelopes as well as a wide range of specialized machinery for HVAC systems.
- HVAC_CATALOG Library: Provides manufacturer-specific components modeled according to their operational and control curves.

The toolkit offer the following main features:

- Capability for the design and sizing of equipment, air ducts, and fluid piping, as well as their control.
- The toolkit includes a large number of modeled components useful for HVAC networks, such as rooms, fluid volumes, human thermal models, pipes and ducts, heat exchangers, flow regulators, pumps, and compressors, etc.

- It contains macro-components used in HVAC systems, including chillers, air handling units, fan-coils, splitters, and boilers with gas composition calculations, etc.
- Includes an industry-standard fluid database with refrigerants such as R410A, R407C, R507A, and R1234ZEE, as well as other fluids like humid and dry air, water, natural gas, and hydrogen, etc.
- The specific formulation of this library accounts for air relative humidity to perform indoor air quality assessments.

Figure 4 and Figure 5 illustrate the palette of some of the components included in the HVAC toolkit.

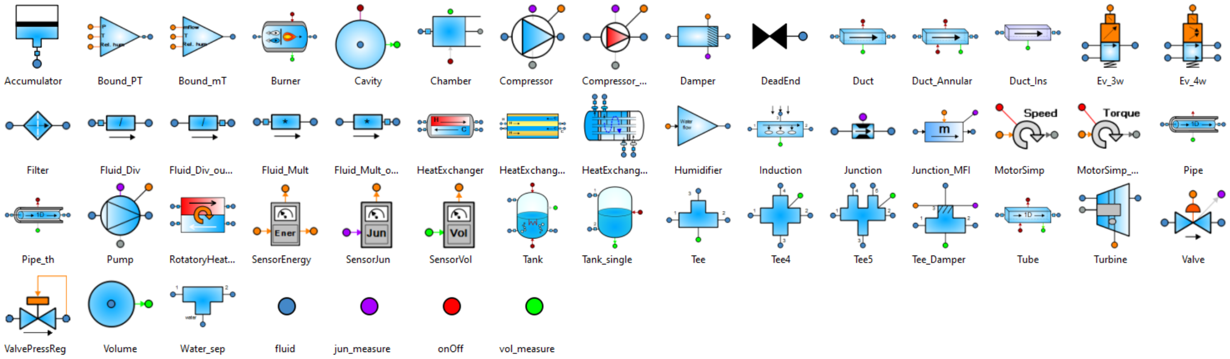

Figure 4: Palette of the HVAC library

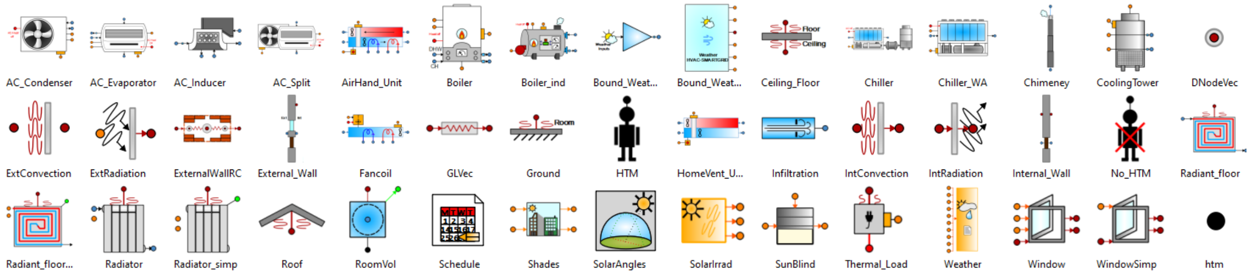

Figure 5: Palette of the BUILDINGS library

For this project, the HVAC library has been slightly modified to be used on the modeling of the BOP of the electrolyser, as well as for the modeling of the hydrogen storage system. In this approach, the pipes and boundary components have been adjusted to properly initialize the hydrogen calculation within the components.

4.4 FLUIDAPRO toolkit

FLUIDAPRO toolkit is designed to model and simulate complex dynamic fluid networks. Thanks to the multidisciplinary philosophy of EcosimPro, this library can be easily coupled to heat

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transfer effects and control loops. FLUIDAPRO also includes a fluid database and a set of thermodynamic functions able to work with different physical approaches for the calculation of the properties.

The toolkit provides the user with the capability of simulating the effects associated to fluid systems through different components such as volumes, heat exchangers, chemical reactors, tanks, pumps, pipes, valves or actuators.

Some of the main features of the toolkit are the following:

- Gas, liquid and two-phase flow regimes for ideal or real fluids.
- Reverse flow, inertia and high speed phenomena such as pressure waves and water hammer considered.
- Standard fluid database and a set of thermodynamic functions able to handle four different categories of fluids:
    - Perfect gases.
    - Simplified liquids, where energy and transport properties do not depend on pressure.
    - Van der Waals fluids.
    - Real fluids, considering all possible zones of operation: liquid, superheated, supercritical and two-phase flow.
- Calculation of a wide variety of effects like concentrated and distributed pressure losses, bubble formation and collapse due to cavitation, heat transfer between wall and fluid, tanks with level computation, pneumatic and hydraulic actuators, different types of valves and pressure regulators, heat exchangers, turbo-machinery, etc.
- Special device for the calculation of chemical reactions and chemical equilibrium.
- Adaptable code able to incorporate new components and capabilities.
- Easy-to-share models between EcosimPro users and also exportable as black boxes to be simulated independently.
- Multiple possibilities of interaction with external engineering software like Matlab/Simulink, Excel, etc.

The palette of components of the FLUIDAPRO toolkit is shown in Figure 6.

For this project, the FLUIDAPRO toolkit has been used to model the intermediate TES, connecting the nuclear BOP with the electrolyzer BOP.

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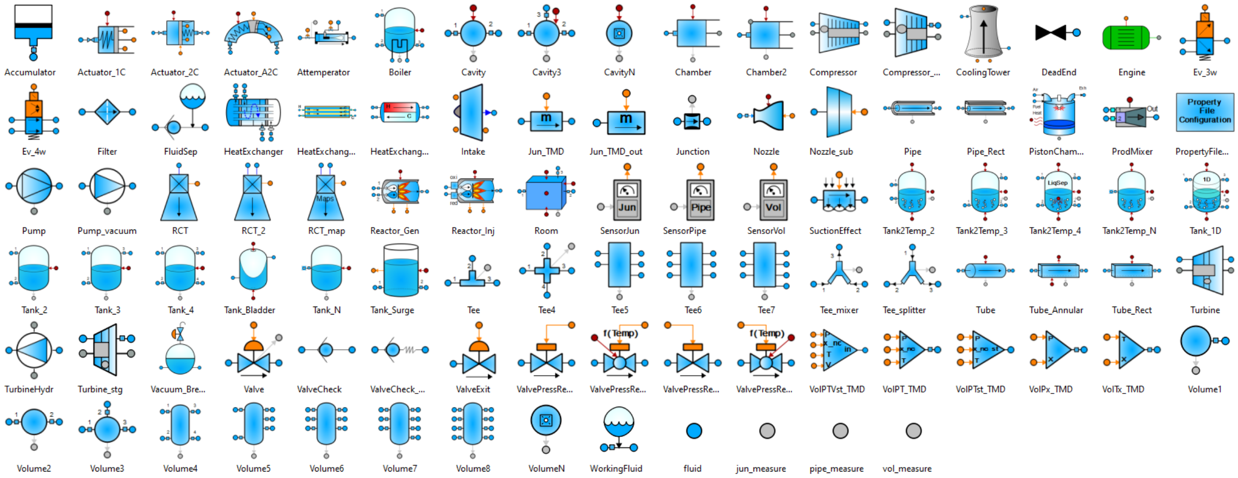

Figure 6: Palette of the FLUIDAPRO library

4.5 SMART_GRID toolkit

SMART-GRID library allows users to model and simulate micro and smart grid systems, including energy conversion from renewable sources. The toolkit aims to provide a tool for energy balance systems in small, medium and big systems, analyse the power balance and simulate different production-consumption scenarios.

The toolkit is formulated according to long-term transient and steady approaches. For this reason, the electric connections use the ELECTRIC-DQ toolkit as a natural counterpart, even though nothing prevents it from combining with other electric simulation domains with the expected reduction in performance.

Renewable energy components in the library can be understood as renewable resources (sun irradiation, wind, water flow…) to electric energy. All of them are based on performance curves, defined through tables and interpolation methods. Most of them expect an electric voltage phasor from outside and will return an electric current phasor.

For the environmental conditions simulation, four main variables are considered: Temperature, sun irradiation and position or wind speed, among others.

The palette of the components contained in the SMART_GRID library is shown in Figure 7.

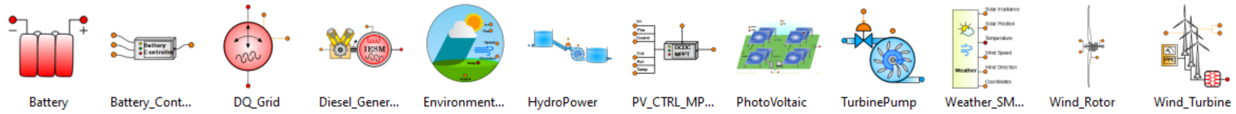

Figure 7: Palette of the SMART_GRID library

In this case, this library has been used to model and simulate the renewable energy sources included in the project scope, specifically wind and photovoltaic energy. Additionally, components from the toolkit have been utilized to generate the electrical grid of the system.

5 Model Description

The following section presents the description of the Energy Hub simulator developed by Empresarios Agrupados Internacional with EcosimPro®, considering the previously mentioned configuration.

The design and implementation of the subsystems within the model have been carried out by balancing the trade-off between simulation convergence speed and result accuracy. Additionally, this design process takes into account a future comparison with the Modelica-based model of the same system and the results obtained using the PERSEE tool.

The subsequent sections detail the assumptions considered in the model, the system boundary conditions, and the control philosophy implemented for this specific case. Additionally, the main computational capabilities of the simulator, as well as its limitations, will be outlined.

5.1 Schematics

The simplified scheme of the Energy Hub simulator for model development in EcosimPro® is similar to the one used for the Modelica models. In this case, this scheme is based on the configuration scheme described in TANDEM/Deliverable 2.5 [6].

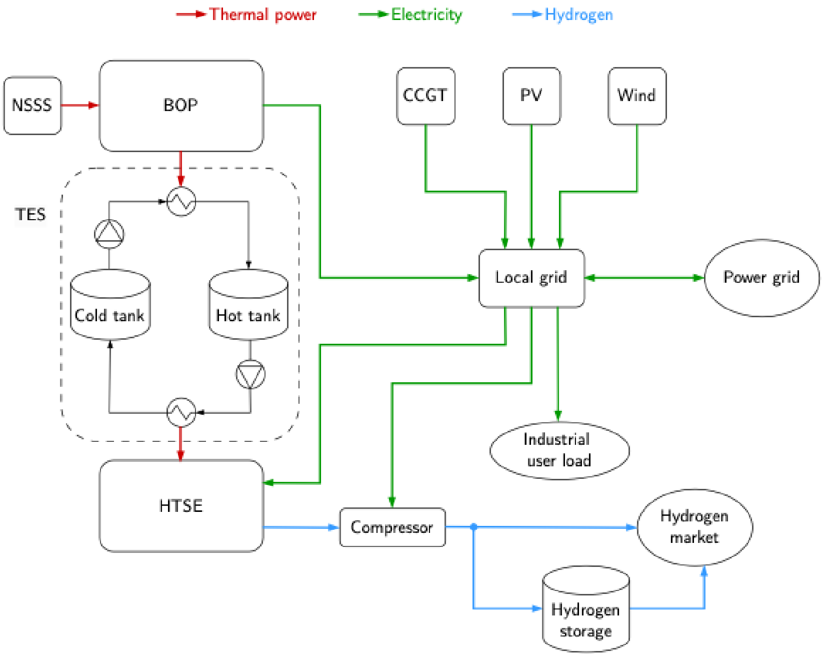

Figure 8: Energy Hub alternative configuration scheme ([6])

In Figure 8, the three loops that make up the different fluid and electrical networks of the system can be distinguished:

- 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.

Considering the scope of this deliverable and following a similar approach to the work conducted in the Modelica simulator, the thermal grid focuses on the connection between the BOP of the nuclear plant and the BOP of the electrolyzer through a two-tank TES system utilizing Therminol 66. This system enables decoupling the operation of the reactor and the electrolyzer, enhancing overall system flexibility.

On the other hand, the electrical grid has been modeled in a simplified manner, interconnecting all components through a general grid that allows each component to either draw or supply energy as needed.

Lastly, the hydrogen network links the electrolyser plant to the hydrogen compression and storage system, from which hydrogen is extracted according to demand.

This design has been used to develop the schematic of the simulator in EcosimPro®, as illustrated in the Figure 9.

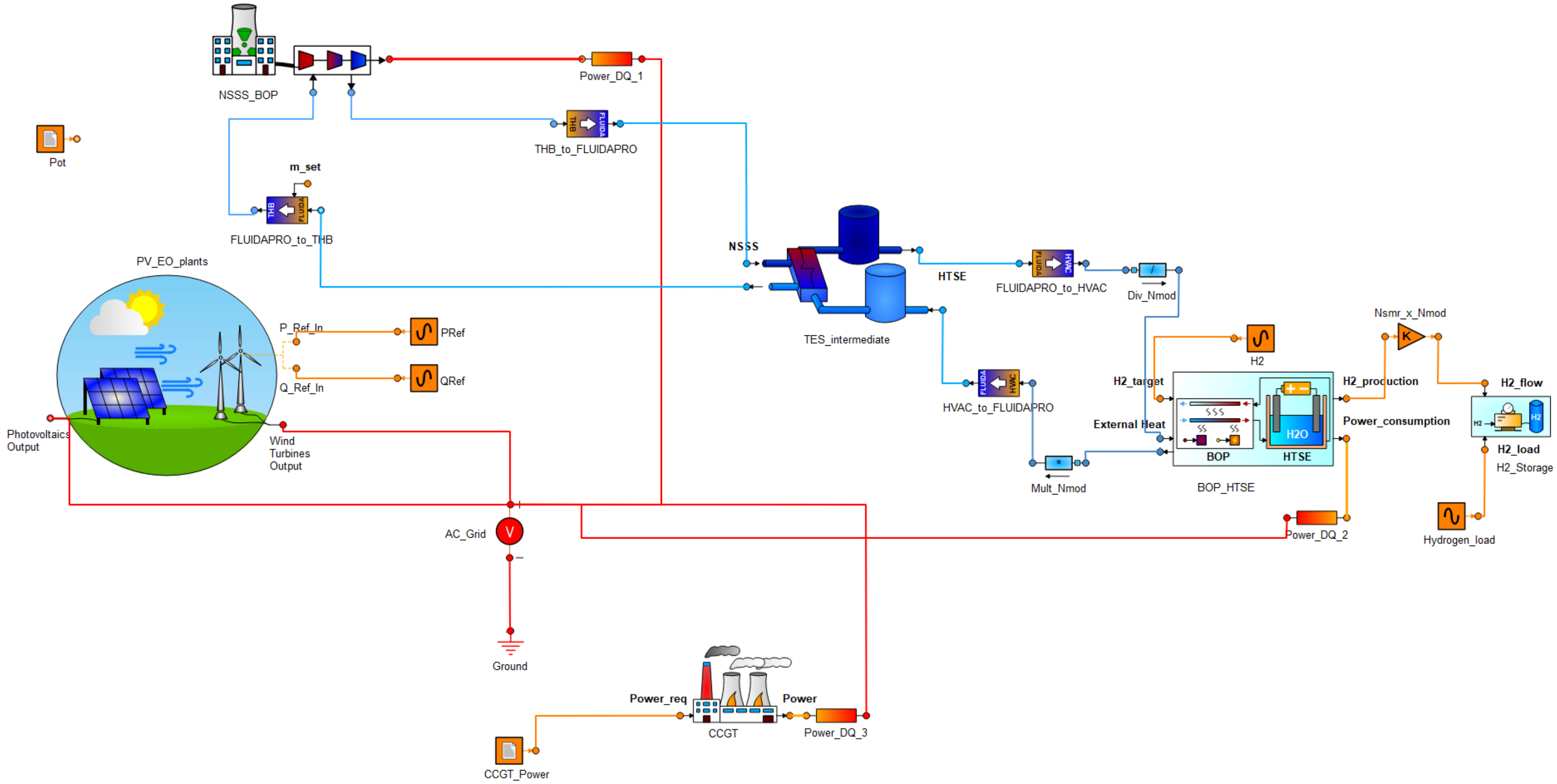

Figure 9: Schematic of the Energy Hub simulation model in EcosimPro®

The code names of the main components included in the model and the description of the models that they represent are provided in Table 1.

Component Name	Description
NSSS_BOP	Nuclear island consisting of the SMR and the BOP of the reactor.
TES_intermediate	Intermediate thermal energy storage based on a two-tank thermal oil system
PV_EO_plants	Renewable energy sources including the solar plant and wind farm
BOP_HTSE	Electrolyser plant comprising the HTSE and its BOP
H2_Storage	Hydrogen storage system consisting of the compressor and hydrogen tank
CCGT	Combined Cycle Gas Turbine plant
THB_to_FLUIDAPRO / FLUIDAPRO_to_THB	Port converter between the Thermal Balance library and FLUIDAPRO, and vice versa
HVAC_to_FLUIDAPRO / FLUIDAPRO_to_HVAC	Port converter between the HVAC library and FLUIDAPRO, and vice versa
Power_DQ	Analog signal port converter to the ELECTRIC_DQ library
AC_Grid	System electrical grid

Table 1: Code names of the main components of the Energy Hub simulator

The systems mentioned in the previous table consist of various models and components that enable the simulation of their dynamic operation. Below, the schematics of each specific system are presented, along with a list of the equipment that comprises them.

For more details on the modeling of each system, refer to the following sections of this deliverable.

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NSSS_BOP component

The schematic of the nuclear plant is shown in Figure 10. It illustrates the BOP of the reactor, including all its components, such as the power-generating turbines or other key systems like heat recovery or pumping.The list of main components is provided in Table 2.

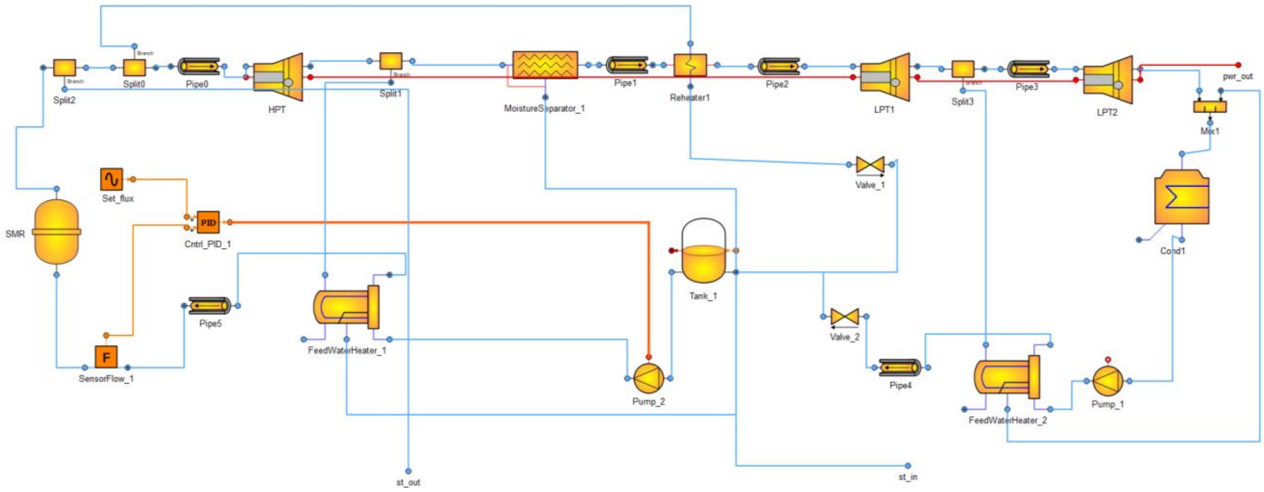

Figure 10: NSSS_BOP schematic

Component Name	Component Type	Description
SMR	THERMAL_BALANCE.Generator	Thermal power source representing the SMR model
HPT, LPT1 and LTP2	THERMAL_BALANCE.Turbine	High-pressure and low-pressure turbines
MoistureSeparator_1	THERMAL_BALANCE.MoistureSeparator	Moisture separator between turbines
FeedWaterHeater	THERMAL_BALANCE.FeedWaterHeater	Feedwater heater systems
Pump	THERMAL_BALANCE.Pump	Water pumps
Tank_1	THERMAL_BALANCE.Tank	Intermediate water accumulator
st_out	THERMAL_BALANCE.Water	Water extraction point port
st_in	THERMAL_BALANCE.Water	Water return point port
Cntrl_PID_1	CONTROL.Cntrl_PID	Main plant controller

Table 2: Code names of the NSSS_BOP components

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TES_intermediate component

The schematic of the intermediate thermal storage system includes two tanks—one for the Therminol 66 oil stored at a higher temperature and the other at a lower temperature—along with heat exchangers that connect the system to both the nuclear BOP and the electrolyser BOP, as well as the connecting pipelines. This schematic is shown in Figure 11.

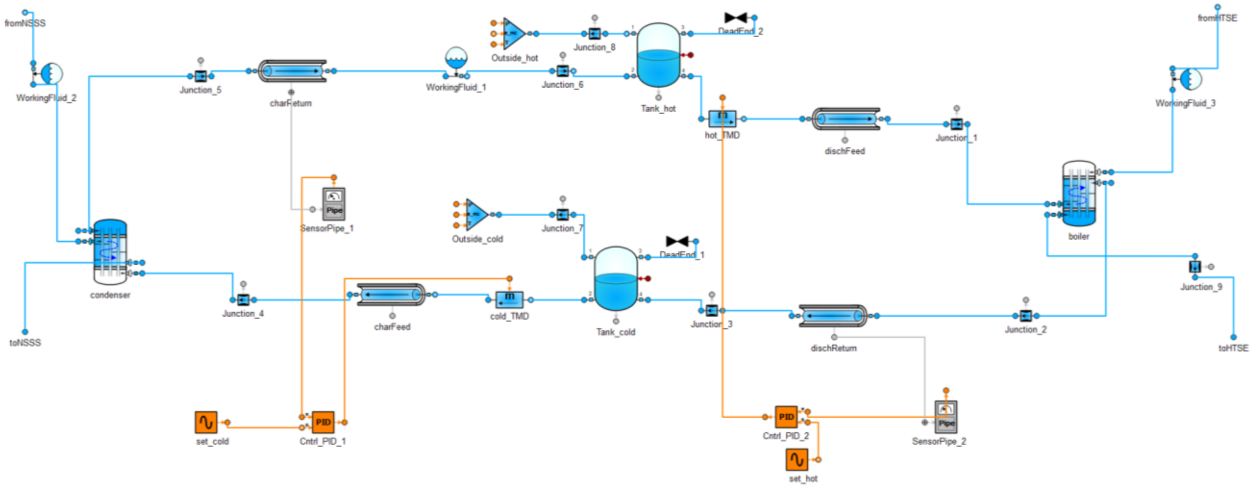

Figure 11: TES_intermediate schematic

The following table provides a brief description of the key elements in the schematic.

Component Name	Component Type	Description
Tank_hot	FLUIDAPRO.Tank_4	High-temperature oil storage tank
Tank_cold	FLUIDAPRO.Tank_4	Low-temperature oil storage tank
charFeed / charReturn	FLUIDAPRO.Pipe	Pipeline network connecting the TES to the nuclear BOP
dischFeed / dischReturn	FLUIDAPRO.Pipe	Pipeline network connecting the TES to the electrolyser BOP
condenser	FLUIDAPRO.HeatExchanger	Heat exchanger for TES charging

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Component Name	Component Type	Description
boiler	FLUIDAPRO.HeatExchanger	Heat exchanger for TES discharging
hot_TMD	FLUIDAPRO.Jun_TMD	Ideal pump for high-temperature fluid
cold_TMD	FLUIDAPRO.Jun_TMD	Ideal pump for low-temperature fluid

Table 3: Code names of the TES_intermediate components

BOP_HTSE component

The schematic of the electrolyzer BOP, shown in Figure 13, includes the piping system and heat exchangers responsible for recovering the thermal energy available at the electrolyzer outlet. It also features the HTSE and an electric boiler, which adjusts the steam temperature according to the system's thermal requirements. Notably, this schematic incorporates components from the HVAC library, along with modified elements such as pipes and boundary components, specifically adapted for hydrogen use.

On the other side, Figure 12 presents the HTSE schematic, including its control system. All electrolyzer components have been specifically developed based on the Modelica model created by CEA in the frame of the TANDEM open source Modelica Library and reference [8] to align with the scope of this deliverable. These components are not currently available in any existing EcosimPro® library.

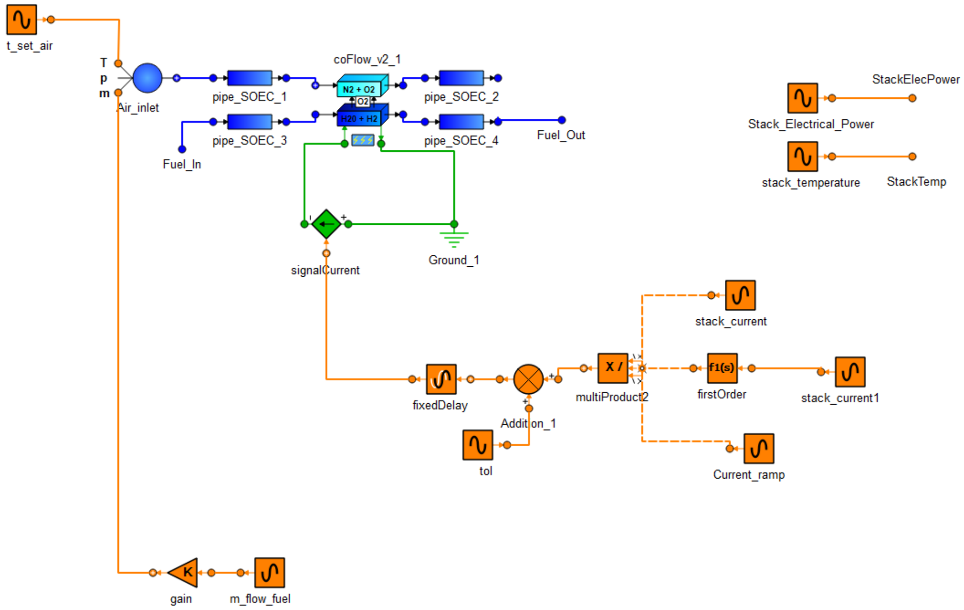

Figure 12: HTSE schematic

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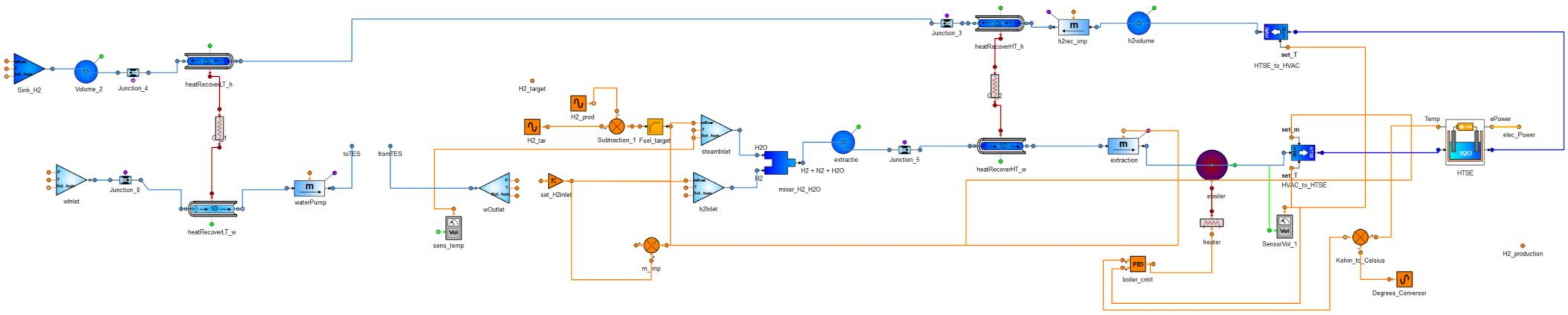

Figure 13: BOP_HTSE schematic

Component Name	Component Type	Description
HTSE	-	HTSE model
eboiler	-	Electrical boiler
heatRecoveryLT_h / heatRecoveryLT_w	HVAC.Pipe	Low temperature heat exchanger
heatRecoveryHT_h / heatRecoveryHT_w	-	High temperature heat exchanger
extraction / h2rec_imp / waterPump	HVAC.Juntion_MFI	Ideal pumps
mixer_H2_H2O	-	Ideal steam – hydrogen mixer

Component Name	Component Type	Description
HVAC_to_HTSE	-	HVAC library to HTSE port converter
Fuel_target	-	PI controller with limiter
wInlet	HVAC.Bound_PT	Water inlet
Sink_H2	-	Hydrogen outlet

Table 4: Code names of the BOP_HTSE componets

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H2_Storage component

The hydrogen storage system primarily consists of a three-stage screw compressor and a hydrogen storage tank, as shown in Figure 14. In this case, each stage of the compressor has been modeled independently and then coupled to form the three-stage compressor.

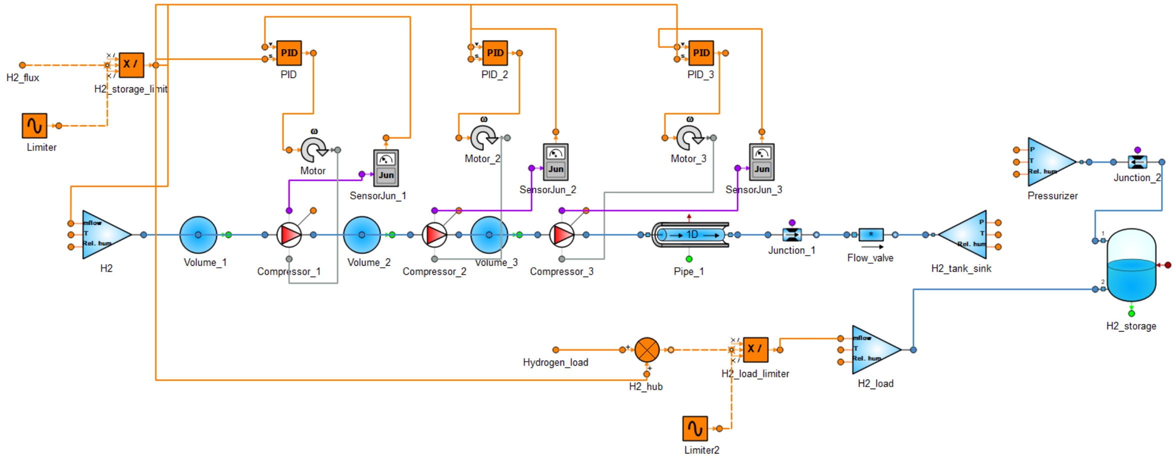

Figure 14: H2_Storage schematic

Component Name	Component Type	Description
H2_storage	HVAC.Tank_single	Hydrogen storage tank
Compressor_*	HVAC.Compressor_screw	One-stage screw compressor
Pressurizer	HVAC.Bound_PT	Relief pressure system to prevent excessive pressures buildup inside the tank
PID_*	CONTROL.Cntrl_PID	PID controller for each stage to ensure a consistent mass flow
H2_hub	CONTROL.Addition	System to determine whether hydrogen is being injected into or extracted from the tank
H2	HVAC.Bound_mT	Hydrogen inlet

Table 5: Code names of the H2_Storage components

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PV_EO_plants component

The PV_EO_plants component integrates both the wind farm and the photovoltaic plant. Its schematic includes the component used to read and process meteorological data, as well as the photovoltaic panels with their control system and the wind turbines.

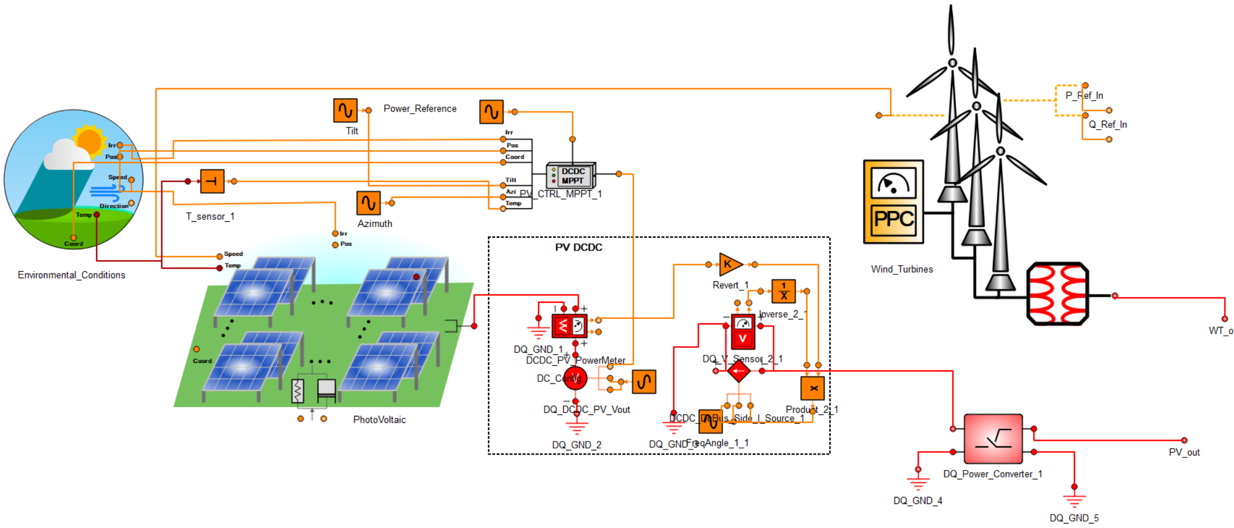

Figure 15: PV_EO_plants schematic

Component Name	Component Type	Description
Enviromental_Conditions	SMART_GRID.Enviromental_Conditions	Enviromental data component
PhotoVoltaic	SMART_GRID.PhotoVoltaic	Group of photovoltaic panels
PV DCDC	-	Set of components for managing the power generated by the PV panels
PV_CTRL_MPPT_1	SMART_GRID.PV_CTRL_MPPT	PV controller system
Wind_Turbines	SMART_GRID.Wind_Turbine	Group of wind turbines
DQ_Power_Converter_1	SMART_GRID.DQ_Power_Converter	DC to AC converter for connecting the PV panels to the grid

Table 6: Code names of the PV_EO_plants components

5.2 Assumptions and Limitations

In this section, the assumptions considered in the modeling of the different systems are presented, considering the scope of the task.

Nuclear plant

- Although the study case used as the basis of the simulator "*run7*" includes two SMRs, 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.
- The SMR has been modeled as a thermal source with a nominal value of 540 MW, without considering the transient behavior of neutron kinetics or fuel rod temperature calculation.
- The working fluid in the system is water in liquid-vapor state.
- The BOP has been sized to achieve a maximum thermal extraction of 50 MWth, resulting in a generated electrical power of 155 MWe. If no heat is extracted, the nominal electrical power increases to 170 MWe.

Thermal network - TES

- An intermediate thermal storage system has been used instead of a single fluid network due to the greater flexibility provided by this system, allowing the decoupling of the nuclear plant and electrolyser operations.
- As previously mentioned, the thermal network is limited solely to the connection between the BOP of the nuclear plant and the electrolyser's BOP. Therefore, it is assumed that the system does not supply heat to other potential users. This can be modified by adding additional consumers to the TES system.
- Therminol 66 thermal oil has been used as the operating fluid for the TES system, similar to its use in the TANDEM Modelica library.
- Thermal losses in the oil storage tanks and piping are considered negligible.
- Pumping systems have been assumed to be ideal, with flow imposed instantaneously. However, the overpressure exerted by these systems has been accounted for.
- Heat exchangers (HX) have been sized to achieve a nominal thermal flow of 50 MWth.

High Temperature Steam Electrolyser plant

- The only hydrogen-producing component in the system is the HTSE, as required in the "run7" case.

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- The sizing of the HTSE (number of modules) was performed to accommodate a maximum cogeneration power of 100 MWth. In this configuration, there are 25 modules per SMR unit.
- Similar to the SMR case, only a single electrolyzer module has been implemented to reduce computational cost. The results were then extrapolated to match the total number of modules in the system.
- The BOP of the electrolyser discharges hydrogen into a network after reducing its temperature with heat recovery systems, which is used to heat the incoming water to the system. However, this hydrogen network has not been modeled in detail and is considered as a sink.

Hydrogen Storage

- As mentioned earlier, a three-stage screw compressor has been used to increase the pressure of the hydrogen entering the system. This has been modeled as three independent compressors, allowing proper adjustment of the compression parameters for each stage.
- It is assumed that the hydrogen enters at a pressure of 1 bar and a temperature of 20°C.
- In such systems, mechanisms are usually included to reduce the temperature of the fluid at the compressor outlet. However, considering the objective of the task, this process has been simplified by assuming that the hydrogen entering the tank does so at the compressor outlet pressure and at 20°C.
- A pressure relief valve has been introduced in the tank to prevent the pressure from exceeding the design pressure of 30 bars during filling.

Wind farm and Photovoltaic plant

- It has been assumed that the wind farm consists of Vestas V164/9500 turbines, each with a power output of 9.5 MW.
- The solar panels are considered fixed with an azimuth of 0 degrees and a tilt of 40 degrees. The number of panels, as well as their size, has been sized to achieve the nominal power required for the study, which is 200 MW.
- The meteorological data used for this deliverable corresponds to the first week of January 2019 at the Fos sur Mer location, obtained from PVGIS [9].

Combined Cycle Gas Turbine

- The combined cycle plant has been modeled in a simplified manner, in accordance with the scope of the project.

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- This configuration considers the Combined Heat and Power (CHP) system to deliver only electrical power, omitting any thermal power export. In this setup, the CCGT operates with a rated electrical power of 80 MWe.

Electrical Grid

- The electrical grid has been simulated in a simplified manner, assuming that the components are capable of injecting or extracting the required energy without limitation.

5.3 Boundary Conditions

The boundary conditions define the operating conditions at the limit of the model's scope, representing values imposed on the system that influence its behavior. In the case of the Energy Hub simulator, these conditions primarily depend on hydrogen production and demand, the thermal power extracted from the nuclear BOP, and the enviromental conditions affecting the renewable energy generation.

In this setup, the boundary condition values have been incorporated into the model through files or tables, allowing user modifications. The following table summarizes the boundary conditions and the components displayed in the simulator schematic (Figure 9) from which they can be adjusted.

Boundary Condition	Component name
Setpoint of the CHP electrical power production [MWe]	CCGT_Power
HTSE hydrogen production objective per module [kg/s]	H2
Hydrogen externally required to the H_2 storage [kg/s]	Hydrogen_load
Enviromental data such as wind speed or solar irradiation [-]	PV_EO_plants
Thermal power extracted form the SMR - BOP [Wth]	Pot

Table 7: Boundary Conditions in the Energy Hub simulator

5.4 Model Data

This section presents the most representative data of the main components. Considering the objective of analysing the results compared to the ones of Modelica and PERSEE, the sizing of the components has been based on the input data from the TANDEM Modelica library. For more detailed information, refer to TANDEM/Deliverable 2.3 [4], as well as the Modelica TANDEM library available on Gitlab [5].

Nuclear plant

The main components of the nuclear plant are the SMR and the turbine group. This group consists of three turbines: one high-pressure turbine and two low-pressure turbines. The nominal operating parameters of the system are described in the following tables.

Variable	Value
Thermal power [MW]	540
Outlet temperature [°C]	300
Outlet pressure [bar]	45
Water flow [kg/s]	240

Table 8: Rated operating conditions of the SMR

Variable	Value
Outlet temperature [°C]	160
Outlet pressure [bar]	7.46
Water flow [kg/s]	218
Isentropic efficiency [-]	0.9

Table 9: Rated operating conditions of the High Pressure Turbine

Variable	Value
Outlet temperature [°C]	100
Outlet pressure [bar]	0.801
Water flow [kg/s]	182
Isentropic efficiency [-]	0.9

Table 10: Rated operating conditions of the Low Pressure Turbine 1

Variable	Value
Outlet temperature [°C]	40
Outlet pressure [bar]	0.07
Water flow [kg/s]	165
Isentropic efficiency [-]	0.9

Table 11: Rated operating conditions of the Low Pressure Turbine 2

Thermal network - TES

For the intermediate thermal storage system, several key components can impact its performance. These components include the storage tanks, heat exchangers, and the piping network.

In this case, starting from the values available in the TANDEM Modelica library models, the heat exchanger parameters have been adjusted to achieve a nominal heat exchange of 50 MWth.

The geometric values of the main components are presented below.

Variable	Value
Tanks volume [m^3]	5110
Tanks height [m]	18.67
Hot tank temperature [°C]	250
Cold tank temperature [°C]	200
Initial State Of Charge (SOC) [-]	0.5
Fluid [-]	Therminol 66

Table 12: TES tanks main parameters

Variable	Value
Tubes length [m]	24
Number of tubes [-]	1250
Internal diameter of the tubes [m]	0.013
Tube passes [-]	2
Wall density of the tubes [kg/m^3]	7763
Specific heat of the tubes wall [J/kg·K]	510.4

Table 13: Geometrical data of the condenser

Variable	Value
Tubes length [m]	8.2
Number of tubes [-]	1150
Internal diameter of the tubes [m]	0.013
Tube passes [-]	2
Wall density of the tubes [kg/m^3]	7763
Specific heat of the tubes wall [J/kg·K]	510.4

Table 14: Geometrical data of the boiler

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Variable	Value
Pipes length [m]	500
Internal diameter of the pipes [m]	0.5
Nominal mass flow [kg/s]	430

Table 15: Geometrical data of the pipeline

High Temperature Steam Electrolyser plant

In the case of the electrolyser and its BOP, the geometric and operational data used are those included in the corresponding models from the TANDEM library. These data refer to the hydrogen production of a single module, as indicated in the Assumptions and Limitations section. Below, the most significant parameters of the BOP are provided. For more detailed information on each component, refer to the GitLab repository [5] and TANDEM/Deliverable 2.3 [4].

Variable	Value
Low-temperature HX tubes length [m]	1
Low-temperature HX number of tubes [-]	105
Low-temperature HX diameter of the tubes [m]	0.01 (cold side) – 0.25 (hot side)
High-temperature HX tubes length [m]	3
High-temperature HX number of tubes [-]	1005
High-temperature HX diameter of the tubes [m]	0.1 (both sides)
Wall density of the tubes [kg/m^3]	7800
Specific heat of the tubes wall [J/kg·K]	1000

Table 16: HTSE – BOP geometrical data

Variable	Value
Inlet water temperature [°C]	47.5
Inlet water pressure [bar]	5
Inlet hydrogen temperature [°C]	200
Inlet hydrogen pressure [bar]	1
Inlet air pressure [bar]	1

Table 17: HTSE – BOP input fluids data

Hydrogen Storage

The compression system and the hydrogen storage tank have been sized to achieve the output parameters described in TANDEM/Deliverable 3.2 [3]. Additionally, as mentioned in the Assumptions and Limitations section and considering the scope of this deliverable, both systems

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have been decoupled to avoid the modeling and sizing of the heat exchanger system required to reduce the hydrogen temperature at the compressor outlet.

The key parameters of both systems are presented in Table 18 and Table 19.

Variable	Value
Type [-]	Screw
Stages [-]	3
Pressure ratio of each stage [-]	3.1
Total pressure ratio [-]	30
Nominal flow rate [kg/s]	2.3
Nominal axial speed [rpm]	5500

Table 18: Hydrogen compressor main data

Variable	Value
Capacity [kg]	16000
Tank height [-]	22.5
Initial SOC [-]	0.5

Table 19: Hydrogen storage main data

Wind farm and Photovoltaic plant

The parameters of the wind farm, as well as the number of turbines, are based on the information available in TANDEM/Deliverable 3.2, specifically for the "run7" case, and on reference [10]. On the other way, as previously mentioned, the number and size of the photovoltaic panels have been designed and adjusted to achieve the nominal power specified in the deliverable.

Variable	Value
Number of wind turbines [-]	4
Wind turbine type [-]	Vestas V164/9500
Turbines nominal power [MWe]	9.5
Number of panels [-]	1000
Number of modules per panel [-]	20000
PV module performance [-]	0.2
Total area [km^2]	5
PV nominal power [MWe]	200

Table 20: Wind farm and PV plant parameters

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Simplified models

Finally, the key parameters of the remaining simplified components, namely the CCGT and the electrical grid, are included.

Variable	Value
Grid nominal frequency [Hz]	50
Nominal voltage [kV]	380
Number of AC phases [-]	3
CCGT nominal power [MWe]	80

Table 21: Simplified components main parameters

5.5 Control Philosophy and Operation

The Energy Hub simulator includes various control loops that adjust the operating conditions of the systems based on the imposed boundary conditions.

For the control system design, it is essential to consider the previously mentioned assumptions, as they help identify which system parameters will change over time and how this constrains the system.

The following section provides a brief description of the control loop implemented in each system.

Nuclear plant

Unlike the control system implemented in the TANDEM Modelica library, the electrical power produced by the turbines is adjusted based on the system's heat demand, making it one of the controlled variables. This control acts on the required extraction flow, considering the enthalpy difference between the steam extraction point and the return point to the BOP. Additionally, the inlet and outlet flow rates are set to be equal, preventing system imbalances. This variation in control will lead to differences in the results, as shown in the following section.

Additionally, the flow passing through the SMR steam generator is set to its nominal value (240 kg/s), ensuring a thermal output of 540 MWth. To achieve this, a control loop is implemented using a PID controller, which measures the inlet flow to the reactor and adjusts the water pump at the tank outlet to maintain the nominal flow rate.

The remaining system valves self-regulate to maintain the nominal pressure conditions of the system.

Thermal network - TES

The control system incorporated into the TES is very similar to the one available in the Modelica model. It operates on two pumps, each located at the outlet of a respective tank, and adjusts the necessary flow to ensure that the temperature at the heat exchangers' outlet within the tank system reaches the desired value. The required temperatures in each pipeline (see Figure 11) are summarized in the following table.

Variable	Setpoint value
charReturn pipe temperature [°C]	250
dischReturn pipe temperature [°C]	200

Table 22: Setpoints values of the TES system controller

High Temperature Steam Electrolyser plant

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 inlet water flow.

Regarding the control of the electrolyzer, the same type of control as available in the TANDEM library is implemented. In this case, the system adjusts the electrical current supplied based primarily on the proportion of water in the fuel entering the electrolyzer, allowing for greater or lesser hydrogen separation. For further details, refer to TANDEM/Deliverable 2.3 [4] and the Git repository of the TANDEM library [5].

Wind farm and Photovoltaic plant

In this component, the control system is minimal, as its operation depends on environmental conditions. The key aspect to highlight is the control of the photovoltaic panels, which can generate more or less energy depending on parameters such as azimuth, irradiation, tilt, ambient temperature and the nominal voltage of the array of PV panels (300 V).

Combined Cycle Gas Turbine plant

Finally, considering that the CCGT is a simplified component, its control system is based on a PID controller that regulates the output power according to the demanded power, incorporating a delay time of 1800 seconds to simulate the time required for the system to change its operating regime.

Additionally, the component has been modeled so that the demanded power accounts for the system's efficiency, allowing for the consideration of dynamic efficiency.

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6 Results

To conduct the technical study using the simulator developed in EcosimPro®, a simulation was conducted by adjusting the boundary conditions to match those used in the coupled PERSEE–Modelica simulator. This approach enables a direct comparison of results obtained from these tools, making it possible to identify discrepancies between systems.

Additionally, it is important to highlight the methodology used to obtain the boundary conditions applied in the simulation. To this end, a simulation was carried out using the soft-coupled Modelica simulator – PERSEE tool, where the setpoints generated by the PERSEE optimisation were simulated with the Modelica model to verify wether they could be met according to a more physically representative tool.

This soft-coupling method slightly affects the optimised values, potentially causing discrepancies during simulations due to the calculation methods of each tool. To mitigate these differences, a tighter interaction between both models is required, which is analysed and will be described in Deliverable 3.4.

Regarding the simulation period, it covers the first week of January 2019 in the Fos-sur-Mer location. However, at the beginning of the last day of simulation, it stops due to the TES being completely discharged, making it unable to meet the system requirements imposed by PERSEE. Consequently, the simulation duration is reduced to 520k seconds, which is approximately 6 days.

This discharging issue, which occurs similarly in the simulation performed with the Modelica model and is potentially caused by a more idealized behavior of the systems in PERSEE, highlights the fact that a generic MILP model for the thermal energy storage is not refine enough to correctly represent the reality. During the simulation, a constant hydrogen demand of 8257 kg/h is assumed, while production varies over time according to the hourly parameters set by the PERSEE optimisation.

Similarly, both the heat extracted from the nuclear BOP and the energy produced by the CCGT are imposed as variable hourly values according to the requirements of the optimization tool.

Additionally, the initial state of charge for both the thermal storage and hydrogen storage systems is set at 50%. The remaining system parameters are adjusted through the control loops described earlier.

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The following section presents the simulation results by comparing them with those obtained from the PERSEE tool and the Modelica-generated model. To achieve this, the key system parameters are compared to evaluate the consistency of the results.

6.1 Comparison with PERSEE

Nuclear plant

The first system to be compared is the SMR and its BOP, given its significance in the Energy Hub. The key parameters of interest in this system are the extracted heat and the generated electrical power.

Figure 16 illustrates the electrical power generated in the nuclear BOP. A notable difference can be observed at certain operating points between the value obtained with EcosimPro®, marked in blue, and the value obtained with PERSEE, marked in red. These differences are more pronounced when the thermal extraction from the BOP decreases, reaching a maximum peak of 14 MWe (4.1% deviation approximately), but are almost negligible when the system operates at maximum extraction, with a difference of only 0.6 MWe (0.2% deviation).

This discrepancy is mainly attributed to the implemented control system in the EcosimPro® simulator, which, as previously mentioned, prioritizes heat extraction.

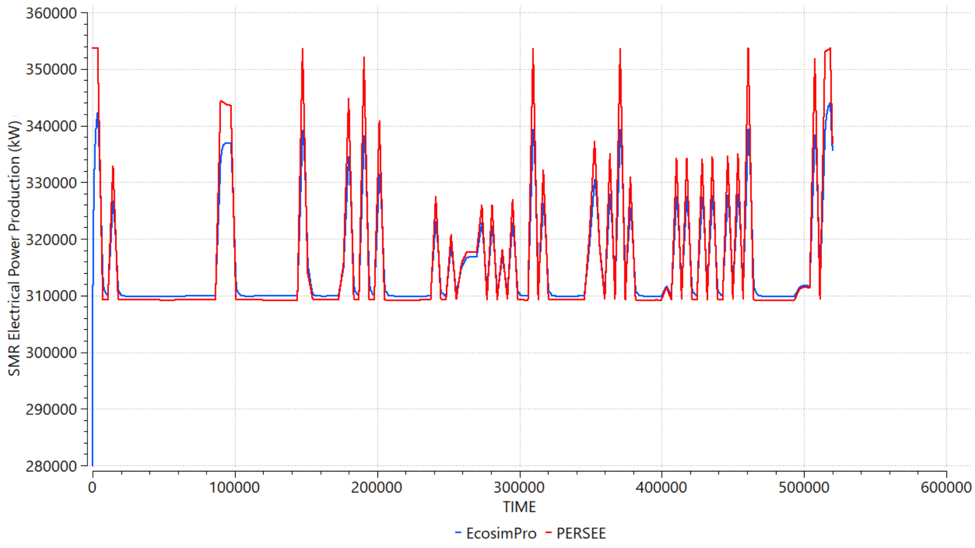

Figure 16: SMR Electrical power generation – EcosimPro® vs PERSEE

Conversely, when analyzing the extracted thermal power (Figure 17), it is observed that it perfectly matches the values obtained in PERSEE. It is important to emphasize that although the extracted power is an input value to the system, the comparison is made with the actual heat exchanged in the TES system condenser. This approach ensures an accurate accounting of the heat utilized in cogeneration.

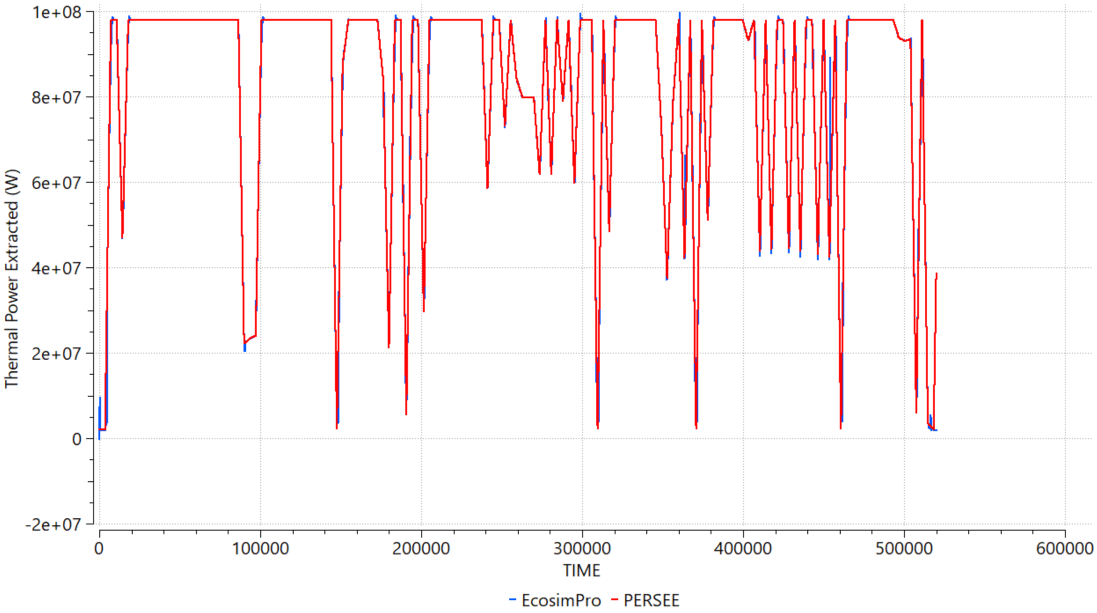

Figure 17: SMR Cogeneration power – EcosimPro® vs PERSEE

In the previous figure, it can be observed how the system becomes unstable at the end of the simulation due to the complete discharge of the TES system, causing the simulation to stop.

Thermal network – TES

Next, the system closely connected to the operating mode of the SMR is analyzed. The primary variable of interest in this system is the TES state of charge (Figure 18), as it directly impacts the overall system performance.

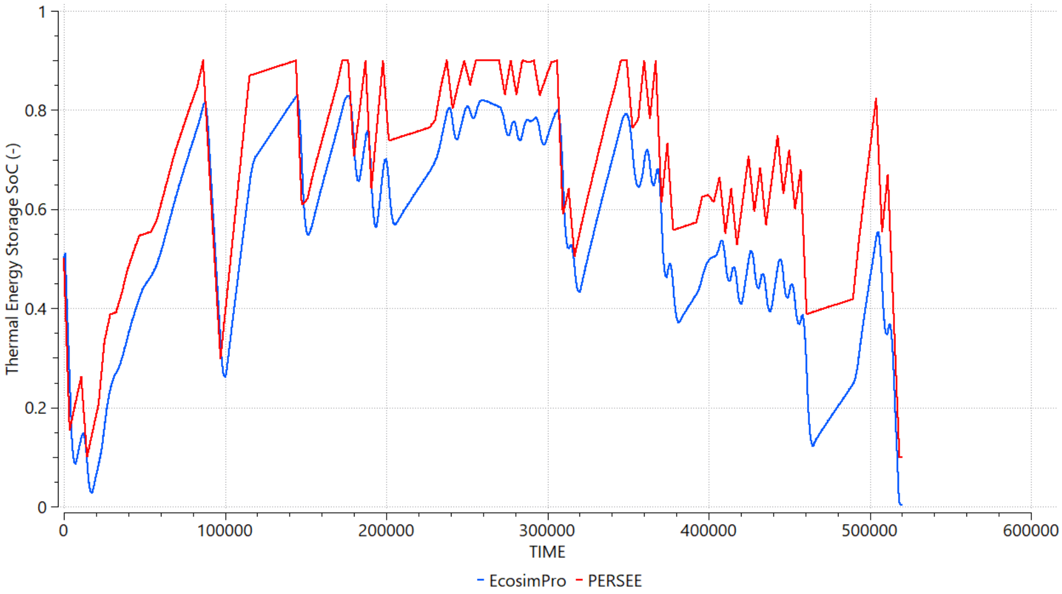

Figure 18: TES state of charge – EcosimPro® vs PERSEE

Once again, with the EcosimPro® results shown in blue and the PERSEE results in red, discrepancies are observed in the system. However, the operational trends remain very similar. Additionally, the system performs better during the charging process than during the discharging phase, which is expected given that the amount of heat extracted from the SMR is a fixed parameter. Once again, at the end of the simulation, the state of charge drops to zero, suggesting that the optimal control sent by PERSEE needs to be reviewed, along with minor improvements to its TES model to better align with the EcosimPro® model. This also highlights the importance of hard-coupling macro techno-economic tools like PERSEE with highly detailed models, enabling the optimisation of most system components.

In this case, the differences between the results are attributed to possible thermal inertias of the Therminol 66 within the storage tanks, as well as the fluid's behavior when absorbing and releasing heat, the characteristics of the control system itself and the sizing of the heat exchangers. This will also be observed during the TES discharge process.

High Temperature Steam Electrolyser plant

In the case of the electrolyser, several key parameters need to be analyzed. These parameters include the hydrogen production rate, measured at the electrolyzer outlet; the heat extracted from the TES, measured at the heat exchanger; and the total energy consumption of the electrolyser system, which includes both the electric boiler and the electrolyser itself.

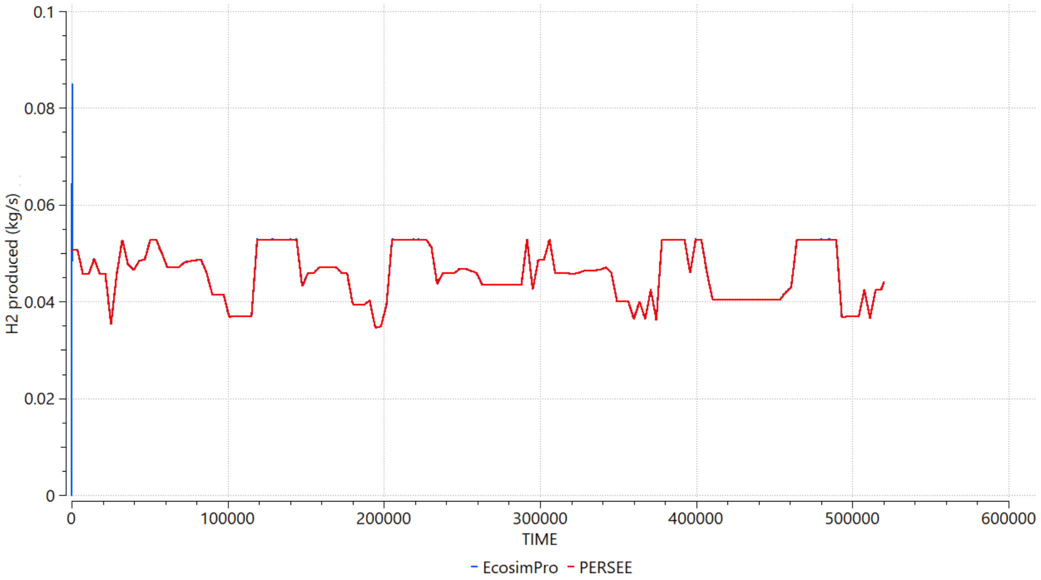

Figure 19: Hydrogen production – EcosimPro® vs PERSEE

As shown in Figure 19, and considering that it is a boundary condition of the system, the amount of hydrogen produced by the electrolyser matches perfectly in both tools. A peak can be observed at the beginning of the simulation in the case of EcosimPro®, but this is due to the initialization and startup of the electrolyser, which involves thermal inertia in the inlet steam temperature to the cell. Once this startup phase is overcome, the system operates identically in both models.

Regarding the thermal power extracted from the TES for use in the BOP of the electrolyser, shown in Figure 20, a very similar behavior can be observed in both cases, with a discrepancy of less than 4 MWth (4% deviation approximately) in certain periods. This discrepancy, as previously mentioned in the TES case, is attributed to the fluid behavior, the control system, and the sizing of the heat exchangers, which were designed to achieve a nominal power of 50 MWth for a specific nominal flow rate. This will be studied in greater detail in the comparison with Modelica.

Additionally, the startup of the electrolyzer plant at the beginning of the simulation is clearly visible, as well as the moment when the TES is fully discharged at the end of the simulation.

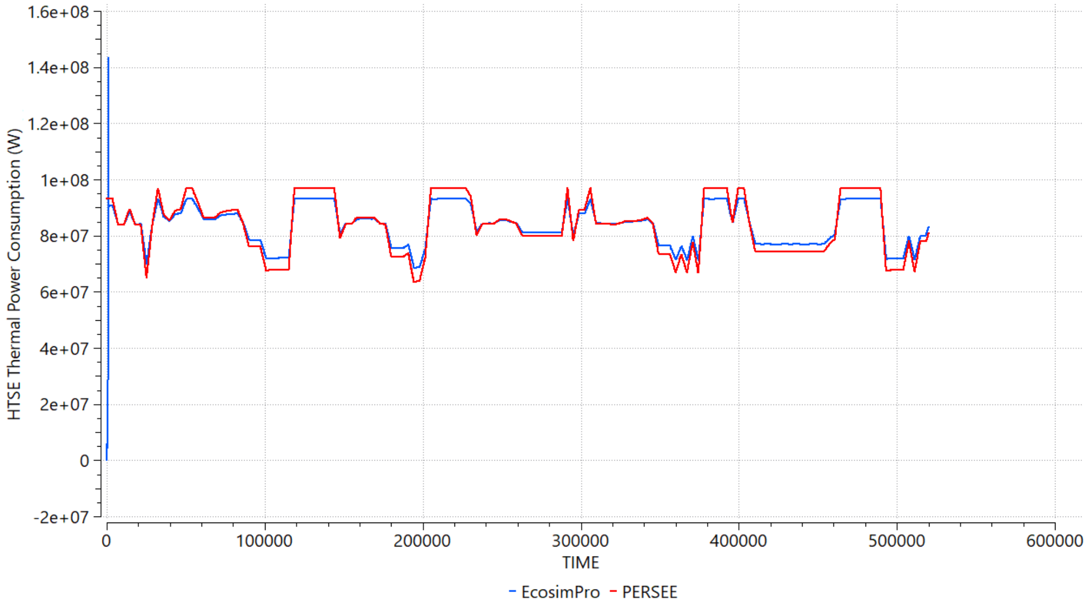

Figure 20: HTSE thermal power – EcosimPro® vs PERSEE

Finally, the electrical power consumption of the electrolyzer and the electric boiler in its BOP is analyzed, as shown in the following figure.

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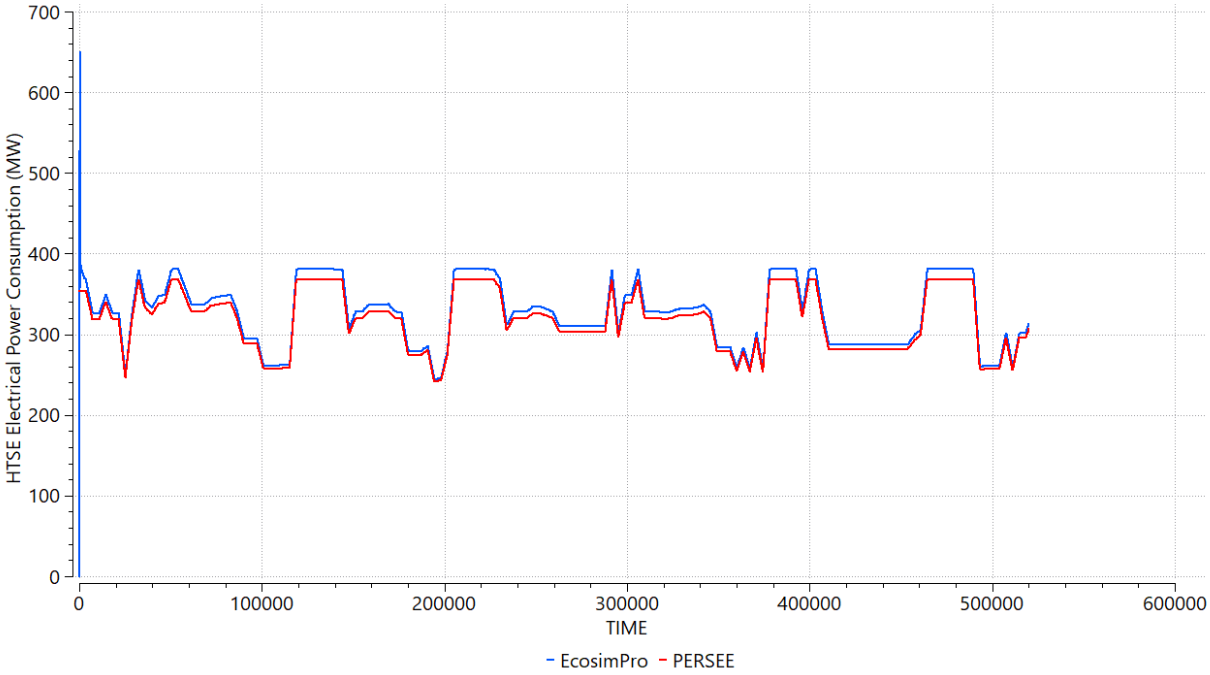

Figure 21: HTSE electrical power consumption – EcosimPro® vs PERSEE

In this case, a larger difference between models is observed, reaching a maximum disparity of 12.3 MWe (3.4% deviation). Although it is not possible to directly verify with PERSEE whether this difference originates from the electrolyzer or the boiler consumption, a comparison with Modelica reveals a similar disparity, confirming that the difference stems from the boiler consumption. This discrepancy is attributed to the inlet temperature of the fluid to the boiler, due to the current sizing of the heat exchanger.

However, considering the established simplifications and assumptions during the modelling process, an 3.4% deviation can be deemed acceptable for this type of process.

Hydrogen Storage

To analyze the behavior of hydrogen storage, the power consumed by the compressor to reach a pressure of 30 bar and the state of charge of the storage system have been compared.

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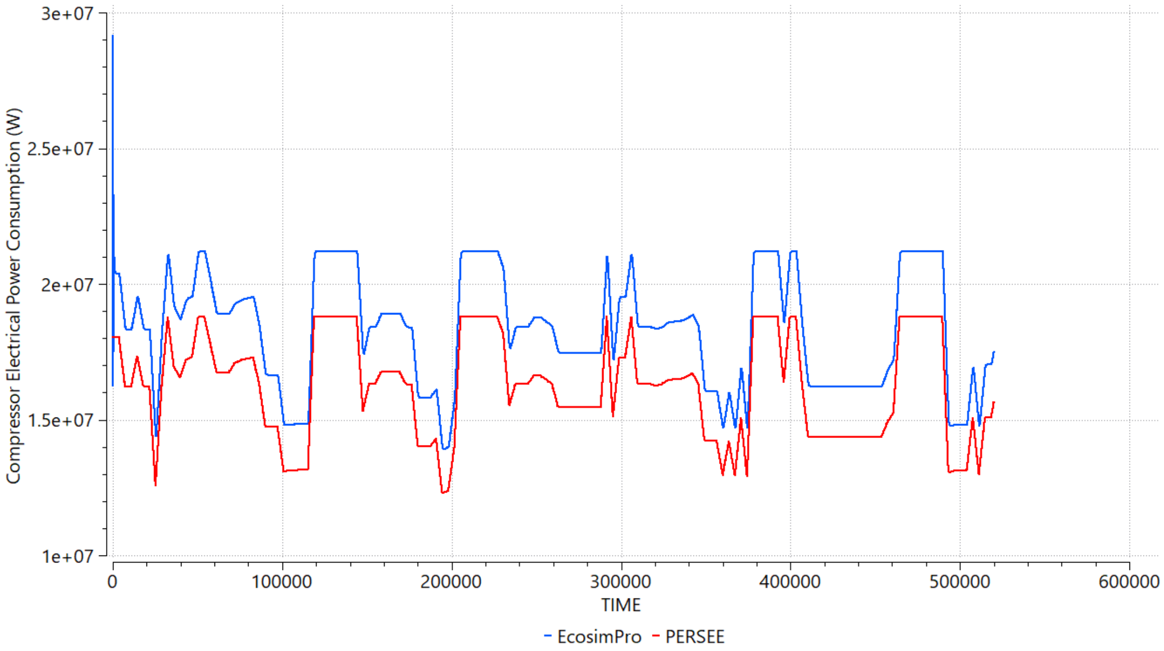

Figure 22: Hydrogen compressor power consumption – EcosimPro® vs PERSEE

In the previous figure, a significant difference in the hydrogen compressor's electrical consumption can be observed, with discrepancies reaching nearly 2.5 MWe (13% deviation). This deviation is mainly attributed to differences in the calculation methodology. In PERSEE, the energy calculation is performed ideally ([3]), assuming certain fixed parameters such as the specific heat at constant pressure of hydrogen or a constant engine efficiency. In contrast, the dynamic model in EcosimPro® accounts for these variations over time, as well as fluid inertia and mechanical inertia of the moving parts of the compressors.

However, it is noticeable that the difference between the highest and lowest compressor consumption is similar in both cases, suggesting that the graph appears to be vertically shifted upward due to these calculation differences. This confirms that the calculation for the compressor's electrical power in PERSEE, while still correct, may be slightly underestimated.

On the other hand, the observed behavior of the hydrogen state of charge is similar in both cases. However, a vertical shift in the state of charge can be seen, as well as a 1500-second delay on the horizontal axis. This is associated with the startup inertia of the electrolyser, which was previously mentioned and can be observed at the beginning of the simulation, where a steeper upward ramp is present compared to PERSEE. If this ramp did not exist, the SOC of the tank would be nearly identical.

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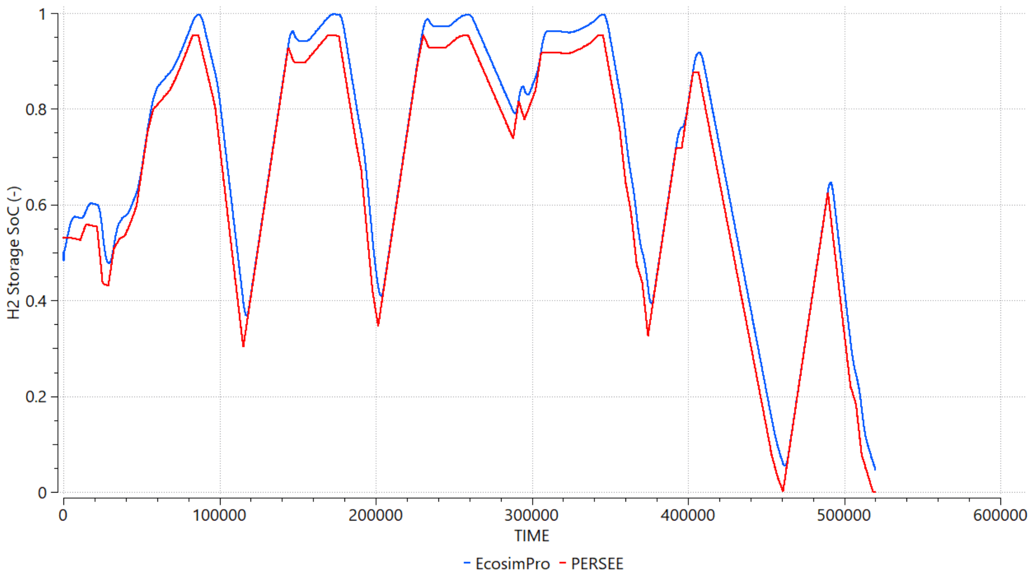

Figure 23: Hydrogen storage state of charge – EcosimPro® vs PERSEE

Wind farm and Photovoltaic plant

Regarding the electrical production from renewable sources, the following comparative graphs illustrate the electrical power generated by the photovoltaic plant and the wind farm.

Figure 24 presents the photovoltaic production over the six days of simulation. In this case, although the production trends align well, there is a significant difference in the absolute values, with a maximum discrepancy of 28.3 MWe (19.3% deviation). After analyzing the reason for this significant difference with the developers of the model in PERSEE, it was determined that the deviation originated from the implementation of different solar panel mounting configurations. In EcosimPro®, a fixed-axis system was used, while in PERSEE, a tracking system was implemented. This difference might affect to both the estimation of PV electrical production and PV CAPEX compared to the values estimated in D3.2.

After identifying this issue, the electrical production results for the fixed-axis configuration were obtained for use in PERSEE, and a comparison was conducted with the model generated in EcosimPro® (Figure 25). In this case, it can be observed that the system performance is quite similar in both cases (around 5% deviation).

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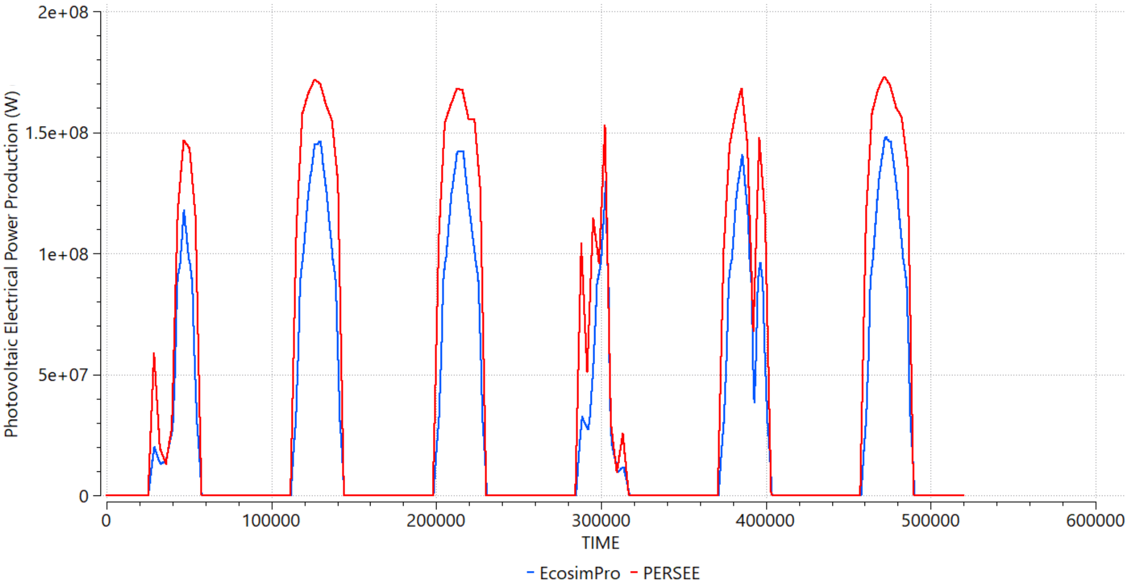

Figure 24: PV plant electrical power production (panels with tracking) – EcosimPro® vs PERSEE

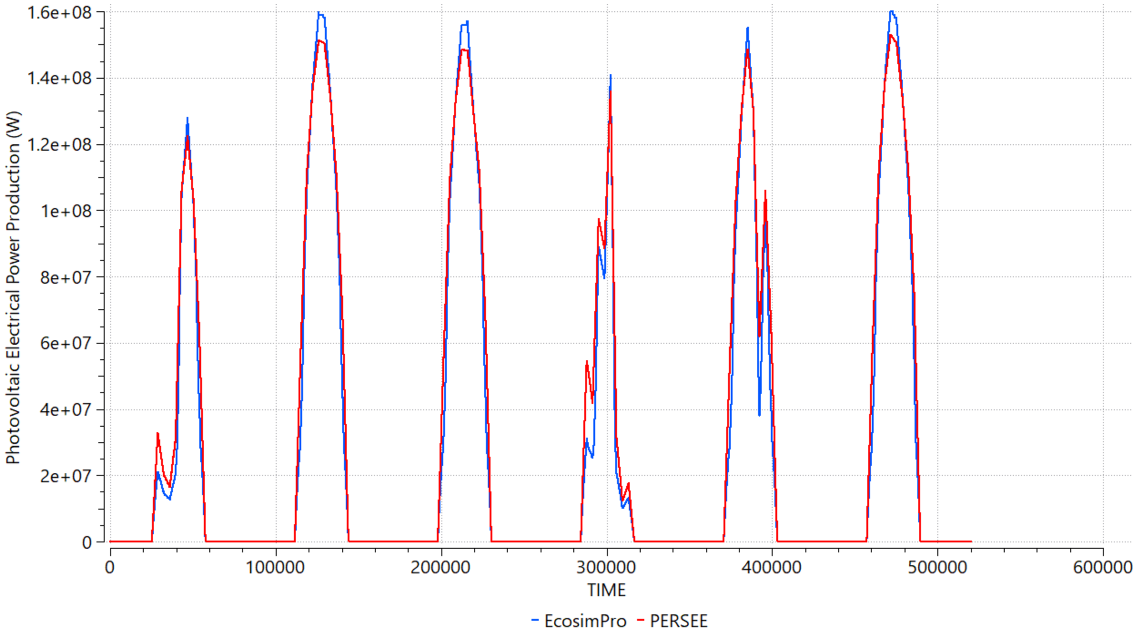

Figure 25: PV plant electrical power production (fixed panels) – EcosimPro® vs PERSEE

The results obtained for the electrical production from wind turbines are also consistent between both models, yielding very similar outcomes. These results only differ when the production approaches the wind turbine's maximum capacity, with a maximum deviation of 13%. These discrepancies are attributed to the manufacturer's operating curves, which may vary slightly between models. It is important to note that the results used in PERSEE were obtained directly from reference [11].

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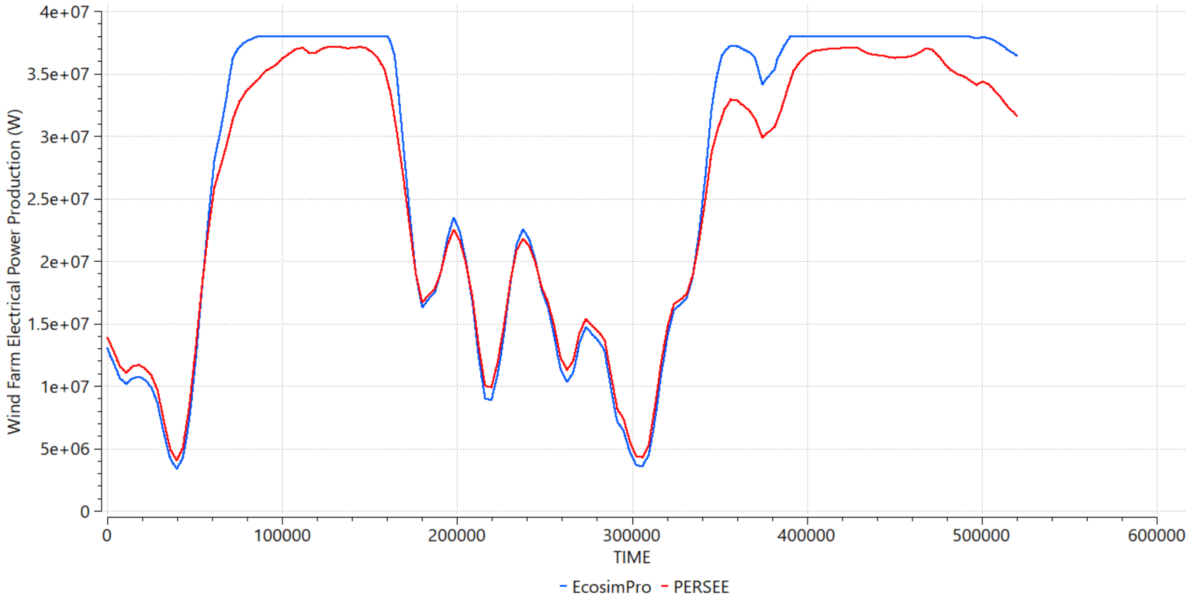

Figure 26: Wind farm electrical power production – EcosimPro® vs PERSEE

CCGT plant

Finally, the results of the CCGT electrical production are presented. These results are trivial, considering that the component is highly simplified, making it possible to observe that the production matches exactly.

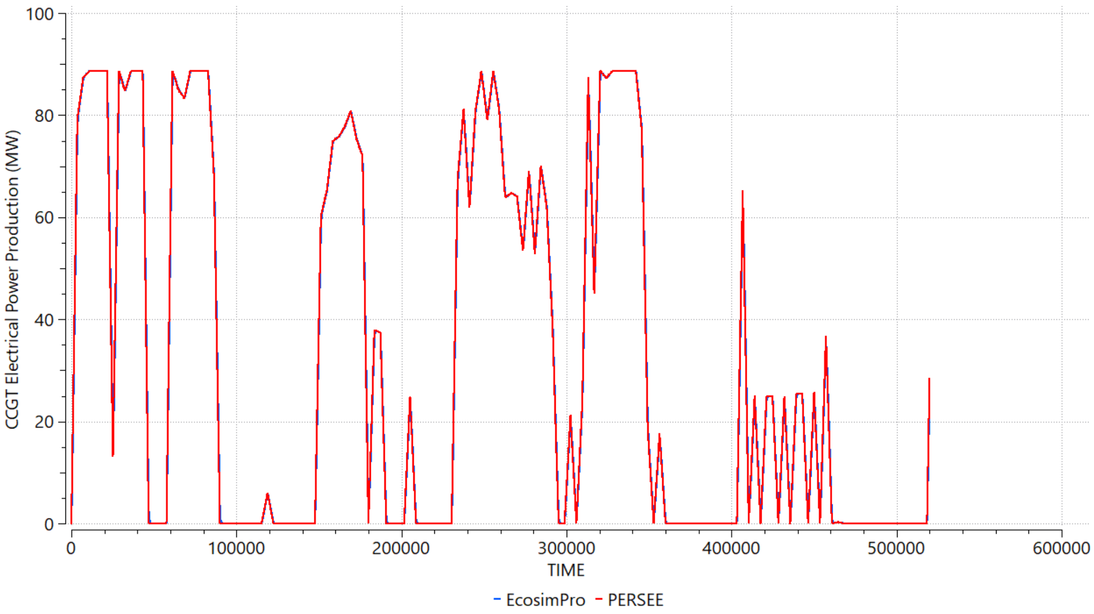

Figure 27: CCGT electrical power production – EcosimPro® vs PERSEE

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6.2 Comparison with Modelica

In the case of the comparison with Modelica, the procedure is similar to the previous case. However, in this case, it is possible to compare additional system variables, allowing for a more in-depth analysis.

Nuclear plant

As previously mentioned, the Modelica SMR model features a control system focused on electrical production, whereas the EcosimPro® model prioritizes thermal extraction. This distinction impacts the results, as shown below.

Figure 28 compares the electrical production of the nuclear BOP, with EcosimPro® results in blue and Modelica results in red. Similar to the comparison with PERSEE, a peak difference of 13 MWe (3.8% deviation) is observed at certain operational points. However, during heat extraction, the deviation decreases significantly, just as it did in the PERSEE model. This discrepancy is again attributed to the control system configurations.

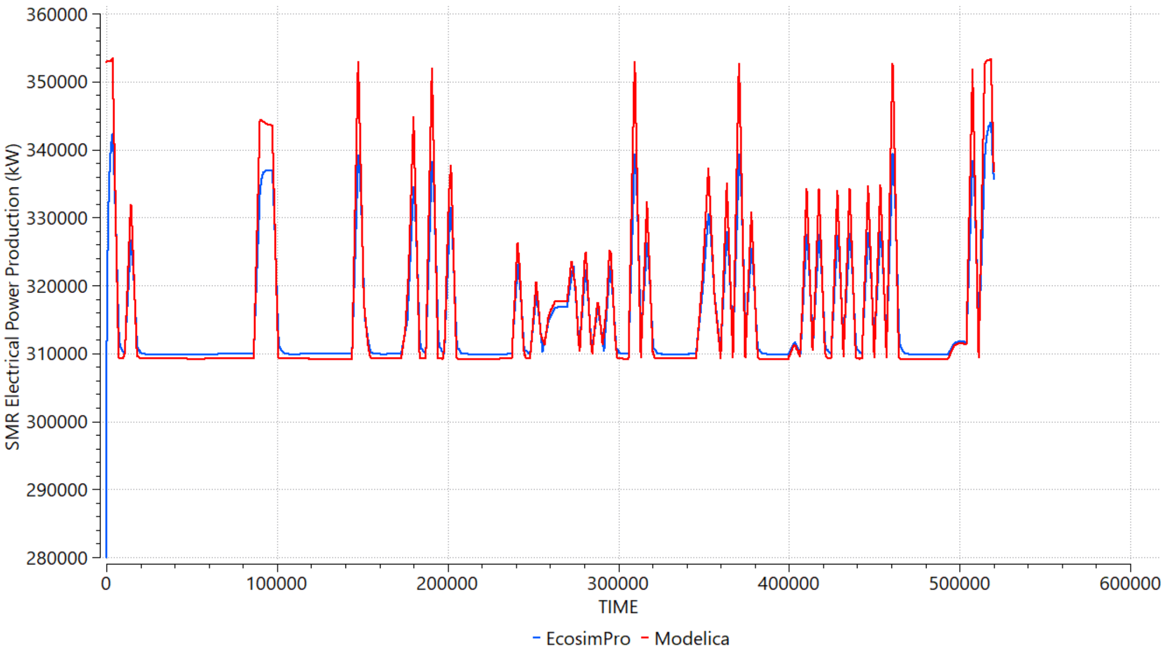

Figure 28: SMR electrical power generation – EcosimPro® vs Modelica

When comparing the three models, it is evident that the Modelica model (red line) aligns more closely with the PERSEE study model (green line) than the EcosimPro® model (blue line). This near-complete agreement in results is primarily due to the implemented control system.

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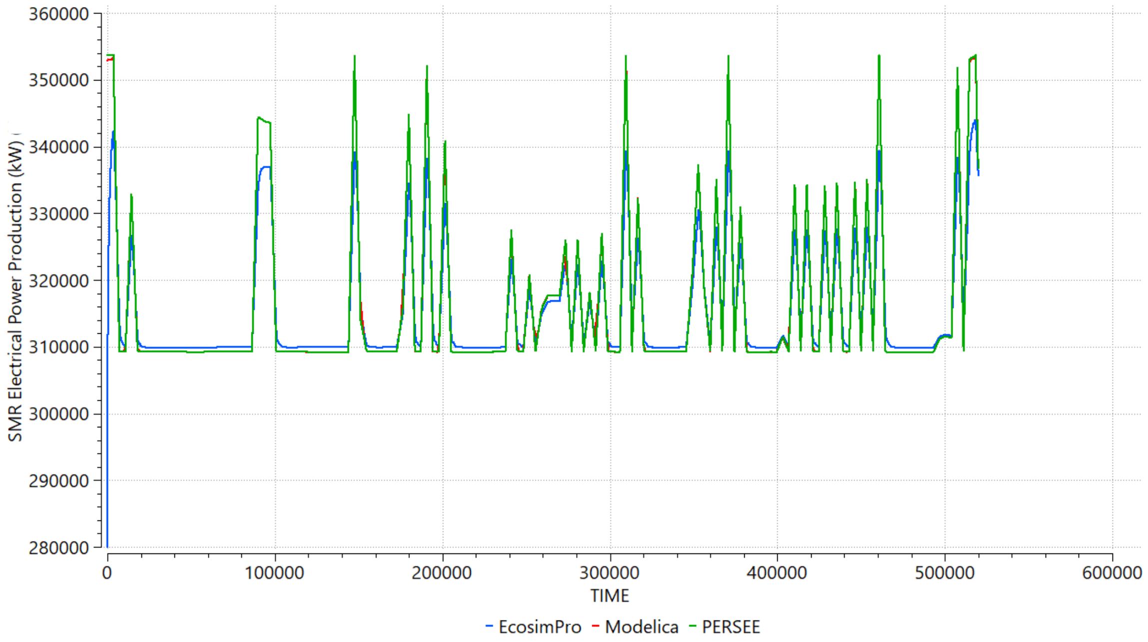

Figure 29: SMR electrical power generation – EcosimPro® vs Modelica vs PERSEE

On the other hand, and for the same reason, the EcosimPro and Modelica models show some differences in the results obtained when analysing heat extraction from the BOP. In Figure 30, a difference of 1.8 MWth (1.9% deviation) in the extracted heat within the nominal region can be observed, which will directly impact the TES system connected to the BOP.

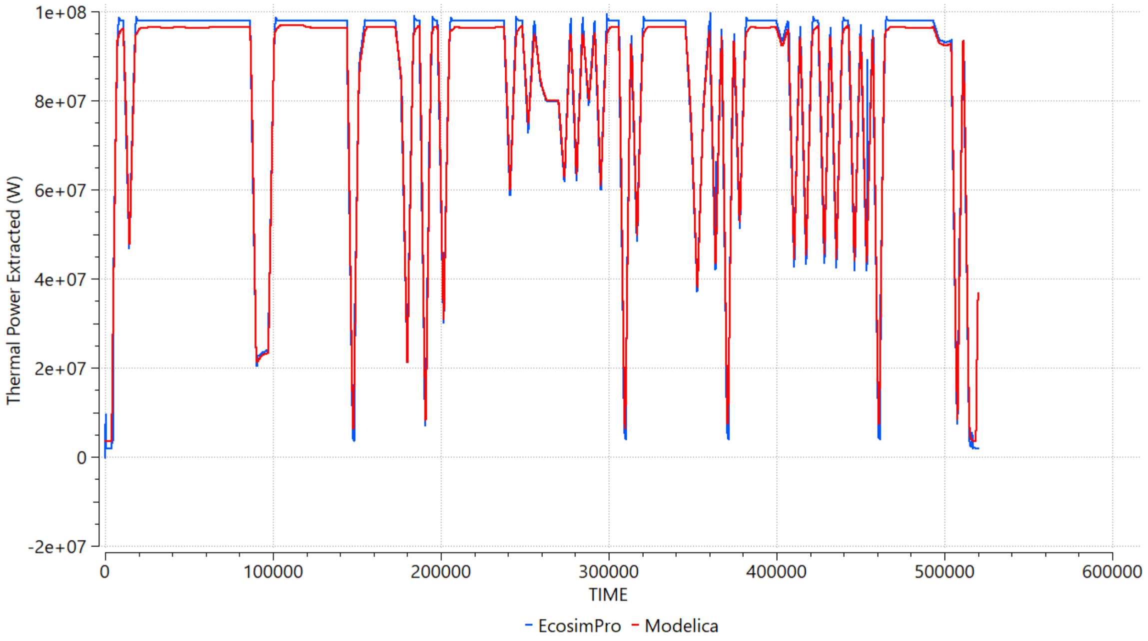

Figure 30: SMR cogeneration power – EcosimPro® vs Modelica

Comparing the three systems, it can be observed that, in this case, EcosimPro® aligns more closely with the results obtained in PERSEE, thanks to its integrated control system.

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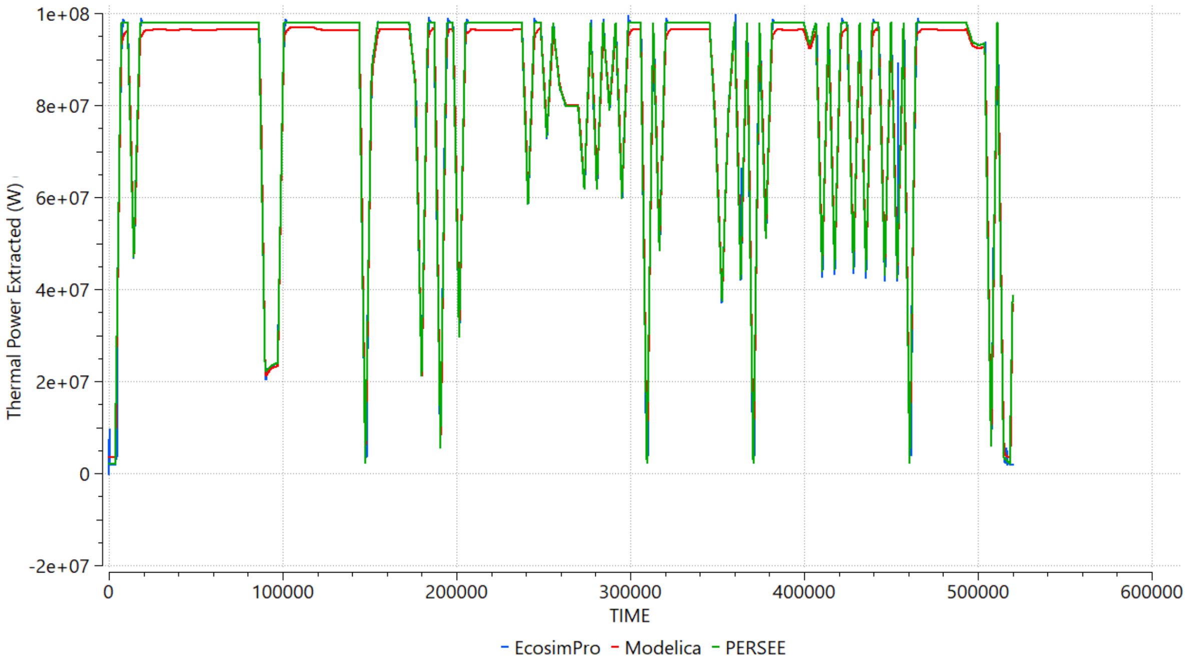

Figure 31: SMR cogeneration power – EcosimPro® vs Modelica vs PERSEE

Thermal network – TES

To compare the TES system, the differences in the state of charge of the TES systems will be examined, and the reasons for these differences will be analyzed in greater depth.

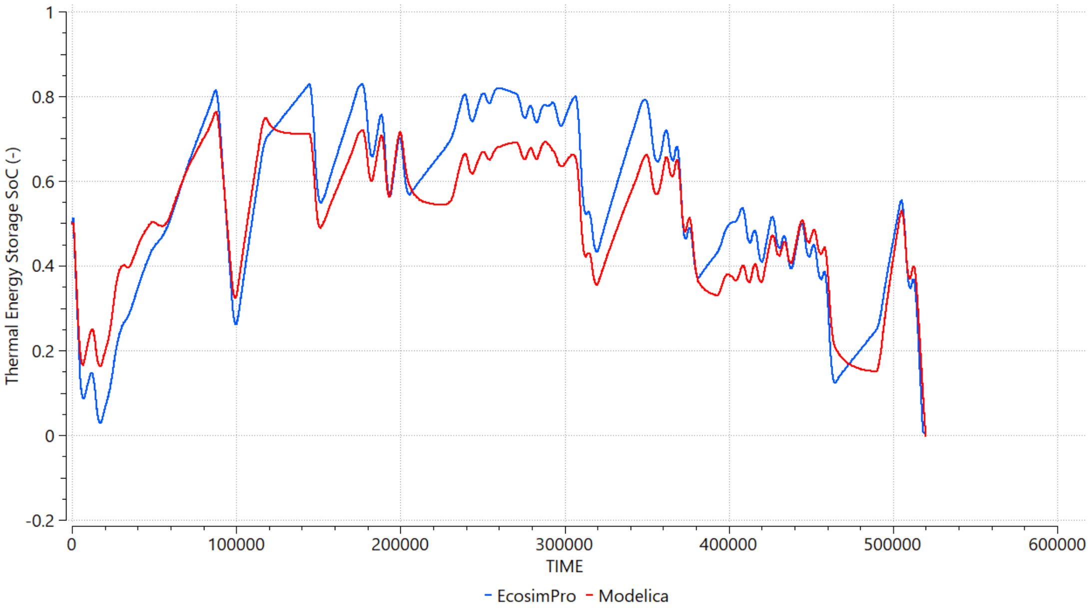

Figure 32: TES state of charge – EcosimPro® vs Modelica

Observing the graph in Figure 32, it is evident that both systems exhibit similar behavior, aligning for most of the simulation. However, a notable difference appears between seconds 200k and

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300k, where the TES system in EcosimPro® achieves a higher charge than in Modelica. This also occurs around seconds 330k and 400k. To investigate the cause, a comparison of the charging and discharging flows of the hot tank is presented below.

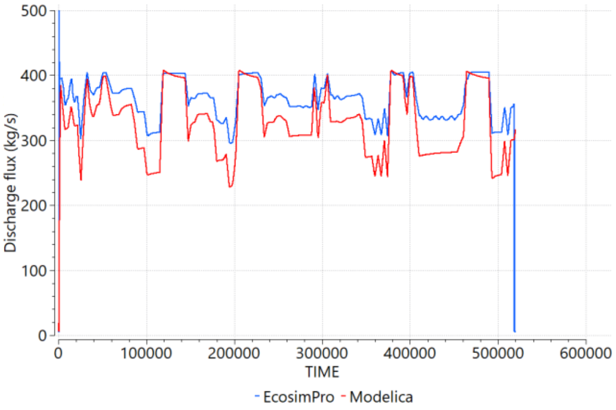

Figure 33: TES discharge – EcosimPro® vs Modelica

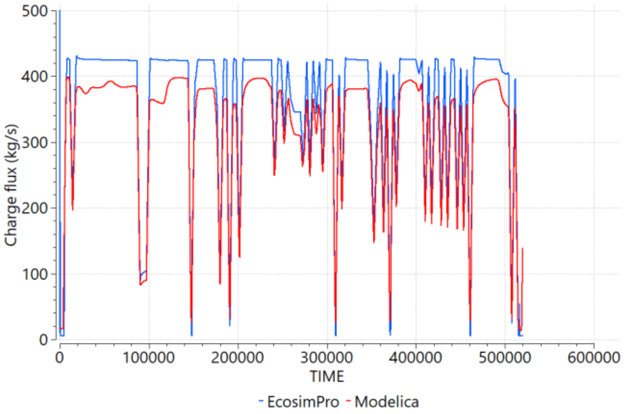

Figure 34: TES charge – EcosimPro® vs Modelica

Figure 33 and Figure 34 illustrate the charging and discharging flows of the TES, respectively.

Observing the discharge flow of the systems, it is noted that under nominal conditions, they behave similarly. However, under non-nominal conditions, the discharge of the system in EcosimPro® is higher than in Modelica. Considering the control system implemented in the model, this aligns with the thermal flow extracted from the system.

On the other hand, during the charging process, the nominal flow conditions are higher in the EcosimPro® model. This justifies a higher state of charge after a long charging transient due to imbalances in incoming or outgoing flow. These differences are attributed to the sizing of the system's heat exchangers and their nominal operating points, which affect the amount of heat entering or leaving the system.

However, when comparing the state of charge across all three models (Figure 35), it becomes evident that the TES system in EcosimPro® aligns more closely with PERSEE during charging phases, while still maintaining a certain difference from this target system.

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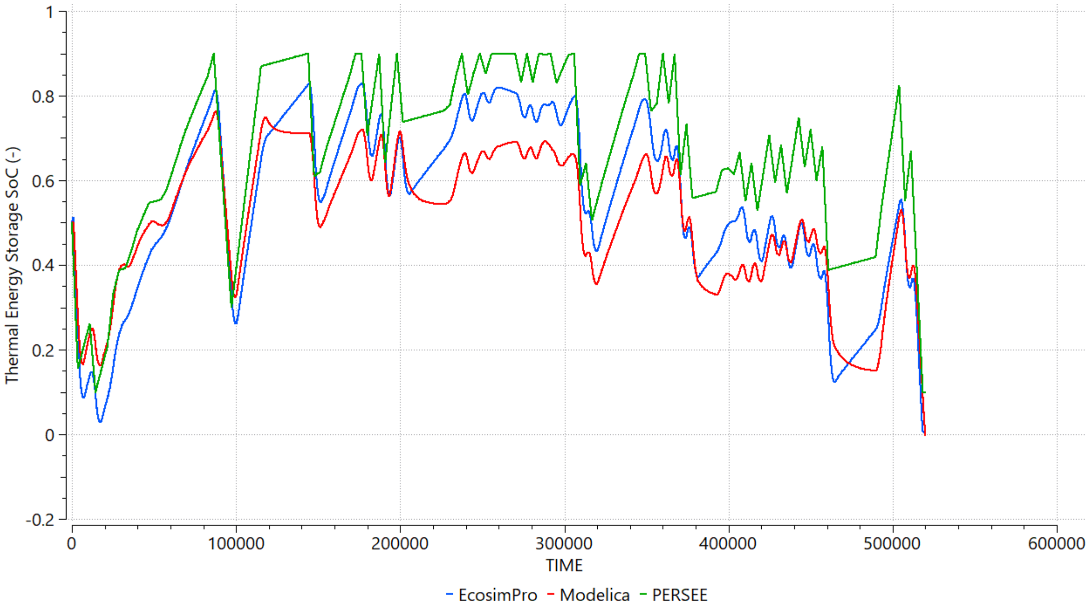

Figure 35: TES state of charge – EcosimPro® vs Modelica vs PERSEE

On the other hand, it is important to mention that, while the EcosimPro® simulator more closely approximates the behavior of PERSEE compared to the Modelica simulator, in general, thedifferences between the EcosimPro® and Modelica simulators are smaller than those between EcosimPro® and PERSEE.. This highlights the limitations due to the MILP formulation of PERSEE compared to the nonlinear formulation of Modelica and EcosimPro®, requiring a more refined interaction in the coupled Modelica and PERSEE model, as mentioned earlier.

High Temperature Steam Electrolyser plant

Regarding the electrolyser and its BOP, the study focuses on the electrical energy consumed by the systems as well as the thermal power extracted from the TES.

Figure 36 presents the thermal power extracted from the TES, showing differences similar to those observed in comparison with the PERSEE model. In this case, considering the TES discharge graph as a reference (Figure 33), it is evident that despite having a higher discharge flow, the system is unable to deliver the same amount of heat as in the Modelica model. In this case, it is evident that this difference is mainly due to the sizing of the heat exchanger and its nominal operating point. Since the system operates below that nominal point (440 kg/s), it does not deliver the expected amount of heat.

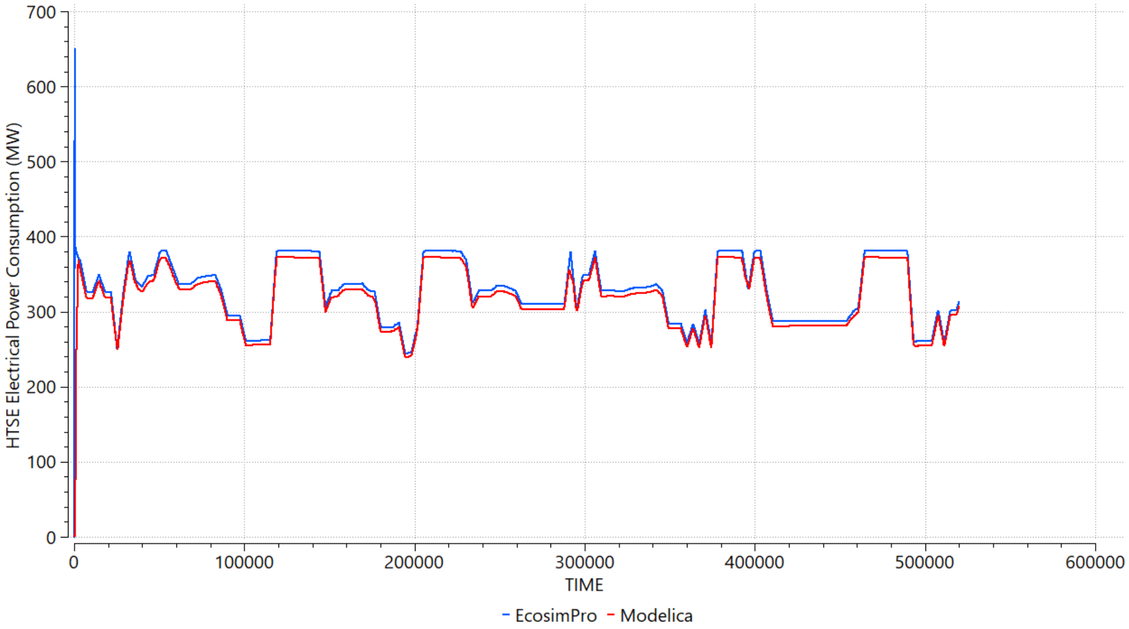

Figure 36: HTSE thermal power – EcosimPro® vs Modelica

If we compare the three systems, it is possible to observe that the model developed in EcosimPro® deviates from the expected behavior at certain points in the simulation, with an deviation similar to the one mentioned in the comparison with PERSEE—approximately 4%. Additionally, a slight variation between Modelica and PERSEE is also noticeable, which could be attributed to the fluid behavior and the control system implemented in the model.

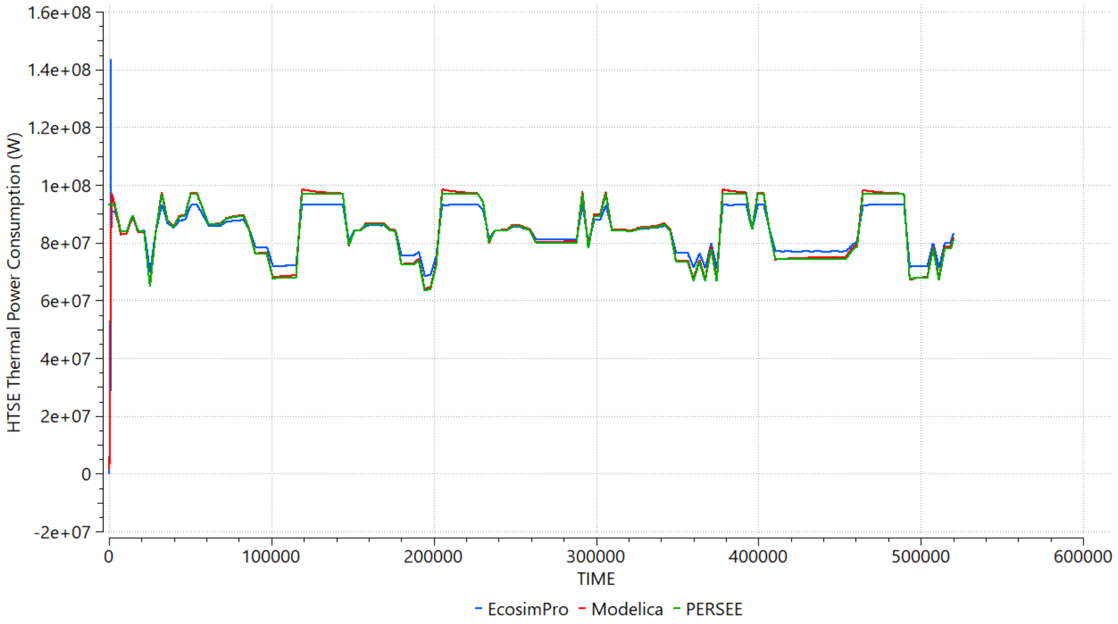

Figure 37: HTSE thermal power – EcosimPro® vs Modelica vs PERSEE

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Regarding the electrical power consumed by the electrolyzer system and the electric boiler, it is possible to observe nearly the same difference between EcosimPro® and Modelica as the one found with PERSEE, as shown in the following figure.

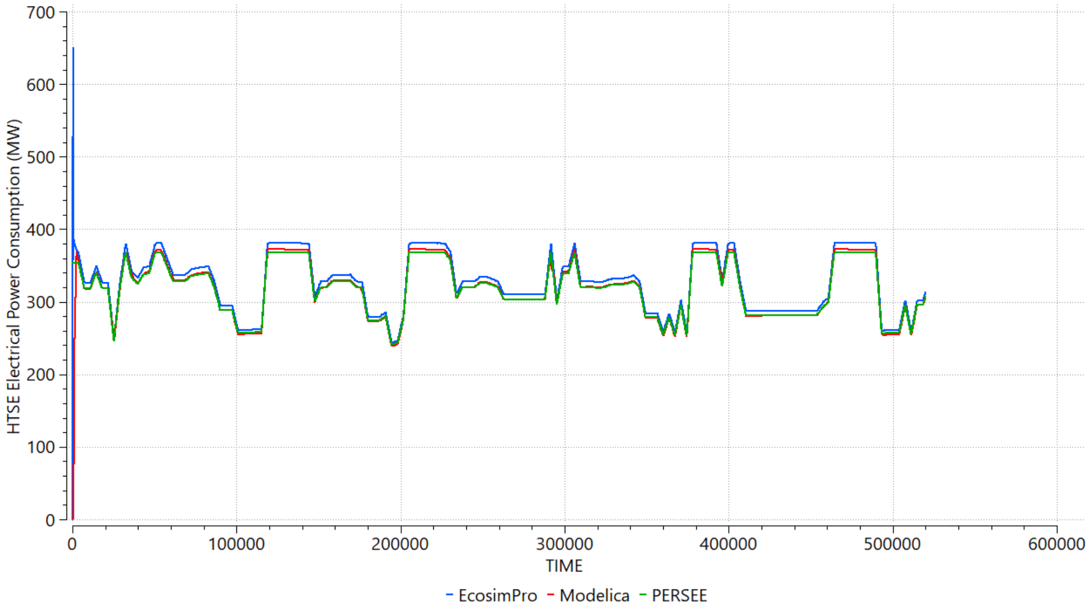

Figure 38: HTSE electrical power consumption – EcosimPro® vs Modelica vs PERSEE

In this case, although the maximum difference in electrical consumption is lower with Modelica (around 8.7 MWe, a 2.3% deviation), it is now possible to determine the source of this deviation by analyzing the electrical consumption of the two components separately.

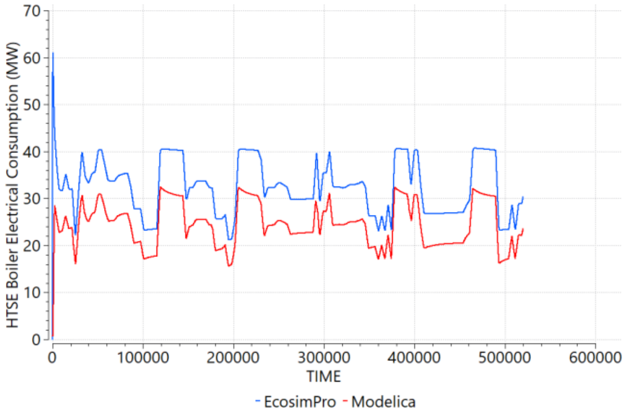

Figure 39: HTSE boiler electrical consumption – EcosimPro® vs Modelica

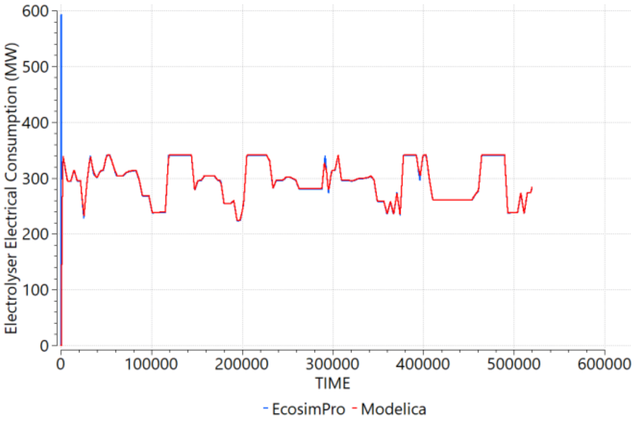

Figure 40: HTSE electrolyser electrical consumption – EcosimPro® vs Modelica

As mentioned during the comparison with PERSEE and as observed in Figure 38, the electrical consumption of the electrolyzer is almost identical in both systems. This confirms that the

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difference in electrical consumption originates from the electric boiler responsible for increasing the inlet temperature of the electrolyzer (Figure 39). This discrepancy reaches up to 9.8 MWe (32.4% deviation), which is a highly significant value to consider.

While part of this increased heat demand can be attributed to the lower heat extraction from the TES (4 MWth), this alone does not fully justify such a large difference between the two systems. Additionally, observing Figure 39, it is evident that the range of power consumption, from the lowest to the highest operating point, is around 2 MWe greater in EcosimPro® than in Modelica. This suggests that the discrepancies stem from the sizing of the heat exchanger located just before the boiler, which results in a lower inlet temperature in the EcosimPro® boiler model. This occurs due to the operating point of the heat exchanger, which is deviated from its nominal point (with 100% production in the electrolyzer).

On a positive note, since the electrical consumption of the electrolyzer is the dominant factor, the total system consumption deviation remains below 5%, as previously described. This is considered acceptable given the simplifications made in the models, such as modeling a single electrolyzer module and extrapolating the results to the total number of modules, or the modeling precision of the systems to reduce simulation time.

Finally, it is confirmed that hydrogen production is similar in both models, just as observed in the comparison with PERSEE.

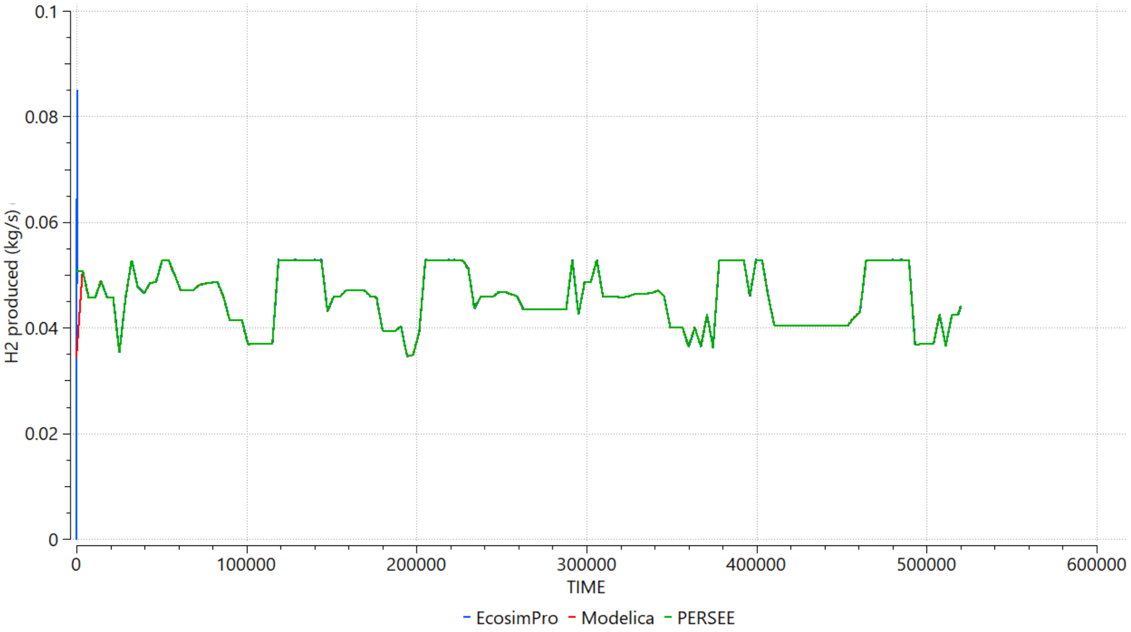

Figure 41: Hydrogen production – EcosimPro® vs Modelica vs PERSEE

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Hydrogen Storage

In the case of hydrogen storage, the comparison will only be made based on the state of charge of the tank, as the compression system was not modeled in Modelica. Regarding the hydrogen tank, it is important to mention that the Modelica model has been developed in a simplified manner, without considering dynamic effects, which may slightly affect the results obtained.

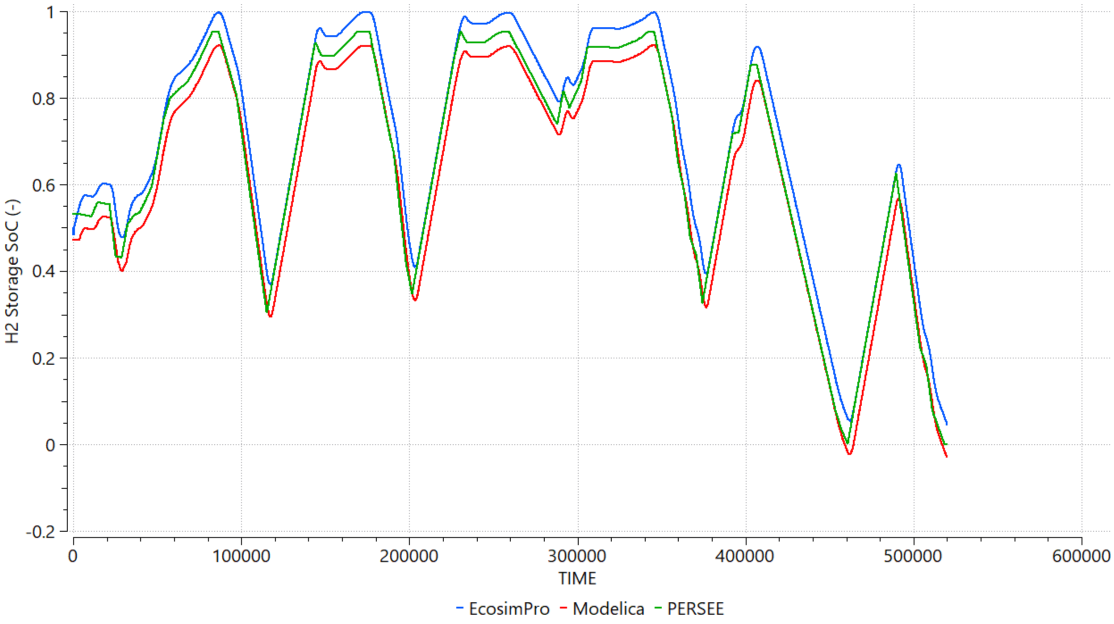

Figure 42: Hydrogen storage state of charge – EcosimPro® vs Modelica vs PERSEE

The Figure 42 illustrates the state of charge of the tank over time. Similar to what occurred with the PERSEE model, a difference between the models can be observed, where the EcosimPro® graph appears to be shifted vertically upward. This is attributed to the system's initial startup during the filling process, as seen in the early stages of the simulation with a steep initial slope. After this phase, the system behaves similarly in all three cases.

Interestingly, the PERSEE results are almost equidistant between the EcosimPro® results, which are positioned higher, and the Modelica results, which are positioned lower. This trend suggests that dynamic effects in this system may not be as significant as in others previously analyzed.

In conclusion, this study shows almost identical behavior across all systems, suggesting that with better calibration of the system's startup phase and steady-state operation, all three models should align almost perfectly.

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Rest of the components

For the remaining components, which include the solar plant, the wind farm, and the CCGT, no comparison has been made since a zero energy contribution was assumed in the simulation performed with Modelica.

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7 Conclusion

A nuclear hybrid energy system simulator corresponding to the energy hub configuration studied in TANDEM has been developed with the EcosimPro® simulation tool. It enabled for benchmarking the simulation model of hybrid energy system developed with the TANDEM Modelica library and the one implemented in the optimization tool PERSEE for the TANDEM/WP3 studies against this new EcosimPro® model. The objective was to give first elements to ensure the predictivity of the hybrid energy system models implemented in the energy hub studies in TANDEM/WP3.

Note that the the level of the model implemeted in the PERSEE optimization tool came from a compromise between computing time and accuracy, as well as the constrains of the MILP formulation. It is not expected that the PERSEE model can reach the same level of performance as the Modelica-based and EcosimPro® models. Further studies have been conducted within the project to assess the impact of the lump models of PERSEE against the Modelica-based simulator on the techno-economics optimisation results (see TANDEM/Deliverable 3.4).

Regarding the benchmarking results, although it has been concluded that most critical systems exhibit discrepancies below 5% deviation —which is acceptable given the modeling approach— it is important to highlight certain aspects following the technical analysis.

The main issue identified, which arises in both the EcosimPro® and Modelica simulators, is the simulation stopping due to the complete discharge of the TES system. This issue highlights the need for a tighter integration between the dynamic Modelica model and the techno-economic optimizer to optimize the setpoints on the TES control system in PERSEE. Certain differences were also identified in the evolution of the TES system's state of charge between EcosimPro® and Modelica. However, these discrepancies are due to the system's sizing and the defined nominal operating point, making the results between both systems acceptable.

Another significant issue identified in this study, particularly relevant due to its connection with Deliverable 3.2, is a difference regarding the type of photovoltaic panel mounting imposed in the PERSEE simulator. This difference might affect to both the estimation of PV electrical production and PV CAPEX compared to the values estimated in D3.2.

An additional aspect identified during the study was the discrepancy between EcosimPro® and Modelica in the electrical consumption of the boiler at the electrolyzer inlet, attributed to the sizing of the heat exchanger located upstream of the boiler. However, considering that the total variation in electrolyzer consumption remains around 2.3% at its peak values, along with certain system assumptions and simplifications, this deviation is considered acceptable.

Lastly, an important aspect to highlight is the differences observed in the study of hydrogen compressor power consumption. When comparing with the EcosimPro® model, a discrepancy of around 13% was observed throughout the simulation. However, since the consumption range remains similar in both systems, it was concluded that this difference is due to an underestimation caused by the theoretical calculation approach used in PERSEE. In conclusion, the simulations conducted with the three tools align to a considerable extent, and the results can be regarded as acceptable in most cases, with only specific systems in PERSEE requiring further analysis to ensure their proper functioning.

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