The TANDEM open-source Modelica-based library and coupling with existing simulation tools assessing nuclear safety and techno-economic viability

TANDEM conference

Stefano Lorenzi (PoliMi), Guido Masotti (PoliMi), Thorsten Hollands (GRS)

TANDEM

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Atomic Energy Community ('EC-Euratom'). Neither the European Union nor the granting authority can be held responsible for them.

Analysis framework and methodology for studying NHES

Analysis framework and methodology for studying NHES

Modelling and methodologies developed during the TANDEM project!

Why is the world a better place after the TANDEM project?

Why is the world a better place after the TANDEM project?

1. We have developed an **Open-Source Modelica "TANDEM" model library** aimed at simulating the behavior of power plants, systems and components, including SMRs, and needed to analyse the hybrid systems;
2. We have developed two **hybrid system simulators for the district heating and energy hub cases** to be employed in the techno-economics tools in WP3 and safety analysis in WP4;
3. We have developed coupling between **safety codes (CATHARE and ATHLET) and Modelica BoP models** to perform the safety analysis considering the integration of SMRs into hybrid energy system.

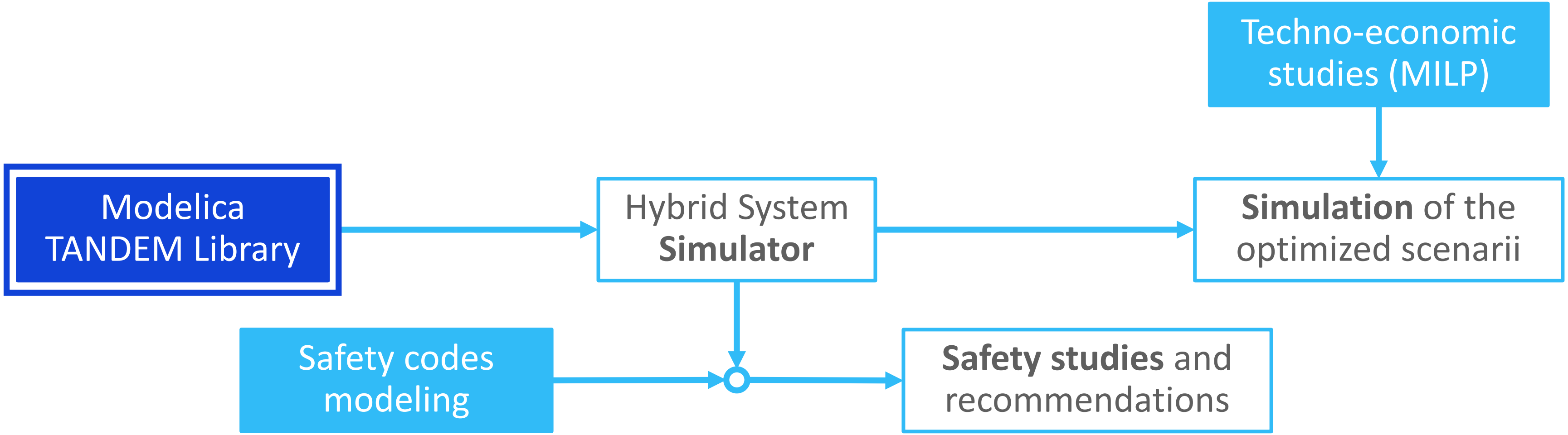
TANDEM

Why is the world a better place after the TANDEM project?

1. We have developed an **Open-Source Modelica "TANDEM" model library** aimed at simulating the behavior of power plants, systems and components, including SMRs, and needed to analyse the hybrid systems;
2. We have developed two **hybrid system simulators for the district heating and energy hub cases** to be employed in the techno-economics tools in WP3 and safety analysis in WP4;
3. We have developed coupling between **safety codes (CATHARE and ATHLET) and Modelica BoP models** to perform the safety analysis considering the integration of SMRs into hybrid energy system.

TANDEM

Modeling for SMR the integration



TANDEM

Functional requirements of the TANDEM library

The TANDEM library has been developed to be used to

- assess the dynamic response of the system to variations in boundary conditions
- monitor that the process variables remain within the allowed operational ranges
- design control systems to meet technical requirements
- satisfy commodity demands

The modelling should:

- reproduce the physical behaviour of the components (process variables in the HES – mass flow rates, temperatures) and provide the information useful for the TE analysis
- include time dependent modelling
- allow the possibility to vary the main input parameters

The Modelica TANDEM Library [2][3]

https://gitlab.pam-retd.fr/tandem/tandem

1. SMR
   a. NSSS
   b. CI-BOP
2. Electrical Grid
3. District Heating
4. Storage
   a. Thermal
   b. Electrical *Simplified*
5. RES *Simplified*
6. [RO] Desalination *Simplified*
7. H2
   a. [PEM] Low Temperature *Simplified*
   b. [SOEC] High Temperature

Developed by:

POLITECNICO MILANO 1863

TANDEM

Supporting Libraries

- ThermoSysPro & ThermoPower

EDF POLITECNICO MILANO 1863

Thermohydraulics (& control) modeling: power plants, heat storages, district heating…

- Buildings

BERKELEY LAB

Buildings (& supporting systems) modeling: → electrical grid

- CEA_Energy_Process_Library

cea

Energy processes & associated media: hydrolysis, fuel cells…

- WindPowerPlant

tgm Die Schule der Technik

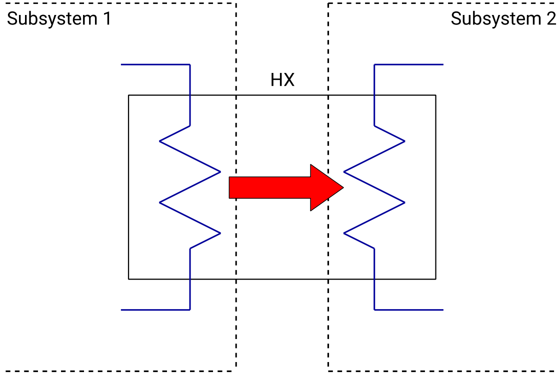
Models injecting variable electrical power to the grid

TANDEM

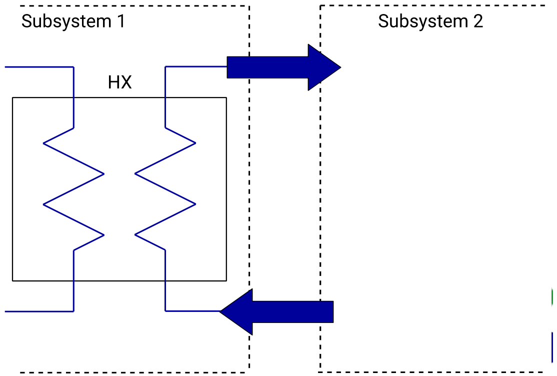
General approach

- Simplified modelling strategies will be adopted for components that are only **electrically coupled** to the HES (batteries, LTE, RO desalination)
- Different Modelica libraries (Modelica Standard Library, ThermoPower, ThermoSysPro, Buildings…) will be employed for the modelling of the single components → development of **dedicated adaptors** will allow for the coupling of subsystems based on different libraries into HES architectures
- Two coupling approaches will be considered:
  - **A) Thermal coupling**: the exchanged variable is the thermal power flux within the heat exchangers
  - **B) Fluid coupling**: the exchanged variables are the properties of the fluid flowin from one component to the other
- Models will be compatible with both **OpenModelica** and **Dymola**

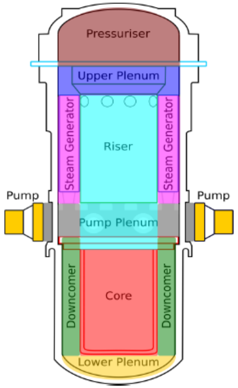
A)



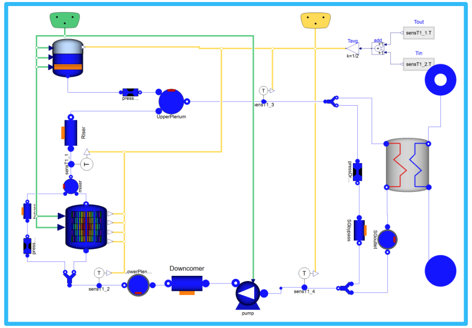
B)



Example of Module: the E-SMR from ELSMOR

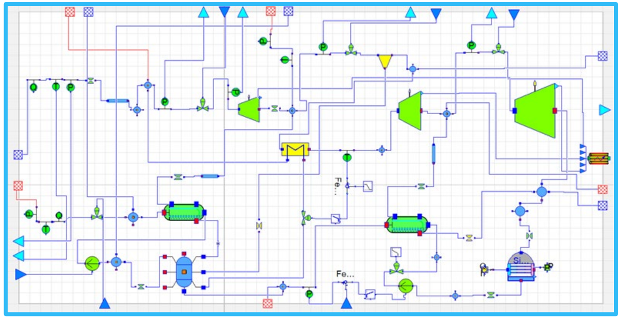


Nuclear Steam Supply System



x2

Conventional Island - BoP



x3

Multiple available models:

- Benchmark purpose
- Control strategies
- Specialized models: interfaces (thermal or fluid), number of heat extraction points, inertia, modeling approaches/simplifications…
- Documentation available [2],[3] to make your choice

TANDEM

Usages of the library

Customizable HES simulator by assembling the available bricks...
→ or even new bricks of your own ! (depending on your need)

HES operation studies:

- Heat load transients (daily, seasonal…)
- Response to electrical grid needs (flexibility)
- Analyses of
  - Architecture design
  - Operation strategies
  - Control logic

↘

Optimization : MILP, genetic algorithms…

HES accident scenarii:

- Provide realistic boundary conditions
  → solicitation on the reactor
- Allow preliminary studies

↘

CATHARE, ATHLET…
but also, potentially, neutron or thermo-mechanical codes

TANDEM

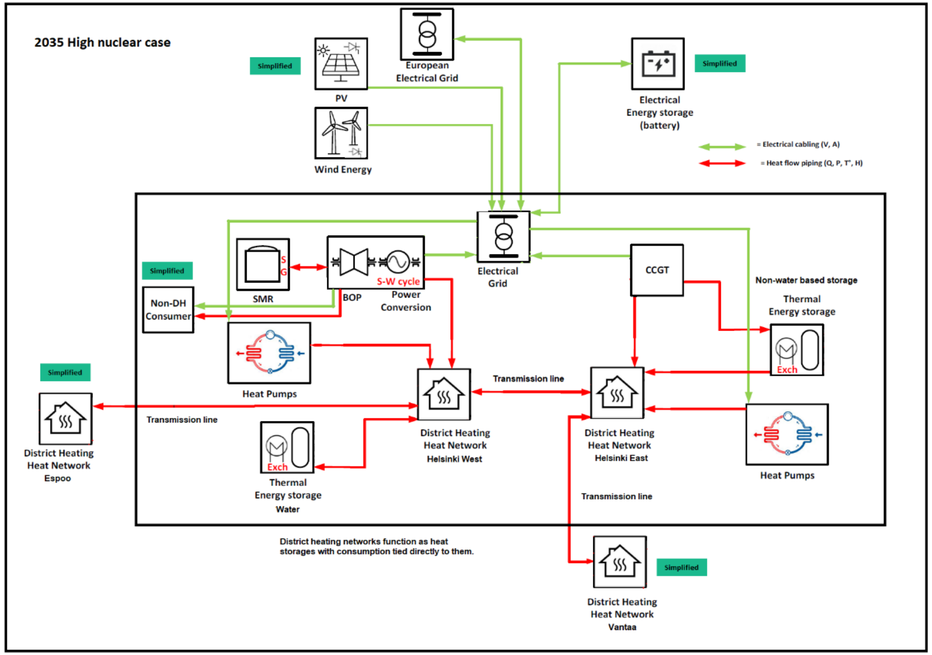
Why is the world a better place after the TANDEM project?

1. We have developed an **Open-Source Modelica "TANDEM" model library** aimed at simulating the behavior of power plants, systems and components, including SMRs, and needed to analyse the hybrid systems;
2. We have developed two **hybrid system simulators for the district heating and energy hub cases** to be employed in the techno-economics tools in WP3 and safety analysis in WP4;
3. We have developed coupling between **safety codes (CATHARE and ATHLET) and Modelica BoP models** to perform the safety analysis considering the integration of SMRs into hybrid energy system.

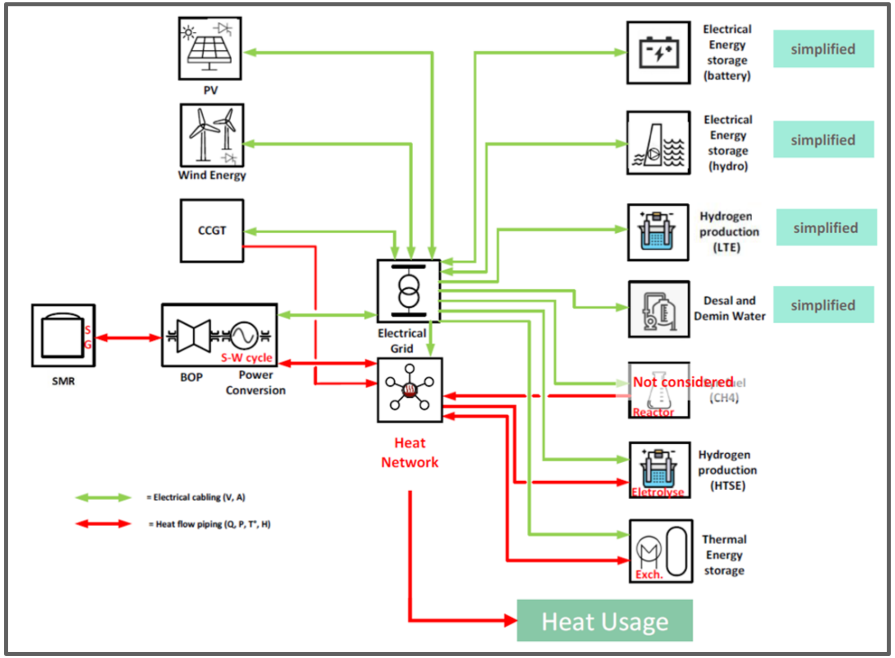
TANDEM

Reference case studies

District Heating and Power Supply (Northern European case)

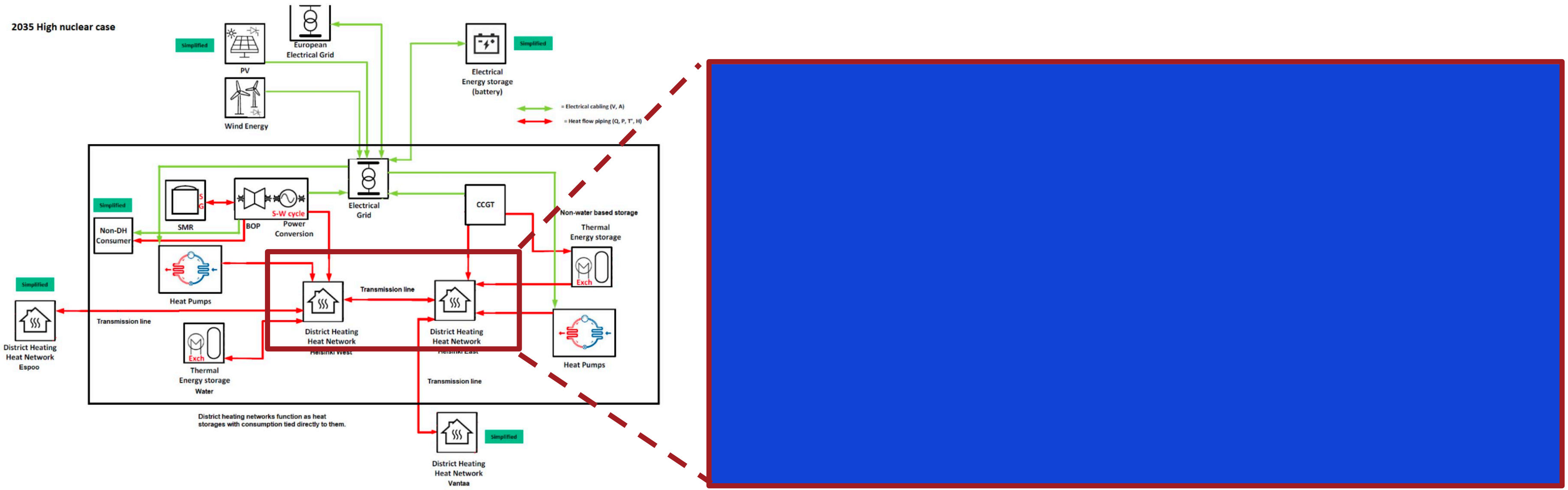


Energy Hub (Southern European case)



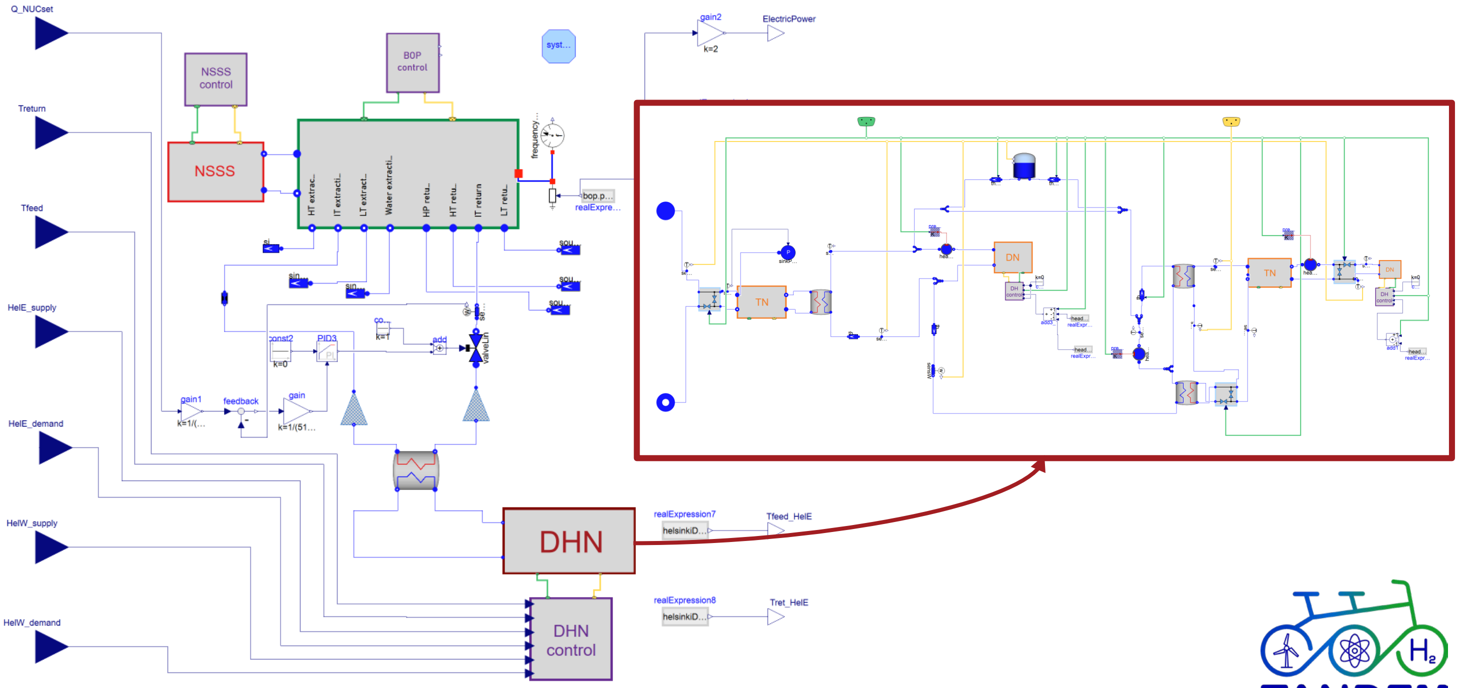
District heating – Detailed layout

Translation of the scheme in a detailed, **“control-oriented”** architecture to be implemented in Modelica. The goal is to be able to implement the control actions required to meet the system’s requirements and be consistent with the techno-economic optimisator logic.



District heating – Building the simulator

- TANDEM
  - SMR
    - NSSS
    - BOP
  - EnergyStorage
  - H2production
  - Desalination
  - Methanation
  - Tools
  - Renewables
  - PowerSources
  - ElectricalGrid
  - DistrictHeating
    - Test
    - Components
    - Control
  - TestCases

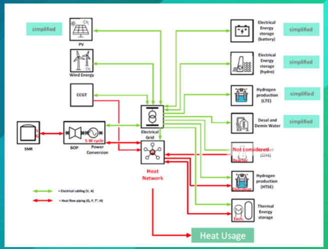


District heating – Simulation examples

- Simulation of power flows within the NHES accounting for system dynamics
- Implementation of different control strategy to maintain system within allowed limits
- Tracking of critical variables on the nuclear side

TANDEM

Energy hub – Detailed architectures



Focus on technologies resulting from the techno-economic optimisations in WP3:
HTSE for hydrogen production, **two-tanks TES** to increase flexibility

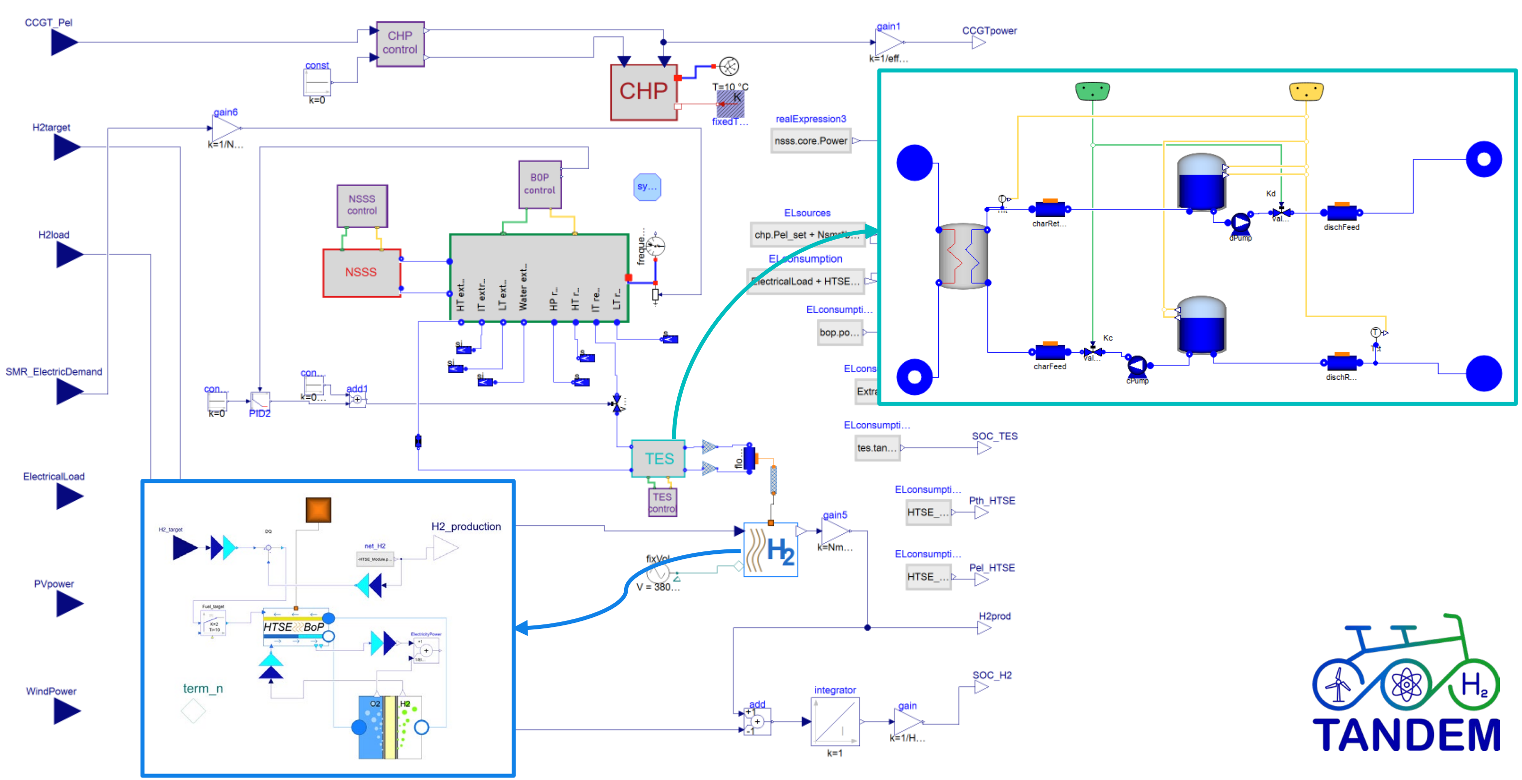
Coupled energy hub architecture

Decoupled energy hub architecture

TANDEM

Energy hub – Building the simulator

- TANDEM
  - SMR
    - NSSS
    - BOP
  - EnergyStorage
    - ThermalStorage
    - ElectricalStorage
  - H2production
    - HTSE
    - LTE
  - Desalination
  - Methanation
  - Tools
  - Renewables
  - PowerSources
  - ElectricalGrid
  - DistrictHeating
  - TestCases



Energy hub – Simulation examples

- Tracking of thermal and electrical power flows within the system
- Estimation of storage evolution and dynamics of commodities beyond electricity
- Evaluation of the impact of steam extraction on the SMR operation

TANDEM

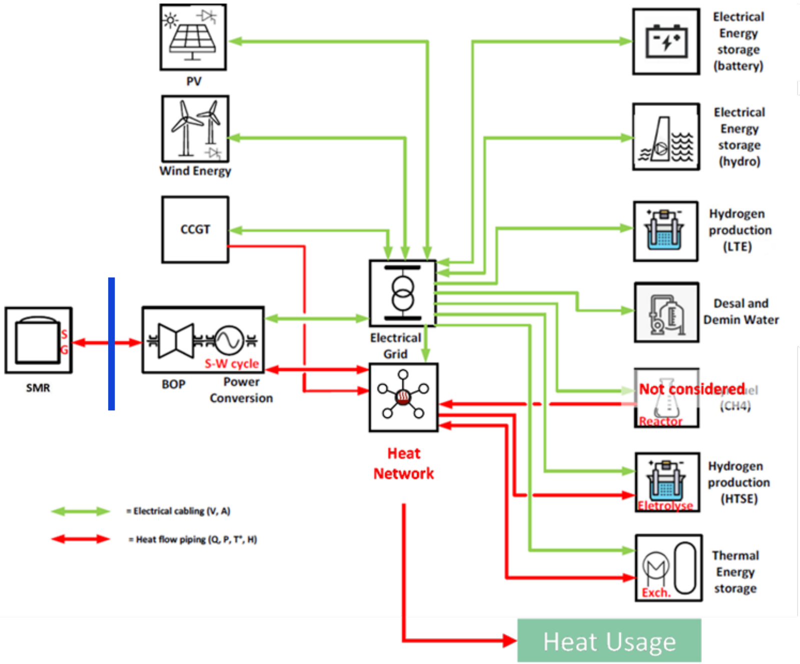
Why is the world a better place after the TANDEM project?

1. We have developed an **Open-Source Modelica “TANDEM” model library** aimed at simulating the behavior of power plants, systems and components, including SMRs, and needed to analyse the hybrid systems;
2. We have developed two **hybrid system simulators for the district heating and energy hub cases** to be employed in the techno-economics tools in WP3 and safety analysis in WP4;
3. We have developed coupling between **safety codes (CATHARE and ATHLET) and Modelica BoP models** to perform the safety analysis considering the integration of SMRs into hybrid energy system.

TANDEM

Coupling of HES with safety codes for SMR

- The SMR behaviour is simulated by safety codes
- Analyses of normal operation, transients, AOO and design basis accidents



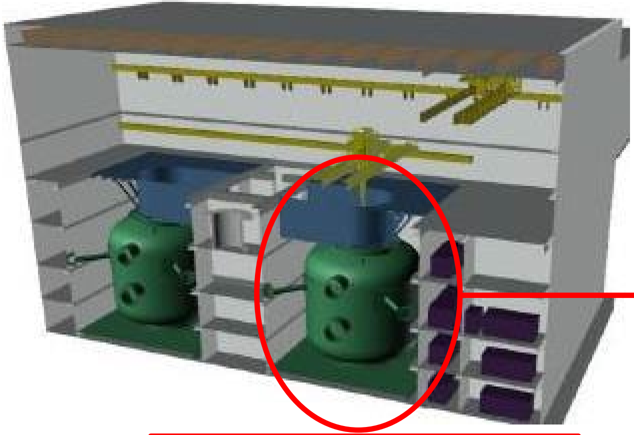
- Modelica model of the HES
- Balance-of-plant model of the turbine/generator unit as interface to safety code

TANDEM

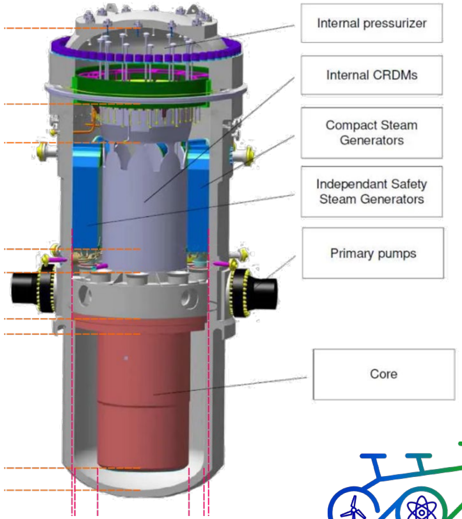
E-SMR - NUWARD like design

Multi-SMR units at one location

	E-SMR	EPR
Thermal power	540 MW	4300 MW
Electrical power	167 MW	1600 MW



One single unit only



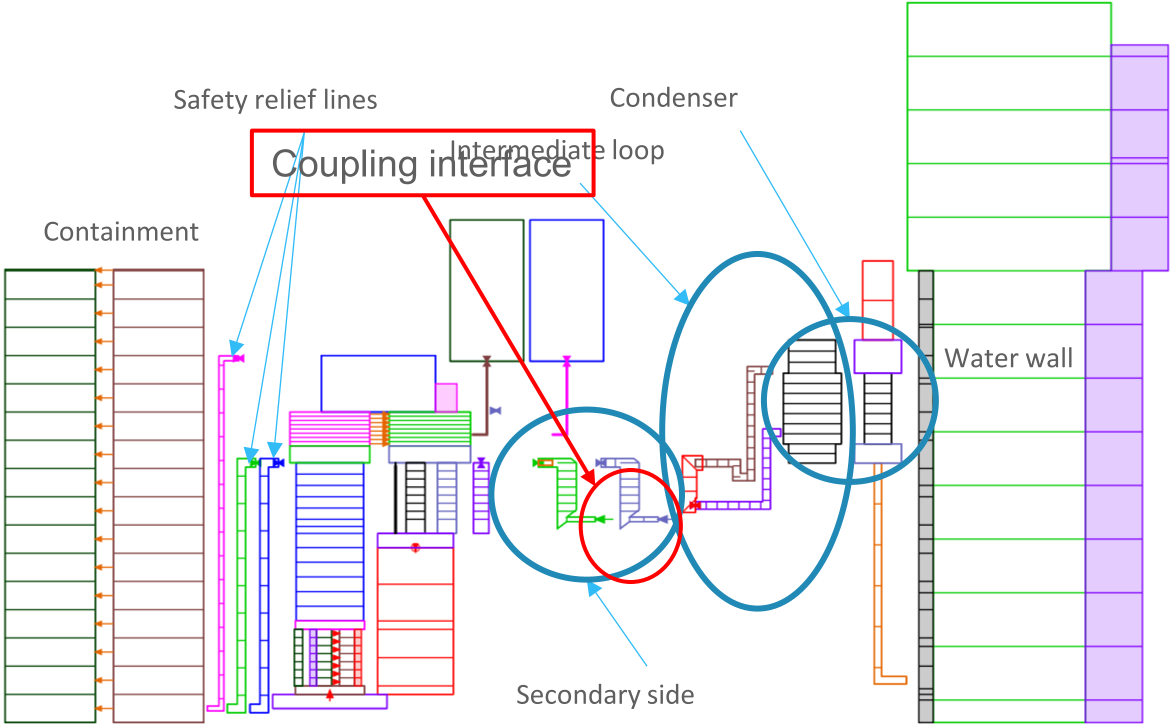
Source: ELSMOR - E-SMR dataset description

TANDEM

Safety Codes
AC2/ATHLET (GRS) and CATHARE (CEA)

- **Safety Codes**
  Safety codes are used to assess the safety of nuclear power plants, research reactors and spent fuel pools in different scenarios during normal operation, transients and accidents.
- **AC^2/ATHLET**
  ATHLET stands for "Analysis of Thermal Hydraulics of Leaks and Transients".
  The ATHLET thermal hydraulics code is part of the code package AC^2.
  Developed by Gesellschaft für Anlagen und Reaktorsicherheit (GRS), Germany.
- **CATHARE**
  CATHARE is a system thermal-hydraulics code.
  Developed by CEA (French Atomic Energy Commission), EDF (Electricity de France), Framatome and the IRSN/ASNR (Radio-protection and Nuclear Safety Institute).

ATHLET Input deck for E-SMR, comparable for CATHARE



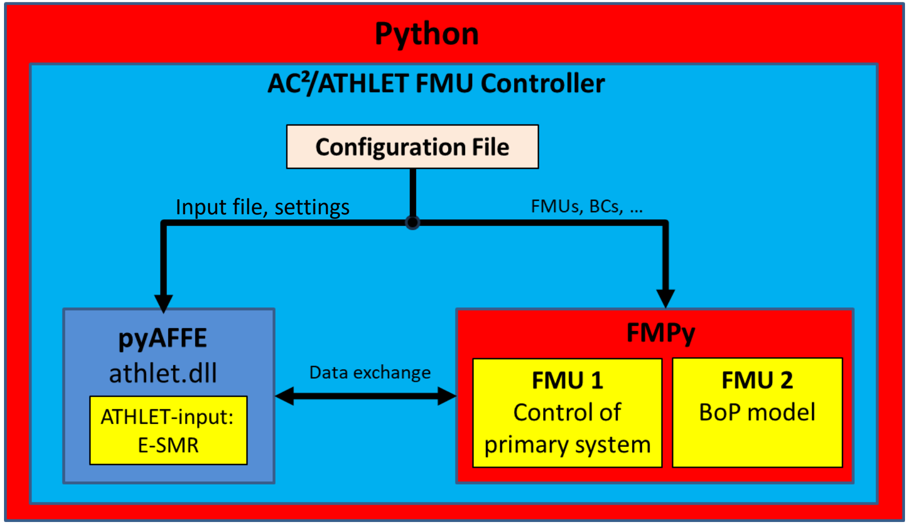
- Developed by GRS and LEI in the frame of EC funded ELSMOR project
- Detailed modelling of the primary circuit
- Simplified secondary side
- Designed for SBO and LOCA scenarios

TANDEM

Coupling of Safety Codes and Modelica - Python Coupling -

AC²/ATHLET FMU controller

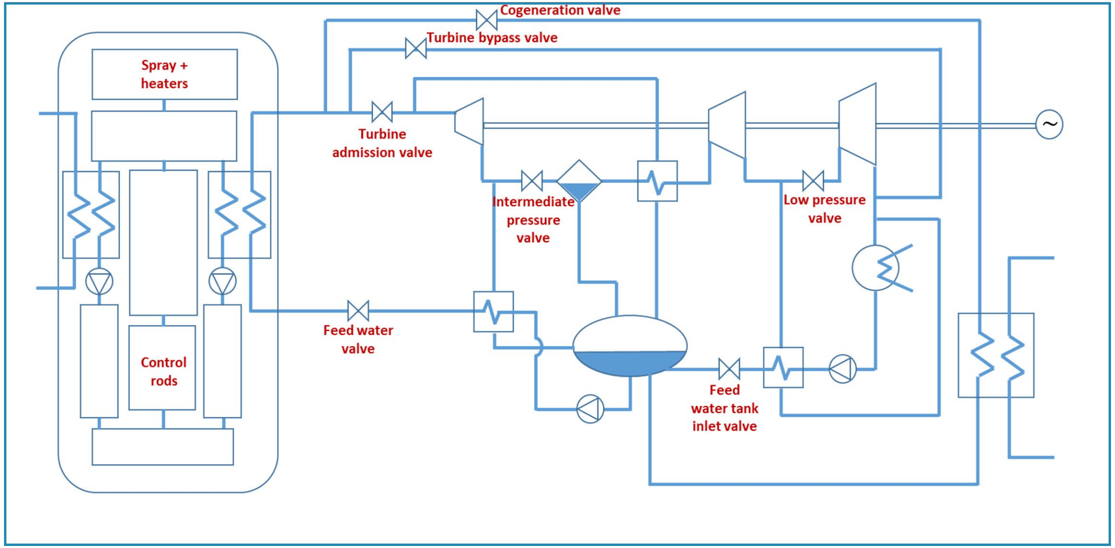
- ATHLET-Python interface pyAFFE (part of AC²)
- ATHLET control by python, transfer of data from/to ATHLET possible
- Python library FMPy used to handle FMUs
- Several instances of FMUs possible
- Specification of data to be exchanged by configuration file
- During simulation ATHLET is called first and the FMUs successively
- Time step size determined by ATHLET
- Low pass filter to dampen high frequency oscillations



Coupling of Safety Codes and Modelica
- CATHARE/Modelica Control systems development -

Nuclear Steam Supply System controls

Controlled variable	Actuator
Primary avg. temperature	Control rods
Primary pressure	Spray + heaters
Pressurizer level	Volume control system

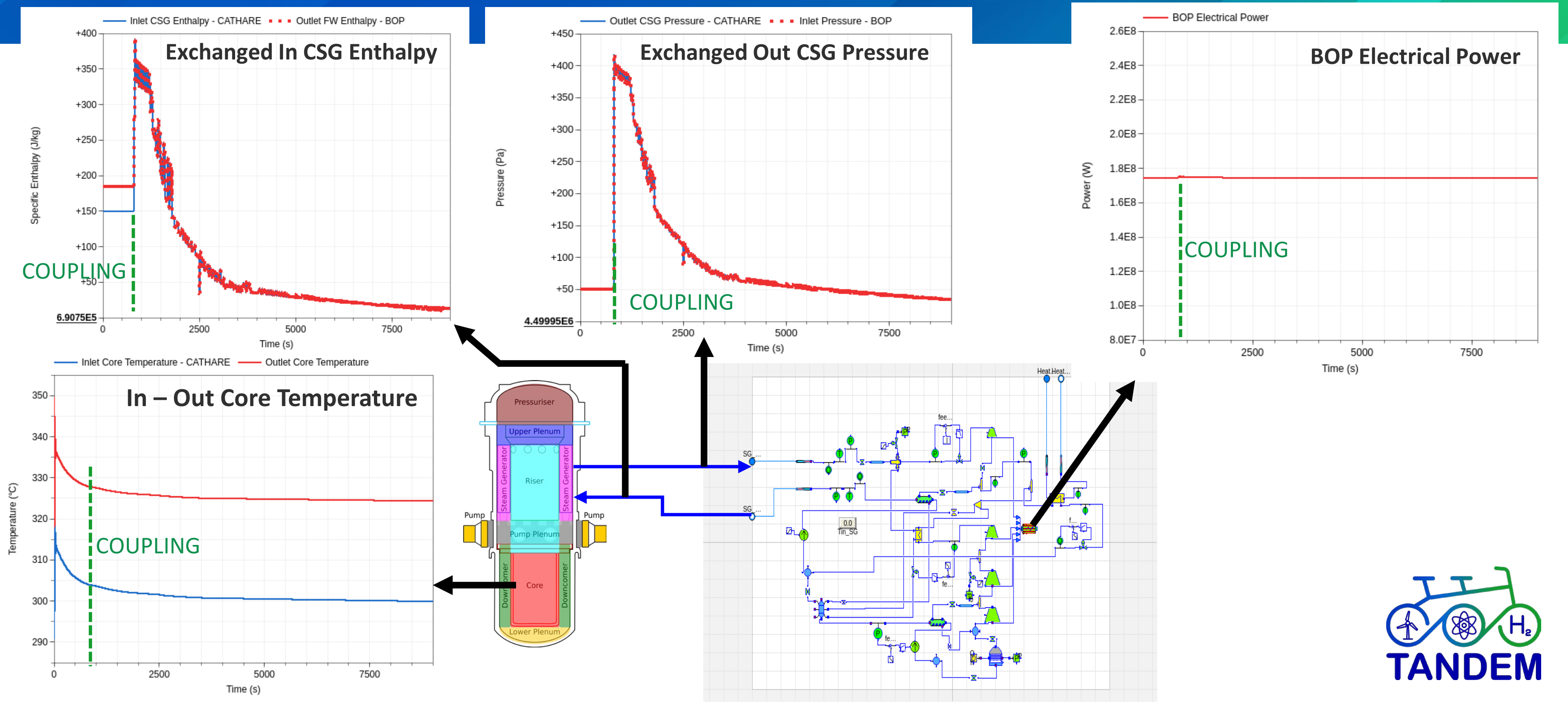


Balance of Plant controls

Controlled variable	Actuator
Turbine frequency	Turbine admission valve
HP turbine pressure	Feed water valve
IP turbine pressure	Intermediate pressure valve
LP turbine pressure	Low pressure valve
Feed water tank pressure	Tank inlet valve

TANDEM

Steady State Coupling CATHARE/Modelica



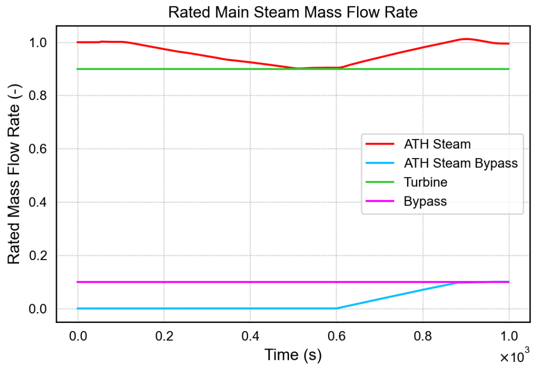
Steady State Coupling ATHLET/Modelica
90 % Electricity / 10 % Heat

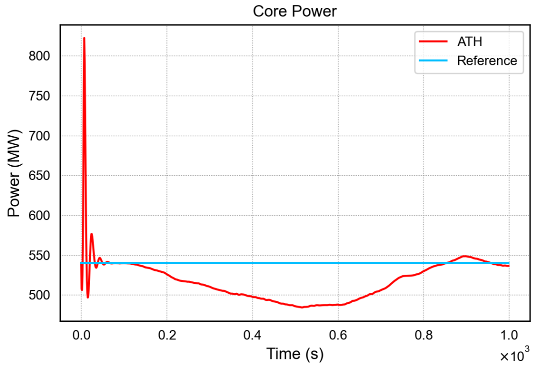
Steady state condition of the facility covers

- 90 % of steam mass flow rate → electricity production
- 10 % of steam mass flow rate → heat generation

To reach the steady state

- Demanded power reduced to 84 % of full power (2 % / min)
- Opening of the bypass valve to 60 % (33 % / 100 s)
- Core is almost at full power





TANDEM

Conclusions

- **Modelica library** with the components (SMR, heat storage, renewables, hydrolysers, district heating…) to build a **customizable NHES simulator** → see TANDEM cases on district heating and energy hub cases
- TANDEM activities enables both **techno-economics studies of NHES** (optimization of layout & capacity + problem dispatchment) and **safety studies through coupling with safety codes.**
- The first version of the library has been developed for the needs of the TANDEM project but it can support the **development of energy system integration** within both the nuclear and non-nuclear community.

TANDEM Partners

TANDEM

cea

ansaldo nucleare

CIRTEN – Consorzio Interuniversitario per la Ricerca Tecnologica Nucleare

POLITECNICO MILANO 1863

IN SUPREMÆ DIGNITATIS 1343 UNIVERSITÀ DI PISA

ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development

enen

TRACTEBEL ENGIE

EMPRESARIOS AGRUPADOS

EDF

ENERGORISK

nucleareurope

fortum

GRS

IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

VTT

ÚJV

European Commission

Get in touch for more information:

STEFANO LORENZI, GIORGIO SIMONINI, VÍCTOR AMEZCUA, THORSTEN HOLLANDS

stefano.lorenzi@polimi.it, giorgio.simonini@edf.fr, vamezcua@empre.es, thorsten.hollands@grs.de

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or he European Atomic Energy Community ('EC-Euratom'). Neither the European Union nor the granting authority can be held responsible for them.

TANDEM

Bibliography

1. C. Vaglio-Gaudard et al. « The TANDEM Euratom Project: Context, Objectives and Workplan ». Nuclear Engineering and Technology 56, nº 3 (mars 2024): 993-1001. https://doi.org/10.1016/j.net.2023.12.015.

2. G. Simonini et al. "Modelica models description for the 'TANDEM' library", 2024. https://tandemproject.eu/resources/.

3. G. Simonini et al. "Integrating Small Modular Reactors into Hybrid Energy Systems: the TANDEM Modelica library", IAEA SMR conference, Wien, Austria, 2024.

4. G. Masotti et al. "Simulation of flexible small modular reactor operation with a thermal energy storage system", IAEA SMR conference, Wien, Austria, 2024.

5. G. Masotti et al. "Dynamic Modelling and Optimisation of a Small Modular Reactor for Electricity Production and District Heating in the Helsinki Region". ICAPP, Las Vegas, NV, 2024.

TANDEM