INTEGRATING SMALL MODULAR REACTORS INTO HYBRID ENERGY SYSTEMS: THE TANDEM MODELICA LIBRARY

G. SIMONINI, V. FERRARA, Y. HAMMADI, S. HOCINE-RASTIC
EDF
Chatou, France
Email: giorgio.simonini@edf.fr

S. LORENZI, G. MASOTTI
Politecnico di Milano,
Milan, Italy

N. ALPY, D. HAUBENSACK, S. MATHONNIERE, R. TALPIN
CEA
Cadarache - IRESNE / Grenoble, France

A. BAUDOUX, D. JOURET, F. PAPPALARDO, B. TOURNEUR
Tractebel
Town/City, Belgium

Abstract

The rapid evolution of Small Modular Reactor (SMR) technology has triggered renewed interest in exploring innovative applications within the framework of nuclear hybrid energy systems. SMR, given their greater flexibility in terms of siting and power rates, are one of the most suitable candidates to be integrated in energy systems aimed at providing multiple energetic assets. In this context, feasibility studies as well as techno-economics analysis should be supported by proper modelling tools able to facilitate the integration of SMRs with other energy system components, such as renewable plants, energy storage systems, hydrogen production, etc. This paper presents the TANDEM Modelica library developed within the TANDEM Project – a Horizon Europe project aimed at developing methodologies and tools to facilitate the safe and efficient integration of SMRs into smart low-carbon hybrid energy systems. The TANDEM library is based on several staple libraries (e.g., ThermoPower, ThermoSysPro, Modelica Standard Library) from which the main components of a hybrid energy system are derived, e.g., N3S, BoP and power conversion systems, electrical and thermal energy storage, electrical grid, conventional power plants, hydrogen production with low and high temperature electrolysers, district heating…. The library is meant to be a versatile platform, offering a unified framework for the dynamic simulation and analysis of complex interactions within nuclear hybrid energy systems. Key features of the library include modularity, extensibility, and compatibility with existing library and simulation tools, including safety codes. Possible applications enabled by the library include the analysis of different operational strategies and the optimization of the hybrid energy system configuration and components' design in terms of efficiency, reliability and/or CO2 emissions.

1. INTRODUCTION

The energy transition is one of the greater challenges that humans must deal with for the next decades; Europe has, for example, set an objective of net-zero carbon production by 2050. To reach such targets, electrification and promotion of carbon free electricity sources, such as renewables, are one of the main solutions. However, to deal with residential and industrial heat demands, nuclear cogeneration may be both more economically interesting and more effective to develop than solutions based on electricity (e.g., heat pumps).

In this context, Small Modular Reactors (SMR) may play a key role. Because of their size in terms of power, comparable to fossil fuel plants to be substituted, they can easily be integrated in the existing electrical grid. Moreover, they can integrate energy hubs (industrial hubs or residential areas) to satisfy local heat needs.

SMR cogeneration is a quite recent topic, which is emphasized by the regain of interest in SMR in the last years with several projects being in advanced state of the design process. In this context, the TANDEM Euratom project [1] has the objective of developing methodologies and tools to ease the safe and effective integrations of SMR in *Hybrid Energy Systems* (HES). Among the main outputs of the project, the open-source TANDEM Modelica library has been developed: the objective is to provide the bricks to build an easily customizable simulator of the HES to perform techno-economic studies and provide realistic boundary conditions for safety studies assessing the impact of cogeneration.

This paper presents the main characteristics of the TANDEM library. §2 give an overview of the library and its TANDEM context, §3 provides a description of all the components of the first version of the library while §0 briefly cites some first uses of it before concluding (§5).

2. LIBRARY DESCRIPTION AND STUDY CASES

The first version of the library was made available ([2], [3]) to the public in mid-2024. Within the TANDEM scope, the library focused on providing the bricks to model two predefined study cases [4]:

- **The district heating (DH) and power supply**
  The HES configuration for this study case targets a large urban area. The main objective is decarbonizing the production of heat and electricity with special focus on residential heating. As demonstrative cases in the TANDEM project, a Finnish and a Czech applications are investigated. An important feature for the DH case, is the seasonal and daily variations of heat demand which must be correctly represented in the models.
- **The energy hub (eHub)**
  This study case is inspired from a harbor-like infrastructure, which can be characterized as a complex distribution network of several energy carrier fluxes (power, heat, gas, hydrogen…) linking production units and consumers. In the TANDEM project the focus is on electricity and heat fluxes only, to avoid excessive modelling complexity. Concerning end-users, hydrogen production and desalination are, for example, considered.

For both cases, the objective is being able to simulate operating scenarii with different configurations; in particular low and high penetration of SMR must be modelled to assess the impact of nuclear cogeneration on some techno-economic and environmental key parameters [5]. Together with the SMR, other production units (for example Combined Cycle Gas Turbine (CCGT), conventional Nuclear Power Plants (NPP), nuclear Heat Only Boilers (HOB), renewables…), storage units and heat pumps may be considered according to forecasted European trajectories.

To accurately represent these complex systems and the interactions between their components, the TANDEM library targets a dynamic representation of the main components. In its first version, the focus has been set on some key components (see § 3); "minor" components (especially electricity only users) have been modelled with a simplified approach because of their limited impact on the global system and to limit the burden of a too complex simulator. In the future, the library may keep evolving to:

- improve the modelling of some components,
- include new HES components (e.g., methanation)
- and provide models for different technologies.

Concerning this last item, for example, the TANDEM library is focused today on PWR technology, because of its maturity and the development status of such reactors in Europe; however, Advanced Modular Reactors (AMR), could be included for more long-term studies. Another example concerns hydrogen production technology, which is rapidly evolving: *Solid Oxide Electrolyser Cell* (SOEC) and *Proton Exchange Membrane* electrolyser (PEM) are provided today in the library, but additional technology may be considered in the future.

The library is not developed from scratch: it is supported by well-established Modelica libraries:

- **ThermoPower** [6] and **ThermoSysPro** [7]: respectively developed by *Politecnico di Milano* and *EDF R&D*, these two libraries are mainly dedicated to power plant modelling; including components such as heat exchangers, turbines, pumps…
- **CEA_Energy_Process_Library**: developed by the CEA, the goal of this MSL (Modelica Standard Library) compatible library is to regroup various models focused on energy processes

(electrolysis, fuel cells, chemical conversion to molecules of interest, gas storage etc.) but most importantly a great diversity of fluid medium and components.

- **Buildings** [8]: exhaustive library dedicated to building modelling, it has been used within the TANDEM library for the electrical system.
- **WindPowerPlants**: this library has been developed at the Technical Engineering College (TGM) and is used to model the contribution of energy generation from the wind power plants integrated into the hybrid energy system, starting from wind data; a detailed description of the library's structure and underlying assumptions is available in [9].

Concerning its usage, the TANDEM library can be used to build customizable simulators for different HES configurations. The simulator can then be used to perform techno-economical studies considering the complex interaction of the system components focusing on different timescales: from load variations (characteristic time of a few minutes) to seasonal variations characteristic time of several months). It can also be used to provide realistic boundary conditions to safety codes for safety studies; for example, to assess the propagation of rapid heat load variations up to the nuclear island, but also to consider the potential benefits of having additional systems (e.g., heat storage), even though not safety rated, to manage fast turbine transient (e.g., islanding). Finally, the simulator can be used for optimization studies: on the entire system level or focusing on a single component while considering its interactions with the other connected components.

3. COMPONENTS

This section provides a brief description for the components of the first version of the TANDEM library. Further details on the modelling assumptions and some illustrative or benchmark results can be found in [3].

3.1. Small Modular Reactor (SMR)

As said above, the focus for the TANDEM project is on SMRs based on the Pressurized Water Reactor technology. In this first version of the library, only a model for a PWR-SMR is provided.

3.1.1. Nuclear Steam Supply System (N3S)

The reference SMR design considered in the scope of the TANDEM project is the European SMR (E-SMR) reactor, a conceptual design developed within the framework of the ELSMOR Euratom project [10]. The E-SMR design relies on typical SMRs features (integrated design, compact steam generators, etc.).

The TANDEM library provides two versions of the N3S, relying on different supporting libraries, namely ThermoSysPro and ThermoPower. The two models are based on a similar modelling approach, adopting point kinetics equations for the neutronics and a one dimensional thermal-hydraulic model to simulate the coolant flow through the N3S components, despite some differences in terms of underlying assumptions. For instance, a simplified pressurizer model is encompassed in the version based on the ThermoPower library, relying on the assumption of equilibrium between liquid and vapor phases, whereas the distinction between phases is accounted for in the ThermoSysPro model. The N3S operation is regulated by a constant core average temperature control program. The temperature is maintained at its setpoint value by regulating the external reactivity insertion in the core: by direct reactivity insertion from a proportional-integral (PI) controller in the ThermoPower model and by a proportional (P) controller of the rod insertion speed in the ThermoSysPro one.

The rationale for developing two models based on different libraries in parallel is to be able to benchmark the simulation outcomes, thereby increasing confidence in the results.

3.1.2. Conventional Island – Balance of Plant (CI-BoP)

Three main versions of Balance Of Plant have been developed, using the ThermoPower (2 models) and ThermoSysPro libraries respectively. Both approaches share common features: cycle design follows a preliminary CYCLOP calculation [11] which was performed to define the optimal cycle coordinates (P, H) (optimized for power generation), as well as the cycle architecture to be implemented. Typically, the compromise between simplification and representativeness led to the consideration of a low-temperature reheater and a high-temperature reheater, rather than a larger cascade of these components. Cogeneration capacities are provided by controllable steam extraction lines at high pressure - HP (45bar, 300C), intermediate pressure - IP (7.5bar, saturated) and low pressure - LP (0.8bar, also saturated). Typically, the former could be used for high temperature steam electrolysis, thermal storage or any other asset requiring high grade steam, the second for thermal storage or lower temperature electrolysis and the latter for district heating. In fact, some of these possibilities have already been successfully applied in R&D studies ([12], [13]).

It's worth mentioning that the motivation for duplicating the modeling is to provide benchmark possibilities but also to enable the exploration of numerical aspects by proposing possibilities for fluid and thermal port connections. These connections are used either to connect the various components of the TANDEM library, or to connect the CI-BoP with the N3S system modeling code (namely, CATHARE or ATHLET): for this purpose, new fluid port for *Functional Mock-up Units (*FMUs) have been developed and their operational efficiency has been demonstrated.

Two first versions of the BoP model, one with ThermoSysPro and one with ThermoPower, have a quasi-static modeling approach. The same approach was followed by [14] for cogeneration studies with a French PWR1300: it demonstrated its relevancy as far as the scope of the use of the model primarily addresses the thermodynamic aspects linked to cogeneration flexibility. A second CI-BoP version, based on the ThermoPower library, also accounts for the dynamic aspects of the main components in the steam cycle.

3.2. Electrical Grid

The electrical grid component serves as a connection between electrical ports of various electrical producers and consumers such as the BOP, HTSE, etc. The grid component is divided in 2 sub-components:

- The grid node, a base element including electrical line impedance, compensation devices and transformers. Several nodes can be put in series or parallel to produce various grid architectures.
- The "node array" which consists of a serialization of identical nodes with the same loads connected along the line. This allows for a faster configuration of a large grid with homogeneous load repartition.

The node input and output are directly connected to the line impedance. The compensation device, supply transformer and load transformer are all connected in parallel to the output, after this impedance. The transformers can be left floating, i.e., it is not mandatory to connect a power supply or a load.

The electrical line is modelled as a RLC (R-resistor, L-inductor, C-capacitor) impedance, characterized by a linear impedance value. The linear capacity of the line is neglected by default which is realistic for lines shorter than 150 km. The linear impedance value is typical value for 380 kV overhead lines. Transformers characteristics (X/R, Zcc and power) are interpolated from typical values found in the literature ([15], [16] and [17]) based on the voltage operating point.

3.3. Thermal Storage (TES)

The technology selected for the storage of thermal energy is a sensible heat storage system based on a two-tanks configuration and employing thermal oil as a sensible medium. Such system comprises a hot and cold tank, with the sensible fluid flowing from one tank to the other during the charging and discharging processes, as well as centrifugal pumps and control valves to drive the latter flows.

The TES model relies on components from the ThermoPower library to simulate pump and control valve behavior and to build heat exchanger and tank models. The latter is based on mass and energy balance equations to simulate the fluid's accumulation. Moreover, several versions of the TES model are available in the library, differing in terms of the adopted heat exchanger models, either with simplified static heat exchangers or dynamic shell and tube heat exchangers. The TANDEM library also includes illustrative controllers to regulate the charging and discharging processes.

It is worth highlighting that the TES model available in the TANDEM library allows for the investigation of several integration strategies within the hybrid system. These range from direct integration with the reactor's BOP to the connection with an intermediate heat network. In the first case, high temperature steam could be used for TES charging, whereas the steam produced by TES discharging could be directed back to the BOP to boost its electrical power output beyond the rated value [12]. Alternatively, coupling through an intermediate loop facilitates flexible operation in terms of thermal power dispatch, exploiting the TES to meet variable heat demands, for instance.

3.4. Main Thermal Users

3.4.3. District Heating

The district heating network is represented by two main components, the transmission line and the distribution network, as presented in previous studies [13]. Both models are based on components from the ThermoPower library and are used to represent the heat supplied from the power plant to the final heat consumer. In particular, the transmission line is composed of a hot and a cold leg, representing the fluid flow over the distance separating the heat source from the consumer. The model accounts for the thermal inertia of the metal wall of the pipeline as well as heat losses and pressure drop. It is worth noting that the latter are significant due to the long distances travelled by the fluid; hence, centrifugal pumps are modelled at the hot and cold leg inlets to drive the flow in the transmission line. On the other hand, the distribution network model is adopted to simulate the ramifications of pipelines distributing heat to consumers in a specific urban area. This component is modelled as a water volume at a fixed pressure, reflecting the inertia of the fluid within the distribution network and exchanging thermal power with the heat consumers, other distribution networks, and other heat sources within the area.

3.4.4. High Temperature Steam Electrolyser (HTSE)

The HTSE system is modelled in two parts. The first part, based on the ThermoSysPro library, is the Balance of Plant (HTSE-BoP) module, which provides steam to the electrolyser primarily using heat from an external source (i.e. the SMR) and *economizers*. The second part is the stack, where its fluidic, thermal, and electrochemical behavior is represented, following the low-level control and physical equations described in [18]. The main assumptions of the model include that all electrolysis cells are identical, thermally controlled, and that the anode and cathode fluids move in a co-flow configuration. The stack control system is designed to maintain constant steam conversion.

3.5. Simplified Models

3.5.5. Auxiliary Sources: CHP and Heat Pumps

A simplified approach has been adopted to simulate the conventional Combined Heat and Power (CHP) plants and the heat pumps. They are considered as ideal heat sources, exchanging the thermal and electrical power flows with other HES components according to the value specified by an external controller. For the heat pumps, the electrical power absorbed from the grid is directly proportional to the thermal power output, set by the controller, through a user-defined Coefficient Of Performance (COP).

3.5.6. Electrical Storage: Battery

The battery model is represented by a black box component, exchanging electrical power, e.g., with the electrical grid. The power signal, provided by a dedicated controller, is integrated to compute the state-of-charge of the storage device, which will be fundamental to regulate the input power signal to avoid battery charging when the maximal storage capacity is reached or discharging when the State Of Charge (SOC) is at its minimal level.

3.5.7. Low Temperature Electrolyser (LTE)

The considered technology for the LTE model is the Proton Exchange Membrane (PEM) one. Being a simplified component, the Balance of Plant (LTE-BoP) is not represented, and only the electrolysis stack is modelled in detail. We assume that the input water feeds the stack at the convenient mass flow rate (following the desired H2 production target), and that a water conditioning loop allows to regulate the feeding water's temperature around the operating value. The stack module is based on four types of equations: electrical equations, mass balance equations, thermal modelling equations and electrochemical equations that follows some semi-empirical correlations from [19]. Finally, the LTE component is controlled through a PI block which adapts the current intensity applied to the stack module to reach the H2 production target.

3.5.8. Desalination

The desalination plant is modelled as a black box converting a given input power into freshwater output. The reference technology considered within the framework of the TANDEM project is reverse osmosis, given its widespread applications. As a result, this end-user will be only electrically coupled to the hybrid energy system. The power absorbed from the grid is integrated to compute the energy delivered to the plant, which is proportional to the amount of produced fresh water by the specific energy consumption, a parameter defining the desalination plant performances.

3.5.9. Renewable

The only variable renewable source modelled within the scope of the project is wind power, whereas the solar power profile is considered to as a boundary condition incorporated in the global electricity output of the hybrid system architecture. Regarding the wind farm model, the open-source library *WindPowerPlants* has been adopted to simulate the contribution of the renewable power generation to the HES electrical output.

4. EXAMPLES OF FIRST USES

In the context of the TANDEM project, the library will be used to build a simulator for the two configurations briefly described in §2. In the meanwhile, some first applications allowed by the library have been published. For example, [13] presents a first version of the DH simulator, connecting the SMR (ThermoPower N3S and ThermoSysPro CI-BoP) to the DH component. In [12] the library was used to explore the potential of heat-storage to improve the flexibility performance of a SMR. The models that supported both applications are provided as part of the library, in the *TestCases* subpackage of the library.

5. CONCLUSIONS

The Modelica TANDEM library is one of the main deliverables of the TANDEM Euratom project. Its objective is to provide the main bricks to build an easy customizable simulator of *Hybrid Energy Systems*. It constitutes a valuable tool to perform techno-economical studies considering the complex interactions between the diverse components of the HES: SMR, CCGT, thermal storage, electrical grid, hydrogen production, district heating…. It can also be used to provide realistic boundary conditions for safety studies, by a coupling with safety codes.

Despite the young age of the library (published mid-2024), some applications have already been developed and the relative results published. In the next future, more complex applications, i.e., the whole representation of the two TANDEM study cases (see §2) will be performed. To widen its application domain, new components will potentially be developed in the future to include, for example, Advanced Modular Reactors.

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