**Dynamic modelling of a nuclear hybrid energy system with hydrogen production via high temperature steam electrolysis**

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**Abstract**

Integrating Small Modular Reactors (SMRs) into nuclear hybrid energy systems (NHES) represents a promising approach to improving energy utilisation efficiency while balancing the intermittency of variable renewable energy sources. In particular, by flexibly allocating the SMR’s thermal power either for electricity generation or to drive industrial processes, these systems can contribute to the energy transition and benefit from revenue streams from multiple markets. However, the strong coupling among the various subsystems leads to complex challenges in designing and operating the NHES.

In this context, it is of paramount importance to investigate the dynamics of the system and to develop effective control strategies to meet variable load and industrial user requirements while complying with the operational constraints of the system. In this paper, an illustrative NHES architecture integrating a light-water cooled SMR with a high-temperature steam electrolysis hydrogen production plant is studied. The object-oriented modelling language Modelica is used to analyse the response of the system to different demand variations. The results show the potential impacts of varying commodity demands on the SMR’s balance of plant and on the nuclear island, indicating that the NHES can meet highly variable demands while maintaining the reactor’s power at a stable level.

## INTRODUCTION

In the context of the energy transition, hydrogen, as a versatile and potentially low-carbon energy carrier, is a promising solution to support the decarbonisation of power supply and hard-to-abate sectors, including transportation and industrial processes. As a result, hydrogen demand is projected to significantly grow in the future [1]. However, hydrogen can effectively contribute to the decarbonisation of the energy sector only when it is produced from low-carbon energy sources, such as renewables or nuclear power. Being a dispatchable power source that is able to provide both electricity and heat to drive the hydrogen generation process, the latter could take a leading role for such application. A tight coupling between the nuclear power plant and the hydrogen production facility would be in line with the deeper integration of energy systems, including energy sources, vectors, and end-users, envisaged by the European Union to reduce greenhouse gas emissions in electricity generation and industrial applications, so to enhance overall system efficiencies and competitiveness [1]. When compared to the current energy system structure, which operates mostly independent generators to meet isolated end-user requirements—such as industrial heat requirements or the delivery of power to the grid—this vision represents a radical paradigm shift.

The coupling between a nuclear reactor and a hydrogen production plant is facilitated in a so-called nuclear hybrid energy system (NHES), integrating different energy sources, storage devices, and industrial applications. One key advantage of such systems is their flexibility, being capable of meeting variable commodity demands by dynamically allocating the power generated by the reactor to the various NHES subsystems [2]. The flexibility of such systems is projected to have various economic benefits, allowing the NHES to access multiple markets associated with the generated commodities and optimise operations to maximise revenue streams. For instance, when electricity prices are low or commodity prices are high, the NHES might be operated to boost the production of commodities beyond electricity, such as hydrogen, by allocating a larger share of the generated thermal and electrical power to the industrial process rather than to the power grid. Small Modular Reactors (SMR) are seen as a particularly suitable nuclear technology to be integrated into NHES, primarily due to their lower size, which enables a closer deployment to industrial facilities [3]. The availability of thermal and electrical power in an NHES facilitates the production of hydrogen via high-temperature steam electrolysis (HTSE), with the water splitting process taking place in solid oxide electrolysis cells (SOEC). HTSE has the advantage of a lower electric power consumption with respect to low-temperature electrolyser technologies, thereby improving the process efficiency [4]. However, HTSE is less suited for flexible operation and features a lower technological maturity. As of today, the coupling between HTSE and nuclear power plants is explored in several research programs [5, 6] and demonstration projects [7].

A fundamental aspect in NHES research is the investigation of the dynamic behaviour of the overall system in several scenarios and the development of control strategies to meet both variable commodity demands while keeping the system within the allowed operational limits. As a result, it is possible to delve into the response of the system, e.g., in terms of perturbations on the nuclear island triggered by the flexible operation of the NHES.

In this work, the dynamic model of a NHES architecture comprising a light-water cooled SMR, together with its energy conversion system, and a HTSE is presented. A “reactor-follows-hydrogen” operational mode is investigated, assuming an imposed hydrogen load and regulating the NHES operation accordingly in terms of electrical and thermal power flows. The objective is to propose a dynamic simulator to assess the capabilities in terms of flexible operation of such system in line with the operational philosophy of NHES, i.e., by maintaining the reactor at nominal conditions.

##  system architecture and dynamic models

This section presents the NHES architecture along with the dynamic models upon which the simulator is built on. The models are developed in the Dymola environment using the object-oriented modelling language Modelica, an acasual, equation-based language promoting the interchangeability of models, typically collected in libraries, to build complex models through a plug-and-play approach [8]. This work leverages on the latter features by adopting components available in open-source libraries and combining them to build the overall NHES simulator. For instance, the nuclear steam supply system (NSSS) and balance of plant (BOP) models stem from the Modelica TANDEM library, delivered by the homonymous Euratom project [9]. The TANDEM project aims at investigating the integration potential of SMRs into NHES from a technical, economic, and societal standpoint [5]. To meet this objective, dedicated tools have been developed within the framework of this project, including the aforementioned Modelica library collecting components to build various NHES architectures and assess their dynamic response.

The dynamic model of the NHES architecture is depicted in the schematic of Fig. 1. The NSSS and BOP model, shown in the figure, are provided by the TANDEM library and are described in Section 2.1. A more detailed description is devoted to the HTSE model in Section 2.2, which is introduced in this work. Finally, Section 2.3 offers a comprehensive outline of the NHES architecture, highlighting the control strategy governing its operations.



*FIG. 1. NHES dynamic simulator in Modelica.*

### Nuclear steam supply system and balance of plant

In this work, the considered nuclear technology is the European SMR (E-SMR) conceptual design, a 540 MWth, pressurized, light-water cooled SMR introduced in the ELSMOR Euratom project [10]. The latter reactor design is the foundation of the investigations performed within the TANDEM project; hence, a dynamic model for its simulation is available in the TANDEM Modelica library. The model is based on the point kinetics equations as far as the neutronics is concerned, together with a one-dimensional finite volume approach to simulate the thermal hydraulics of the primary loop. For a detailed description of the NSSS model used in this project, the reader is referred to previous studies performed with the model [11, 12].

Additionally, the TANDEM library offers a variety of BOP models that are based on various modelling strategies and Modelica libraries. The ThermoPower library, an open-source collection of components for modelling thermal power plants and energy conversion systems developed at Politecnico di Milano, was used to build the BOP model for this study. The BOP architecture outlined in the TANDEM project, presented in earlier studies [11, 12], consists of a high-pressure (HP) and a low-pressure (LP) turbine stage separated by a moisture separator and a reheater. A condenser is located at the LP turbine outlet. The feedwater line consists of two pumps, a feedwater tank, and LP and HP preheaters that are supplied by steam bled from the two turbine stages. It is worth noting that the BOP model based on the ThermoPower library introduced in previous works [11] has been further developed as part of the TANDEM project’s activities, moving from a simplified, static heat exchangers to one-dimensional shell and tube heat exchangers for the reheater and feedwater preheaters, thereby improving the representativeness of the dynamics of the system.

Furthermore, the BOP architecture adopted in this work has been adapted to facilitate the integration with the HTSE, introducing steam extraction and return points compatible with the requirements of this industrial process. In particular, the following interconnection strategy is proposed: after condensing in the reheater hot side, the fluid is split in two branches, a first branch that directs the condensate to the feedwater tank and a second one delivering the condensate to the HTSE steam generator (HTSE-SG). The subcooled water obtained from the thermal power exchange with the HTSE is subsequently mixed in the feedwater tank. This extraction point was selected for its thermodynamic state compatibility since high temperature saturated liquid is used for the evaporation of the HTSE process water, avoiding the possible technological issues of having phase transitions on both sides of a conventional heat exchanger. Moreover, the minor perturbations on the BOP, and hence on the nuclear island, in off-design conditions represent a further advantage. As a matter of fact, the nominal conditions of the BOP have been adjusted consistently with the rated thermal power delivered to the HTSE. In off-design conditions, i.e., when the thermal power fed to the HTSE is reduced, variations from nominal flow rates occur mostly at the reheater’s hot side outlet, with a minor impact on the overall BOP performance in terms of steam extraction upstream of turbine inlets. On the other hand, the amount of power that can be supplied to the HTSE is considerably limited by the extraction of thermal power at this stage of the steam cycle. This restriction is imposed both by the steam flow rate driving the reheater’s operation, determined by the LP turbine inlet temperature requirements, and by the lower bound for the subcooling delimited by the process water inlet temperature that enters the HTSE steam generator.

### High-temperature steam electrolysis hydrogen production plant

The considered HTSE architecture implemented in the Modelica language, shown in Fig. 2, is composed primarily of the solid oxide electrolyser stack (SOE), which comprises several cells where the water splitting reaction occurs, and the necessary balance of plant components to guarantee proper fluid conditions [13]. Two separate flows enter the SOE: air on the anode side and a steam and hydrogen mixture on the cathode side. In this layout, liquid water at ambient conditions is heated in a first heat exchanger, CAT-HX1, which raises the temperature nearly to saturation. After that, the flow exploits thermal power extracted from the nuclear reactor to evaporate in the HTSE-SG. After mixing with a portion of the generated hydrogen flow to attain the desired molar composition of 90% steam and 10% hydrogen (requested for chemical stability in reducing atmosphere), the temperature is raised further in a second heat exchanger, CAT-HX2, exploiting the SOE cathode outlet flow. Finally, the SOE cathode intake temperature requirements, which are outlined in Table 1, are satisfied by adjusting the flow temperature using an electrical heater (CAT-eHTR). A similar approach is applied on the anode side, where ambient air is heated in the AN-HX heat exchanger before being brought to the appropriate temperature by the AN-eHTR electrical heater. It is assumed that the SOE is running in exothermic mode, which results in outflow temperatures that are greater than intake temperatures.

The simulator displayed in Fig. 2 is the outcome of modelling the latter architecture using the Modelica language. The Modelica Standard Library already defines the required medium models for the system, which are water, steam-hydrogen mixture, and air. The last two models assume ideal gas behaviour. Furthermore, the dynamic model’s components are drawn from the ThermoPower library, particularly from the *Water* and *Gas* packages, leveraging the interchangeability of pre-existing models. In this preliminary version of the simulator, a simplified, zero-dimensional modelling technique was used to develop dedicated models for the recuperative heat exchangers CAT-HX1, CAT-HX2, and AN-HX, thus disregarding their dynamic behaviour. On the other hand, the HTSE-SG relies on a finite volume approach that is consistent with the modelling strategy used for the BOP heat exchangers. The components of the SOE model are the anode and cathode channels, the cell solid structure (i.e., electrodes and electrolyte), and the interconnect, which separates the various cells and provides the stack with mechanical support. The anode and cathode channels, in particular, are modelled as zero-dimensional components based on dynamic mass and energy balance equations that take into account the convective and radiative heat transfer with the cell and the interconnect, as well as the exchange of oxygen and steam and hydrogen molecules in the anode and cathode sides, respectively. The electrochemical model included in the SOE cell component provides the correlation between the current and voltage at cell level, then considering electrical series connection within a stack [14]. In particular, the voltage is expressed as a combination of the reversible voltage (given by the thermodynamic of the reaction at the operating temperature) and the ohmic and activation overpotentials, while concentration losses are neglected. Ohmic losses are generated by the electrical resistances of the electrodes and the electrolyte and are proportional to the cell current. The activation overpotential is estimated using the Butler-Volmer equations [15]. Cell temperature has a significant impact on both the reversible voltage and the electrical losses, which in turn impact the cell voltage and thus the hydrogen production process and the electrolyser’s operation.

TABLE 1. SOE OPERATING CONDITIONS.

|  |  |  |
| --- | --- | --- |
| Parameter | Value |  |
| Rated electrical/thermal power | 53.3/12.5 | MWe/MWth |
| Operating pressure | 1 | bar |
| Cathode inlet/outlet temperature | 800/835 | °C |
| Anode inlet/outlet temperature | 800/827 | °C |
| Cathode inlet/outlet flow rate | 5.35/2.06 | kg/s |
| Anode inlet/outlet flow rate | 27.41/30.69 | kg/s |
| Cathode inlet composition (H2O/H2) | 90/10 | mol/mol |
| Cathode outlet composition (H2O/H2) | 27/73 | mol/mol |



*FIG. 2. HTSE dynamic model in Modelica.*

### Nuclear hybrid energy system

Fig. 1. illustrates the overall NHES simulator, composed of the subsystems previously discussed. Specifically, the BOP is coupled to the NSSS and HTSE models through fluid exchange connectors, transmitting the fluid’s condition and flow rate at the interfaces. In order to replicate the power supplied by the NHES to the power grid, the BOP and HTSE are also electrically linked with each other and to an external load, which is simulated using a component included in the ThermoPower library.

This work investigates an operational mode designated as “reactor-follows-hydrogen”, where the power delivered to the HTSE (and thus the produced hydrogen) is an imposed boundary condition, and the BOP is operated to comply with the resulting requirements regarding the thermal power to be delivered to the HTSE. However, this is not the only possible operational strategy; for instance, the opposite approach, “hydrogen-follows-reactor”, could also be considered. In this mode, the nuclear power plant is managed to meet variable load demands by diverting excess thermal power to the HTSE, with hydrogen production adjusted accordingly. External control systems, which include control loops based on proportional-integral (PI) controllers to govern the system’s operation, are assigned to each subsystem. The “reactor-follows-hydrogen” strategy is implemented by coordinating the actuators of the three subsystems using a decentralised feedback control approach, with the control variable being independently controlled based on the deviation of the corresponding process variable from its setpoint by means of the PI controllers. Table 2 summarises the pairings of process and control variables proposed in this analysis, selected based on expert judgement.

TABLE 2. NHES CONTROL SCHEME.

|  |  |  |
| --- | --- | --- |
| Process variable | Control variable | Controller type |
| *NSSS* |  |  |
| Primary coolant pressure | Pressurizer actuators (sprayer, heaters) | Proportional |
| Average core temperature | External reactivity insertion | PI |
| *BOP* |  |  |
| NSSS-SG outlet pressure | HP turbine admission valve opening | PI |
| NSSS-SG outlet temperature | HP pump rotational speed | PI |
| NSSS-SG inlet temperature | HP preheater control valve opening | PI |
| Feedwater tank pressure | LP pump rotational speed | PI |
| HTSE-SG steam outlet temperature | Reheater flow control valve | PI |
| *HTSE* |  |  |
| Steam utilization factor | Process water mass flow | PI |
| Cathode outlet temperature | Anode air mass flow | PI |
| Cathode inlet temperature | Cathode electrical heater power | PI |
| Anode inlet temperature | Anode electrical heater power | PI |

The NSSS control strategy was proposed within the framework of the TANDEM project [12] and consists of maintaining the primary coolant pressure and core average temperature at the desired setpoint values by regulating the pressurizer actuators and reactivity insertion through control rods displacement, respectively. In an NHES, the goal is to maintain as much stability as possible in the reactor’s operation, as opposed to load-following operation, which varies the electrical power output by moving control rods to alter the fission power. For this reason, the reactivity control in this case study is employed to make sure that, in the event of a perturbation on the secondary side—such as that caused by the variable operation of the industrial process—the nominal core average temperature remains constant at its nominal value.

To control the BOP operation, a controller specifically designed to apply the “reactor-follows-hydrogen” strategy has been built. Specifically, the pumps’ rotational speed is controlled to ensure a constant feedwater tank pressure and NSSS-SG outlet temperature. The HP turbine admission valve, which is regulated to maintain the NSSS-SG pressure at the nominal value, further stabilises the NSSS conditions. The reheater’s hot side outlet valving system is adjusted to match industrial user thermal power needs, with the valves regulated to ensure that the HTSE-SG cold side meets the steam temperature requirement. For example, a drop in hydrogen production results in a decrease in the flow of process water, which means that less thermal power needs to be supplied to the HTSE in order to reach the required temperature. The second valve, which admits the condensate straight to the feedwater tank, opens accordingly, and consequently, the valve leading the condensate to the HTSE is partially closed. In nominal conditions, the former valve remains fully closed. On the other hand, in off-design operations, opening the valve affects the temperature of the feedwater tank since the fluid entering it is not subcooled through power exchange with the HTSE, which in turn impacts the temperature of the NSSS-SG inlet. The NSSS would also be impacted by this because of reactivity feedbacks triggered by variations in moderator temperature. To mitigate NSSS-SG inlet temperature fluctuations, an additional control system is introduced. A valve controls the steam bleeding that drives the HP preheater according to the feedwater preheating requirements. As the temperature of the feedwater tank rises, the flow rate to the preheater hot side lowers, resulting in additional steam delivered to the turbine line for power conversion.

A third controller is needed to maintain the HTSE operation within the allowed range when allocating variable electrical power for hydrogen production. As shown in Table 2, PI controllers are also utilised in this instance to determine the actuator signals in order to satisfy the operational requirements, such as SOE stack inlet and outlet temperatures. To prevent significant temperature gradients that might jeopardise the electrolyser’s structural integrity, the cathode output temperature is regulated by controlling the anode channel’s air flow rate. Additionally, the SOE’s feed of process water is controlled based on the target steam utilisation factor.

##  SIMULATION Results

The NHES dynamic model is tested by altering the SOE electrical power input, simulating a 10% ramp-down in nominal power followed by a return to rated conditions after attaining steady state. Due to the preliminary design of the HTSE control system, which features a cathode outlet temperature control solely accomplished by changing the air flow rate, the test scenario has been restricted to this power excursion. More severe power reduction would result in a temperature drop that would be unrecoverable by lowering air flow rate, demanding more sophisticated control techniques.



*FIG. 3. Simulation results.*

The simulation results indicate that a variable HTSE operation may be achieved with minimal disturbances on the nuclear island. The first graph in Fig. 3 points out this outcome, with variations in fission power limited to 0.1 MWth. This suggests that, as the average core temperature remains close to its setpoint value, stabilisation of the temperature may be achieved without the requirement for an external reactivity injection. As the second graph highlights, these perturbations are mainly mitigated by the NSSS-SG inlet temperature control, which effectively keeps this variable near its nominal value throughout the whole transient. In this case study, the ramp-wise drop in SOE input power reduces the thermal power supplied by the BOP to the HTSE. As a result, the BOP converts a larger fraction of thermal power into electricity, boosting the electrical power production by approximately 0.2 MWe. However, it is worth noting that this difference is minor when compared to the variations in power provided to the grid, which is estimated as the difference between the BOP power production and the power assigned to the HTSE (ignoring, at this stage, the auxiliaries’ power consumption). In this example, the grid power increases from around 123 MWe to about 129 MWe, resulting in a 5% variation by relying on the HTSE’s flexible operation rather than the nuclear reactor’s. Overall, the control system demonstrated its ability to fulfil the necessary operating conditions in each subsystem, such as controlling variations in the electrolyser steam utilisation factor and HTSE operating temperatures.

##  Conclusions

In this work, the dynamic model of an NHES integrating a light-water cooled SMR and an HTSE-based hydrogen production plant is presented. The model, developed with the object-oriented modelling language Modelica, may be used to examine different control strategies and assess the entire system’s dynamic response while modulating the hydrogen production process, adopting a “reactor-follows-hydrogen” operational mode. The proposed simulator should be viewed as an initial step towards the development of a tool to perform various assessments on such systems, allowing for the comparison of different configurations, focusing on the interconnections between BOP and HTSE, and identifying potential challenges in operating the integrated NHES architecture. For example, the study presented in this work pointed out the constraints of extracting the required thermal power at the reheater’s hot side outlet, as well as the limited flexibility margin in terms of SOE power variation using the outlined preliminary control system. The considered system could, however, be able to meet varying grid demands without having a significant impact on the nuclear island operation, according to the simulator’s initial findings. This suggests that NHES could be a viable way to meet the growing demands for power grid flexibility.

Future developments will focus on the investigation of different interconnection strategies, to identify the most appropriate solution for the NHES overall efficiency and flexibility, and on the improvement of the models to enhance the representativeness of the system’s dynamics, with the ultimate goal to create a reliable NHES simulator to be applied in real-world applications.

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