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

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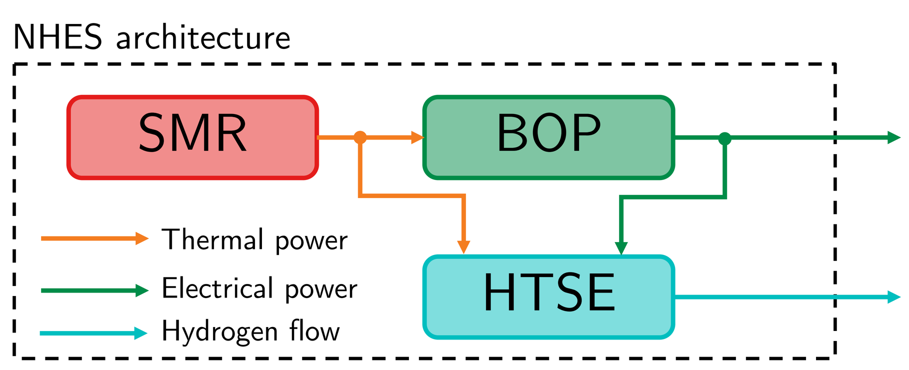
INTRODUCTION

A **nuclear hybrid energy system (NHES)** integrates a nuclear reactor with other energy sources, storage devices, and industrial processes. This study investigates the coupling between a **light-water cooled Small Modular Reactor (SMR)**, together with its balance of plant (BOP), and a **high temperature steam electrolysis (HTSE) hydrogen production plant**. In this architecture, the thermal power of the SMR is used to evaporate the process water of the hydrogen production plant, which is then superheated to the required temperature levels through heat recovery and electrical heaters.



- **Low-carbon** hydrogen production system.
- High power **flexibility** of the overall system, allowing to cope with variable grid requirements.
- **Steady nuclear reactor** operation at rated conditions.
- Increased sources of **revenues** (electricity and hydrogen market).

A **dynamic model**, developed in the object-oriented modelling language **Modelica**, is applied to investigate the transient response of the coupled system. The proposed tool represents an initial step to assess the system's **capability to meet variable loads** while minimising perturbations on the nuclear island.

DYNAMIC MODELS

The dynamic simulator is built upon the nuclear reactor, the power conversion system, and the hydrogen production plant. It relies on **open-source Modelica libraries**, namely the *ThermoPower* [1] and *TANDEM* [3] library.

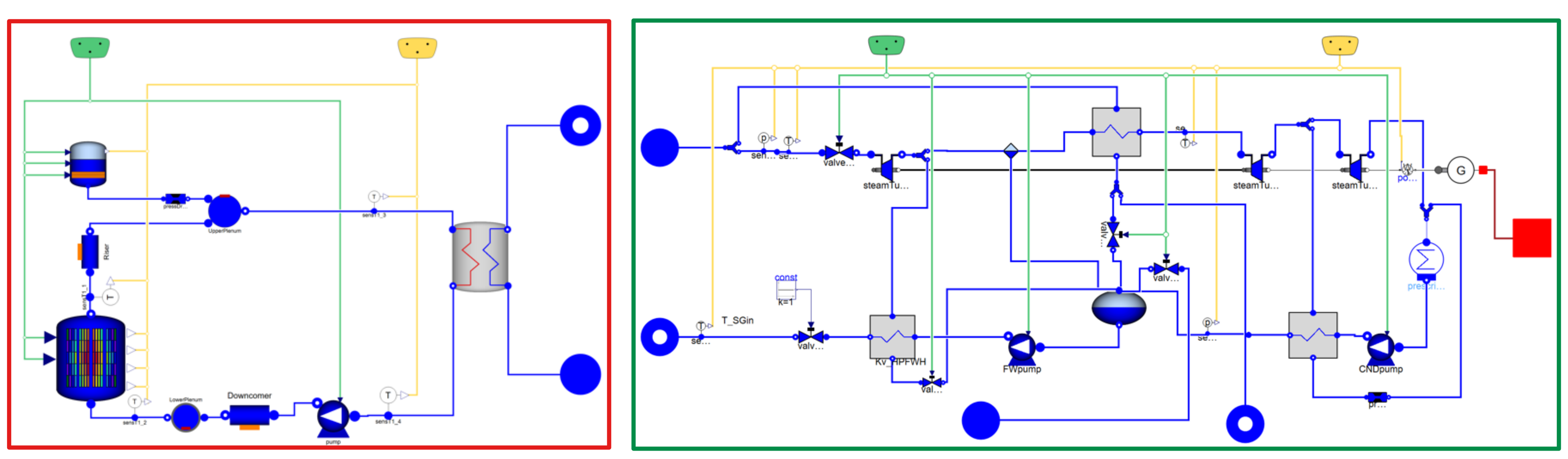


Figure 1. Dynamic model of the SMR and its balance of plant.

The dynamic models of both the SMR, for which the pressurised water reactor-type **European SMR (E-SMR)** conceptual design has been considered as reference, and its BOP are available in the *TANDEM* library. However, the BOP model has been modified to include **appropriate interconnection points** with the hydrogen production plant. The SMR and BOP are modelled using a **1D finite volume approach** to capture the plant's dynamics.

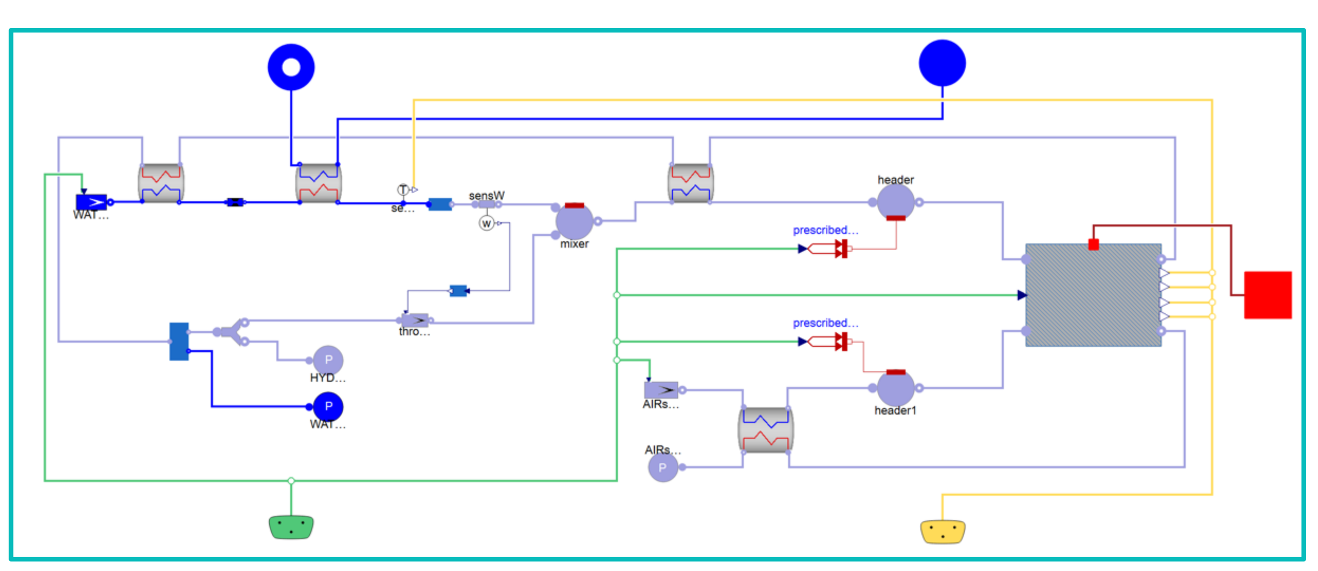
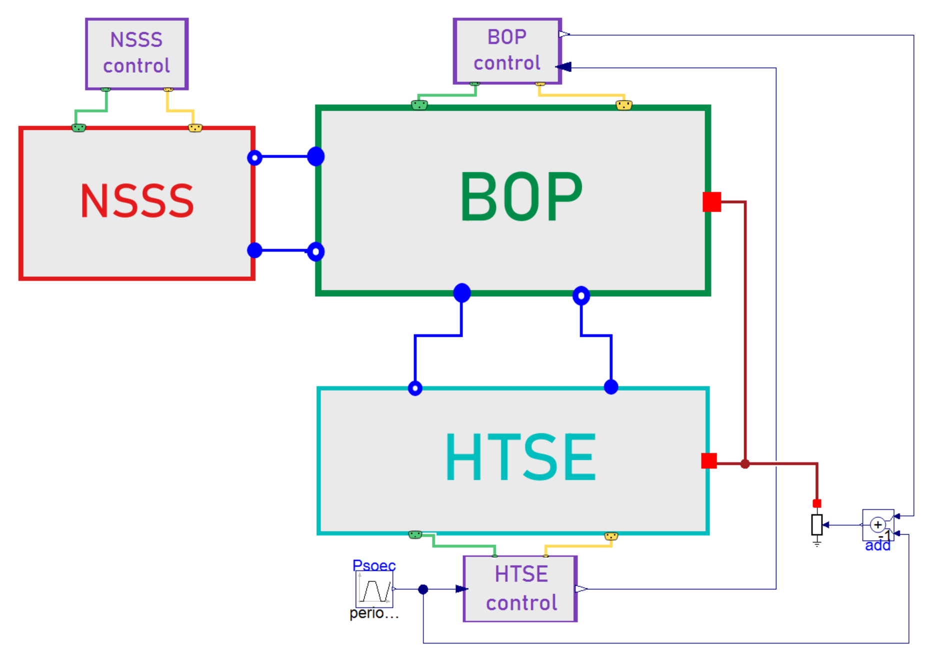


Figure 2. Dynamic model of the HTSE hydrogen production plant.

The hydrogen production plant was sized for a thermal power input from the BOP of **12.5 MW_{th}**, resulting in an electrical power demand of **53.3 MW_e** and a hydrogen output of about **0.4 kg/s**. A combination of recuperative heat exchangers and electrical heaters ensure that the **temperature requirements** of the hydrogen production process are satisfied [2]. The components of the HTSE model are based on a **quasi-static approach**, limiting the capabilities to simulate the dynamic response of the system. Lastly, the solid oxide electrolysis cell component encompasses the **electro-chemical** model governing the hydrogen production process.

CONTROL AND OPERATIONAL STRATEGY

Figure 3 shows the overall dynamic simulator and the considered control strategy for the BOP and the HTSE that governs the system's operation. A **decentralised control approach**, using proportional-integral controllers, is applied to adjust control actions based on deviations in process variables from their setpoints. Additionally, the NSSS employs a constant average core temperature control program.



Process variable	Control variable
BOP	
NSSS-SG outlet p	HP turbine admission valve
NSSS-SG outlet T	HP pump rotational speed
NSSS-SG inlet T	HP preheater control valve
Feedwater tank p	LP pump rotational speed
HTSE-SG steam outlet T	Reheater flow control valve
HTSE	
Steam utilization factor	Process water mass flow
Cathode outlet T	Anode air mass flow
Cathode inlet T	Cathode electrical heater power
Anode inlet T	Anode electrical heater power

Figure 3. Dynamic simulator and control scheme.

The operational philosophy investigated in this work is the **REACTOR-FOLLOWS-HYDROGEN** mode, 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. This is one of the possible strategies, since, on the other hand, the system could be operated to meet a variable grid demand by modulating the thermal and electrical power allocated to the HTSE.

TRANSIENT RESULTS

The dynamic behaviour of the NHES model is evaluated by applying a perturbation to the **electrolyser electrical power input**. The test scenario involves a 10% ramp-down of the nominal power, followed by a return to rated conditions after steady state is reached. This scenario aims to assess the system's robustness and **flexibility** in managing power excursions and **variations in hydrogen demand**.

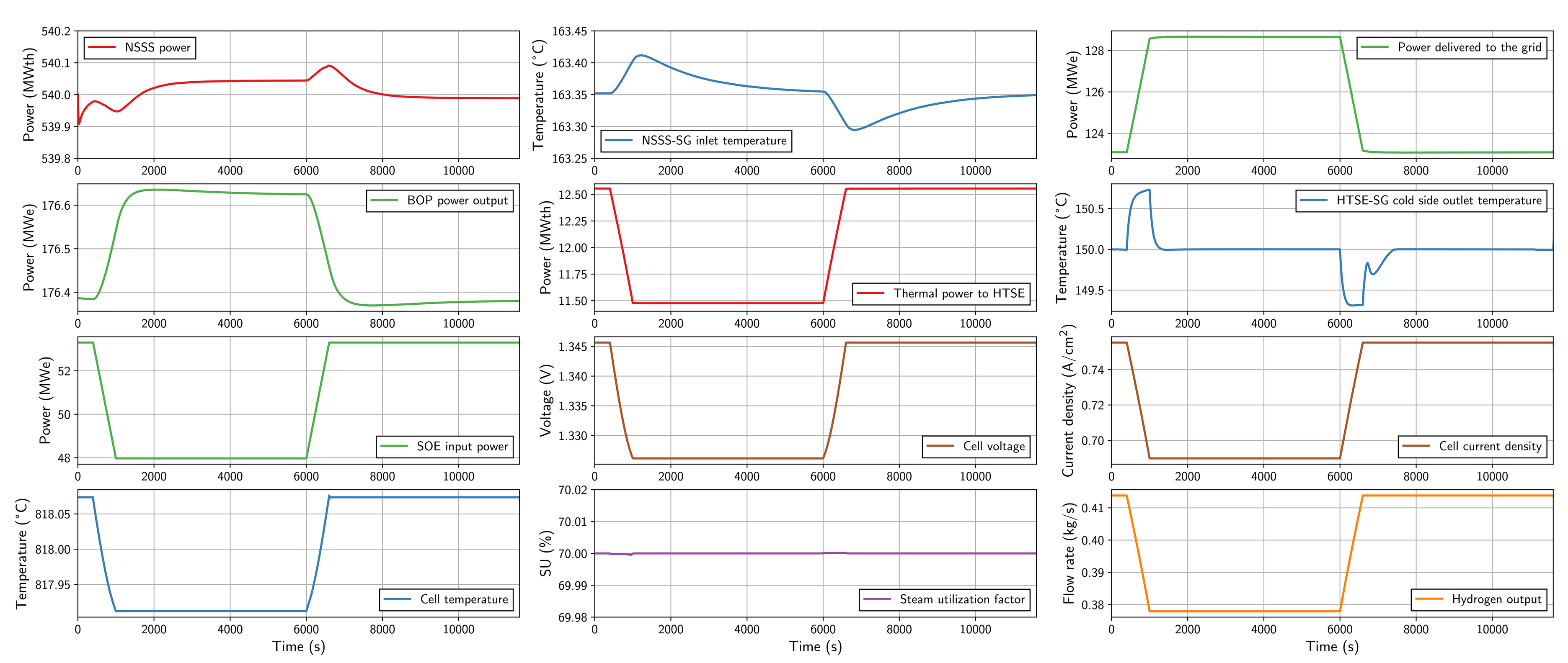


Figure 4. Transient simulation results.

Figure 4 presents the resulting dynamic response. The simulation highlights the following findings:

- Variable HTSE operation is managed with minimal impact on the nuclear island, as temperature and pressure in the NSSS and BOP remain stable despite HTSE power demand fluctuations.
- BOP power output does not experience significant variations, with considerable modulation of grid power possible due to the high electrical power allocated for hydrogen production, showcasing NHES flexibility.
- The proposed control strategy handles moderate power changes well, but more advanced schemes are needed to manage larger HTSE power deviations, ensuring that the cell temperature requirements are met.

These results indicate that the NHES architecture can provide **flexible, grid-supportive operations without negatively affecting the nuclear island**, making it a promising solution to support the increasing penetration of variable renewables in the power grid and to meet the growing hydrogen demand.

CONCLUSIONS

The proposed simulator represents a first step for the analysis of such NHES architecture, enabling a comparison of different configurations and interconnections between the BOP and HTSE. Initial results show the system **can meet varying hydrogen demands** without significantly impacting the nuclear island. Future work will explore alternative **interconnection strategies and control schemes** to enhance efficiency and flexibility while improving the models to better capture system dynamics.

REFERENCES

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