Development of a techno-economic methodology for the analysis of flexible nuclear hybrid energy systems

In the context of the energy transition, rising shares of variable renewables and the need to decarbonise sectors that are hard to abate call for energy systems capable of providing both flexibility and low-carbon electricity, heat, and fuels. Nuclear Hybrid Energy Systems (NHES), where nuclear reactors are tightly integrated with other energy sources, storage devices and non-electric applications, are attracting growing interest, but their implementation presents strongly interconnected technical, economic, regulatory and policy challenges.

This thesis work develops a holistic methodological framework to analyse NHES from a system level to their role in broader energy systems, for instance, in long-term decarbonisation strategies. The approach starts from a context analysis that characterises local requirements and demands, as well as policy and market conditions, and uses it to define scenarios for NHES deployment. Considering this background, physics-based models are developed to represent NHES architectures, with particular attention to thermal interconnections, and are applied to assess the flexible operation, control strategies, transient behaviour, and safety-relevant aspects of the integrated systems. In particular, safety analysis is enabled by coupling the dynamic simulators with thermal-hydraulic system codes for the primary loop to evaluate transients and safety margins, with the aim of supporting regulators and safety authorities to define guidelines for the deployment of hybridised reactors. Moreover, the tools are embedded into techno-economic optimisation schemes that determine optimal layouts and dispatch strategies under different boundary conditions, accounting for operational constraints resulting from the system dynamics captured through the aforementioned simulators. Finally, nuclear cogeneration and an archetypical NHES configuration, characterised through the detailed system-level models, are integrated into country-level long-term energy planning frameworks to explore if and how NHES can contribute to decarbonisation pathways.

Applications to illustrative case studies highlighted the importance of having an interdisciplinary framework for NHES analyses that integrates technical, economic and policy dimensions. In this work, these systems were analysed from a progressively broader point of view, ranging from subsystem-level investigations to their integration into country-level energy system models.
Overall, the case studies indicate that nuclear cogeneration and NHES could represent a viable option for providing low-carbon heat and hydrogen while enhancing system flexibility and supporting grid stability. The resulting technically grounded framework is applied to derive policy-relevant insights and recommendations. In particular, if these systems emerge as cost-competitive options, policymakers should consider creating an enabling environment, for example, by adapting regulatory and licensing frameworks, so that the potential deployment of NHES architectures can be appropriately assessed.