Dynamic modelling and optimisation of a Small Modular Reactor for electricity production and district heating in the Helsinki region

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ABSTRACT

The decarbonisation of the heat sector represents one of the main challenges to be tackled for the energy transition. In this context, nuclear reactors could play a key role by providing dispatchable and low-carbon heat and power. This paper investigates the potential of integrating a light-water cooled Small Modular Reactor (SMR) into a nuclear hybrid energy system (NHES), in which the thermal power produced by the reactor is dynamically allocated for power production or to drive non-electric applications, in particular for supplying heat to the district heating network (DHN) in the metropolitan area of Helsinki, Finland. The aim of this work is to propose a NHES architecture tailored for this purpose, encompassing the SMR, the balance of plant, and the DHN. The proposed balance of plant, obtained with the CYCLOP tool, has been modified by including an intermediate heat exchanger to transfer thermal power to the DHN. These subsystems were modelled in the object-oriented modelling language Modelica to test the dynamic response of the global architecture in different case studies based on the Backbone optimisation model output. The ultimate goal of this work is to evaluate the opportunities of deploying a NHES to supply heat to the DHN in the Helsinki area, focusing on dynamic operation to meet different heat requirements. In general, the simulation outcomes indicate that the NHES could meet variable heat demands while operating the reactor at nominal conditions. However, a notable mismatch between the power flows obtained with the dynamic model and those generated by the optimiser is observed. This discrepancy can be partially attributed to the DHN's high thermal inertia, pointing out the importance of considering the system's dynamics when estimating its optimal operation.

Keywords: Nuclear hybrid energy system, Small Modular Reactor, district heating, dynamic model, techno-economic optimization.

1. INTRODUCTION

In the European Union, around half of the final energy consumption is driven by heating and cooling requirements, with space and water heating needs in buildings accounting for the largest share [1]. Since these demands are currently primarily satisfied with fossil fuels, the decarbonisation of this sector is of paramount importance to achieving climate change mitigation objectives. The case studies presented in this work focus on scenarios related to the Finnish energy system, where district heating (DH) already covers approximately half of the country's overall heating demands [2]. However, the heavy reliance on fossil fuels

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for heat generation necessitates a radical transformation to attain Finland's objective of carbon neutrality by 2035 [3].

This paper aims at addressing the prospect of using nuclear power for this kind of application. There exists a range of experiences showcasing the use of nuclear reactors for district heating, especially in Eastern Europe, where the reactors are operated as combined heat and power (CHP) generators. In the Finnish context, an initial project to deliver the heat produced by the Loviisa-3 nuclear power plant to the district heating network of the area of Helsinki was ultimately abandoned [4]. In this perspective, Small Modular Reactors (SMRs) offer a great potential not just for power production but also for non-electric applications [5]. Finland is currently exploring the option of deploying SMRs designs, e.g., the LDR-50 reactor, tailored to its district heating requirements [3]. The integration of SMRs within a so-called nuclear hybrid energy system (NHES), in which the nuclear power source is tightly interconnected with other energy sources and non-electrical uses, can be a valuable option to investigate [5]. They enable the streamlined full-power operation of the nuclear reactor, optimally allocating the produced energy among different applications based on market conditions. Several research initiatives, such as those coordinated by the Integrated Energy System (IES) program led by the Idaho National Laboratory [6], are addressing the challenges that are faced in NHES, arising mainly from the strong interconnection between the various subsystems. In addition, the Euratom-funded TANDEM project [7] is investigating the integration of light-water cooled SMRs in NHES from multiple standpoints, ranging from safety assessment to the techno-economic optimisation of the overall system. The analysis proposed in this work is a preliminary application of the tools developed in the framework of this project. In particular, the dynamic models of NHES components, developed in the object-oriented modelling language Modelica, are applied to test the response of a light-water cooled SMR operated in CHP mode and integrated with the district heating network of the Helsinki metropolitan area.

The primary objective is to explore the NHES dynamics, particularly in response to variable heat demands observed across different seasons, while operating the SMR continuously at full thermal power. These scenarios, derived from a techno-economic optimization of the system's operation, are intended to test the consistency of the NHES operation with the optimiser's output to assess the viability of deploying such systems within the Finnish context. The paper is structured as follows. Section 2 offers a brief overview of the methodology adopted for the development of the work. In the following section, the dynamic models of the NHES subsystems are presented. Section 4 introduces the case studies that were considered to test the response of the system, while the simulation outcomes are reported in Section 5.

2. METHODOLOGY

The analysis outlined in this work represents an initial effort to integrate different tools to perform a comprehensive assessment of a NHES architecture. This involves optimising the system's design, focusing on the operational points of the balance of plant using the CYCLOP tool, and determining the operational strategy from a techno-economic optimisation in Backbone. The resulting architecture is then modelled in the Modelica language to simulate its behaviour across various scenarios, thereby integrating the dynamics of the system into the assessment.

2.1. Balance of plant optimisation in CYCLOP

As a first step, a preliminary configuration of the BOP is setup and optimised using the CYCLOP tool. The primary goal of this software, developed by the CEA [8], is to ease the straightforward construction of thermodynamic cycles and the steady-state optimisation of their nominal design point, without any component sizing at this stage, only using macroscopic values describing the quality of each component (turbines and pumps isentropic efficiencies, exchangers pinch points, pressure drops in pipes, heat leaks, etc.). These values are taken from the state of the art of the domain and known existing projects. The main boundary conditions of the system are fixed, and the remaining free parameters are optimised by the tool to maximise electricity production. The off-design aspects, including partial load operation, or transients are not taken into account. This tool was qualified against existing projects data (900 MW and 1300 MW French pressurised water reactors, Superphénix fast breeder reactor [8]). The results of such a tool can be used as the initialization state in Dymola software (see Section 2.2). The CYCLOP optimisation of the BOP, shown in Figure 1, leads to an electrical net production of 174 MW and a net efficiency of 32.2%.

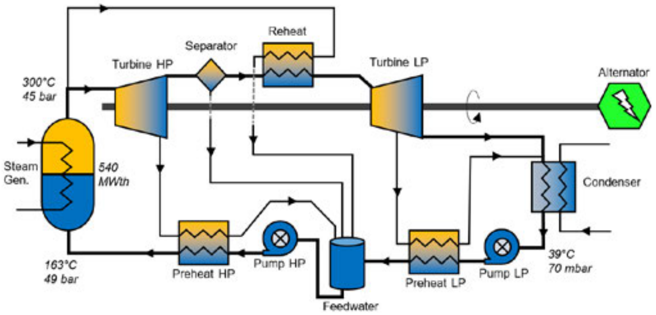

Figure 1. Considered BOP architecture.

2.2. Dynamic modelling in Modelica

The dynamic models of the NHES subsystems are developed in the object-oriented modelling language Modelica, implemented within the simulation environment Dymola. Modelica was chosen primarily for its suitability to simulate complex engineering systems, allowing for the independent construction of NHES submodels and their subsequent versatile coupling into global models adopting a plug-and-play approach [9]. The proposed models are used to evaluate the dynamic response of the system across different scenarios, simulating the operational demands given by the techno-economic optimiser. Specifically, they aim to assess the NHES ability to satisfy these demands while complying with operational constraints and to test and verify suitable control strategies.

2.3. Techno-economic optimisation in Backbone

Backbone is an adaptable energy systems modelling framework designed for studying the design and operation of energy systems, for both operational scheduling and investment planning. The framework has been developed as an open-source tool (available online in [10]) using the General Algebraic Modeling System (GAMS). Backbone can model both high-level, large-scale systems and fully detailed smaller-scale systems. The framework is based on mixed-integer programming, and it features unit commitment decisions for power plants and other energy conversion facilities. The formulations and equations that Backbone is built upon are described in detail by Helistö et al. [11]. Moreover, the optimisation process encompasses the whole production portfolio, heat storage systems, and transfers between different urban areas, accounting for the techno-economic characteristics of various technologies and consumer requirements. The Backbone modelling framework is input data-driven, meaning that there a very few hard coded features and that the user can flexibly define the structure and features of individual Backbone models through input data and parameter settings. The Backbone model used in this work represents the Helsinki metropolitan area's district heating and cooling system. The model topology is composed of grids, nodes, units, and lines. These elements define the energy system model's physical layout. Specific data relevant to the Helsinki metropolitan area, such as regional demand time series of district heating and district cooling, are implemented in the model. The model includes existing production capacity in the area and the studied NHES submodel. Documentation and validation of the Helsinki metropolitan area model are explained in detail by Pursiheimo et al. [3].

3. DYNAMIC MODELS

This section provides an overview of the dynamic models employed to simulate the response of the integrated energy system. All the proposed models are built upon components of the ThermoPower library, an open-source library offering models to simulate thermal power plants and energy conversion systems [12]. The NHES, shown in Figure 2, is composed of three submodels, namely the nuclear steam supply system (NSSS), the BOP, and the DH network (DHN). Additionally, each submodule has its own control system, which ensures that the operational strategy provided by Backbone is met in compliance with the system's constraints.

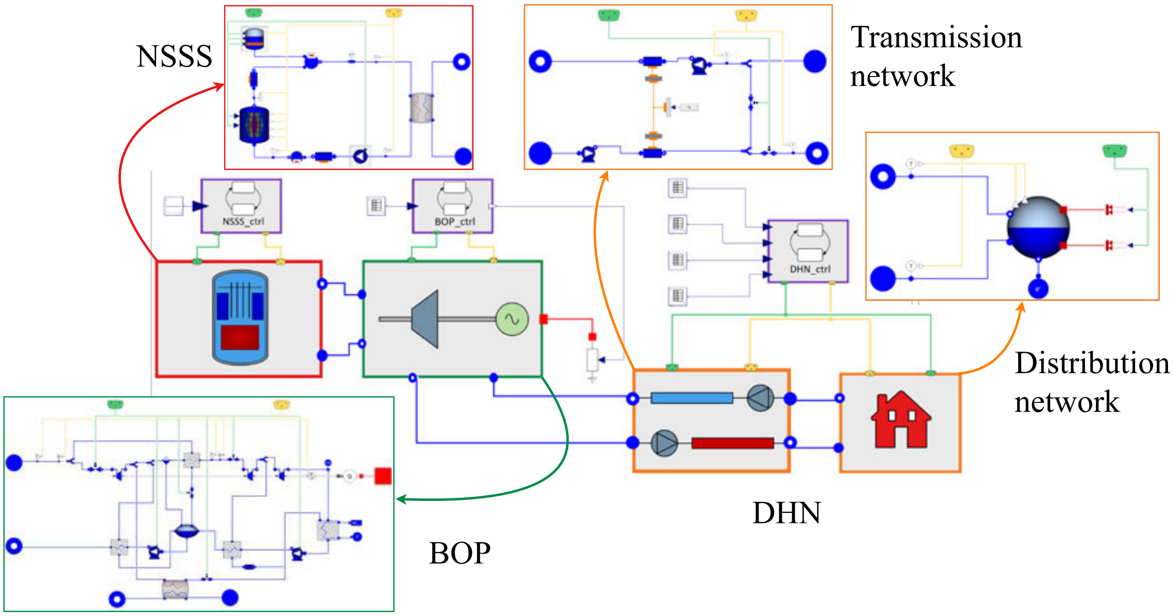

Figure 2. Dynamic model of the NHES architecture.

3.1. Nuclear steam supply system

The reference design and data considered for the SMR have been developed within the framework of Euratom's ELSMOR project [13]. The proposed reactor concept, which is also referred to as the European SMR (E-SMR) design, features the typical characteristics of an integral pressurised water reactor (see Table I for the main parameters), with all the main components—including the core, the pressurizer, and the six compact steam generators—housed within the reactor pressure vessel. The core model relies on point kinetics equations, accounting for reactivity feedback given by fuel and moderator temperatures and poison concentrations. In addition, it allows computing the temperature distributions in the fuel rods by applying the time-dependent heat equation to control volumes derived from an axial and radial discretization of the pins. The flow in the coolant channels, as well as in the riser, the downcomer, and the steam generator tubes, is modelled through a finite volume 1D approach, with the governing equations of mass, energy, and momentum balance equations solved in each control volume. Moreover, the pressurizer dynamics are represented assuming thermal equilibrium between the liquid and vapour phases, whereas the reactor coolant pump simulator is given by ThermoPower's *Pump* component. As for the control strategy, the only considered controlled variable is pressure. The controller modulates the flow rate of sprayers and electrical heater power in the pressurizer according to the difference between the measured primary pressure and its setpoint. No control system is considered to regulate the movement of the control rods; instead, the reactor's power is allowed to vary due to reactivity feedbacks.

Table I. Main E-SMR parameters.

Nominal thermal power	540	MWth
Nominal electrical power	170	MWe
Primary temperatures (core inlet/outlet)	300/324	°C
Secondary temperatures (SG inlet/outlet)	163/300	°C
Operating pressures (primary/secondary)	150/45	bar
Mass flow rates (primary/secondary)	3700/240	kg/s
Maximal power extraction for district heating	135	MWth
Minimal electrical power output	135	MWe

3.2. Balance of plant

The BOP model is used to represent the whole closed steam cycle, encompassing the high-pressure (HP) and low-pressure (LP) turbine stages, the HP and LP pumps, the feedwater tank, the moisture separator, as well as the reheater, the condenser, and the two preheaters. In addition to the components listed above, an intermediate heat exchanger (IHX) with a transmission capacity of about 135 MWth enables the transfer of thermal power to the DHN. The heat exchange occurs by extracting steam from the HP turbine outlet and directing it to the IHX. Here, it condenses by heating up the water flowing in the transmission network of the DH system, and, following that, the condensate is injected into the condenser, merging with the feedwater flow. The reference BOP architecture, derived from the optimisation in CYCLOP within the framework of the TANDEM project, has been conceived for full-power operation to serve as a starting point to investigate different hybridization options. As a result, the operational points adopted in Modelica exhibit some differences compared to the optimised layout, attributable to the dynamic model's simplifying assumptions and inclusion of the steam extraction system.

Similarly to the NSSS model, the BOP model relies on components from the ThermoPower library. In particular, the steam turbine is modelled using ThermoPower's *SteamTurbineStodola* component, featuring constant isentropic efficiency and an inlet pressure linked to the steam flow rate by Stodola's law. Simplified models were developed for the heat exchangers in the steam cycle and for the IHX; a static approach was selected for these components, disregarding pressure losses and lumping all spatial aspects into a global conductance to estimate the heat transfer between the two streams. This simplifying assumption will strongly affect the dynamics of the system, especially considering the crucial role of the BOP in distributing power flows among the various applications. For this reason, while the models presented in this work may offer an initial insight into the response of the system, their limits in capturing the complete dynamics of the system must be acknowledged.

The objective of the BOP control strategy is twofold. On the one hand, to satisfy the requirements in terms of commodity demands, and on the other, to maintain the system within its operational limits. The proposed control system is based on a decentralised scheme in which five proportional-integral-derivative (PID) controllers independently control the system according to the evolution of the corresponding process variables, as reported in Table II. The bypass valve opening is controlled to meet a given DH feed temperature requirement, which in turn will be dependent on the DH power demands and on the outdoor temperature. Moreover, the operating conditions of the steam generator are maintained at nominal values in order to limit perturbations resulting from the steam extraction process to the NSSS. This requirement is achieved by regulating the turbine admission valve to maintain the steam generator pressure stable and by adjusting the feedwater pump speed to avoid fluctuations in the steam outlet temperature. Similarly, the conditions at the LP turbine inlet are controlled through a dedicated admission valve, which ensures that the pressure of the steam delivering heat to the DHN remains constant, whereas the inlet temperature is regulated by modulating the steam flow delivered to the reheater through a dedicated valve.

Table II. Process and control variables pairings for the BOP model.

Process variable	Control variable
Steam generator pressure	HP turbine admission valve opening
Intermediate pressure	LP turbine admission valve opening
LP turbine inlet temperature	Reheater control valve opening
Steam generator outlet temperature	Feedwater pump speed
DHN feed temperature	Bypass valve opening

3.3. District heating network

The DHN model includes the transmission network (TN), intended to transfer the hot water to the end consumers, and a distribution network (DN), representing the ramifications of pipelines delivering the heat to the single buildings in the urban area of interest. Regarding the latter, a simplified approach was adopted to focus just on the main factor affecting the dynamics of the NHES architecture: the thermal inertia given by the mass of water within distribution pipelines. Therefore, the DN model is represented by a closed water volume at fixed pressure, with its size estimated by the known total capacity. The contribution of consumers and other heat sources, derived from the techno-economic optimisation, is accounted for through dedicated connectors.

As an initial estimation to size the TN, a heat transportation distance of 20 km is assumed, consistent with the emergency planning zone required by Finnish regulation [14]. The pipeline geometry was determined to obtain a pressure drop in the pipelines below 1 bar/km, leading to the choice of the DN600-type pipelines as the most suitable option to deliver the thermal power of 135 MWth considered in the analysis. The key components of the model are the main pipelines and the pumping stations that regulate the flow in the transmission line. For the former, the aforementioned finite volume 1D fluid flow model of the ThermoPower library is adopted, employing Colebrook's equation to estimate pressure losses and accounting for thermal losses through the pipe wall with the ground. The insulation of the wall, as well as its thermal inertia, is considered through a dedicated component from the ThermoPower library.

To enable temperature control in the DHN, a bypass system is implemented, depicted in the *Transmission network* block in Figure 2, consisting of two valves that are regulated simultaneously: one to adjust the flow delivered to the DN and another to stabilise the pressure levels in the transmission line. In particular, the opening of the valves is controlled so that the return temperature from the distribution network is consistent with the requirements dictated by the environmental conditions. As mentioned above, the feed temperature control is performed at the BOP level, acting on the bypass valve opening. However, since this control scheme regulates the water temperature that leaves the power plant, the target temperature is adjusted to account for thermal losses and the fluid's travel time in the transmission line to satisfy the temperature needs of the consumer.

4. CASE STUDIES

The case studies considered to assess the dynamic response of the system were selected according to the power flows from the optimisation of Helsinki's metropolitan district heating system. This DHN is composed of several distribution networks, namely Espoo, Vantaa, and two additional networks to cover Helsinki's higher demands, serving the western and eastern parts of the city, each interconnected with dedicated transmission lines. In this analysis, the NHES is considered to be connected to Espoo's distribution network, while the heat exchanges foreseen with the other networks are lumped within the net demand. From the results for the yearly optimisation provided by the Backbone modelling framework, reported in Figure 3, two daily profiles were extracted to test the dynamic response of the system, aiming to reflect the varying heating and temperature requirements, driven by outdoor conditions, during the winter and summer seasons. As reported on the left-hand side of Figure 3, where the total heat demand, satisfied partially by the NHES and partially by conventional heat sources according to the Backbone output, is represented, the typical optimal operational curves consist of continuously extracting the maximal amount of heat while regulating DHN temperatures in the winter season. On the other hand, during the summer, the temperatures are maintained constant, and the thermal power delivered to the DHN is tailored to the demand. In the selected daily curves, representing the hottest and coldest days of the year, the NHES must meet challenging requirements in terms of flexible operation due to the significant variation in temperature level required in the winter and in power in the summer.

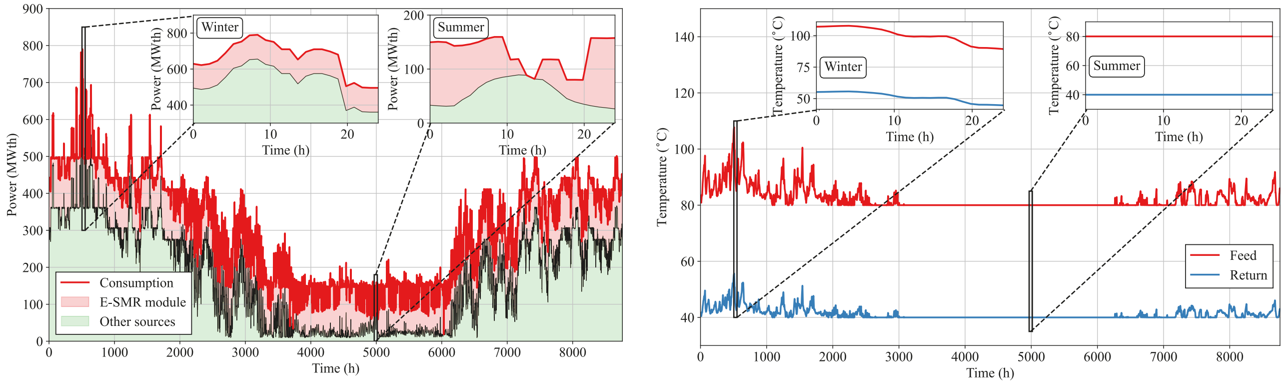

Figure 3. Case studies in terms of power (left) and temperature (right) requirements.

5. RESULTS

In this section, the simulation results obtained by testing the NHES model with the two sets of boundary conditions in terms of DH temperatures and heat demand and supply are presented. The outcomes obtained in the winter and summer cases are displayed in Figure 4 and Figure 5.

Overall, the results suggest that the NHES can meet highly variable thermal load and feed temperature demands, all while maintaining the SMR at full capacity. It is worth mentioning that there are still some fluctuations in the core's thermal power, which follow the same trend as the steam extraction process. These are triggered by the strong moderator temperature feedback that characterises a boron-free reactor such as the E-SMR and that arises due to the variations in feedwater conditions, which, in turn, are determined by the selected BOP control strategy, ultimately affecting the primary coolant state. Furthermore, the BOP controller proved to be capable of maintaining the process variables, such as the turbine inlet conditions, at a stable level.

In the case study addressing the district heating requirements in the summer, the regulation of thermal power extracted from the BOP effectively meets the DHN temperature setpoints. The features of the implemented control strategy for the DHN lead to a mismatch between the delivered heat obtained from the dynamic model with respect to the profile extracted from Backbone, specifically with a time delay of about two hours, which corresponds to the travel time of the fluid within the transmission line. As a matter of fact, when the heat required by the distribution network decreases, a temperature increase is avoided by opening the bypass valve in the transmission network to reduce the heat supply to the distribution network. This leads to an increase in the returning water temperature, and thus the heat exchanged in the IHX needs to be reduced to attain the feed temperature requirements. The electrical power output varies accordingly, i.e., with a time delay with respect to the Backbone output. In general, the trend of the power flows obtained with the dynamic model is consistent with the Backbone outcome, despite a significantly smoother variation related to the high thermal inertia of both the distribution and transmission networks.

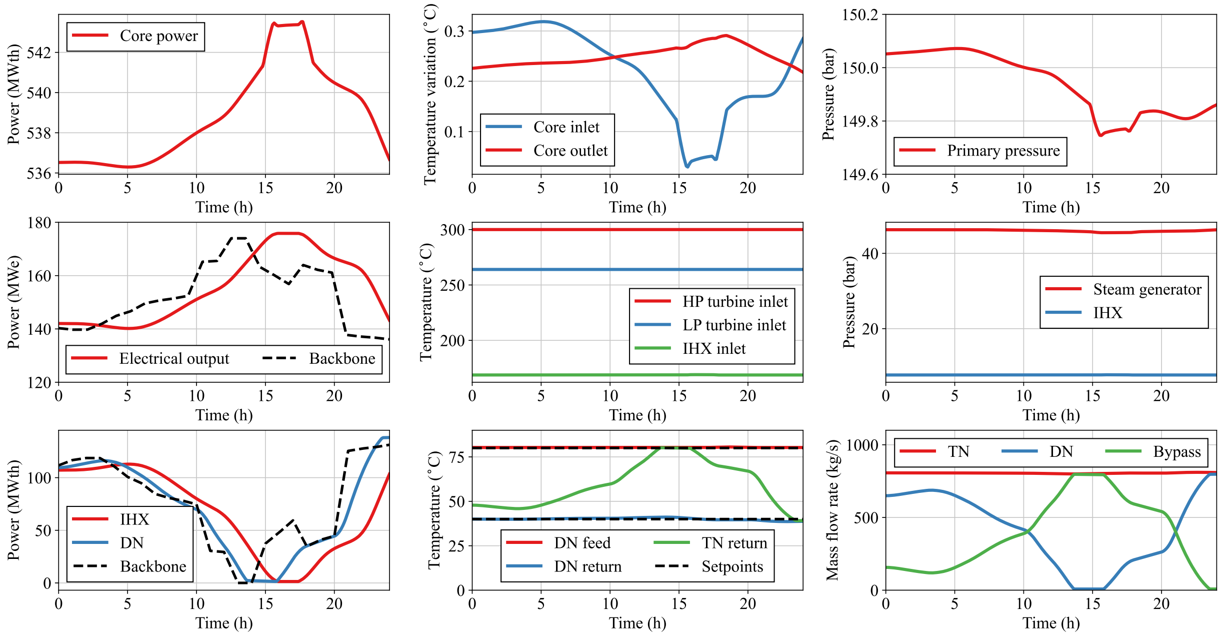

Figure 4. Simulation results for the "summer" case study.

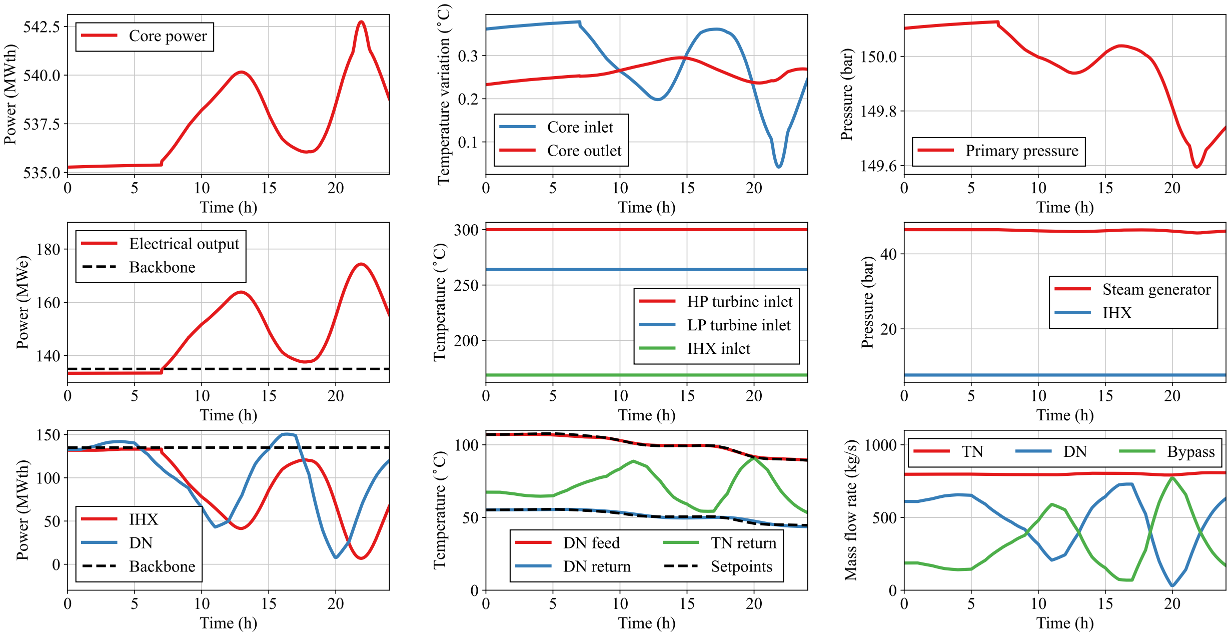

Figure 5. Simulation results for the "winter" case study.

On the other hand, the thermal power supplied by the NHES to meet the varying temperature requirements in the winter significantly differs with respect to the optimisation outcome, primarily due to the adopted control strategy within the dynamic model. For example, the return temperature remains lower than the feed temperature yet decreases over time when the heat absorbed by the consumer is higher compared to the supply. This requirement is met by opening the bypass valve, which in turn increases the temperature of the fluid returning to the NHES. The higher inlet temperature, together with the decrease in needed feed temperature, leads to a significant decrease in thermal power extracted from the NHES. According to the operational philosophy analysed in this work, the residual energy will be converted into electricity, and the resulting electrical energy delivered to the grid is higher with respect to the Backbone value by about 490 MWh, which corresponds to 15% additional electricity generation compared to the value considered in the optimisation at the expense of district heat. This mismatch occurs primarily as a result of the heat accumulation capability of the transmission network, accounted for within the dynamic modelling framework. The additional electrical power might be delivered to the grid, thereby affecting the economic performance of the NHES, or the expected power output could be met, e.g., by modulating the SMR power. In general, it is fundamental to be able to accurately predict the actual electric power output of the system to submit a consistent day-ahead bid to the electricity market and thus prevent potential financial penalties.

6. CONCLUSIONS

The proposed study involves the analysis of a nuclear hybrid energy system, integrating a light-water cooled SMR with Helsinki's metropolitan district heating network. The reactor allocates its energy for either electricity generation or supplying district heat according to the optimal load setpoints obtained from the Backbone optimisation framework, with minimal perturbations on the primary side due to reactivity feedbacks. Concerning the NHES design, the E-SMR concept was considered as a reference for the nuclear reactor, and a tailored BOP layout was developed with the CYCLOP tool. Moreover, the dynamic model of the global NHES architecture, comprising the nuclear reactor with its energy conversion system and the DHN, was built in the Modelica language, and the response of the system was tested by imposing the optimal operation conditions extracted from Backbone.

Overall, the considered control strategy effectively met the required district heating conditions, satisfying fluctuating heat and temperature demands in both the summer and winter scenarios while exhibiting minimal variations in the reactor's thermal power output. Moreover, the dynamic simulation of the system highlighted the importance of accounting for the impact of thermal inertia of both the distribution and transmission networks, along with the role of the selected control strategy on system dynamics, since, as it has been shown in the winter scenario, it might significantly affect the system's operation and, consequently, its economic performance. In the optimisation framework, the time delay due to the fluid's travel time might become a relevant factor, especially considering the high variability of electricity prices throughout the day. In this context, it might be worthwhile increasing the interactions between the dynamic model and the optimiser, ensuring that the latter encompasses the aspects mentioned above.

In conclusion, this analysis may provide an initial insight into the viability of deploying such systems in Finland, supporting decision-makers in evaluating the most suitable configuration to meet the evolving district heating requirements and determining their optimal operation, while also accounting for the dynamic behaviour of the overall architecture.

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DISCLAIMER

REFERENCES

[1] European Commission. Directorate General for Energy., *Policy support for heating and cooling decarbonisation: roadmap.* Publications Office, 2022. [Online]. Available: https://data.europa.eu/doi/10.2833/977806

[2] A. Teräsvirta, S. Syri, and P. Hiltunen, ‘Small Nuclear Reactor—Nordic District Heating Case Study’, *Energies*, vol. 13, no. 15, p. 3782, Jul. 2020, doi: 10.3390/en13153782.

[3] E. Pursiheimo, T. J. Lindroos, D. Sundell, M. Rämä, and V. Tulkki, ‘Optimal investment analysis for heat pumps and nuclear heat in decarbonised Helsinki metropolitan district heating system’, *Energy Storage and Saving*, vol. 1, no. 2, pp. 80–92, Jun. 2022, doi: 10.1016/j.enss.2022.03.001.

[4] M. Lipka and A. Rajewski, ‘Regress in nuclear district heating. The need for rethinking cogeneration’, *Progress in Nuclear Energy*, vol. 130, p. 103518, Dec. 2020, doi: 10.1016/j.pnucene.2020.103518.

[5] *Nuclear–Renewable Hybrid Energy Systems*. in Nuclear Energy Series, no. NR-T-1.24. Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY, 2023. [Online]. Available: https://www.iaea.org/publications/15098/nuclear-renewable-hybrid-energy-systems

[6] S. M. Bragg-Sitton, R. Boardman, C. Rabiti, and J. O’Brien, ‘Reimagining future energy systems: Overview of the US program to maximize energy utilization via integrated nuclear-renewable energy systems’, *Int J Energy Res*, vol. 44, no. 10, pp. 8156–8169, Aug. 2020, doi: 10.1002/er.5207.

[7] C. Vaglio-Gaudard *et al.*, ‘The TANDEM Euratom project: Context, objectives and workplan’, *Nuclear Engineering and Technology*, 2023, doi: https://doi.org/10.1016/j.net.2023.12.015.

[8] D. Haubensack, C. Thévenot, and P. Dumaz, ‘The Copernic / Cyclop Computer Tool : Pre-Conceptual Design of Generation 4 Nuclear Systems’, presented at the 2nd International Topical Meeting on High Temperature Reactor Technology, Beijing, 2004, pp. 1–11.

[9] S. E. Mattsson, H. Elmqvist, and M. Otter, ‘Physical system modeling with Modelica’, *Control Engineering Practice*, vol. 6, no. 4, pp. 501–510, Apr. 1998, doi: 10.1016/S0967-0661(98)00047-1.

[10] J. Kiviluoma, E. Rinne, T. Rasku, and N. Helistö, ‘Backbone—An Adaptable Energy System Model—GitLab Repository. 2018’. [Online]. Available: https://gitlab.vtt.fi/backbone/backbone

[11] N. Helistö *et al.*, ‘Backbone—An Adaptable Energy Systems Modelling Framework’, *Energies*, vol. 12, no. 17, p. 3388, Sep. 2019, doi: 10.3390/en12173388.

[12] F. Casella and A. Leva, ‘Modelling of thermo-hydraulic power generation processes using Modelica’, *Mathematical and Computer Modelling of Dynamical Systems*, vol. 12, no. 1, pp. 19–33, Feb. 2006, doi: 10.1080/13873950500071082.

[13] S. Lansou *et al.*, ‘ELSMOR – towards European Licensing of Small Modular Reactors: Methodology recommendations for light-water small modular reactors safety assessment’, *Open Res Europe*, vol. 3, p. 158, Sep. 2023, doi: 10.12688/openreseurope.16360.1.

[14] G. Locatelli and M. Mancini, ‘Emergency planning zone: Constraints and opportunities for the development of nuclear energy and exploitation of its process heat’, *Energy Resources: Development, Distribution and Exploitation*, pp. 79–138, 2011.