DOI: 10.22146/jnteti.v14i2.17426

Advancing Indonesia's Energy Transition: Coal-to-Nuclear (C2N) Simulation Study

Irfan Eko Budiyanto[1], Sinta Uri El Hakim[2]

[1] PT PLN Nusantara Power, Jl. Ketintang Baru 11, Surabaya 60231, Indonesia
[2] RWTH-Aachen (Rheinisch-Westfälische Technische Hochschule Aachen) University, Templergraben 55, Aachen, Cologne 52056, Germany

[Received: 20 December 2024, Revised: 13 March 2025, Accepted: 9 April 2025]
Corresponding Author: Irfan Eko Budiyanto (email: irfan.eb@pln.co.id)

ABSTRACT — Indonesia's ambitious net-zero emissions (NZE) target for 2060 necessitates a transformative shift from coal-dependent power systems to nuclear energy sources. Although previous studies have explored various aspects of energy transitions, limited attention has focused on the possibility of replacing existing coal-fired boilers with nuclear reactors while maintaining the input and output parameters of the current infrastructure. This paper presents an approach to facilitating Indonesia's nuclear energy transition by a coal-to-nuclear (C2N) simulation study. Specifically, the focus is on the 400 MW coal-fired power plant (CFPP), which relies on coal combustion. This study was designed to model the conversion process of the coal combustion system to a modular nuclear reactor setup while preserving the existing steam turbine and generator infrastructure. The foundation of this study was that the replacement of the nuclear reactor-based heat source must meet the requirements of the pre-existing water and steam cycle design. Various configurations for substituting the current boiler with a nuclear reactor were analyzed in this study, by considering engineering, operational, and modeling aspects. Results from model simulations for nine different operating conditions showed a deviation of the main-steam temperature of about 3% of the design value, starting at 120 MWe and above. Nevertheless, all other parameters of the conversion simulation results demonstrated a very small deviation. The deviation was close to the actual existing operational conditions of the previous CFPP. This paper highlights how the simulation demonstrated a promising integration of legacy infrastructure with emerging nuclear technology.

KEYWORDS — Nuclear Energy Transition, Power Plant Simulation, Coal-to-Nuclear Conversion, Coal-Fired Boilers, Nuclear Reactors.

I. INTRODUCTION

Indonesia has conveyed its commitment to achieve net-zero emissions (NZE) in 2060 at the The UN Climate Change Conference in Glasgow (COP26) meeting to address the world's future energy challenges. As one of the largest energy companies in Indonesia, the State Electricity Company (PT PLN) has developed a green Electricity Supply Business Plan (Rencana Usaha Penyediaan Tenaga Listrik, RUPTL) for the 2021–2030 period to support this commitment. One of the strategic initiatives in the RUPTL is to optimize the use of new energy as a power plant supply to improve the energy mix [1]. The strategy also considers and reviews the implementation of nuclear power plants in Indonesia. Several countries have studied and implemented this nuclear energy transition strategy. The common strategy is through the conversion of coal-fired power plants (CFPP) to nuclear power plants with the coal-to-nuclear (C2N) mechanism [2]. This mechanism converts a steam power plant coal combustion system into a modular nuclear reactor equipped with a steam generator. However, this mechanism still maintains the existing steam turbine and generator system.

The transition from coal-based power to renewable energy systems presents challenges that can be addressed through innovative energy storage and power cycle solutions. Molten salt energy storage systems can be integrated with existing steam turbines to increase flexibility and efficiency while connecting to renewable sources [3]. For small modular reactors (SMR), various power cycles have been analyzed to improve thermodynamic efficiency and reduce costs. Traditional steam cycles can achieve up to 33.5% efficiency for water-cooled reactors, while gas-cooled helium reactors can reach efficiencies of 52.9% at 1,000 °C using binary cycles combining Brayton and Rankine cycles [4]. Additionally, coupling modular high-temperature nuclear reactors with steam cycles can achieve higher efficiencies than traditional nuclear technology [5]. These repowering strategies offer potential pathways for reducing greenhouse gas emissions while maintaining energy security and leveraging existing power plant assets. Various configurations have been analyzed, including integrating thermal energy storage (TES) for flexibility [6] and adapting existing steam turbine systems to SMR steam conditions [7]. The latter study has found that replacing the high-pressure turbine stage is the most economically advantageous option. High-temperature SMRs, such as the Kairos Power design, showed promise for integration with existing coal plant infrastructure [8].

Although previous studies have explored various aspects of energy transitions [5], [7], [8], limited attention has been given to replacing existing coal-fired boilers with nuclear reactors while adhering to the input and output parameters of the current system. The pressure, temperature, mass flow, and enthalpy of the feedwater must align with the operational parameters of the existing setup. Furthermore, the main properties of the steam generated by the steam generator must meet the requirements of the high-pressure (HP) turbine. Similarly, the hot reheat steam produced must satisfy the parameters needed by the existing intermediate-pressure (IP) turbine, with cold reheat steam inputs based on the HP turbine's output parameters.

This study developed a simulation for a C2N power plant to address these research gaps. The C2N simulation was designed to model the process of converting a coal combustion system to a modular nuclear reactor configuration, while maintaining the current steam-turbine and generator infrastructure. This study highlights the potential of such simulation in facilitating the adoption of clean energy technologies, thereby advancing Indonesia's efforts towards a sustainable and low-carbon future.

II. RELATED WORKS

A. POINT KINETICS

Point kinetics is a fundamental concept in nuclear reactor physics, especially for calculating neutron flux and reactivity. The point kinetics equations (PKEs) provide a simplified model that describes the time-dependent behavior of neutron populations and delayed neutron precursors within a reactor. These equations assume that the reactor behaves as a point source, a valid assumption for small reactors, or when small reactivity insertions occur [9]. The PKEs consist of coupled ordinary differential equations that express the relationship between neutron density, reactivity, and the concentrations of delayed neutron precursors. The dynamics of these equations are influenced by several factors, including the number of delayed neutron groups, which can range from one to six or more, depending on the reactor type and operational conditions. The PKEs remain a crucial tool in reactor kinetics, enabling efficient predictions of reactor behavior during various operational scenarios [10]. The PKEs are described in (1) and (2):

$$\frac{dn(t)}{dt} = \frac{\rho(t)-\beta}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i C_i(t) + S(t) \quad (1)$$

$$\frac{dC_i(t)}{dt} = \frac{n(t)}{\Lambda} - \lambda_i C_i(t) \quad (2)$$

where $n(t)$ is neutron population at time *t*, $C_i(t)$ is precursor for delayed neutron in energy group of *i* and time of *t*, $S(t)$ is neutron source production at time of *t*, Λ is neutron generation time, β is delayed neutron fraction, λ_i is decay constant of delayed neutron precursor for energy group of *i*, and $\rho(t)$ is reactivity at time *t*.

In nuclear reactor physics, the total reactivity within the core is a critical parameter, representing the sum of various contributions from different reactivity mechanisms. This summation approach provides a thorough understanding of how various factors influence the reactor's performance and safety margins. Total reactivity is influenced by several feedback mechanisms, including temperature coefficients, control rod positions, and the presence of reactor poisons. All these factors must be considered to ensure the reactor operates safely and efficiently. The reactivity contribution from the control rods is determined using the control rod design data. Thus, the total reactivity in the core is calculated by summing all contributing reactivities, as shown in (3) and (4):

$$\rho_{total} = \rho_{excess} + (\rho_{CR} + \rho_{Xe} + \rho_T) \quad (3)$$

$$\rho_{CR} = \sum_{i=0}^{n} \rho_{CR_i} \quad (4)$$

where ρ_{total} is total reactivity, ρ_{excess} is excess reactivity from fuel, ρ_{CR} is total control rod reactivity, ρ_{Xe} is poison reactivity of Xenon, ρ_T is negative temperature reactivity from Doppler effect, and ρ_{CR_i} is control rod reactivity from control rod number *i*.

One of the key contributors to reactivity is the temperature coefficient, which shows how changes in temperature affect the reactor's reactivity. For example, as the fuel temperature increases, the Doppler effect usually reduces reactivity by broadening the neutron absorption resonances in the fuel [11]. Additionally, the reactivity from control rods, liquid boron, and reactor poisons must be considered. When control rods are inserted into the reactor core, they absorb neutrons, decreasing reactivity. In contrast, when control rods are withdrawn, they introduce positive reactivity, which can lead to an increase in power output if not carefully controlled. These factors must be managed properly to ensure the reactor operates safely and efficiently.

B. HIGH-TEMPERATURE GAS-COOLED REACTOR PEBBLE-BED MODULE (HTR-PM)

The high-temperature gas-cooled reactor pebble-bed module (HTR-PM) is a Chinese demonstration plant developed by the Institute of Nuclear and New Energy Technology at Tsinghua University. The plant consists of two 250 MW pebble-bed modular reactors, each with a steam generator, feeding a single 210 MW steam turbine. A pilot fuel production line is expected to manufacture 300,000 pebble fuel elements annually. The project aims to demonstrate the economic competitiveness of commercial HTR-PM plants and show that they do not require accident management procedures or off-site emergency measures [12]. The HTR-PM is designed with several safety features to ensure robust and reliable performance. One such feature is the minimal radioactive inventory in the primary helium coolant during normal operating conditions, meaning that even in the event of a release, no emergency measure is required. Additionally, during a reactivity accident or a loss of coolant accident, the rise in fuel element temperature does not result in a significant additional release of radioactive substances [13].

The HTR-PM incorporates the inherent safety principles of the modular high-temperature gas-cooled reactor (HTGR). Its lower power density, reliable performance of coated particle fuel, and balanced system design ensure the maintenance of fundamental safety functions. Features such as a large negative temperature coefficient, a substantial temperature margin, low excess reactivity due to online refueling, and the use of control rods support safe operation and limited accident temperatures. The decay heat is passively removed from the core under any designed accident conditions through natural mechanisms such as heat conduction or radiation to ensure that the maximum fuel temperature remains below 1,620 °C. This containment prevents core meltdown and significant radioactive releases into the environment by keeping nearly all fission products within the silicon carbide (SiC) layer of the TRi-structural ISOtropic (TRISO)-coated fuel particles. Additionally, the HTR-PM design allows for a slow progression of accidents due to the high heat capacity of fuel elements and graphite internal structures. In cases where the coolant is completely lost, it takes days for the fuel elements to reach their maximum temperature [13].

III. METHODOLOGY

This study started with data retrieval on the main parameters of the existing CFPP process. The research object was a 400 MWe Paiton CFPP with a reheating system, owned by PLN Nusantara Power, which has been in operation since 1993. This study used the main parameters of the design and process at their various operating conditions as reference. The variants included warming conditions, turbine rolling, turbine nominal speed of 3,000 rpm, initial load, and load up to 400 MWe. The main parameters compiled consisted of pressure (in kg/cm^2), temperature (in ^{o}C), mass flow (in kg/s), and enthalpy (in kJ/kg). Parameter data were obtained from the heat-mass balance design by the Paiton CFPP main equipment manufacturers, as well as from steady state observation data at Paiton CFPP under various operating conditions. As the design data and operating parameters of the Paiton CFPP were only available for limited authorities, this study was conducted solely through direct on-site observations.

The premise of this study was that the heat source substitute derived from the nuclear reactor should be able to follow the input and output parameters as designed for existing water and steam cycle requirements. Based on the observation data at Paiton CFPP, this study found that the input parameters of the existing feedwater system range from a temperature of 30 to 250 ^{o}C and a pressure of 45 to 190 kg/cm^2. For the existing main steam output parameters, the temperature ranges from 350 to 540 ^{o}C, with pressure ranging from 42 to 169 kg/cm^2.

This study utilized SMRs that operate within this range of water and steam cycle parameters. The International Atomic Energy Agency (IAEA) shows that one of the SMRs in this parameter range that is already in operation is HTR-PM from Tsinghua University, China [14]. This study utilized this SMR, an HTGR with specifications as described in the supplement to the IAEA's Advanced Reactors Information System (ARIS) [14]. For the substitution of the existing boiler with a nuclear reactor and primary system as a heat source, several configurations were analyzed in this study. The analysis was carried out by considering the pros and cons of engineering aspects, operational aspects, and modeling aspects.

The first configuration involved an HTR-PM helium primary system with a molten-salt TES secondary system, as shown in Figure 1. The secondary system utilized one heat exchanger unit for the helium and molten-salt, adhering to nuclear-safety class standard. Four heat exchanger units generated steam from the tertiary system in accordance with the existing boiler panel configuration.

The primary system employed helium gas within a cold and hot header system. This system was subjected to a heat exchanger with molten salt. The use of molten salts as heat transfer fluids (HTFs) and TES mediums was driven by their high heat capacity, low vapor pressure, and broad operational temperature range, which could reach up to approximately 500 °C [15]. Recent studies have highlighted the potential of various molten salt compositions, including quaternary nitrate-based salts, which have demonstrated excellent heat transfer performance and thermal stability [16]. Additionally, chloride eutectic mixtures have been explored for their high heat storage density and lower cost, making them promising alternatives for high-temperature applications [17]. Overall, the use of molten salts as HTFs and TES mediums presents a promising approach to improving the efficiency and sustainability of energy systems. Their unique properties and versatility made them essential for the future of both solar and nuclear energy technologies.

In this configuration, molten salt served as the secondary system and was circulated through four heat exchanger units, substituting the original boiler panels. Pressurized water was employed in the economizer and waterwall heat exchangers as the tertiary working fluid, while superheated steam was utilized in the tertiary system within the superheater and reheater heat exchangers.

On the engineering aspect, this configuration has the benefit that TES is applicable for cogeneration and other necessities [18]. TES systems become increasingly important for improving energy efficiency in various applications. TES has been integrated into cogeneration plants, including nuclear power plants, to enhance operational flexibility and meet varying heat demands [19]. The technology encompasses sensible heat, latent heat, and thermochemical storage, with sensible heat TES being the most cost-effective and widely used. TES integration in cogeneration systems significantly improves overall efficiency, with one study reporting a total cogeneration efficiency of 75% [19]. Recent research has explored innovative cogeneration systems for green hydrogen production and energy generation. These systems integrated various technologies to improve efficiency and reduce environmental impact. Integrating large-scale green hydrogen systems with coal-based cogeneration processes significantly reduces carbon emissions, although it results in increased operating costs [20]. Cogeneration has been applied such as for green-hydrogen production with a solid oxide electrolysis cell (SOEC) that utilizes heat energy from the TES [21].

Operation-wise, this configuration offers the advantage of the balance of plant operations utilizing tertiary systems that are well separated from the primary system risks. Furthermore, in terms of modeling, this configuration also provides the virtues of heat exchanger models of the tertiary system, which is in common with the panel model of the existing boiler. However, this configuration imposes the disadvantage that new equipment additions are particularly intensive. Therefore, operations were more intensive and were compulsive in terms of modeling and control systems.

The second configuration still utilized a helium gas primary system, equipped with hot and cold headers. The helium gas was directly circulated to four heat exchangers, which replaced the function of the existing boiler panels, through the individual control of circulator fans. The secondary system in the economizer and waterwall heat exchangers used pressurized water as the working fluid. Meanwhile, the superheater and reheater heat exchangers use superheated steam as the secondary fluid (Figure 2).

From the engineering aspect, this configuration has the advantage that a helium high heat source allows more flexibility to meet the requirements for the heat-exchanger model according to the current boiler panel. However, they require heat exchangers as steam generators within the nuclear safety class and demand a rigorous engineering design and installation to ensure helium impermeability control.

The control of helium impermeability in HTGR has been a critical focus in previous research to ensure the reactor's safety and efficiency. Studies have investigated the use of advanced ceramics and metal alloys in key components, which have shown promising resistance to helium diffusion under extreme operating conditions. Tests conducted on these materials have confirmed their ability to maintain structural integrity while minimizing leakage over prolonged periods. These efforts lay a strong foundation for improving the reliability and sustainability of HTGR technology. Earlier studies on HTGR have focused on improving control systems and resolving issues related to helium coolant. A method for cascaded power-level control, relying exclusively on adjusting helium flow rates, has been introduced and has shown promising results in terms of stability and performance [22].

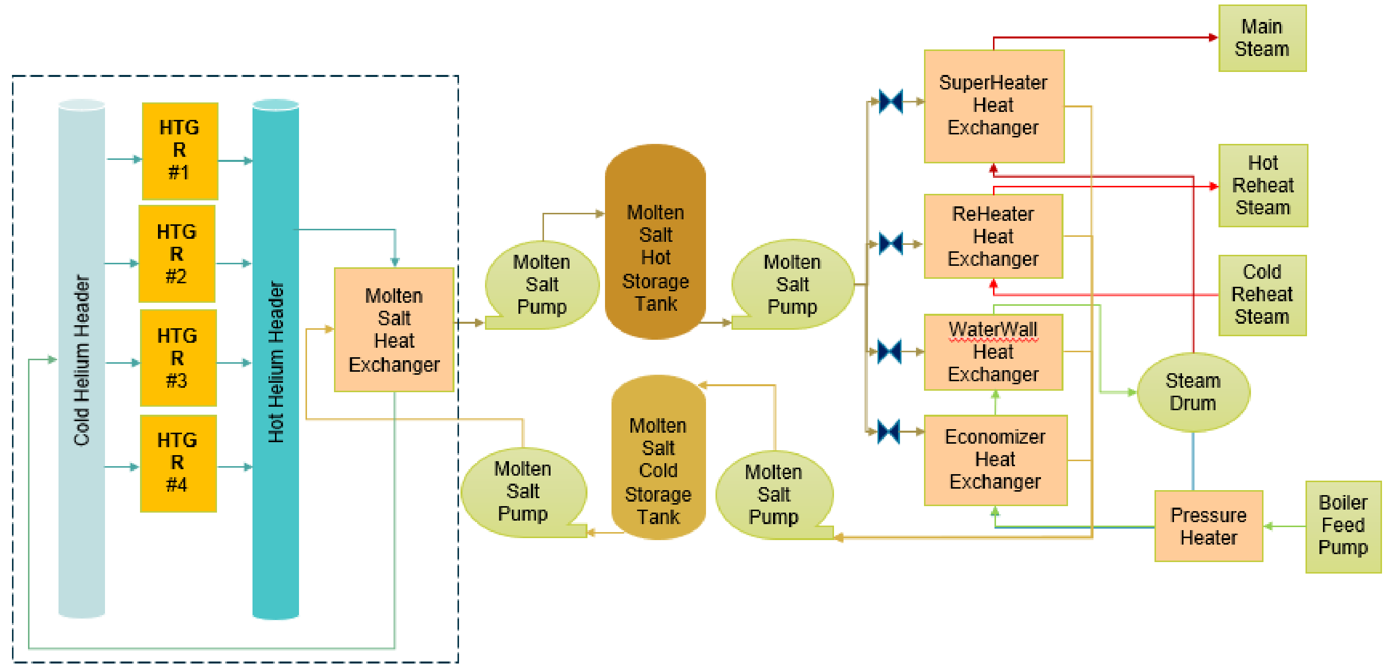

Figure 1. Helium primary system with molten-salt TES configuration.

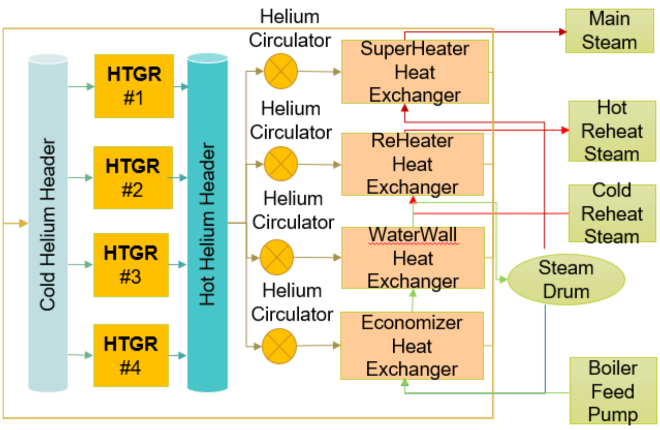

Figure 2. Helium primary system with heat exchanger configuration.

From an operational perspective, this configuration offers key advantages, particularly in its ability to allow seamless control and adjustment of steam generation processes. These processes function in a manner closely resembling the existing boiler system, simplifying operations. Additionally, from the modelling perspective, this configuration is beneficial as it preserves the existing boiler panel's model and control mechanisms. However, one disadvantage is the need to manage the substantial heat demands for each heat exchanger individually using helium circulators. The helium circulator is utilized to regulate the distribution of mass flow from the header, ensuring it meets the specific heat energy requirements of each individual heat-exchanger panel. Typically, the helium circulator consists of equipment designed as a fan or blower. Its operation can be adjusted by controlling the rotational speed, allowing for precise management of the mass flow output to achieve the desired levels. This adjustability ensures that the system can efficiently respond to varying operational demands while maintaining optimal performance.

Moreover, it adds complexity to the modeling process, particularly in transferring heat from the helium source to each existing boiler panel model. Transferring heat from the helium source is a critical process in various thermal systems, particularly in those involving high temperature gas reactors or advanced heat exchangers. Helium, known for its inert properties and high thermal conductivity, is often used as an HTF due to its ability to efficiently carry thermal energy without undergoing significant changes in its physical properties. In these systems, heat is transferred from the helium source, typically a reactor or a heat-generating component, to the heat exchanger panels or other heat-absorbing units. The transfer occurs through a series of carefully designed systems, such as helium circulators and heat exchangers, which regulate the mass flow and ensure optimal thermal energy distribution. By controlling the flow rate and pressure, the system ensures that the heat from the helium is effectively transferred to the working fluid, maintaining the required temperature and pressure for subsequent energy generation processes. This heat transfer process is essential for maintaining the overall efficiency and safety of high-performance energy systems, as it allows for the effective utilization of the energy generated from the helium source.

Based on the two previous configurations, a third, a more streamlined configuration option was proposed. This configuration utilized a complete HTR-PM reactor package along with its steam generator. Four reactor units with steam generators utilized a feedwater header and a steam header to match the design parameters of the existing system. This configuration employed a tertiary system through a heat exchanger, which functioned as a reheating system for the existing turbine design (Figure 3).

This configuration offers advantages, including compact reactor design, utilizing a common SMR HTGR design equipped with respective steam generators. The steam generator in HTGRs is often designed to be integral to the reactor system, which reduces the complexity and potential failure points associated with traditional designs that utilize separate steam generation systems. For instance, the Holtec Inherently Safe Modular Underground Reactor (HI-SMUR)

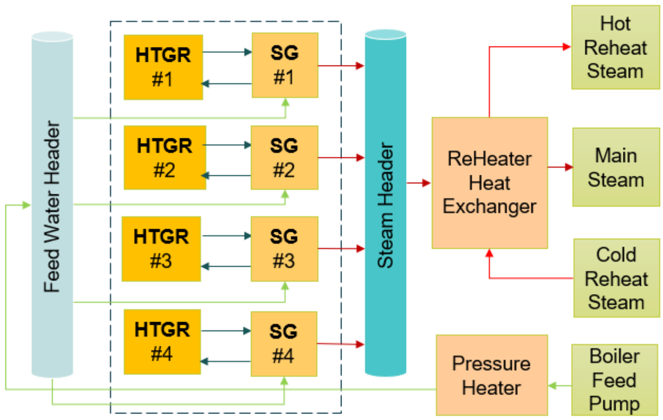

Figure 3. HTGR fitted with steam generator configuration.

features an integrated design where the steam generator is directly connected to the reactor vessel, eliminating the need for extensive piping and enhancing safety through reduced risk of leaks [23].

This configuration utilized a feed water header and a steam header. The feed water header ensured that the mass flow output from the existing feed water system was evenly distributed to each steam generator, adhering to its design limitations. Meanwhile, the steam header ensured that the mass flow requirements of the existing main steam system were met through the accumulated steam production from each steam generator.

The operation was more straightforward, particularly the combustion control, than in each of the previous boiler panels. At an earlier time, in boiler systems, the role of combustion panels, such as the economizer, evaporator, and superheater, was effectively taken over by the design of the steam generator. However, this steam generator design did not incorporate provisions for reheating the steam that exited the existing high-pressure steam turbine. To overcome this limitation, the configuration introduced a single heat-exchanger model specifically designed to function as a reheater system. This addition ensured that the reheating process was adequately addressed, compensating for the absence of a reheat mechanism in the original steam generator design.

However, a proper engineering design was required for a heat exchanger for the reheater, which applies steam to the steam fluid. Studies on heat exchangers employing steam-to-steam fluid transfer had concentrated on enhancing thermal performance and operational reliability. Researchers had investigated various configurations, such as shell-and-tube and plate designs, to determine their efficiency under high temperature and pressure conditions [24]. Experimental tests demonstrated that optimizing surface area and material selection improved heat transfer rates and minimized thermal losses [25]. Additionally, advanced simulation techniques were utilized to model fluid dynamics and heat exchange processes, validating experimental results and guiding design improvements. These efforts provided significant advancements in the development of robust and efficient steam-to-steam heat exchanger systems for industrial applications [26].

Moreover, this configuration required proper operation parameters for the reheater's heat exchanger, to get steam properties that meet the design requirements for existing turbines. From a modelling perspective, this configuration required relatively complex permissive modifications to operate the existing previous plant model, with the replacement of the boiler model with a steam generator and the reheater's heat exchanger.

For the last two configuration options, the heat-mass balance model simulations were conducted using the Cycle-Tempo software. Figure 4 demonstrates a heat-mass balance of a helium primary system with the heat exchanger configuration at 400 MWe generator output.

The reactor was modelled with heat exchangers, designed so that the inlet and outlet helium parameters were close to the HTR-PM design. The cold header was modelled with a serial valve as a placeholder for the mass flow splitter of the helium entering each reactor. The hot header was modelled with heat sinks from the outgoing helium of each reactor, as well as the header exit heat source (with accumulated mass flow from all heat sinks). The superheater was modelled with three heat-exchanger panels, corresponding to the arrangement in the existing boiler. These panels comprised the final superheater, the subdivision panel, and the low-temperature superheater. The reheater was modelled with two heat-exchanger panels, following the panel arrangement in the existing boiler, which included the first reheater and the final reheater. Additionally, two heat-exchanger panels were modelled to replace the functions of the economizer and evaporator in the previous boiler arrangement. Thus, in total, along with the previously mentioned models, seven heat exchanger models were used to replace the four functions of the previous panel arrangement in the existing boiler, employing a counter-flow heat-exchanger design.

The helium gas, which exited the four heat exchanger panels, was directed through a helium circulator. This device functioned as a regulator for the mass flow rate, ensuring that the heat requirements of each individual heat-exchanger panel were effectively met and maintained during the process.

Furthermore, this study carried out a heat mass balance of an HTGR fitted with a steam generator configuration at 400 MWe generator output (Figure 5). This configuration employed four HTR-PM reactors, each integrated with a steam generator. The model was equipped with a pressure reduction valve (PRV) to lower the feedwater pressure to 7 bar. A splitter valve was used in the feedwater header to distribute the feedwater mass flow to each steam generator. The steam produced by the four steam generators was stored in the steam header, with its output temperature being higher as the main steam entered the turbine. The model's heat exchanger was utilized for steam heat transfer and functioned as a reheater for the cold reheat steam exiting the intermediate pressure turbine. The output parameters of the heat exchanger were designed to meet the required specifications of the main steam and hot reheat steam for the existing turbine.

IV. RESULTS AND DISCUSSION

The heat-mass balance model simulation conducted earlier provided results that this study then analyzed for each configuration. The helium primary system with heat-exchanger configuration indicated that the helium-to-reactor temperature was 32.4%, higher than the HTR-PM design, which was around 331 °C, going beyond the design limit of 250 °C for the inlet water to the steam-generator HTR-PM. Despite this, the pressure and mass flow rates of helium entering and exiting the reactor remained consistent with the values outlined in the

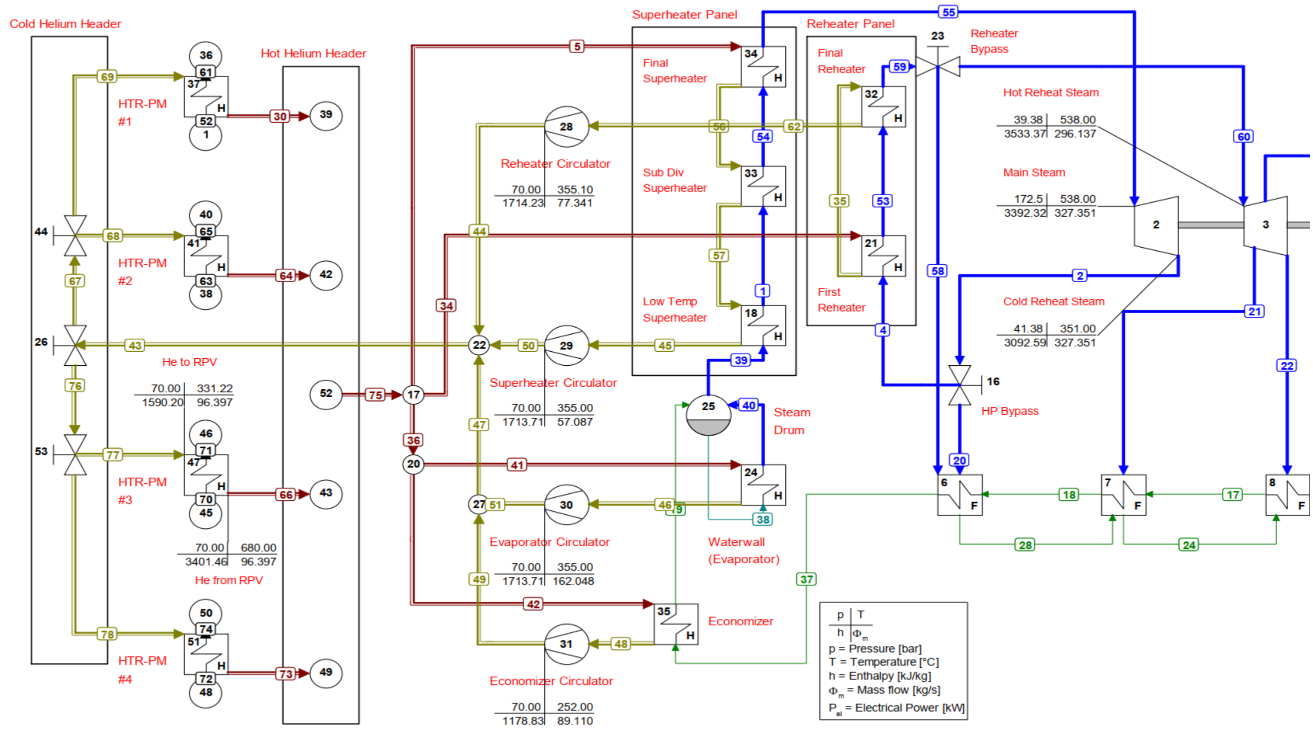

Figure 4. 400 MWe heat-mass balance of the helium primary system with heat exchanger configuration.

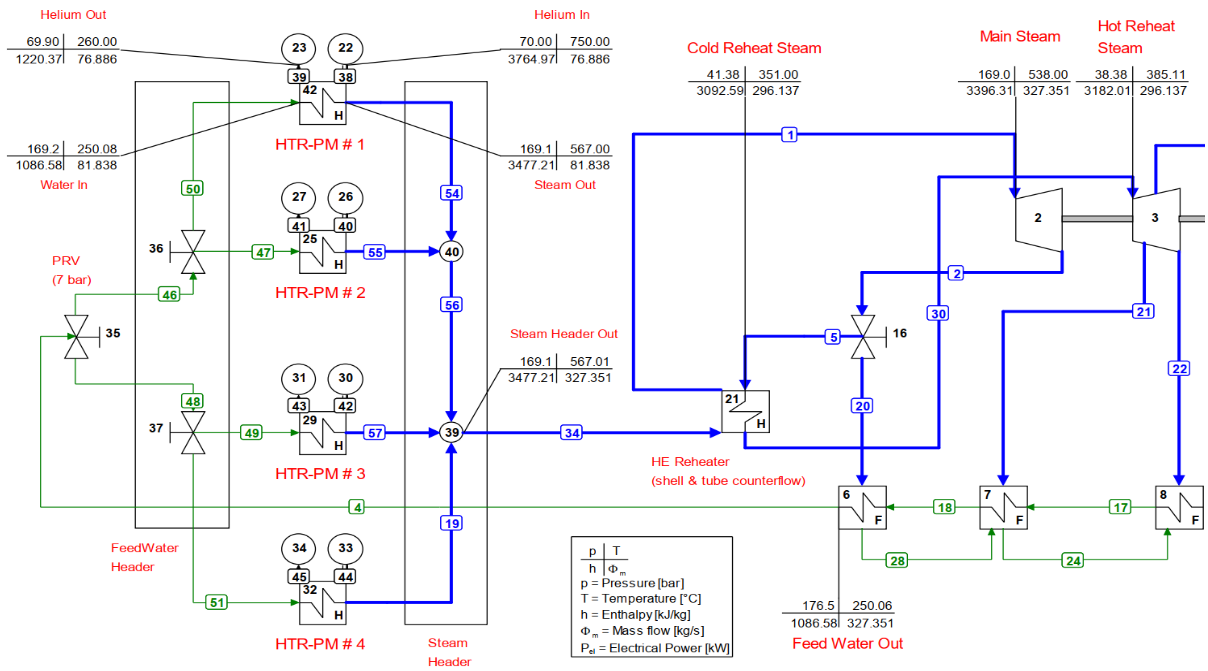

Figure 5. 400 MWe heat-mass balance of HTGR fitted with steam generator configuration.

HTR-PM design, confirming alignment with the original specifications.

For the HTGR with a steam generator configuration, the feedwater header exhibited four mass flow distribution outlets with a rate of 81.8 kg/s, which remains within the HTR-PM design limit of 94.9 kg/s for water inlet mass flow. The steam header also demonstrated that all inlet mass flow values were 81.8 kg/s, remaining within the HTR-PM steam-out mass flow design limit of 94.9 kg/s. The model simulation shows that the feed water pressure to the steam generator was 169.2 bar, from the design value of 132.5 bar or 127%. At the same time, the helium-out temperature to the reactor is 260 °C, compared to the design of 250 °C, or 104%.

The steam temperature coming out of the header remained sufficiently high (567 °C) to meet the main steam requirements of the existing high-pressure steam turbine. Therefore, the energy was used to heat the cold-reheat steam exiting the high-pressure turbine through a heat exchanger that acted as a panel reheater, like the function of the previous boiler. The output from the reheater heat exchanger showed that the produced main steam and hot-reheat steam matched the specifications required by the existing steam turbine, which were 538 °C and 385 °C, respectively, at a load of 400 MWe.

The heat mass balance analysis indicated that the energy required by the existing steam turbine was in full accordance with the design specifications from the earlier stage. This included a precise match in key parameters such as the mass flow rates, as well as the temperature and pressure values for both the main steam and the reheat steam, all of which were consistent with the expected operational conditions outlined in the original design.

Based on the heat-mass balance model simulation conducted at a 400 MWe generator output, the final configuration demonstrated more favorable results, remaining well within the design limits of the HTR-PM system. As a result, it was concluded that this configuration was better suited for the conversion of two 400 MWe CFPP to operate with HTR-PM nuclear reactors. The simulation findings suggested that this configuration would be compatible with the transition scenario, offering a more feasible approach for integrating nuclear technology into the existing coal plant infrastructure. The configuration was then validated by simulating the heat-mass balance model under various operating conditions according to the existing CFPP operations, including warming, turbine rolling, turbine nominal speed, 12 MWe initial load, 100 MWe load, 120 MWe load, 200 MWe load, 300 MWe load, up to 400 MWe nominal load.

Figure 6 presents the validation bar chart showing the percentage of deviations between simulated and reference values from the Paiton CFPP design and operational data. Those Paiton CFPP reference values were used as related standards for calculating deviations percentages. Validation was conducted on the parameters of pressure, temperature, mass flow, and enthalpy. Validation was performed on the main systems of the conversion tapping, which include feedwater, main steam, cold reheat steam, and hot reheat steam. Simulated results parameters were derived by point kinetics and heat mass balance calculations.

Results from model simulations for nine different operating conditions showed deviation of the main-steam temperature of about 3% of the design value, starting at 120 MWe and above. The most deviation accumulation of simulated parameters was observed at the hot reheat steam tapping-point of 200 MW load. However, those accumulated deviation values were still below 4.5%, with the most substantial deviation from the simulated pressure values. Tuning was considered appropriate for the model formulation derived from the regression equations calculated.

Nevertheless, all other parameters of the conversion simulation results demonstrated a very small deviation of up to 3%, which was within the acceptable limits of the feedwater and steam operating parameters commonly set at Paiton CFPP. Those included mass flow and enthalpy at all tapping points in all nine operational condition variations, as well as pressure at the main steam tapping point. The deviation was in close line with the actual existing operational conditions of the existing CFPP. At operating conditions below 120 MWe, the simulation results were most approaching the actual conditions of the existing CFPP operation and design, particularly during the initial start-up conditions, including warming, turbine rolling, and initial load.

The results indicated that the simulation study of converting a CFPP to a nuclear reactor configuration had successfully met the expected outcomes, demonstrating that a nuclear reactor could receive feedwater parameter input and existing cold reheat steam. In addition, another expected outcome was the steam generators that could produce main steam and hot-reheat steam according to the needs of existing steam turbines.

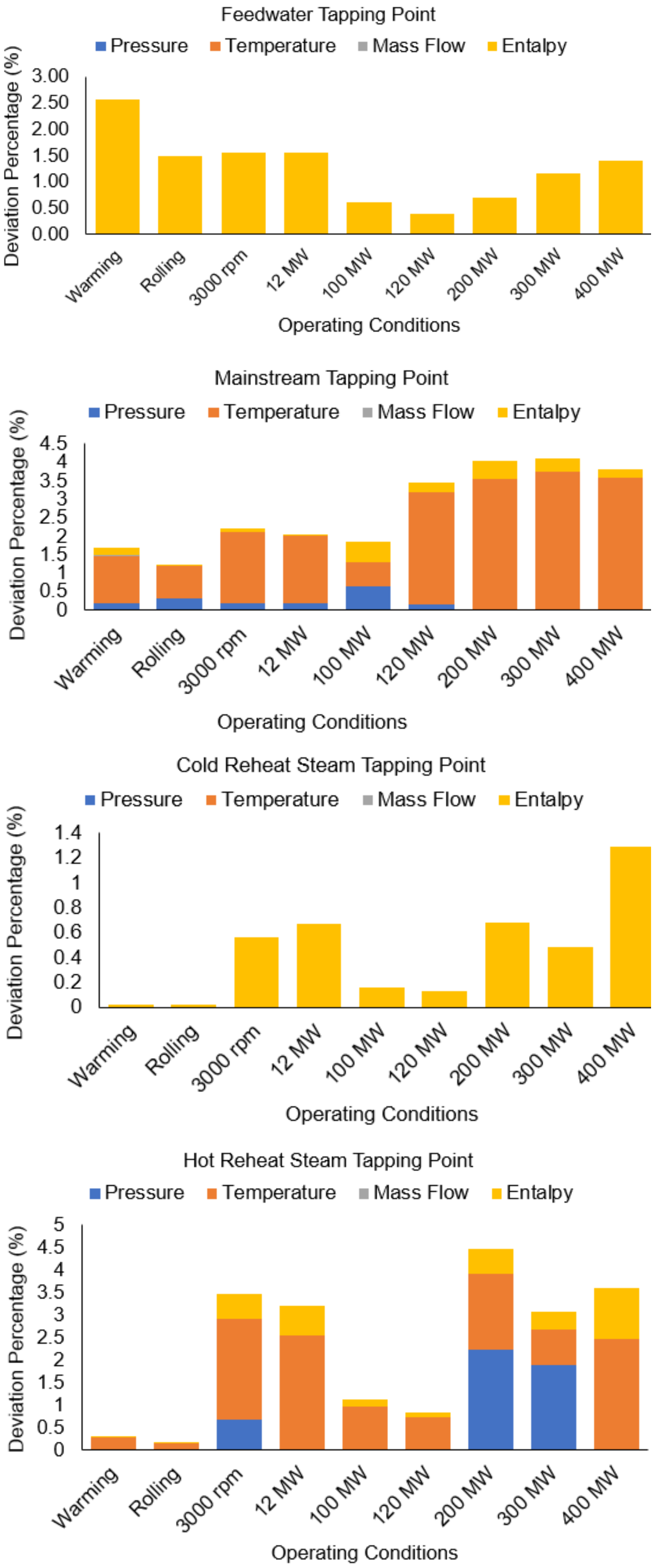

Figure 6. Simulated parameters deviation.

This study obtained comparative results between existing coal power plants and C2N conversion power plants. The fuel of the existing coal power plant was previously used subbituminous coal, with a carbon content of 35–45%, which is classified as low range coal (LRC) to medium range coal (MRC).

For the power plant that resulted from the C2N conversion, the fuel was replaced in accordance with that used by the HTR-

PM reactor, which was low-enriched uranium-235 (LEU-235) of 8.5%, in the form of spherical elements with TRISO coating. The heat source of the existing CFPP previously used a pulverized-coal boiler with a single drum type, balance draft, and control circulation radiant reheat. For the simulated C2N conversion power plant, the heat source was replaced with four units of modular pebble-bed HTGR, each equipped with a steam generator. In addition, this study used one unit of heat exchanger for the purpose of reheating the systems required for the existing steam turbines.

Meanwhile, the existing coal power plant required boiler combustion support systems. They included flue gas and air system, with main equipment consisting of a primary air fan (PAF), forced draft fan (FDF), induced draft fan (IDF), primary air heater (PAH), and secondary air heater (SAH), and electro-static precipitator (ESP) as the main equipment for capturing particulate as a combustion product. Coal and ash handling facilities were also required, composed of the main equipment of coal conveyor, ship unloader, and the area for coal yard or stockpile. However, for the C2N-converted power plant, these systems and facilities were no longer needed, hence significantly less equipment was required. As the HTR-PM reactor utilized Helium gas as its primary system, it only required the supplementary helium purification system, as well as the reactor cavity cooling system (RCCS), to serve as an auxiliary coolant for the reactor core containment.

However, from the aforementioned comparisons, this study demonstrated the key finding that C2N conversion could be carried out with the same water and steam systems as the existing CFPP. The existing water system, which remained unchanged and could be used, was composed of condensate and feedwater systems with the main equipment of condenser, condensate extraction pump (CEP), low-pressure heater (LPH), deaerator, boiler feedwater pump (BFP), and high-pressure heater (HPH). Meanwhile, the existing steam system that has remained unchanged consists of the main equipment as a tandem compound and reheat system steam turbine, as well as the existing main generator with the original type 473MW/18KV three-phase synchronous generator.

This study provided a contribution to the previous researcher. Previous studies have explored various configurations for adapting existing steam turbine systems to SMR conditions. A study on repowering a 460 MW coal plant with pressurized water reactor SMR technology has found that replacing the existing intermediate pressure section with a new high-pressure turbine stage is the most economically advantageous option [8]. Key considerations for SMR steam turbines include wet steam expansions, water erosion reduction, and standardization to reduce construction time and costs [27].

This study addressed the gaps identified in the aforementioned research. This study resulted in a simulation model for the conversion process of the coal combustion system to a modular nuclear reactor setup while preserving the existing steam turbine and generator infrastructure. The same existing feedwater and steam turbine system can still be used as before, with no significant equipment upgrades or enhancements. While this paper does not address them in-depth, other critical factors such as public acceptance, management of spent fuel, infrastructure security, and technology transfer must also be considered [28]. It should be emphasized that retrofitting the existing fleet with SMRs is intended to complement, not replace, the planned initial nuclear power plants, both in terms of development and their role within the energy system. Another key consideration is environmental protection. For SMR nuclear plants, comprehensive environmental impact assessments must be conducted to evaluate the effects thoroughly. These assessments should actively involve public participation and include cross-border impacts. Although these studies will be determined individually [29], they currently fall beyond the scope of this paper.

V. CONCLUSION

This study concludes that C2N transformation is a promising approach to energy transition, as it utilizes existing CFPP infrastructure. By replacing the coal-fired boiler with a nuclear reactor, the simulation study demonstrates that operational parameters closely align with previous conditions. This result indicates that the C2N conversion simulation in this study can preserve the existing system, especially the feedwater system, steam turbine, and generator.

The approach developed in this study focuses on revitalizing CFPP assets by repurposing them into nuclear-based facilities, providing a more sustainable alternative to constructing entirely new nuclear power plants. By leveraging existing infrastructure, this approach accelerates the transition to nuclear energy without requiring substantial resources in new plant development.

Furthermore, the study emphasizes the value of such simulation models in promoting the adoption of clean energy technologies, thereby supporting Indonesia’s long-term goal of achieving a low-carbon, sustainable energy future. This contribution is especially relevant to Indonesia’s ongoing efforts to move towards a more sustainable, low-carbon future by reducing its dependence on fossil fuels and enhancing the role of nuclear energy in its energy mix.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper. No financial or personal relationships exist that could have influenced the research, analysis, or outcomes reported in this study. The research was conducted independently of any affiliations or commercial entities that could benefit from the findings.

AUTHORS’ CONTRIBUTIONS

Conceptualization, Irfan Eko Budiyanto and Sinta Uri El Hakim; methodology, Irfan Eko Budiyanto; software, Irfan Eko Budiyanto; validation, Irfan Eko Budiyanto and Sinta Uri El Hakim; formal analysis, Irfan Eko Budiyanto; investigation, Irfan Eko Budiyanto; resources, Irfan Eko Budiyanto; data curation, Irfan Eko Budiyanto; writing—original draft preparation, Irfan Eko Budiyanto; writing—reviewing and editing, Irfan Eko Budiyanto and Sinta Uri El Hakim; visualization, Irfan Eko Budiyanto; project administration, Irfan Eko Budiyanto.

REFERENCES

[1] Kementrian Energi dan Sumber Daya Mineral, “Rencana Usaha Penyediaan Tenaga Listrik PT Perusahaan Listrik Negara (Persero) Tahun 2021 sampai dengan Tahun 2030,” PT Perusahaan Listrik Negara (Persero), 2021.

[2] S. Xu *et al.*, “Repowering coal power in China by nuclear energy—Implementation strategy and potential,” *Energies*, vol. 15, no. 3, pp. 1–27, Feb. 2022, doi: 10.3390/en15031072.

[3] W. Kosman and A. Rusin, “The application of molten salt energy storage to advance the transition from coal to green energy power systems,” *Energies*, vol. 13, no. 9, pp. 1–18, May 2020, doi: 10.3390/en13092222.

[4] V. Kindra *et al.*, "Thermodynamic analysis and comparison of power cycles for small modular reactors," *Energies*, vol. 17, no. 7, pp. 1–22, Apr. 2024, doi: 10.3390/en17071650.

[5] M. Dudek, M. Jaszczur, and Z. Kolenda, "Thermodynamic analysis of modular high-temperature nuclear reactor coupled with the steam cycle for power generation," *Arch. Thermodyn.*, vol. 40, no. 4, pp. 49–66, Dec. 2019, doi: 10.24425/ather.2019.130007.

[6] Ł. Bartela *et al.*, "Repowering a coal power unit with small modular reactors and thermal energy storage," *Energies*, vol. 15, no. 16, pp. 1–28, Aug. 2022, doi: 10.3390/en15165830.

[7] H. Łukowicz, Ł. Bartela, P. Gładysz, and S. Qvist, "Repowering a coal power plant steam cycle using modular light-water reactor technology," *Energies*, vol. 16, no. 7, pp. 1–25, Apr. 2023, doi: 10.3390/en16073083.

[8] Ł. Bartela *et al.*, "Techno-economic assessment of coal-fired power unit decarbonization retrofit with KP-FHR small modular reactors," *Energies*, vol. 14, no. 9, pp. 1–25, May 2021, doi: 10.3390/en14092557.

[9] K. Prantikos, S. Chatzidakis, L.H. Tsoukalas, & A. Heifetz, "Physics-informed neural network with transfer learning (TL-PINN) based on domain similarity measure for prediction of nuclear reactor transients," *Sci. Rep.*, vol. 13, pp. 1–13, Oct. 2023, doi: 10.1038/s41598-023-43325-1.

[10] X. Chen and A. Ray, "On singular perturbation of neutron point kinetics in the dynamic model of a pwr nuclear power plant," *Sci*, vol. 2, no. 2, pp. 1–10, Jun. 2020, doi: 10.3390/sci2020030.

[11] J. Li, "Computational perturbation methods for moderator and doppler temperature coefficients in the european pressurised reactor core analysis," in *2020 Int. Conf. Comput. Electron. Commun. Eng. (iCCECE)*, 2020, pp. 201–204, doi: 10.1109/iccece49321.2020.9231053.

[12] Z. Zhang *et al.*, "Current status and technical description of Chinese 2 × 250 MWth HTR-PM demonstration plant," *Nucl. Eng. Des.*, vol. 239, no. 7, pp. 1212–1219, Jul. 2009, doi: 10.1016/j.nucengdes.2009.02.023.

[13] Z. Chen, Y. Wang, and Y. Zheng, "Discussion on the accident behavior and accident management of the HTGR," *Nucl. Eng. Des.*, vol. 360, pp. 1–11, Apr. 2020, doi: 10.1016/j.nucengdes.2019.110497.

[14] International Atomic Energy Agency, "Advances in small modular reactor technology development. A supplement to: IAEA advance reactor information system (ARIS) 2022 edition." Access date: 18-Sep-2024. [Online]. Available: https://aris.iaea.org/publications/SMR_booklet_2022.pdf

[15] P. Bhatnagar, S. Siddiqui, I. Sreedhar, and R. Parameshwaran, "Molten salts: Potential candidates for thermal energy storage applications," *Int. J. Energy Res.*, vol. 46, no. 13, pp. 17755–17785, Jul. 2022, doi: 10.1002/er.8441.

[16] W.N.A.W. Muhammad, M.N.A. Mohamad, and M.F. Tukimon, "Characterization and heat transfer performance of quarternary nitrate based molten salts," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 97, no. 1, p. 35–46, Sep. 2022, doi: 10.37934/arfmts.97.1.3546.

[17] P. Pei *et al.*, "Two new chloride eutectic mixtures and their thermo-physical properties for high temperature thermal energy storage," in *Int. Conf. Appl. Energy 2019*, 2019, pp. 1–5, doi: 10.46855/energy-proceedings-4058.

[18] J.M. Sala, "Thermal energy storage systems for cogeneration and trigeneration systems," in *Woodhead Publishing Series in Energy, Advances in Thermal Energy Storage Systems (Second Edition)*, Cambridge, United Kingdom: Woodhead Publishing, 2020.

[19] S.H. Ghazaie *et al.*, "On the use of advanced nuclear cogeneration plant integrated into latent heat storage for district heating," *Sustain. Energy Technol. Assess.*, vol. 50, pp. 1–14, Mar. 2022, doi: 10.1016/j.seta.2021.101838.

[20] S. Liu, X. Gu, S. Yang, and Y. Qian, "Can green hydrogen and waste heat utilization improve energy conservation and emission reduction of coal-based cogeneration processes?," *J. Clean. Prod.*, vol. 389, pp. 1–12, Feb. 2023, doi: 10.1016/j.jclepro.2023.136045.

[21] G. Min, S. Choi, and J. Hong, "A review of solid oxide steam-electrolysis cell systems: Thermodynamics and thermal integration," *Appl. Energy*, vol. 328, pp. 1–26, Dec. 2022, doi: 10.1016/j.apenergy.2022.120145.

[22] Z. Dong, Z. Zhang, Y. Dong, and X. Huang, "Cascaded HTGR power-level control only by regulating primary helium flow rate," *IEEE Trans. Nucl. Sci.*, vol. 67, no. 8, pp. 1780-1790, Aug. 2020, doi: 10.1109/tns.2020.2995704.

[23] K. Singh, I. Rampall, and J. Rajkumar, "On the thermal-hydraulic essentials of the Holtec inherently safe modular underground reactor (HI-SMUR) system," in *Proc. ASME 2011 Small Modul. React. Symp.*, 2011, pp. 95-106, doi: 10.1115/SMR2011-6633.

[24] S. Mahmoudinezhad, M. Sadi, H. Ghiasirad, and A. Arabkoohsar, "A comprehensive review on the current technologies and recent developments in high-temperature heat exchangers," *Renew. Sustain. Energy Rev.*, vol. 183, pp. 1–16, Sep. 2023, doi: 10.1016/j.rser.2023.113467.

[25] A. Barakat and B. Sun, "Enhanced convective heat transfer in new triply periodic minimal surface structures: Numerical and experimental investigation," *Int. J. Heat Mass Transf.*, vol. 227, pp. 1–12, Aug. 2024, doi: 10.1016/j.ijheatmasstransfer.2024.125538.

[26] S. Muthukrishnan *et al.*, "Support vector machine for modelling and simulation of heat exchangers," *Therm. Sci.*, vol. 24, no. 1, pp. 499–503, 2020, doi: 10.2298/tsci190419398m.

[27] S. Ray, "Steam turbine development for small modular reactors," in *Proc. ASME Turbo Expo 2023, Turbomach. Tech. Conf. Expo.*, 2023, pp. 1–6, doi: 10.1115/gt2023-103401.

[28] S. Hong, C.J.A. Bradshaw, and B.W. Brook, "Global zero-carbon energy pathways using viable mixes of nuclear and renewables," *Appl. Energy*, vol. 143, pp. 451–459, Apr. 2015, doi: 10.1016/j.apenergy.2015.01.006.

[29] Nuclear Energy Agency, "Small modular reactors: Challenges and opportunities, nuclear technology development and economics." Access date: 18-Sep-2024. [Online]. Available: https://www.oecd-nea.org/upload/docs/application/pdf/2021-03/7560_smr_report.pdf