

Dynamic System Modeling and Hydrogen Co-generation Analysis of Nuclear Integrated Energy System for Saemangeum Energy Cluster

Hyung-Seok Lim ^a, Joo Hyung Seo ^b, Ji Yong Kim ^{a*}

^a Department of Quantum System Engineering, Jeonbuk National University,
567 Baekje-daero, Jeonju, 54896, Republic of Korea

^b Department of Nuclear Engineering, Ulsan National Institute of Science and Technology,
50 UNIST-gil, Ulju-gun, Ulsan, 44919, Republic of Korea

*Corresponding author: jykimth@jbnu.ac.kr

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1. Introduction

Achieving carbon neutrality is one of the urgent and important issues of our time, and the need for the development of sustainable low-carbon emission sources continues to increase. Variable renewable energy (VRE) can be considered for a carbon-free solution. However, inherent intermittency and variability limit its practical utilization as a reliable energy source. Therefore, the integration of VRE with reliable and sustainable sources such as nuclear power is inevitable. As the share of VRE generation in the electrical grid increases, the variability of net load that nuclear power plants must serve also increases. This type of issue burdens nuclear power plants beyond conventional baseload operation mode and requires flexible load-following operation. Load-following in conventional nuclear power plants is achieved primarily by maneuvering the reactor power through control rod (CR) position adjustment [1]. The repeated adjustment of the reactor power using CR can pose the potential risk of fuel and structural material failure by thermal stress and threaten their long-term integrity [2]. Moreover, when the instantaneous grid demand exceeds the sum of the reactor output and the renewable generation, a supply deficiency arises, and grid stability deteriorates. Nuclear integrated energy systems (N-IES), which couple a nuclear system with various energy conversion and storage sub-systems, have been proposed to address these challenges [3]. Among the available non-electrical applications that can be integrated into an N-IES, hydrogen co-generation is most promising due to its ease of storage and transport, as well as its effectiveness as mean to accelerating the decarbonization of sector beyond the power generation, such as industry and transportation.

In this study, a nuclear integrated energy system that couples an innovative Small Modular Reactor (i-SMR) plant with a proton exchange membrane (PEM)-based hydrogen production-storage system is proposed. A dynamic system model for the proposed N-IES was developed using the OpenModelica language under the Dymola environment. The feasibility of the proposed system was analyzed using the developed dynamic system model for the Saemangeum energy industrial cluster.

2. Numerical Methods

2.1 Nuclear Integrated Energy System

An integrated energy system was designed by coupling an i-SMR with hydrogen production and storage systems. A schematic of the proposed system is shown in Fig. 1. The proposed N-IES consists of the reactor primary system, balance of plant (BOP), and PEM-based hydrogen sub-systems. The hydrogen system of the N-IES consists of an electrolyzer, a fuel cell, and a high-pressure hydrogen storage tank. The reference reactor model used in this study was the i-SMR currently under development in the Republic of Korea [4]. The standard i-SMR design consists of four 170 MWe reactor modules, corresponding to a total plant capacity of 680 MWe. The present N-IES incorporates two units of i-SMR plants, comprising eight modules with a total capacity of 1,360 MWe.

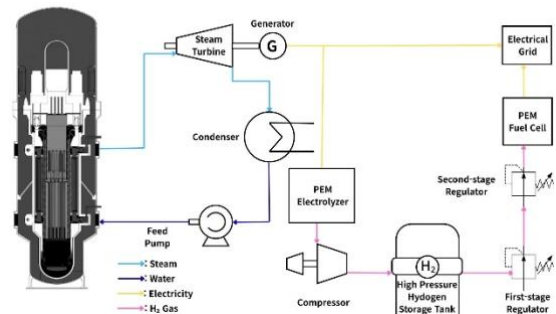


Fig. 1. Schematic diagram of the i-SMR based N-IES.

For the simplicity of the current analysis, the present system dynamic model only considers a single module out of the two i-SMR plant units. Therefore, the electrical demand was linearly scaled down to the one of eighth of its original value by assuming that all modules inside the proposed N-IES share the electrical load equally and exhibit identical system dynamics. This approach assumes that all reactor modules have identical specifications and are operated under a common control strategy [3, 4].

Electricity generated by the i-SMR module is primarily supplied to the regional grid, and any surplus is converted into hydrogen through the PEM electrolyzer.

The hydrogen produced is pressurized up to 70 MPa by a compressor and stored in the high-pressure hydrogen storage tank, from which it is supplied to the PEM fuel cell when the grid requires additional power beyond the rated power of the i-SMR plus instantaneous RVE generation. Both the PEM electrolyzer and fuel cell were modeled as low-temperature PEM systems operating at 80°C, and the storage tank is designed with a maximum capacity of 1,000 tons [5]. Hydrogen compression is performed in three stages to improve isothermal efficiency, while depressurization is similarly carried out in two stages [6].

2.2 Case study: Saemangeum Energy Cluster

The Saemangeum area, located in Jeonbuk State of the Republic of Korea, is currently undergoing an unprecedented industrial expansion. The Saemangeum National Industrial Complex has attracted large-scale manufacturing investments and is also regarded as a promising candidate site for hyperscale artificial intelligence (AI) data centers. Therefore, in the current study, the Saemangeum site was selected as the target of the feasibility case study.

The Saemangeum energy cluster considered in this study includes 2.8 GW of photovoltaic (PV) capacity, and the establishment of a green hydrogen production cluster at this site is also under active review. Since the site combines large-scale intermittent renewable generation with planned hydrogen production facilities, it represents a suitable case for evaluating the proposed N-IES. However, as the cluster has not yet been completed, a postulated grid scenario was established in this study based on the metering data for the Jeonbuk State region provided by the Korea Power Exchange (KPX). The PV generation data were scaled in proportion to the installed PV capacity of the Saemangeum area, and the planned 0.1 GW of wind power capacity was also included in the scenario. Consequently, the postulated scenario represents a renewable configuration in which PV accounts for approximately 96 % of the total installed capacity. The dynamic simulation was performed over a two-year period (17,520 h) with a one-hour time step.

3. Results and Discussion

Fig. 2 shows the accumulated hydrogen storage inventory over the 2-year hydrogen co-generation operation using the proposed N-IES in the Saemangeum energy cluster. The results indicate that the initial hydrogen inventory had dissipated and a closed seasonal cycle was established based on the annual electrical demands and VRE generation rate trends. It should be noted that all given values are on a per-module basis. The annual electrical energy consumed by the electrolyzer was 252.15 GWh, and the annual fuel cell generation was 78.47 GWh, yielding a round-trip efficiency of 31.1 % for the electrolyzer–fuel cell pathway. The round-trip efficiency further decreased to 29.8 % when we

considered the work consumed by the compressor (11.45 GWh). This implies that the losses along the storage-and-regeneration pathway are non-negligible, suggesting that direct utilization of the produced hydrogen is energetically more favorable than its use for re-electrification.

The annual hydrogen production per module was 4,696 tons, corresponding to 37,571 tons when scaled to the whole eight modules, which is approximately 2.68 times the production target of the Saemangeum green hydrogen cluster (14,000 t/year). The storage inventory fluctuated between 20.4 tons and 298.5 tons, forming a distinct seasonal cycle in which hydrogen accumulates during the summer (June–August) and is consumed throughout the remainder of the year. The peak inventory reached only 29.8 % of the 1,000 t design capacity, and the tank remained at its lower limit for 27.5 % of the year. The annual grid import was 173.96 GWh, corresponding to a self-sufficiency ratio of 90.36 %, while renewable curtailment was evaluated as 0.42 % of the available renewable generation. Although the electrolyzer consumed most of the surplus electricity and thereby minimized curtailment, the shortage issue during the winter was not fully resolved owing to the pronounced seasonality of the PV-dominated renewable configuration in this study.

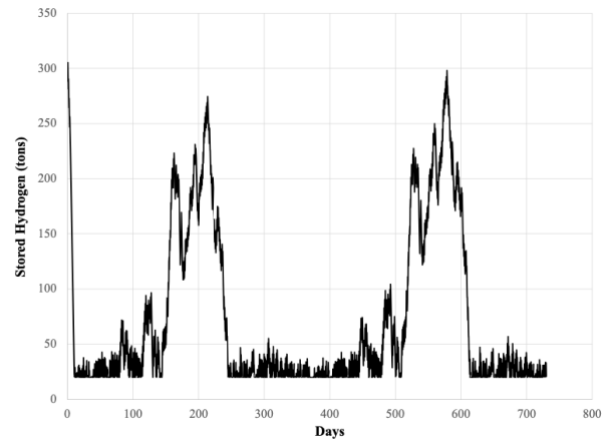


Fig. 2. Accumulated hydrogen mass behavior during the annual load following operation over two years

4. Conclusions

A dynamic system model of an i-SMR–based integrated energy system was developed using OpenModelica language in under Dymola environment. The hydrogen was utilized as interim energy storage medium for the IES systems. The feasibility of the proposed system was analyzed for Saemangeum energy cluster under postulated electrical grid demands and VRE generation scenarios. The results demonstrate that the hydrogen co-generation system integrated into the proposed IES effectively buffers the vulnerability and variability of renewable generation, limiting renewable curtailment to 0.42 % while maintaining the i-SMR at its rated power. The evaluated round-trip efficiency of the

storage-and-regeneration pathway for hydrogen was shown to be around 31.1 %, which indicates that utilization of the generated hydrogen as a final product is more effective than using it as a means for the re-electrification. The produced hydrogen can be used in various ways, such as feedstock for the chemical fertilizers required by the agricultural facilities planned within the Saemangeum energy cluster, or for external sale to realize the hydrogen economy. These applications are expected to mitigate the economic burden associated with the development and deployment of i-SMR.

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