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Development of Nuclear-Renewable Hybrid Energy System using Thermal Energy Storage for Industrial Processes

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1. Introduction

Geographically isolated areas are, in many cases, in shortage of electricity and thermal energy, especially in underdeveloped islands and extreme climate areas. These areas need to be provided with power and energy from the remote main energy sources, or independently equipped with power generation stations.

The Nuclear-Renewable Hybrid Energy System (NRHES), consisting of nuclear system and renewables, is considered to be one of the best solutions to meet specific regional needs and constraints for the isolated areas for energy independence. It compensates for the intermittency of the power generation by the wind and solar energy, providing stable nuclear energy without greenhouse gas emission. The efficiency of the nuclear system can also be improved if it continues power generation without changing the power level greatly and provides the excess energy to the industrial processes. This implies that the NRHES can enhance the efficiency of the power generation by balancing the generation of electricity and the utilization of thermal energy. The overview of the NRHES has been depicted by Idaho National Laboratory with its development program [1,2], and the application of thermal energy storage has also proposed by I. Saru, et al. [3,4,5].

In this paper, the operational scenarios according to the operation steps and weather conditions are established, and the procedure for sizing optimization of the components based on the amount of excess energy is proposed for the NRHES for an exemplary local grid.

2. Development of Nuclear-Renewable Hybrid Energy System

The conceptual design of the NRHES, consisting of small modular pressurized water reactor (SMR), solar photovoltaic power system, wind power system, thermal energy storage system, battery energy storage system, and industrial processes which need constant electric power and thermal energy, is being developed as shown in Fig. 1.

The parameters of the NRHES can be determined considering the bypass flow rate of the steam from the nuclear steam generator, the amount of thermal energy and the electric power for the industrial processes, and the capacity of the battery, as shown in Table 1.

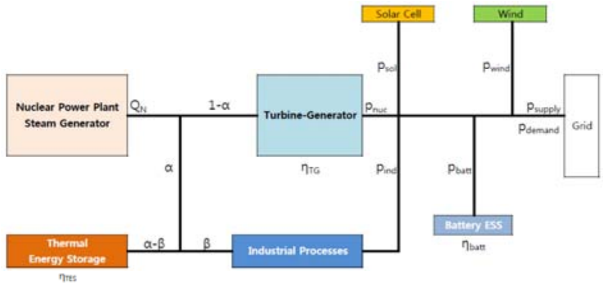


Fig. 1 Nuclear-Renewable Hybrid Energy System Conceptual Configuration

Table 1 Parameters of NRHES Process

Parameters	Description
α	Rate of Bypassed Steam
β	Rate of Bypassed Steam for Industrial Processes
P_{nuc}	Nuclear Power Generation
P_{sol}	Solar Power Generation
P_{wind}	Wind Power Generation
P_{batt}	Battery Energy stored
P_{ind}	Power for Industrial Processes
P_{mar}	Power Margin to Grid
P_{supply}	Grid Power Supply
P_{demand}	Grid Power Demand
Q_N	Nuclear Steam Thermal Energy
η_{TG}	Turbine Efficiency
η_{TES}	Efficiency for Thermal Storage
η_{batt}	Efficiency for Battery energy storage

The NRHES monitors the grid power demand for storing and reusing the excess energy, and determines the amount of the excess energy to industrial processes with optimized sizes of the components based on operational scenarios of the hybrid system as described in the following subsections.

2.1 Excess Energy Storage and Usage

The typical daily energy demand varies according to the time of day indicating that constant power generation system can have excess energy during the whole time of the day as shown in Fig. 2 (Total Generation = Nuclear (60 MWe) + Renewables (30 MWe at peak power generation), Excess Power = Total Generation – Grid Demand). The trend of Grid Demand in Fig. 2 is based on the data of Electric Power Statistics Information system (EPSIS) of Korea Power Exchange

(KPX)) and considers the yearly peak of the local grid. Fig. 2 shows that the amount of excess energy also varies according to the time of day if the NRHES is operated constantly considering the efficiency of the system and components.

The excess energy from the NRHES due to the difference between supply and demand can be stored in the thermal energy storage (TES) system, battery energy storage system (BESS), and chemical and/or mechanical energy storage systems.

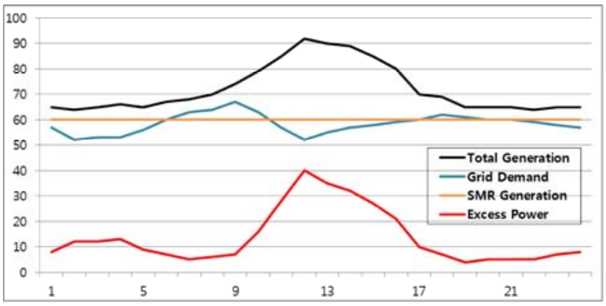


Fig. 2 Daily Power Generation, Demand, and Excess Power

The amount of excess thermal energy (ΔE) can be calculated by monitoring the grid demand and electricity generation by the virtual power plant consisting of nuclear turbine-generator, solar cell generator, and wind generator. The stored thermal energy can be used for the industrial processes as shown in Fig. 3. These can also be converted to electricity again using a dedicated auxiliary generator for the thermal energy storage system.

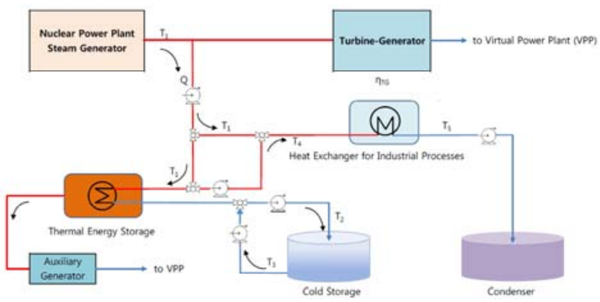


Fig. 3 Storing and Supplying Excess Thermal Energy for Industrial Processes

Various thermal energy storage systems are under development for heating and cooling applications [3,4]. Molten salt mixtures [5] of $Ca(NO_3)_2$, $NaNO_3$, KNO_3, $LiNO_3$, $NaNO_2$, etc., are widely being surveyed for thermal energy storage media with melting temperatures of 100℃ to 200℃ and maximum operating temperature of around 500℃. Optimal medium needs to be determined for the TES with high coefficient of heat transfer, high heat capacity, high density, and low operating pressure.

2.2 Operation of NRHES

The electricity demand of the target grid can be estimated, i.e., based on the present demand. This is the first priority supply by the NRHES, and excess energy from the NRHES is next calculated for the operation of the system.

If an industrial process is provided with constant thermal energy and electricity, the capacity of the thermal storage system and supply to the industrial process should be determined according to the profile of excess thermal energy based on the scenarios as shown in Fig. 4. The energy difference between the daily total excess energy (red) line and the constant supply to the industrial processes (dotted line) is stored in the thermal storage system, whereas the stored energy is released to the industrial process with the amount of the shortage between the supply to the industrial process and excess energy generated.

There can be three operational modes depending on the plant conditions and the amount of excess energy as follows:

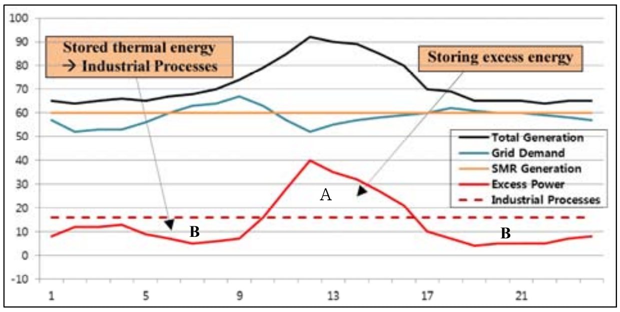
[Operational Mode-1: Initial Operation]
When the NRHES starts for operation initially or after shutdown, the energy storage medium in the thermal storage should be prepared for use to its operating temperature range. The solid salt, for example, will be heated to its melting temperature, and then raised to the operating temperature by the steam from the nuclear steam generator. The battery will be charged by the virtual power plant through the power conversion system converting the alternate current from the nuclear and wind power into direct current for the battery charging. Stable operation of the NRHES for the grid will be followed after all the storage systems are fully charged.

[Operational Mode -2: Stable Operation]
Daily grid demand changes during the time of the day as represented in Fig. 4(a). The amount of thermal energy to be supplied to the industrial processes can be determined by balancing the total amount of excess energy over for thermal energy storage and supply to the industrial processes. That is to say, the stored energy of the sum 'A' will be the same as the sum of 'B' in Fig. 4(a). Thermal energy will be discharged from the TES while the amount of thermal energy to be supplied for the industrial processes is more than the excess energy (area 'B' in Fig. 4(a)). The amount of thermal energy stored and supplied for industrial processes will be

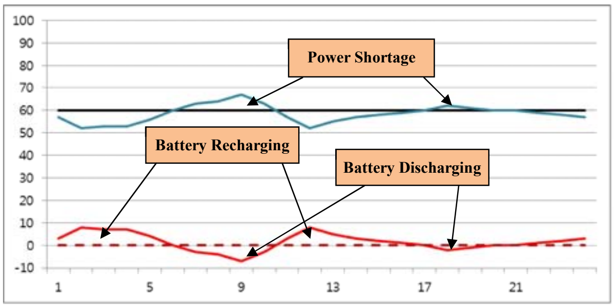
reduced when the wind and solar energy produced is reduced due to the weather conditions.

[Operational Mode -3: Battery Back-up Operation]

Battery will back up the grid demand when there is no power production by the renewables (Power Shortage in Fig. 4(b)). No thermal energy will be supplied to the industrial processes during this operation. Battery will be discharged while the grid demand exceeds nuclear power generation or recharged when grid demand decreases below the nuclear power generation as described in Fig. 4(b).



(a) Nuclear and Renewable Power Generation



(b) Nuclear Power Generation without Renewables

Fig. 4 NRHES Operational Scenarios

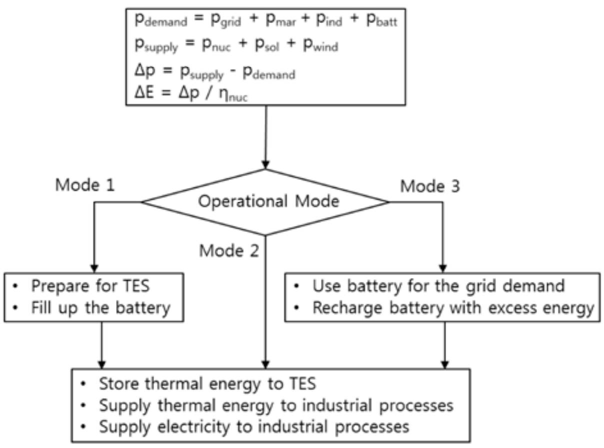


Fig. 5 NRHES Operational Flow for Operational Modes

Fig. 5 shows the operational flow of the NRHES for monitoring the grid demand and controlling the energy supply to the grid, battery ESS, thermal ESS, and industrial processes for each of the operational modes.

2.3 Industrial Application of Excess Energy

The excess thermal energy from the NRHES can be supplied to the industrial processes, with the steam temperature ranges from 40 ℃ to 275 ℃, for hydrogen production, ammonia production, district heating, seawater desalination, and so on. The thermal energy can be supplied from the nuclear steam generator and/or thermal energy storage. The amount of thermal energy supplied to the industrial processes can be maintained constant using the TES which would have optimized size for economy and efficiency of the system and components of the industrial processes. Detailed application of the thermal energy of the NRHES to the industrial processes is to be studied incorporating the state of the art for specific technology.

2.4 Sizing Optimization

The electric capacity of the proposed NRHES is assumed totally 90 MWe consisting of 60 MWe of SMR with 200 MWt, and 30 MWe of renewable power generation by solar and wind. The size of the thermal energy storage can be determined by equating the amount of excess thermal energy to be stored and that of energy to be supplied to the industrial processes such as hydrogen production. The heat capacity and energy density will also be considered for the physical sizing of the thermal tank and flow rate to the industrial processes. The amount of thermal energy for the industrial energy can also be determined by equating the total amount of excess energy above the dotted line to that below the dotted line in Fig. 4(a). The capacity of the battery storage will be determined for backing-up the grid demand while there is no electricity generation by renewables. This is to restrict the role of the battery to emergency back-up and frequency control of the grid. Fig. 4(a) shows the time of battery back-up occurs between around 6 AM to 10 AM, which will be used for the battery sizing. The power shortage can be backed up by the battery ESS with the capacity of 10 MWh and the auxiliary generator using the thermal energy stored in the TES as needed.

The trends, peaks, and lowest points of daily, weekly, and monthly energy generation by renewables should be considered to optimize the capacities of the NRHES components and the amount of energy to be supplied to the industrial processes. The evaluation of the system in viewpoints of efficiency and economy will be performed during the detailed development of the system in terms of Levelized Cost of Energy which will incorporate not only the electricity generation but also the excess thermal energy utilization to be produced by the NRHES.

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Table 2 shows the exemplary sizes of the NRHES components based on the method described in the Operational Mode-2 for maximum capacity of the TES.

Table 2 Sizing of NRHES Components

Elements	Requirements
Output from nuclear system	200 MWt(60 MWe)
Renewable Power Generation	30 MWe
Nuclear Output Variation	16~ 60 MWe
Thermal Energy System Capacity	450 MWh/t
Battery ESS Capacity	10 MWh/e
Supply to Industrial Processes	~ 54 MWt, ~ 1 MWe

3. Conclusion

The hybrid energy systems consisting of the SMR and renewable power generation system can produce electricity without emitting greenhouse gas by being equipped with thermal energy storage system and supplying the excess thermal energy to the industrial processes. The instability of the nuclear reactor operation due to the need to cope with the abrupt changes of the grid demand can be avoided compensating for the intermittency of power generation by the renewables. The sizes of thermal energy storage and the amount of energy supply to the industrial processes can be determined considering the amount of excess energy changing according to the weather conditions, the time of the day, and the operational conditions of the NRHES.

Further research and development are required for the stable and optimal supply of the excess energy to the industrial processes, e.g., hydrogen and/or ammonia production, district heating, seawater desalination. The technologies for energy demand and supply control are under development to incorporate into the variable power generation of electricity and thermal energy. The thermal energy storage system needs to be designed in detail including the medium for energy storage and reconversion process of the stored energy into the power for the industrial processes and/or the grid demand. Technologies for the generation, storage, and transportation of energy carriers such as hydrogen and ammonia need to be developed to meet the industrial requirements of the local areas.

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