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Review on Integration of Energy Storage System to Nuclear-Renewable Hybrid Energy System

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1. Introduction

Nuclear energy plants have traditionally operated as baseload units for the electric grid, meaning that these plants typically operate at constant power without significant output variations. However, the recent increases in renewable generation in many regions requires the flexible operation of nuclear power plants. Because the output from renewable generators is highly variable and with limited predictability, the electric system has to retain the spinning/non-spinning reserves and supplement facilities. A nuclear power plant may be operated in a load-following mode, meaning that its power output can be changed according to the electricity demand adaptably. However, such operation could reduce the economic competitiveness of the nuclear plant. Alternately, one might utilize process heat from the nuclear plant to support industrial applications by diverting the steam flow from the power conversion system to the coupled industry. However, a decision to operate the plant in this alternate mode requires complex economy/policy-related market analysis, plant design optimization and infrastructure investment.

A thermal Energy Storage System (ESS) could be utilized as a buffer to smooth the fluctuation of electricity demands and renewable generation. First, ESS can be used for Energy Arbitrage, in which the energy is stored when the prices are low and discharged at times of high demand. Second, ESS can be used to provide stable energy supply in short-term (e.g., frequency or voltage regulation) and long-term (e.g., spinning/non-spinning and supplemental reserves). Third, the stored energy can be sold to produce goods and services other than electricity when this is the preferred economic choice; this practice refers to Energy Storage Proxy. All of these operating modes can support the grid need for flexible generation while providing revenue to the nuclear power plant and integrated energy system.

The integration of ESS into Nuclear-Renewable Energy System (NRHES) is actively being investigated in the U.S. and elsewhere. In the current study, NRHES and thermal energy storage technologies are briefly reviewed. Then, as an introduction to leading research activities in this topic area, the thermal energy storage system currently being investigated at the U.S. Department of Energy Idaho National Laboratory (INL) is presented.

2. Nuclear-Renewable Hybrid Energy System

NRHES is a conceptual system that integrates multiple generators (e.g. nuclear, fossil, renewables), energy storage, electricity generation, and industrial customers [1]. Interest in this concept has primarily emerged due to environmental concerns. Global climate change has been identified as an international issue, with many countries agreeing to reduce their respective greenhouse gas (GHG) emissions. Renewable energy has been promoted as a carbon-free source, resulting in increasing penetration in the electricity generation sector that is boosted by both political support and technical improvements. However, in many instances renewables are partnered with fossil generation (coal and natural gas) to manage renewable variability, but this misses the carbon-free energy supply target. As seen in Fig. 1, the renewable share in Germany has increased from approximately 11% in 2005 to 47% in 2019, but the GHG emissions in Germany have been reduced by only 12.78% in the same time frame.

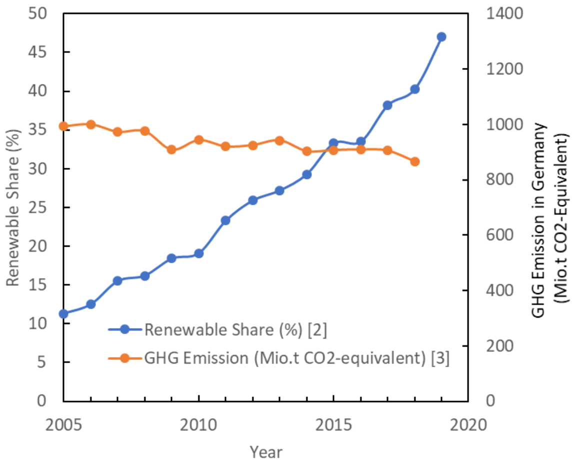

Fig. 1. Renewable Shares and GHG Emission in Germany [2, 3]

The combination of nuclear and renewable generators would provide an improved solution for reliable carbon-free energy supply; however, there are still challenging issues to be resolved to ensure stable and sustainable energy supply. Among them, intermittency of renewables may the most challenging issue. Due to highly variable and mostly unpredictable output from renewables (with the exception of the daily solar cycle, which can be impacted by cloud cover), dispatchable energy sources must be provided as supplemental reserves, which can significantly burden both investors and utilities. Although nuclear power plants produce little emission, the demand for flexible operation could generate technical operation and maintenance challenges and economic impact due to reduced revenue to the plant. To relieve the flexibility demands and make the best use of nuclear power plants, two options have been considered in NRHES (see Fig. 2).

First, the process heat from nuclear reactors can be applied to industrial facilities when electricity demand is low. Candidate process heat applications could include seawater desalination, petroleum refining, hydrogen production, and coal gasification; lower temperature heat application could include district heating. Considerations for process integration include reactor inlet/outlet temperature, working fluid, operating pressure, and heat capacity [4], as well as regional industries and needs. Additionally plant design modifications may be required and design optimization conducted; license amendments may also be needed. In particular, multi-module Small Modular Reactor (SMR) plants may be suitable to achieve load following by modulating output. In a multi-module system, each reactor module of the nuclear reactor can be operated at 100% power. Rather than reducing the plant load as electricity demand varies the output could be distributed to various industrial customers to produce valuable products.

Second, energy storage can be integrated to enhance the revenue of nuclear power plant operation. There are several types of an energy storage systems including thermal storage (sensible and latent heat), mechanical storage (pumped hydro, flywheel, compressed air), chemical storage (hydrogen and batteries) and electrical storage (capacitor and electromagnetic conductor). In general, electrical storage is more expensive than other storage types and is limited in storage duration. Thermal storage is particularly suitable for nuclear integration due to its relative low cost and high round-trip efficiency [5].

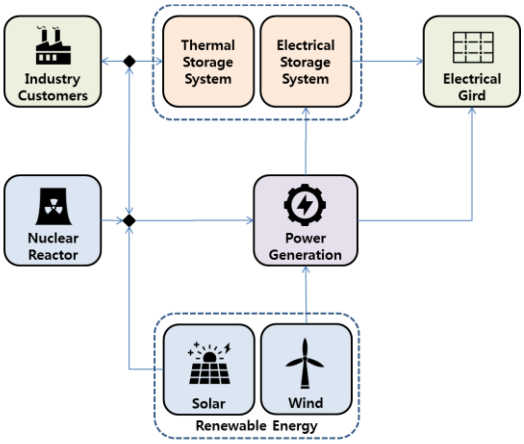

Fig. 2. Example Schematic of Nuclear-Renewable Hybrid Energy System

3. Thermal Energy Storage Systems

Thermal energy storage (TES) systems are designed to store heat or cold for later use to overcome the mismatch between energy generation and use. There are three primary types of TES: sensible heat storage, latent heat storage and thermochemical storage.

Sensible heat storage stores energy by increasing or decreasing the temperature of the storage material. Candidate materials should have high thermal capacity. Typical materials used in sensible heat storage have a volumetric thermal capacity ranging from 1.28 to 4.17 $MJ/m^3{\cdot}K$ [6]. Water, thermal oils and molten salts are suitable for sensible heat storage. In particular, molten salts are adequate for high-temperature applications above temperature limits of the other materials (400 ℃ for thermal oils and 342 ℃ for water at 150 bar).

Latent heat storage uses the phase change of a material – specifically melting and solidification. The best known and used phase change material (PCM) is water. In general, the energy storage density of latent heat storage is much higher than the sensible heat storage. Latent heat storage offers higher storage capacity up to 250 kWh/t with efficiencies from 75 to 90% meanwhile the sensible heat storage offers a storage capacity ranging from 10 to 100 kWh/t with storage efficiencies between 50 and 90% depending on the storage materials and thermal insulation technologies [7]. Although many materials have been studied for PCM, only a few of them have been commercialized [8, 9] due to various problems such as phase separation, corrosion, long-term stability and low heat conductivity.

Thermochemical energy storage systems store energy through an endothermic reaction that converts thermal energy to chemical bond energy. An exothermic reaction is used to release the stored energy. Thermochemical storage can offer the highest storage density among the aforementioned storage systems. Promising thermochemical materials (TCMs) such as $MgSO_4{\cdot}7H_2O$, $FeCO_3$, $Ca(OH)_2$, $Fe(OH)_2$, and $CaCO_3$ can provide very high energy storage density ranging from 1.4 to 3.3 GJ/m^3 [10], compared with less than 0.1 MJ/m^3 for sensible heat storage and 0.3 to 1.5 GJ/m^3 for latent heat storage [9]. However, thermochemical TES systems are not yet commercial and require research and development (R&D) to improve understanding of their performance and implementation and to find the best thermochemical material.

Figure 3 shows the volumetric storage capacities of PCM and TCM compared to water. Although the latent heat and thermochemical storage could offer higher storage capacity than the sensible heat storage, the sensible heat storage using molten salt and thermal oil is currently used for the large-scale thermal storage of the concentrated solar power (CSP) plants. The benefit of molten salt based thermal storage is that the high temperature heat can be provided directly to the industrial customers without additional heating. The energy produced from primary sources is converted to electricity to deliver it to the customer, but this process accompanies the significant energy conversion loss. For the high-temperature applications, the direct supply of high-temperature heat could be more economical. However, it should be noted that a direct supply of thermal energy could be limited by the distance between the energy source, storage and customers [12], whereas the transmission loss of electricity would be much lower than that of thermal energy. Hence, when developing an integrated energy system with thermal storage, the thermal loss to the environment and the hydraulic loss of heat transfer liquids need to be considered.

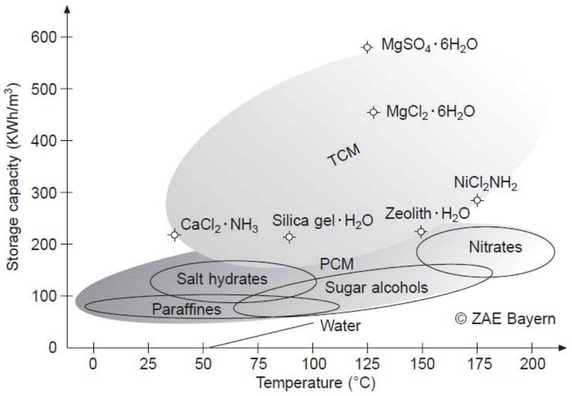

Fig. 3. Comparison of storage capacities of PCMs and TCMs compared to water [11]

5. Thermal Energy Storage R&D at INL

Coupling of thermal energy storage devices with nuclear power generation unit has been studied at Idaho National Laboratory (INL) in the U.S Department of Energy Office of Nuclear Energy Integrated Energy Systems Program (formerly Nuclear-Renewable Hybrid Energy Systems) [13]. INL has recently designed and will build a Dynamic Energy Transport and Integration Laboratory (DETAIL) for installation within INL's Energy Systems Laboratory (ESL). A high-level schematic of DETAIL is shown in Fig. 4.

The primary objective of DETAIL is to demonstrate the dynamic behavior of Integrated Energy System (IES), including simultaneous, coordinated, and efficient 'transient' distribution of electricity and heat. As such, several energy system simulators for power generation, energy storage, and industrial heat end users are included or planned for interconnecteion within DETAIL. DETAIL will be a first-of-kind experimental facility to support understanding and demonstrating dynamic behavior of IES. For example, the real-time integration with electrical grid, renewable energy inputs, thermal and electric energy storage, and energy delivery to an end user, etc. can be tested to improve our understanding of how to optimize energy flows while maintaining overall system stability and operational efficiency of all assets in the system.

A Thermal Energy Distribution System (TEDS) is the backbone thermal loop of the DETAIL facility through which energy (heat) can be delivered from system to system. As of 2019, INL has completed TEDS design and is currently pursuing its construction. TEDS is designed by carefully taking into account overall system configurability, controllability, and measurability. TEDS includes a packed-bed thermocline tank as a thermal energy storage option. The packed-bed single thermocline tank was chosen due to its potential value of cost reduction for storing thermal energy relative to other storage options. Also, in order to determine the optimal design of a packed-bed thermal storage tank with a target storage capacity (200 kWh), thermal modeling and analysis has been performed. For example, in the TEDS loop, relevant design parameters for the packed-bed thermocline tank, such as tank shape (aspect ratio) and filler size, have been determined via parametric numerical study [14]. In particular, exergy efficiency and tank utilization rate have been evaluated for various design parameter values under various operational conditions with charging and discharging modes and, based on that, the final design of the packed-bed thermocline tank was determined. Fig. 5 illustrates the fundamental operational modes (i.e., charging and discharging) for the packed bed thermocline tank and shows an example of the design parametric study.

5. Conclusion

Concerns on global climate change and energy security are transforming the conventional energy systems to potential Hybrid Energy Systems with increased penetration of renewable energy. Nuclear-Renewable Hybrid Energy Systems would be a suitable configuration to meet future environmental, political, and economic demands. For the successful deployment of NRHES, proper coupling with advanced non-nuclear system/component is critical in addition to enhancement of nuclear energy technologies. Integration of SMRs in an NRHES configuration is a valuable R&D topic to optimize the configuration of the hybrid energy system. Thermal storage systems may also be well-suited for NRHES and are actively being studied all over the world. Collaboration with other international researchers in this growing area for energy system R&D is essential to securing a reliable, resilient and sustainable energy systems in the future.

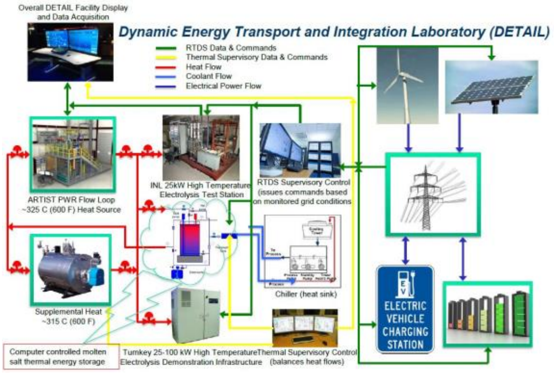

Fig. 4. Illustration of Dynamic Energy Transport and Integration Laboratory (DETAIL) [13]

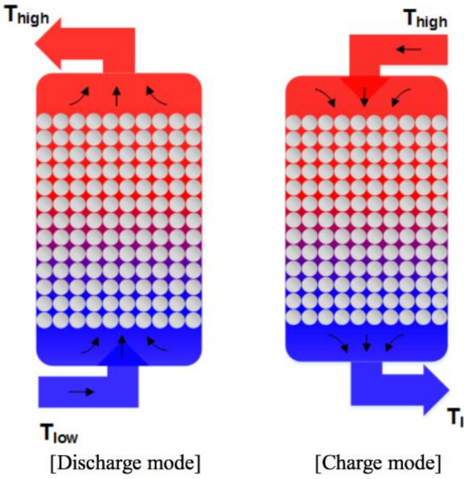

Fig. 5. Flow path of working fluid (heat delivery medium) through packed bed thermocline tank during discharge and charge modes [14]

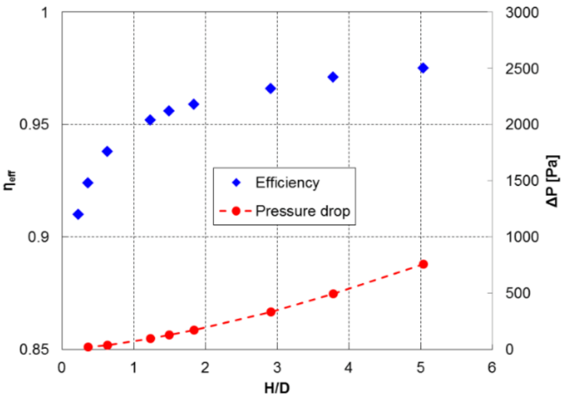

Fig. 6. Example of design parametric study for TEDS thermocline tank; effect of tank aspect ratio [14]

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