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An Evaluation of Strength and Weakness of Coupling Options for Nuclear-Renewable Hybrid Energy System

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1. Introduction

As nuclear power is responsible for more than 30 percent of total electricity generation in Korea, co-utilization of nuclear and renewable energy is garnering attention as a strategic carbon-free option in conjunction with the Korean government's pro-renewable stance. As such this co-utilization strategy is well poised to balance, enhance, and complement those two technologies, providing reliable supplies of electricity. From this perspective, a Nuclear-Renewable Hybrid Energy System (NHES) is a potential game-changer for Korea's evolving electricity grids that are aimed at balancing the intermittency from renewables, while improving overall economics in the power sector.

2. Objectives

This study develops a decision support framework and conducts an expert survey to facilitate the user to determine which co-utilization strategy is most appropriate and whether it is properly implemented for its specific purpose. Considering a combined use of nuclear and renewable energy is an emerging technology and still at the conceptual design stage, top-down approaches offer limited coverage on the NHES because of their scant design descriptions. Subsequently, it becomes difficult to fully engage experts in details of the NHES project. To provide more accurate information for targeted co-utilization options, an expert survey was conducted on the Nuclear-Wind Hybrid Energy System for District Heating (NWHES) and Nuclear-PV-Demand Response (DR) Hybrid Energy System for an alternative ESS (Energy Storage System) (NPDHES) so that valuable insights could be gathered from experts, using a bottom-up approach in the form of case studies. More specifically, this bottom-up approach enables an appropriate depiction and assessment of the energy systems in the context of South Korea.

3. Methods and Results

3.1. Evaluation Framework for Nuclear-Renewable Co-utilization Systems

The ultimate goal of post-project assessment is to demonstrate the achievements of technology development and to identify areas for improvement. Toward this end, energy projects that require large-scale budgets call for systemically developed Figures of Merit (FOM) to properly measure and assess their multifaceted impacts. However, no solid consensus has yet been reached on what are the critical indicators to assess integrated nuclear-renewable energy systems. To this end, four criteria and their sub-detailed FOMs were constructed by reviewing the Yale Environmental Performance Index [1], UN Sustainable Development Goals [2], and the workshop report of Idaho National Laboratory [3] with a focus on the importance of sustainability, while maintaining relevance and suitability for the measurement.

The selected FOM set covers the four main criteria: 1) viability of business model, 2) environmental impact, 3) technology maturity, and 4) policy domain (see Table 1). To identify levels of agreement from experts on each questionnaire item in a coherent manner, the survey was carried out using the same scale, a five-point scale (see the detail in Appendix).

Table 1 Overview of the survey questionnaire: four criteria and their sub-detailed FOM

Viability of Business Model	Environmental Impact
• Process Heat Applications • Load-Following Service • Renewable Energy Integration	• Land and Water Impact • Emissions Produced During Operation • Hazardous Materials • Hazardous Fumes (Air quality) • Short-Term Safety Concerns
Technology Maturity	**Policy Domain**
• Technology Readiness Level (TRL) • Timeline for Construction	• Replacing Aging Fossil-fuel Infrastructure (Energy Security) • Licensing Certainty

3.2. Two coupling-options for a combined use of nuclear and renewable energy: NWHES and NPDHES

In this study, we propose and assess two coupling-options for a combined use of nuclear and renewable energy. General layouts for each nuclear-renewable coupling are as follows:

3.2.1. Nuclear-Wind Hybrid Energy System for District Heating (NWHES)

Accommodating massive levels of PV in the traditional power system will require a comprehensive understanding of potential challenges in net-load shape during the middle of the day due to its non-dispatchable nature. Thus, it is necessary for countries like the Republic of Korea to seek methods of harmonizing nuclear power with solar generation, which could be practically the only form of combination that can economically mitigate CO2 emissions. In this work, industrial demand response resources coupled with the nuclear power fleet are implemented to address variability and uncertainty from PV plants as an alternative form of energy storage. As a result, while PV outputs fluctuate, the electricity output at the end can be stable since DR resources attune themselves to PV power generation accordingly.

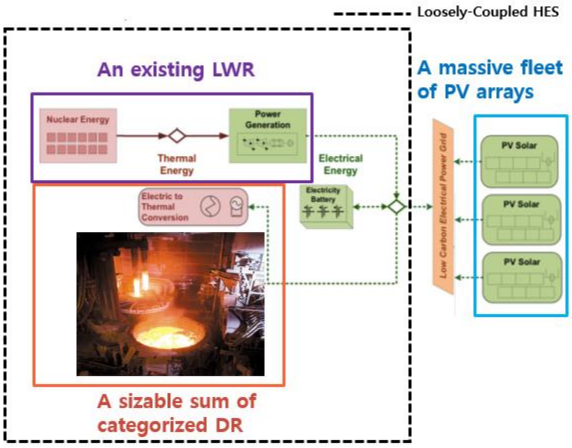

Figure 1 DR based electrically-coupled hybrid energy system topology[1]

3.2.1. Nuclear-PV-Demand Response Hybrid Energy System for an alternative ESS (NPDHES)

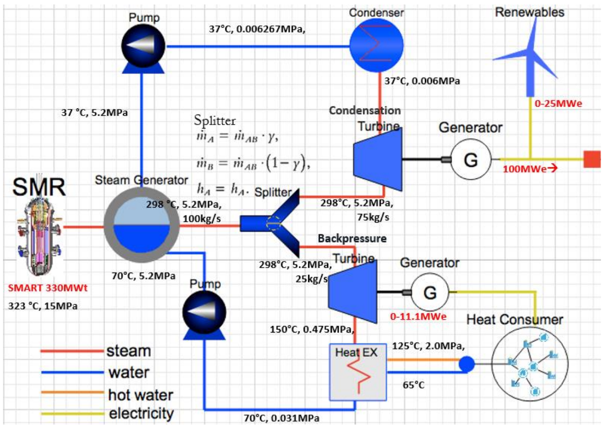

Figure 2 Nuclear-Wind Hybrid Energy system layout basically follows a Rankine cycle with a flexible thermal load

In 2016, Korea Electric Power Corporation (KEPCO) specified that renewables with capacities over 20MW must comply with technical regulations for maintaining power quality. In this regard, a Nuclear-Wind energy system coupled with district heating was proposed to balance the intermittency within the region where that intermittency occurs. This cogeneration system could increase thermal efficiency from 30% to >42% while mitigating the intermittency of a 25MW wind farm. Design parameters based on a SMART nuclear reactor (330MW-thermal, 100MW-eletric) developed in Korea were selected for this cogeneration concept.

3.3. Survey design and implementation

In the next phase of the survey, participants were meticulously selected in a two-step procedure to ensure the depth of opinions, as the strength of the survey depends on the expertise of those completing it. We first identified key experts through the NHES literature, workshop attendance roster, and conference proceedings. Those identified experts were classified into four groups so that each cohort comprised five to six experts represents the fields of nuclear engineering, renewable energy, system integration, and energy administration (including a regulatory body), respectively. Lastly, a cover letter with the online survey link (Google Forms) was delivered to the experts in November 2018 via email. To encourage experts' participation in the survey and elicit their honest, forthright, and candid answers, the survey was conducted anonymously.

3.4. Results

A total of twenty-five experts—thirteen from South Korea and twelve from the U.S.—were contacted, among which ten experts filled in the questionnaire. This resulted in a fairly remarkable response rate of 40%, indicating a heightened interest in Korea's energy issues. In relation to sampling bias, exclusion of particular fields among the aforementioned four groups was highly likely, because the survey did not ask to signify each respondent's primary area of expertise for the purpose of guaranteeing anonymity. However, we deliberately decided to assume that responses are unbiased and equally collected with respect to the respondent's area of expertise as this work is the first attempt to identify and quantify experts' perceptions of the HESs within the situation in Korea. We also posited that a standard deviation smaller than one herein only indicates an inherent trait of the survey itself and interpreted it as a divergence of opinion with no practical importance. Table 2 and Table 3 below give an overall picture of the estimated FOMs or two co-utilization options. The initial results lead to the following findings:

[1] Note: Figure is reconstructed from (Bragg-Sitton et al., 2016) [4]

Table 2 Respondents' assessment on the FOM for NWHES

	Viability of Business Model			Environmental Impact					Technology Maturity		Policy Domain	
ID	Process Heat Applications (District heating)	Load-Following Service	Renewable Energy Integration	Land and Water Impact	Emissions Produced During Operation	Hazardous Materials	Hazardous Fumes (Air quality)	Short-Term Safety Concerns	TRL	Timeline for construction	Replacing Aging Fossil-fuel Infra	Licensing Certainty
A	4	3	4	0	0	0	0	2	6	6-10 years	4	2
B	4	2	3	1	0	0	0	0	3	6-10 years	4	2
C	3	2	3	1	0	1	0	1	5	6-10 years	4	1
D	3	4	4	0	0	0	0	0	6	1-5 years	4	2
E	4	4	4	0	0	0	0	2	5	11-15 years	4	1
F	2	1	2	1	0	1	0	0	8	1-5 years	3	3
G	0	0	2	0	0	1	0	0	6	6-10 years	2	2
H	3	3	3	1	1	0	0	1	4	6-10 years	3	1
I	3	4	3	0	1	1	1	0	6	1-5 years	4	3
J	4	3	2	3	4	0	0	1	6	1-5 years	4	2
μ	3	2.6	**3**	**0.7**	**0.6**	**0.4**	**0.1**	0.7	5.5	N/A	**3.6**	1.9
σ	1.18	1.28	0.77	0.9	1.2	0.49	0.3	0.78	1.28	0.64	0.66	0.7

Table 3 Respondents' assessment on the FOM for NPDHES

	Viability of Business Model			Environmental Impact					Technology Maturity		Policy Domain	
ID	Process Heat Applications (Industrial DR)	Load-Following Service	Renewable Energy Integration	Land and Water Impact	Emissions Produced During Operation	Hazardous Materials	Hazardous Fumes (Air quality)	Short-Term Safety Concerns	TRL	Timeline for construction	Replacing Aging Fossil-fuel Infra	Licensing Certainty
A	3	4	3	1	0	0	0	1	7	6-10 years	3	3
B	4	2	3	1	0	0	0	1	3	6-10 years	4	2
C	3	3	2	3	2	1	2	1	6	6-10 years	4	1
D	3	4	4	0	0	1	0	0	6	1-5 years	4	2
E	4	4	3	1	1	1	1	1	7	1-5 years	2	4
F	3	0	2	2	0	1	0	0	6	6-10 years	2	1
G	3	3	4	2	1	3	1	1	9	6-10 years	4	2
H	1	3	3	1	1	0	0	1	4	6-10 years	3	1
I	3	4	3	1	1	1	1	0	6	1-5 years	4	3
J	3	4	2	2	3	1	0	0	5	6-10 years	4	2
μ	3	**3.1**	2.9	1.4	0.9	0.9	0.5	**0.6**	**5.9**	N/A	3.4	**2.1**
σ	0.77	1.22	0.7	0.8	0.94	0.83	0.67	0.49	1.58	0.46	0.8	0.94

Note: μ: average, σ: standard deviation.
See Appendix for details about rating scales and variables on survey questions.
Individual value highlighted in bold indicates the relative advantage of one technology over another.

3.4.1. Viability of Business Model

NWHES and NPDHES received the same rating of business opportunity in their process heat applications. But experts' evaluation of process heat applications on NWHES varied considerably compared to that of NPDHES. This result may be caused by uncertainty from a windfarm's intermittency. NPDHES was rated very positively due to its ability of load-following service. Experts seemed to value the economic potential of country-level DR, but still have reservations about its reliability and quality (see the standard deviation). NWHES was seen as slightly more effective than NPDHES in incorporating variable supply resource, and this underpins that dynamic steam bypassing technology could be an intuitive and efficacious method in addressing intermittency.

3.4.2. Environmental Impact

Both NWHES and NPDHES unanimously appear to be environmentally friendly sources of energy. More specifically, NWHES earned higher scores than NPDHES in most environmental FOMs. This finding may reflect that the reduced size of SMR is directly correlated with the betterment of environmental impacts. Overall, the experts predicted that NWHES and NPDHES would have a low safety risk, while giving a higher rating to NPDHES. One interpretation of this result is that many experts prefer the already established technologies.

3.4.3. Technology Maturity

NWHES was regarded as having further room for technological improvement. NPDHES shows far greater standard deviation of TRL than for any other FOMs. This may be due to the lack of specifications on NDPHES's sub-systems, such as technical characteristics of industrial DR.

3.4.4 Policy Domain

Most experts contended that both NWHES and NPDHES will bring substitution effects on aging fossil-fuel power plants. NWHES's relative advantage in this FOM reflects its prominent role of flexibility, and this might encroach on the share of LNG's potential as a backup. Experts tended to rate NPDHES to be in a slightly more advantageous position for licensing when compared with the existing nuclear power plants. This suggests that thermally-coupled nuclear-renewable models may need to be developed in such a way that they can ensure safety under both normal and off-normal conditions.

4. Conclusions

This study established a systematic tool of measurement for the integrated nuclear-renewable system and focused on how experts, encompassing nuclear engineering, renewable energy, system integration, and energy administration, rate NWHES and NPDHES. The advantages and disadvantages of these two NHESs were investigated through an expert-based survey as a way to identify the prospects for implementing co-utilization plans. The survey results highlight considerations regarding proper usage of proven subsystems or technology to enhance the viability of the NHES. The results also emphasize the tradeoffs between different parts of the energy system as well as co-synergies of interlocking energy sources.

Acknowledgments

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Appendix

Survey questionnaire:
https://goo.gl/forms/yDAdRCAtB2nCC4iK2