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Analysis of Economic Feasibility for Nuclear Renewable Hybrid Energy System

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1. Introduction

It has been recognized that the integration of nuclear and renewable energy sources has emerged to compensate the pros and cons of the energy sources while maintaining energy system stability and maximizing the economic benefits [1]. While there could be many factors to determine the future energy system portfolio (e.g., technological matureness, political concerns, public acceptance), the economic competitiveness would be the most important factor [2,3].

LCOE (Levelized Cost of Electricity) is a principal tool for representing a unit cost of the electricity generation over a lifetime of a facility or a plant [4]. Since the configuration of Nuclear Renewable Hybrid Energy Systems (NRHES) includes Energy Storage Systems (battery for short term storage and thermal energy storage for long term storage), to evaluate the economic feasibility, LCOE calculation considering ESS is necessary.

In this study, the economic feasibility of NRHES compared to HES has investigated. First, a software for calculating a LCOE for a hybrid energy system, Hybrid Energy-system Cost Optimization (HECO) has been developed. Secondly, the parametric analysis has been conducted for a preliminary NRHES configuration based on data in Ref. [2] and [4] and the influential factors for LCOE have been identified. Thirdly, the economic feasibility has been analyzed by assuming specific condition. The net load variations and differences between maximum and median net load have been examined and the insights for flexibility resources have been derived. The net load variation by base load rate was analyzed to construct electricity supply scenarios and the economic feasibility of each scenario was analyzed.

2. Economic Analysis Framework

2.1 LCOE Calculation [5]

Basically, LCOE would be calculated as follows:

$$LCOE = \frac{\Sigma_t \frac{(OM + F\&W + Tax)}{(1+r)^t} + TCC}{\Sigma_t \frac{E}{(1+r)^t}} \qquad (1)$$

where,
OM: Operation and Maintenance costs,
F&W: Fuel and Waste costs,
TCC: Total Construction Costs,
Tax: Corporate taxes,
r: Discount Rate,
E: Electricity output in MWh.

TCC can be calculated as follows:

$$\begin{aligned} TCC &= OCC + IDC \\ &= OCC + \Sigma_t (cx_t \cdot OCC) \cdot [(1+m)^t - 1] \qquad (2) \\ &\quad (t = lt, ..., 0) \end{aligned}$$

where,
OCC: Overnight Construction Cost,
IDC: Interests during Construction,
cx_t: Construction expenditures in month *t*,
m: monthly cost of capital during construction,
lt: month of construction.

The costs in Eq. (1) can be varied depending on the purpose of the analysis. In this study, the structure in Ref. [6] has been used, in which costs are categorized into 9 groups: 1) Capitalized Pre-Construction Costs, 2) Capitalized Direct Costs, 3) Capitalized Indirect Services Costs, 4) Capitalized Owner's Costs, 5) Capitalized Supplementary Costs, 6) Capitalized Financial Costs, 7) Annualized O&M Cost, 8) Annualized Fuel Cost, 9) Annualized Financial Cost [6].

2.2 LCOE Calculation Considering ESS [6]

LCOE of plant with ESS would be calculated as follows:

$$LCOE = \frac{\Sigma_t (C_{Plant} + C_{ESS})}{\Sigma_t E_{out,Plant} + E_{out,ESS}} \qquad (3)$$

where,
C: Cost
E: Electricity output in MWh

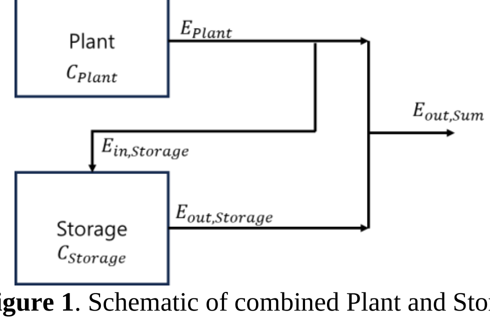

Figure 1. Schematic of combined Plant and Storage System

2.3 Development of HECO

To ease the LCOE calculation and support the sensitivity analysis, a simple program, Hybrid Energy System Cost Optimization (HECO) has been developed by C# language. Users can calculate the LCOEs simply by filling the boxes. Hybrid energy system can be configured by adding the energy generation plants and their types and penetration rates can be specified. The calculation data and outputs are written in the output files for further analysis and the sensitivity of cost parameters or hybrid energy system configurations can be investigated by varying the parameters. In **Figure 2** and **Figure 3**, the main display and the baseline calculation are presented, respectively. User can put inputs (e.g., project life, capacity, overnight construction cost, etc.) and LCOE calculated as a result would be presented in the right side of the display.

Figure 2. Main Display of HECO

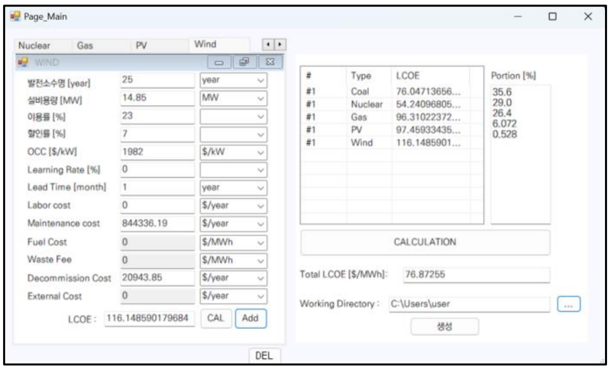

Figure 3. Calculation Display with Inputs and Outputs

3. Numerical Test

3.1 LCOE Calculation of each plant

LCOE has been calculated with IEA's Data in 2020 as shown in **Table I**. Note that the electricity generation rate of renewable energy such as wind and solar could not be predicted and controlled. Therefore, they should come with electricity storage devices (i.e., batteries). Therefore, the cost of electricity storage system (ESS) for renewable energy should be considered. The LCOE of Renewable Energy with battery whose storage rate is around 20% has been calculated with Ref.[4], [7] and Ref.[8] as shown in **Table II**.

Table I. Cost Data and LCOE Results

	Gas	**Coal**	**Nuclear (Conventional)**	**Nuclear (SMR)**	**PV**	**Wind**
Net Capacity [MW]	491	954	1377	100	0.1	14.85
Lifetimes [year]	30	40	60	60	25	25
Capacity factor (%)	85	85	85	90	15	23
Discount rate (%)	7	7	7	7	7	7
Construction Period [year]	3	4	7	3	1	1
OCC [USD/kW]	1,107	1,151	2,157	5,200	1,240	1,982
O&M [USD/MWh]	11.36	11.62	18.44	17.60	12.91	28.22
Carbon [USD/MWh]	10.8	23.6	-	-	-	-
Fuel [USD/MWh]	60.82	27.47	9.33	9.1	-	-
Decommission [USD/MWh]	0.07	0.03	0.03	-*	0.7	0.7
LCOE(HECO) [USD/MWh]	**96.31**	**76.05**	**54.24**	**78.93**	**97.46**	**116.15**

*Include to O&M

Table II. LCOE of Plant with ESS

	PV	Wind	SMR*
	Short Term		Long Term
Capacity (Plant/ESS)	Plant: 23 MW ESS: 10 MWx4hr	Plant: 14.85 MW ESS: 10 MW x 4hr	Plant: 100 MW x 2 ESS: 20 MW x 10hr
Round Trip Efficiency (%)	83	83	70
LCOE [$/MWh]	143.35	165.83	93.32

*Assume that the TES is used as electricity generation.

3.2 Sensitivity Analysis of Economic Parameters

○ Construction Cost

Construction cost could increase or decrease due to various causes, such as inflation rate, experiences/ technological maturity and the savings by process replications. According to the Ref.[9], the prices of construction materials have increased significantly; Fabricated Steal Plate by 54%, Carbon Steel Piping by 106%, Electrical Equipment by 25%, Fabricated Structural Steel by 70% and Copper Wire and Cable by 32%. However, according to the report of Korea Power Exchange (KPX), the construction cost would be reduced by 32% for PV and 12% for Wind in 2025 compared to 2020 (these cost reductions do not include the cost of battery) [4].

Figure 4 shows the effects of construction cost change to LCOE. For Coal and LNG plant, LCOE increases by less than 5% despite a 20% increase in construction cost. This is because the proportion of construction costs among the costs required for Coal and LNG power generation is low, as can be seen in **Table III**.

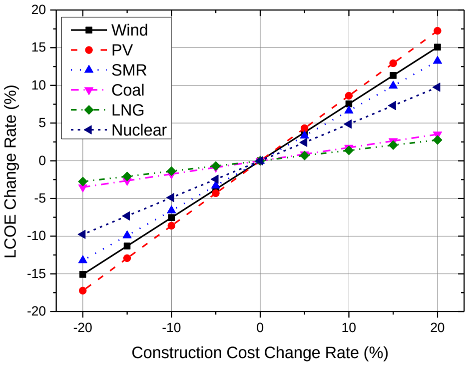

Figure 4. The effect of construction cost change to LCOE (x-axis: construction cost change rate, y-axis: LCOE change rate)

Table III. The Portion of TCC compared to Total costs

	TCC	NPV of Cost	Portion of TCC (%)
Gas	6.04E+08	4.37E+09	13.8
Coal	1.26E+09	7.20E+09	17.5
Nuclear (Conventional)	3.81E+09	7.81E+09	48.8
Nuclear (SMR)	5.78E+08	8.74E+08	66.1
PV	2.15E+05	2.36E+05	91.1
Wind	4.34E+07	5.33E+07	81.4

The 2020 - 2036 LCOE for each power source, estimated based on the past and future forecast data([3],[4],[10]), is shown in the **Table IV**. And based on the LCOE expectations, the LCOEs for hybrid energy system in 2020, 2030 and 2036 were compared without ESS in **Table V**.

Table IV. LCOE Expectation for Plants

[USD/MWh]	2020	2025	2030	2036
Gas	96.31	97.33	97.97	98.57
Coal	76.05	77.58	78.09	78.56
Nuclear (Conventional)	54.24	55.52	56.35	57.13
Nuclear (SMR)	78.93	81.65	83.79	85.87
SMR + ESS	93.32	95.57	98.06	100.08
Wind	116.15	105.64	102.14	98.16
Wind + ESS	165.83	160.05	156.44	152.32
PV	97.46	70.57	62.56	52.76
PV + ESS	143.35	115.52	107.23	97.08

Table V. LCOE Expectation for Hybrid Energy System [2]

	2020	2030	2036
Coal [%]	35.6	19.7	14.4
Gas [%]	26.4	22.9	9.3
Nuclear [%]	29.0	32.4	34.6
PV+Wind** [%]	6.6	21.6	30.6
Others*** [%]	2.4	3.4	11.1
LCOE w/o ESS [USD/MWh]	76.90	74.08	69.67

* Reference year of cost reduction is 2020. For 2030 and 2036, the cost reductions have been estimated with respect to 2020's LCOEs.
**Ratios of Generation Capacity of PV and Wind were 92:8 in 2021, and 66:34 in 2036
***Assume the LCOE for other generation is 106.70 USD/MWh which is the average LCOE for subsystems (e.g., coal, gas, nuclear, photovoltaic and wind).

○ Gas Price

The fuel cost of Gas is quite volatile. Since 2001, the highest price was 1265.6 USD/ton in 2022, and the lowest was 312.8 USD/ton in 2002 [11]. **Figure 5** shows the trend of fuel price and LCOE. Owing to large variations of Fuel Price, the LCOE for HES would be varied significantly as shown in **Table VI**. **Table VI** presents the LCOE based on the 2020s energy mix portfolio of Hybrid Energy System. To optimize the LCOE for Hybrid Energy System with assumption that the gas price is the highest, the scenarios are constructed by adjusting the portion of Hybrid Energy System.

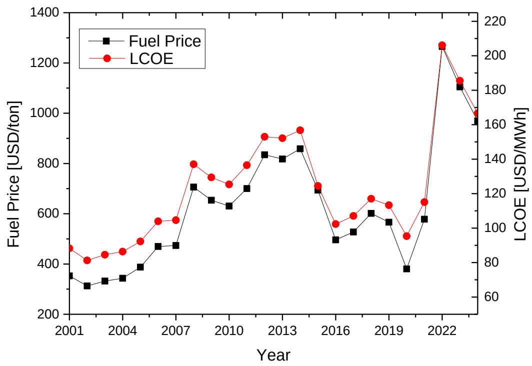

Figure 5. Fuel Price and LCOE of Gas (LNG) (1 USD = 1,200 KRW)

Table VI. Effect of Fuel Price to LCOE for Hybrid Energy System

Year	**LCOE for Gas**	**LCOE for Hybrid Energy System**
2014	156.77	93.15
2015	124.45	84.46
2016	102.34	78.52
2017	107.03	79.78
2018	117.05	82.47
2019	113.30	81.46
2020	95.35	76.64
2021	115.11	81.95
2022	206.09	106.41
2023	185.50	99.53

4. Economic Feasibility Analysis for Nuclear Renewable Hybrid Energy System

For consisting economically feasible NRHES, it has to be considered both the LCOE of each energy source and the variability of them. In **Figure 6 ~ 7**, the electricity demand range and net load range are presented, respectively. The demand and net load varied by up to 186.0 MW and 226.6 MW per unit hour, respectively. To maintain the electricity grid stable, it is needed to deal with the net load variation. NRHES can deal with significant differences of net load variation ESS or load-following.

Figure 8 ~ 10 present the electricity demand and the example of certain scenario; penetration rate of SMR 90% (Scenario 1), 80% (Scenario 2), 70% (Scenario 3). The net load of Scenario 1 ~ 3 were increased by up to 181.5 MW, 248.5 MW and 315.5 MW per unit hour, respectively, and decreased by up to 194.2 MW, 230.8 MW and 292.2 MW per unit hour, respectively.

According to the net load variation analysis of Scenarios, the size of ESS can be selected as 200 MW for scenario 1, 230 MW for scenario 2 and 300 MW for Scenario 3. With selected ESS size and 2036's LCOE expectation data in **Table IV**, the LCOEs of Scenario 1~3 are calculated and shown in **Table VII**. To compare these Scenarios with the 2036's HES configuration that in **Table V**, the net load variation and ESS size, and LCOE are calculated and shown in **Table VIII**. The net load was increased by up to 319.5 MW and decreased by up to 303.3 MW per unit hour.

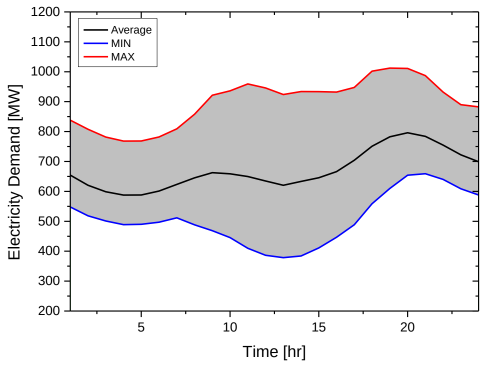

Figure 6. Maximum and Minimum Demand

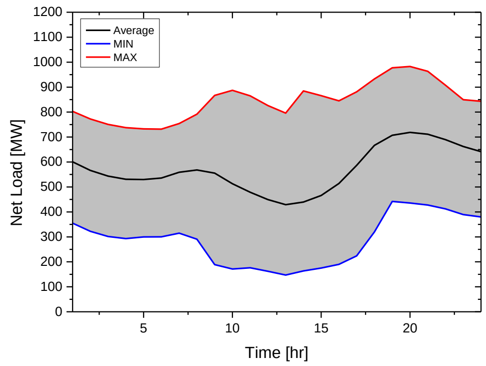

Figure 7. Maximum and Minimum Net Load

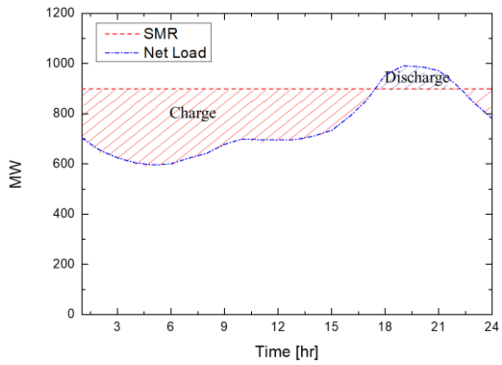

Figure 8. Electricity Supply Example of Scenario 1

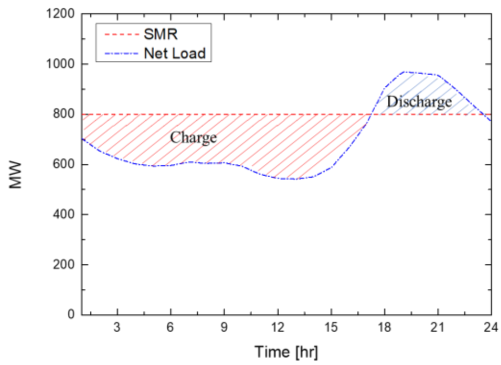

Figure 9. Electricity Supply Example of Scenario 2

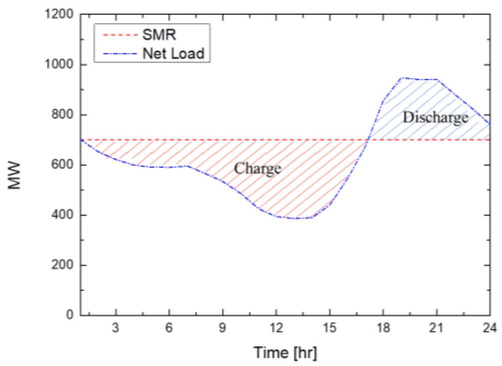

Figure 10. Electricity Supply Example of Scenario 3

Table VII. LCOEs Calculation of Scenario 1~3

	Scenario 1	Scenario 2	Scenario 3
SMR [MW]	900.0	800.0	700.0
PV [MW]	396.0	792.0	1,188.0
Wind [MW]	133.0	266.1	399.1
ESS [MW]*	200.0	230.0	300.0
LCOE [USD/MWh]	87.7	86.43	85.91

*Duration hour: 4hr

Table VIII. LCOE Calculation for HES

	2036
Coal [MW]	152.5
Gas [MW]	98.5
Nuclear [MW] (Conventional)	346.0
PV [MW]	1,211.8
Wind [MW]	407.1
Others [MW]	117.5
ESS [MW] *	300.0
LCOE [USD/MWh]	76.48

*Duration hour: 4hr

5. Conclusions

This study aims to 1) analyze the economic evaluation (LCOE) of HES, 2) calculate it based on domestic environmental conditions, and 3) analyze the economic feasibility of NRHES. This study identifies variables that significantly affect the economic feasibility from the perspective of HES and assesses their impact through sensitivity analysis. And also identifies the variability of renewable energy based on domestic environmental conditions (e.g. weather) and configure NRHES reflecting them.

As analyzed in Section 4, the penetration of renewable energy in both NRHES (Scenario 3) and HES (2036s in **Table V)** are assumed to be the same at 30%. However, the LCOE of NRHES is higher than that of HES. This discrepancy arises because the economic evaluation of NRHES was based on the cost of the relatively expensive Energy Storage System (ESS), specifically Battery Energy Storage Systems (BESS), under conservative assumptions. Since the cost of ESS is quite higher, the LCOE of the system could be lowered by reducing the size of ESS through load following, which is a distinct advantage of SMR.

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