Motivations and Challenges in Utilization of Combined Heat and Power Cycle for the Nuclear Power Plants in Korea

Seong-Woo Kang[a], Man-Sung Yim[a*]
[a]*Nuclear and Quantum Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of KOREA*
[*]*Corresponding author: msyim@kaist.ac.kr*

1. Introduction

Amid increase in the global energy demand, there are more and more urgency around the world to meet the rising demand through carbon-free resources to reduce greenhouse gas emissions. However, the share of power generation using the natural gas in the Republic of Korea (ROK) is actually expected to increase by 2030 to handle the intermittency problem caused by reliance on renewable energy. Since the heavy reliance on intermittent carbon-based energy source (e.g. liquified natural gas, LNG) may actually curtail the efforts to reduce greenhouse gas emissions [1], the ROK may have no choice but to utilize nuclear energy to the fullest to lower the greenhouse gas emissions.

The ROK's 2050 Carbon-Neutrality Strategy expects the costs of renewables to keep decreasing, ultimately expecting the market-induced widespread of the renewable energy in Korea (i.e. without government incentives in the future). The Korean government also expects technologies related to fuel cell, carbon-free hydrogen, and energy storage systems (ESSs) to catch up to allow moving away from traditional power sources such as fossil fuels and nuclear energy [2]. However, electricity is closely intertwined with national security and economy. Therefore, power supply and demand for the future should be predicted in a conservative manner and not just in an optimistic point of view. According to *The 9th Basic Plan of Long-Term Electricity Supply and Demand*, even the 8th Basic Plan from 2017 under-predicted the maximum electrical power demand during the winter of 2017 and summer of 2018 by 3.0 GW and 6.4 GW, respectively [3]. It showed the difficulties in predicting the power demand even just couple of years ahead, partly due to global warming. With climate changes due, it is impossible to accurately predict the power demand for the year 2030 or 2050.

Therefore, the government and the power industry should also develop technologies to utilize other existing carbon-free sources such as nuclear energy to the fullest. One method a traditional power source such as nuclear may increase its utilization is through what is known as combined heat and power cycle (CHP), also known as cogeneration. Through application of CHP, a power plant may take advantage of the waste heat produced during power generation, ultimately increasing its overall efficiency. Since the main purpose of nuclear plant is to produce electricity reliably, it may become more sustainable carbon-free source of electricity through the CHP application.

Unlike fossil fueled power plants, there are limited cases of the nuclear cogeneration around the world, with none in Korea. The purpose of this paper is to show the reasonings behind it and what obstacles must be overcome for the nuclear power plants to more utilize its waste heat through combined heat and power cycle.

2. Status of Electrical Power Generation in ROK

In ROK, most power generation occurs at southern parts of the country, while majority of energy uses are in the metropolitan area. This characteristic of the market traditionally required long transmission lines, making the power demand difficult to be controlled through market function and also requiring large-scale investment to secure the stable supply of electricity. Thus, Korea has one large vertically-integrated government subsidiary company (Korea Electric Power Corporation, KEPCO) to function as 1) the transmission company responsible for high voltage transmission networks, 2) distribution company responsible for local distribution, and 3) electricity seller.

Table 1. Status of the Power Generation Companies Registered to the Korea Power Exchange (KPX) in 2020 [4]

Description			**Number of Registered Companies**	**Installed Capacity (MW)**
Retail Supplier (KEPCO)			**1**	**-**
Generation Companies	KEPCO's Subsidiary Companies		6	83,840
	Independent Power Producers		20	22,118
	Renewable Energy Companies	Solar	4,006	4,369
		Small Hydro	22	92
		Wind	71	1,539
		Bio Energy, Landfill Gas	39	242
		Fuel cell	19	254
		Tidal	2	2
		Renewable Energy subtotal	4,159	6,498
	Integrated Energy Supply		28	6,915
	Wastes		41	178
	Others		5	51
	Generation Subtotal		**4,259**	**119,600**
Self-generation Plant Owners			22	4,111
Community Energy Systems			10	881
Total			**4,291**	**124,592**

As for the power generation, the installed capacity of the private independent power producers, renewable energy companies, and community energy systems (CES) have been rising steadily. Nonetheless, most of the generated power are from few power generation companies which are KEPCO subsidiary (5 thermal, 1 hydro and nuclear). This is shown in Table 1, as KEPCO's subsidiary companies accounts for nearly 2/3 of the installed capacity in Korea. From Table 1 and Table 2, the installed capacity of the nuclear power accounts for roughly 1/4 and 1/6 of KEPCO's subsidiary companies and total generation capacities, respectively. The installed capacity of the renewables is comparable to that of nuclear energy; however, the amount of generated electricity in 2020 by renewables were less than 1/4 of the electricity generated by nuclear. This implies that the capacity factor of the renewables may limit itself from becoming major carbon-free replacement to the fossil fuels for the foreseeable future. Thus, nuclear power may be necessary to reach the greenhouse gas reduction goals set by the Korean government.

Table 2. Status of the Installed Capacity and the Actual Power Generation in the ROK by Resources in 2020 [5]

Resource Category	**Installed Capacity (MWe)**	**Generated Electricity (GWh)**
Nuclear	23,250	160,184
Coal	36,853	196,499
LNG	41,170	145,893
Renewables	20,862	37,830
Oil	2,247	2,282
Pumped Hydro	4,700	3,271
Others	109	6,150
Total	**129,191**	**552,108**

3. Status of CHP in ROK and Legal Limitations for Nuclear Cogeneration

Though KEPCO is responsible for the transmission, distribution, and sale of electricity as well as majority of the generation, there are some exceptions to the market. Community Energy System (CES) companies and Integrated Energy Supply (IES) companies are the exceptions in which that they may produce and supply/sell electricity through their own distribution lines. Electric Utility Act defines CES as a power generation facility with capacity of less than certain scale prescribed by presidential decree and supplies electricity directly to its regional users without going through KEPCO. Distribution line of the CES must not overlap with national distribution line (i.e. of KEPCO), and the CES must supply certain minimum amount of electricity used by its region. The CES may buy/sell electricity from/to the national electricity supplier (i.e. KEPCO) when there is over/under supply of electricity to the region it is responsible for [6]. Integrated Energy Supply Act defines IES as companies that can provide heat to the regional-commercial or industrial complexes. However, IES also may be treated legally as CES if they also provide electricity to its region in addition to heat.

In practice, CES and IES are different in that the main purpose of CES is to provide electricity to the regions where there is little to no national distribution line, whereas the purpose of the IES is to provide heat or heat plus electricity to the residential-commercial or industrial complexes. Therefore, if nuclear power plants are to apply CHP scheme and produce additional application from its waste heat such as desalination or district heating, it may become similar to the case of IES companies. Table 3 lists some of the characteristics of the CES and IES companies.

Table 3. Differences between Community Energy Systems and Integrated Energy Supply Companies

Characteristics		**Community Energy Systems (CES)**	**Integrated Energy Supply (IES)**
Business Structure		Electricity (at least 60% of regional demand)	Heat or Heat + electricity
Condition for the Business		At least 60% of its regional electrical demand	Supplying heat to its region
Duty to Supply Electricity		Yes	No
Power Exchange	**Its Own Produced Electricity**	Direct sales to its region	Use directly or sell to KPX
	Electricity Surplus	Sell to KPX or KEPCO	Sell to KPX
	Electricity Shortage	Buy from KPX or KEPCO	Buy from KEPCO

IES companies may choose to be treated as power generation company or as CES by Electric Utility Act through legal fiction, in which case they must also follow characteristics of the CES in the Table 3. The CES companies must have electrical generation capacity of less than 35MWe, whereas IES treated as CES through legal fiction must have capacity of less than 150MWe and 250MWe for residential-commercial and industrial complexes, respectively [4].

Currently in Korea, all CHP cycle occurs through IES companies, with gas turbines and heat recovery steam generator (HRSG) and none are related to nuclear. Korea District Heating Corporation, KDHC, accounts for 80% of the CHP plants. In the past, KDHC would receive heat energy from KEPCO subsidiary CHP generation companies and sell the heat to the region. However, as KDHC became bigger, it started to build and operate its own CHP plants to sell electricity and heat. Its heat supply is used for the residential-commercial complexes through district heating and cooling system.

Since KHNP is subsidiary of KEPCO and with all its electricity sold through national transmission and distribution line, it cannot be legally defined as CES and thus must operate similar to KDHC if nuclear power plants are to be used for the cogeneration applications in Korea. Therefore, considering the Electric Utility Act, the KHNP for its consideration of CHP should either 1) follow the example of KDHC for the future operation of its nuclear cogeneration plants, or 2) allow KDHC to operate the cogeneration part of the business separately.

4. Limitations of using Cogeneration on Existing Nuclear Facilities

Majority of CHP installations are from fossil fuels, as examples based on U.S. shown in Figures 1 and 2. Generally, the fossil-fueled plants steam turbines used in CHP cycles are classified as non-condensing or extraction turbines. For non-condensing steam turbines for CHP applications, steam may be extracted after the intermediate-pressure (IP) turbines, i.e. before entering the low pressure (LP) turbines. This method exhausts steam directly to commercial or industrial purposes at some common backpressures, where lower pressures are often used in district heating systems and higher pressures are typical for industrial applications. Extract turbines has one or more openings in its turbine casing to extract steam at an intermediate pressure, which is higher than pressure available from non-condensing turbines, and used typically for industrial purposes. A typical steam turbine CHP configuration is shown in Figure 3.

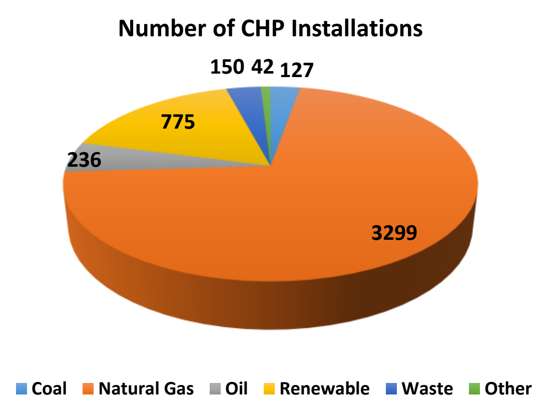

Figure 1. Number of Combined Heat and Power Installations (excluding Waste Heat to Power) in the United States

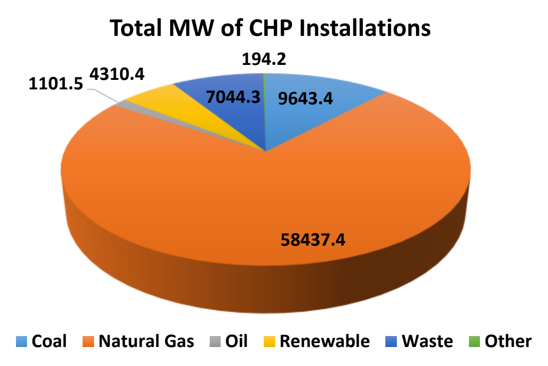

Figure 2. Total Capacity (in MW) of Combined Heat and Power Installations States (excluding Waste Heat to Power) in the United States

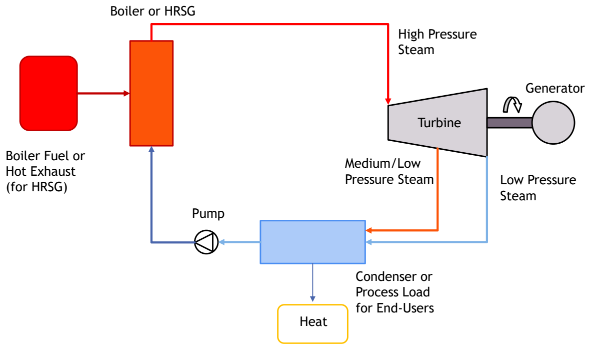

Figure 3. Typical Steam Turbine Cogeneration Configuration

Table 4. Limitations of CHP applications for Nuclear Power Plants

Limitation	Type of Limitation	Possible Solutions
Relatively low temperature of the steam	Technical	- Long-term answer: development of higher-temperature reactors (high-temperature gas reactor, molten-salt reactor, sodium-cooled fast reactor, etc.) - Short-term answer: use heat for low-temperature uses (district heating, desalination)
Reduction in power efficiency	Economical	- Cost-benefit optimization for the operation (between full power generation vs partial power generation + heat energy uses)
Additional investment to construct the required heat transmission network	Economical	- Extensive economic analysis (for the existing plants) - Designing the network at a building stage of the nuclear plants when the capital cost of heat extraction technology is small compared to the whole plant capital cost
Impact on the plant operation safety	Technical	- Additional extensive examinations on the safety, security, and environmental impacts of adding CHP applications to the nuclear plants
Shortening lifetime of the control systems	Technical/ Economical	- Optimization for the operation - Additional research on materials to increase lifetime

Summary of some of the limitations of applying CHP on the nuclear power plants are listed in Table 4. One of the limitations of using most commercialized nuclear steam cycle for cogeneration is the relatively low temperature of the steam. For example, waste heat from the gas turbine typically ranges above 500°C. On the other hand. most light water reactors can only produce approximately 300°C steam at maximum after steam generator (i.e. boiler on Figure 3). Furthermore, once the steam is extracted after going through the turbine (i.e. as medium or low-pressure steam on Figure 3), the temperature of the steam decreases even further. In case of nuclear plant, it compromises safety technologically to remove heat before the HP turbines (i.e. as high-pressure steam in Figure 3) for the CHP applications because it may impact the steam generator pressure, which in turn impacts the primary system of the nuclear plant and the core neutronics.

In case of nuclear cogeneration, relatively-low temperature of the extracted steam limits application of nuclear cogeneration to district heating or desalination. More advanced nuclear reactor designs such as high-temperature gas reactor, molten-salt reactor, or sodium-cooled fast reactors may allow better CHP applications, but commercialization of these advanced designs may be decades away.

There are several early nuclear reactors with comparatively lower power ratings that has been used for the purpose of cogeneration around the world. Most of the nuclear cogeneration application for district heating has been developed within northern European or former Soviet states where the cold climate year-round requires long heating periods. There are number of cases of using nuclear plants for seawater desalination, most notably in Japan, Pakistan, and Kazakhstan [9,10]. However, most of those are designed in the building stage of the nuclear plants, when the capital cost of heat extraction technology for the nuclear plant is considered negligible compared to the whole capital cost. Applying required modifications to the existing nuclear power plants for the purpose of cogeneration are rarely considered by nuclear operators, as large nuclear power plants are already optimized to provide base load capacity. To modify the existing plant may 1) require additional investment to construct the required heat transmission network, 2) reduce the power generation efficiency by removing part of the steam from the secondary system, and 3) require additional extensive examinations on the safety, security, and environmental impacts.

Heat loss and lower generation efficiency would result in less revenue through selling of electricity. It would also risk safety issues by being in more transient states (i.e. changes in primary and secondary system temperatures and pressures) which may impact the lifetime of core control systems such as control rods to keep the core stable, adding to additional costs.

In addition, the viability of CHP for the nuclear power plants will depend on good baseload of operation, both in terms of an on-site electrical demand and heat demand. However, in practice, an exact match may rarely occur. Therefore, using other energy storage systems such as TES may allow increased efficiency of the nuclear cogeneration operation in the future when most of power generation from the fossil fuels are ultimately replaced by carbon-free generation including renewables and nuclear energy. There are little to no technological limitations on applying CHP technology for the purpose of district heating or desalination using the existing nuclear power plants in Korea if proper examinations take place to ensure safety of the system. If steam is to be taken out before the HP turbines for higher temperature steam applications than district heating or desalination, better system control, additional heating source, and further safety analysis are required.

Nonetheless, to promote carbon-neutrality goals for the future, leaning on power generation from just the renewables may not be enough. Therefore, nuclear power must find a way to increase utilization as stable carbon-free energy source, and the CHP application of nuclear energy may allow coexistence with renewable energy. However, utilizing district heating or desalination for the CHP applications to any nuclear plants in Korea may need to overcome issues in economics, regulations, and even public acceptances of having CHP applications. More advanced CHP applications with higher-temperature steam extractions may have technological limitations with current nuclear power plants, but there are many ongoing researches on CHP applications on large commercial power plants and small modular reactors [11-16]. Advancement in nuclear technology such as development of small modular reactors and advanced reactors along with cogeneration systems may allow utilization of even higher-temperature steam for the CHP applications of the nuclear power plants in the future.

Acknowledgements

This research was supported by National Nuclear R&D Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2021M2D1A1084847).

REFERENCES

[1] Cho, So-Bin, and Man-Sung Yim. "Examining the feasibility of nuclear-renewable hybrid energy system in Korea: A case-based analysis of high penetrations of solar energy." International Journal of Energy Research 44.10 (2020): 8133-8143.
[2] 2050 Carbon Neutral Strategy of the Republic of Korea -Towards a Sustainable and Green Society. The Government of the Republic of Korea, 2020.
[3] The 9th Basic Plan of Long-Term Electricity Supply and Demand. The Government of the Republic of Korea, 2020.
[4] Korea Power Exchange. <https://www.kpx.or.kr> Last retrieved Aug 18th, 2021.
[5] "Korean Nuclear Industry." Korea Atomic Industrial Forum. <https://www.kaif.or.kr>. Last retrieved Aug 18th, 2021.
[6] Electric Utility Act of Korea. The Government of the Republic of Korea.
[7] Integrated Energy Supply Act. The Government of the Republic of Korea.
[8] U.S. Department of Energy Combined Heat and Power and Microgrid Installation Databases. <https://doe.icfwebservices.com/>. Last retrieved Aug 18th, 2021.
[9] Opportunities for Cogeneration with Nuclear Energy. International Atomic Energy Agency, 2017.
[10] Nuclear Cogeneration: civil nuclear in a low carbon future. The Royal Society. <https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/nuclear-cogeneration/>, 07 Oct 2020.
[11] 가압경수로 열병합발전 설계개발 및 검증, 한국수력원자력 자체 연구보고서, 2020.
[12] Technical Overview Report on Small and Innovative Reactor Technologies, 한국원자력학회 원자로시스템기술연구부회, 2020.
[13] Optimization Study of the SMART Desalination Plant, KAERI, TR-2145/2002, 2002.
[14] Shandong Haiyang Nuclear Energy Heating Project.
[15] Hydrogen Production using Nuclear Energy, IAEA Nuclear Energy Series, 2013.
[16] Private-public partnership will use nuclear energy for clean hydrogen production, Xcel Energy and Idaho National Laboratory, 2020.