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Preliminary Economic Analysis based on Optimization of Green Ammonia Plant Configuration in the Middle East for Import into Korea

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〈Abstract〉

Hydrogen is considered a key energy source to achieve carbon neutrality through the global goal of ‘net zero’. Due to limitations in producing green hydrogen domestically, Korean companies are interested in importing green hydrogen produced overseas. The Middle East has high-quality solar energy resources and is attracting attention as a region producing green hydrogen using renewable energy. To build a green ammonia plant, optimization of the production facility configuration and economic feasibility analysis are required. It is expected that it will contribute to reviewing the economic feasibility of constructing overseas hydrogen production plants through preliminary economic feasibility analysis.

Keywords : Green Hydrogen, Green Ammonia Production, Solar Power, Ammonia Synthesis, Preliminary Economic Feasibility Analysis

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1. Introduction

Energy systems around the world are changing. The demand shock of the pandemic and the supply shock that came with Russia's invasion of Ukraine present immediate challenges but will not stop the transition away from fossil fuels in response to the threat of runaway climate change.

According to DNV's Energy Transition Outlook (ETO) 2023, which provides a detailed forecast of the demand and supply of energy towards 2050 as well as a pathway to reach net zero emissions, decarbonization of electricity provides the mainstay of the transition[1].

The government of the Republic of Korea established the first legal basic plan for the hydrogen economy through the "1st Hydrogen Economy Implementation Basic Plan" in November 2021. Accordingly, a plan was announced to increase hydrogen supply from 220,000 tonnes in 2020 to 3.9 million tonnes in 2030 and 27.9 million tonnes in 2050. Among them, hydrogen imported from overseas is 1.96 million tonnes in 2030 and 22.9 million tonnes in 2050, and dependence on hydrogen imports is continuously increasing from 50.3% in 2030 to 82.1% in 2050[2].

Accordingly, Korean companies are showing great interest in building overseas green hydrogen production complexes. Australia and the Middle East are attracting attention as major target countries for the construction of production complexes.

The Middle East is emerging as one of the most competitive regions in green ammonia production. Many foreign companies are planning to invest in green ammonia production plants in the Middle East.

This study aimed to optimize the configuration of green ammonia production facilities with an annual capacity of 200,000 tonnes in the Middle East and perform a preliminary economic feasibility analysis accordingly.

2. Global Hydrogen Production Trend

Until 2020, most hydrogen production was gray hydrogen reformed from fossil fuels, but after 2025, gray hydrogen is expected to decrease and blue hydrogen through CCS (Carbon Capture and Storage) and green

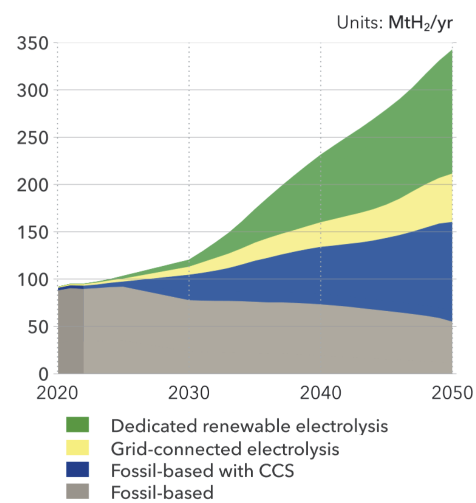

Fig. 1 Forecast global hydrogen production by production route[1]

hydrogen produced through renewable energy are expected to gradually increase as shown in Fig. 1.

Due to the imbalance between regions capable of producing economically green hydrogen and regions consuming it, it is expected that the volume of hydrogen that Korea should import from overseas will continue to increase. Therefore, transporting the produced green hydrogen becomes another key competitive advantage.

Since hydrogen, which liquefies at -253° C, is technically difficult to transport over long distances, converting it into ammonia, which liquefies at -33.4° C, and transporting it has recently been accepted as an economical alternative [1]. Therefore, in this study, ammonia was set as the final product.

Therefore, in addition to producing green hydrogen, it is essential to have a port that can handle ammonia.

The Middle East, along with Australia, is considered a competitive region capable of producing and transporting green hydrogen globally. In particular, in the Middle East, there are ports that can handle ammonia in the UAE (United Arab Emirates) and Oman, as shown in Fig. 2.

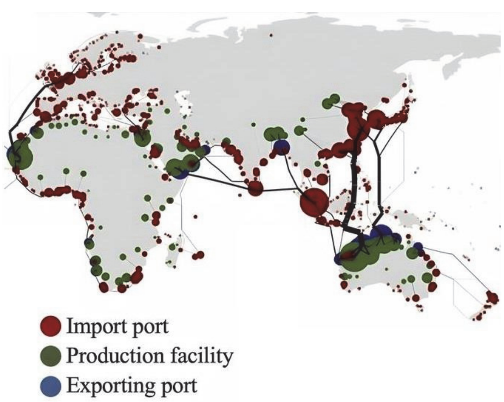

Fig. 2 Ammonia export and import ports in the Middle East and Asia

3. Optimization of Green Ammonia Production Facility Configuration

The configuration of the major facilities for producing green ammonia is as follows.

- Renewable energy generation complex
- Renewable energy configuration
- Hydrogen production facility (HPF)
- Ammonia production facility (APF)

The facility configuration was optimized based on producing 200,000 tonnes of green ammonia per year for 25 years and transporting it to Korea.

3.1 Renewable Energy Generation Complex

The area near UAE, which has a well-prepared ammonia shipping port, is one of the candidate sites for green ammonia production.

The solar resource is homogeneous in the coast area and increased from the coast to inland. The average photovoltaic(PV) power output on the coast was 4.9 kWh/kWp per day, which was analyzed to be economically feasible for solar power generation[3].

The average wind speed along the UAE coast was found to be 4-5 m/s, which is higher than the minimum wind speed of 3-4 m/s for wind turbine operation, as shown in Fig. 3. However, it was analyzed as lacking economic feasibility because it was lower than the minimum profitable average wind speed of 5.5 m/s mentioned in the report published by the European Union's Joint Research Center (JRC)[5]. Therefore, solar PV was considered for renewable energy production.

To determine the capacity of solar PV plant, it was produced a block level time series as a step 1, which was then used in the techno economic model to optimize the solar plant capacity. After the solar plant capacity were optimized the energy production assessment were run for the finalized capacity of the Project. Loss factors for energy simulation were calculated or assumed as bifaciality factor (0.08), rear structural shade (10%), rear mismatch (2.0%), and module transparency (5.0%).

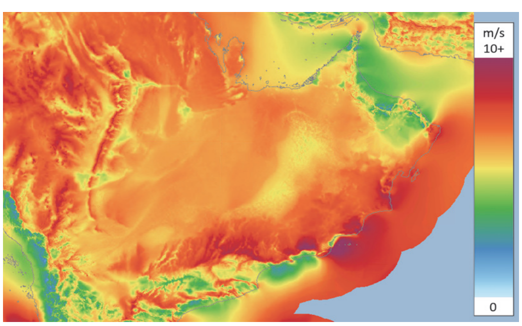

Fig. 3 Mean wind speeds across the Middle East at 100 m elevation[4]

The low tolerance for changes in production rates by an ammonia synthesis plant drive much of the optimization effort.

The NREC (New and Renewable Energy Complex) requires BESS (Battery Energy Storage System) facilities that can accommodate the variability of renewable energy generation. The operating philosophy of the BESS system is to store any excess energy production from the solar PV when excess power is being generated.

3.2 Hydrogen Production Facility (HPF)

Water electrolysis utilizes electricity to convert water into hydrogen and oxygen. It is seen as a key technology in enabling a net-zero energy system. Water electrolysis can take place over wide range of operating temperatures, from room temperature up to 800 ˚C and using different electrolytes.

Alkaline water electrolysis could be classified as a “mature and well established” technology since it was successfully demonstrated on industrial scale as early as the beginning of the 20th century[6].

Therefore, in this study, alkaline water electrolysis was proposed considering the maturity of the current technology and production stability.

After the hydrogen is produced it can be used as a raw material for ammonia production in the Haber-Bosch(HB) ammonia synthesis process. Intermediary storage of hydrogen will be required in case hydrogen production and hydrogen usage are out of phase.

Therefore, in this study, an additional hydrogen storage tank was introduced to reduce ammonia production variability. In addition, since wind power generation is not considered, it is difficult to supply power at night, so it is necessary to increase the capacity of the H_2 storage tanks.

3.3 Ammonia Production Facility (APF)

The currently most-used, and widely considered most-mature, production method for ammonia is the Haber-Bosch process[7].

For green ammonia production, the Haber-Bosch process can be combined with water electrolysis instead of methane reforming to produce hydrogen, as shown in Fig. 4.

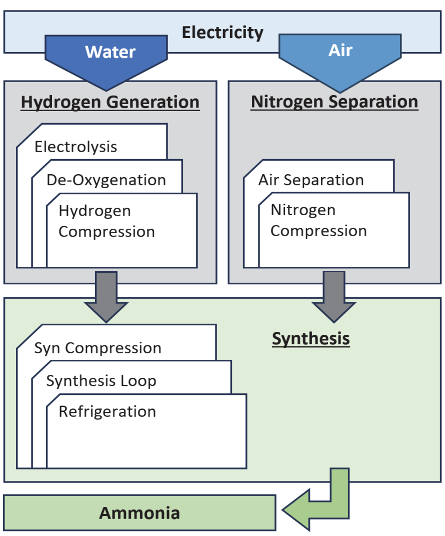

Fig. 4 Electricity-based green ammonia production method with the Haber-Bosch process for ammonia synthesis[8]

The Haber-Bosch process is currently the main industrial process for the production of (non-renewable) ammonia[8]. The overall process converts nitrogen (N_2) to ammonia (NH_3) through a reaction with hydrogen (H_2) according to the stoichiometric equation below.

$$N_2\,(g) + 3H_2(g) \rightarrow 2NH_3\,(g)$$
$$\Delta_f H° = -45.64\ kJ/mol_{NH3}$$

The process requires a catalyst in order to convert the very unreactive nitrogen gas and achieve a viable reaction rate. The catalyst accelerates the scission of the strong triple bond between the nitrogen atoms but requires elevated temperatures and pressures to do so. The second of the equation has fewer moles of gas, therefore an increase of pressure will shift the equilibrium towards conversion of nitrogen and hydrogen to ammonia.

Iron-based catalysts are an industrially proven catalyst type and are the most studied and widely applied in ammonia synthesis.

To obtain nitrogen feed gas for green ammonia production, an air separation device is required to separate the nitrogen from the air. Techniques for this purpose include fractional distillation, cryogenic air separation units (ASU), membrane separation, pressure swing adsorption and vacuum pressure swing adsorption.

Heat integration is key for a cryogenic distillation unit in order to maintain an energy efficient process. The incoming compressed fresh air is pre-cooled with relatively cold gases from the distillation column. A rough estimation of the energy required in the cryogenic ASU is 0.2 kWh/Nm^3 N_2 gas. Typical turndown ratio is 40% of design capacity. Due to the use of liquid nitrogen storage which provides a buffer of nitrogen, it is not necessary to operate the ASU at lower turndown rates.

Ammonia storage, either at the ammonia production plant and/or in the export terminal will be required for managing the irregular ammonia production and shipping schemes.

Ammonia can be kept in tanks at either:

- Low pressure (<10 barg) at ambient temperature in a gaseous state;
- High pressure at ambient temperature (30 barg at a maximum of 50° C) in a liquid state;
- Low pressure at low temperatures (atmospheric at -33.3° C) in a liquid state.

The location of the ammonia tanks and the length of the transport pipe can determine the type of the tanks.

3.4 Hydrogen and Ammonia Production Facility Capacity Calculation

The simulation model for optimization of configuration considers the following aspects:

- Solar PV-Powered Ammonia Production
- Grid Electricity Backup (optional)
- Excess Solar PV Utilization
- Role of Hydrogen (H_2) Storage

The model sets the minimum ammonia load which can be covered to then determine the required H_2 SOC (State of Charge) levels demanded to avoid a shortfall in this period of time. In case there is not a shortfall with the targeted H_2 then it is possible to increase the supply to the load.

The electrolyzer plant capacity calculation is driven by an optimization of the mix of renewable energy, BESS, hydrogen storage and ammonia synthesis plant size. The SHARE model simulation tool implemented takes all of these factors into account for a given plant life, factoring in degradation of key equipment, to derive optimal sizing capacity.

As shown in Fig. 5, the algorithmic logic of the simulation is as follows:

- In terms of renewables dispatch, the algorithm analyzes on an hourly basis the energy produced from solar PV, which would be used to produce green ammonia.

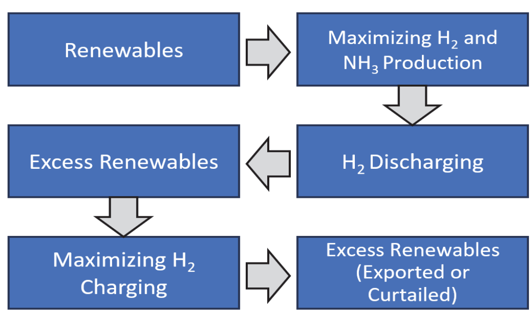

Fig. 5 Algorithm logic to maximize NH_3 production and avoid curtailment

- In terms of hydrogen storage charging the role is to avoid electricity imports, which occur only when: there is no H_2 in the H_2 storage and/or there is no solar PV electricity to power the HB plant electricity.
- For ammonia production, this is constrained by the ramp rates and minimum loading capacities of the plant. To further maximize the production of ammonia after ensuring meeting the minimum criteria for process stability the following steps are taken:

1) Use available renewables and excess H_2 energy stored to produce H_2 and NH_3.
2) In case there is more excess renewables after reaching the target NH_3 production for the hour, produce more H_2 for storage.
3) Any additional renewables after charging H_2 to their maximum capacity are exported back to the grid.

Based on the preliminary modelling, the following key capacities are determined for the HPF and APF:

- 600 MW of electrolysis plant (alkaline water electrolysis)
- 1.2 GW of solar PV
- 100 tonnes of hydrogen buffer storage
- Capacity of 1,200 tonnes per day has been settled for ammonia plant (Haber-Bosch technology).
- Liquid ammonia storage in 2x30,000 m^3 storage tanks., considered the minimum to provide redundancy and ensure export ship loading can be completed typically with a single storage tank.

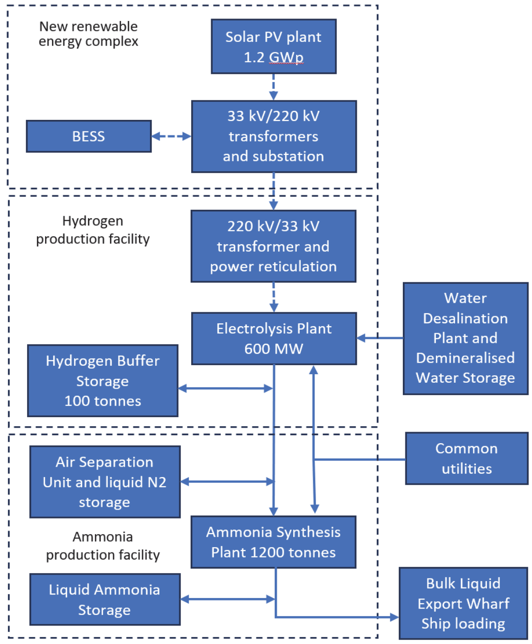

Fig. 6 Block Flow Diagram - Integrated Renewable Power-to-Ammonia Facility Concept

The overall concept configuration for the integrated NREC including hydrogen and ammonia production facilities can be illustrated with the overleaf high-level block flow diagram as shown in Fig. 6.

4. Preliminary Economic Analysis

The economic analysis was performed for the selected sizes using the SHARE model simulation tool. The cost estimate is based on other recent projects, and past experience. Normally, actually accrued cost is within an accuracy range of +50%/-30% as defined for Class V estimates in accordance with AACE (Association for Advancement of Cost Engineering).

The results of the estimated construction cost calculation are as follows:

- Solar PV: $600/kW
- Electrolysis: $900/kW
- H_2 Storage: $500/kg
- Ammonia plant: $197/kg
- Ammonia Storage: $917/m^3$

The O&M (Operating and Maintenance) costs are considered: spare parts management services, routine maintenance (planned), preventive maintenance (planned), corrective maintenance (unplanned), general services, supervision and control, management of decommissioning and disposal of used components, etc.

The results of the estimated O&M cost calculation are as follows:

- Solar PV: $8/kW
- Electrolysis: $22.5/kW
- H_2 Storage: $10/kg
- Ammonia plant: $5.5/kg
- Ammonia Storage: $9.2/m^3$

According to recent research results, the import price of ammonia from Saudi Arabia in the Middle East to Korea around 2030 is estimated to be $4.9/kgH_2$[9]. Since the main factor that determines the unit price is the transportation distance, the case of importing from UAE is expected to be similar.

5. Conclusion

In this study, the configuration optimization of a plant to produce 200,000 tonnes of green ammonia per year was performed.

Although the UAE's solar energy resources were of high quality, wind energy was found to be uneconomical. The optimal capacity of each facility was calculated as the minimum capacity of the facility that can maximize the operation rate, considering the volatility of renewable energy.

In order to reduce volatility when configuring production facilities due to limited supply of electricity produced from solar energy, BESS, hydrogen tank, and ammonia tank were included as buffers in the configuration, and the optimal capacity was calculated through simulation.

The economic feasibility of green ammonia still appears to be lower than that of gray ammonia and blue ammonia. However, many countries are providing subsidies for green ammonia to support competitiveness.

Additionally, according to DNV Energy Transition Outlook 2023, future technological advancements are expected to improve the price competitiveness of green ammonia as plant construction costs, operating costs and transportation costs are lowered [1].

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