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청정에너지기술

# Techno-economic Analysis of Power To Gas (P2G) Process for the Development of Optimum Business Model: Part 2 Methane to Electricity Production Pathway

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## Abstract

This study shows the summary of the economic performance of excess electricity conversion to hydrogen as well as methane and returned conversion to electricity using a fuel cell. The methane production process has been examined in a previous study. Here, this study focuses on the conversion of methane to electricity. As a part of this study, capital expenditure (CAPEX) is estimated under various sized plants (0.3, 3, 9, and 30 MW). The study shows a method for economic optimization of electricity generation using a fuel cell. The CAPEX and operating expenditure (OPEX) as well as the feed cost are used to calculate the discounted cash flow. Then the levelized cost of returned electricity (LCORE) is estimated from the discounted cash flow. This study found the LCORE value was ¢10.2/kWh electricity when a 9 MW electricity generating fuel cell was used. A methane production plant size of 1,500 Nm$^3$/hr, a methane production cost of \$11.47/mcf, a storage cost of \$1/mcf, and a fuel cell efficiency of 54% were used as a baseline. A sensitivity analysis was performed by varying the storage cost, fuel cell efficiency, and excess electricity cost by ±20%, and fuel cell efficiency was found as the most dominating parameter in terms of the LCORE sensitivity. Therefore, for the best cost-performance, fuel cell manufacturing and efficiency need to be carefully evaluated. This study provides a general guideline for cost performance comparison with LCORE.

**Keywords :** Returned electricity, Fuel cell, Renewable methane, Economics

## 1. 서 론

Power-to-Gas converts excess renewable electricity into hydrogen gas via electrolysis [1]. The produced hydrogen can be stored and transported through the existing natural gas infrastructure. However, a better way to store and transport the converted gas is to convert hydrogen into natural gas. Producing methane or natural gas from hydrogen reduces the potentiality of hydrogen escaping to nature which has global warming potential (GWP) of 5.78 kg $CO_2$ eq./kg hydrogen over a 100-year time horizon [2]. Bloomberg prediction shows that, for net zero scenario, the natural gas with CCS and hydrogen will be a major electricity generation technology by 2030 [3]. Fuel cell will play an important role for hydrogen or natural gas conversion to power and wide range of fuel cell technology can convert with a process efficiency of about 60% [4,5]. Integration of gas to power and power to gas is an effective means of transitioning to a net zero carbon emission goal.

Renewable energy is not a continuous power generation source and requires energy storage in battery or any other form. One possible way for smooth transitioning of (or to/from) renewable energy is the technologies to convert excessive electricity from wind or solar into a chemical fuel and vice versa [6]. The first process is performed in an electrolyzer while the reverse process is performed in a fuel cell, and due to the nature of the process and materials requirement, both processes cannot be performed with the same equipment. The studies in the literature are focusing on proton conducting fuel cell for both electrolysis and electricity generation [6].

Hydrogen or methane energy storage as an alternative to the battery storage is getting attraction all over the world and as a part of that many countries are introducing roadmaps with specific targets including improvements in electrolyzer and fuel cell technologies [7-10]. A fuel cell converts the chemical energy from the methane in natural gas into electricity through a chemical

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reaction with oxygen. Fuel cell is highly efficient equipment that reduces fuel usage and shortens capital investment payback period. Studies in the literature have been ongoing to combine the electrolyzer and fuel cell in a single device called proton conducting fuel cell [6]. Fuel cells are available in different sizes (as small as 1 kW to multiple MW) and make it usable in a wide range of project sizes with comparable installation cost in between small and big projects.

The levelized cost of electricity (LCOE) for fuel cell process utilizing the cheapest hydrogen or fossil natural gas is in the range of ¢10.3 to ¢15.2/kWh electricity produced [11]. A case study presented by US Department of Energy (DOE) describes the CAPEX required for the fuel cell process which includes transmission infrastructure upgrade equipment cost installation, cost as well as the Operational Expenditure (OPEX) for the feedstock natural gas cost [12]. However, a complete techno-economic evaluation from the utilization of excessive electricity for hydrogen production to synthesis and storage of methane and electricity generation with fuel cell is not available. In this study, the authors use the cost obtained from their previous study which consists of methane production using excessive electricity, natural gas storage, and electricity generation with fuel cell . The complete economic assessment of this process is described in the study.

## 2. Material and methods

The excess electricity for methane production process is discussed in detail in the previous study and among many methane production pathways the cooling water recirculation pathway is selected as the most economical pathway [13]. This pathway reduces the cooling water requirement in the process. This methanation pathway uses two-stage isothermal and single stage adiabatic reactor. The process diagram, the chosen pathway is shown in Figure 1 from the author’s previous study [13].

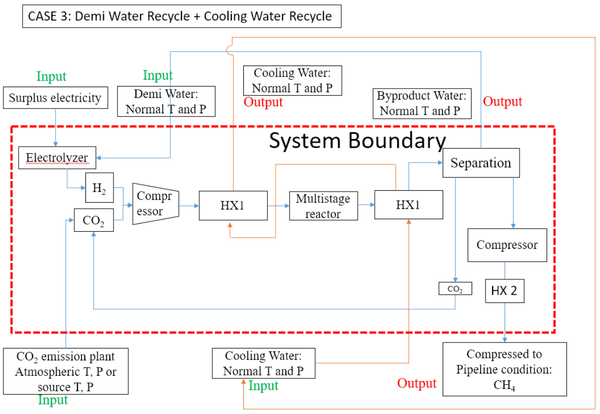

**Figure 1.** Case 3, recycles the cooling water is the selected path forward to the Phase II study.

Electrolyzer cost is based on 4.63 $kW/Nm^3$ of $H_2$ and \$380/kW as assumed in authors previous article [13]. Hydrogen is produced by electricity consumption in an electrolyzer and power consumption in the electrolyzer is an important parameter for hydrogen production efficiency. The average power consumption is 4.63 $kW/Nm^3$ hydrogen produced. This number is obtained from Green Hydrogen Systems, a Denmark based electrolyzer manufacturer company [14]. US Department of Energy estimated the CAPEX for electrolyzer as \$380/kW [13,15].

Fuel cell system cost is an anticipated cost for 3 MW sized fuel cell from an informal conversation with a European fuel cell supplier. The other size project costs were determined by six-tenth rule as the quantity of fuel cell stack produced by the manufacturer significantly impacts on the production cost [16]. Costs for the other sizes are projected from this information. All the fuel cell cost evaluations were verified by DOE target price [17].

### 2.1. Levelized Cost of Returned Electricity (LCORE)

LCORE was calculated with costs from excessive electricity to methane synthesis, methane storage, and electricity re-generation.

The excess electricity available during certain times of the day is used by an electrolyzer along with water. The hydrogen is produced from the electrolyzer and mixed with $CO_2$ before sending to the multi-stage reactor system. The complete infrastructure and operation required for electricity to methane production is considered for methane production cost. In the next stage, produced methane is sent to the fuel cell for power generation. Storage costs in the natural gas pipeline (natural gas grid) were used instead of building a natural gas storage. Produced methane enters the natural gas grid in one location and extracted in a separate location, and this pathway is considered for natural gas storage and transportation. The complete infrastructure and operation required for this fuel cell system are taken into consideration for the power generation cost calculation. All the CAPEX and OPEX are used with a discounted cash flow model for the LCORE calculation.

Levelized Cost of Methane (LCOM) is calculated by taking all the CAPEX, operation expenditure, feedstock cost etc. A discounted cash flow-based model were used for LCOM calculation. A simple presentation of the LCOM calculation is:

$$\text{LCOM} = \{(\text{overnight capital cost} \times \text{capital recovery factor} + \text{fixed O\&M cost})/\ (8760 \times \text{capacity factor})\} + (\text{fuel cost} \times \text{heat rate}) + \text{variable O\&M cost} \qquad [18]$$

LCORE is calculated in similar way the LCOM is calculated. Methane storage cost is also included in the LCORE calculation. LCOM and methane storage cost combinedly considered as the feedstock methane cost as methane is feedstock for this process. The methane production cost A discounted cash flow-based model were used for LCORE calculation.

## 2.2. Capital Expenditure (CAPEX) and Operating Expense (OPEX) Estimation

OPEX in general includes inventory costs, marketing, payroll, insurance, step costs, and funds allocated for research and development. As a part of this assumption and calculation no specific items were considered but fixed OPEX is considered as 3% of the Engineering, Procurement and Construction (EPC) and variable OPEX is taken as 4% of the EPC. Table 1 lists the basic assumption considered for this study.

Natural gas consumption in a fuel cell is an established Industrial process and large-scale processes is available for commercial deployment [19]. The site development and large-scale fuel cell are not very common but based on some vendor data the following CAPEX is assumed for the fuel cell-based power generation system using natural gas. Fuel cell size as well as the power generation can vary significantly based on the amount natural gas consumed. Therefore, this study proposes 4 different fuel cell sizes related to the 4 different methane production plant capacity in the stage one. Table 2 summarizes the fuel cell size and corresponding methane plant capacity.

**Table 1.** Plant output and operation data

| **Scale** | | |
|---|---|---|
| Capacity | 100% | |
| Operating Hours | 8000 | Hours/Year |
| **CAPEX** | | |
| Process Contingency (% of Tech, Uncertain EPC Costs) | 5.0% | |
| Engineering Procurement and Construction Cost (EPC) | 30% | |
| **Project Debt Terms** | | |
| Loan Interest Rate | 2% | |
| Financing Fee | 1.0% | |
| Repayment term | 30 | year |
| **Depreciation** | | |
| Salvage value (% of the TDC) | 0% | |
| **Economic Assumptions** | | |
| Project Economic life | 30 | years |
| Project tax life | 30 | years |
| Discount Rate | 10.0% | |
| **OPEX (% of EPC cost)** | | |
| Variable OPEX (output level dependent) | 4.0% | |
| Fixed OPEX (output level independent) | 3.0% | |
| **Escalation Factors** | | |
| Electric power consumption | 0.1% | |
| Variable OPEX | 2.0% | |
| Fixed OPEX | 2.0% | |
| EPC Costs | 2.0% | |
| **Tax Assumptions** | | |
| Income Tax Rate | 25.0% | |

**Table 2.** Fuel cell size relevant to the methane production capacity

| | Fuel Cell SizeMethane Plant Capacity ($Nm^3$/hr) |
|---|---|
| 45 | 0.3 MW |
| 500 | 3 MW |
| 1,500 | 9 MW |
| 5,000 | 30 MW |

The equipment and installation costs were obtained from consultation with the equipment supplier and EPC. Construction phase labor cost is included in the EPC cost as shown in Table 2. Table 3 summarize the estimated CAPEX for the fuel cell plant. Site improvement, offsite development, water, pipeline costs are taken from a typical requirement of the fuel cell used for electricity generation.

Electrical interconnection and electrical system also use typical values for a project in California.

The input natural gas and air to the fuel cell typically requires compression before supplying to the fuel cell.

The relevant natural gas production scale is to be selected for each individual sized fuel cell system: i.e., 500 $Nm^3$/hr natural

**Table 3.** The CAPEX assumptions for a 0.3 MW fuel cell

| | Equipment cost (USD)Unit | | | |
|---|---|---|---|---|
| Plant size | 0.3 MW | 3 MW | 9 MW | 30 MW |
| Site improvement | $95,450 | $380,000 | $734,600 | $1,512,800 |
| Offsite, water, pipeline | $183,400 | $730,000 | $1,411,200 | $2,906,200 |
| Fuel cell system | $550,000 | $2,200,000 | $6,600,000 | $22,000,000 |
| Electricity interconnection | $125,600 | $500,000 | $966,600 | $1,990,550 |
| Electrical system | $170,800 | $680,000 | $1,314,600 | $2,707,100 |
| Compression and air compressor | $62,800 | $250,000 | $483,300 | $995,200 |
| Total CAPEX | $1,188,000 | $4,740,000* | $11,510,000 | $32,112,000 |

*Very close to DOE target $1500/kW prediction [20] gas production system will be coupled with a 3 MW fuel cell system.

Replacing cost of the fuel cell at 11th and 21st year after initial plant commissioning was also considered for the LCORE calculation.

A major assumption for the LCORE calculation is that the produced methane stored in the natural gas grid requires an additional $1 per mcf for storage. The produced methane storage is important and can be an expensive item if onsite storage is required. For the simplicity of this study and a less construction extensive approach, produced methane storage in the existing natural gas infrastructure is assumed. Putting the natural gas in the pipeline is good for long term storage. The cost can vary significantly but considering the price of natural gas ranging from $4~ $8/mcf, $1/mcf is a typical assumption.

Another major assumption is that the fuel cell system will operate 8,000 hours per year. Other assumptions are fuel cell efficiency 54% (aligned with DOE target by 2020), zero electricity cost for excess electricity used in the methane production stage [20].

## 3. Results and Discussion

### 3.1. LCORE

Figure 2 show the LCORE cost varying plant size and relevant methane production cost. The plant size about 1,500 Nm$^3$/hr methane production capacity reduces the electricity production cost to about ¢10.2 per kWh electricity from ¢35.6/kWh electricity for the 45 Nm$^3$/hr methane production plant. Major savings come from the CAPEX reduction per MW of fuel cell system. As shown in Table 3, the plant size is 10 times (from 0.3 MW to 3 MW), but the CAPEX increases only 4 times. However, the CAPEX for the 30 MW capacity system increases about 6.7 times compared to the 3 MW capacity system. As shown in Figure 2, the electricity reproduction cost initially decreases significantly and at above 9 MW the cost change is less than 10% even the plant capacity increases more than 3 times, and the trend is similar as observed for the methane production cost as found in the authors previous study in Figure 3 [13].

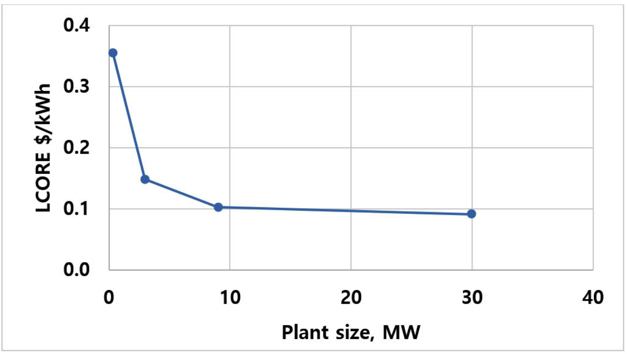

**Figure 2.** LCORE vs Plant Capacity

**Figure 3.** LCOM vs Plant Capacity from Phase 1 Study [13]

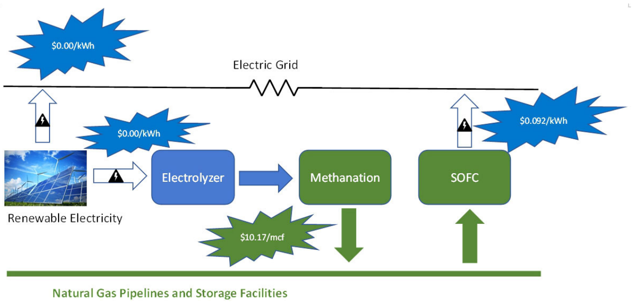

**Figure 4.** Process diagram of 5,000 Nm$^3$/hr size of plant with Solid Oxide Fuel Cell (SOFC)

Figure 4 shows the process diagram with relevant costs of 5,000 Nm$^3$/hr of plant size. The major cost components shown in the figure are electrolysis for hydrogen production, methane production process, methane storage in the natural gas pipeline, and fuel cell including the electrical interconnection process for the produced electricity supply to the grid. Table 3 shows the cost components for the different sized plants.

### 3.2. Sensitivity Analysis

The excess electricity cost plays a significant role in the LCORE. Figure 5, show the effect of variation of excess renewable electricity cost to the LCORE. The excess electricity cost increases the reproduced electricity cost significantly: the LCORE is ¢41 per kWh electricity when excess electricity is available for ¢8 per kWh compared to the LCORE is ¢10.2 per kWh electricity when excess electricity is available for 0 cost. The cost increase is aligned with the process efficiency of electrolyzer, methane production process, and fuel cell efficiency. Fuel cell efficiency is dependent on the fuel cell manufacturer: the efficiency varies significantly based on the technology as well as manufacturer. The future improvement in the technology will improve the reproduced electricity cost even the excess electricity or electricity for the hydrogen production process is expensive in places like Europe.

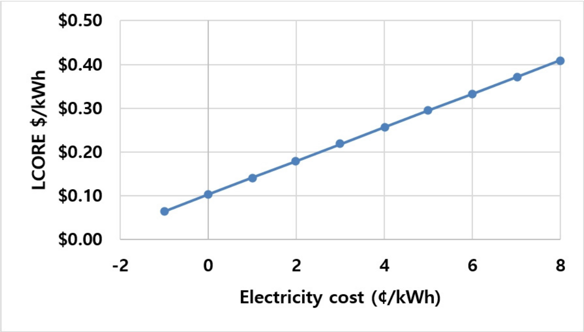

**Figure 5.** LCORE variation with the excess renewable electricity cost used for methane production (plant size 1,500 Nm$^3$/hr, methane cost $11.47/mcf, storage cost $1/mcf, fuel cell efficiency 54%)

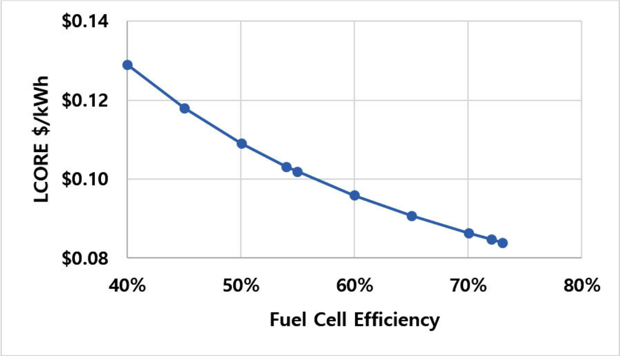

**Figure 6.** LCORE variation with the change in fuel cell efficiency (plant size 1,500 Nm$^3$/hr, methane cost $11.47/mcf, storage cost $1/mcf)

This study assumes fuel cell efficiency of 54%. Figure 6, shows the LCORE variation with the change of fuel cell efficiency. Increase in fuel cell efficiency from 54% to 70% reduces the LCORE from ¢10.2/ kWh to ¢8.3/ kWh. Fuel cells need to be carefully chosen even if the low efficiency fuel cell technology is available for a lower price and can play a major role in lowering the electricity generation cost significantly. Improvement in fuel cell technology/efficiency will ensure the use of hydrogen as an energy storage medium by improving the electricity round-trip efficiency.

Figure 7, shows the LCORE variation with the change in methane storage cost. This study assumes the methane storage in existing natural gas pipeline. With the support from local and/or federal government the methane storage cost can be reduced as well as the reproduced electricity cost. However, if the natural gas pipeline is not available nearby and storage system building is required the reproduced electricity production cost will increase as shown in the figure. Proper involvement and/or incentive from government will play an important role in such project and injection of renewable natural gas in the natural gas grid.

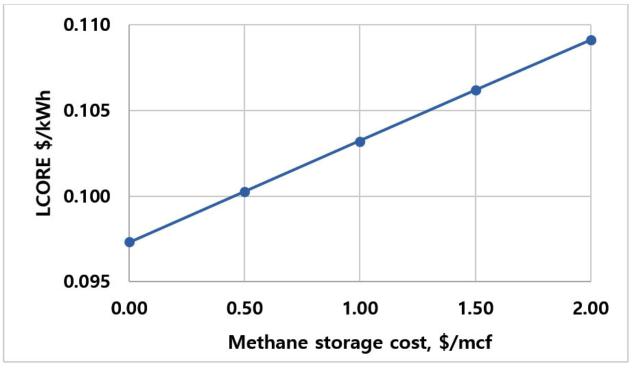

**Figure 7.** LCORE variation with the change in methane storage cost (plant size 1,500 Nm$^3$/hr, methane cost $11.47/mcf, fuel cell efficiency 54%)

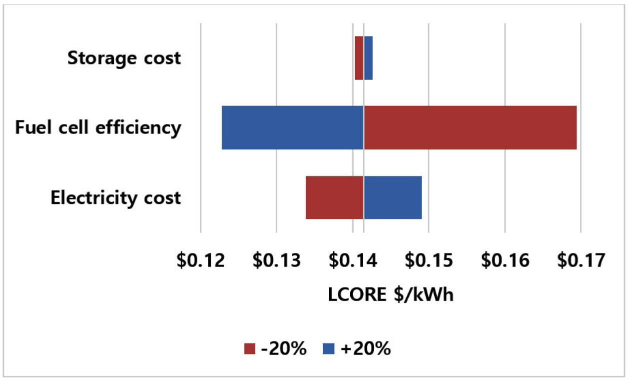

**Figure 8.** Sensitivity analysis of the levelized cost of electricity generation with ±20% change in the storage cost, fuel cell efficiency, and excess electricity cost (baseline: CH4 plant capacity 1,500 Nm$^3$/hr, 9 MW fuel cell, excess electricity cost 1¢/kWh, $1/mcf CH$_4$ storage cost, and 54% fuel cell efficiency)

In Figure 8, the sensitivity analysis is performed for excess electricity cost, fuel cell efficiency, and methane storage cost towards the reproduced electricity. CH$_4$ plant capacity 1,500 Nm$^3$/hr, 9 MW fuel cell, excess electricity cost ¢1/kWh, $1/mcf CH4 storage cost, and 54% fuel cell efficiency are the baseline assumptions. The baseline parameters (excess electricity cost, methane storage cost, and fuel cell efficiency) are varied up to ±20% in the sensitivity analysis. The sensitivity analysis indicates that the fuel cell efficiency is the dictating item towards the LCORE value. Electricity cost is the second dominating parameter for LCORE and ±20% variation from $1/mcf CH$_4$ storage cost is the least dominating parameter for LCORE value.

## 4. Conclusions

This study performs the economical assessment of the levelized cost of electricity production using a fuel cell where natural gas is produced from hydrogen with renewable electricity. LCORE of different size plant is compared and found as $0.092/kWh for the 30 MW fuel cell system as well as 5,000 Nm$^3$/hr capacity plant.

Efficiency of fuel cell has the highest sensitivity affecting this value. The CAPEX for the different size plants is estimated as a part of the LCORE estimation. The study also performs the sensitivity analysis using fuel cell efficiency, electricity cost for hydrogen production, and methane storage cost parameters. Fuel cell efficiency is found to be the most sensitive parameter, and electricity cost was the second most sensitive parameter.

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## Nomenclature

CAPEX: Capital Expenditure
CCS: Carbon Capture and Sequestration
DOE: Department of Energy
EPC: Engineering, Procurement and Construction
GWP: Global Warming Potential
LCOM: Levelized Cost of Methane
LCORE: Levelized Cost of Returned Electricity
OPEX: Operating Expenditure
P2G/PtG: power to gas

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