IX.4 Performance and Cost Analysis for a 300 kW Tri-Generation Molten Carbonate Fuel Cell System

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Overall Objectives

- Examine strategies for improving the performance and reducing the cost relative to the one-off Orange County Sanitation District (OCSD) tri-generation system
- Explore scenarios in which the molten carbonate fuel cell (MCFC) tri-generation system has particular cost benefits including the scenario for charging electric vehicles

Fiscal Year (FY) 2015 Objectives

- Develop meaningful definitions for cell, stack, electrical, hydrogen production efficiencies in tri-generation modes
- Formulate cost models for MCFC stack, mechanical and electrical balance of plant (BOP), pressure swing adsorption (PSA), compression, storage, dispensing (CSD), and vehicle charging system
- Determine the performance and cost benefits of a MCFC plant that can co-produce electric power, hydrogen, and heat
- Explore strategies to improve the performance of the system in combined heat and power (CHP) and combined heat, hydrogen, and power (CHHP) modes

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration (MYRDD) Plan.

(A) Future Market Behavior

(C) Inconsistent Data, Assumptions and Guidelines

(E) Unplanned Studies and Analysis

Contribution to Achievement of DOE Systems Analysis Milestones

This project will contribute to achievement of the following DOE milestones from System Analysis section of the Fuel Cell Technologies Office MYRDD Plan.

- Milestone 1.17: Complete analysis of program technology performance and cost status, and potential to enable use of fuel cells for a portfolio of commercial applications (4Q, 2018)
- Complete analysis of the potential for hydrogen, stationary fuel cells, fuel cell vehicles, and other fuel cell applications such as material handling equipment including resources, infrastructure and system effects resulting from the growth in hydrogen market shares in various economic sectors. (4Q, 2020)

FY 2015 Accomplishments

- Formulated a consistent system performance model of thermally-integrated natural gas (NG) fuel processor and MCFC stack in the electricity and hydrogen generation mode (CHHP)
- Set up cost models and performed cost analysis of the MCFC tri-generation system, showing installed capital costs of \$510,000 for the MCFC system, \$615,000 for CSD and PSA, \$55,000 for auxiliary heater and water distribution, and \$37,000 for electric vehicle (EV) charging
- Conducted sensitivity analysis to determine the required price for H_2; for fixed electricity price of \$0.103/kWh (U.S. average), hydrogen can be priced at \$6.50/kg for 125 kg/day co-production
- Integrated EV charging in the revenue stream shows that the cost of hydrogen can be reduced by ~\$0.80/kg for each \$0.10/kWh premium applied to EV charging

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INTRODUCTION

The demand for lower-volume hydrogen production systems at dispersed locations is projected to increase to meet the needs of fuel cell cars and other applications. Tri-gen systems that can produce electricity, heat, and hydrogen, are being proposed and developed. One example of such a system is the molten carbonate fuel cell based tri-gen plant installed at the OCSD water treatment facility in Fountain Valley, California. This system operates on NG or digester gas to nominally produce up to 250 kW of electricity, 200 kW of useful heat (as low pressure steam), and 100 kg-H_2/d. This study sets up a generic model of a tri-gen plant that can sell hydrogen, sell the power to the grid or recharge EVs. The analysis calculates efficiencies that account for the values of the products (power, hydrogen, and heat), and estimates the earning potential of the plant and future cost reductions.

APPROACH

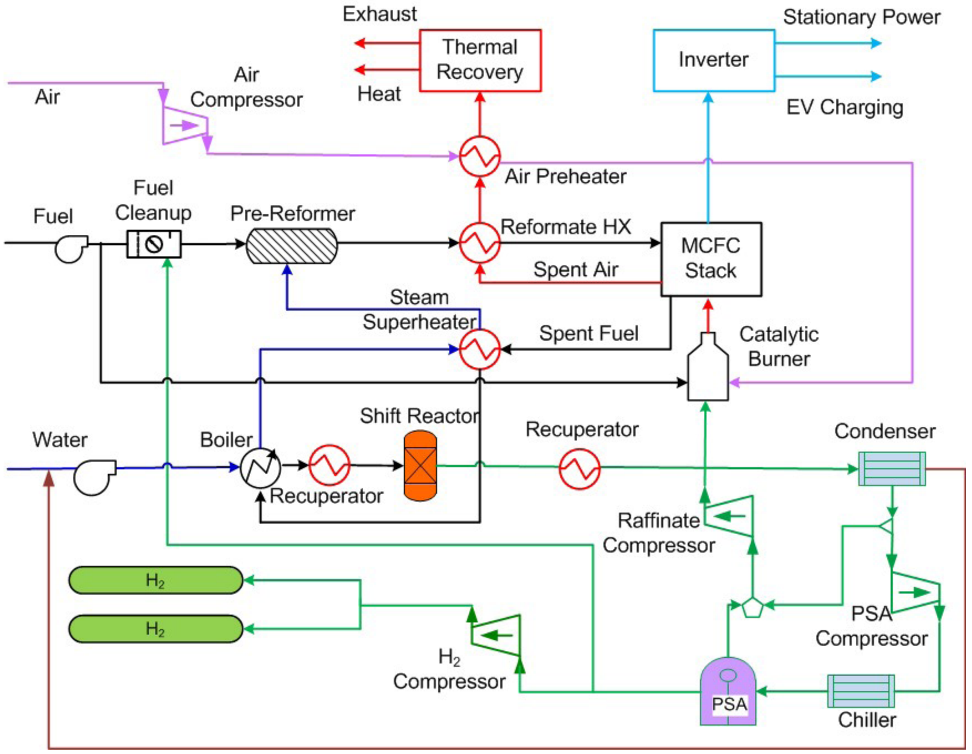
The analysis is conducted using systems modeling and cost estimation. The performance evaluation is based on metrics that include energy efficiencies and cost of the system over the lifecycle.

- Identifies the technology, component, or design criteria that limit the system performance (efficiency, emissions), in both the CHP and tri-gen modes of operation
- Identifies and quantifies the major cost contributors, potential cost reduction opportunities, and projects future costs based on advances in component technology, capacity scale-up, and volume production

RESULTS

A generic tri-gen system was analyzed for the performance and cost analysis, Figure 1. The case selected for the analyses is based on a 300 kW molten carbonate fuel cell to serve as a direct comparison with the one of a kind system at OCSD. In our case, the system is operating solely with NG as fuel. The natural gas passes through a high temperature polisher for sulfur removal and is pre-reformed before entering the anode side of the MCFC. The reformate leaving the stack passes through a low temperature shift and further compressed to 10 bar. A four-bed PSA unit separates and purifies the hydrogen before the hydrogen is further compressed and stored for delivery. Revenue sources include hydrogen for fuel cell electric vehicles, electricity to grid or directly to EV charging stations, and waste heat recovery.

Considering the stack and system performance, the model was tuned to match current performance metrics given the available open information in the literature on the existing plant. Table 1 summarizes the system performance for the tri-gen system modeled for (a) pure electric mode and (b) combined electric and H_2 mode for a maximum hydrogen



HX - heat exchanger

FIGURE 1. MCFC tri-gen system performance model

TABLE 1. Summary of system performance for CHP and CHHP modes

	Pure Electric	Combined Electric and H_2 Mode	Comments for Performance in Combined Electric and H_2 Mode
Net H_2 Production (kg/d)	**0**	**125**	79 kW_t supplemental fuel to burner
Net Electrical Power (kW_e)	258.1	183.1	5% increase in fuel input to stack
Fuel Utilization (%)	73.0	60.0	Terminal limits of fuel utilization (U_F)
Oxygen Utilization (%)	60	60	Fixed O_2 utilization, variable U_F
Cell Voltage (mV)	768.9	816.4	Higher Nernst potential at lower U_F
Stack DC Gross (kW_e)	300.0	274.9	
Stack Actual Efficiency (%)	51.1	51.1	Stack efficiency does not increase because of higher burner load
Gross Electrical Efficiency (%)	46.4	42.6	Lower gross electrical efficiency in spite of higher cell voltage
H_2 Production Efficiency (%)	87.3	89.4	
PSA Efficiency (%)		43.0	Efficiencies inclusive of electric power consumed in PSA and H_2 compressors
H_2 Storage Efficiency (%)		83.9	
Net Electrical Efficiency (%)	46.4	27.6	
Fuel Processor Efficiency (%)	0.0	26.2	
Thermal Efficiency (%)	32.7	23.2	Waste heat used to raise hot water. Lower if steam is raised.

production rate of 125 kg/d. Through several iterations as well as input from industry, we calibrated the model such as the fuel input to the stack and burner as more hydrogen is co-produced. As the hydrogen production level increases beyond 50 kg/d, the fuel utilization is kept constant at 60%. More fuel is introduced to the stack and burner with the constraint of maintaining the stack temperature at 650°C. At 125 kg/d, a net electrical power of 183 kW can be produced which is 40% more for the case of constant fuel input. Electrical efficiencies decrease as more hydrogen is co-produced. The net efficiency is the power supplied to the grid relative to all fuel input to the station and all parasitic power including reformate compressor to the PSA and hydrogen compression to storage. The net electrical efficiency decreases from ~47% when no hydrogen is produced to ~28% at rated hydrogen production. The net hydrogen efficiency is the ratio of the hydrogen produced to the total fuel energy content. At rated hydrogen generation of 125 kg/d and available at the refueling pressure, the net hydrogen efficiency increases to 26%. Not accounting for the waste heat, at rated hydrogen production the hydrogen and electrical efficiencies sum up to 54%.

Figure 2 shows the estimated capital costs for the 300 kW tri-gen system analyzed. A process flow based approach to estimate the MCFC stack cost was employed in the present study. First, all major process steps required in the manufacture of all components of the stack are identified.

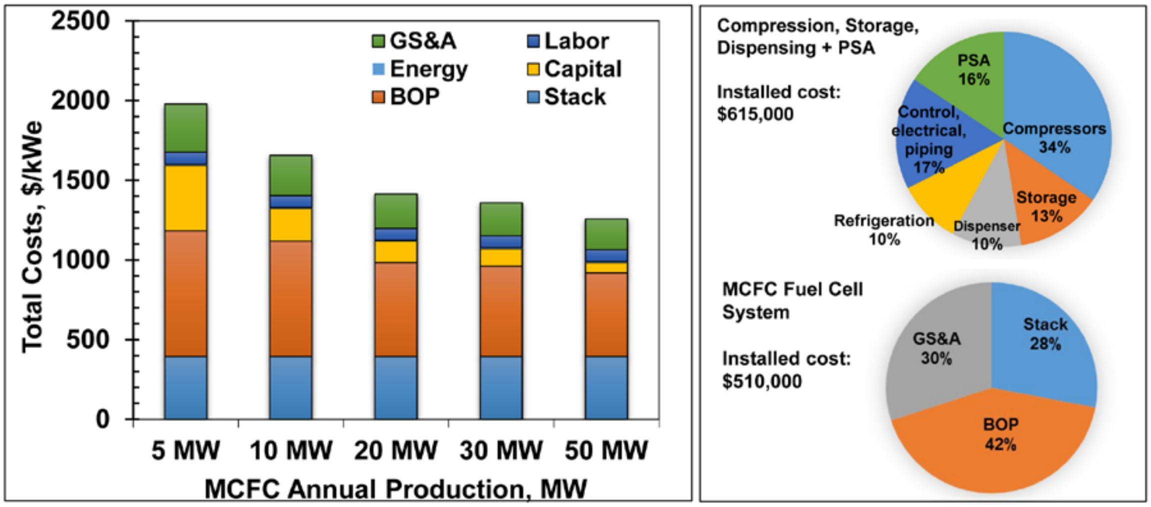


FIGURE 2. Estimated capital costs for MCFC stack and BOP

The key technical details of each manufacturing step (material mass, process temperature, machine cycle time, labor requirement) are used to develop a cost estimate for that step. Process flows, materials and equipment requirements have been identified in the literature, especially patents. Cost of materials and equipment has been found in literature and from direct inquiries with vendors. BOP estimates were determined through a combination of direct manufacturing analysis, component specification calculations, supplier quotations, literature searches, and scaling factors. Hydrogen supply and dispensing is designed for 125 kg/d cascade dispensing and cooling for on-board storage at 700 bar. For compression and storage of hydrogen, we consider a minimal station design without back-up compressors. The model assumes two compressors; each compressor operates at 50% of the designed flow. For lower volume and cost reduction, the pressure of the low pressure storage tank is increased to 482 bar. Low and high pressure cascade tanks are used with pressures of 482 bar and 875 bar, respectively. All storage is designed based on Type IV composite tanks and refrigeration unit is used to allow fast filling rates. Considering the materials and designated flow rates, the cost for a similar system for compression storage and dispensing of hydrogen as the OCSD can be reduced to $500,000. Since the OCSD compressors were oversized, we used the H2A model to calculate the cost of two 31 kW units. The cost of compressors were reduced to approximately $200,000. Considering a one of a kind demonstration unit, costs are bound to be high, partly because of learning experience and components that are only available for specific flows. In our present base case analysis, components are assumed to exist at reasonable high production volume at rated capacities. The installed costs between stack and hydrogen purification and storage are similar, costing $510,000 for the stack (annual production rate of 20 MW) and $615,000 for purification and storage. Compressors account for the main capital cost contribution.

The cost of hydrogen has been evaluated based on H2A FCPower tool. For a facility with hydrogen co-production and a fixed charge of electricity at 10.3 ¢/kWh, hydrogen needs to be priced at $6.50/kg, as shown in Figure 3, for maximum production capacity of 125 kg/d. For 75 kg/d, the cost increases to over $9/kg. The minimum price of hydrogen depends, however, strongly on the price of electricity and feedstock costs. Revenues from a higher electricity price can offset the price of co-produced hydrogen; for instance, at electricity prices of 18 ¢/kWh the hydrogen cost is reduced to $4/kg. The higher revenue from electricity alone will also make the price of hydrogen less sensitive to capacity changes. For the base case, a hydrogen price of $6.50/kg, the tornado chart in Figure 3 shows the sensitivity for the hydrogen price, with $1 cost reduction possible with capital expenditure reduction, stack replacement frequency to 10 years or feedstock price reduction. Further capital cost reductions of stack compression and storage may reduce the price by the same amount.

We are considering that the facility or business owner will provide electric vehicle charging for employees of customers. In addition to electric power being delivered to the grid or to a facility, some of the power can be used for electric vehicle charging. For EV charging, the assumptions for our base case and cost estimates consider four 6-kW units costing $3,000 each and two 50-kW fast charging stations at $10,000 each. Assuming 10 hours of operation per day, charging capacity of 12 kWh/vehicle and for 125 kg-H_2/d co-production, the facility can charge up to 150 vehicles/day. At full charging capacity utilization, the price of hydrogen is reduced by ~$0.80/kg for each $0.10/kWh premium[11] for EV charging.

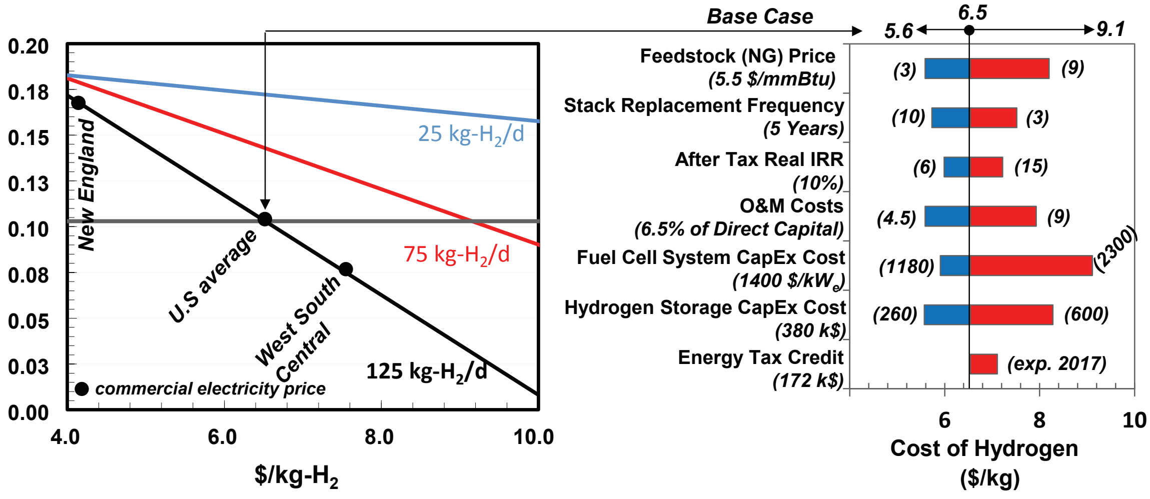


FIGURE 3. Sensitivity of hydrogen price versus the price of electricity, the amount of hydrogen co-produced, and capital costs

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[1] A 10 ¢/kWh premium means the station charges 10 cents more per kilowatthour than the residential rate available at that location.

CONCLUSIONS AND FUTURE DIRECTIONS

This study analyzed a 300 kW tri-gen plant that can sell hydrogen, sell the power to the grid or recharge electric vehicles. The analysis conducted has defined efficiencies that account for the values of the products (power, hydrogen, and heat), capital cost and the earning potential of the plant.

- The high temperature fuel cell subsystem generates hydrogen by reforming the supplied fuel within the stack. The combined efficiency for the production of electric power and hydrogen can exceed 54%.
- For a facility with hydrogen co-production and a fixed charge of electricity at 10.3 ¢/kWh, hydrogen needs to be priced at $6.50/kg. Revenues from a higher electricity price can offset the price of co-produced hydrogen.
- The cost of hydrogen can be reduced by selling the EV charging power at a rate higher than the prevalent commercial rate.

In the remaining part of FY 2015, the analysis will explore strategies to improve the performance and economics of the tri-gen system considering the following.

- Electrochemical separation and compression and trade-off between PSA compressor, H_2 recovery and compression
- Analyze larger, 1,000 kW and 1,500 kW MCFC systems to improve the economics and increase revenues by adapting the production of power and hydrogen relative to peak hour demand

FY 2015 PUBLICATIONS/PRESENTATIONS

1. Ahmed, S., Papadias, D., Ahluwalia, R., Hua, T., Roh, H-S., "Performance and Cost Analysis for a 300 kW Tri-generation Molten Carbonate Fuel Cell System," 2015 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting, June 9, 2015.