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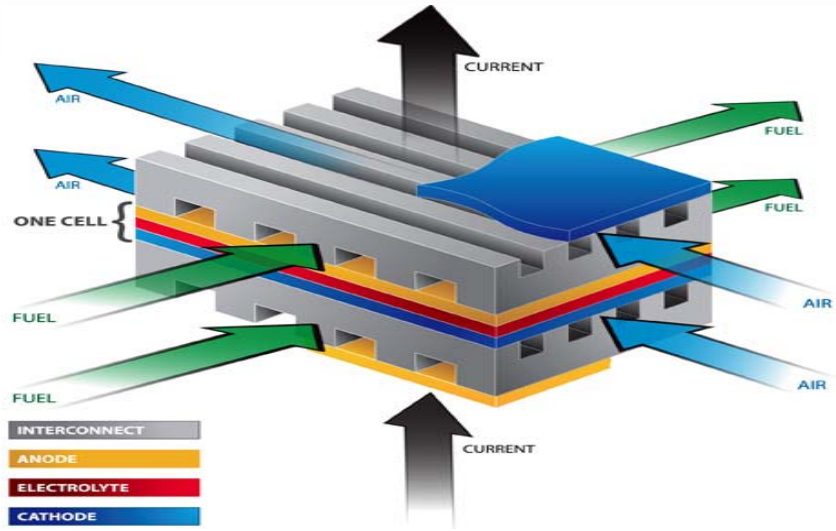

Assessment of the Distributed Generation Market Potential for Solid Oxide Fuel Cells

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U.S. DEPARTMENT OF ENERGY

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Executive Summary

The focus of the solid oxide fuel cell (SOFC) program at the National Energy Technology Laboratory (NETL) is to develop low-cost, highly efficient solid oxide fuel cell power systems that are capable of simultaneously producing electric power with carbon capture when integrated with gasification. To accomplish this goal, research and demonstration projects are being undertaken to enhance the reliability and the robustness of the SOFC system. NETL's SOFC technology roadmap is focused on developing and demonstrating progressively larger megawatt electric (MWe) class natural-gas-based systems to validate and advance SOFC technology for natural gas and gasified coal-based utility scale power generation. As the SOFC technology advances from its current state to utility scale, it is possible that MWe class systems could penetrate the distributed generation (DG) market segment. If the SOFC technology were to penetrate the DG market, this would have the added benefit of lowering system costs by establishing operational experience and a manufacturing base.

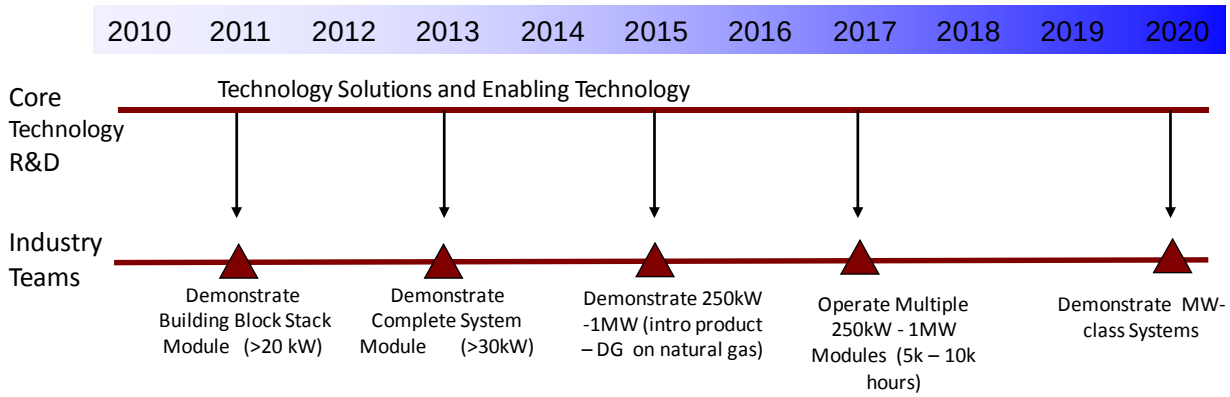
This report analyzed the strengths of the SOFC system in conjunction with relevant DG market segments in the United States (U.S.) and determined that natural gas compressor stations, grid strengthening, and data centers were potential early market-entry opportunities. These three DG market segments are projected to demand two gigawatts (GWs) of additional power between now and 2018 and 25 GWs between now and 2040. Historical experiences with related technology, including effects of increased production capacity on capital costs, were used to evaluate the market penetration necessary for a cost competitive DG SOFC system. This analysis showed that the DG SOFC system becomes cost competitive with other fossil-fuel based DG technologies after 25 MWe of installed capacity, around 2025, based on the demonstration of the first SOFC DG unit in the year 2020. The SOFC DG application validates and enables the technology for utility scale systems with carbon capture, and forms an essential first phase of the NETL technology development roadmap, which is based on the vision to develop a commercially competitive utility-scale system with carbon capture.

1 Introduction

The nearly reversible process of electrochemical conversion of chemical energy to electrical energy using fuel cells has long been recognized as one of the technologies that can revolutionize the power generation industry. In particular, the solid state technology of solid oxide fuel cells (SOFC), with its potential to generate power at electric efficiencies that are higher than conventional Carnot-cycle based heat engines, has been considered to be well-suited for stationary power generation. (1) In addition, the ability of these systems to harness the energy from syngas in a fashion that is environment-friendly, with negligible nitrogen oxide (NOx) emissions, combined with their amenability to carbon capture is highly synergetic with the mission of the National Energy Technology Laboratory (NETL) to develop technologies to generate clean power with coal. Accordingly, NETL has been leading the research and development (R&D) of progressively larger SOFC systems that would culminate in the evolution of a large-scale central power generation systems, which has the potential to meet the transformational goals envisioned in the 2040 time frame. The R&D focus of the near-term NETL SOFC program, shown in Exhibit 1-1, is to enhance the reliability and the robustness of the SOFC systems through the development and demonstration of MW-class natural-gas-based systems while exploiting their marketability in distributed generation (DG) applications. The long-term vision of the program is to utilize the manufacturing and operational experience established by the development of commercial MWe-class natural-gas-fueled DG SOFC systems to validate and advance the technology for natural gas (NG) and gasified coal-based central power generation.

This report explores relevant segments of the United States' (U.S.) distributed generation market that are potentially early market-entry opportunities for SOFC systems. Historical experiences with related technology, including effects of increased production capacity, were used to evaluate market penetration of a DG SOFC system based on the development of a reference plant design, which meets the needs of the identified markets while being consistent with industrial system projections. The envisioned path to SOFC deployment for utility-scale applications to meet NETL goals and its synergy with the DG SOFC experience will be discussed.

Exhibit 1-1 Near-term SOFC program timeline



2 DG Market Opportunity

The ability to provide base load power at high efficiency, which minimizes CO_2 emissions, with negligible NOx, sulfur oxides (SOx), and noise pollution supplemented by the availability of waste heat, form the core of the SOFC strengths that match well with the requirements of typical DG applications. Key market characteristics that are important to the market-entry of a new technology such as the SOFC include:

- Unit size compatibility
- Regulatory Environment
- Small group of buyers/large number units versus a large number of buyers/large number of units in market segment
- Trade-off between reliability and economics
- Capital cost versus cost of electricity (COE)

Due to their high efficiencies, SOFCs can be marketed for environmental friendliness allowing other market forces such as public relations to enable market entry at premium prices through early-technology adopters.

Typical characteristics of the DG market, distinguished by its two main market segments, electric power and combined heat and power (CHP), are shown in Exhibit 2-1. The CHP market appears to be an opportunity for the SOFC systems in the longer term, primarily due to the lack of near-term market opportunity, shown in Exhibit 2-2, which is exacerbated by the relatively high capital cost anticipated with the initial SOFC systems. On the other hand, NG compressor stations, electrical substations, and data centers, which fall under the electric power segment, represent a significant near-term opportunity for SOFC systems with over 2 GW of market potential, as shown by an assessment of the DG market in Exhibit 2-3**,** based on a study by Pike Research. (2) Assuming the usual market growth rates (3), the electric power segment can be forecasted to be greater than 25 GW by 2040 and represents a considerable market opportunity even in the long term.

Exhibit 2-1 DG market segment and characteristics

DG Market Segment	Applications	Characteristics
Electric Power	Electrical substations Natural gas compressor station power Data centers Back-up power (e.g. offices, large-scale commercial) Enhanced Oil Recovery	Opportunities for base-load power Focused customer base (small group of buyers, large number of units) Risk of grid failure important driver
Combined Heat & Power (CHP)	Large commercial (e.g. hotels, hospitals) Institutional (e.g. colleges, military bases, museums) Small retail and related applications Municipal	Dispersed U.S. customer base Established incumbent technologies Low cost required for market entry

Exhibit 2-2 CHP market opportunity (2)

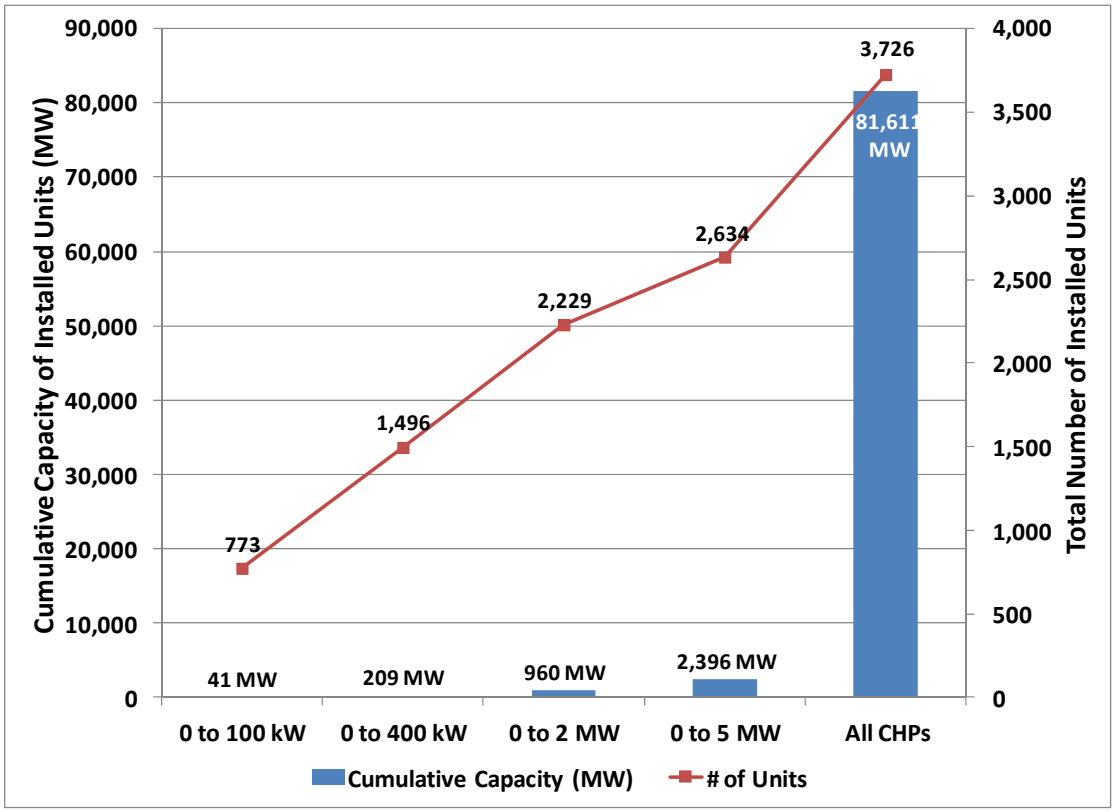
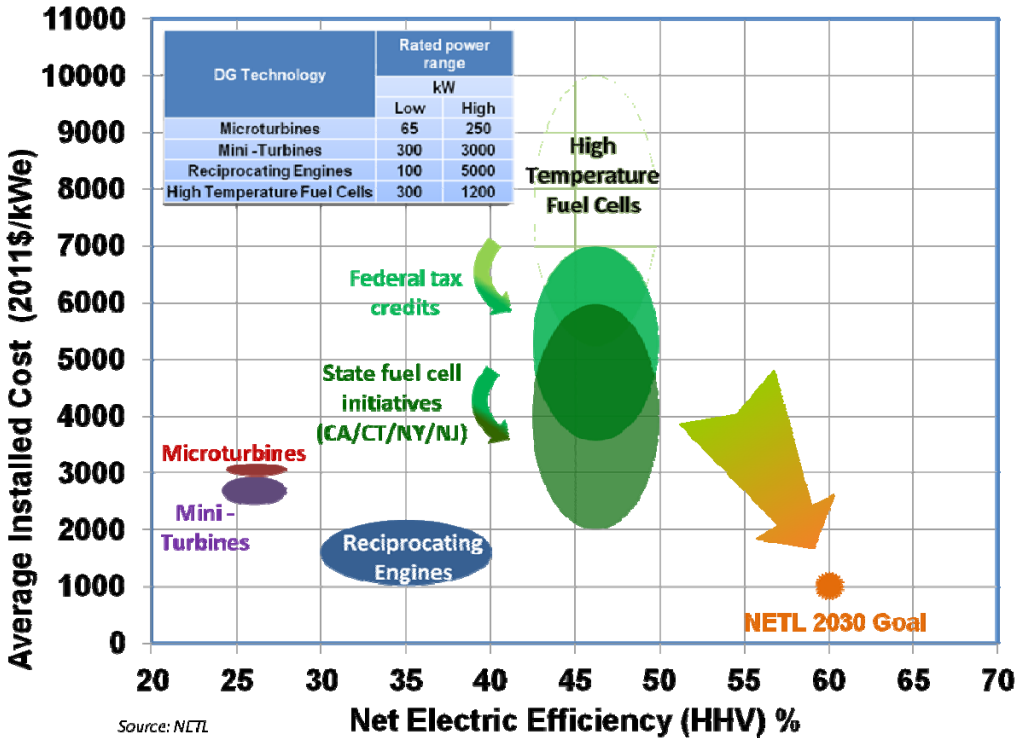


Exhibit 2-3 DG market potential

DG Market Segment	Applications	2011 - 2018 Market Growth	DG Unit Size (80% of market)
Power	Natural gas compressor stations power	1.4 GW	5 kW – 1 MW
	Electrical substations: grid strengthening	500 MW	1 – 2 MW
	Data centers (central): prime power	6 MW	5 kW – 1 MW
	Electrical substations: backup power	?	> 5 kW
	Large-scale commercial: online backup power	2 GW	300 kW – 1.5 MW
	Offices: online backup power	2 GW	100 – 500 kW
CHP	Large commercial CHP	900 MW	200 – 800 kW
	Institutional CHP	500 MW	> 500 kW – 1.5 MW
	Small commercial CHP	800 MW	4 – 60 kW
	Municipal CHP	400 MW	> 400 kW – 1.5 MW

Exhibit 2-4 shows a comparison of the average installed costs for current commercial high temperature fuel cells (molten carbonate and SOFC) and conventional heat engine-based technologies such as the reciprocating engines, the micro turbines, and the mini turbines, all of which also compete in the DG arena. (4), (5), (6), (7), (8), (9), (10), (11) Microturbines, ranging in sizes from 50kW to 250kW, and mini-turbines comprising the range from 300kW to 3 MW, are relatively newer classes of gas turbine technologies that are particularly suited for DG applications. Propelled by advancements in the underlying internal combustion engine technology, the reciprocating engines, which have lower capital costs and higher electrical efficiencies than the micro and mini turbines, are leading contenders in the DG market. Although both these technologies have the ability to provide stable and reliable power and are amenable to modularization too, the SOFC technology, which produces negligible SOx and NOx pollutants while releasing 30 percent less CO_2 for a given power rating, has a significantly smaller emission footprint. Current subsidies, including federal tax credits and state fuel cell initiatives (7), (8), (9), (10), (12) lower the cost to the end-consumer enabling the fuel cells to compete with the other DG technologies. However, the goal of the NETL SOFC technology development plan, presented in Section 3, is to enable fuel cell technologies to be commercially competitive with other fossil-fuel based DG systems without assistance from subsidies. Commercial competitiveness can be achieved by reducing the cost of the DG SOFC system to below $1000/kWe in 2030.

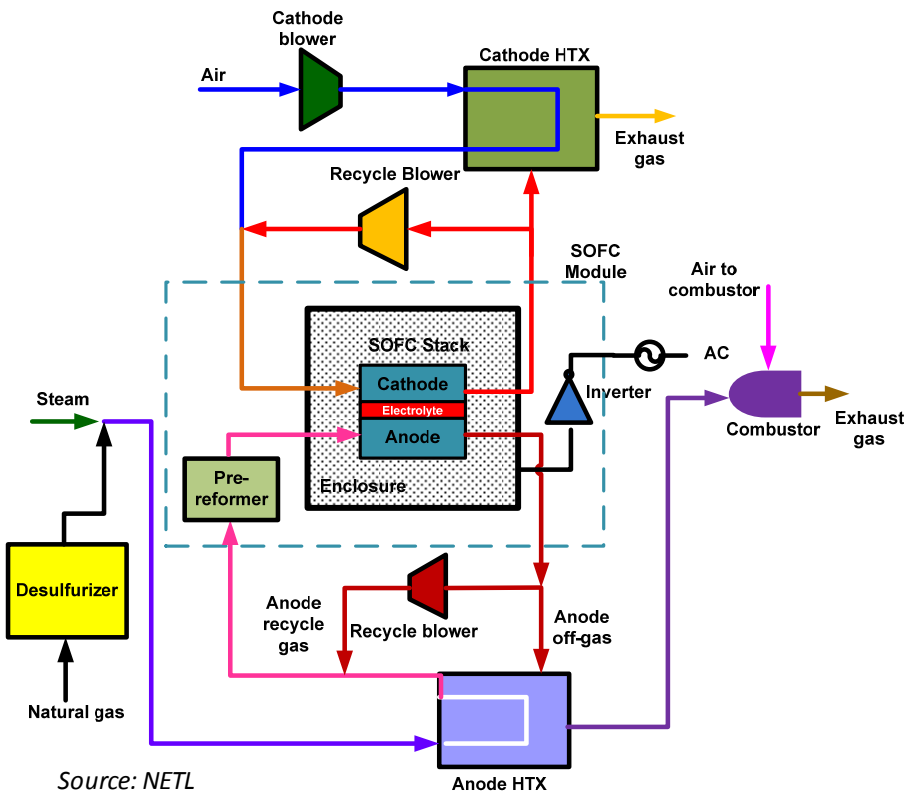
Exhibit 2-4 Current status of Fossil-Fuel DG technologies (4) (5), (6), (7), (8), (9), (10), (11), (12)



3 SOFC Technology Development Plan

Based on current industry developments (13), (14), the SOFC DG process shown in Exhibit 3-1, which features internal (to the stack) reformation of NG, was selected as the reference configuration for the technology development. Desulfurized NG is fed directly to the SOFC module and mixes with the recirculated anode off-gas, which supplies the steam required for reformation of inlet NG to syngas. To prevent cracking and deleterious carbon formation, a pre-reformer, which converts the higher hydrocarbons into methane, is generally included before completing the reformation internal to the stack. Internal reformation, while eliminating the need for specialized process equipment, utilizes part of the heat generated in the stack directly for the endothermic reformation reaction, and reduces consequently the air flow rate needed to maintain a desired stack temperature gradient resulting in higher process efficiency. Air supplies the oxidant to the cathode, and heat exchangers on both the anode and cathode side are appropriately designed to keep the desired temperature gradient across the stack. The heat that is created from burning the electrochemically unutilized fuel is available for further use.

Exhibit 3-1 Reference SOFC DG process



Source: NETL

The reference process was modeled using Chemcad (Chemstations, Inc.) and the corresponding system efficiency was computed to be 52.0 percent (relative to the higher heating value [HHV] of the incoming natural gas) assuming current SOFC performance. Exhibit 3-2 shows the evolution of the technology, envisioned according to the timeline shown in Exhibit 1-1. The first 1 MW class DG unit, targeted to be brought online in 2020, features a higher efficiency of 61.3 percent (HHV), reflecting advances in SOFC performance and stack design, which can support

fuel utilization values as high as 90 percent. During this R&D phase, the primary focus will be to improve the stack degradation rate from the current 1.5 percent per 1000 hrs to a commercially viable value of 0.2 percent per 1000 hrs, typical for other conventional technologies. (15) The stack cost target for the Nth of a kind unit assuming mass-manufacturing related cost advantages along with learning from repetition and increased capacity, is 225 $/kWe in 2011 dollars, which corresponds to stack cost target of 175 $/kWe in 2007 dollars set in earlier programs. (16) The escalation of the stack cost from 2007 dollars to 2011 dollars was based on a bottoms-up approach and is explained in the NGFC update study. (17) The Nth of a kind commercially competitive DG unit transitions to the evolution of large-scale power plants, culminating in the development of the Nth of a kind utility-scale natural gas fuel cell (NGFC) plant with carbon capture.

Exhibit 3-2 SOFC technology development plan

	Today's SOFC DG	2020 SOFC DG (1st 'Unit')	Nth of a Kind SOFC DG (Advanced Performance)	Early Utility NGFC Plant with CCS
Capacity	>30kW	250kW – 1 MW	Up to 5 MW	≥ 100 MW
Carbon Capture	No	No	No	Yes (>95%)
NG Reforming	Internal	Internal	Internal	Internal
Cell Overpotential, mV	140	70	70	70
Fuel Utilization, %	80	90	90	90
Degradation, %/1000 hr	1.5	0.2	0.2	0.2
System Efficiency, % (HHV)	52.0	61.3	61.3	64.2
SOFC Commercial Stack Cost Target, $/kW (2011$)	N/A	N/A	225	225

4 SOFC DG Performance and Costs

Exhibit 4-1 lists the salient operating and design parameters used in the evaluation of the performance of a 1 MWe SOFC DG reference system modeled in Chemcad based on the process shown in Exhibit 3-1 and corresponding to the assumptions of the technology development plan, shown in Exhibit 3-2.

Exhibit 4-1 Design and operating parameters of 1 MWe SOFC DG reference system

Parameter	Today's SOFC DG	2020 SOFC DG (1st 'Unit')	Nth of a Kind SOFC DG (Advanced Performance)
Net AC Power, kW	1000		
Operating Pressure, atm	1.0		
Operating Temperature, C (F)	750 (1382)		
Natural Gas Feed, lb/hr	321.5	272.7	
Cell Voltage, V	0.792	0.830	
Current Density, mA/cm^2	400	400	

Inverter Efficiency, %	97	97
Auxiliary Loads, kW	24	24
Net AC Efficiency (LHV)	57.6	67.9
Net AC Efficiency (HHV)	52.0	61.3

The capital costs for the Nth of a kind DG system in 2011 dollars, categorized into module and balance of plant (BOP) costs and itemized by the major components, are tabulated in Exhibit 4-2. An additional area of 10 percent, over and above the nominal design area, is installed to compensate for the 0.2 percent per 1000 hrs degradation. This is based on the results of a detailed study (17), which included consideration of linear and first-order degradation models and stack operational scenarios, to optimize the amount of additional area, taking into account the stack lifetime along with the stack-replacement frequency.

Exhibit 4-2 Nth of a kind SOFC DG system capital costs (2011$)

Module costs ($/kWe)	2011$
SOFC Stack	225
Enclosure	30
Transport & Placement	14
Site Foundations	44
Inverter	68
Pre-Reformer	29
Total Module	411
Total Module with 10% extra installed area for 0.2%/1000 hr stack degradation	452
BOP costs ($/kWe)	2011$
NG Desulfurizer	110
Cathode Air Blower	18
Cathode Recycle Gas Blower	45
Cathode Heat Exchanger	56
Anode Recycle Gas Blower	17
Air Combustor	51
NG Pre-Heater	2
Accessory Electric Plant	199
Instrumentation &Control	33
Total BOP	531
Total System ($/kWe)	983

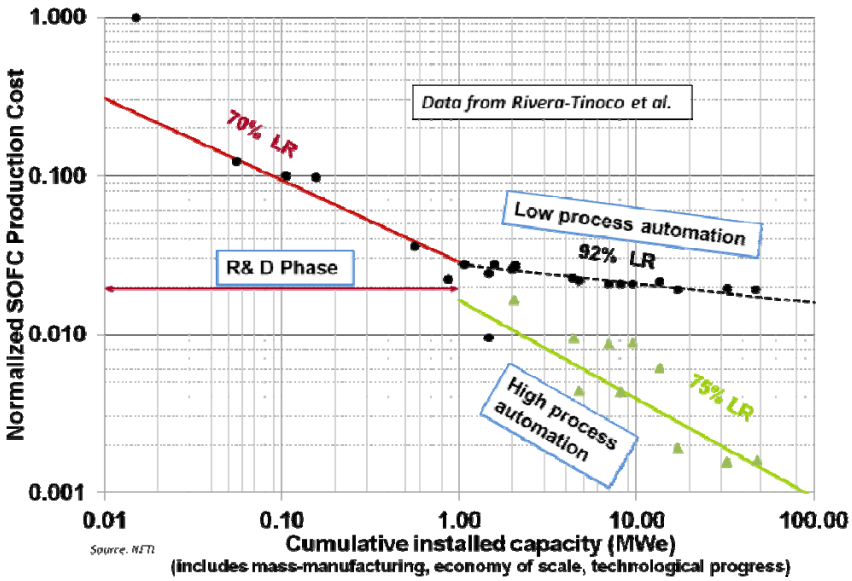
5 SOFC Cost Reduction Roadmap

The learning or experience curve is a standard method (18) used in the industry to project production costs for an Nth of a kind unit based on the cost of the first unit. Forecasting models, including the National Energy Modeling System (NEMS), rely on this curve to predict future costs. (19) It is based on cost reductions observed with the increase in installed capacity due to repetitive reproductions of a unit of the same technology. The most commonly used curve is based on the premise that cost reductions take place every time the cumulative production is doubled.

The ratio of the cost after doubling the capacity to the original cost is termed the learning rate (LR) and generally varies directly with the maturity of the technology. The lower the maturity of

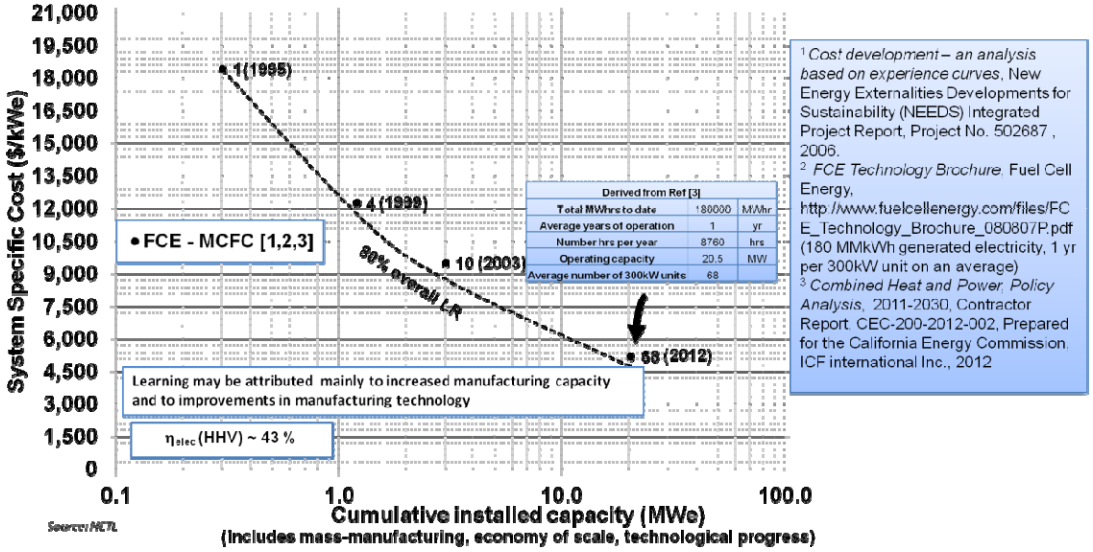
the technology, the lower the LR, implying a higher cost reduction percentage with each doubling in capacity. While there is limited data on the learning rates that can be associated with SOFC technology, the H.C. Starck SOFC production experience, discussed in the study of Rivera-Tinoco (20) and shown in Exhibit 5-1[1], along with the molten carbonate fuel cell experience depicted in Exhibit 5-2 (4), (21), (22) indicate that learning rates as high as 80 percent are realizable due to the relatively low maturity of the fuel cell technology. A learning rate of 80% indicates that the cost of a SOFC system will drop 20% with each doubling of installed SOFC capacity.

Exhibit 5-1 H.C. Starck SOFC production learning curve (20)



[1] Note that the production capacity in Exhibit 5-1 is based on the maximum production capacity of the factory and does not reflect actual capacity installed.

Exhibit 5-2 Molten carbonate fuel cell experience (4), (21), (22)



The learning curve methodology was used in charting a cost curve for the DG SOFC system along the developmental roadmap, to discern the potential cumulative installed capacity needed for cost competitiveness with other DG technologies. A learning rate of 80 percent was assumed for the SOFC module, according to the discussions afore, and a 90 percent learning rate was employed for the relatively more mature BOP technologies, during the large-scale manufacturing phase where the units of the class of the first DG units are manufactured.

More specifically, the learning curve methodology was used to work backwards from the target cost of the Nth of a kind MWe-class SOFC plant to determine the cost needed for the first of a kind MWe-class SOFC plant. The target cost for the Nth of a kind MWe-class plant is given in Exhibit 4-2 as about $1000/kWe. This cost target is hoped to be realized after 1 GWe of these SOFC plants are installed based on the DG market potential discussed in Section 2. Given the learning rates and target cost for the Nth of a kind plant, the resulting cost learning curve is presented in Exhibit 5-3. The cost of the first of a kind SOFC DG unit is projected to be about $5700/kWe in Exhibit 5-3. For the SOFC units to become cost competitive with other DG technologies, the cost of the SOFC must fall to about $2500/kWe. The cost curve in Exhibit 5-3 indicates that about 25 MWe SOFCs must be installed for the cost of the first of a kind unit to fall into this range.

Assuming a learning rate of 80 percent for both the module and the BOP, during the initial R&D phase before the demonstration of the first reliable 1 MWe DG unit, yields a today's system cost of ~ 12,000 $/kWe. The costs along the learning curve during the R&D phase are consistent with the costs of about 7,000 to 10,000 $/kWe that are cited for the SOFC systems from Bloom (6), (7), (10), (11), (23), which represent costs after the deployment of several of their 100 kWe units. The learning rate during the R&D period is an apparent average learning rate that, in addition to increases in installed capacity, is a result of mass-manufacturing, technological progress, economies of scale, and process automation. The sensitivity of the learning curve to the learning rate and its impact on the cumulative capacity required for cost competitiveness with other DG technologies are discussed further in the appendix.

The corresponding variation of the COE[1] of the SOFC DG unit, plotted in Exhibit 5-4 as a function of installed capacity, for different natural gas prices shows that the DG units become cost competitive earlier at higher natural gas prices. When compared on a COE basis, the SOFC DG system becomes attractive even at installed capacities as low as 20 MWe (NG price = 6.55 $/MM Btu) due to its much higher electrical efficiency relative to the competing DG technologies. While stack degradation has been taken into account in the COE calculations (17), the estimation of operation and maintenance (O&M) costs introduces uncertainties, especially in comparison to other DG technologies with relatively mature O&M costs. A listing of the assumptions used in evaluating the COE is provided in the appendix along with a discussion of the sensitivity of the COE to the O&M labor. The influences of the SOFC stack cost and the stack degradation rate on the cumulative installed capacity required for cost competitiveness with competing fossil-fuel based DG technologies are also presented in the appendix.

Assuming that the year 2030 corresponds to the Nth of a kind DG SOFC unit (1 GW cumulative installed capacity), the capital cost reduction timeline based on the learning curve, shown in Exhibit 5-5, indicates that a commercial DG product is realizable around 2025, based on the demonstration of the first DG unit in 2020. An estimation of the production costs along the learning curve is depicted in Exhibit 5-6 along with any deficit/surplus, assuming the ability to sell at a price of 2000 $/kWe. It is beneficial from an economic perspective to invest in R&D to bring the cost down to a reasonable value before embarking on large scale manufacturing with reliance on increased capacity to achieve the cost goal. The impact of the initial DG SOFC system cost on the investment needed to break-even with a selling price of 2000 $/kWe is discussed in the appendix.

[1] A capital charge factor of 12.43% corresponding to a 5-yr high-risk financial assumption was used.

Exhibit 5-3 System specific cost learning curve with installed capacity

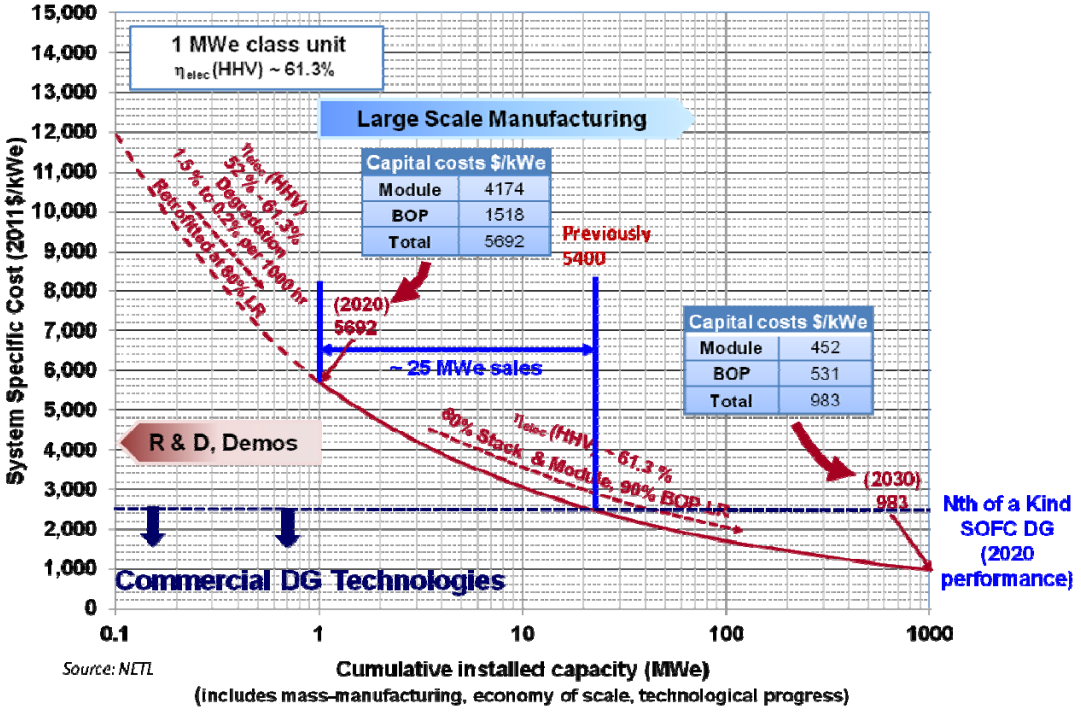


Exhibit 5-4 Cost of electricity with installed capacity for different NG prices

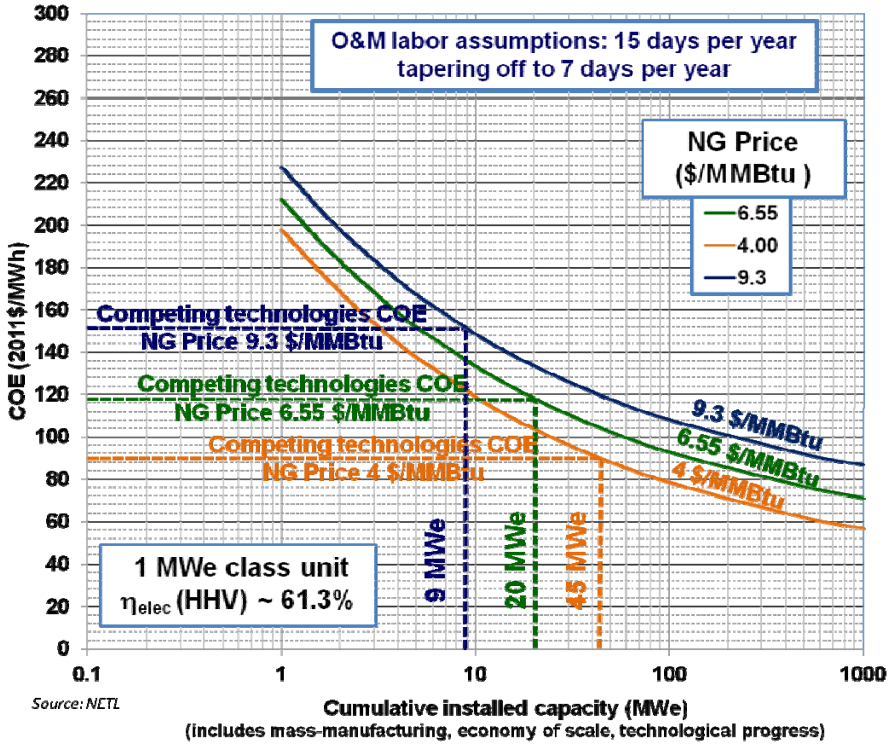


Exhibit 5-5 System specific cost timeline

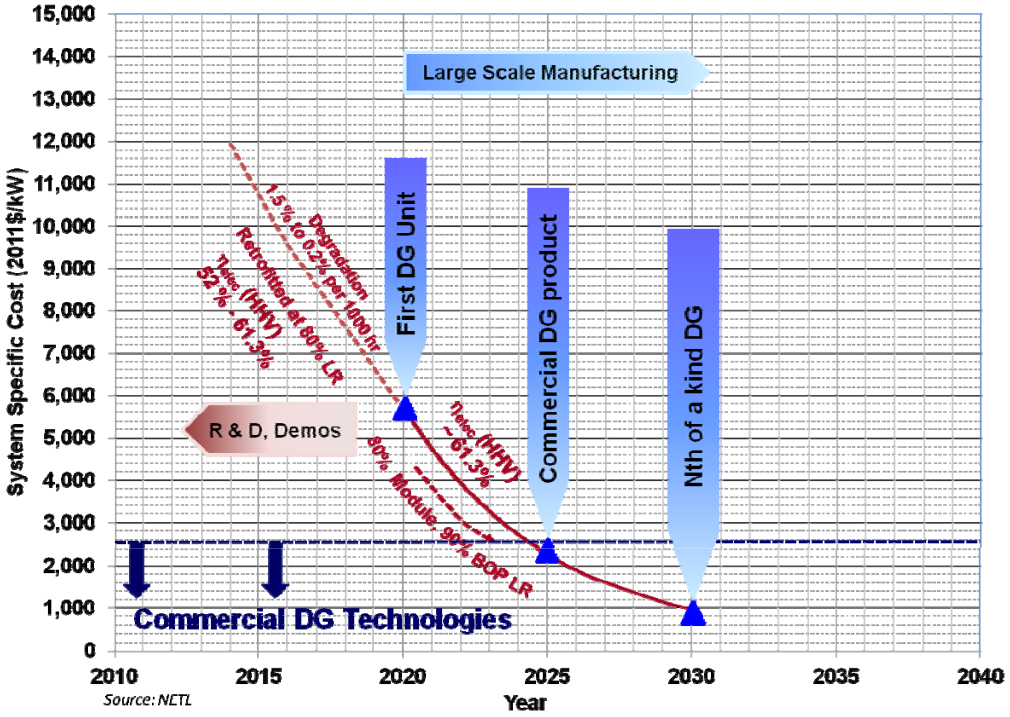
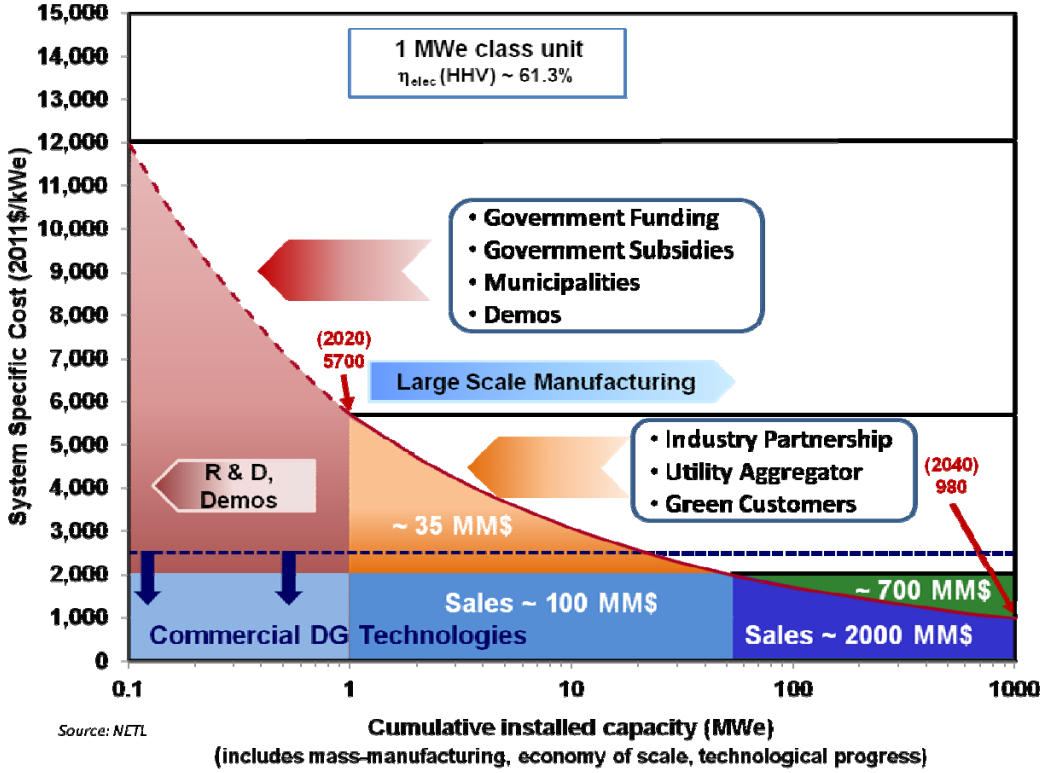


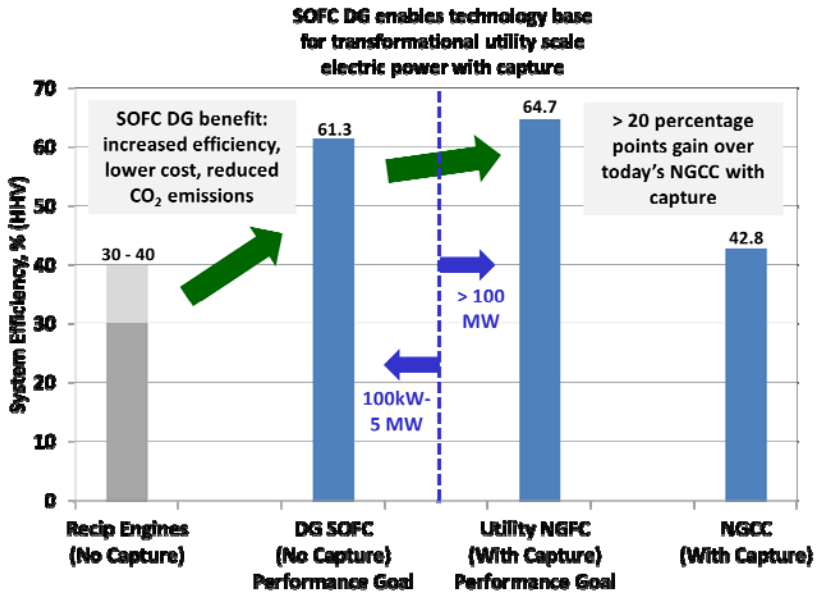
Exhibit 5-6 Projected SOFC system cost



6 Path to utility scale NGFC

As shown in Exhibit 6-1, the MWe-class SOFC DG unit enables the underlying technology for expansion to a utility-scale NGFC system while validating a sealed SOFC system operating at high-fuel utilization (90 percent), both of which facilitate more than 98 percent carbon capture rates. The resulting NGFC system with carbon capture has a potential to operate at efficiencies exceeding 64 percent, at least 20 percentage points higher than today's NGCC cycle with carbon capture, at a cost of electricity that is ~ 18 percent less than the latter. (17) Meanwhile, advances in the gasification and gas clean-up arena will pave the way to the realization of an environmental friendly integrated gasification fuel cell (IGFC) utility-scale system fueled with coal.

Exhibit 6-1 SOFC DG path to an utility-scale NGFC system with carbon capture



7 Conclusion

It was found that a MWe class SOFC system with efficiencies greater than 60 percent along with the associated reduction in CO_2 emissions is particularly suited in the near-term to DG electric power applications, a market segment with significant capacity. Learning curves showed that the SOFC DG system becomes cost competitive with other fossil-fuel based DG technologies after 25 MWe of installed capacity, around 2025, based on the demonstration of the first DG unit in the year 2020, and is consistent with the technology development plan. Higher natural gas prices tend to reduce the time to commercialization due to the higher efficiency of the SOFC DG system. Finally, the SOFC DG application validates and enables the technology for utility scale systems with carbon capture and forms an essential first phase of the NETL technology development roadmap, which is based on the vision to develop a commercially competitive utility-scale system with carbon capture.

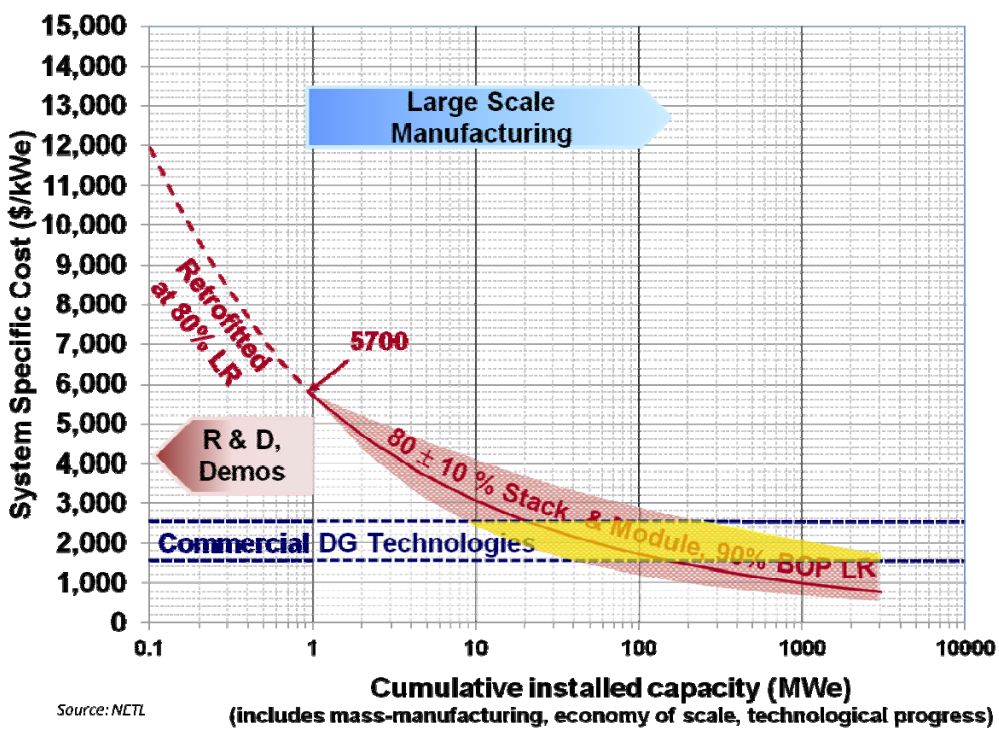
8 Appendix A Sensitivity to Salient Parameters

Sensitivities of the cost competitiveness of the SOFC DG system to the learning rate, the stack cost, and the stack degradation rate are explored in this appendix. The impact of the O&M labor on the COE of the SOFC DG system is also discussed. In addition, the influence of the first DG system cost on the investment cost required (during the production phase) before the SOFC DG system cost becomes equal to the assumed selling price of 2000$/kWe (based on the cost of alternative DG systems) is evaluated.

Sensitivity of the Cost-Competitiveness of SOFC DG System Cost to the Learning Rate

Exhibit A- 1shows the system cost specific learning curve variation for module and stack learning rates varying ± 10 percent from the 80 percent learning rate assumed in Exhibit 5-3. The BOP learning rate was fixed at 90 percent, and the first DG system specific cost was fixed at ~ 5700 $/kWe (as in Exhibit 5-3). The SOFC DG system becomes cost-competitive at a cumulative installed capacity value of ~ 10 MWe at the 70 percent learning rate while at least 200 MWe of installed capacity is required to realize the same objective at the 90 percent learning rate. Module and stack learning rates of at least 80 percent are necessary for the SOFC DG system to be competitive at the lower bound of the commercial DG technologies, which is also shown in the Exhibit, to keep the cumulative installed capacity to a value that, within reasonable margin, is consistent with the available market size.

Exhibit A- 1 Sensitivity of the learning curve to module and stack learning rate



Sensitivity of the SOFC DG System COE to Salient Parameters

Salient assumptions used to evaluate the SOFC DG system COE are listed in Exhibit A- 2.The O&M labor requirement (15 – 7 days per year) used results in variable O&M costs that are similar to the range of reciprocating engine O&M costs (22 ~ 9 $/MWh). Since the O&M costs for the SOFC DG system are expected to be lower than the corresponding costs for the reciprocating engines, a lower bound for the SOFC DG system COE is shown in Exhibit A- 3, which assumes a minimal O&M labor of 1 day per year throughout. This is an achievable goal with mature SOFC systems, and assumes unattended operation with minimal labor time for changing air filters and swapping desulfurizer tanks. Under these assumptions, the SOFC DG system becomes competitive with other DG technologies at an installed capacity of 25 MWe even for NG prices as low as 4.0 $/MMBtu.

The cumulative installed capacity required for the COE to be competitive with other DG technologies (dashed lines indicated in Exhibit 5-4) is shown in Exhibit A- 4 for different SOFC stack costs and stack degradation rates. At stack degradation rates higher than 0.5 percent per 1000 hrs, the cumulative installed capacities required for cost competitiveness become prohibitive even at lower stack costs, highlighting the importance of current NETL SOFC programs that are focused on the reduction of the stack degradation rate.

Exhibit A- 2 Salient assumptions used in the COE calculations

Capacity factor (%)	85
Capital charge factor (High Risk - 5yr) (%)	12.43
SOFC stack life (years)	7.3
Stack degradation rate (% per 1000 hrs)	0.2
Extra stack surface provided (% of initial) to compensate for degradation	10
Time period to stack replacement (calendar years)	7.3
Discount rate for stack replacement (%)	10
Operation and Maintenance	
Maintenance labor/Operating labor	1.15
Maintenance materials/Maintenance labor	1.93
Stack replacement O&M labor rate ($/hr per stack kW)	16
Operating labor rate ($/hr)	39.7
Operating labor burden (%)	30
Operation and maintenance labor (days per year)	Linearly varying from 15 for the FOAK to 7 for the NOAK

Exhibit A- 3 SOFC DG system COE based on an O&M labor of 1 day per year

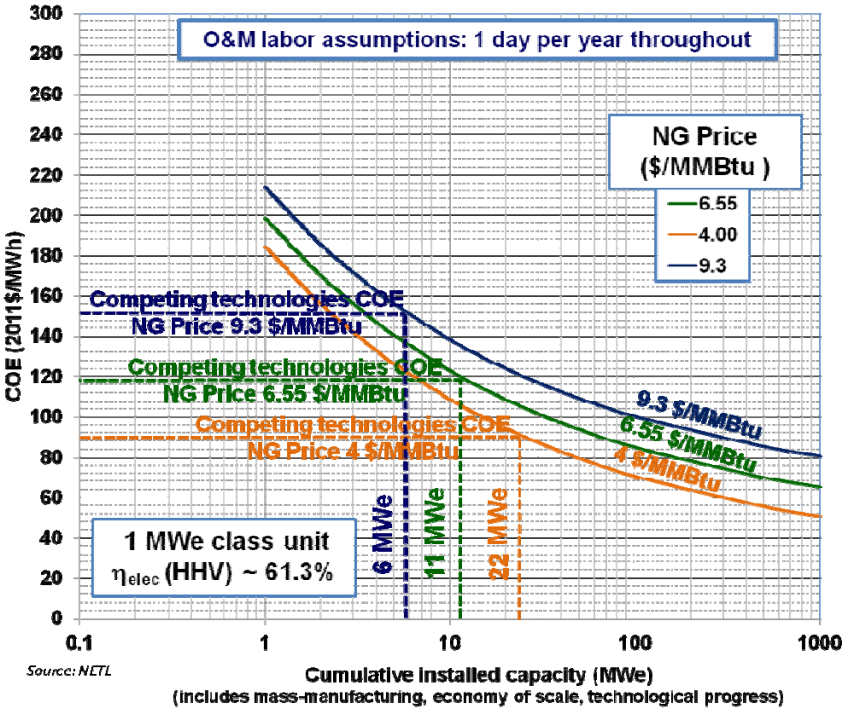
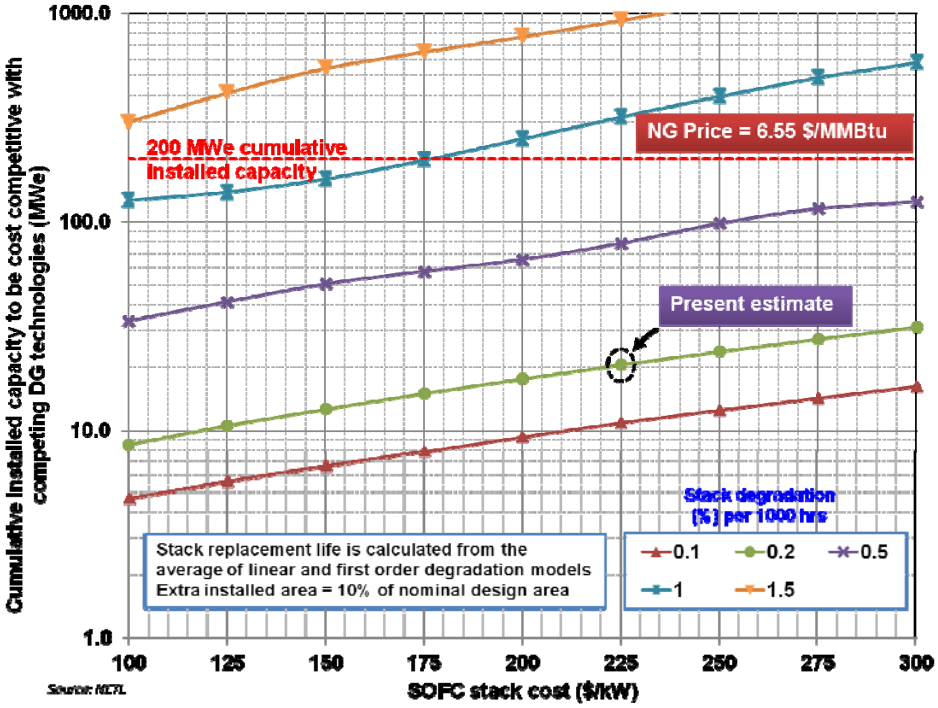


Exhibit A- 4 Sensitivity of cumulative installed capacity for cost competitiveness of the SOFC DG system to SOFC stack cost and degradation rates



Variation of Investment Cost during Production Phase with the First SOFC DG System Cost

The effectiveness of the initial R&D phase in decreasing the overall investment costs during the production phase is shown in Exhibit A- 5 where the cost of the first DG unit at the culmination of the R&D phase was varied from 5700 $/KWe to 10,000 $/kWe. This chart is analogous to Exhibit 5-6 and employs the same learning rate of 80 percent for the stack and the module and 90 percent for the BOP. As the cost of the first DG unit entering the large scale production phase increases (associated with decreases in the level of cost reduction during R&D phase) the overall investment goes up drastically for the same selling price of 2000 $/kWe. It is essential to reduce the system specific cost to below 7000 $/kWe to keep the net investment (or subsidies) during the production phase to less than 100 MM$, as depicted in Exhibit A- 6, which shows a variation of the investment needed to breakeven at the selling price of 2000 $/kWe. The corresponding cumulative installed capacity also remains at a value below 100 MWe, which is supported readily by the available market size.

Exhibit A- 5 Projected SOFC DG system cost based on different first DG unit costs

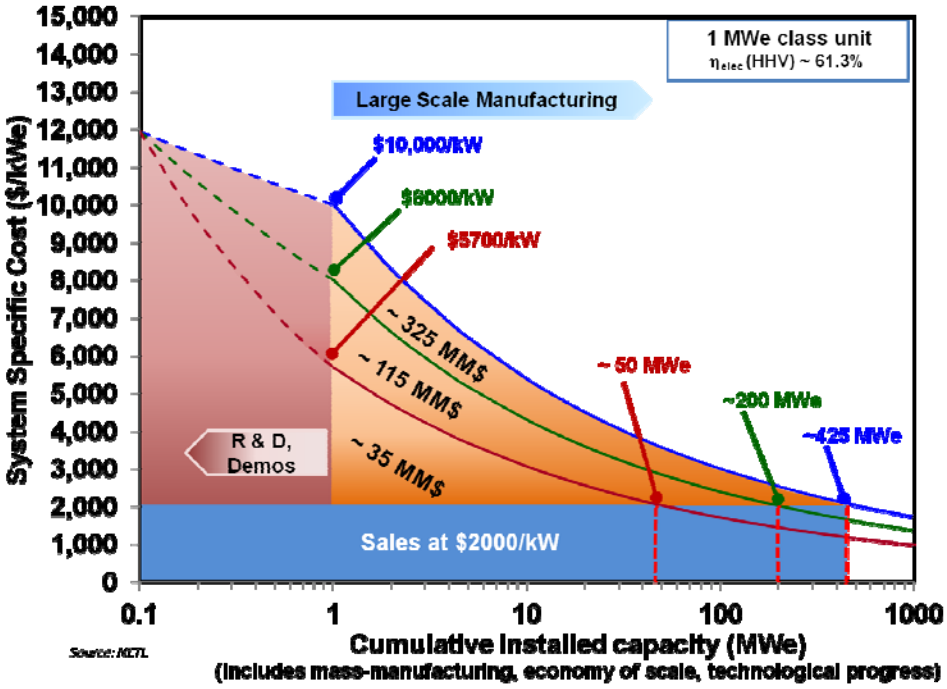
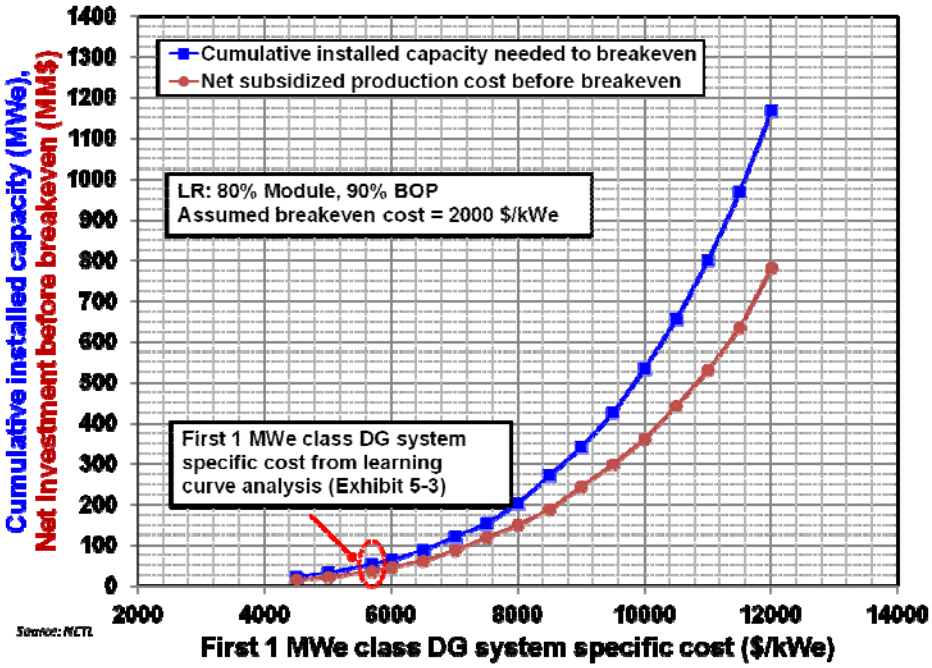


Exhibit A- 6 Variation of SOFC DG system breakeven cumulative installed capacity and total investment during production phase with first DG SOFC system cost



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