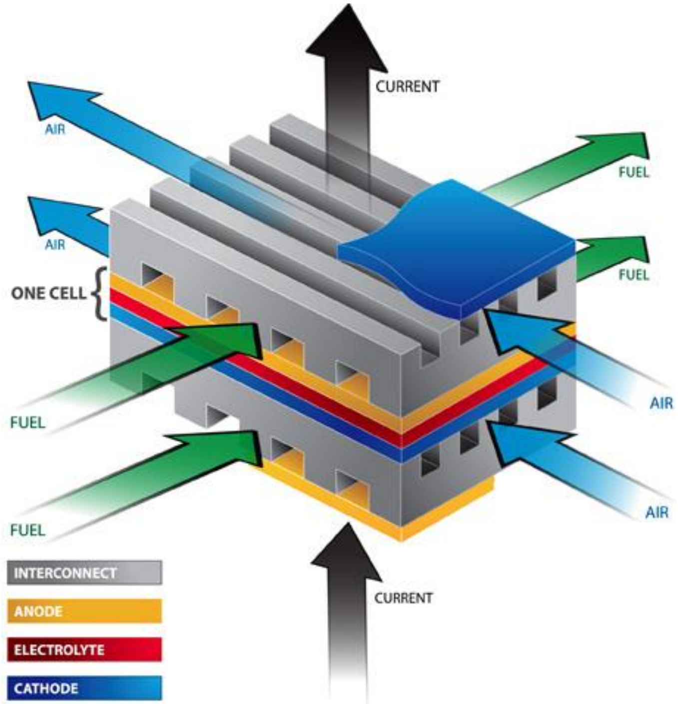



# Assessment of the Distributed Generation Market Potential for Solid Oxide Fuel Cells

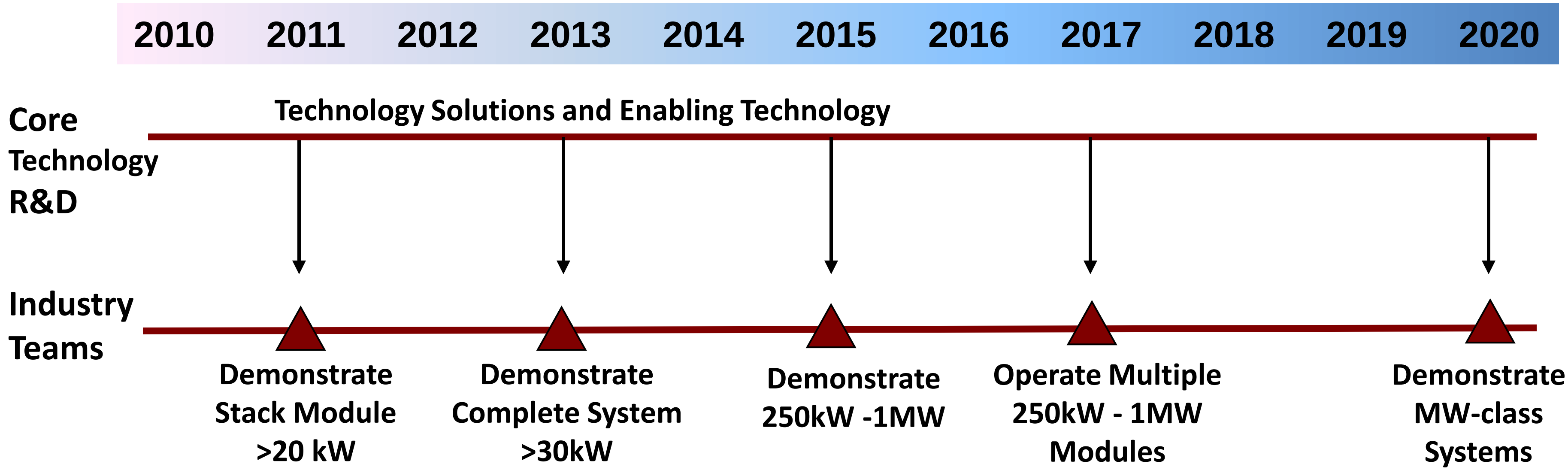
Federal Project Manager: Katrina Krulla

Analysis Team: Dale Keairns, Arun Iyengar, Dick Newby

July 23, 2013

U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

# Near-Term SOFC Program Timeline




- Progressively larger SOFC stacks and systems
- Provide the technology base to permit grid-independent distributed generation applications
- 1 MW natural gas fueled DG systems will establish the manufacturing and operational experience necessary to validate and advance the technology for natural gas and gasified coal-based central power generation

# Study Objectives

- Given SOFC technology strengths, identify relevant U.S. market segments for early distributed generation applications.

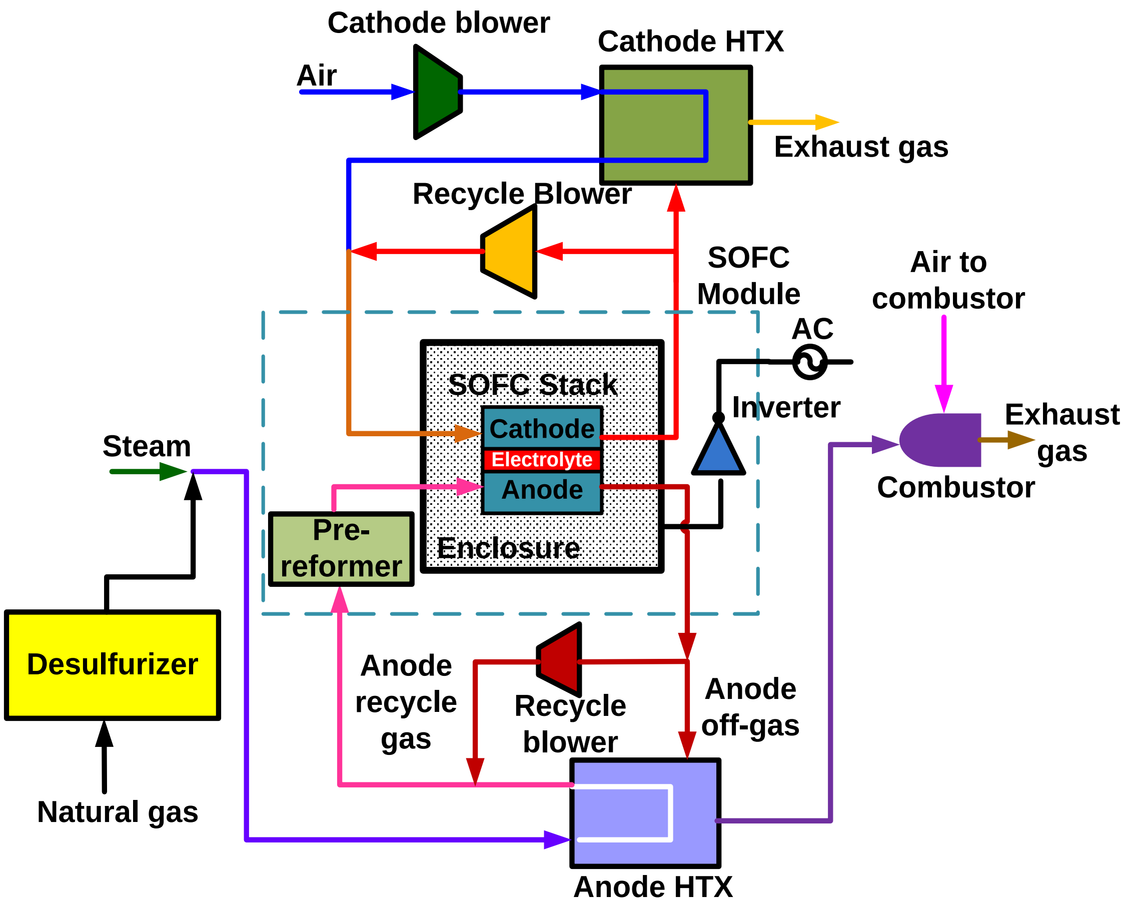
- Develop DG SOFC reference plant design (cost & performance) to meet the market need.

- Utilize related technology experience to understand market penetration necessary for a DG SOFC system to be cost competitive.

- DG path to utility scale applications.

# SOFC DG Process Concept

## *High Efficiency Minimizes $CO_2$ Emissions*




**SOFC Strengths for DG Applications**

- Base load power
- High efficiency / minimum $CO_2$ emissions
- Negligible SOx, NOx emissions
- Low noise
- Availability of waste heat

*Source: NETL*

# What Market Characteristics Are Important?

## *Focus on new technology market entry - SOFC*

- Market unit size compatible with technology capability - SOFC market entry up to 1 MWe
- Regulatory environment - self generation incentives, $CO_2$ related legislation
- Small group of buyers/large number units vs. large number of buyers/large number of units in market segment
- Reliability vs. Economics
- Capital cost vs. Cost of Electricity

# Market Assessment (U.S.)

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

# Distributed Generation Market Potential

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

**Near Term Market Opportunity >2 GW** (natural gas compressor stations, electrical substations: grid strengthening, data centers: prime power)

**Long term market (2040) >25GW**

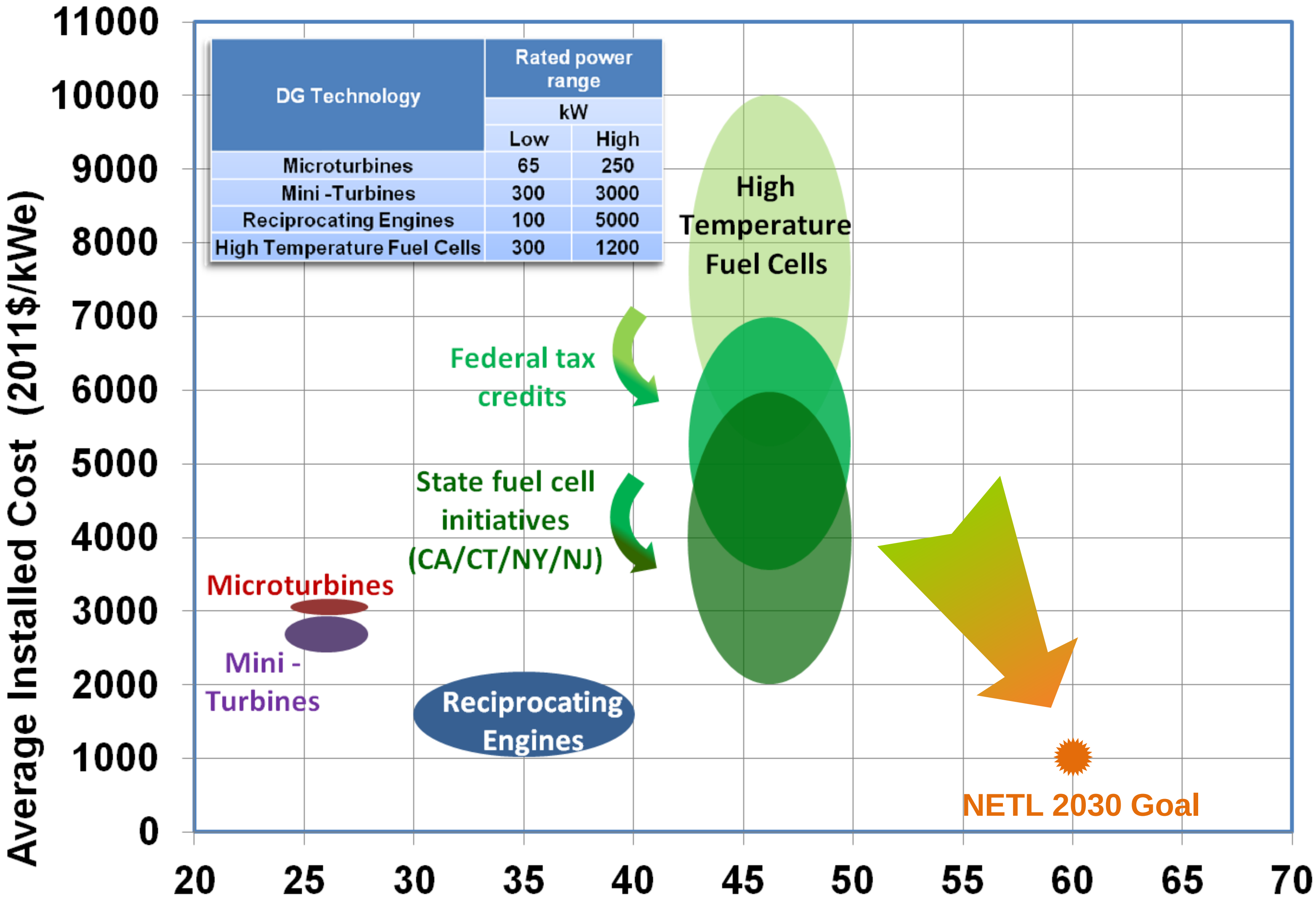
Market Assessment Informs Selection of SOFC DG Reference Plant Design: 1 MWe



*Data Source: PikeResearch is acknowledged for their contribution to informing the market potential analysis, 2040 Market forecast and 2018 Grid strengthening forecast from EIA AEO2013 Reference Case*

# Technology Performance & Cost Perspective

## *Distributed Generation – Current Status*




| DG Technology | Rated power range kW Low | High |
|---|---|---|
| Microturbines | 65 | 250 |
| Mini -Turbines | 300 | 3000 |
| Reciprocating Engines | 100 | 5000 |
| High Temperature Fuel Cells | 300 | 1200 |

*Source: NETL*



NETL

# SOFC Technology Development Plan

| | Today's SOFC DG | 2020 SOFC DG (1st 'Unit') | Nth of a Kind SOFC DG (Adv. Performance) | Early Utility NGFC Plant with CCS |
|---|---|---|---|---|
| Capacity | >30kW | 250kW – 1 MW | Up to 5 MW | $\geq$ 100 MW |
| Carbon Capture | No | No | No | Yes (>95%) |
| NG Reforming | Internal | Internal | Internal | Internal |
| Cell Overpotential, mV @ 400 mA/cm$^2$ | 140 | 70 | 70 | 70 |
| Fuel Utilization, % | 80 | 90 | 90 | 90 |
| Stack 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, $/kW (2011$) | NA | NA | 225 | 225 |

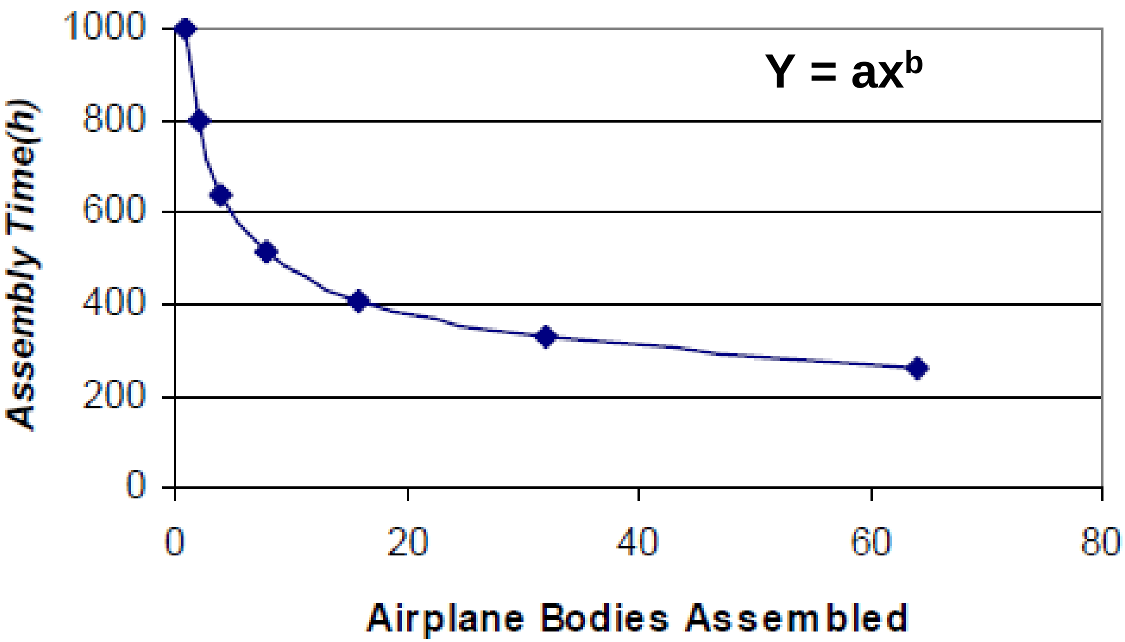
** Cost of degradation accounted for by including additional SOFC stack area*

# SOFC DG System Cost – Nth of a Kind (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** |

# Background – Learning Curves

Sample Learning Curve Function




a = Cost of first unit

x = Number of units produced

b = Learning rate exponent

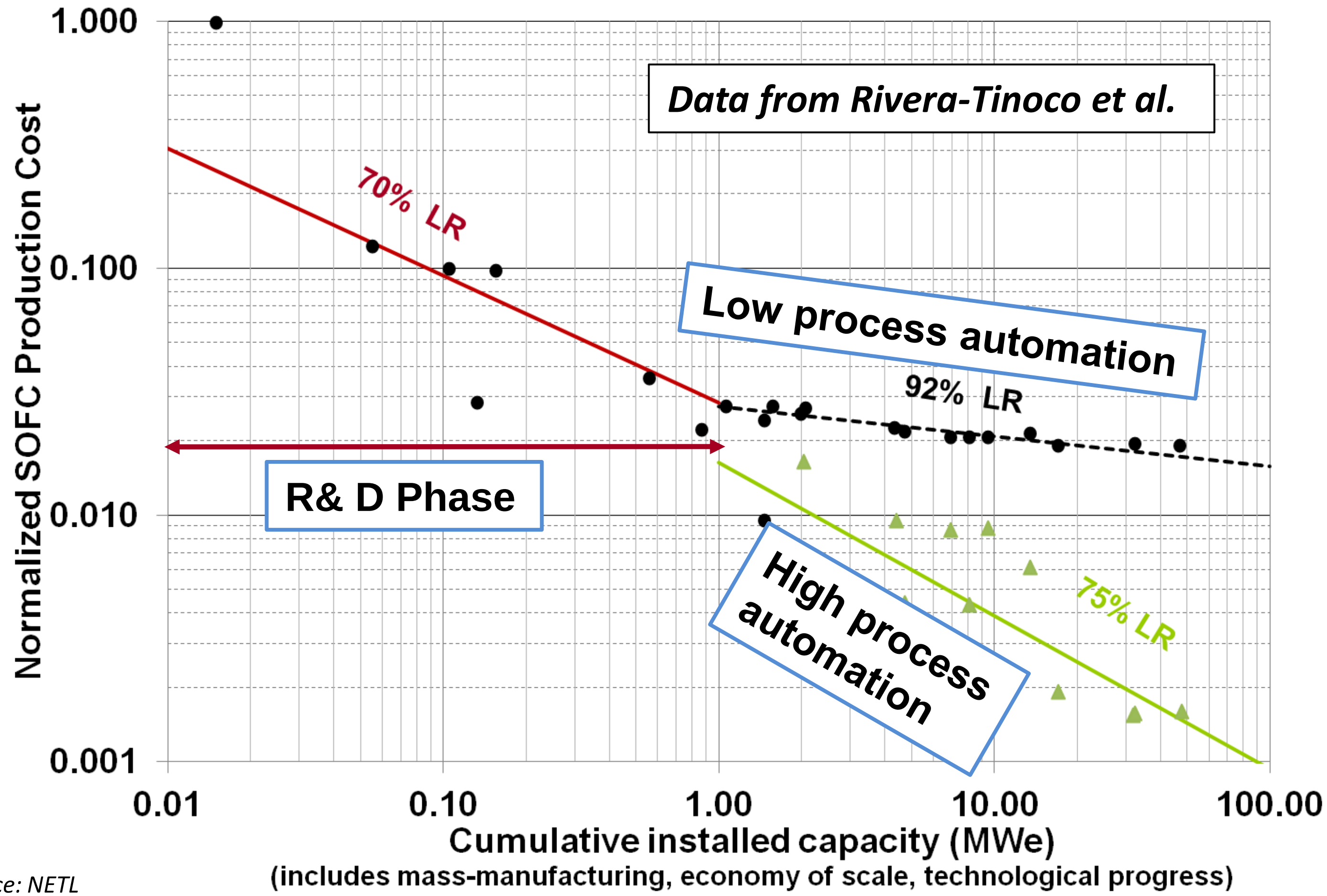
$1 - 2^{-b}$ = Learning Rate, reduction in capital cost for doubling of capacity

- Developed by Wright in 1936 after observing labor time reductions to assemble airplanes.
- In 1998 Mackay & Probert showed that a similar rule could be applied to capital cost reductions in renewable energy.
- Models including NEMS rely on this curve to predict future capital costs.

Source: "Learning and Cost Reductions for Generating Technologies in the National Energy Modeling System (NEMS)" E.Gumerman and C.Marnay. Lawrence Berkeley National Laboratory. University of California Berkeley. January 2004, http://eetd.lbl.gov/ea/emp/reports/52559.pdf

# Capital Cost Reductions

Capital cost reductions for SOFC vary between 30% - 8%



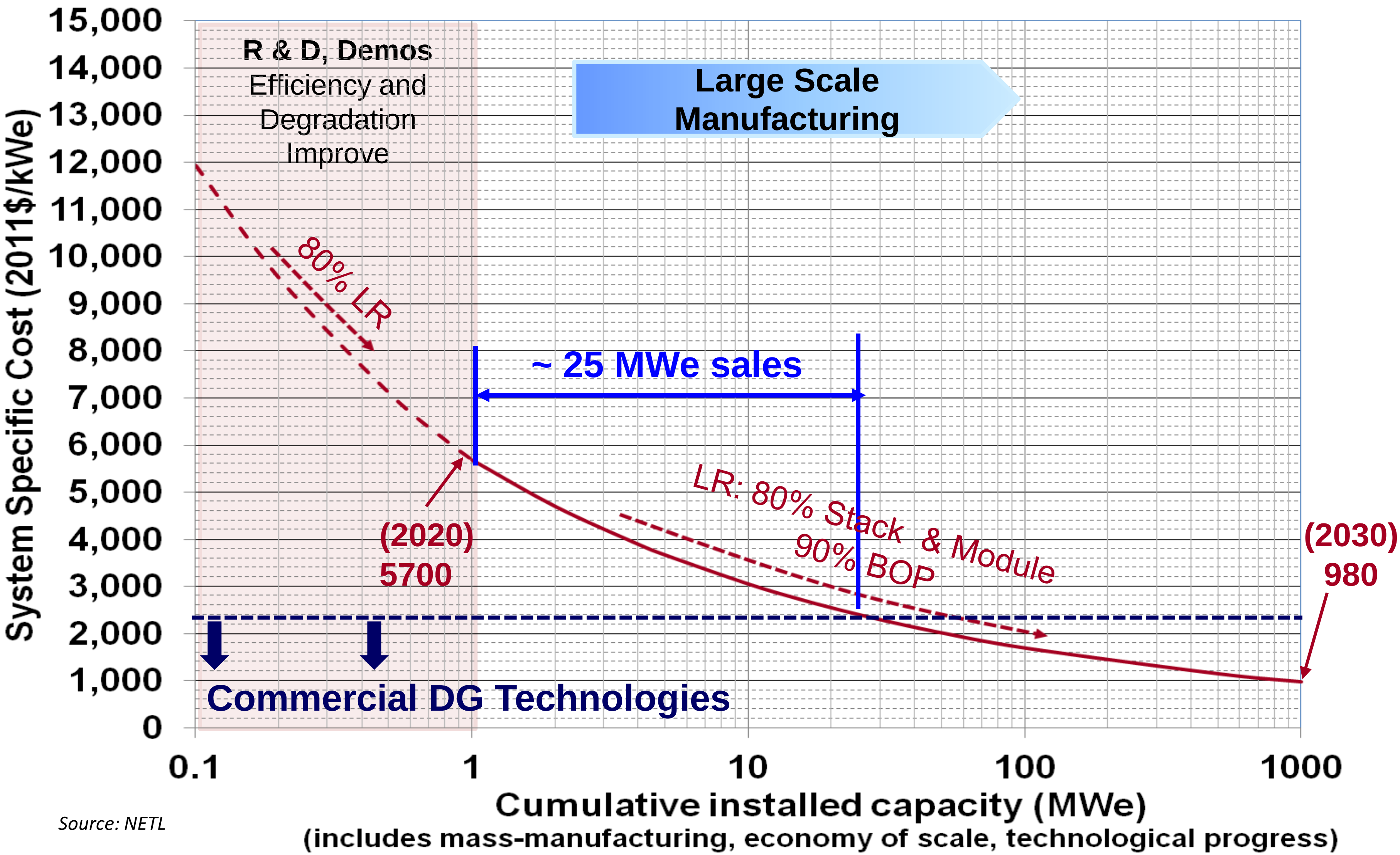

Source: NETL

***Note: LR (%) - cost /(original cost before doubling capacity )shown***


*Alan M cDonald and Leo Schrattenholzer, "Learning Rates for Energy Technologies." Energy Policy, 29 (2001), 255-261;*
*R. Rivera-Tinoco, K. Schoots, B.C.C. van der Zwaan, "Learning Curves for Solid Oxide Fuel Cells," Proceedings of the 18th World Hydrogen Energy Conference, May 16- 21, Essen, 2010*
*Cost development – an analysis based on experience curves, New Energy Externalities Developments for Sustainability (NEEDS) Integrated Project Report, Project No. 502687 , 2006.*

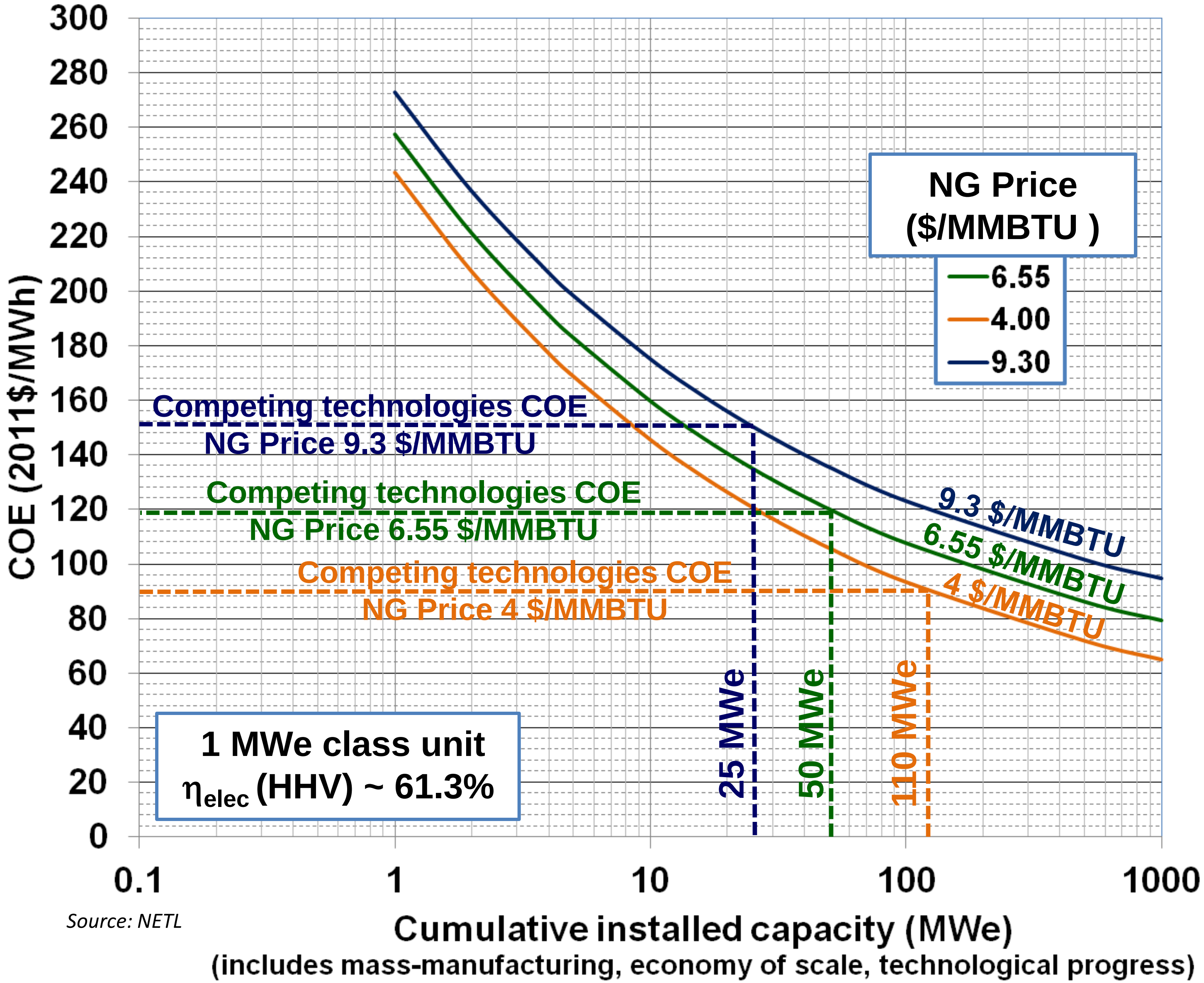
# System Specific Cost

## *Learning Curve – Installed Capacity*




*Source: NETL*

# Impact on NG Price on DG SOFC Cost of Competitiveness




*Source: NETL*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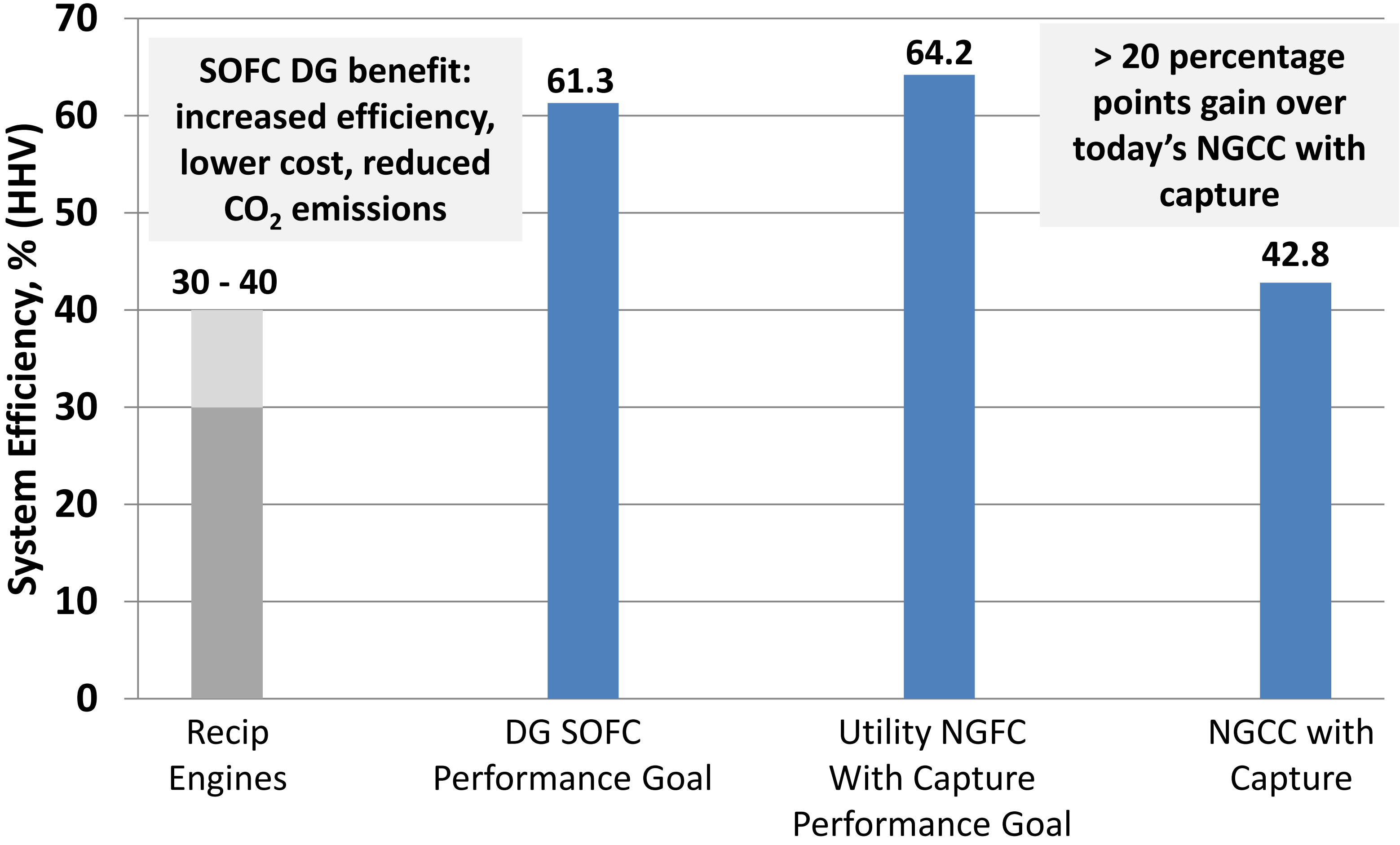
# SOFC DG Enables Technology Base for Transformational Utility Scale Electric Power with Capture



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# SOFC: Meets DG Market Need

## *Path to Utility Scale Power Generation w/o $CO_2$ Emissions*

- Distributed generation market opportunity: electric power (250 kW to MWe class units)
- SOFC DG electric power application
  - Provides > 20 percentage point gain in efficiency
  - Results in significant $CO_2$ emission reduction
- Commercial, cost-competitive SOFC DG product by 2025
  - Consistent with technology development plan
  - ~ 25 MWe installed capacity to achieve competitive cost
- Projected learning to achieve competitive cost is consistent with similar technology commercialization experience
- Higher natural gas price: reduces time to commercialization
- SOFC DG applications provide path to utility scale plants with >98% carbon capture with efficiencies > 60%

# Questions

For More Information Contact:

Katrina Krulla

Katrina.krulla@netl.doe.gov

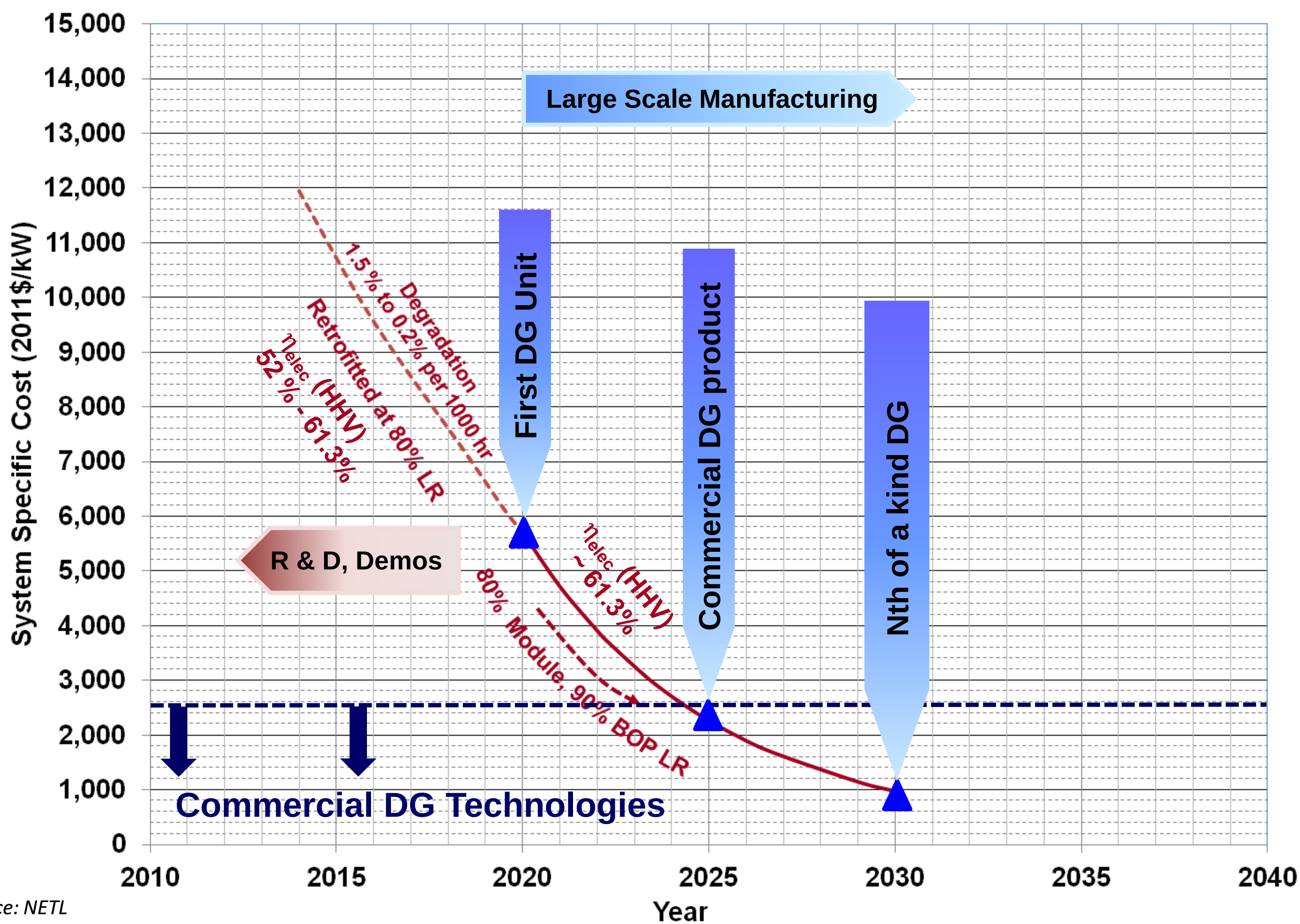
412-386-5366

# SOFC DG Reference Plant Design (1 MWe)

## *Operating & Design Parameters*

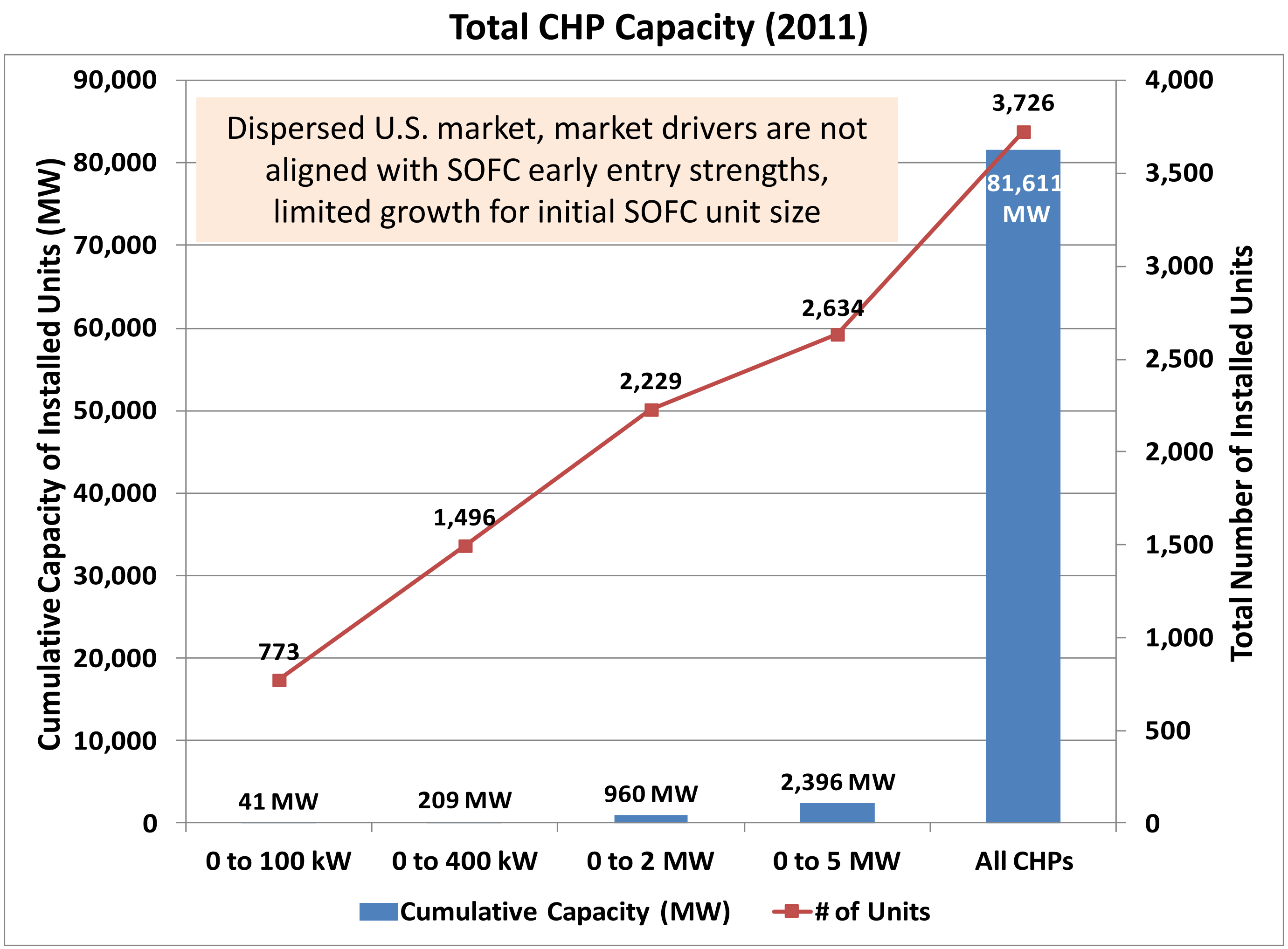
| Parameter | Today's SOFC DG | 2020 SOFC DG (1st 'Unit') | Nth of a Kind SOFC DG (Adv. Performance) |
|---|---|---|---|
| Net AC Power, kW | 1000 | | |
| Operating Pressure, atm | 1.0 | | |
| Operating Temperature, C (F) | 750 (1382) | | |
| Natural Gas Feed, lb/hr | 321.5 | 272.7 | |
| Cell Voltage, 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 | |

# Capital Cost Reductions– Timeline



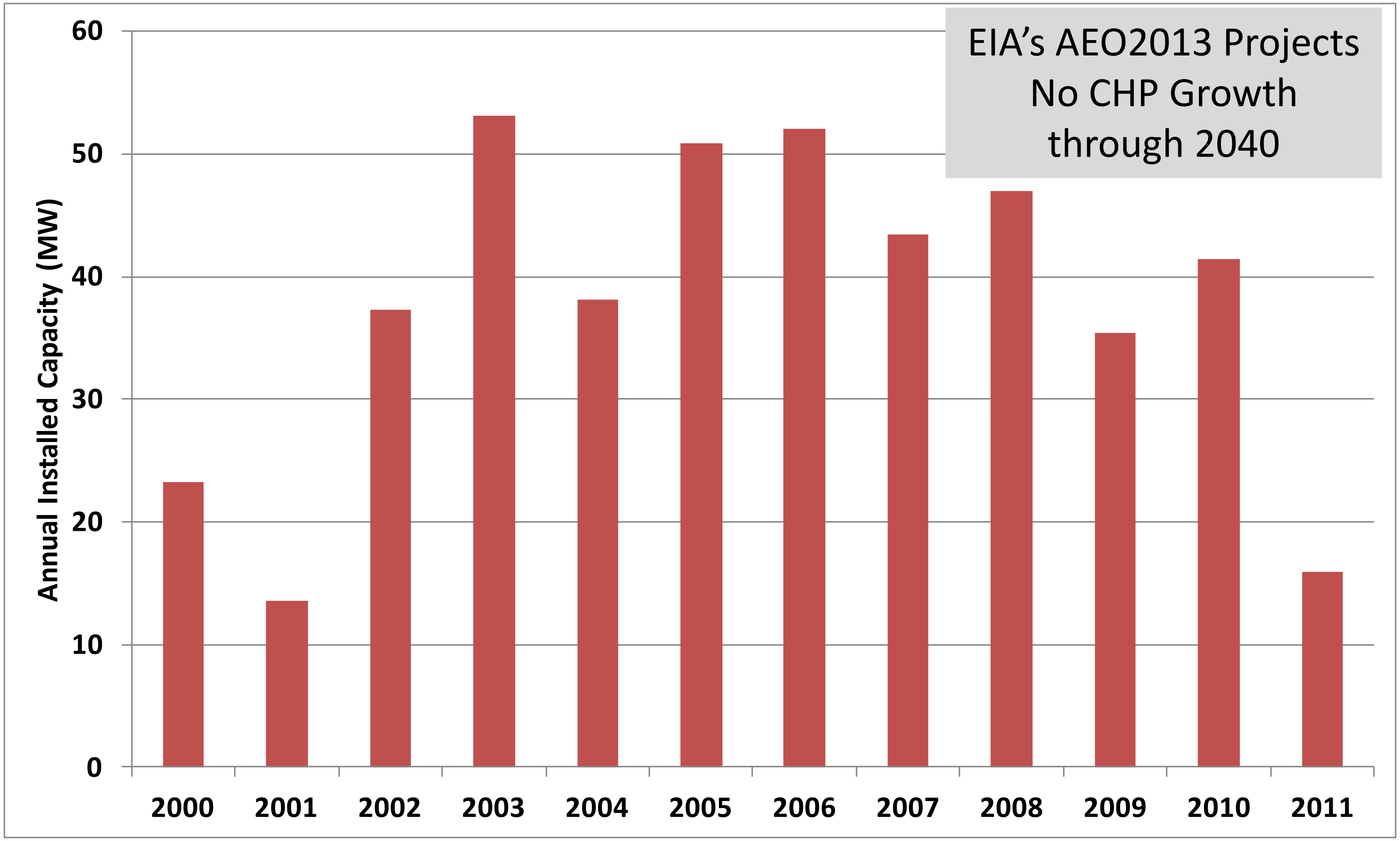

Source: NETL

# CHP Viewed as Possible Future Market Opportunity




*CHP Data Source: Combined Heat and Power Installation Database, http://www.eea-inc.com/chpdata/*

# Annual CHP Installed Capacity: 0 – 2MW






Source: ICF CHP Database