Systems Analysis of Solid Oxide Fuel Cell Plant Configurations

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting

Gregory A. Hackett, Ph.D. NETL Research and Innovation Center June 15, 2018

Mission Execution and Strategic Analysis (MESA)

Site Support Contract support:

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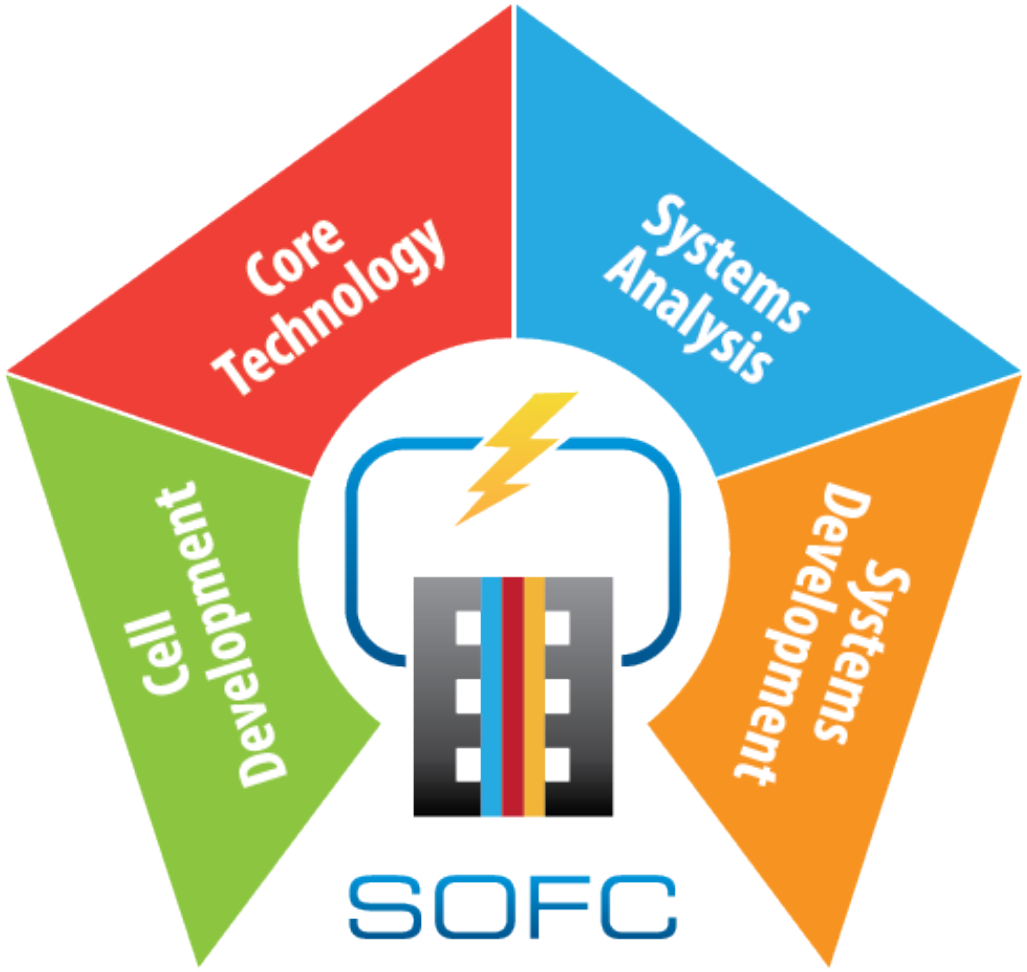
Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF ENERGY

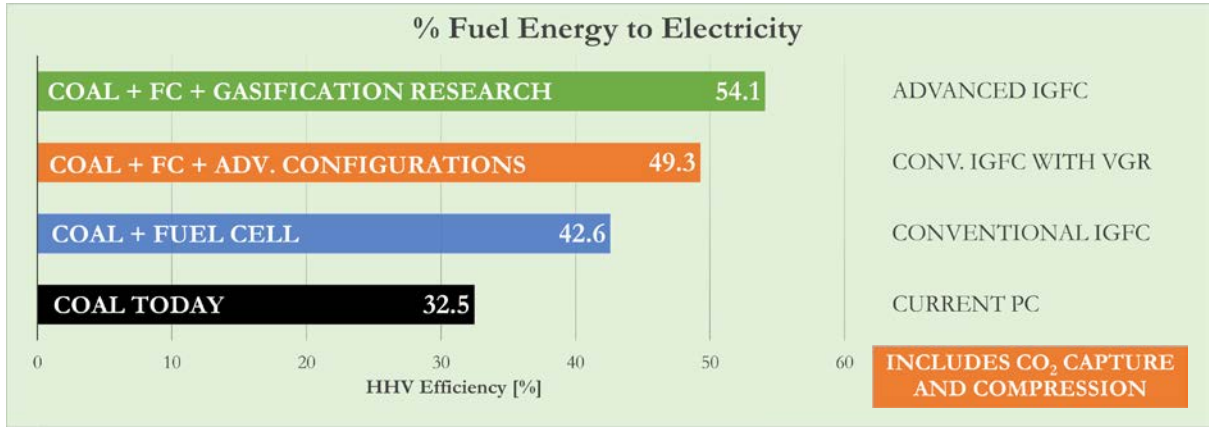
Outline

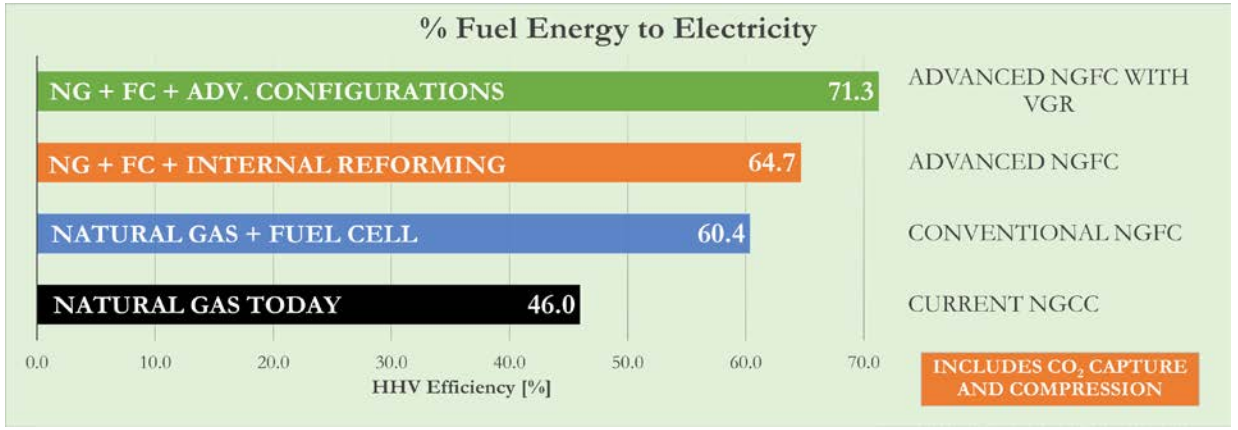
- **NETL SOFC Research Portfolio**
  - Technology Potential
  - Systems Analysis and R&D Connection
- **Systems Engineering and Analysis**
  - Update to NGFC/IGFC Pathway Studies
- **SOFC Technology Distributed Generation Market Potential**

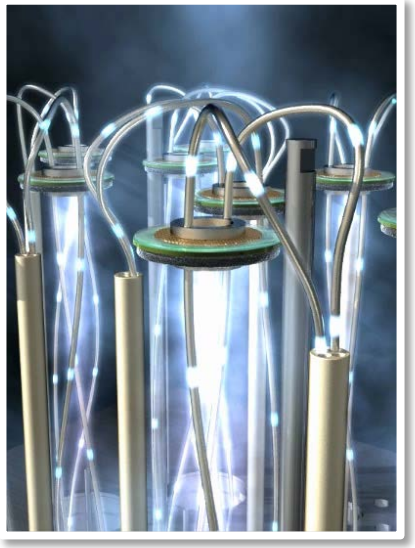


SOFC Technology Potential

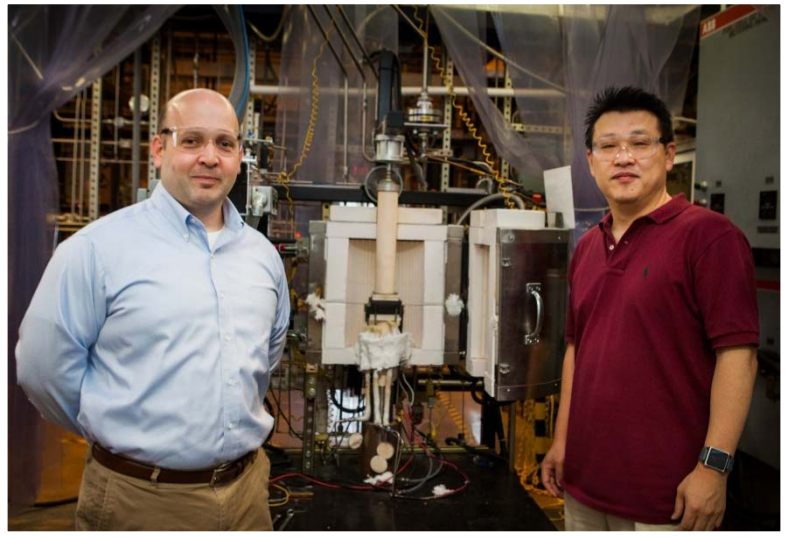
High-Efficiency Coal-to-Electricity Conversion







Basic Experiments



Testing and Simulations

Industrial Partnerships

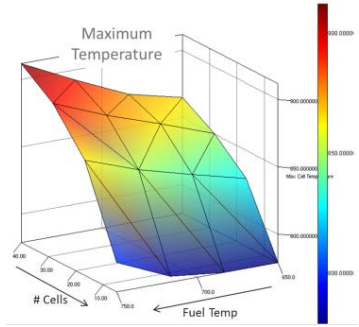
Advanced Manufacturing

Background

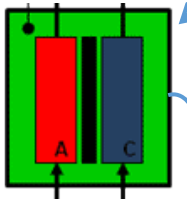
NETL/PNNL Collaboration to Complete Scaling Process

Need design and engineering at several scales to facilitate wide-scale SOFC commercialization

Link NETL and PNNL models at different scales to inform system level and life cycle analyses



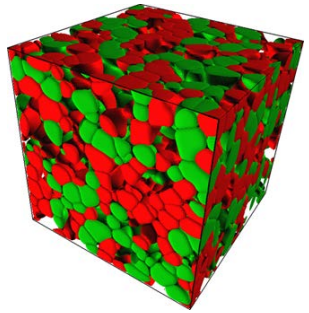
Response Surface Analysis

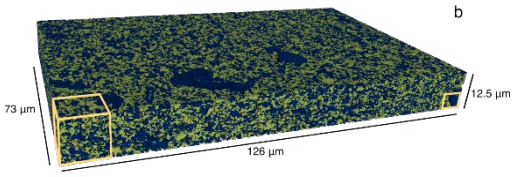


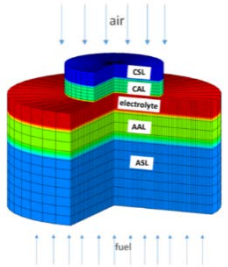
Reduced Order Model (ROM)

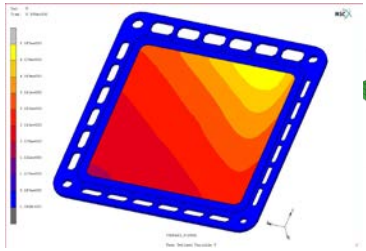
Stack Details

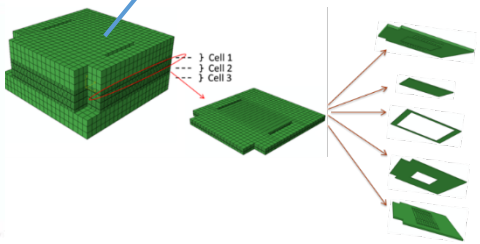
Increasing Scale

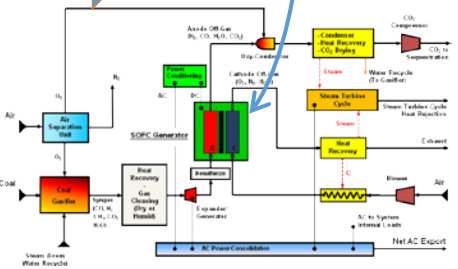












Electrode Microstructure | Single Cell | Multi-Cell Stack | IGFC System Model

NETL | ***PNNL*** | ***NETL***

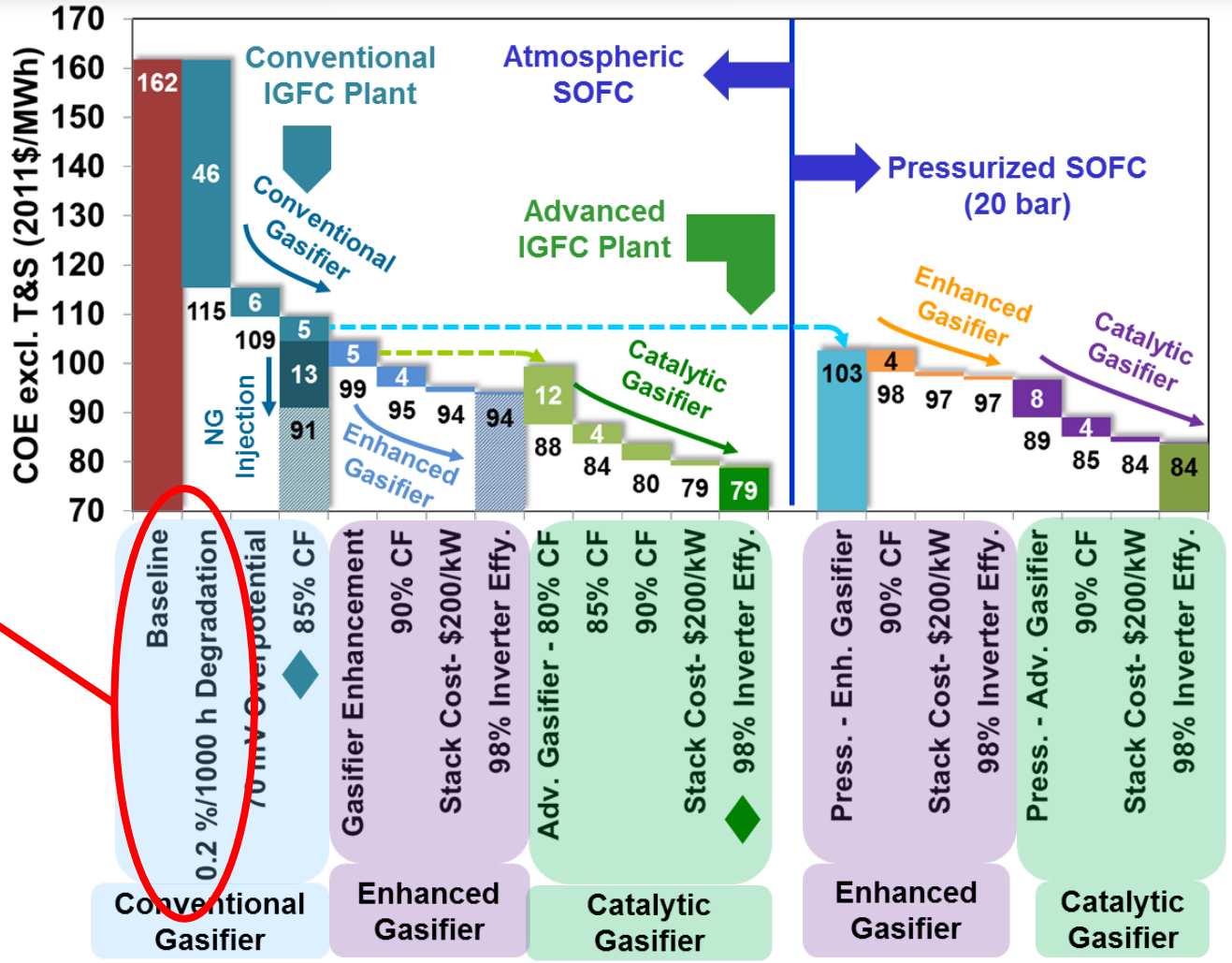
SOFC Systems Engineering and Analysis

Pathway Studies – Cost-of-Electricity

Pathway studies focus R&D efforts to have the most impact

Reduce stack degradation
Reduce cell overpotential

Baseline	
Overpotential [mV]	140
Fuel Utilization [%]	90
Degrad. [%/1000 h]	1.5
Inverter Effy. [%]	97
Stack Cost [$/kW]	225
CF [%]	80



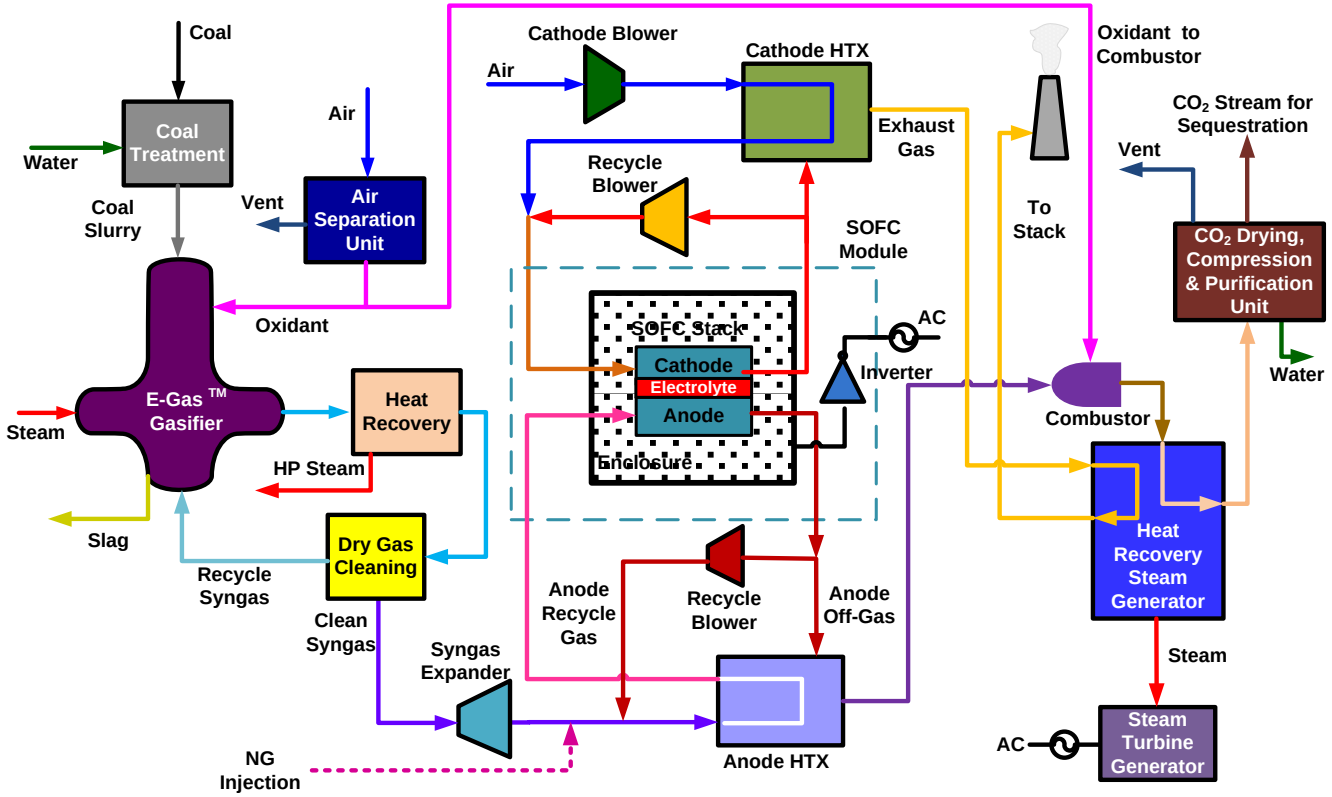
All cases include 90% CO_2 capture

Source: NETL

Systems Engineering and Analysis

Pathway Studies

- Pathway studies evaluated performance and cost of utility-scale (≈550 MWe) SOFC-based power plants

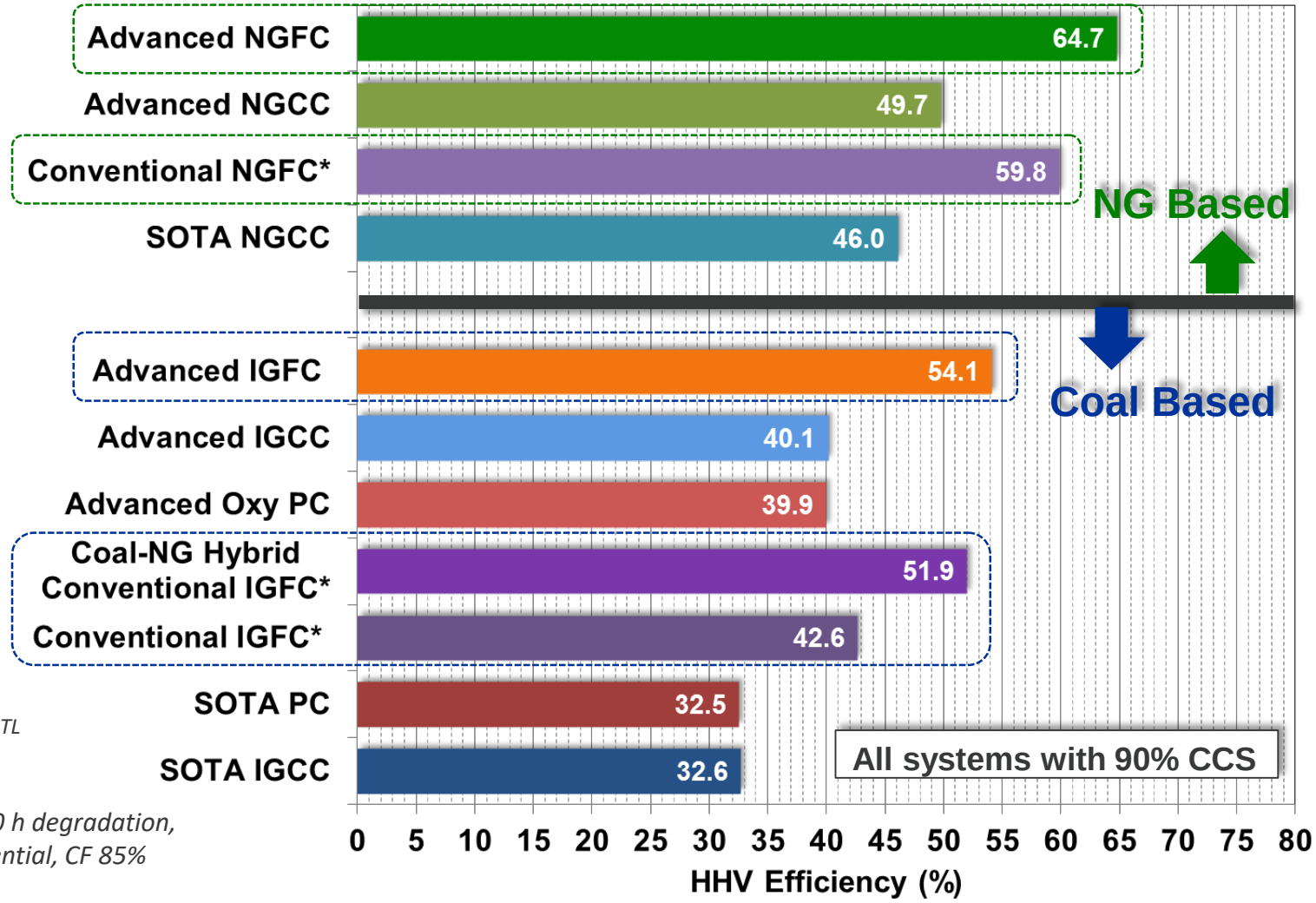


- Studies are being updated in EY18 to include:
  - PNNL SOFC-MP ROM Data
  - Vent Gas Recirculation Concept
  - Operating Pressure Sensitivity
  - Non-Capture Cases
  - Distributed Generation Cases

SOFC Systems Engineering and Analysis

Technology Comparison - Performance

Updates to the pathway studies will include additional technological advances taking SOFC efficiency numbers even higher



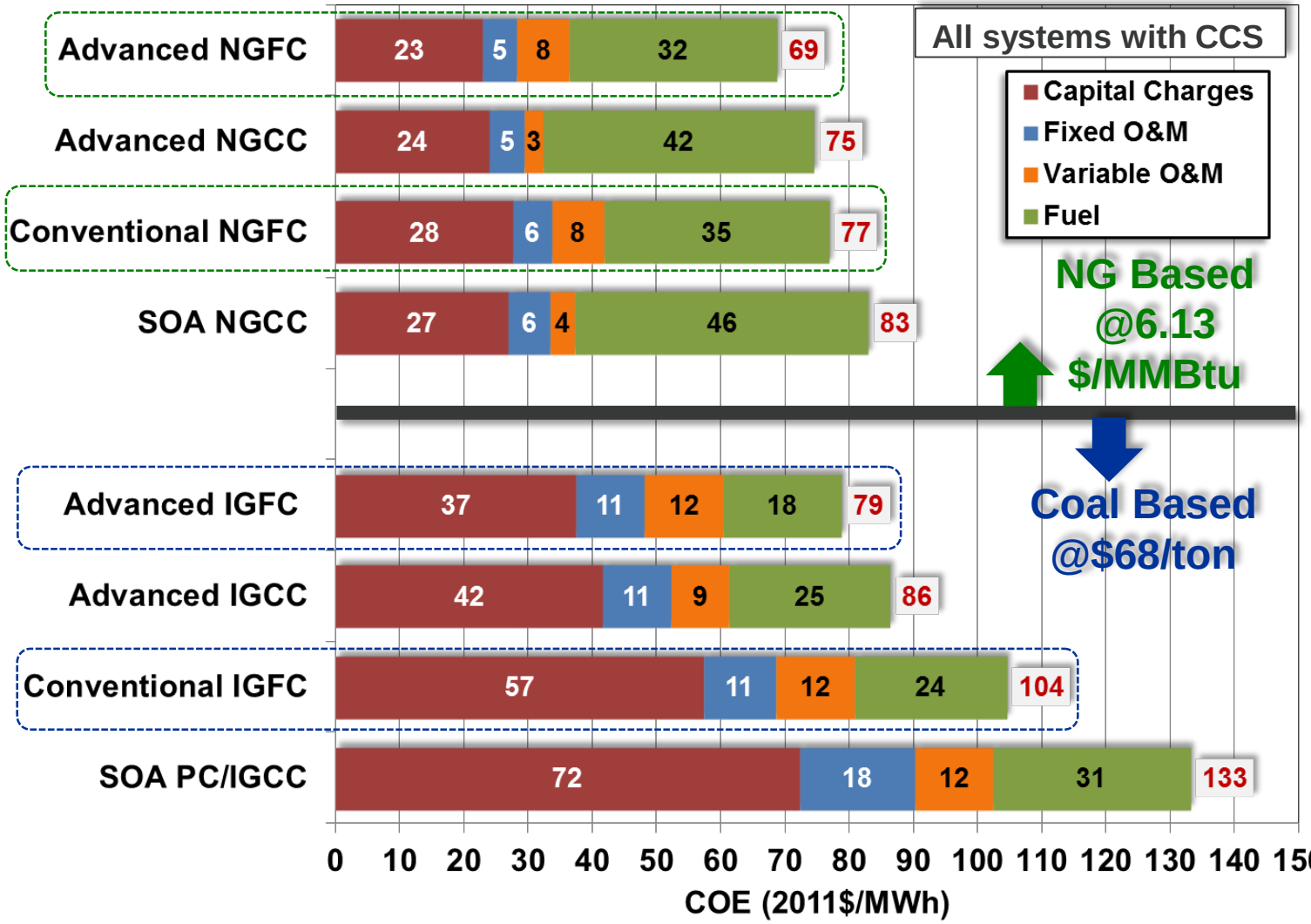
Source: NETL

** 0.2% per 1000 h degradation, 70 mV overpotential, CF 85%*

SOFC Systems Engineering and Analysis

Technology Comparison - Cost of Electricity

Updates to the NETL SOFC system model will generate optimized COE value for comparison with competing technologies

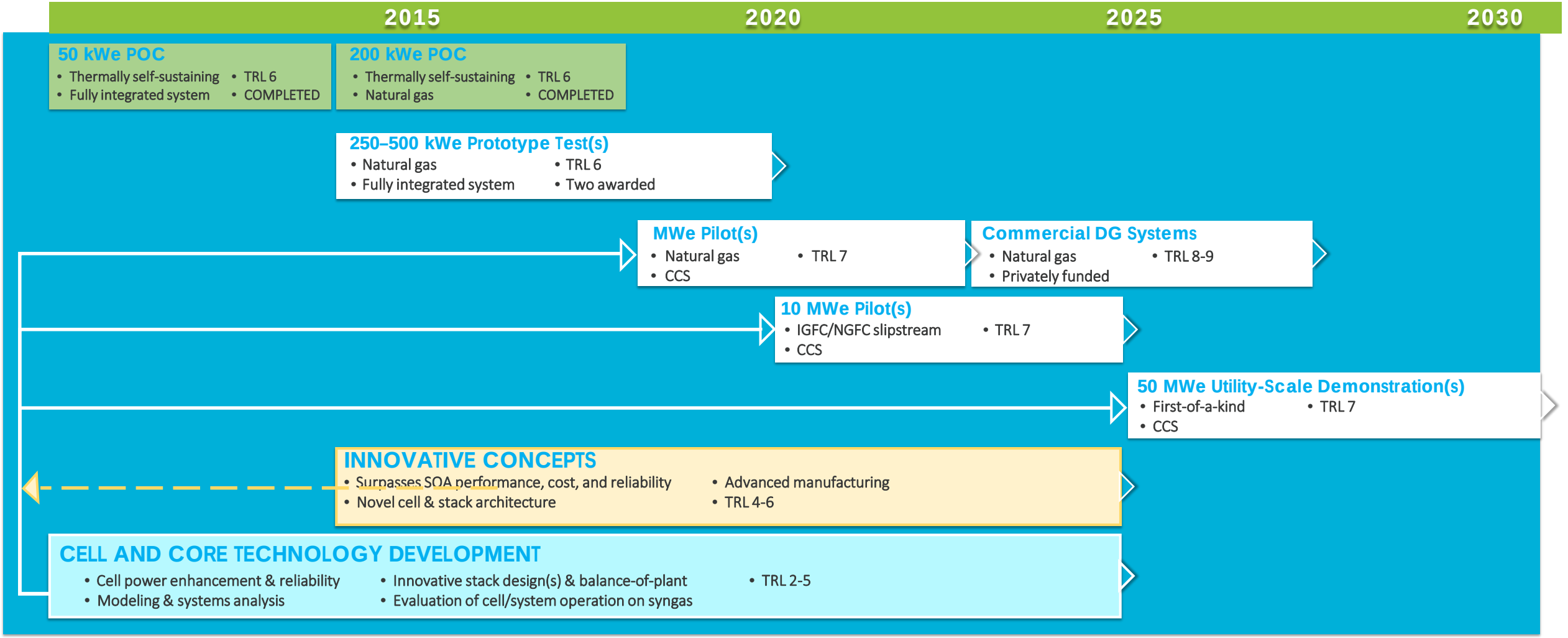


Source: NETL

Systems Engineering and Analysis

SOFC Technology Distributed Generation Market Potential

SOFC Development Timeline



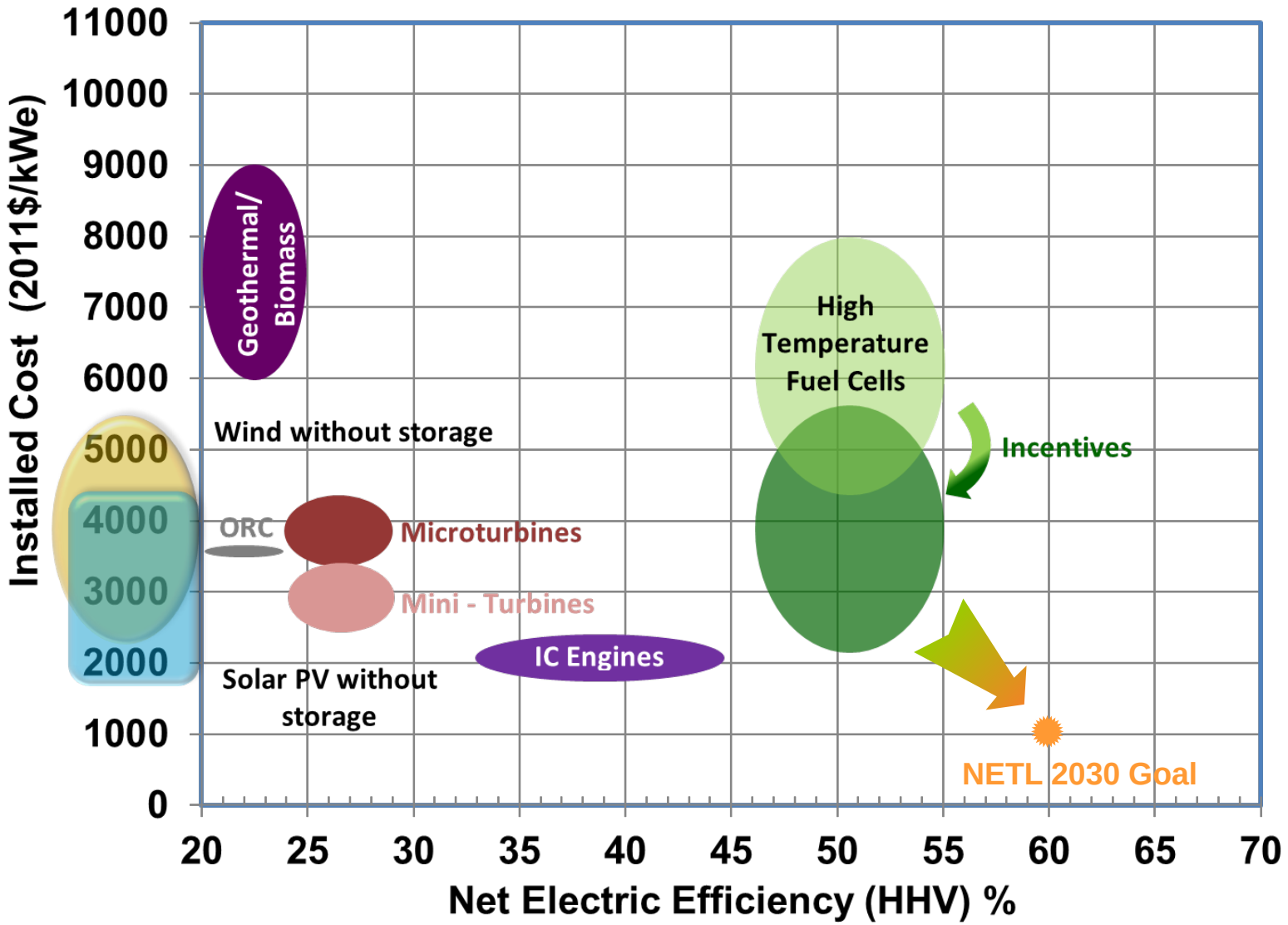
SOFC Technology Development Plan

	Baseline SOFC DG	ca. 2020 SOFC DG (1st 'Unit')	Nth of a Kind SOFC DG (Advanced Performance)	Early Utility NGFC Plant with CCS
Capacity	50 - 250 kW	250 kW – 1 MW	Up to 5 MW	≥ 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
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*

** Assumes mass production volumes*

Technology Performance & Cost Perspective

Distributed Generation – Current Status



DG TECHNOLOGY	RATED POWER RANGE kW	
	LOW	HIGH
Micro-Turbines	65	250
Mini-Turbines	300	3,000
Reciprocating Engines	100	5,000
Solar PV	100	1000
Wind	100	1000
High-Temperature Fuel Cells	300	1,200

Data Sources

Battelle Memorial Institute, "Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications," Jan. 2016

EIA, "Distributed Generation and Combined Heat & Power System Characteristics and Costs in the Buildings Sector -AEO 2017," Jan. 2017

Itron,"2015 Self-Generation Incentive Program Cost Effectiveness Study - SGIP", Oct. 2015

EPA, Catalog of CHP technologies," Sept. 2017

Energy+Environmental Economics, "California Solar Initiative Cost-Effectiveness Evaluation

EPA/ US DOE - Onsite Distributed Generation Systems for Laboratories", 2011

EPRI, Reciprocating Internal Combustion Engine Study," 2016

Energy and Environmental Economics, "Review of Capital Costs for Generating Technologies," Jan. 31, 2017

Energy and Environmental Economics, "Capital Cost Review of Power Generation Technologies - Recommendations for WECC's 10- and 20-Year Studies," March 2014.

NREL, "Distributed Generation Renewable Energy Estimate of Costs," Feb. 2016, https://www.nrel.gov/analysis/tech-lcoe-re-cost-est.html

Danish Energy Agency, "Technology Data for Energy Plants," June 2017 and Aug.2016

Study Objectives

- **Market Segments:** Identify relevant U.S. market segments for early DG applications over relevant capacity ranges
- **Competition:** Identify currently available and in-development competing fossil-based DG technologies; develop cost and performance information for comparison to SOFC
- **DG SOFC Reference Design:** Define an nth-of-a-kind (NOAK) 1 MWe class DG SOFC reference plant design for cost and performance
- **Learning Curve Analysis:** Utilize related technology experience to understand market penetration and cumulative capacity (learning curve) necessary for DG SOFC systems to be cost competitive
- **DG to Utility scale:** Discussion of DG SOFC technology path to utility scale applications

Approach

Market Segments and Competition

- **External Market Analysis Companies (Current Effort)**
  - Seven candidate companies identified and interviewed
  - Three companies contracted

    (Grand View Research, MarketsandMarkets, Market Research Reports)
  - Data compiled and compared.

DG Market Segments and Characteristics

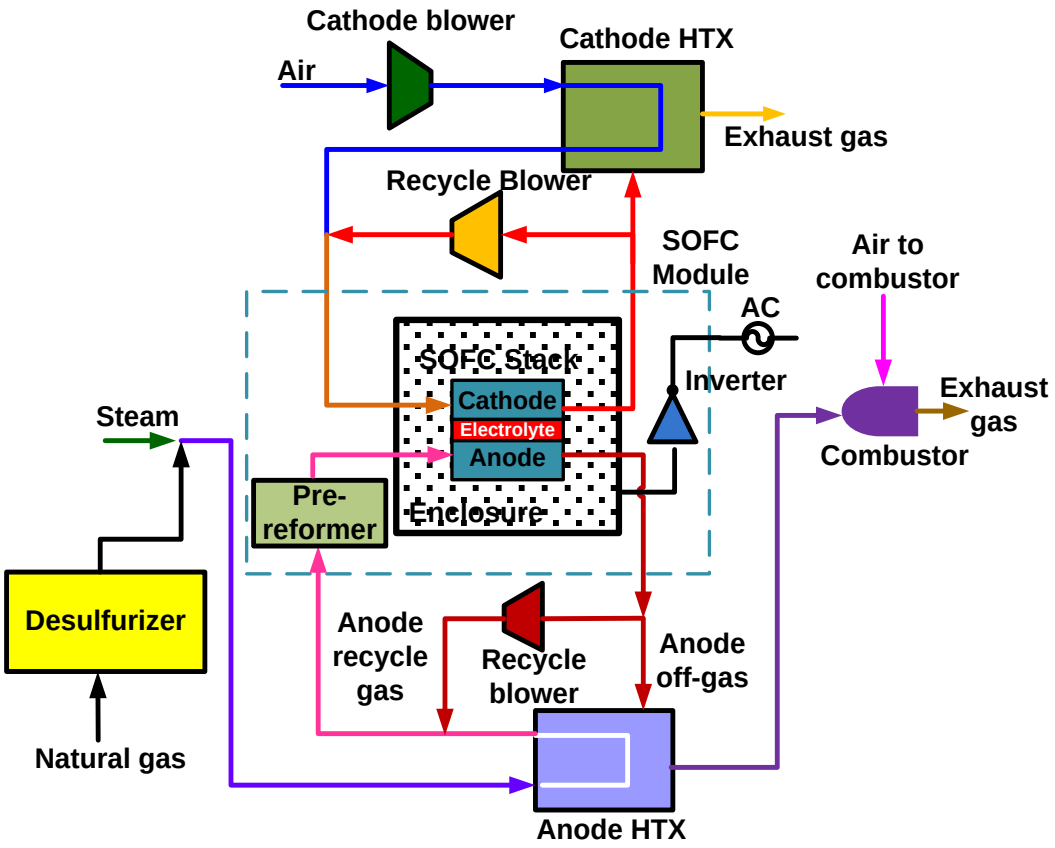
DG Market Segment	Applications	Capacity Requirements (kWe)	General Characteristics	Segment Specific Characteristics
Stationary Continuous Electric Power	Residential	1–5	• On-site power generation • Continuous base-load operations • High electrical efficiency • Fuel flexibility • High availability and reliability • Resiliency to grid outages • Low emission requirements • Low noise pollution • Subsidies and incentive	• Focused customer base • Ease of zoning – both indoor/outdoor • Power quality • Power conditioning
	Commercial	1–5,000		
	Grid support	20–2,000		
	Natural gas compression station	5–1,000		
	Data centers	5–>250		
	Military and defense	1–500		
	Industrial	>250		
	Remote segments	1–250		
CHP	Large commercial (e.g., hotels, hospitals)	4–1500		• High thermal efficiency • Suitable grade waste heat • Dispersed U.S. customer base • Established incumbent technologies • Low cost required for market entry
	Institutional (e.g., colleges, military bases, museums)			
	Small retail and related applications			
	Municipal			
Stationary Emergency and Standby Power	Apartment, office and commercial, buildings, hotels, schools, and a wide range of public gathering places	1–2000	• On-demand power • Resiliency to grid outages • Low fixed maintenance cost	• Quick startup and response • Low cost • Efficiency not key • Emissions not critical

DG Market Analysis - Conclusions

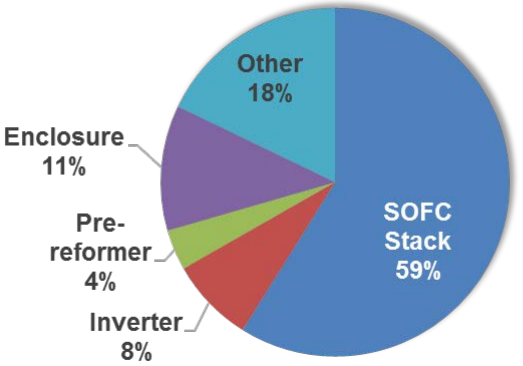
- **Distributed generation market opportunity: electric power (250 kW to MWe class units)**
- **Commercial, cost-competitive SOFC DG product by 2025**
  - Consistent with the technology development plan
  - ~ 25 - 90 MWe installed capacity to achieve competitive cost, which is within the range of current SOFC market projections
  - Requires a DG market penetration of < 2 percent
- **Higher natural gas prices favor SOFC technology**
- **SOFC DG applications provide path to utility scale plants with >98% carbon capture with efficiencies > 60%**

Reference SOFC DG Process

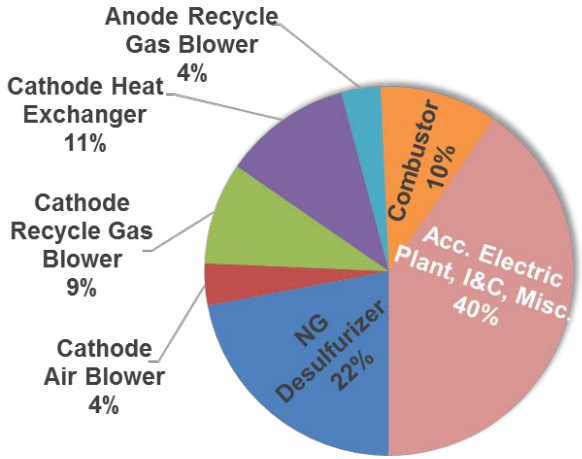
Concept, Performance, and Cost



Parameter	Nth of a Kind SOFC DG Performance
Net AC Power [kWe]	1000
Operating Pressure [atm]	1.0
Operating Temp. [°C (°F)]	750 (1382)
Cell Voltage [V]	0.830
Current Density [mA/cm^2]	400
Gross Power [kWe]	1024
Auxiliary Loads [kW]	24
Net AC Efficiency [LHV]	67.9
Net AC Efficiency [HHV]	**61.3**
Module Cost [2011$/kWe]	452
BOP Cost [2011$/kWe]	531
Total System [$/kWe]	**983**



Module Costs



BOP Costs

Source: NETL

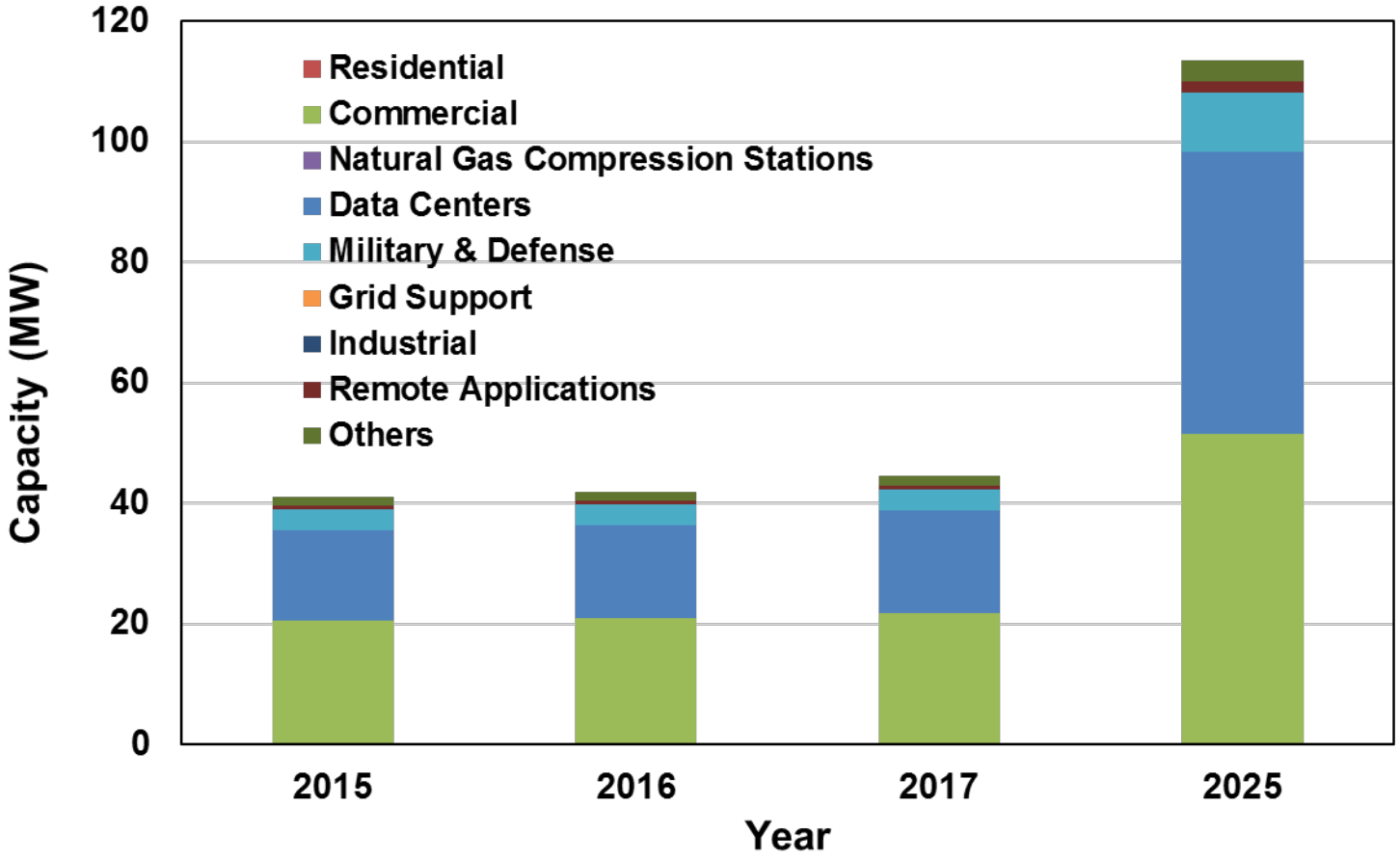
2025 Market Projections

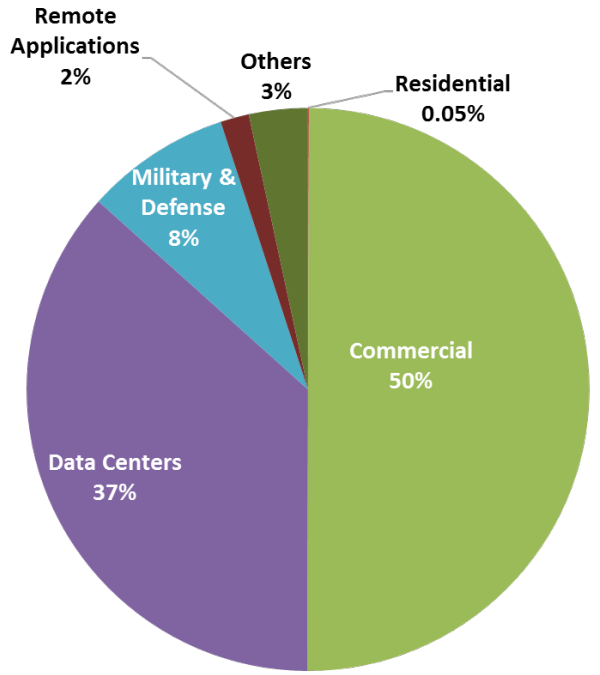
Market Segment	2025 U.S. DG Market Estimation	Capacity Requirements (kW)	U. S. SOFC Market 2025 (MW)
Residential	Small	1 - 5	0.1 – 10
Commercial	4 GW	1 – 5,000	52 - 106
Natural Gas Compression	2.8 GW	20 – 2,000	12
Data Centers		5 – 1,000	10 - 60
Military & Defense	1.5 GW	5 - ≥ 250	23
Grid Support	1 GW	1 – 500	18
Industrial		> 250	2 - 15
Remote Segments		1 – 250	3 - 7
CHP	5 GW	4 – 1,500	0.1
Other		NA	0.1 - 3
Total	14.3 GW		114 - 255

Data Sources
PikeResearch market potential analysis, 2040 Market forecast and 2018 Grid strengthening forecast from EIA AEO2013 Reference Case, 2013
NETL "Evaluation of the Market Potential for DG SOFC Systems at Military Installations," DOE/NETL-2016/02222016, February 2016.
MarketsandMarkets "Solid Oxide Fuel Cell Market – Global Forecast to 2025," Prepared for DOE /NETL October, 2017.
Grandview Research "Solid Oxide Fuel Cell (SOFC) Market - Market Estimates & Trend Analysis," Prepared for DOE /NETL October, 2017.

Total U. S. SOFC market capacity in 2025 114-255 MW; 1–2% of DG market in 2025

U.S. SOFC DG Market Forecast

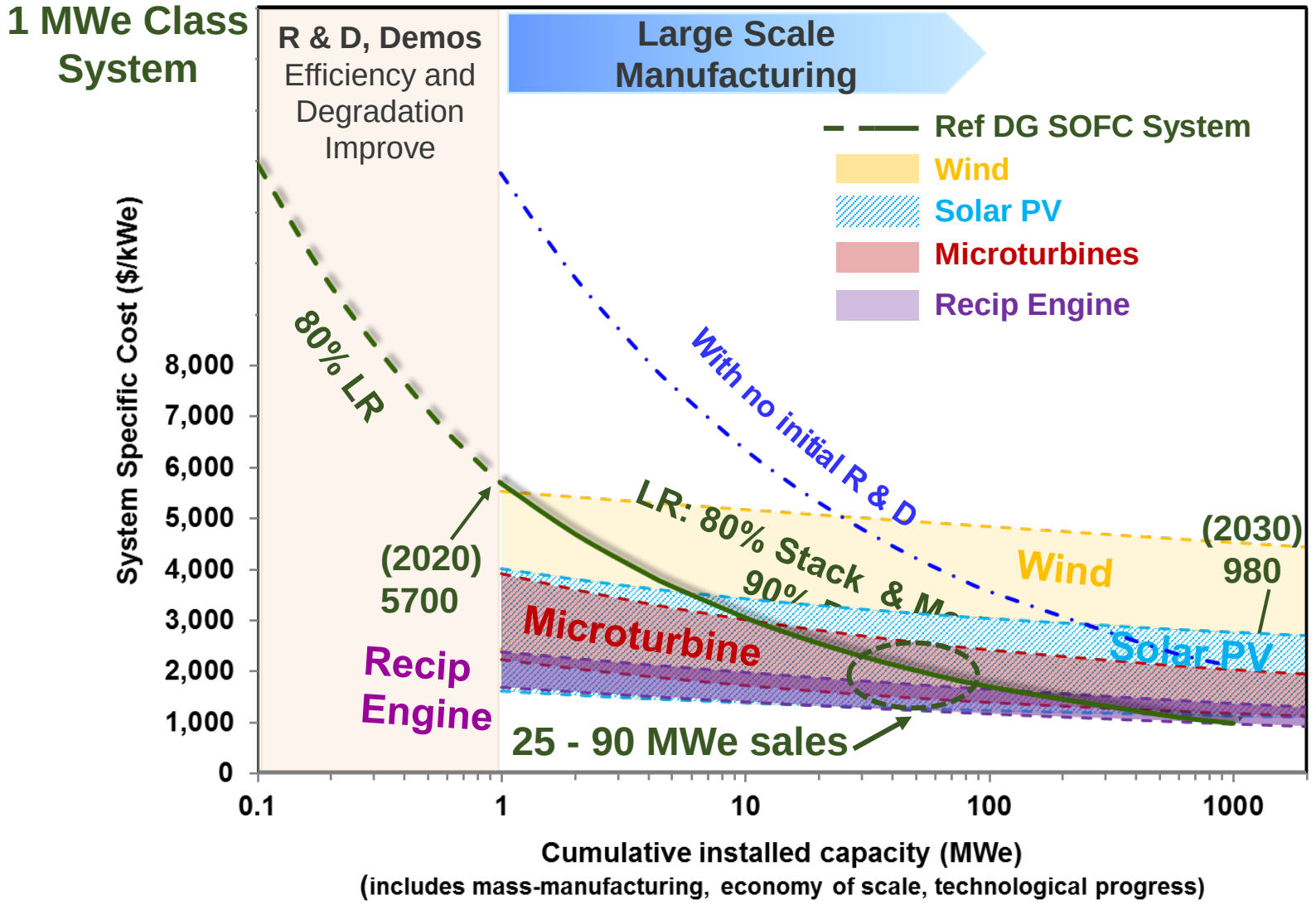




Capacity distribution in 2025

- 114 MW U.S. SOFC Capacity in 2025 – 3 times 2016 capacity
- Commercial and Data Centers accounts for 87% of capacity

$/kW Learning Curve – Installed Capacity



Technology	Learning Rate	Degradation Rate (%/1000 hrs)
Wind	94%	< 0.5

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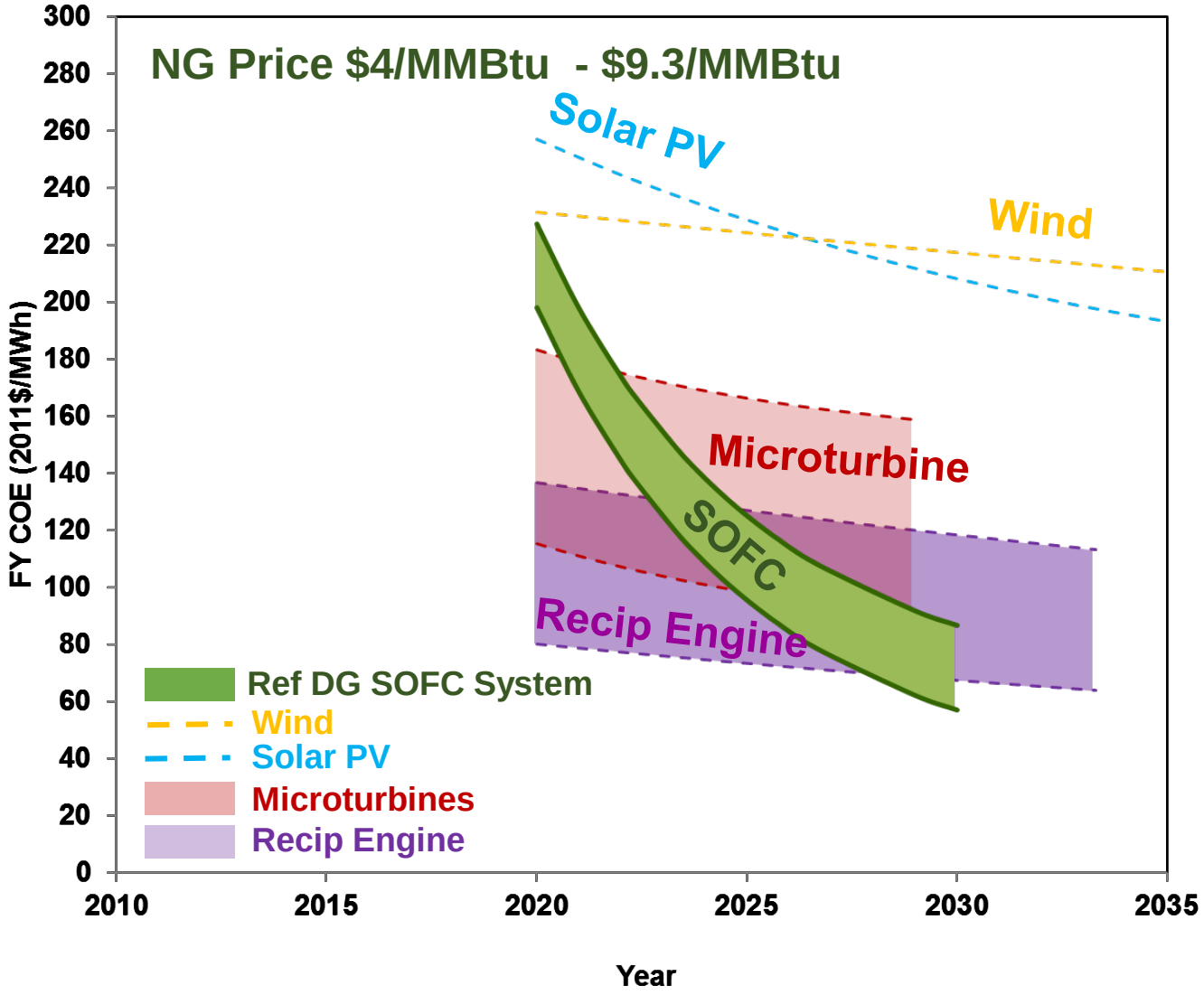
Required sales < 2 % of the projected DG market in 2025

First Year COE – NG Price- Year



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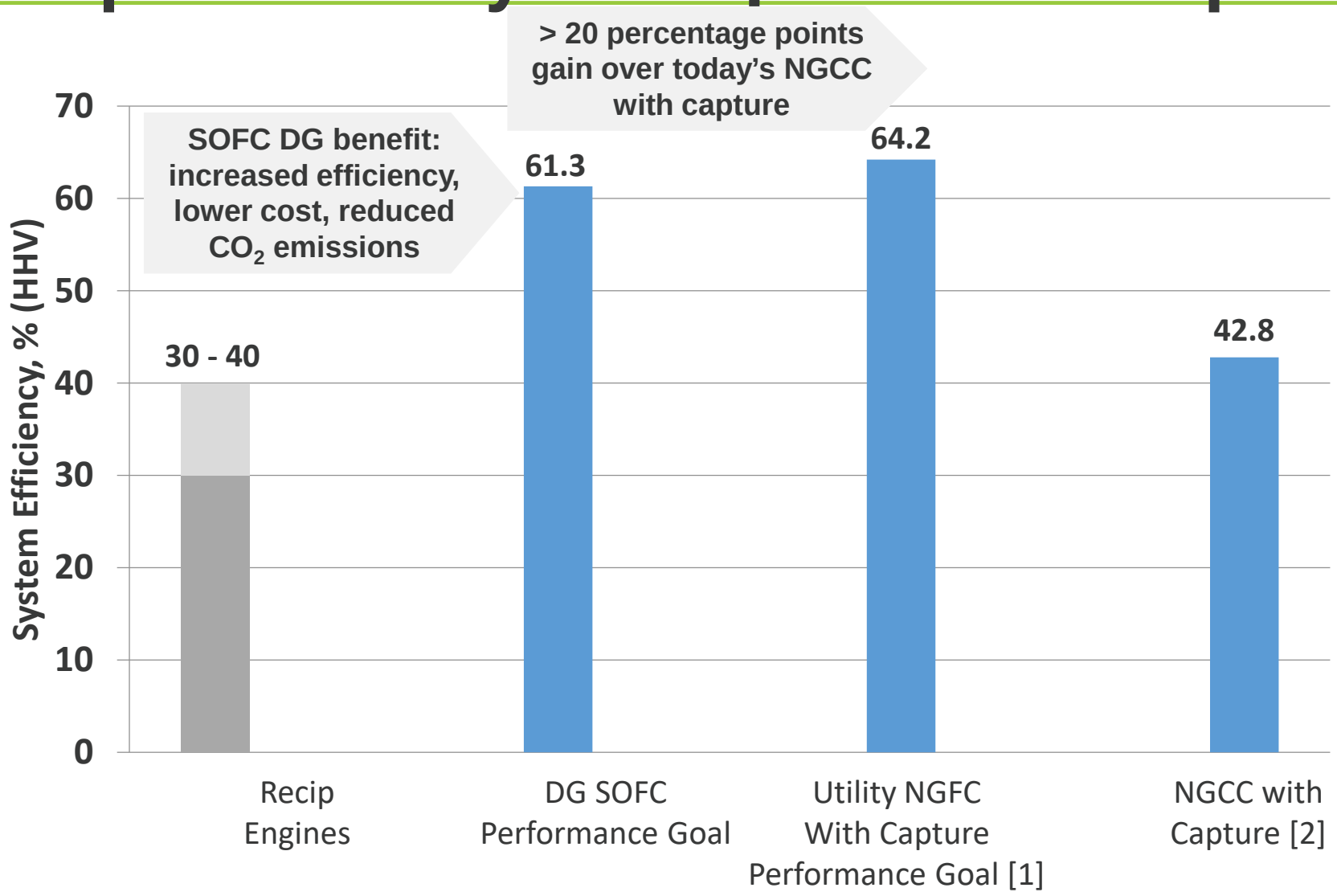
DG SOFC path to utility scale plants with capture



SOFC DG Enables Technology Base for Transformational Utility Scale Electric Power with Capture

Data Sources

1. NETL- "Techno-Economic Analysis of Natural Gas Fuel Cell Plant Configurations," DOE/NETL-2015/04082015, April 2015.

2. NETL, "Cost and Performance for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity," Rev 2, Nov. 2010.

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