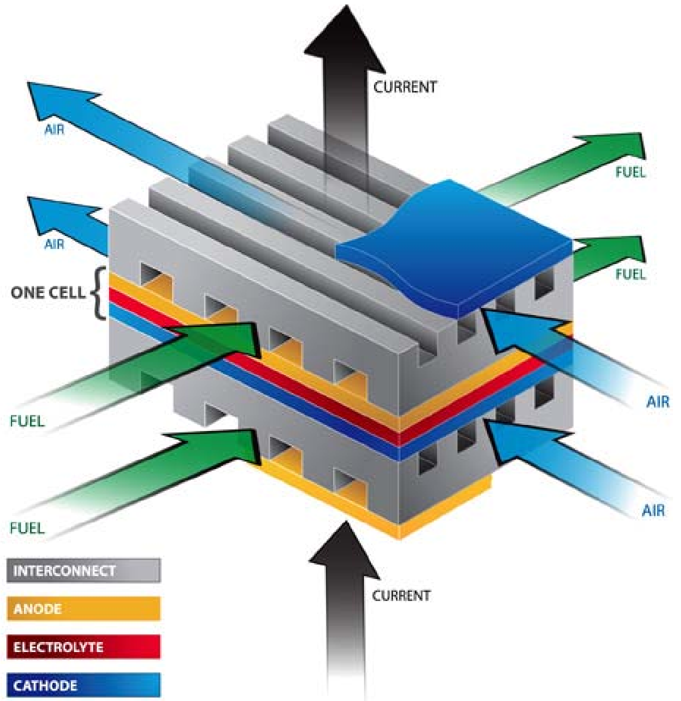

IGFC and NGFC Pathway Studies – Estimation of Stack Degradation Costs and Salient Results

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Summary

- **A methodology for estimation of costs due to stack performance degradation was developed**
  - Both linear and first-order stack degradation models were considered
  - Potential stack operational scenarios and installation of extra stack area to compensate for stack degradation were modeled
- **Extra installed area of 10 percent of the nominal stack area was found to be optimal from a cost perspective**
- **Reduction of the stack degradation rate is necessary for fuel cell systems to be attractive with respect to other state-of-the-art (SOA) technologies for central power stations**
- **At low degradation rates (< 0.3%/1000 hr), the fuel cell systems have the largest potential for the lowest cost of electricity when compared to conventional technologies**
- **Development of solid oxide fuel cell (SOFC) stacks capable of 100 percent internal reforming gives natural gas fuel cell (NGFC) systems a competitive edge over natural gas combined cycle (NGCC) systems**

NETL Techno-Economic Systems Analysis

Integrated Gasification Fuel Cell (IGFC) and NGFC Systems

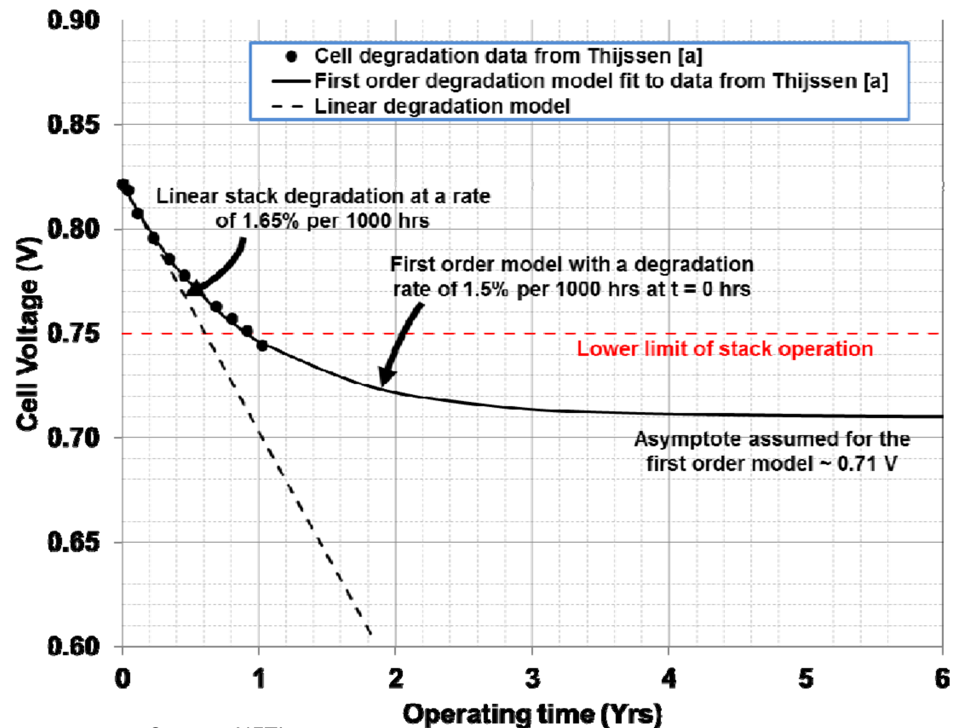
- **Pathway studies evaluated performance and cost of utility-scale (~ 550 MWe) SOFC based power plants**
  - IGFC and NGFC systems with and without carbon capture and sequestration (CCS) were considered
  - Pathway parameters were chosen to introduce technological advances systematically to provide guidance to the SOFC program
  - Included atmospheric as well as pressurized SOFC operational scenarios
  - Major component costs were estimated based on bituminous baseline costs
- **Process updates**
  - A CO_2 purification unit to purify the product CO_2 to pipeline and enhanced oil recovery (EOR) specifications (~ 10 ppmv of O_2) was included
  - NGFC system with complete internal reformation was modeled
- **Cost updates**
  - Costs were updated to 2011$
    - NETL SOFC stack cost target of $225/kW was used in the economic analysis
  - Degradation related costs based on stack degradation model
    - Linear and first order stack degradation considered

Agenda

1. **Estimation of costs due to stack performance degradation**
2. **Salient NGFC/IGFC system results based on cost and process updates**

Stack Degradation Costs
Degradation Models

- **Stack degradation costs were included as variable operation and maintenance (O&M) costs**
- **Frequency of stack replacement was evaluated**
  - Both linear and first-order stack degradation were considered
  - Stack degradation rate was a parameter
  - Installation of extra stack area (up-front) to compensate for degradation was investigated
  - Operational scenario to maintain constant power output was developed

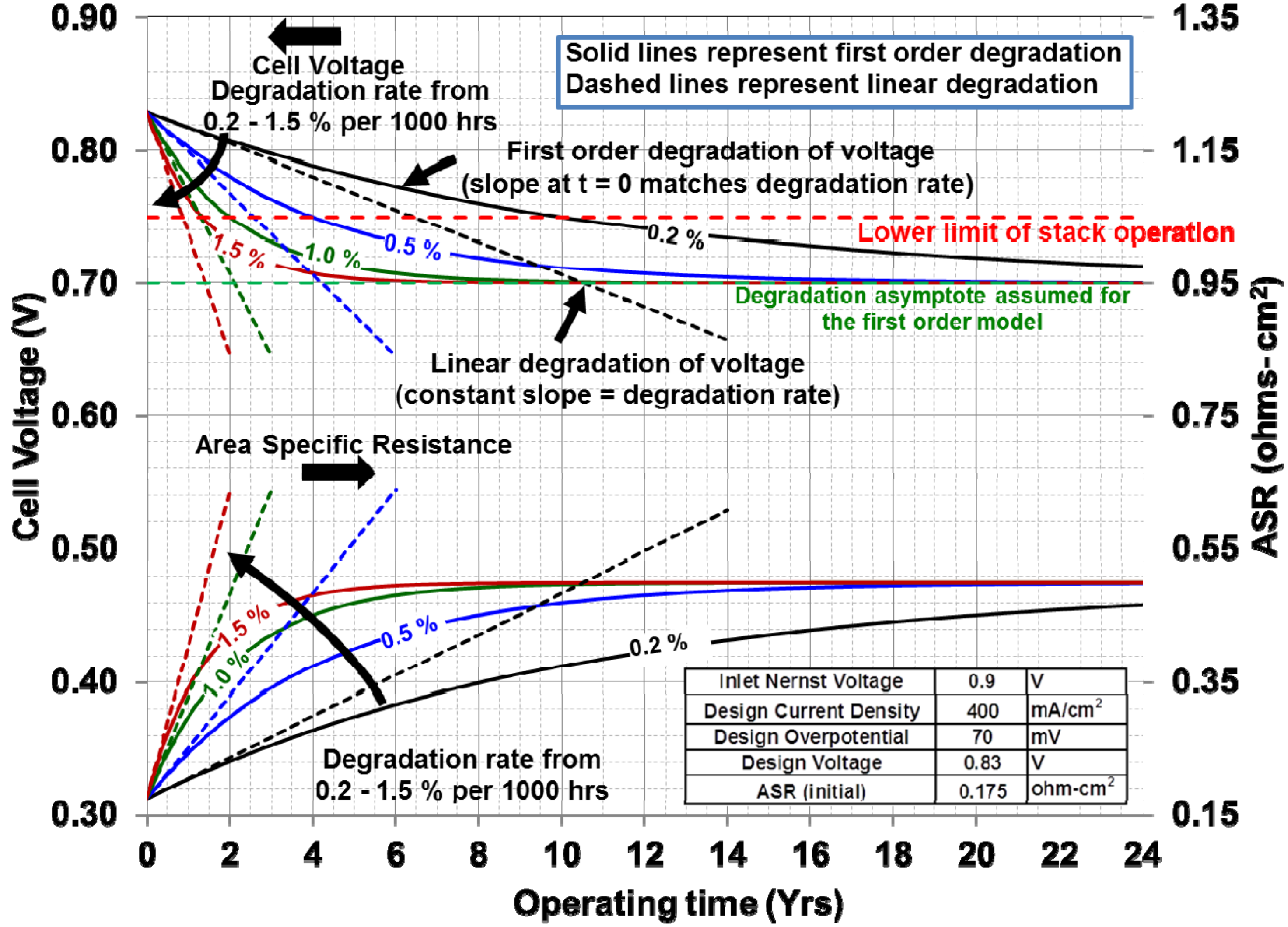


Source: NETL

[a]**Thijssen, J.,** *"Natural Gas-Fueled Distributed Generation Solid Oxide Fuel Cell Systems: Projection of Performance and Cost of Electricity,"* Report Number: R102 04 2009/1, Prepared for: US Department of Energy, National Energy Technology Laboratory, and RDS Contract Number: 41817M2846, March 24, 2009.

Stack Degradation Model

Cell Voltage and Area Specific Resistance (ASR) Variation



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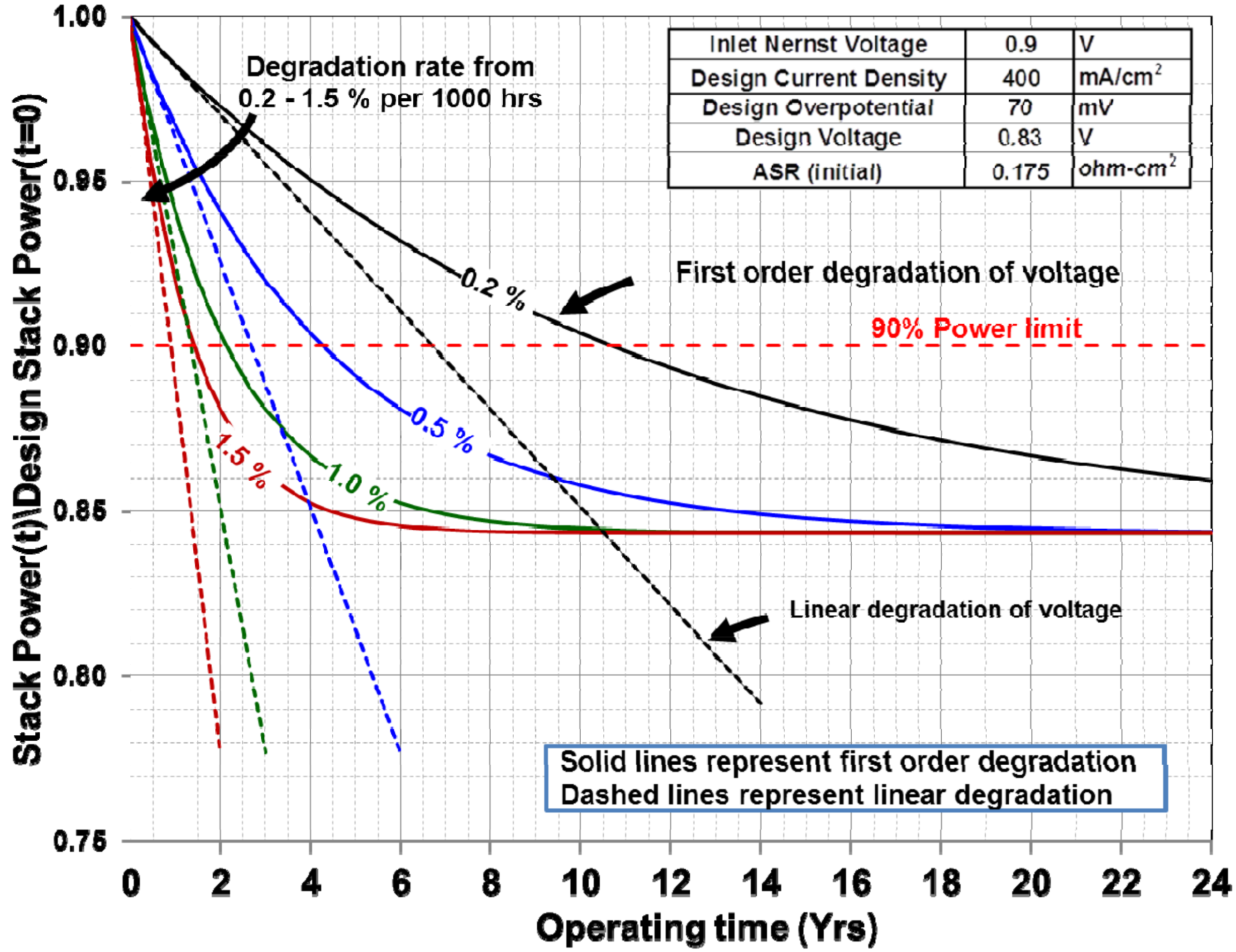
Stack Degradation Model

Power Variation with Time



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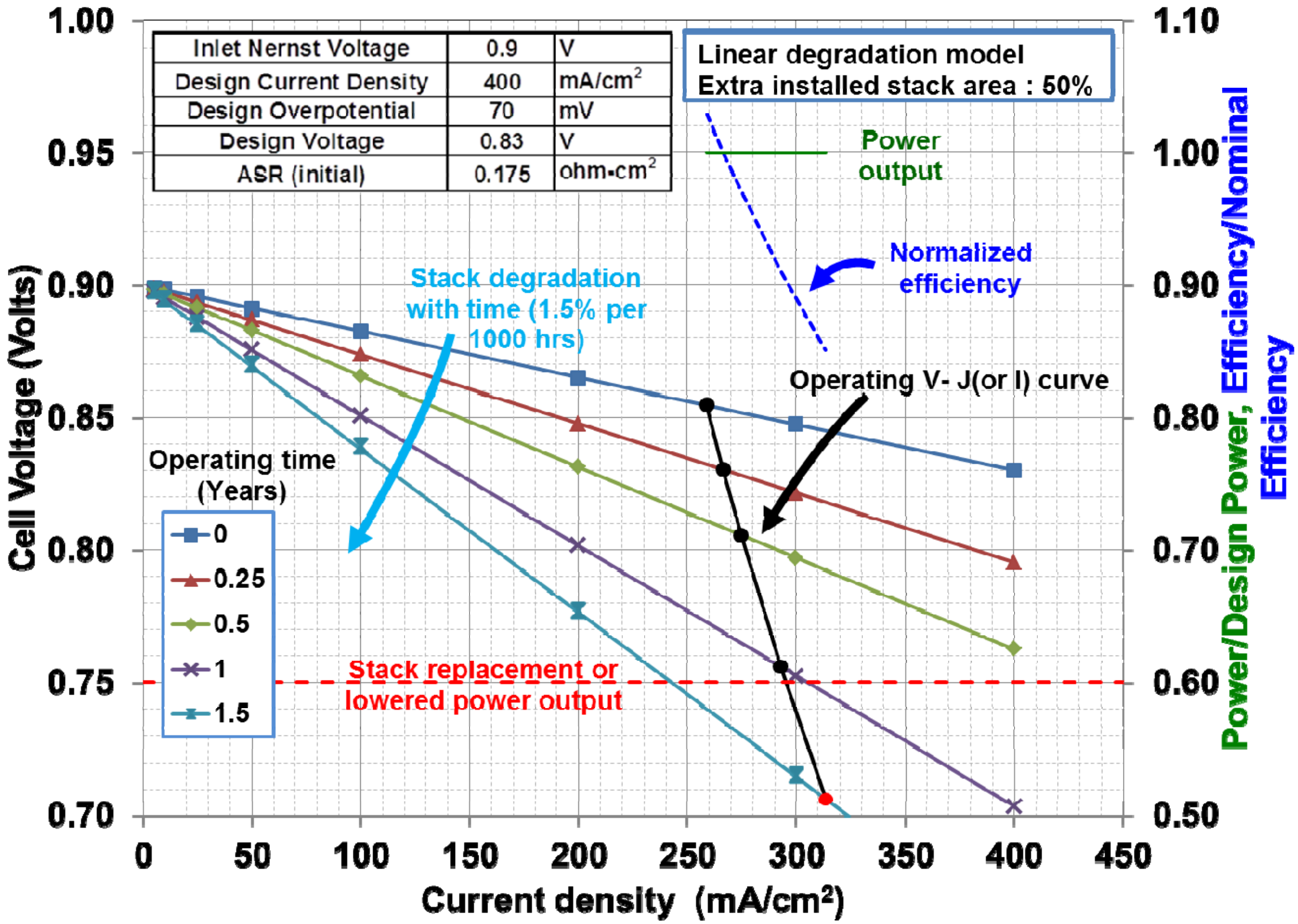
Stack Operational Scenario

Degradation Compensation

- **Increase current density to maintain constant power output**
  - The current density values could be lower than nominal current density depending on the extra stack area installed
  - Efficiency varies from a value higher than nominal to values lower than nominal ultimately
- **Key assumptions**
  - Degradation rate is independent of stack current density
  - Stack ASR is independent of current density
  - Variation in efficiency is not taken into account in cost of electricity (COE) calculations

Stack Operation at Constant Power Output

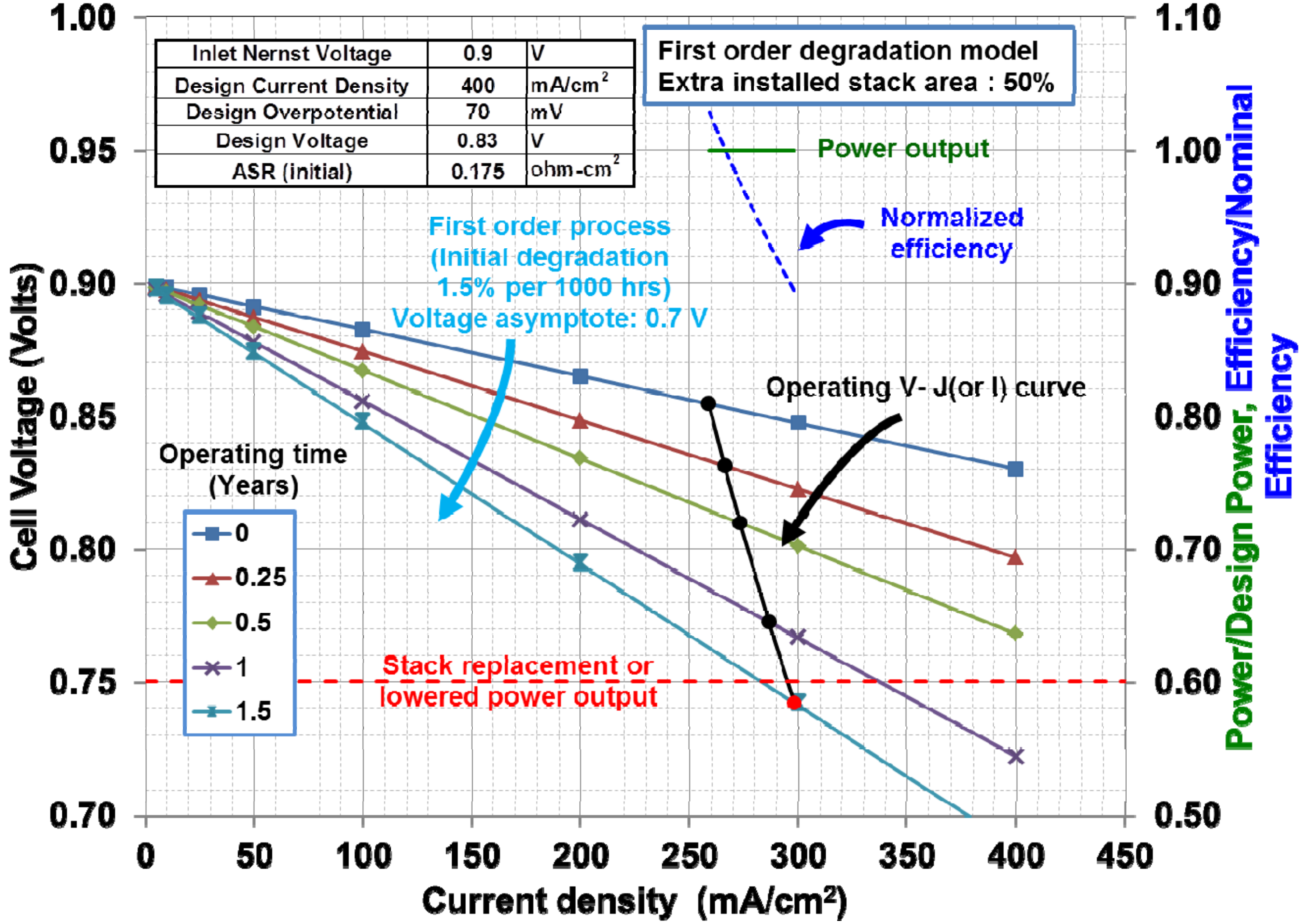
Linear Degradation (1.5% per 1000 hrs)



Source: NETL

Stack Operation at Constant Power Output

First-Order Degradation (1.5% per 1000 hrs)



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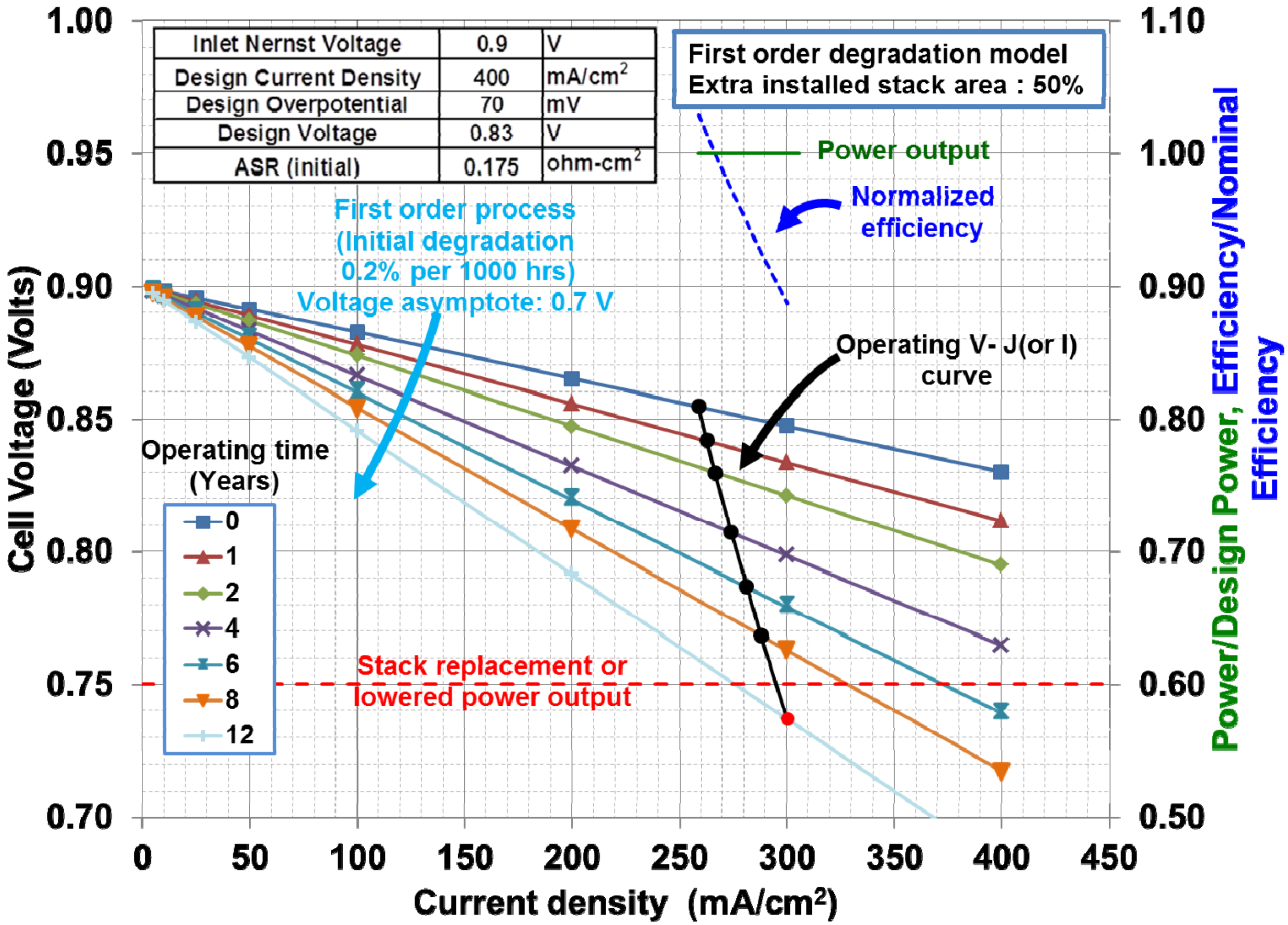
Stack Operation at Constant Power Output

First-Order Degradation (0.2% per 1000 hrs)



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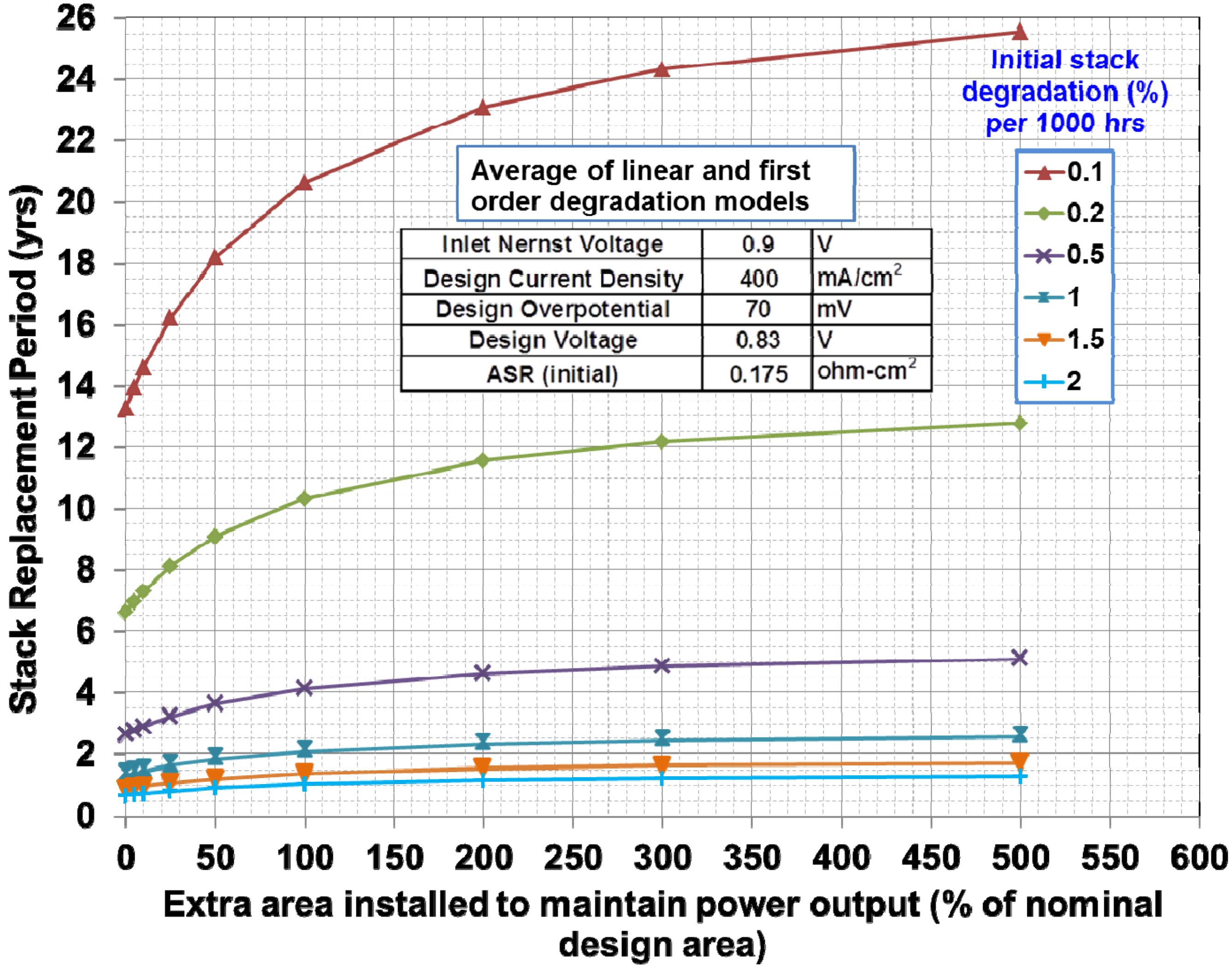
Stack Replacement Period

Average of Linear and First-Order Degradation Models



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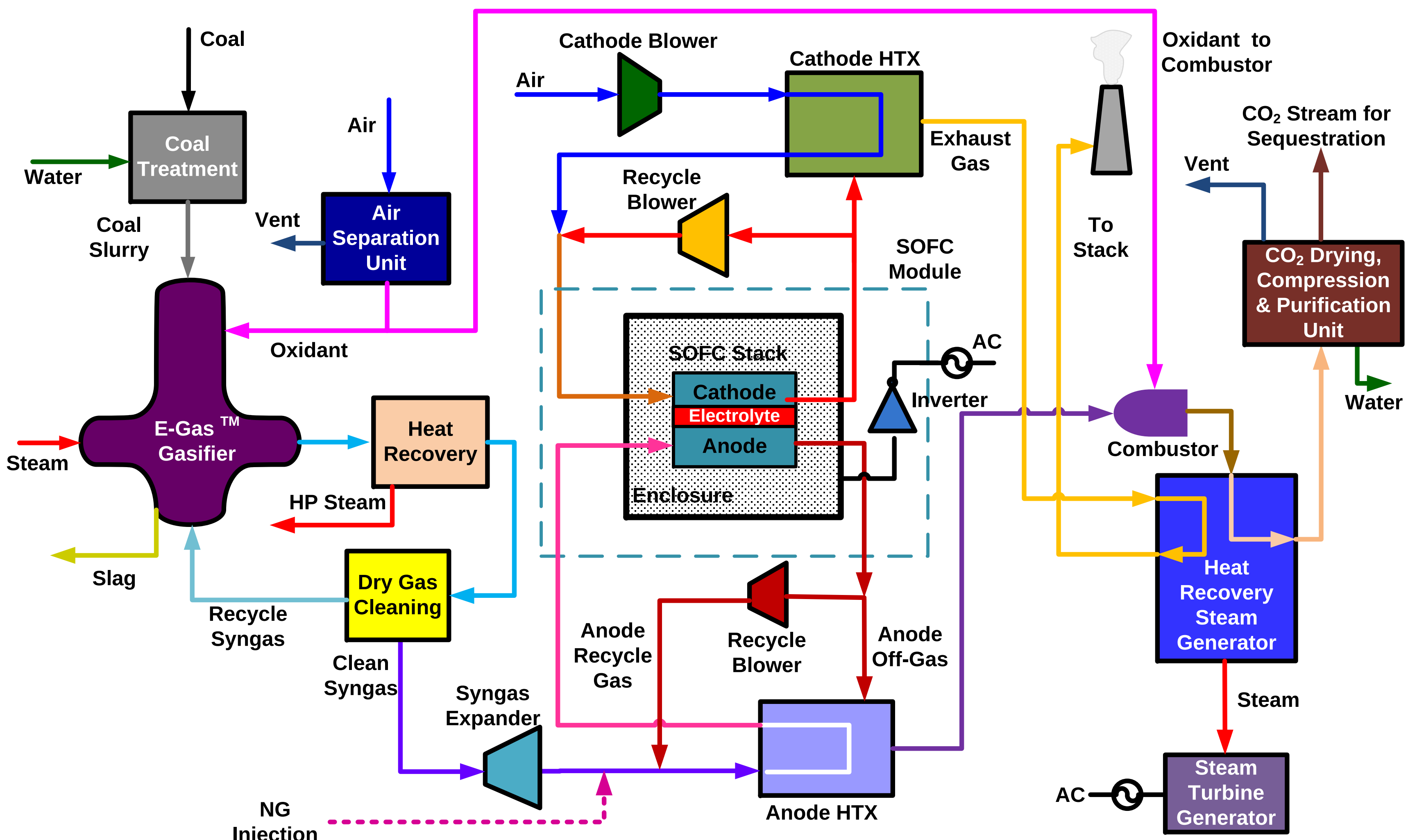
Salient NGFC/IGFC System Results

IGFC Systems

Process Diagram - Atmospheric



Source: NETL

IGFC Systems

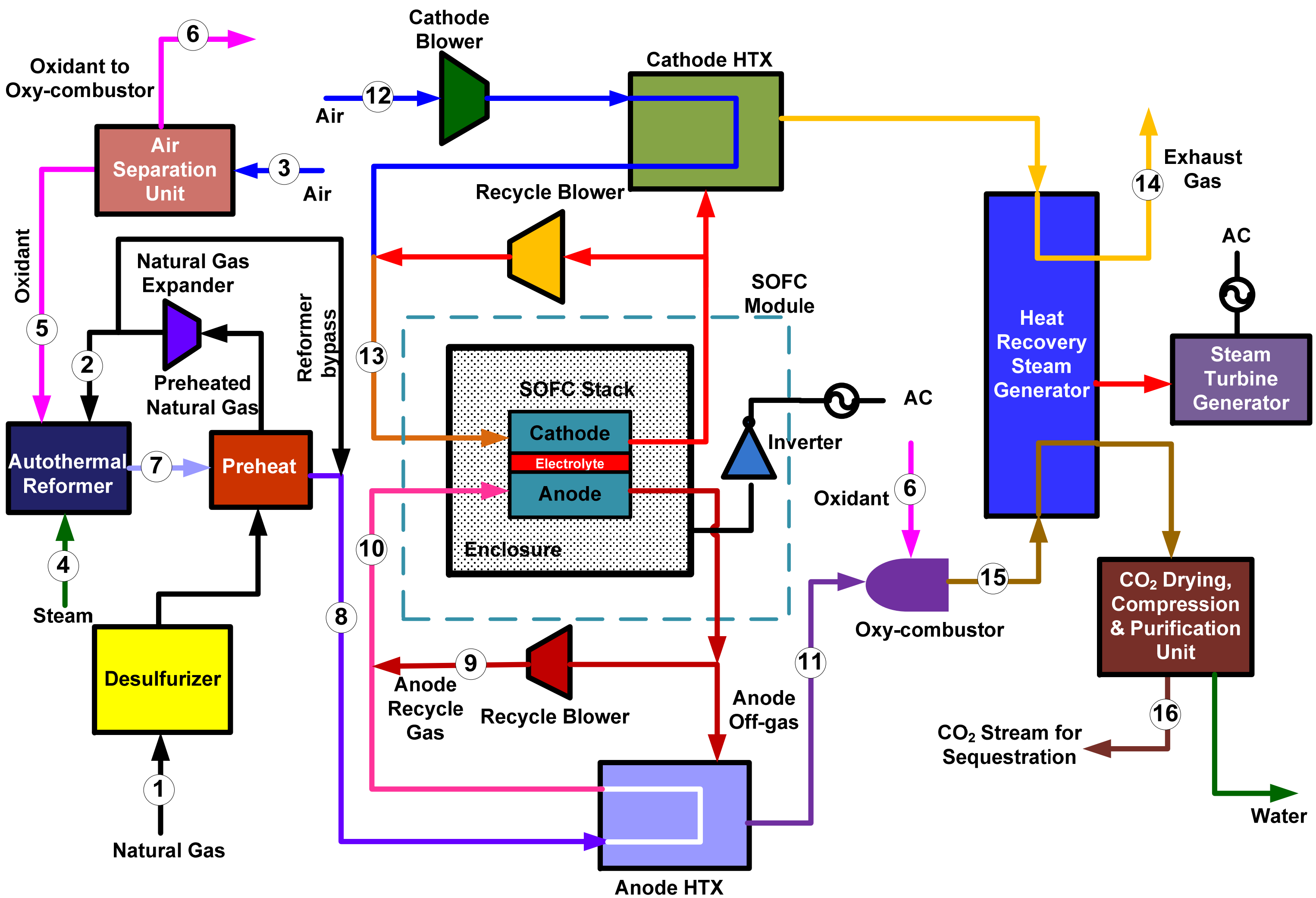
Pathway Studies - Recap

- **Two gasifier configurations were considered:**
  - Conventional gasifier reflecting state-of-the-art (SOA) gasifier technology
    - Dry syngas CH_4 content varying up to 11%
    - Hybrid case with natural gas (NG) injection resulting in a dry syngas CH_4 content ~ 25.6%
  - Advanced catalytic gasifier
    - Low temperature catalytic gasification
    - Dry syngas CH_4 content ~ 31%
- **Technological advances systematically introduced to discern impact**
  - Advanced SOFC performance and degradation rate
  - Pressurized operation (~ 20 bar)
  - Advanced inverter performance
  - Increased system availability
  - SOFC cost reduction

Parameter	Conventional IGFC	Advanced IGFC
Gasifier	Conventional	Catalytic
SOFC Operating pressure	Atmospheric	
Cell Overpotential, mV	70	
Fuel Utilization, %	90	
Current Density, mA/cm^2	400	
Degradation, %/1000 hr	0.2	
Inverter Efficiency (%)	97	98
Stack Cost ($/kW)	225	200
Capacity Factor (%)	85	90

NGFC Systems

Process Diagram – Atmospheric SOFC



Source: NETL

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NGFC Systems

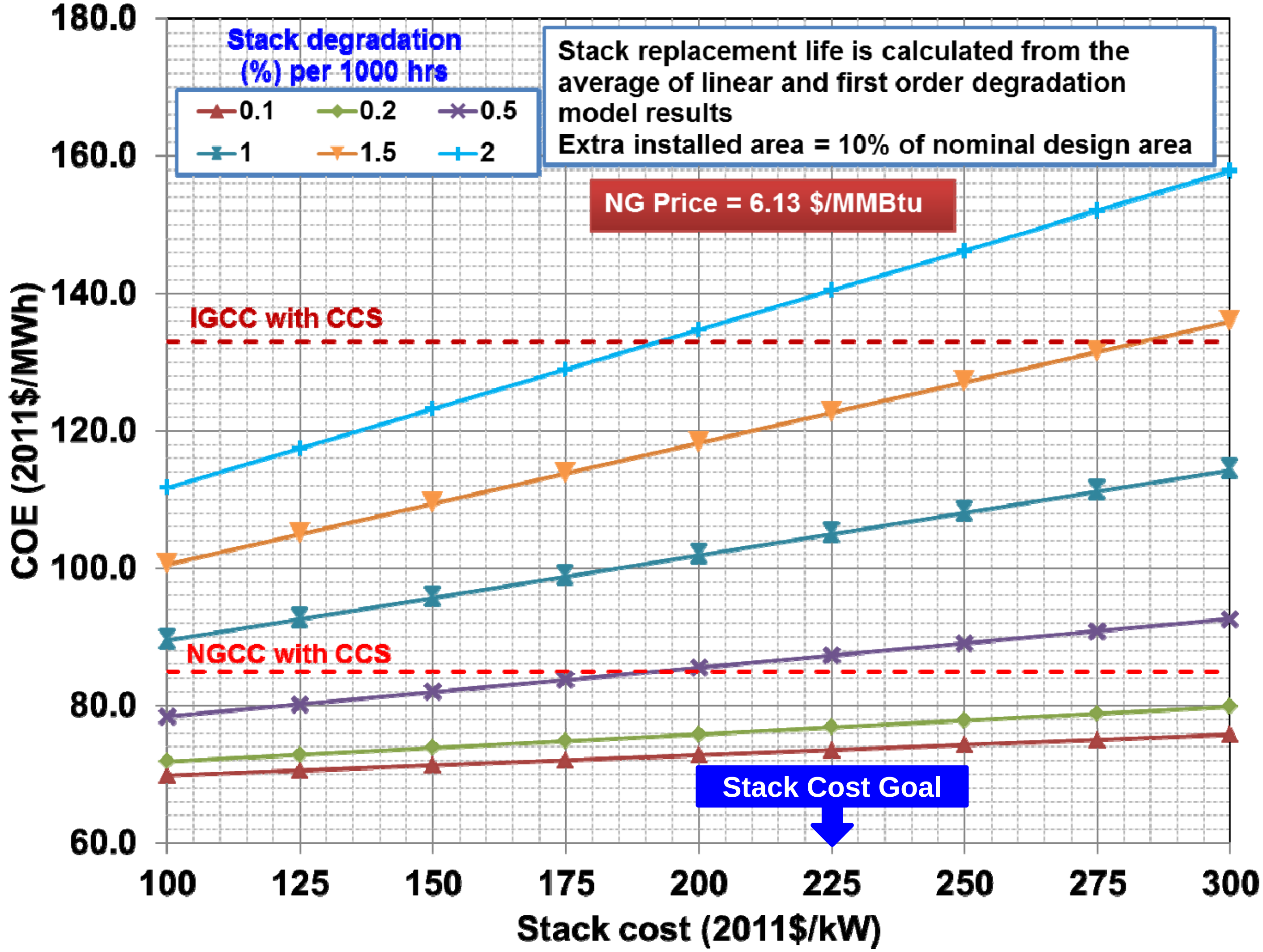
Pathway Studies - Recap

- **Three NG reformation scenarios investigated:**
  - 100 percent external reformation
    - Auto-thermal CPOX reformer
  - 40 percent external reformation
    - External reformation with auto thermal CPOX reformer
    - 60 percent reformation internal to the stack
  - 100 percent internal reformation
    - Pre-reformer included for higher hydrocarbons
- **Technological advances introduced as in IGFC to discern impact**

Parameter	Conventional NGFC	Advanced NGFC
Reformation	40% External	100% Internal
SOFC Operating Pressure	Atmospheric	
Cell Overpotential, mV	70	
Fuel Utilization, %	90	
Current Density, mA/cm^2	400	
Degradation, %/1000 hr	0.2	
Inverter Efficiency (%)	97	98
Stack Cost ($/kW)	225	
Capacity Factor (%)	85	

Effect of Stack Degradation and Cost on COE

Conventional NGFC - Example

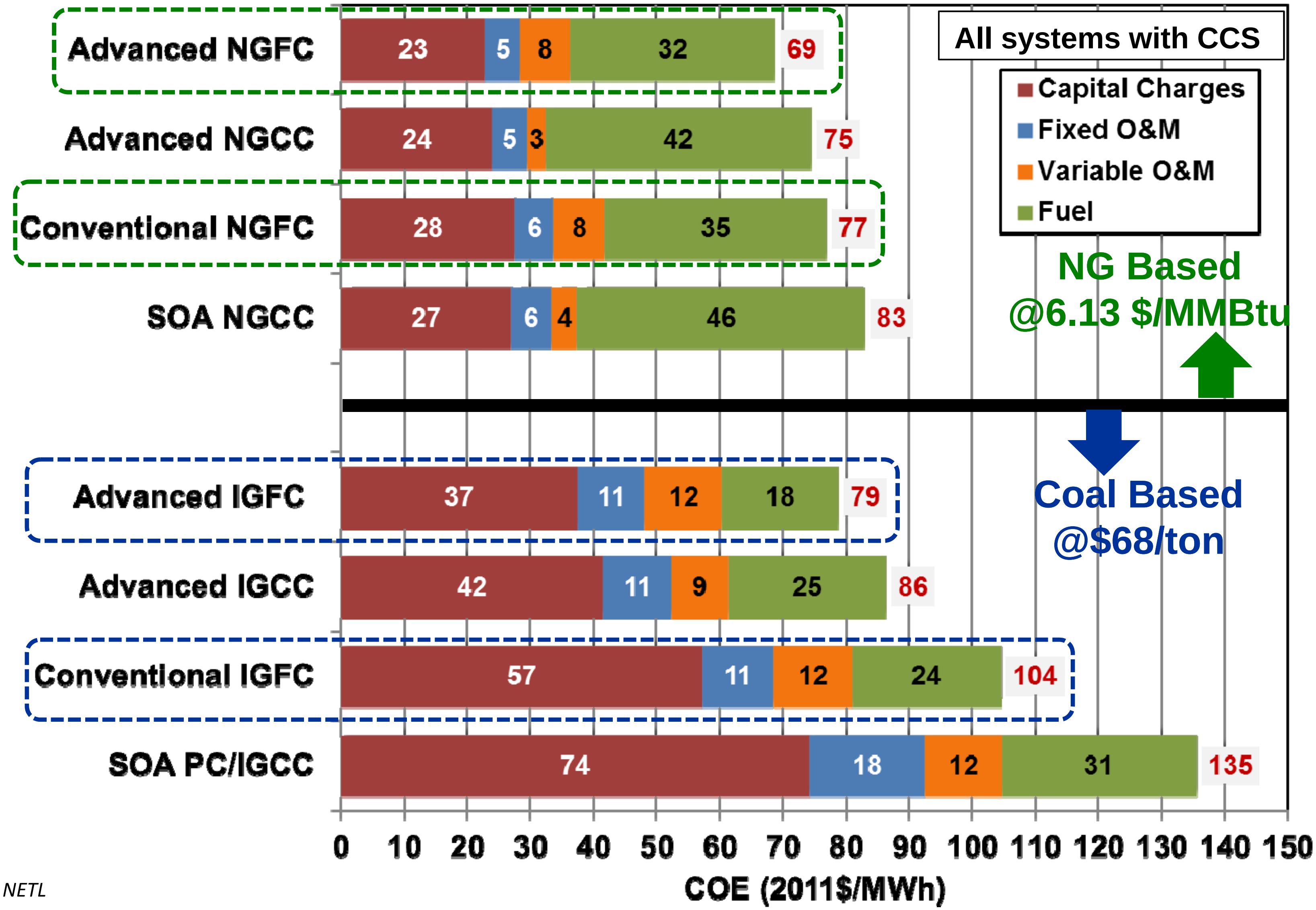


Source: NETL

Degradation rates < 0.3 percent per 1000 hrs for commercial sustenance

Salient IGFC/NGFC Results – COE (excluding T&S)

Comparison with Conventional Technologies



Source: NETL

Advanced fuel cell systems are competitive with NGCC Systems

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- **Development of SOFC stacks capable of 100 percent internal reforming gives NGFC systems a competitive edge over NGCC systems**

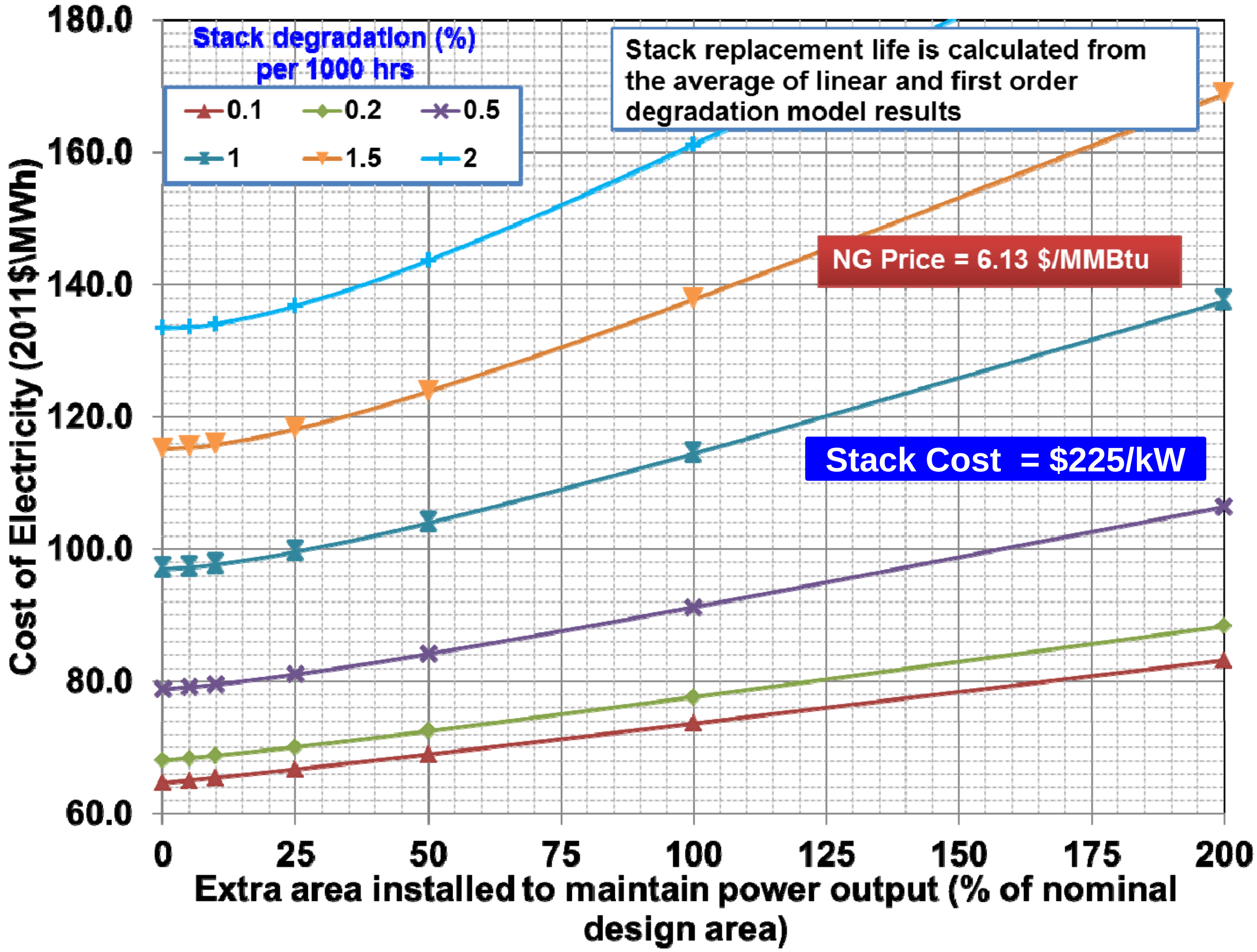
Questions ?

There are no answers without questions!

BACK-UP

NGFC System – 100% Internal Reformation

Effect of Extra Installed Area and COE Implications

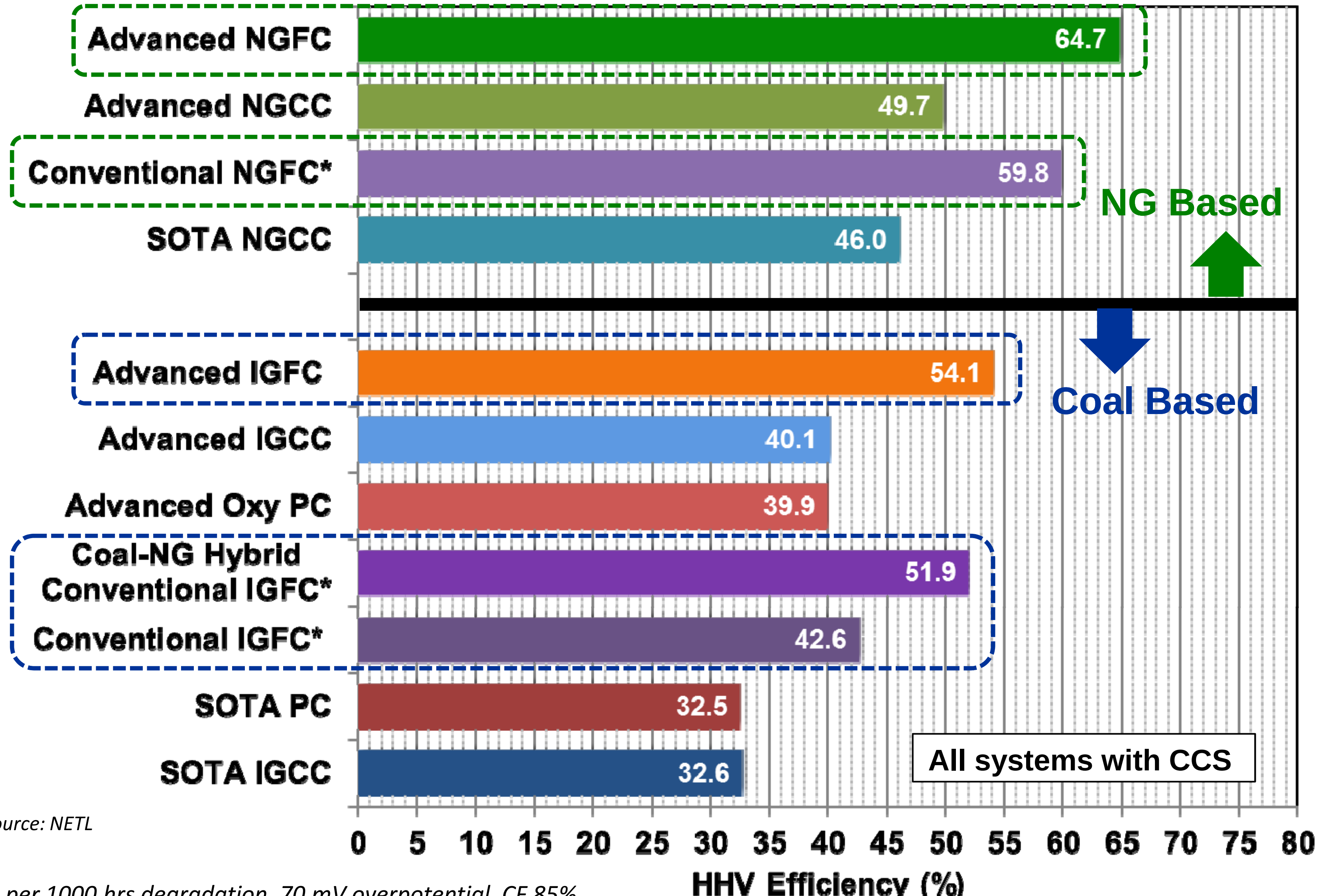


Source: NETL

Installation of extra area > 10% of the nominal area is not beneficial

Salient IGFC/NGFC Results - Performance

Comparison with Conventional Technologies



Source: NETL

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

Fuel cell system performance superior to all other systems