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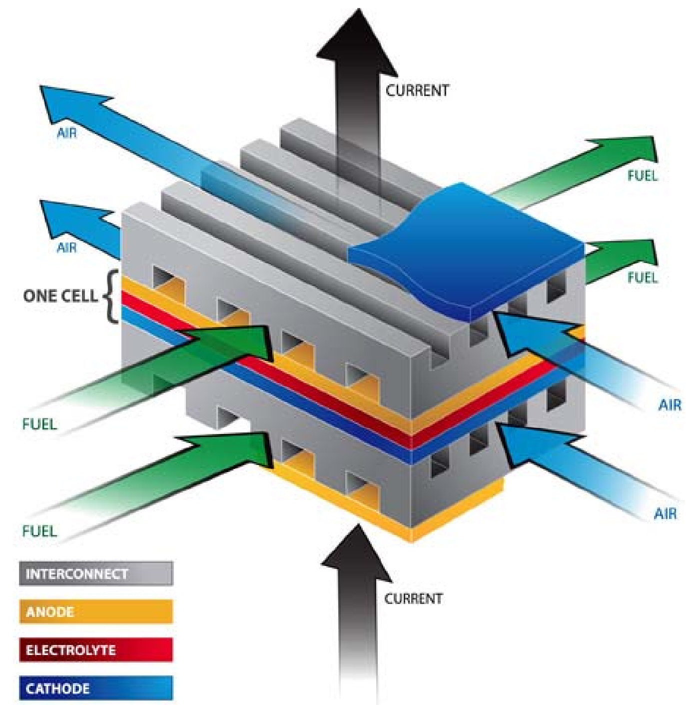

Systems Analysis of Fuel Cell Plant Configurations with Vent Gas Recirculation (VGR)

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Outline

- **Motivation**
- **Application of VGR Concept to IGFC and NGFC Utility Scale Systems**
  - Methodology
  - Results
- **Application of VGR Concept to DG-SOFC Systems**
  - Methodology
  - Results
- **Conclusions**
- **Acknowledgments/Contact Information**

Motivation

- **Solid oxide fuel cell (SOFC) based systems are capable of achieving efficiencies of over 60 percent**
  - Based on electrochemical fuel utilization (FU) of 90 percent
  - State-of-the-art SOFC typically operate at FU of less than 80 percent to prevent performance issues such as:
    - Fuel flow mal-distributions
    - Elevated performance degradation rates
    - Increased overpotentials
  - Simply recirculating the anode vent gas dilutes the fuel
    - Lowers electrochemical potential

NETL, Techno-Economic Analysis of Natural Gas Fuel Cell Plant Configurations, April 2015, DOE/NETL-2015/04082015
NETL, Techno-Economic Analysis of Integrated Gasification Fuel Cell Systems, November 2014, DOE/NETL-341/112613

Motivation

Proposed Solution

Modified Fuel Cell System with Vent Gas Recirculation

- **Investigation of SOFC systems that feature recirculation of the residual fuel in the vent gas after CO_2 capture/dehydration**
- **Concept Advantages:**
  - Allows system efficiency of **GREATER THAN** 70 percent (HHV)
  - Permits nearly 100 percent fuel utilization
  - Improves performance due to increased inlet and average chemical (Nernst) potential
  - Lowers single-pass stack fuel utilization
    - Enables reliable operation at high-system fuel utilization
    - Mitigates fuel mal-distribution concerns
  - Reduces airflow requirements
  - Eliminates the need for an oxy-combustor

Utility Scale IGFC and NGFC with Vent Gas Recirculation Concept

Utility Scale NGFC/IGFC Methodology

- **Applied to utility scale (≈550 MWe) SOFC systems for analysis:**
  - Natural Gas Fuel Cell (NGFC) system
  - Integrated Gasification Fuel Cell (IGFC) system
- **A spreadsheet model was developed to discern general advantages of the proposed system:**
  - Recirculation rate, fuel utilization, capture rate, etc.
  - Used to guide Aspen cases
- **Aspen model modifications:**
  - CO level in CO_2 product designed to be less than 35 ppm (per NETL QGESS)
    - Cryogenic CO_2 purification used (auto-refrigeration)
    - WGS reactor or preferential oxidation (PROX) reactor used
  - Pure CO_2 and H_2O separations are assumed

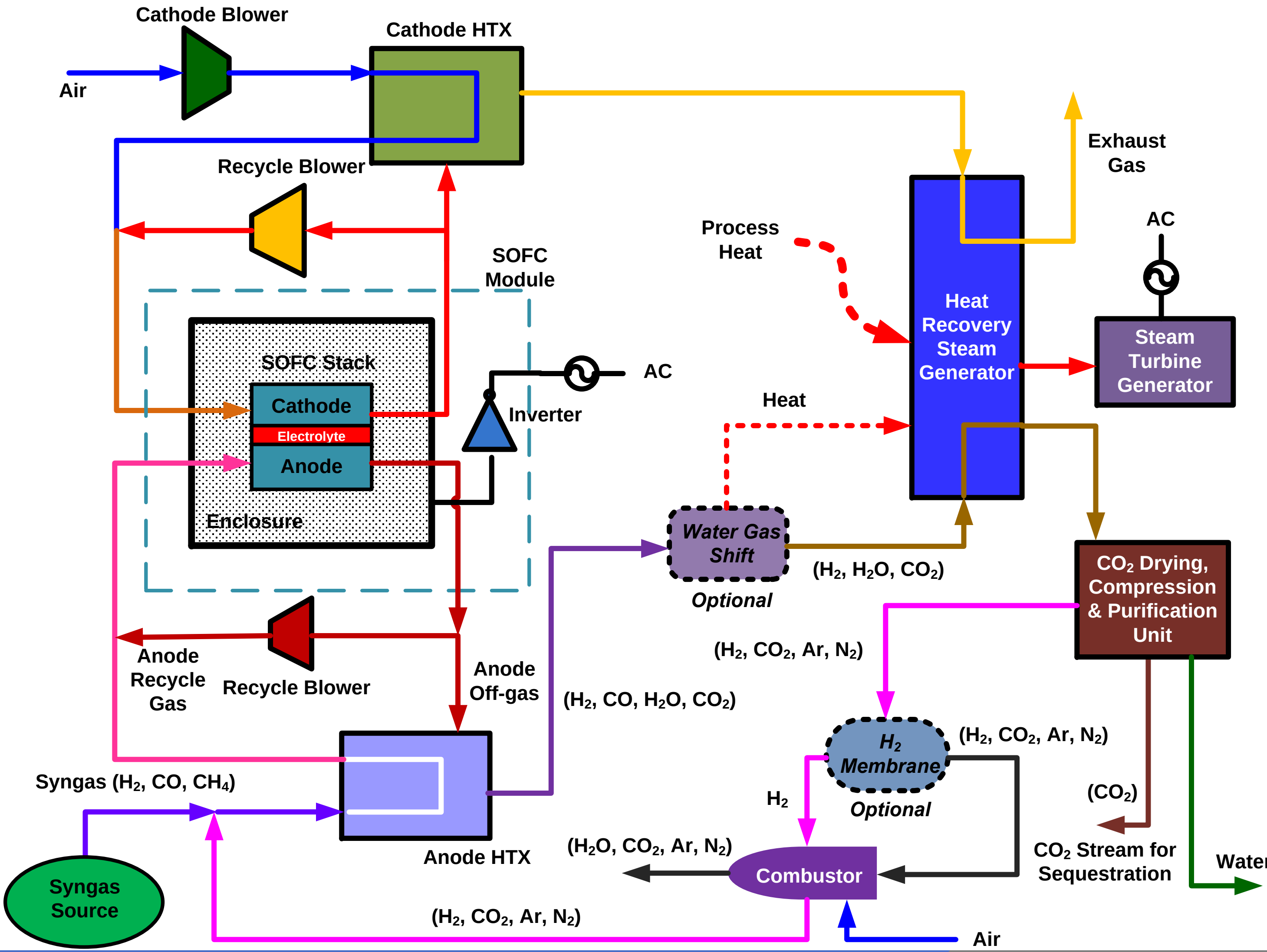
NETL, QGESS, CO_2 Impurity Design Parameters, August 2013, DOE/NETL-341/011212

Utility Scale NGFC/IGFC Methodology

Baseline Case Parameters

Parameter	IGFC	NGFC
Natural Gas Reformation	N/A	100% Internal
Gasifier	Conventional	N/A
Operating Pressure [atm]	1.0	1.0
Overall FU [%]	90	90
Cell Overpotential [mV]	70	70
Degradation Rate [%/1000 h]	0.2	0.2
Current Density [mA/cm^2]	400	400
Inverter Efficiency [%]	97	98
Stack Cost [$/kW]	225	225
Plant HHV Efficiency [%]	42.6	64.7
Plant COE [$/MWh] (excludes T&S)	104.5	68.8

Utility Scale Generalized Configuration

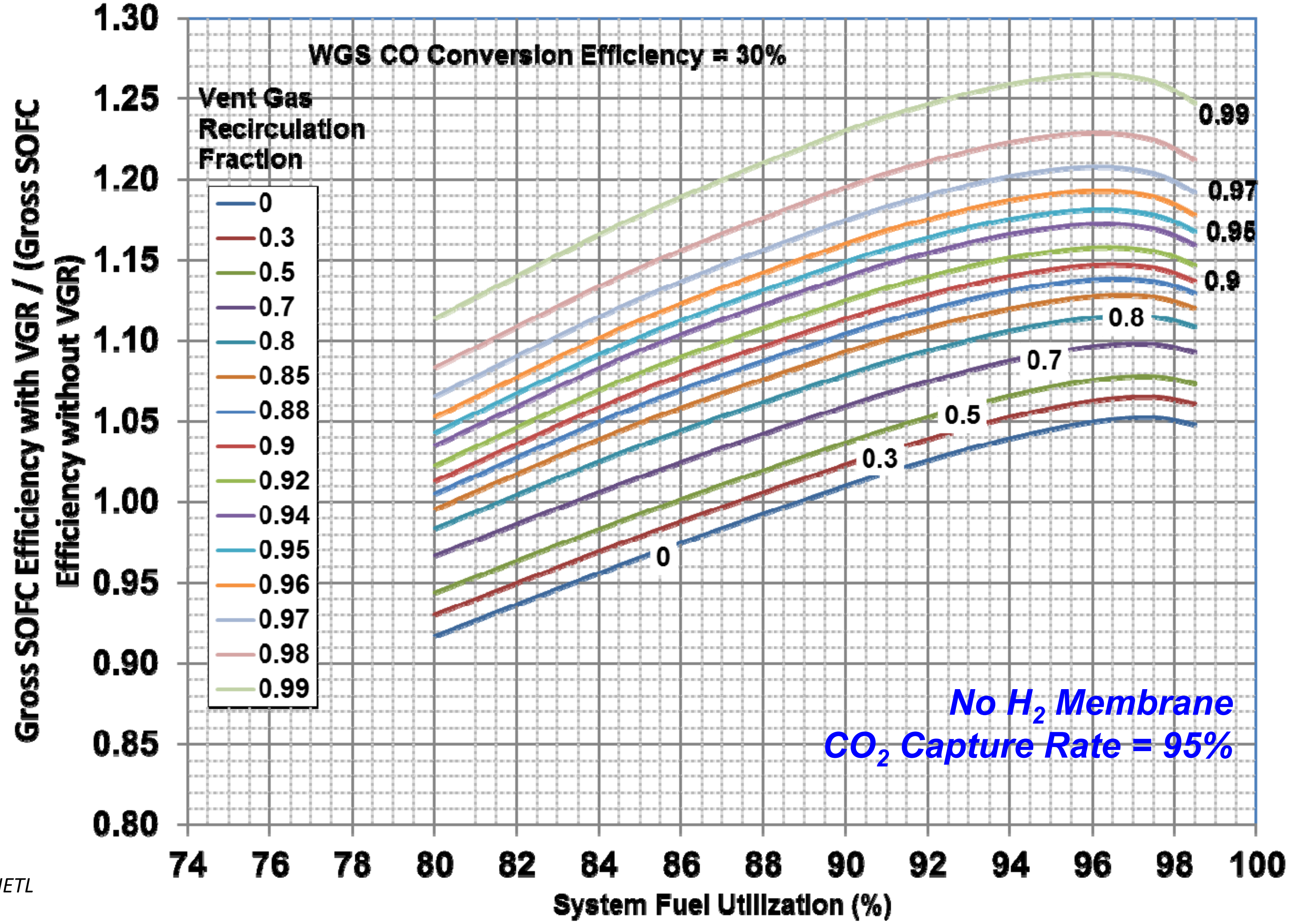


Source: NETL

Utility Scale NGFC/IGFC Configurations

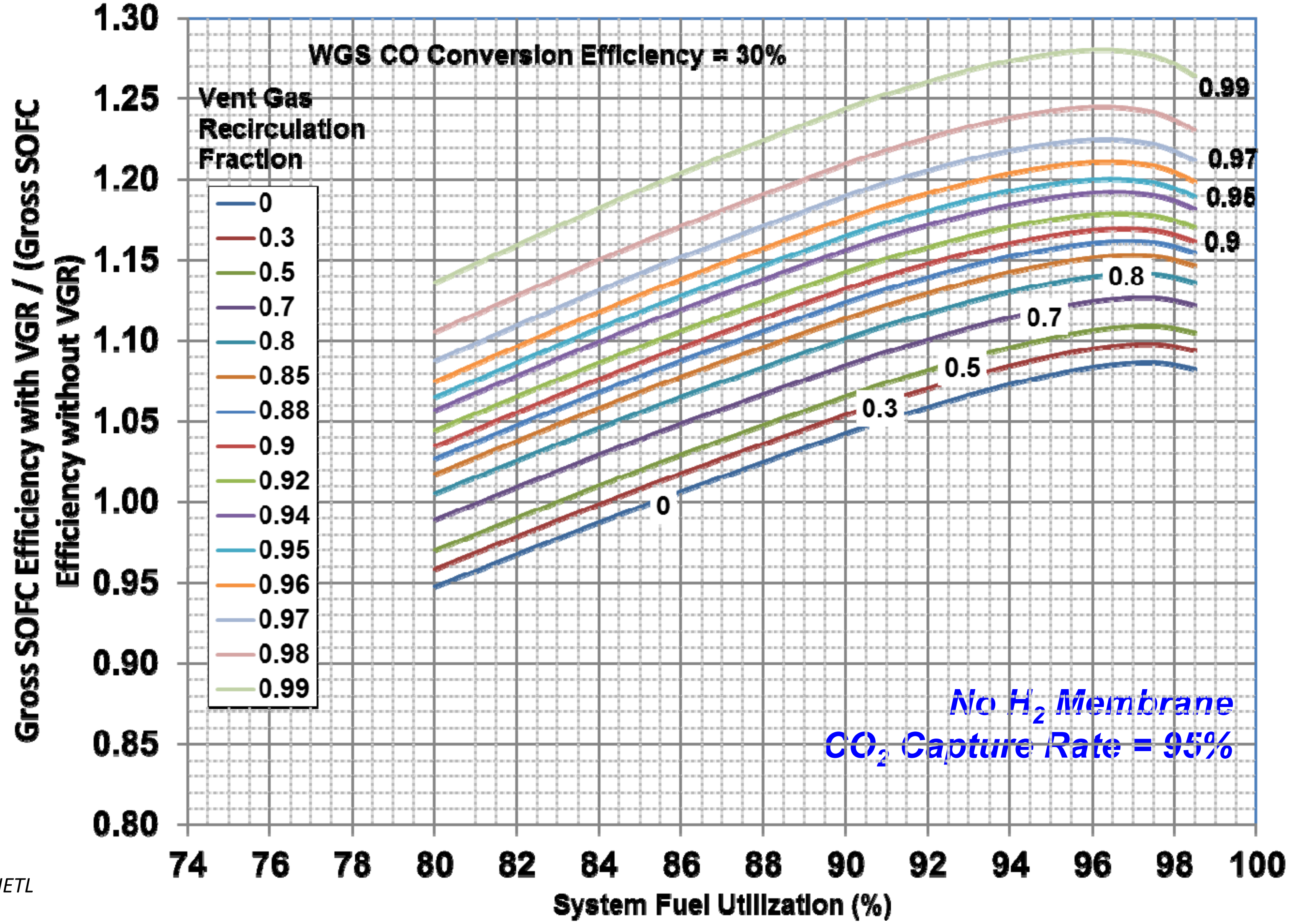
- **Baseline Case**
  - No VGR
  - No water gas shift (WGS) reactor
- **Configuration A**
  - No VGR
  - WGS reactor
- **Configuration B**
  - VGR
  - No WGS reactor
  - Preferential oxidation reactor (PROX)
- **Configuration C**
  - VGR
  - No WGS reactor
  - No PROX reactor
- **Configuration D (IGFC only)**
  - VGR
  - WGS reactor
  - PROX reactor

Results – IGFC Spreadsheet Model



Source: NETL

Results – NGFC Spreadsheet Model



Source: NETL

Results Summary (NGFC/IGFC)

NGFC System*	VGR Fraction	In-stack FU [%]	System FU [%]	WGS CO Conv. [%]	PROX Use	System Eff. [% HHV]	COE* [$/MWh]
Baseline Case	0	78.6	90.0	0	No	64.7	68.8
Configuration A	0	78.6	90.0	96.5	No	65.7	65.8
Configuration B	0.94	43.3	97.5	0	Yes	71.2	62.3
Configuration C	0.94	58.8	97.5	0	No	71.3	61.3
IGFC System							
Baseline Case	0	75.1	90.0	0	No	42.6	104.5
Configuration A	0	76.3	90.0	70.0	No	44.6	99.5
Configuration B	0.92	46.2	97.5	0	Yes	48.6	94.2
Configuration C	0.94	47.5	97.5	0	No	49.3	93.7
Configuration D	0.94	65.2	97.5	30.0	Yes	48.1	93.0

* - Reported cost of electricity does not include transport and storage costs, NG price for NGFC cases = $6.13/MMBTU

Potential Impacts on SOFC Operation

- **Applying the concept to an NGFC system with complete internal reformation eliminates the need for an air separation unit (ASU)**
- **The modified SOFC system with the baseline 140 mV overpotential assumption results in nearly the same efficiency as the un-modified system that assumes advanced performance of 70 mV overpotential**
  - The modified system enables the SOFC pathways even if the advanced SOFC performance goal cannot be met
  - Conversely, if the performance goals are met, the system can be used to lower the capital cost [$/kW] of the overall system by operating at a higher current density (consequently at a higher power output) corresponding to the 140 mV overpotential

Distributed Generation Scale NGFC with VGR Concept

Distributed Generation SOFC System VGR Evaluation

- **The previously discussed investigations were applied to utility scale (≈550 MWe) IGFC and NGFC systems**
  - Need to explore the advantages of the system with VGR on a distributed generation (DG) SOFC system scale of ≈1 MWe
- **Methodology**
  - A baseline natural gas based DG-SOFC system was developed is Aspen based on an earlier developed ChemCAD model
    - DG NGFC system with complete internal reforming baseline case
  - The baseline system will be extended to include the VGR concept
    - Systems with and without CO_2 capture have been explored
  - A cryogenic CO_2 separation system and purification system similar to the utility scale system will be used initially

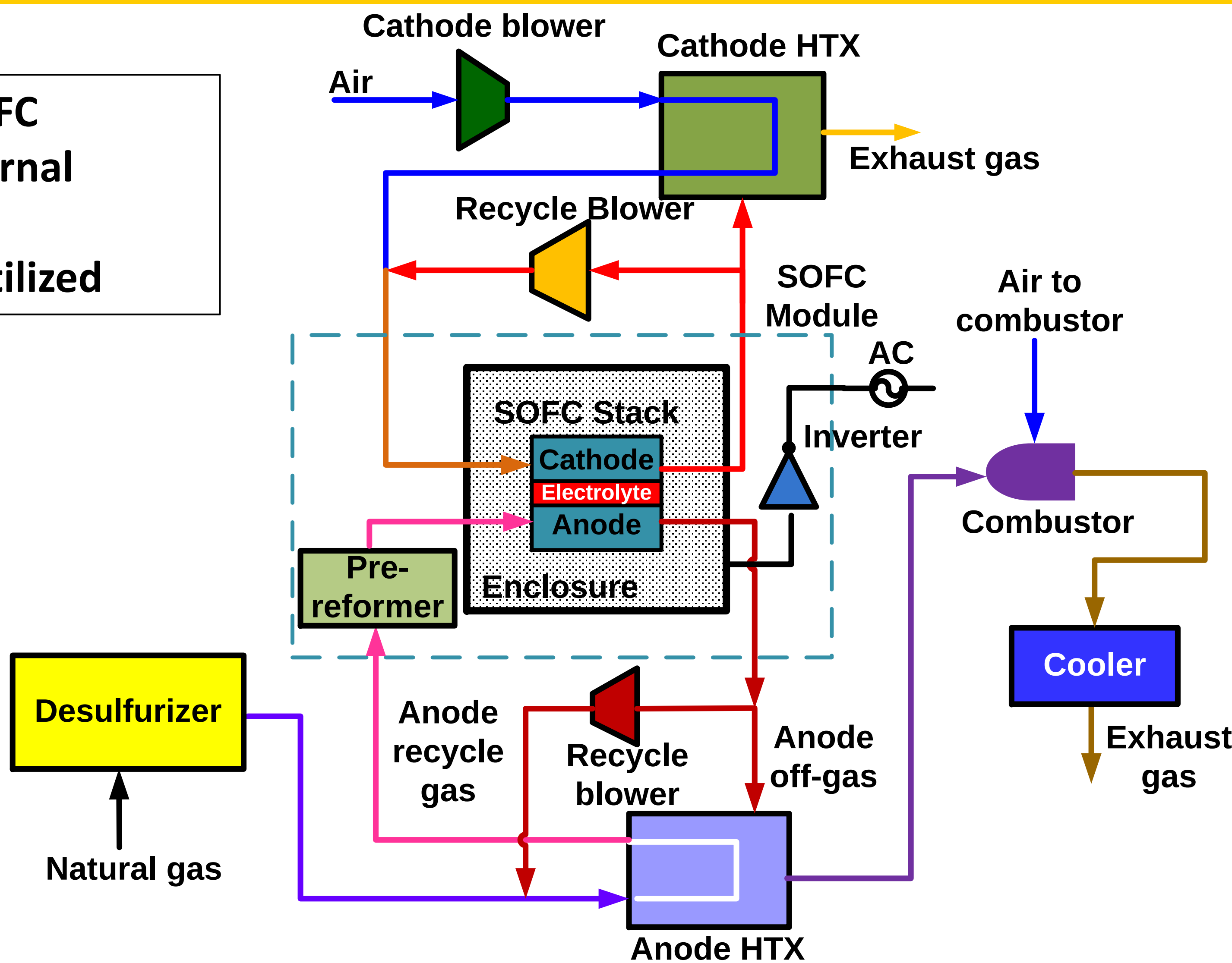
DG-SOFC System Methodology

Baseline Case Parameters

Parameter	IGFC	NGFC	DG
Natural Gas Reformation	N/A	100% Internal	100% Internal
Gasifier	Conventional	N/A	N/A
Operating Pressure [atm]	1.0	1.0	1.0
Overall FU [%]	90	90	90
Cell Overpotential [mV]	70	70	70
Degradation Rate [%/1000 h]	0.2	0.2	0.2
Current Density [mA/cm^2]	400	400	400
Inverter Efficiency [%]	97	98	98
Stack Cost [$/kW]	225	225	225
Plant HHV Efficiency [%]	42.6	64.7	61.0
Plant COE [$/MWh] (excludes T&S)	104.5	68.8	74.9

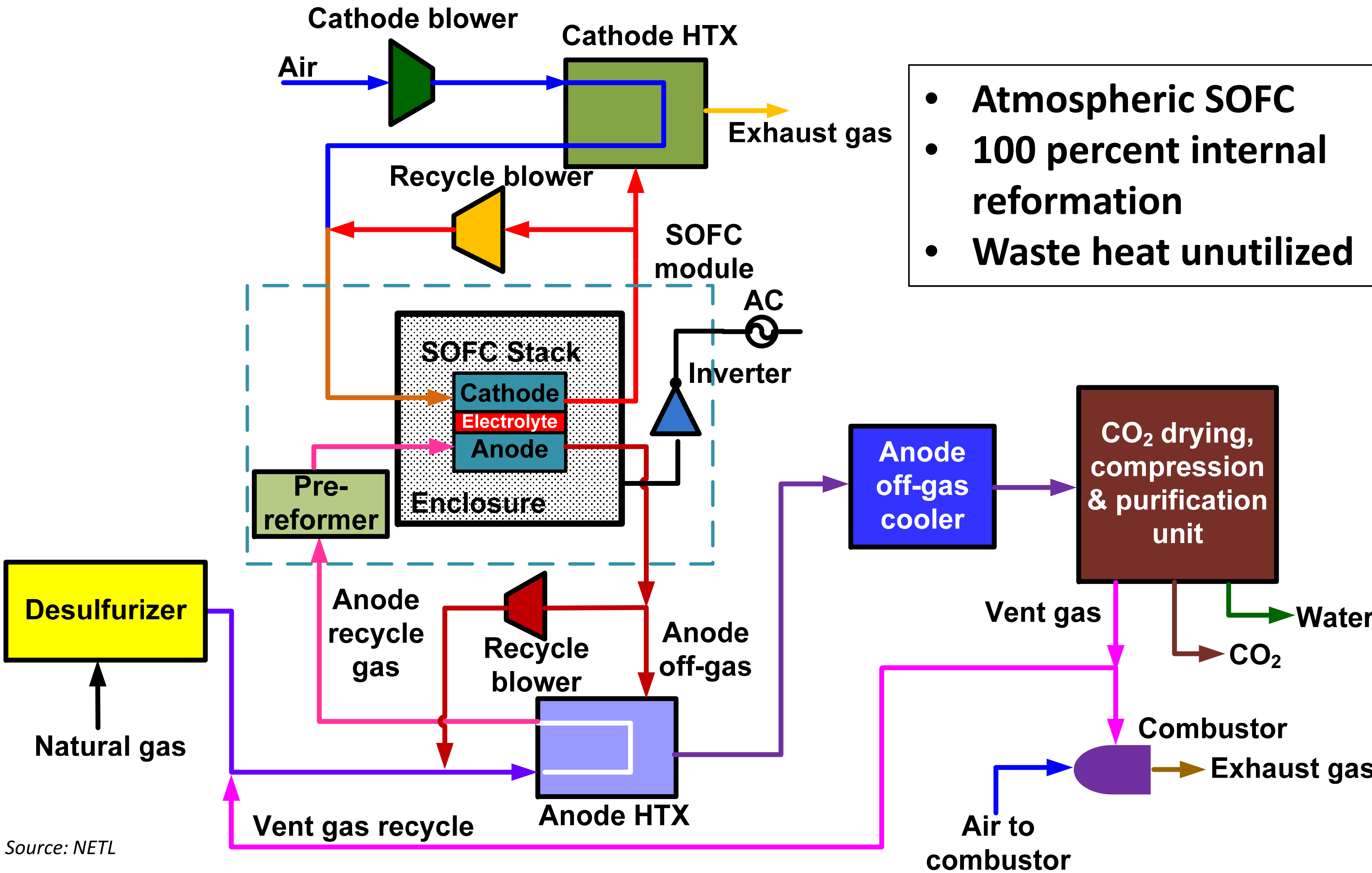
DG-SOFC System Baseline Configuration

- Atmospheric SOFC
- 100 percent internal reformation
- Waste heat unutilized



Source: NETL

DG-SOFC System Configuration w/ VGR



- Atmospheric SOFC
- 100 percent internal reformation
- Waste heat unutilized

Source: NETL

DG-SOFC System Configurations

- **Baseline Case:**
  - DG-SOFC system without carbon capture/storage (CCS)
- **Configuration A:**
  - DG-SOFC system without CCS, but with VGR
  - Dehydration of flue gas only
- **Configuration B:**
  - DG-SOFC system with CCS, but without VGR
- **Configuration C:**
  - DG-SOFC system with CCS and VGR

Results Summary (DG-SOFC)

DG-SOFC System Case	VGR Fraction	CO_2 Capture Rate [%]	In-stack FU [%]	System FU [%]	System Eff. [% HHV]	COE [$/MWh]	Selling Price CO_2* [$/tonne]
Baseline Case No VGR, No CCS	0	0	79	90	61.0	74.9	N/A
Configuration A No VGR, CCS	0	98.0	79	90	57.9	95.2	65.8
Configuration B VGR, No CCS	88	0	61	97.5	62.3	74.1	N/A
Configuration C VGR, CCS	94	93.4	43	97.5	67.5	79.3	17.3

- **Concept results in lower COE when compared to a DG-SOFC system with CCS**
- **Efficiency gains and cost reductions are minimal without CCS (dehydration only)**

* - To break even with VGR, no CCS Case

Conclusions (Utility Scale NGFC/IGFC)

- **The performance and cost of IGFC, NGFC, and DG-SOFC system that incorporated the VGR concepts were investigated**
- **A spreadsheet model of the process material flow was developed**
  - Modified fuel cell system has a potential to increase the IGFC and NGFC system efficiencies by up to 30%
- **Incorporation of the VGR concept into IGFC and NGFC cases with CCS demonstrated:**
  - An efficiency gain of more than 6 percentage points
    - Greater than 70 percent in NGFC case
  - A reduction in COE of nearly 10 percent
  - A high electrochemical fuel utilization of 97.5 percent yet ensuring a reliable fuel cell stack operation with local utilizations potentially below 50 percent

Conclusions – DG-SOFC System

- **DG-SOFC system with VGR and CCS was found to result in a significantly higher performance and lower cost than a <u>DG-SOFC system with CCS</u> but without VGR**
  - An efficiency gain of nearly 10 percentage points
  - ≈17 percent reduction in COE (@NG price of $6.13MM/Btu)
- **The system performance of the DG-SOFC system with VGR and CCS was even higher than a DG-SOFC system without CCS**
  - An efficiency gain of nearly 6 percentage points
  - The system operates at higher voltage and lower in-stack utilization

Conclusions – DG-SOFC System (2)

- **The COE of the system with VGR and CCS was ≈$5/MWh higher than a DG-SOFC system without CCS**
  - Alternate CCS technology with lower cost and auxiliary load demand than a cryogenic CPU can result in a COE comparable to the COE of the system without CCS
  - Potential applications that can use the captured CO_2 can be used to offset the COE difference
  - The COE differences between the system with VGR and CCS and the system without CCS become smaller as the NG price increases
  - The higher stack fuel flow has a potentially beneficial effect by spreading out the cooling effect of the internal reformation
- **Operation of the system with VGR at higher current densities can potentially decrease the capital costs**
  - Operation at the same voltage as that of system with CCS nearly doubles the operating current

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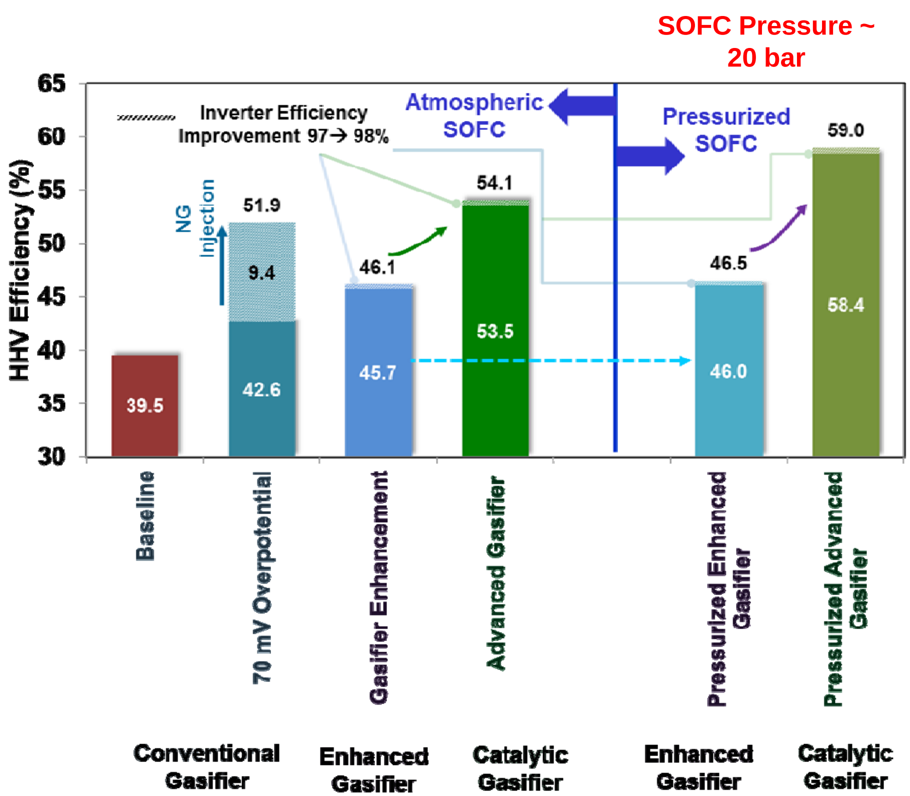
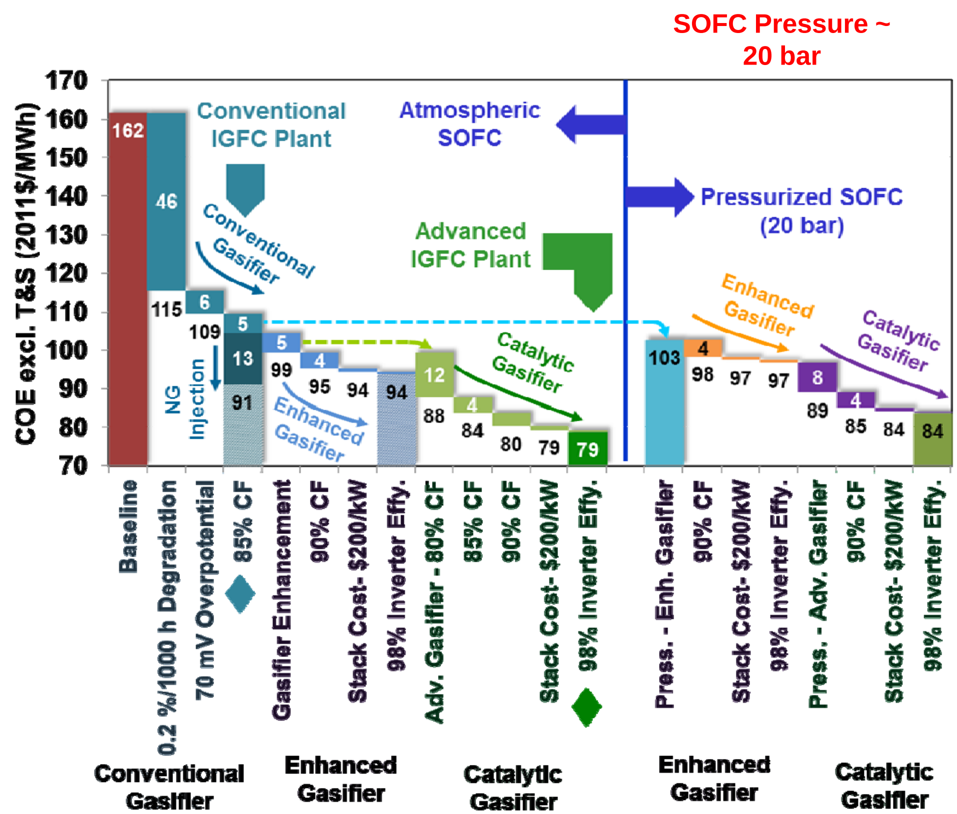
NETL SOFC Group Posters

- **"Phase Field Modeling of Microstructure and Conductivity Evolution in SOFC Electrodes" – Youhai Wen**
- **"Effects of Humidity on Degradation of Sr-Fe-O Infiltrated Solid Oxide Fuel Cells" – Lynn Fan**
- **"Catalyst Infiltration of SOFC Electrodes Assisted by a Bio-surfactant" – Ozcan Ozmen**
- **"Characterization of SOFC Cathode Impedance under Polarization Using Appropriate Counter Electrode Design" – Jay Liu**
- **"Interpretation of Impedance Spectroscopy Data on Porous LSM Electrodes" – Giuseppe Brunello**
- **"Representative Volumes in Highly Heterogeneous Fuel Cell Materials" – Billy Epting**
- **"Ab Initio Modeling of Mn Self-Diffusion in $La_{1-x}Sr_xMnO_3$ (X=0 and 0.25) for Solid Oxide Electrochemical Cells" – Yueh-Lin Lee**
- **"Evidence of the Space Charge Layer Evolution at the YSZ Grain Boundaries" – Xueyan Song**

Backup Slides

IGFC Pathway Results





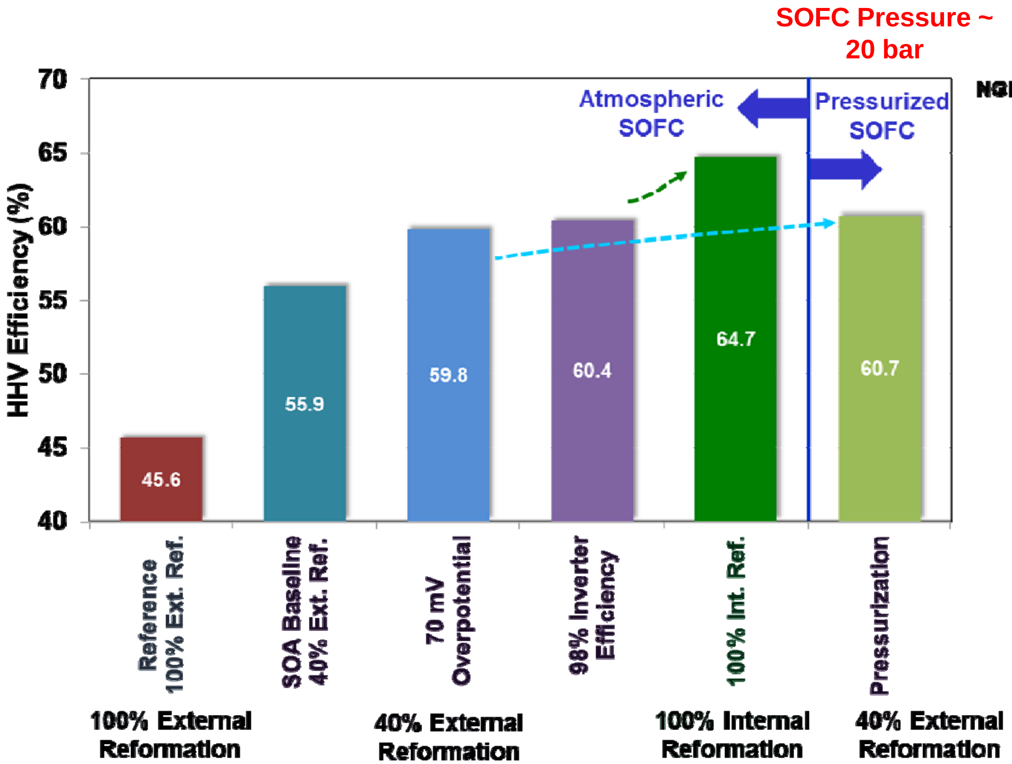
Baseline	
Overpotential, mV	140
Fuel Utilization, %	90
Degrad., %/1000 h	1.5
Inverter Effy. (%)	97
Stack Cost ($/kW)	225
CF (%)	80

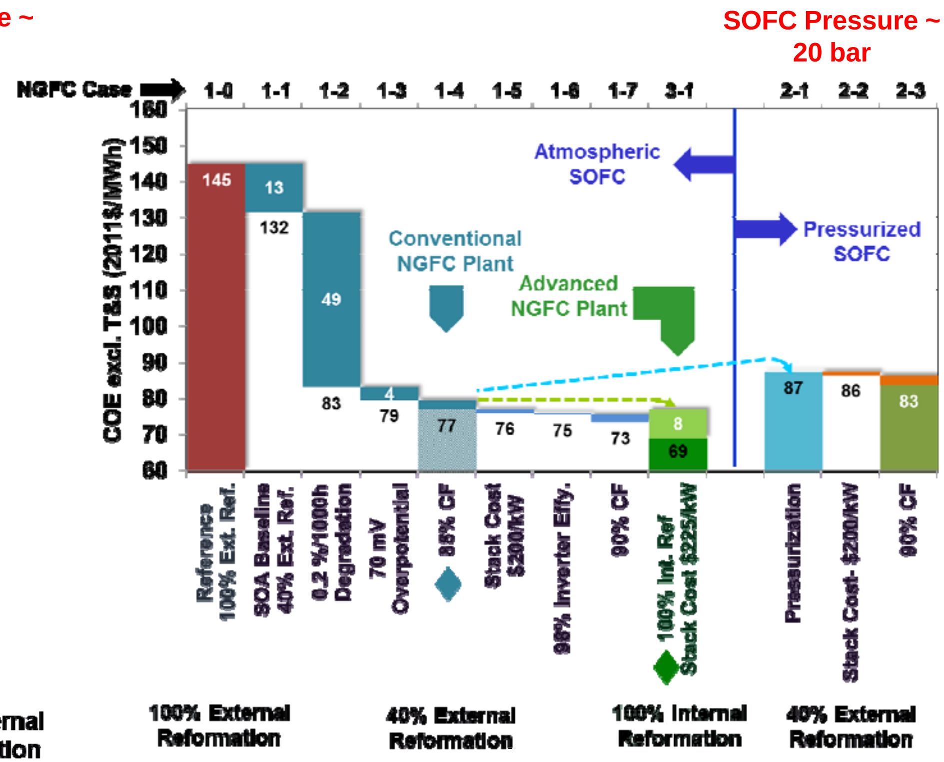
All cases include 90% CO_2 capture

Source: NETL

NETL, Techno-Economic Analysis of Integrated Gasification Fuel Cell Systems, November 2014, DOE/NETL-341/112613

NGFC Pathway Results





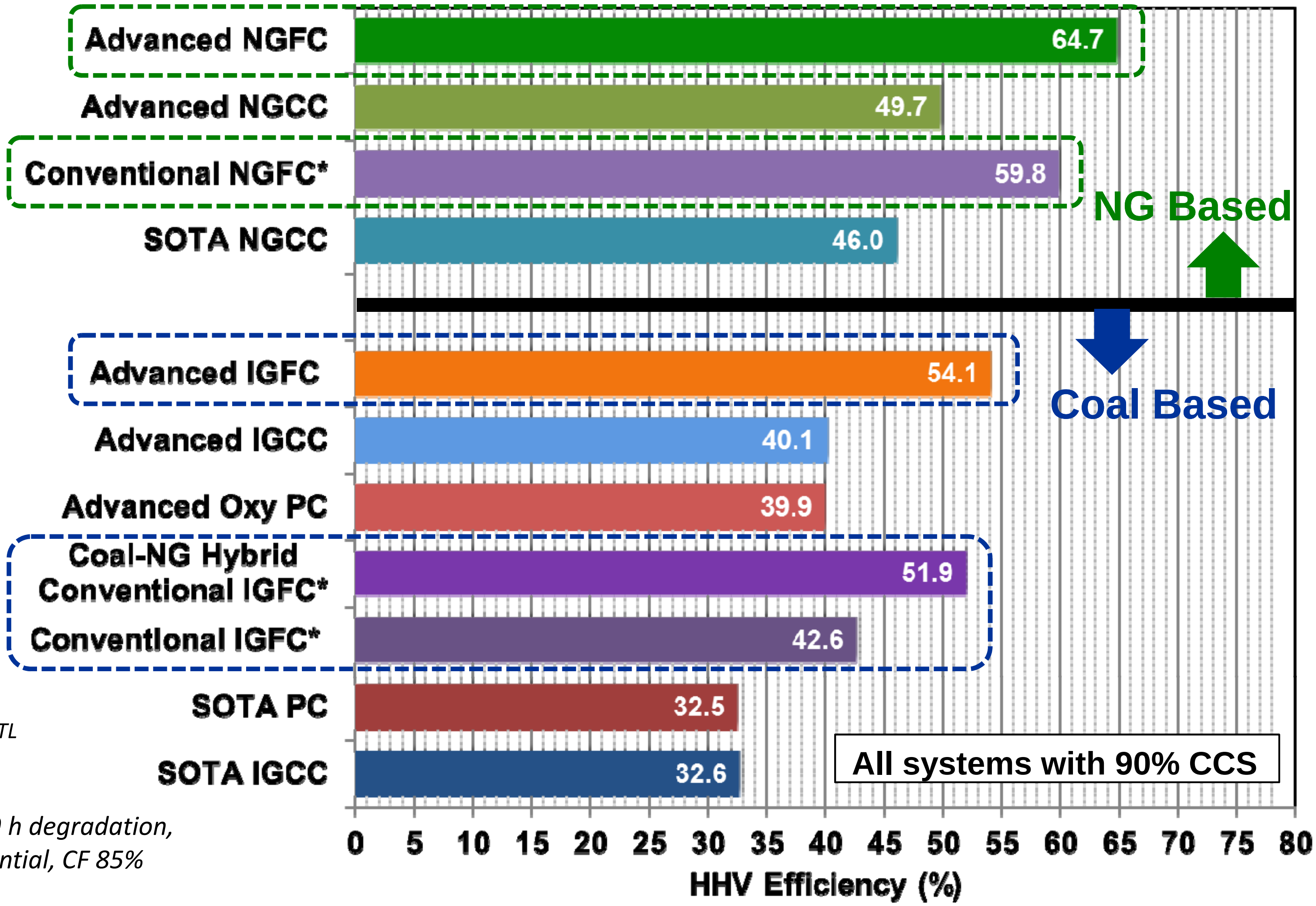
Source: NETL

Reference Plant (Case 1-0) SOFC Parameters	
Reformation	100% Ext.
Overpotential (mV)	140
Degrad. (%/1000 h)	1.5
Inverter Effy. (%)	97
Stack Cost ($/kW)	225
CF (%)	80

All cases include 90% CO_2 capture

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

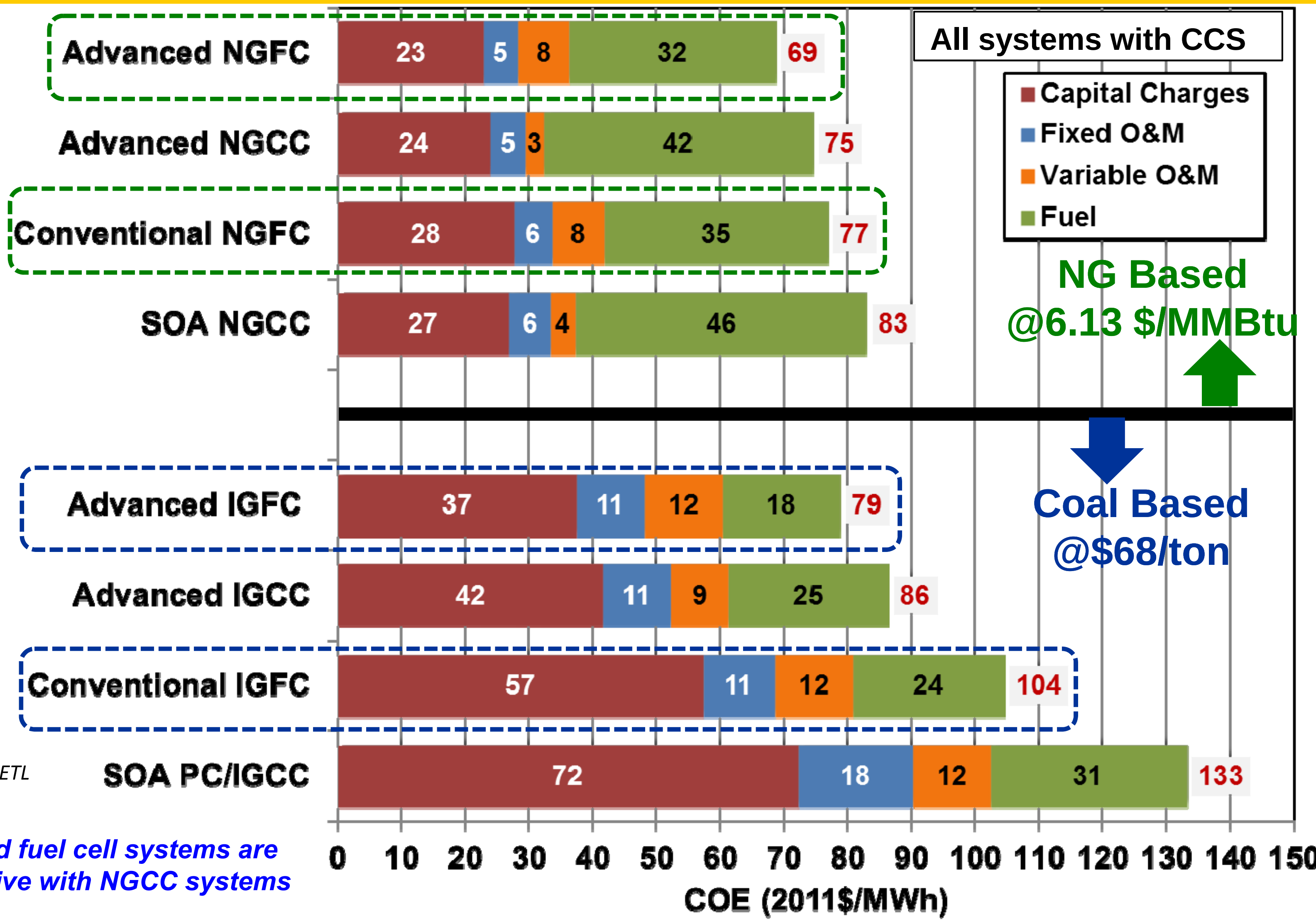
Power Generation Technology Comparison
Performance



Source: NETL

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

Power Generation Technology Comparison
Cost of Electricity



Source: NETL

Advanced fuel cell systems are competitive with NGCC systems