# Status Update on NETL Techno-Economic Analysis

## of Solid Oxide Cells

NATIONAL ENERGY TECHNOLOGY LABORATORY

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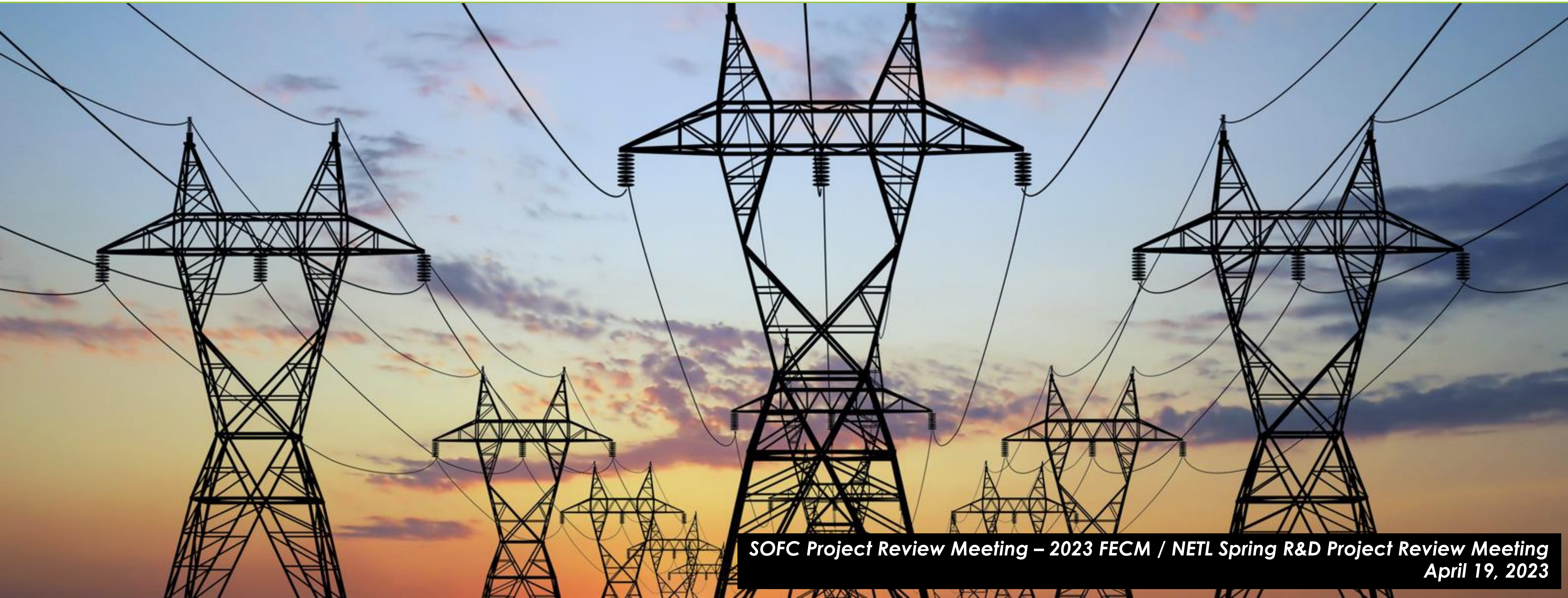
*Strategic Systems Analysis and Engineering*



***SOFC Project Review Meeting – 2023 FECM / NETL Spring R&D Project Review Meeting***

***April 19, 2023***

# Agenda / Acknowledgements

- **Overview**
  - Brief Highlights of Recently Completed Work
- **"Deeper" Dive into Hydrogen Fueled SOFC Analysis**
  - Introduction / Study Assumptions
  - Performance Results
  - Cost Results
  - Sensitivity Studies
  - Conclusions
- **Ongoing and Future Work**
- **Wrap-Up**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# Overview

## Techno-Economic Analysis of NGFC Plant Configurations

## Objective

This study details performance, cost, and pathway information for NGFC systems with CCS to aid in the development of targeted R&D approaches for SOFC fueled by natural gas

## Methodology

**Cost Analysis:**

The cost analysis follows the basis provided in the NETL Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity

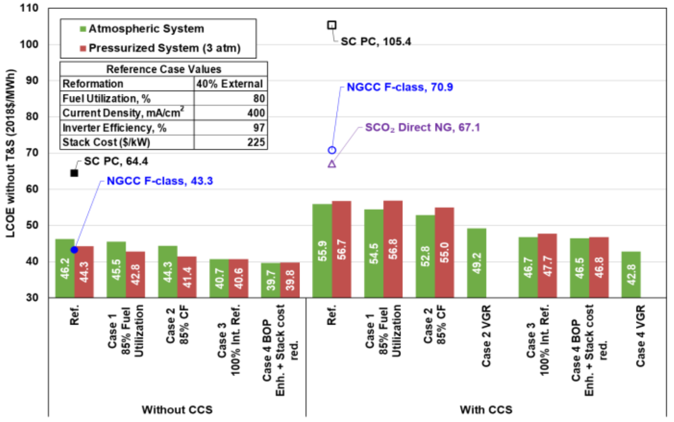
**PNNL-ROM:**

In collaboration with PNNL, NETL has developed a reduced order model based on detailed computational models of a planar SOFC stack. The model is used to predict SOFC performance along with thermal fields

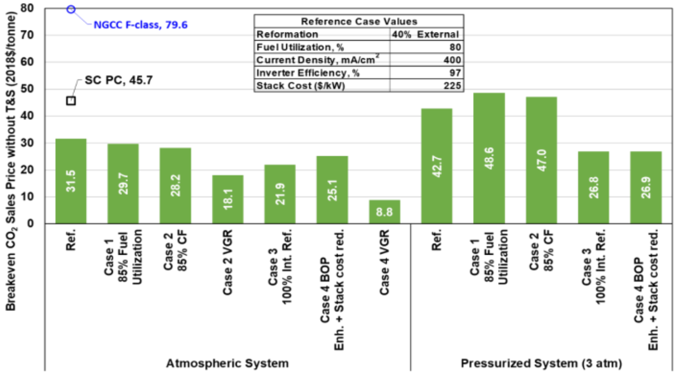
**Methane Reforming:**

Comparison cases involving complete external, complete internal, and partial external reformation. On-cell reforming improves system performance but decreases longevity

## Levelized Cost-of-Electricity




## Cost of $CO_2$ Captured




## Results

**LCOE for the NGFC power plant with CCS is attractive compared to conventional NGCC with CCS**

Development of technologies that enable internal reformation, CCS advancements will have the most impact

The advanced NGFC plant with complete internal reformation and VGR has the **lowest $CO_2$ emission footprint** relative to any other conventional power generation technology without CCS.

Cost reduction steps that can result in an increase of over 12 percentage points in NGFC plant efficiency accompanied by over 23% reduction in the associated LCOE were identified and quantified.

# Overview

## Techno-Economic Analysis of IGFC Plant Configurations

## Objective

This study details performance, cost, and pathway information for IGFC systems with CCS to aid in the development of targeted R&D approaches for SOFC fueled by gasified coal

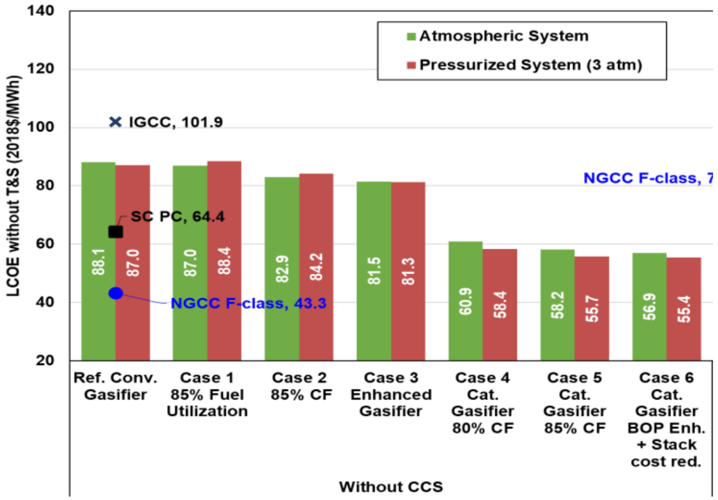
## Methodology

**Cost Analysis:**
The cost analysis follows the basis provided in the NETL Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity

**PNNL-ROM:**
In collaboration with PNNL, NETL has developed a reduced order model based on detailed computational models of a planar SOFC stack. The model is used to predict SOFC performance along with thermal fields

**Gasification Technology:**
The analysis evaluated two operating pressures and three gasification technologies. The gasification configurations included conventional, advanced, and enhanced catalytic technologies.

## Levelized Cost-of-Electricity

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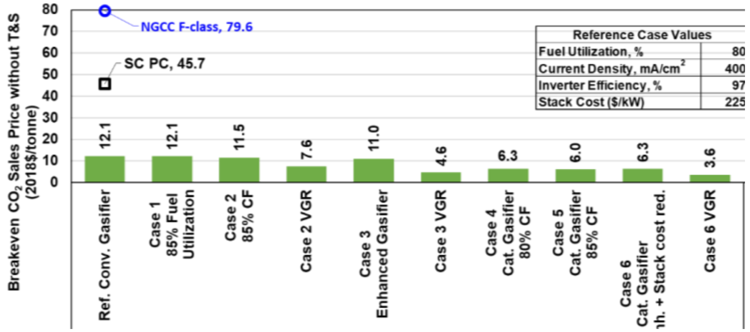



## Results

**IGFC systems have the potential to result in HHV efficiencies that exceed 60 percent, even with CCS.**

IGFC economic competitiveness relative to NGCC (at current natural gas prices) are achievable with significant advances and considerable cost reductions in gasification technology.

SOFC are inherently an effective carbon separator. It produces a concentrated $CO_2$ effluent that is ready for CCS with minimal incremental costs.

Breakeven values of $CO_2$ prices below $10/tonne are achievable.

The VGR concept has the potential to significantly reduce the COE in the short-term even with conventional technologies.

# Overview

## TEA of an SOFC Hybrid Carbon Conversion Concept

### Objective

- Develop an understanding of the potential of coupling solid oxide fuel cell (SOFC) technology in hybrid carbon conversion (HCC) configurations from a cost and performance perspective.

### Outcome

- Techno-economic analysis of an SOFC system paired with compressed air energy storage (CAES)
- Identification of the primary cost and performance drivers for the hybridized system
- Identification of specific process configurations and operating modes that can make the hybridized system cost competitive with traditional NG fossil generation plants

### Approach

- In partnership with Idaho National Laboratory, NETL recently completed an internal screening of multiple HCC concepts that included renewable, nuclear, and energy storage technologies with SOFC.
- NETL has chosen to assess an SOFC+CAES hybrid system for further analysis
- Assess several operating configurations of a 250 MWe SOFC system paired with an 80 MWe CAES-powered turbine
- Analyze process sensitivities to cavern size, turbine operating temp, and charge/discharge timing

### Authors

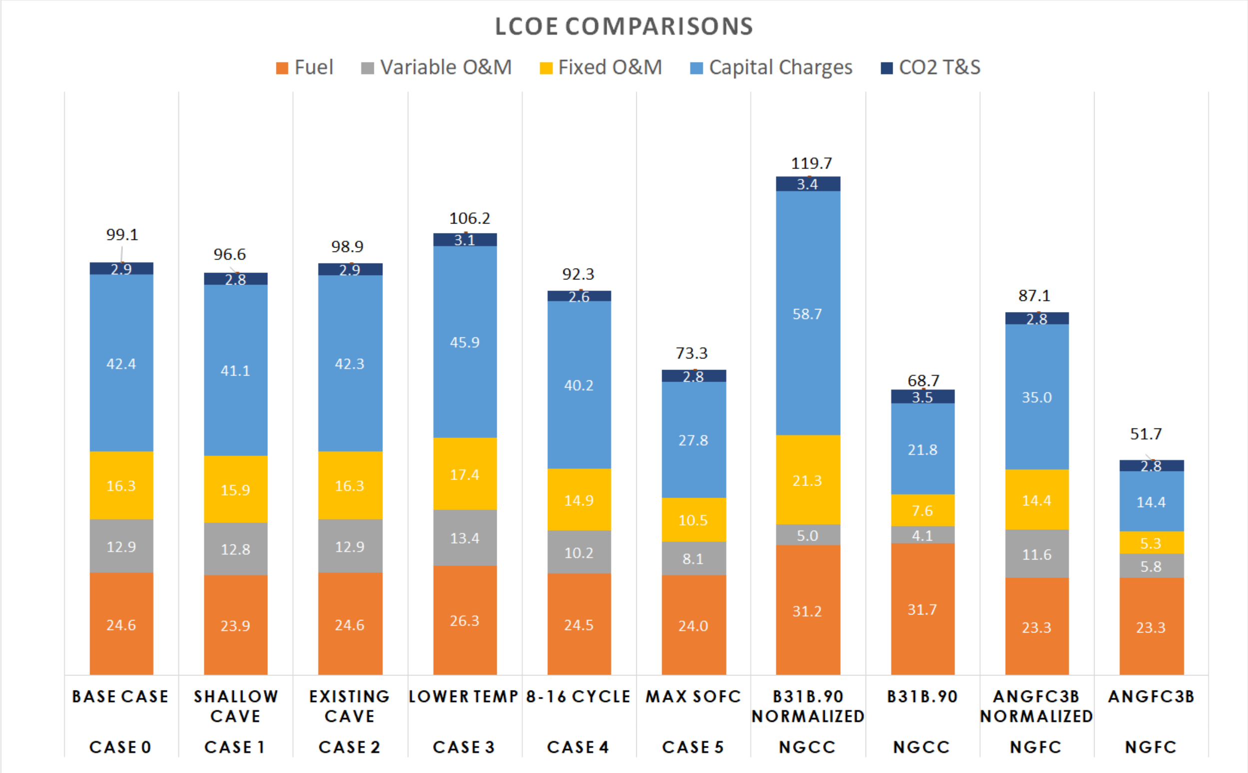

- Kyle Buchheit, Alex Noring, Arun Iyengar, Richard Boardman (INL), Cristian Rabiti (formerly INL), Gregory Hackett

# Overview

## TEA of an SOFC Hybrid Carbon Conversion Concept

### Highlights

- The added flexibility of the hybrid system comes at an increased cost
- A power ratio of ≈3.1 SOFC to CAES thermally integrates the system, eliminating the need for external heat
- The charge and discharge times affect the cavern sizing and compressor power requirements
- When normalized for power output and capacity factors, the hybridized system is cost competitive with NGCC and NGFC plants
- Several items relating to process configuration and operating conditions have been identified for future analysis



# Overview

## TEA of Reversible Solid Oxide Cell Systems

### Objective

- Develop a techno-economic analysis that assesses the cost and performance of a reversible solid oxide cell (r-SOC) system compared to a paired solid oxide fuel cell (SOFC) and solid oxide electrolysis cell (SOEC) system

### Outcome

- Understanding of the tradeoff between increased capital cost of two separate units versus decreased longevity of a single, reversible unit
- Identification of specific process configurations, operating modes, and external parameters that can impact the cost of producing hydrogen (LCOH) in these configurations
- Provide critical information to the SOFC Program on how to best implement SOC technology into integrated energy systems

### Approach

- Compare performance and cost of two systems, one paired SOEC/SOFC system, one single r-SOC system.
- Determine the LCOH for each case and identify the parameters that primarily impact this value.
- Perform sensitivity studies to quantify how these parameters impact cost and identify best-case scenario values
- Craft future work scope based on the results of this initial effort for additional study.

### Authors

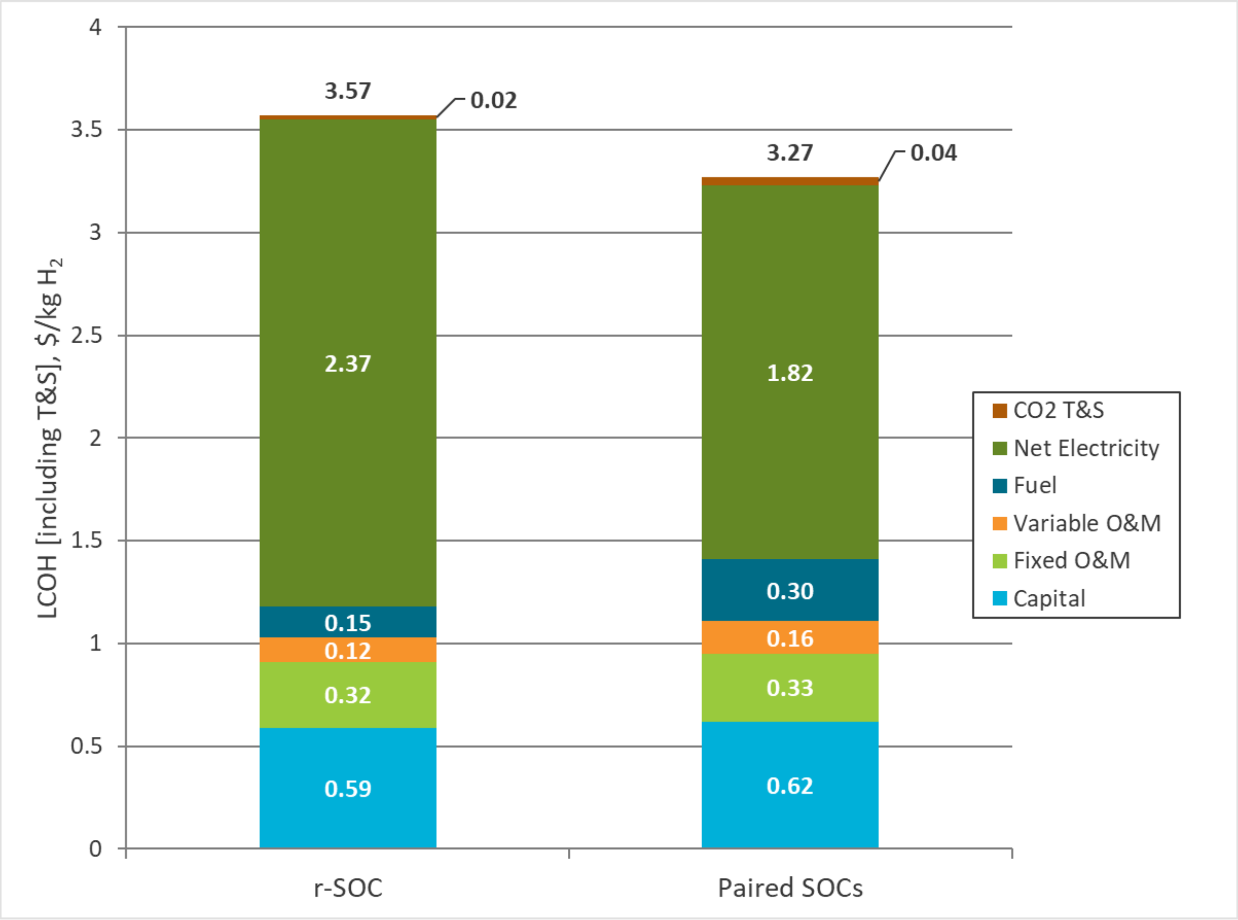
- Alex Noring, Kyle Buchheit, Arun Iyengar, Gregory Hackett

# Overview

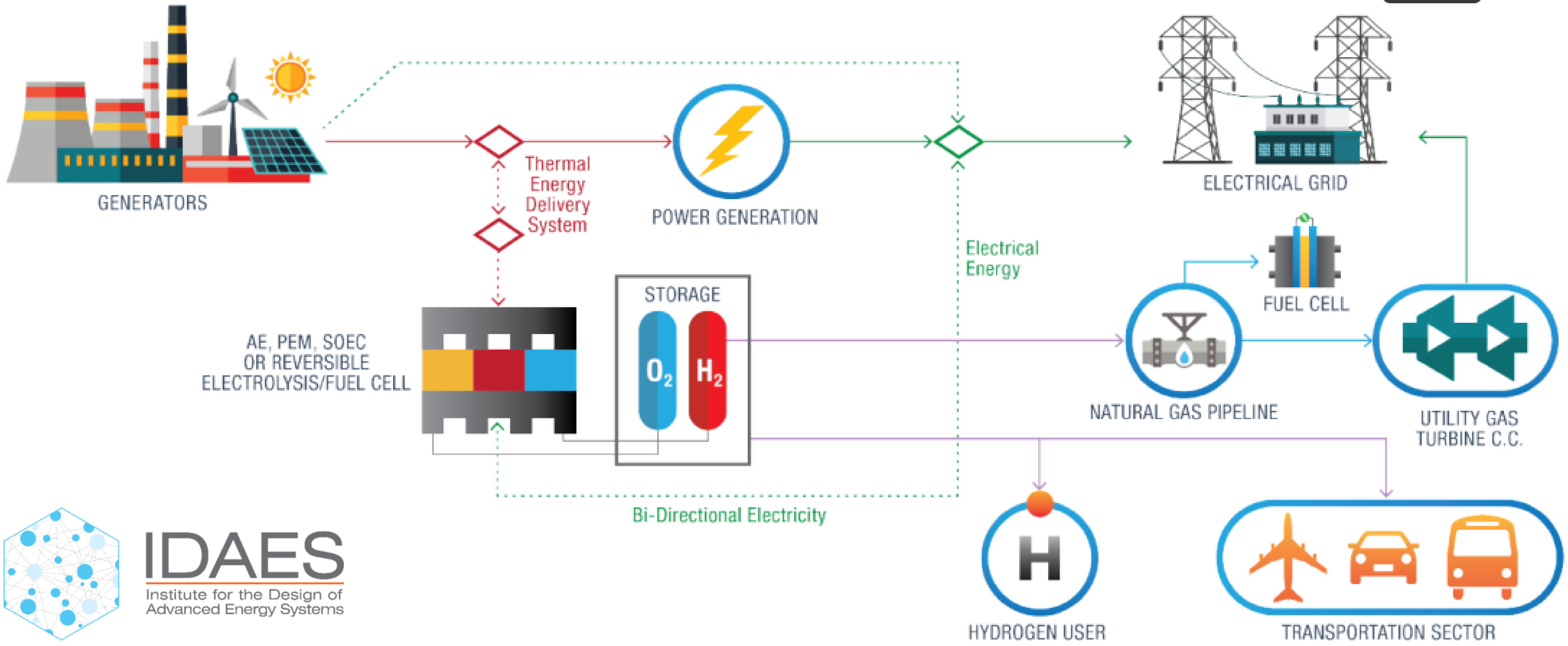
## TEA of Reversible Solid Oxide Cell Systems

### Highlights

- As expected, the cost of purchased electricity significantly impacts the levelized cost of the hydrogen product
- At $60/MWh, the paired SOEC/SOFC results in a lower LCOH primarily due to its ability to generate electrons and $H_2$ simultaneously, lowering net electricity demand
- As the cost of purchased electricity decreases, the reversible SOC system becomes more favorable, at ≈$27/MWh
  - NREL projects an aspirational future electricity price of ≈$20-30/MWh based upon increased penetration of variable renewable energy (VRE). The availability of VRE impacts the LCOH significantly.
- An on-going effort (near completion) will compare multiple low-carbon SOEC cases to compare with the results obtained in this study



# Integrated Energy Systems for Power and $H_2$




IDAES
Institute for the Design of Advanced Energy Systems

The IDAES platform is being applied to explore whether tightly coupled integrated energy systems that have the flexibility to produce both power and hydrogen should play a role in DOE's goals of decarbonizing the power sector by 2035 and broader economy by 2050.

# TEA of Hydrogen-Fueled SOFC Systems

# TEA of Hydrogen-Fueled SOFC Systems

NATIONAL ENERGY TECHNOLOGY LABORATORY

## Study Overview

### Objective

- Quantification of the cost and performance impacts associated with operating SOFC technology on pure hydrogen fuel

### Outcome

- As the generation of hydrogen becomes more prevalent, it is important to understand how using hydrogen as a fuel affects the cost and performance of SOFC systems
- A detailed understanding on the impact of increased heat generation as a result of using pure hydrogen fuel
- Information on specific markets or scenarios where hydrogen fueled SOFC make sense

### Approach

- Execute an analysis of hydrogen-fueled solid oxide fuel cell configurations
- Assess at a smaller scale - May be preferred for comparison, given the expense and role that hydrogen may play in power generation
- The analysis should consider system configurations that aim to mitigate the increased parasitic losses associated with the exothermic hydrogen oxidation reaction
- Compare with previously developed cost and performance information for SOFC systems

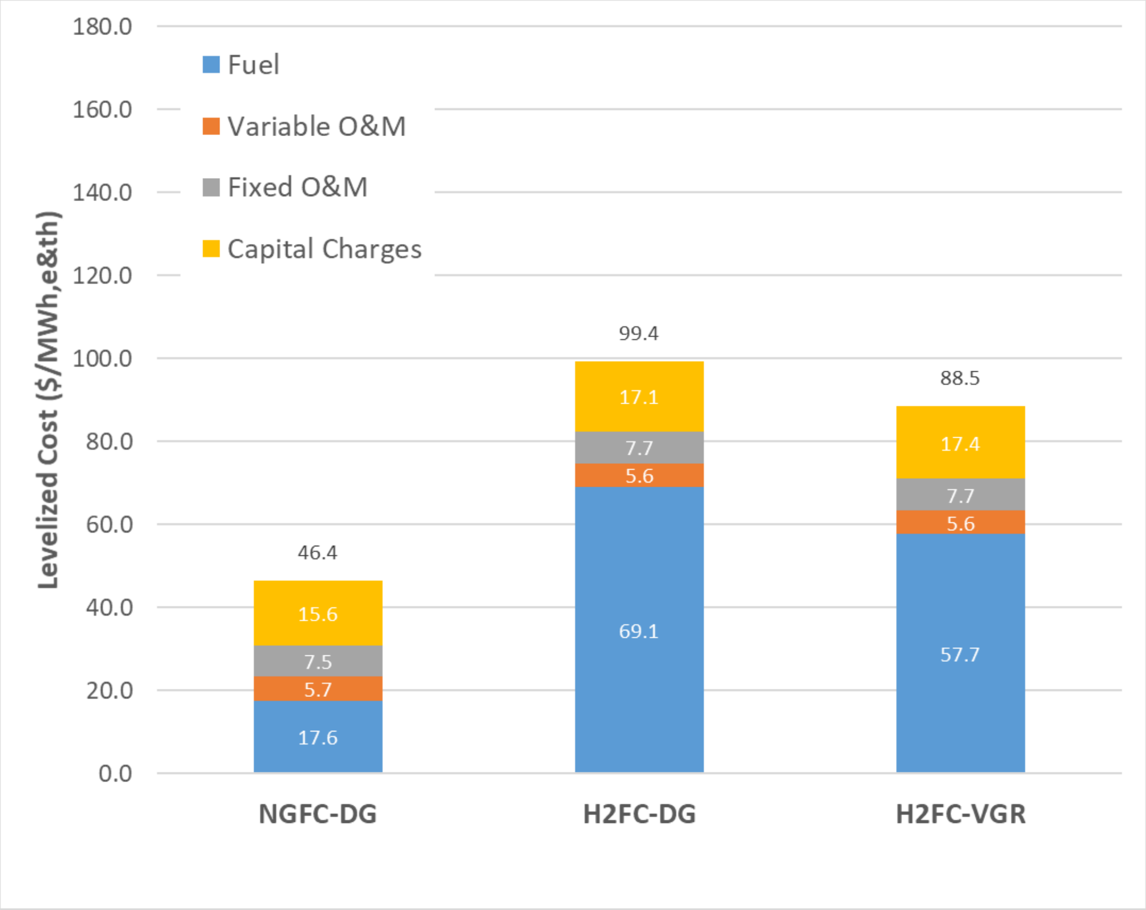
### Authors

- Alex Noring, Kyle Buchheit, Arun Iyengar, Gregory Hackett

# TEA of Hydrogen-Fueled SOFC Systems

## Highlights

- Switching from natural gas to $H_2$ fuel for conventional SOFC systems results in an immediate 15 percentage point drop in electrical efficiency
- The airflow (coolant flow) required is nearly five times the corresponding value for the NGFC-DG system
- When considering electrical output and the recovered heat in the form of hot water, the total efficiency of the $H_2$FC-VGR system surpasses that of the NGFC-DG system
- CHP will need to be a serious consideration for $H_2$ fueled SOFC to be economical
- Final Report, "Techno-Economic Analysis of Hydrogen-Fueled SOFC Systems"
  - Release expected May 2023




Levelized Cost of Electricity when CHP is Considered

# TEA of Hydrogen-Fueled SOFC Systems

## Introduction / Assumptions

- Scale: 5 $MWe_{GROSS}$

- Potential Applications:
  - Locomotives, backup generators, micro-grids, other CHP applications

- Exhaust Steam Heat Utilization:
  - This is a critical consideration for hydrogen-fueled SOFC
  - Cathode, anode, or combined exhaust streams still have moderately high temperatures that need to be cooled before releasing to atmosphere
  - Steam cycles would be cost prohibitive at smaller scales
  - Micro-turbine integration could be an option depending on the end use but would increase system complexity
  - CHP hybridization would utilize waste heat, potentially improving overall system efficiencies; hot water at 140°F will be generated without a specific end-use case

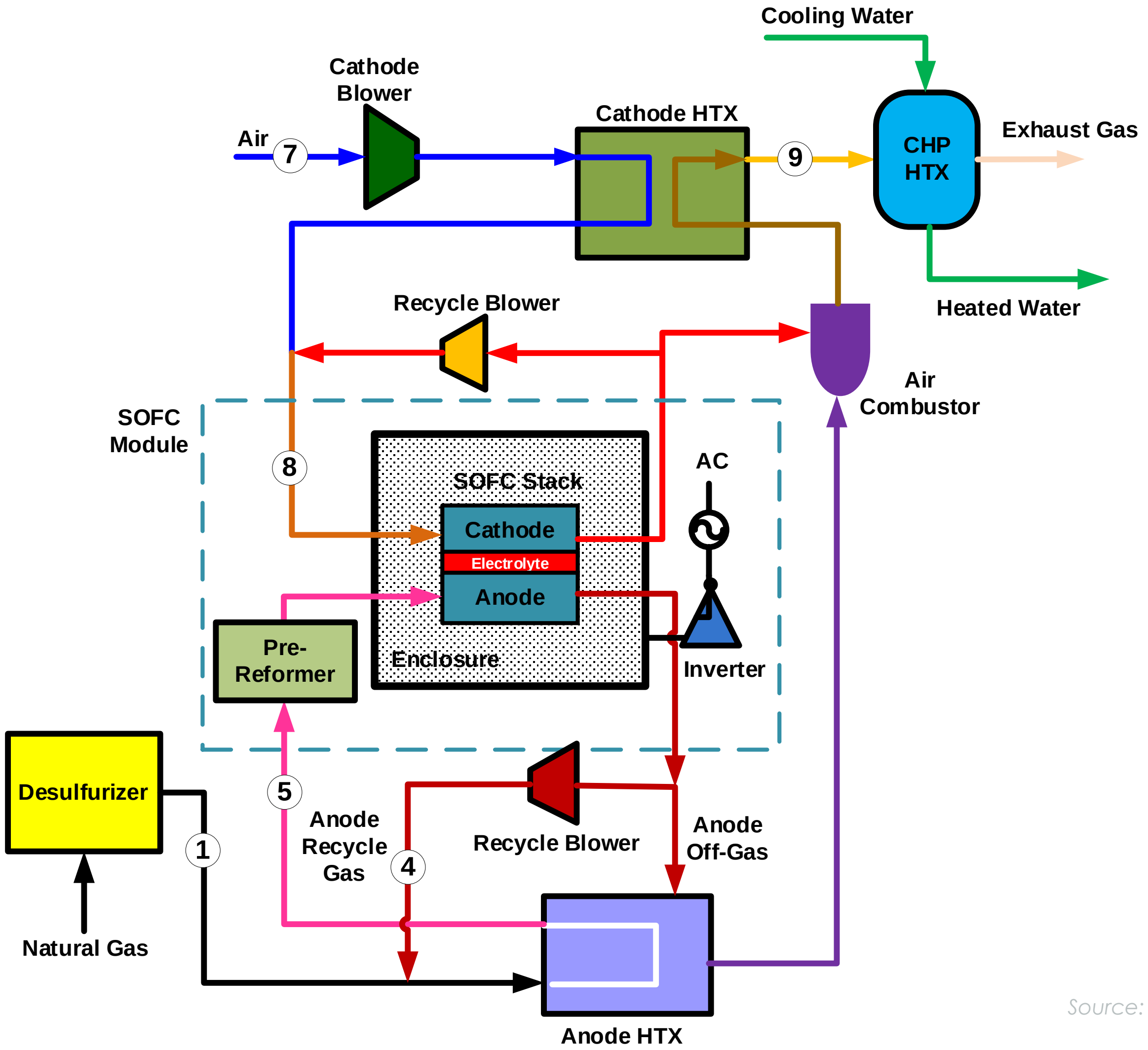
# TEA of Hydrogen-Fueled SOFC Systems



## Introduction / Assumptions

- Comparison Case
  - 5 MWe NGFC-DG
  - No carbon capture, no oxy-combustion
  - Combined anode/cathode exhaust
  - Consider CHP to utilize waste heat
    - Hot water produced

- Several systems are not necessary for a $H_2$ only fueled SOFC
  - Desulfurizer
  - Pre-reformer
  - $CO_2$ sequestration system (for large scale NGFC systems)




Source: NETL

# TEA of Hydrogen-Fueled SOFC Systems

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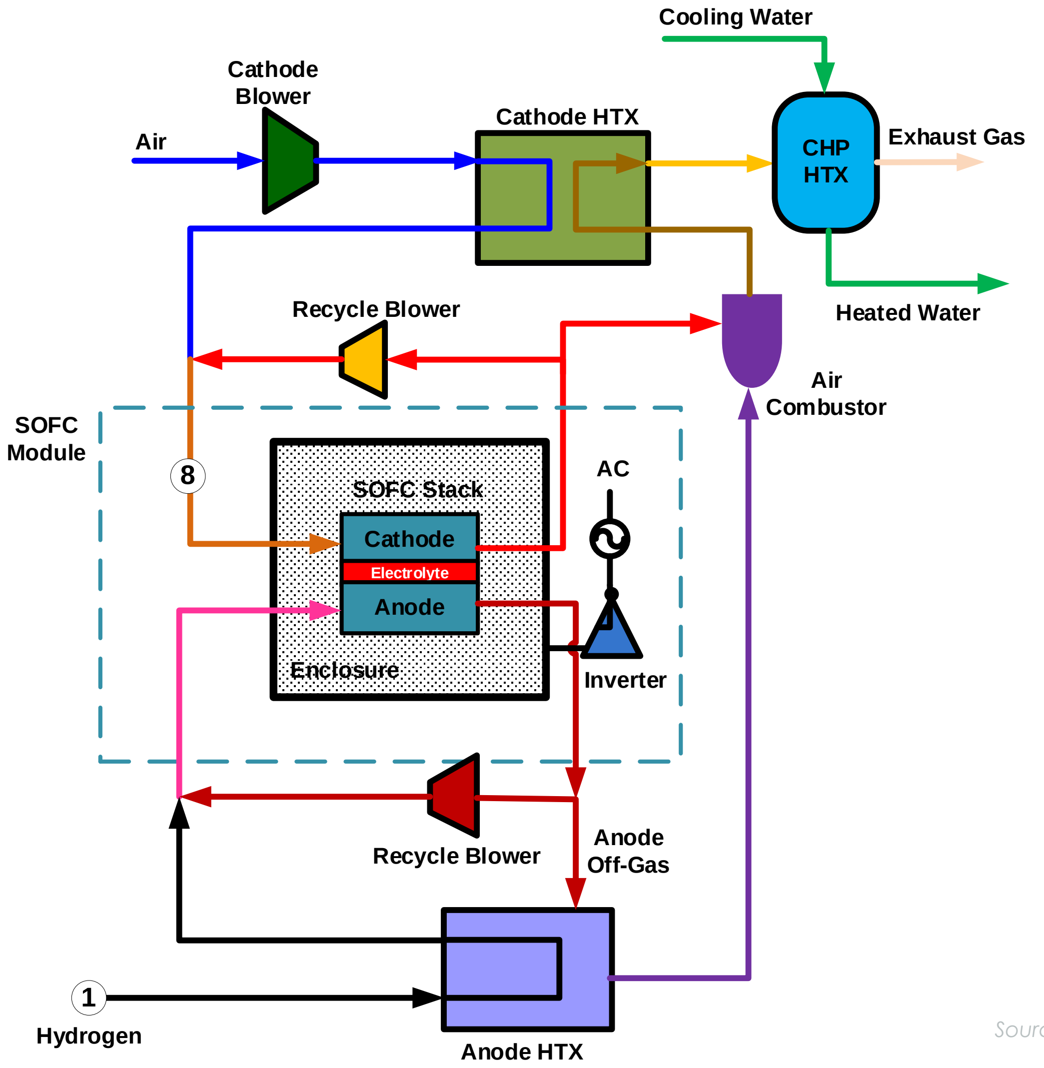
## Introduction / Assumptions

- Key difference from NGFC system configuration regarding anode recycle
  - PNNL SOFC MP 2D model returns anode recycle after the anode HTX instead of before the HTX
- Similar to the NGFC system, unutilized fuel is combined and combusted with cathode air
- Heated water also generated to capture unutilized heat and reduce exhaust gas temperature

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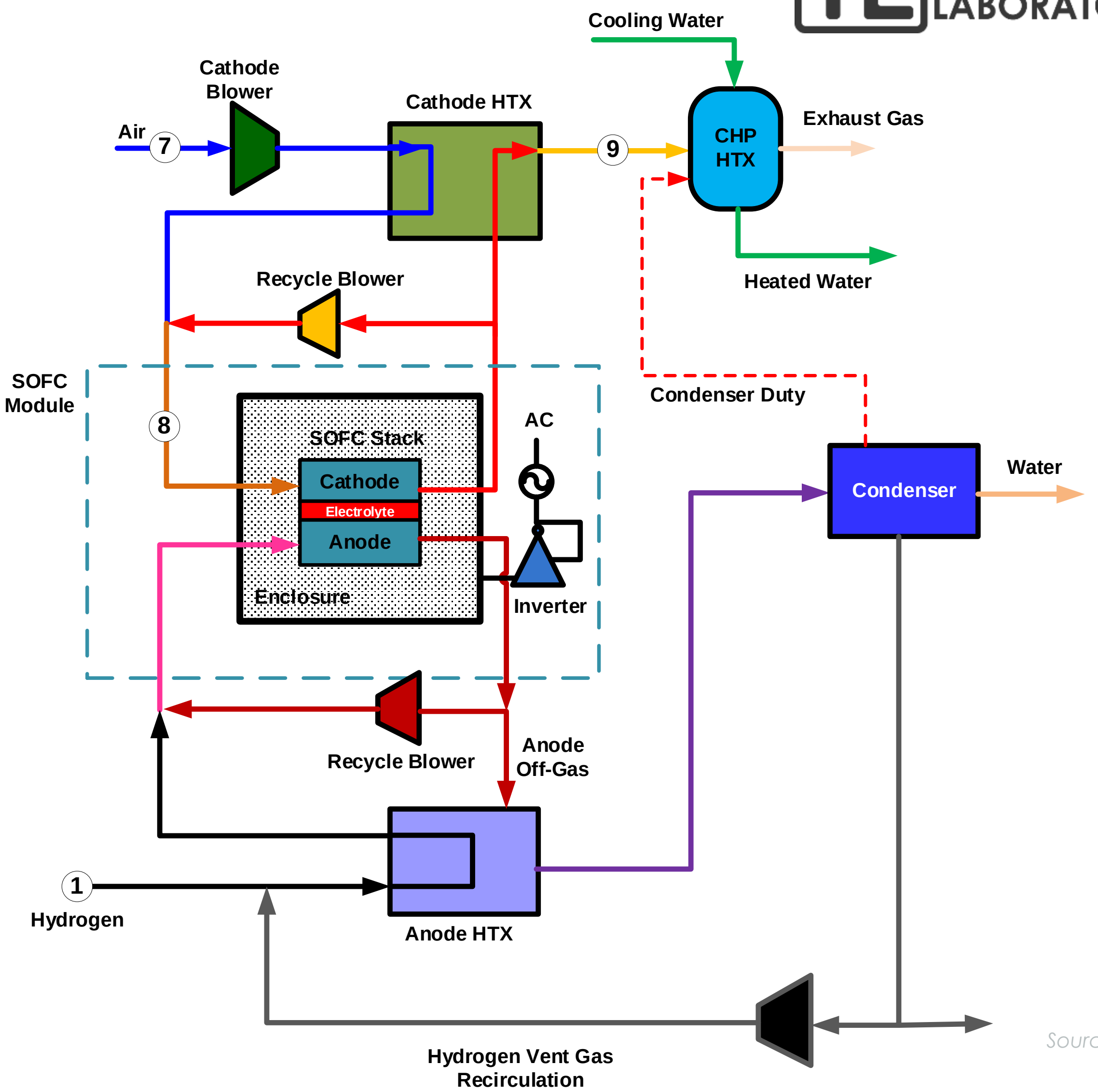
# TEA of Hydrogen-Fueled SOFC Systems

## Introduction / Assumptions

- Hydrogen fuel efficiency could be improved by condensing to remove water from the anode off-gas and recirculating unused hydrogen; vent gas recirculation used in place of air combustion
- Cathode exhaust air used to heat water for CHP along with heat duty from condenser for the VGR
- Purge (1%) required on VGR to prevent the build-up of inert gas

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# TEA of Hydrogen-Fueled SOFC Systems

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## SOFC Assumptions

| NGFC Assumptions | |
|---|---|
| SOFC Fuel Utilization* | 85% |
| Current Density ($mA/cm^2$) | 400 |
| Natural Gas Reformation | 100% Internal |
| Cathode Recycle | 50% |
| Oxygen: Carbon Ratio in Anode | 2.1 |
| SOFC Delta T (°C) | 100 |
| SOFC Max T (°C) | 750 |
| SOFC Pressure | Atmospheric |

| H2FC Assumptions | |
|---|---|
| SOFC Fuel Utilization* | 85% |
| Current Density ($mA/cm^2$) | 400 |
| Natural Gas Reformation | N/A |
| Cathode Recycle | 50% |
| Anode Recycle** | 50% |
| SOFC Delta T (°C) | 100 |
| SOFC Max T (°C) | 750 |
| SOFC Pressure | Atmospheric |

*Fuel utilization defined as percent of fuel consumed by SOFC including main recycle
**Anode recycle set for improving flow distribution across stack

# TEA of Hydrogen-Fueled SOFC Systems

## Performance Results Review

| Plant Output | NGFC-DG | H2FC-DG | H2FC-VGR | Unit |
|---|---|---|---|---|
| SOFC Power | 5,044 | 5,000 | 5,000 | kWe |
| Recovered Thermal Heat | 2,090 | 3,076 | 3,328 | kWth |
| **Auxiliary Load** | | | | |
| Cathode Air Blower | 34 | 159 | 158 | kWe |
| Cathode Recycle Blower | 15 | 80 | 81 | kWe |
| Anode Recycle Blower | 3 | 2 | 2 | kWe |
| VGR Recycle Blower | - | - | 1 | kWe |
| Miscellaneous Balance of Plant[1] | 3 | 2 | 1 | kWe |
| Transformer Losses | 15 | 16 | 16 | kWe |
| **Total** | 70 | 259 | 260 | kWe |
| **Plant Performance** | | | | |
| Net Auxiliary Load | 70 | 259 | 260 | kWe |
| Net Plant Power | 4,974 | 4,742 | 4,742 | kWe |
| Net Plant Electrical Efficiency (HHV) | 60.2% | 45.3% | 52.5% | |
| Net Plant Thermal Efficiency (HHV) | 25.3% | 29.4% | 36.9% | |
| Net Plant Combined Efficiency (HHV) | 85.5% | 74.7% | 89.4% | |
| Single Pass Fuel Utilization | 68.4% | 73.9% | 73.9% | |
| Overall Fuel Utilization | 85.0% | 85.0% | 98.7% | |
| Net Plant Heat Rate (HHV) | 5,979 (5,667) | 7,949 (7,534) | 6,853 (6,496) | kJ/kWh (Btu/kWh) |
| Fuel Feed Flowrate | 567 (1,250) | 270 (596) | 233 (514) | kg/h (lb/h) |
| Thermal Input[2] | 8,261 | 10,470 | 9,028 | kWth |
| CHP Water Use | 0.6 (162.9) | 0.9 (239.7) | 1.0 (259.4) | $m^3$/min (gpm) |

[1] Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[2] HHV of natural gas is 52,449 kJ/kg (22,549 Btu/lb) and HHV of hydrogen is 139,490 kJ/kg (59,970 Btu/lb)

# TEA of Hydrogen-Fueled SOFC Systems

## Costing Assumptions

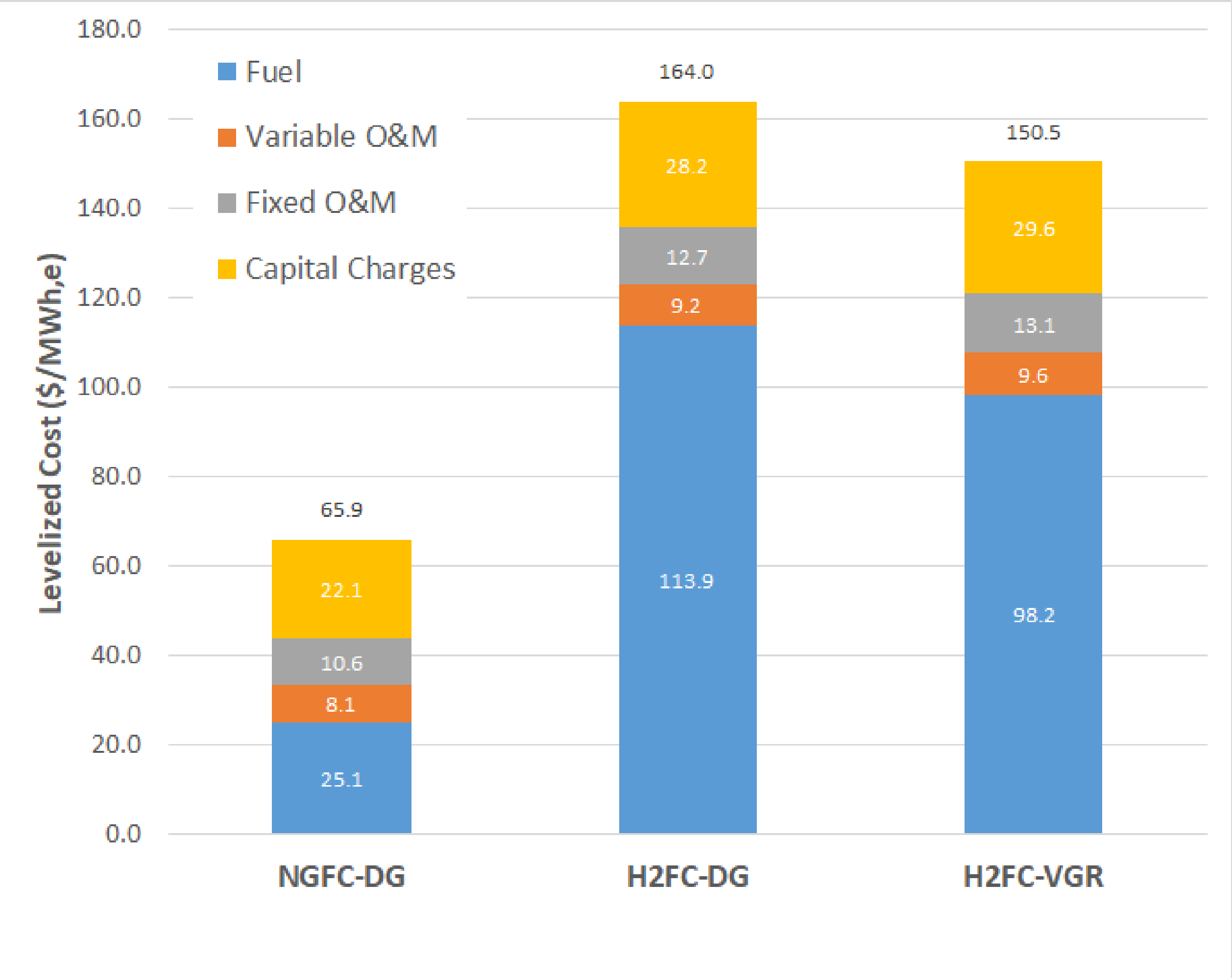
- Many costing assumptions for balance of plant facilities, operating costs, variable costs, etc., typically used for large (≈650 MWe) systems need to be adjusted for smaller scale; earlier NGFC-DG work and a 1 MW gasification + reciprocating engine + CHP study was used as guidance with best engineering judgments

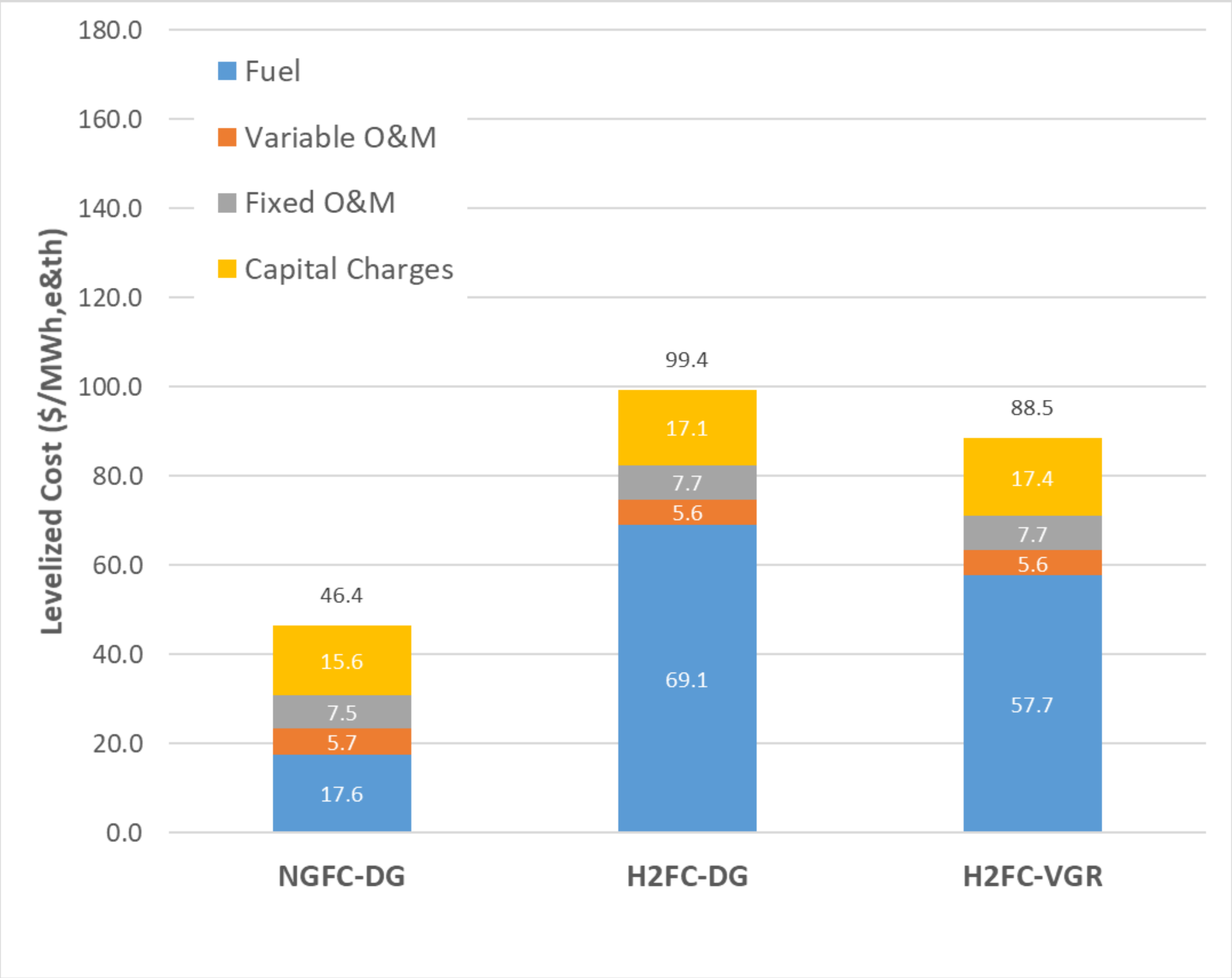
| | Large-Scale SOFC | DG-Scale SOFC |
|---|---|---|
| **SOFC Modules** | 16 modules per section<br>Increase sections to reach target power | One section with only enough modules to reach target power |
| **Operators per Shift** | 6.0 without capture; 7.3 with capture | 0.25 (2 hours to check system per 8-hour shift) |
| **Facility Infrastructure**[1] | Greenfield facilities assume no existing services (makeup water systems, pipelines, waste treatment, etc.) | Reduced or no cost, assuming facilities ready to use with little to no modification needed for SOFC |
| **Land Use** | 100 acres | 3 acres |
| **Cost Structure** | 3-year construction plus 30-year operation, IOU | 3-year construction plus 30-year operation, IOU |
| **Makeup Water Treatment Chemicals** | Included as Operating Cost (used in steam cycle, blowdown, carbon capture, etc.) | None (assuming water for CHP ready to use, and heated water handled separately) |
| **Fuel Cost** | Natural Gas: $4.42/MMBTU | Hydrogen: $2/kg $H_2$ (FECM hydrogen baseline has produced costs ranging from $1.06 to $3.64 per kg) |

[1] Detailed cost accounts available in final report

# TEA of Hydrogen-Fueled SOFC Systems

## Cost Results – Levelized Cost of Electricity



# TEA of Hydrogen-Fueled SOFC Systems

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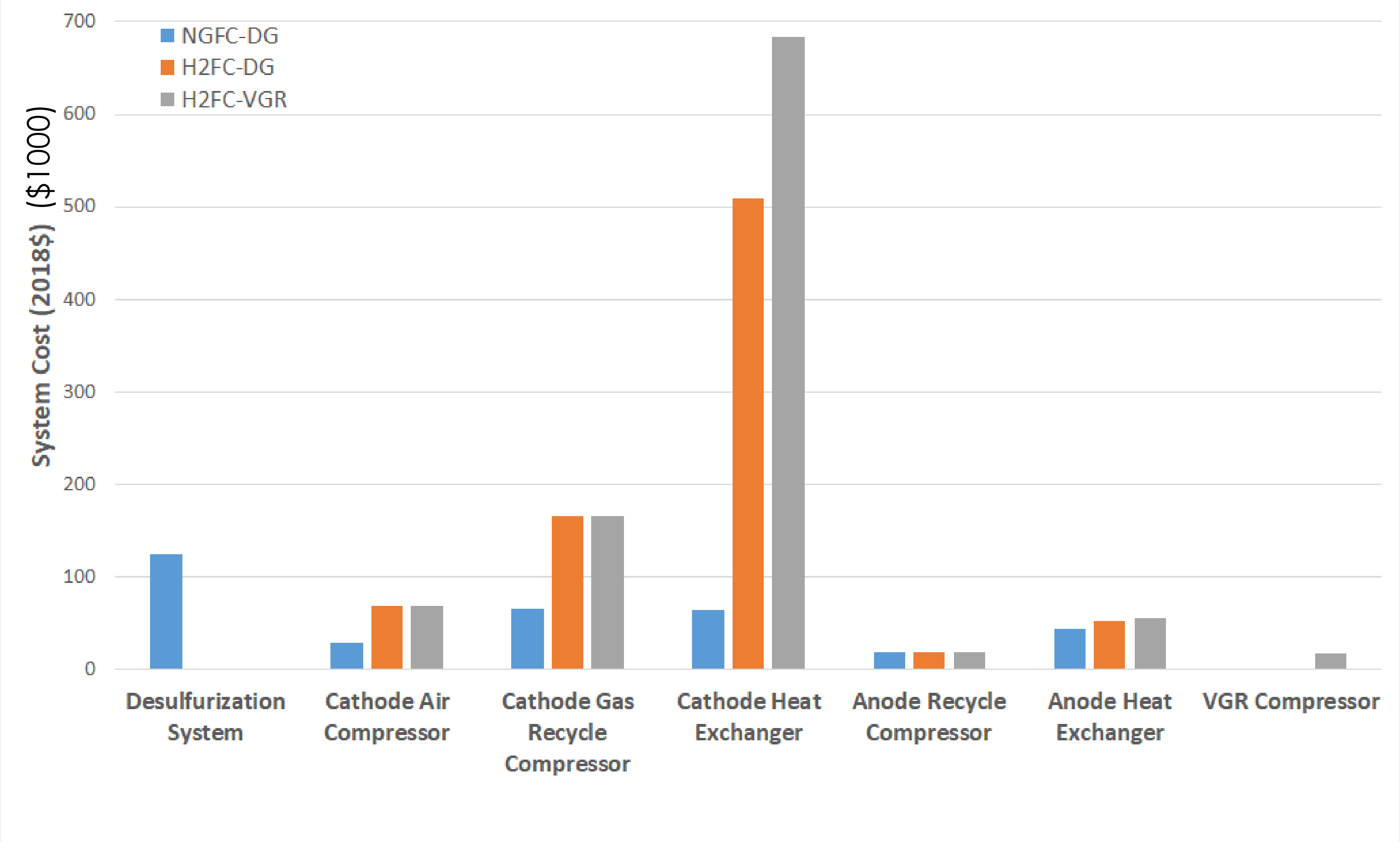
## Cost Results – SOFC Balance-of-Plant



# TEA of Hydrogen-Fueled SOFC Systems

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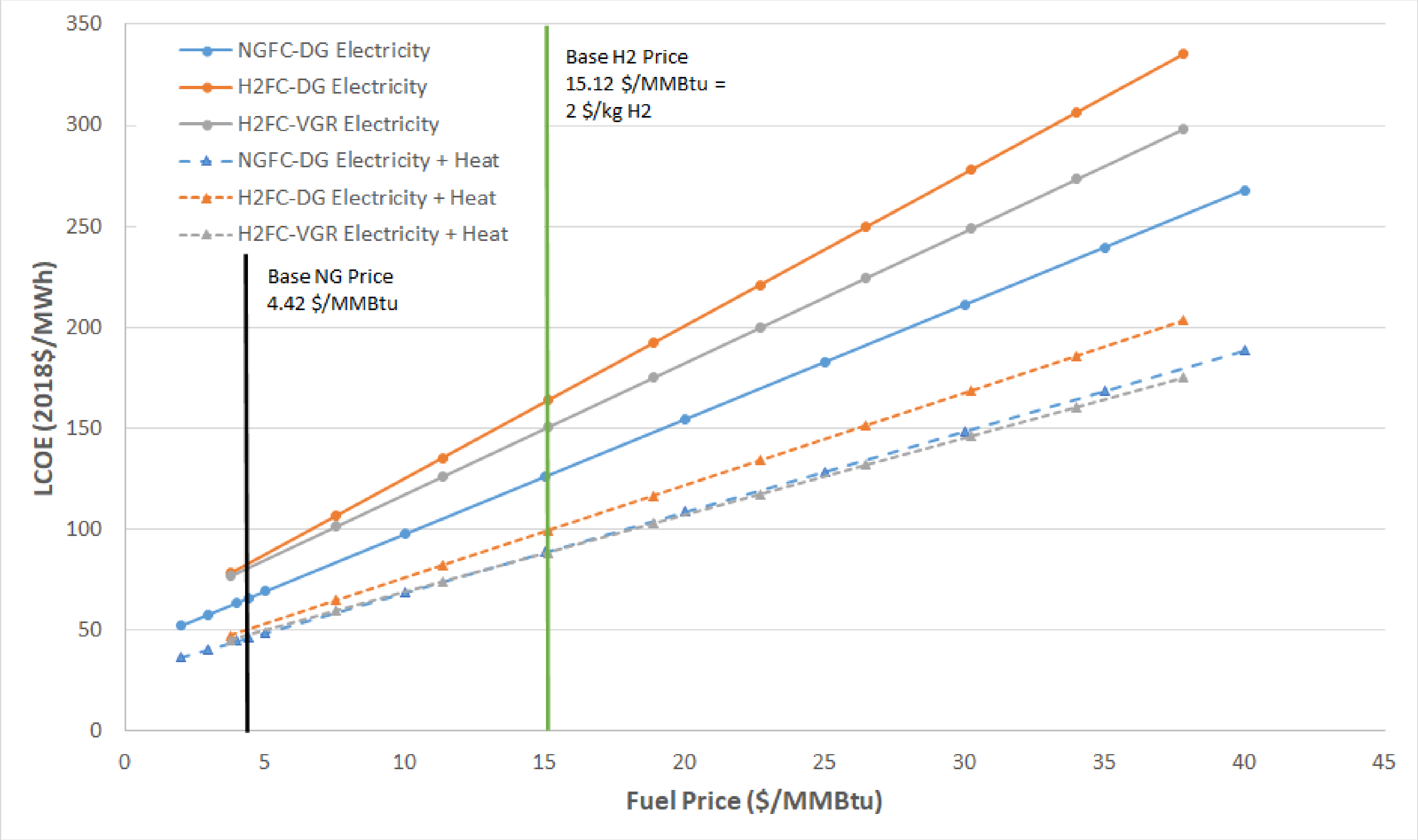
## Cost Results – LCOE with Other Systems

| Configuration | Scale [MW] | COE [$/MWh,e] |
|---|---|---|
| NGFC w/o Capture | 650 | 41.7 |
| NGFC DG w/o Capture, Prior Study | 1 | 81.8 |
| NGFC-DG | 5 | 65.9 |
| $H_2$FC-DG | 5 | 164.0 |
| $H_2$FC-VGR | 5 | 150.5 |
| NG Turbine, CHP Market Study | 10 | 78.3 |
| Alaska CHP | 1 | 344.2 |

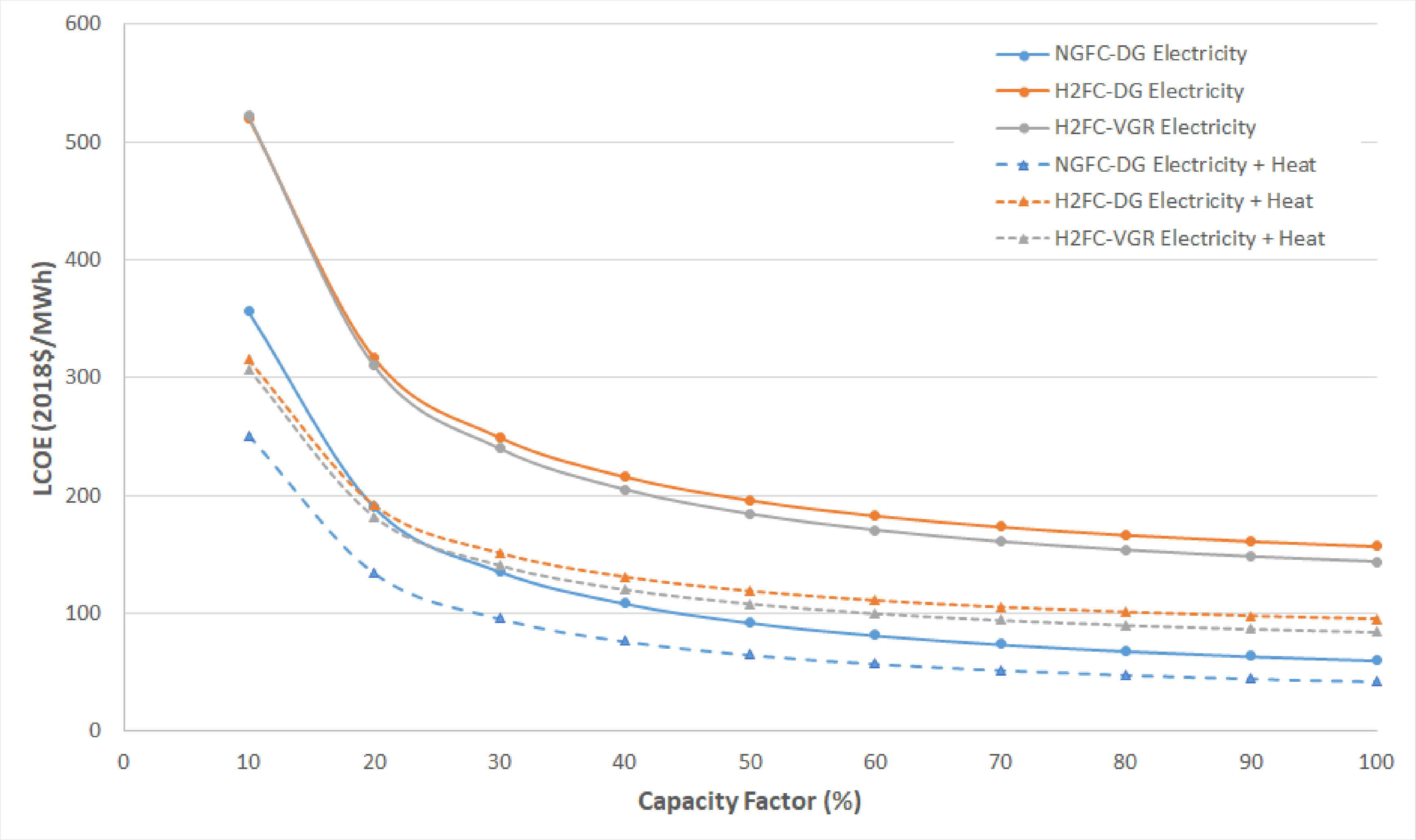
# TEA of Hydrogen-Fueled SOFC Systems

## Sensitivity Study – Fuel Cost



# TEA of Hydrogen-Fueled SOFC Systems

## Sensitivity Study – Capacity Factor



# TEA of Hydrogen-Fueled SOFC Systems

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## Case Comparisons – Cost of Carbon

| | NGFC-DG | H2FC-DG | H2FC-VGR |
|---|---|---|---|
| Gross Plant Output, kWe | 5,044 | 5,001 | 5,002 |
| Net Plant Output, kWe | 4,974 | 4,742 | 4,742 |
| $CO_2$ Emissions, lb/MWh$_{GROSS}$ | 597 | 0 | 0 |
| LCOE ($/MWh) Electricity | 66 | 164 | 151 |
| LCOE ($/MWh) Electricity + Heat | 46 | 99 | 88 |
| **Cost of $CO_2$ Avoided, $/tonne (Electricity Only Basis)** | **-** | **357** | **308** |
| **Cost of $CO_2$ Avoided, $/tonne (Electricity + Heat Basis)** | **-** | **193** | **153** |

# Conclusions and Future Work

## Performance and Cost of Hydrogen Fuel Cells

- Hydrogen fueled SOFC systems experience an ≈15 percentage point drop in electrical efficiency
  - Additional heat produced through the stack could be recovered through generating heated water for use
- Vent Gas Recirculation (VGR) recovers hydrogen and removes products resulting in larger required amounts of air flow through the cathode
  - Increases cathode heat exchanger and air blowers
  - Improved LCOE vs non-VGR
- Direct cooling of stack with water could reduce cathode air usage
- Proton conducting SOFC could be beneficial in this situation

# On-going / Future Work

## Performance and Cost of Hydrogen Fuel Cells

- Large scale electrolysis techno-economic pathway analysis
  - Cost and performance of 1 GW scale SOEC system
  - Anticipated completion: March 2024

- TEA of modular SOFC systems
  - Assess the cost and performance of smaller scale SOFC systems intended for commercialization (e.g. 10, 25, 100 kWe)
  - Anticipated completion: March 2024

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# Questions/ Comments

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