CHANGING WHAT'S POSSIBLE

Fuel Cell & Heat Engine Hybrid Systems

Workshop Introduction

January 26-27, 2017

Objective

Enhance US economic & energy security through

- *Lower cost electricity*
- *Differentiated products for US industry*
- *More efficient resource (NG) utilization*
- *Reduced emissions*

Grid → 2/3 Fossil Fueled with a Delivered Efficiency of 34%

<u>Average Fossil Fueled Grid Efficiency</u>

Fuel	Avg η	T&D η	Net η
Coal	28%	94%	26%
NG	46%		43%
Net FF	36%		34%

Distributed Hybrid Systems → Potential for 2X the current average delivered efficiency

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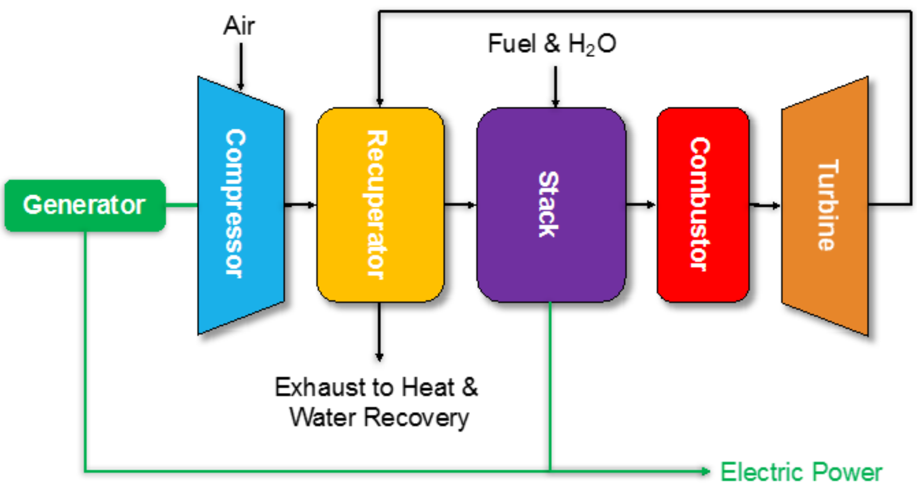
Approach

Leverage thermo-economic synergies between engines and fuel cells to convert fuel to electric power in an economically-attractive and environmentally-friendly manner

Notional Hybrid System

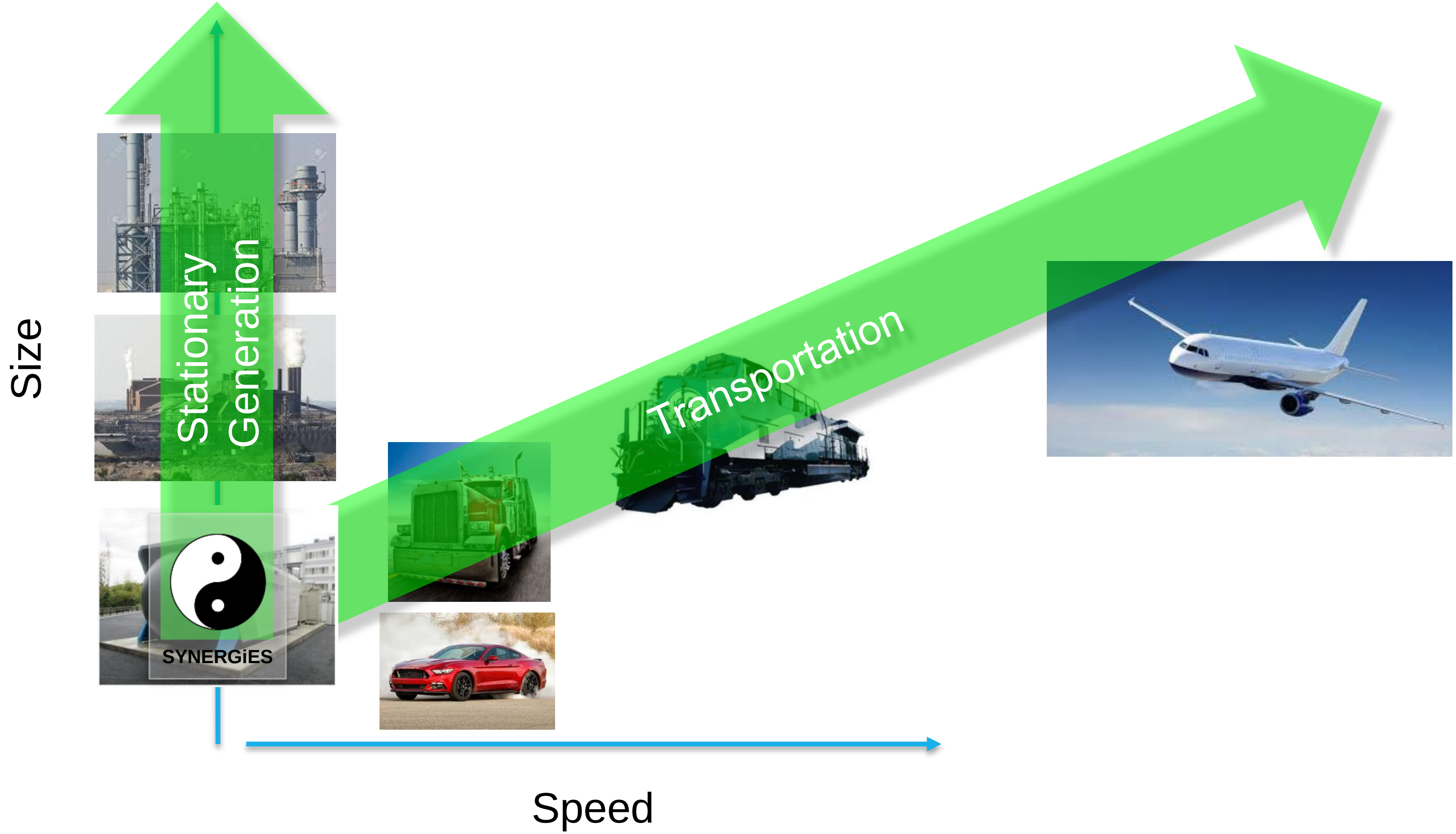


Synergies

1. FC Waste Exergy → Engine Heat
2. Engine is FC balance of plant
3. ↑ Engine Power → ↓ Fuel Cell Power
4. Potential for Pressurized FC Operation
   - Higher Power Density → Smaller Stack
   - Reduced Cooling Parasitic Penalty

Path to Market

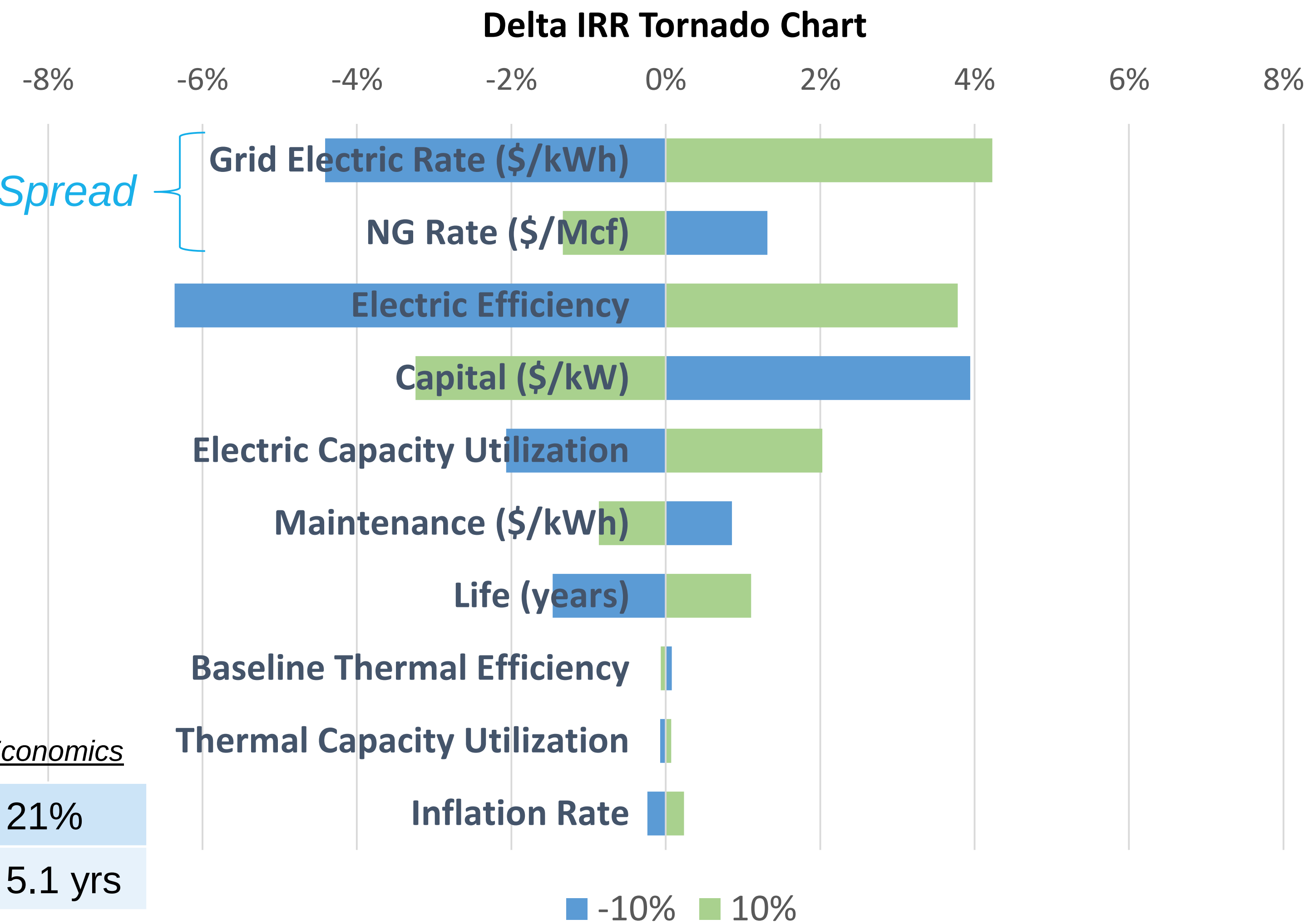
Proposed First Market: Commercial-Scale (100 kW → 2 MW) Distributed Generation



Customer Value Proposition Drivers

Economics Driven by Spark Spread, Electric Efficiency & Capital Cost

Spark Spread



Nom
$0.10
$6.55
70%
$1800
80%
$0.02
20
90%
25%
2%

Nominal Economics

IRR	21%
PB	5.1 yrs

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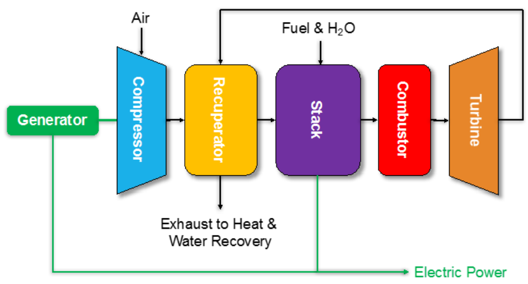
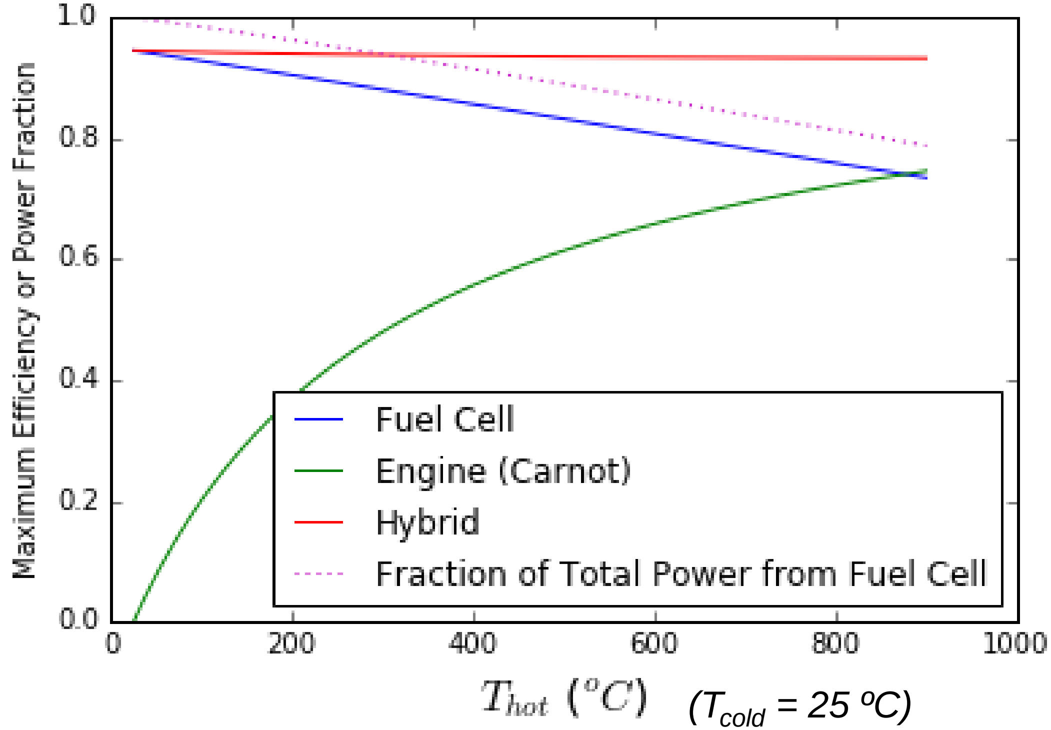
Thermodynamic Synergies

Ideal Illustrative Example

Notional Hybrid System



Engine Operates on FC Waste Exergy



(T_{cold} = 25 ºC)

$$\eta_{Fuel\ Cell} = \frac{\Delta g_f}{\Delta h_f}$$

$$\eta_{Engine} = 1 - \frac{T_{cold}}{T_{hot}}$$

$$\eta_{Hybrid} = \eta_{Fuel\ Cell} + \eta_{Engine}\underbrace{(1 - \eta_{Fuel\ Cell})}_{\text{FC Waste Exergy}}$$

FC Waste Exergy

Cost & Performance Baseline

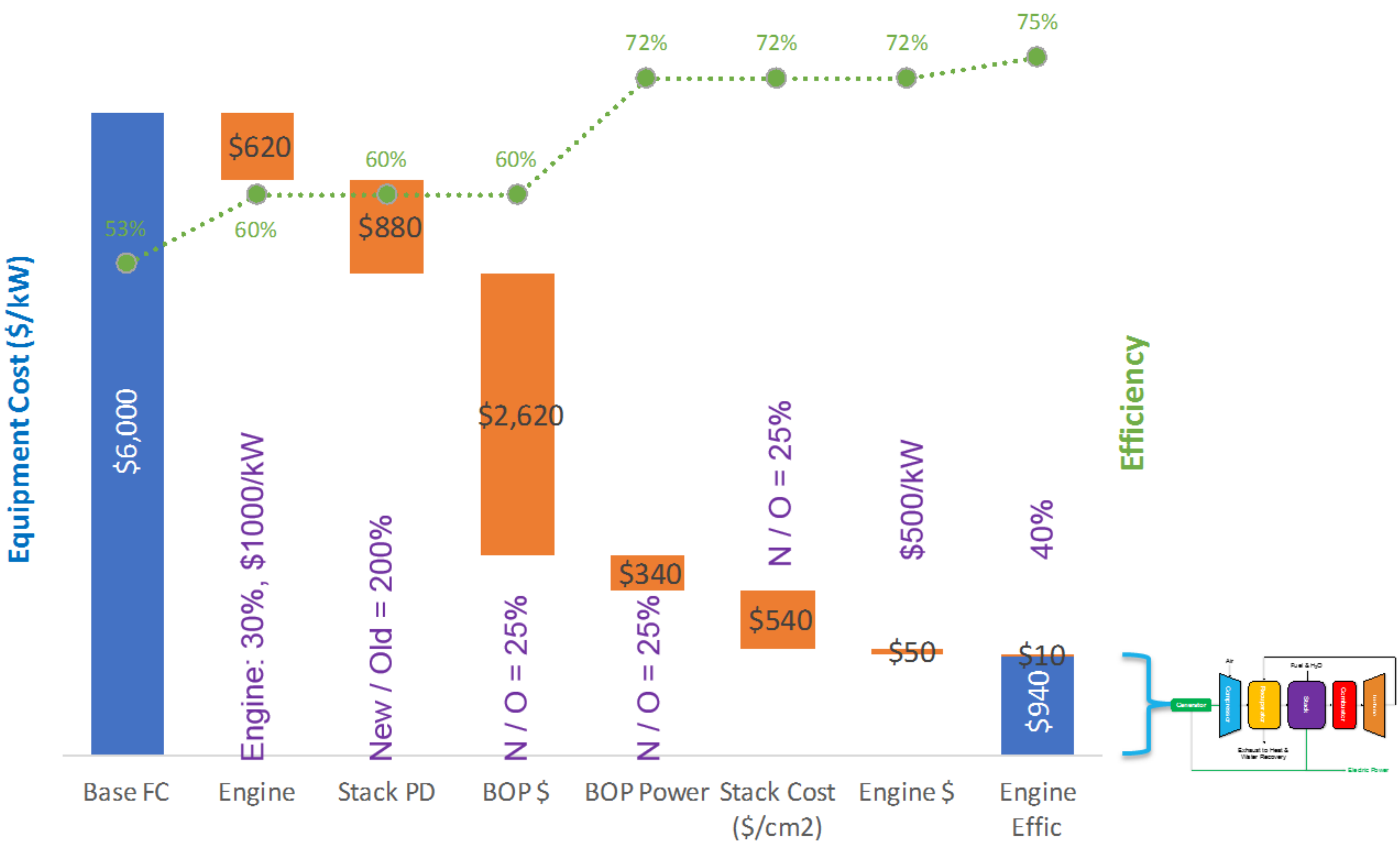
Baseline Fuel Cell System Assumptions

Parameter	Value
Stack Cost ($/cm^2)	0.38
Power Density (mW/cm^2)	250
BOP / Stack Cost Ratio	2
Stack * FP Efficiency	70%
BOP / Stack Power Ratio	0.25

Resulting Baseline Fuel Cell System

Parameter	Value
Electric Efficiency	53%
Equipment Cost ($/kW)	6000

Cost: Synergies & New Concepts



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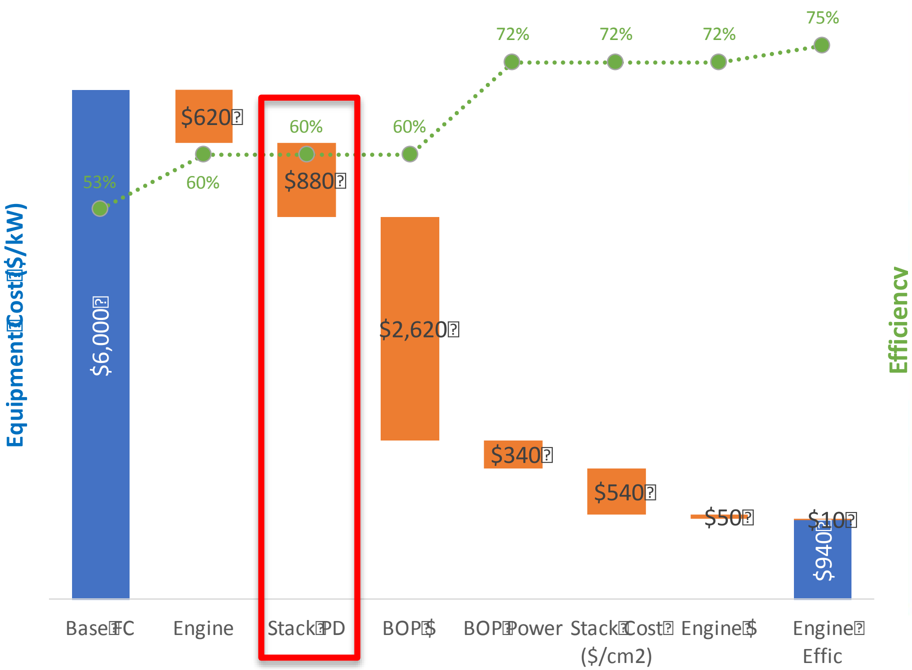
Cost Detail: Stack Cost ($/kW)

Goal : Increased stack power density with no areal specific cost impact

Potential Solution: Pressurization



Stack Power Density
250 → 500 mW/cm²

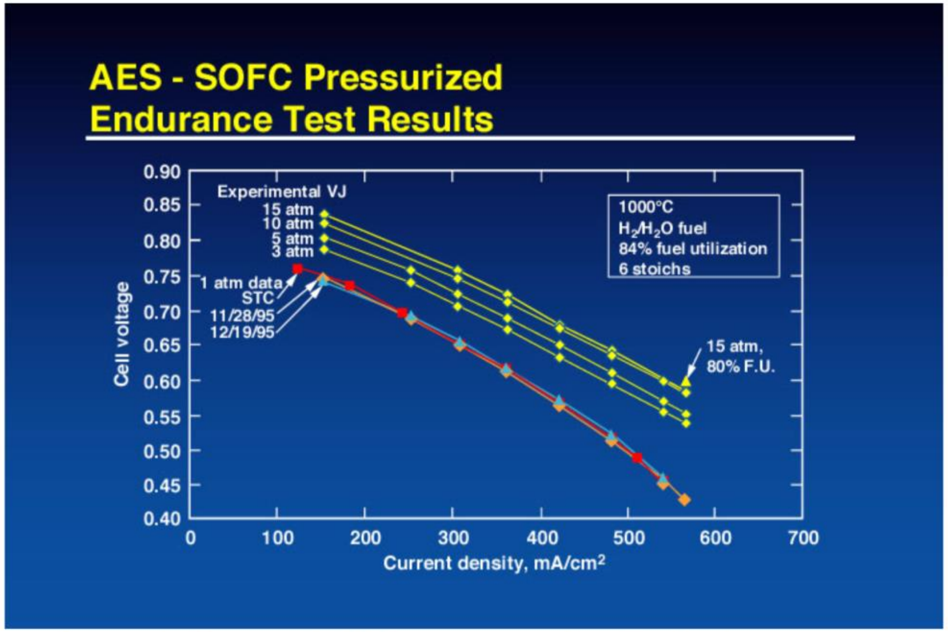


Figure 4-1 – Measured Cell Voltage vs. Current Density at Various Pressures

Ref: Siemens Power Generation, High Temperature Solid Oxide Fuel Cell Generator Development, Final Technical Report, 2007.

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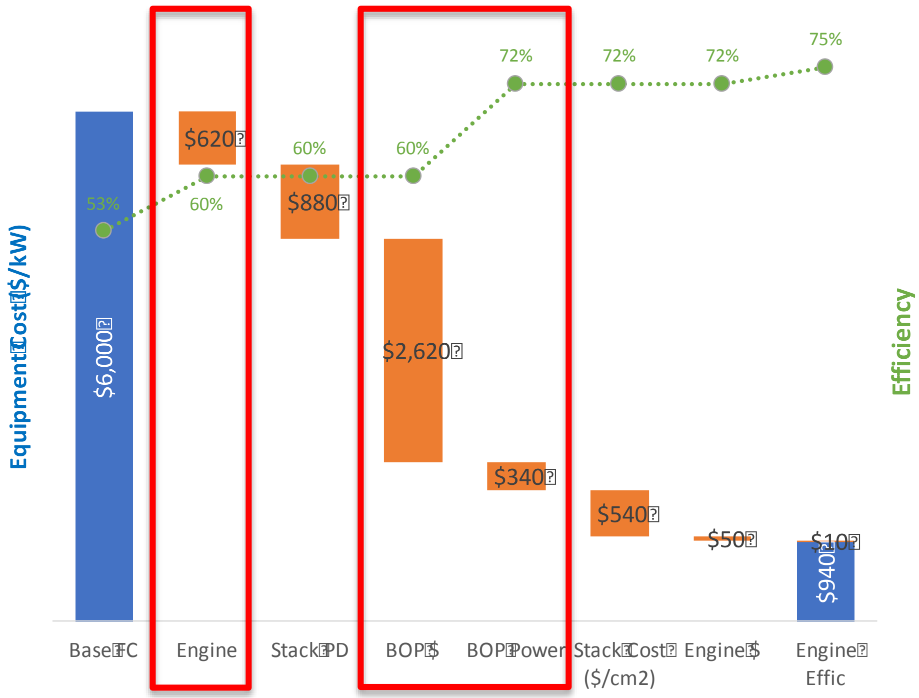
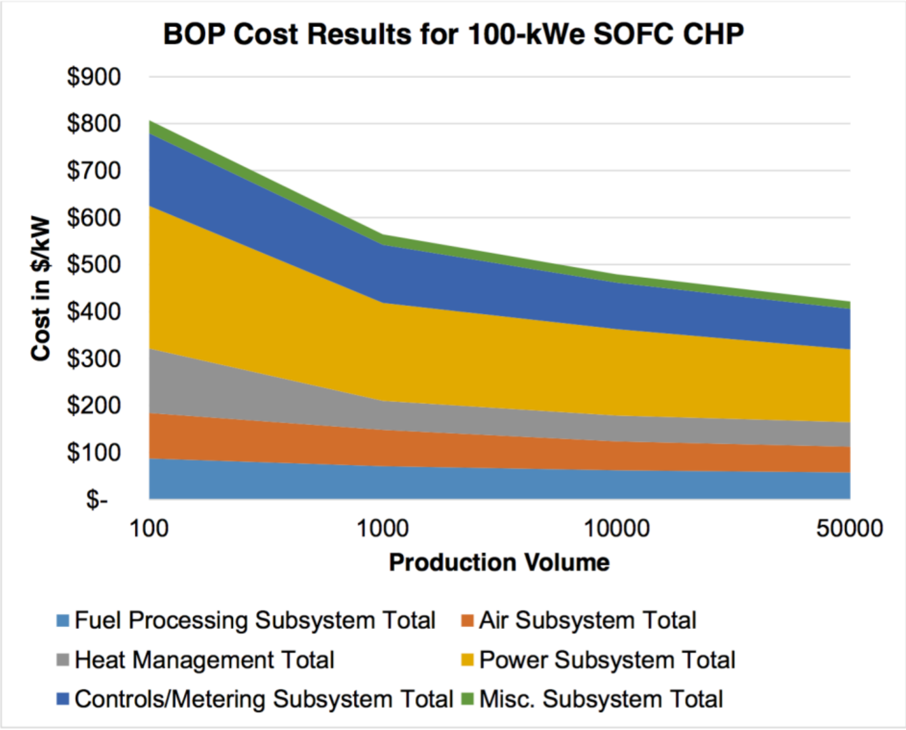
Cost Detail: Engine/BOP Integration

Goal: Achievement of thermodynamic & cost synergies



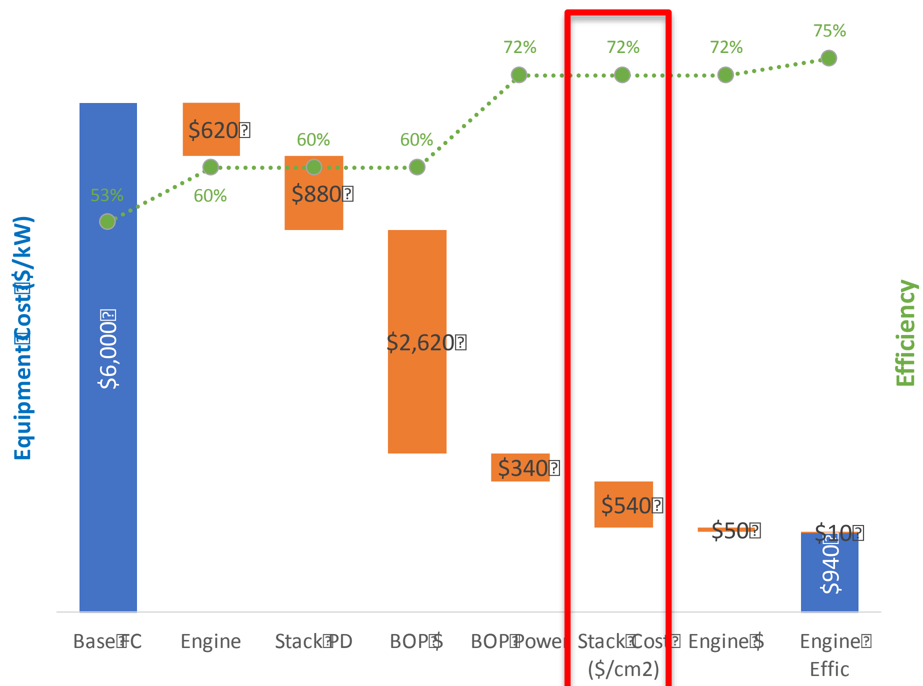


- 40% increase in net efficiency
- 60% decrease in $/kW

Ref: Scataglini et al, A Total Cost of Ownership Model for SOFC in CHP & DG Applications, LBNL

Cost Detail: Stack Cost ($/cm^2)

Goal: Decreased effective stack manufacturing cost (& acceptable durability)



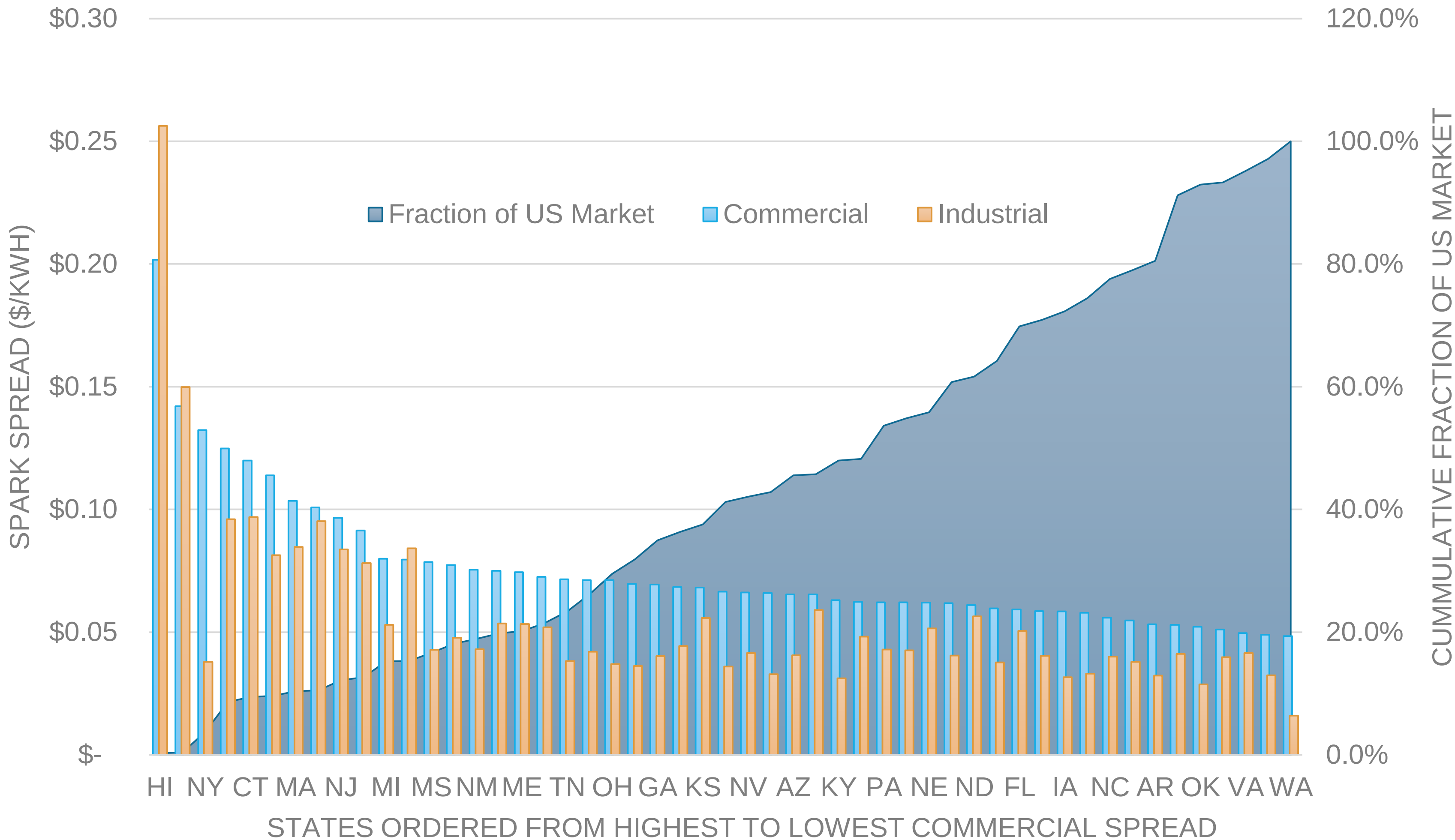
~0.4 → ~0.1 $/cm^2

A few starting ideas . . .

- Manufacturing
  - Automation
  - Reduced material usage
- Materials
  - New MEA materials
  - New supports (e.g. metal)
- BOP Synergies
  - Internal reforming
  - Sulfur tolerance

Market Requirements Drivers

US State Spark Spread



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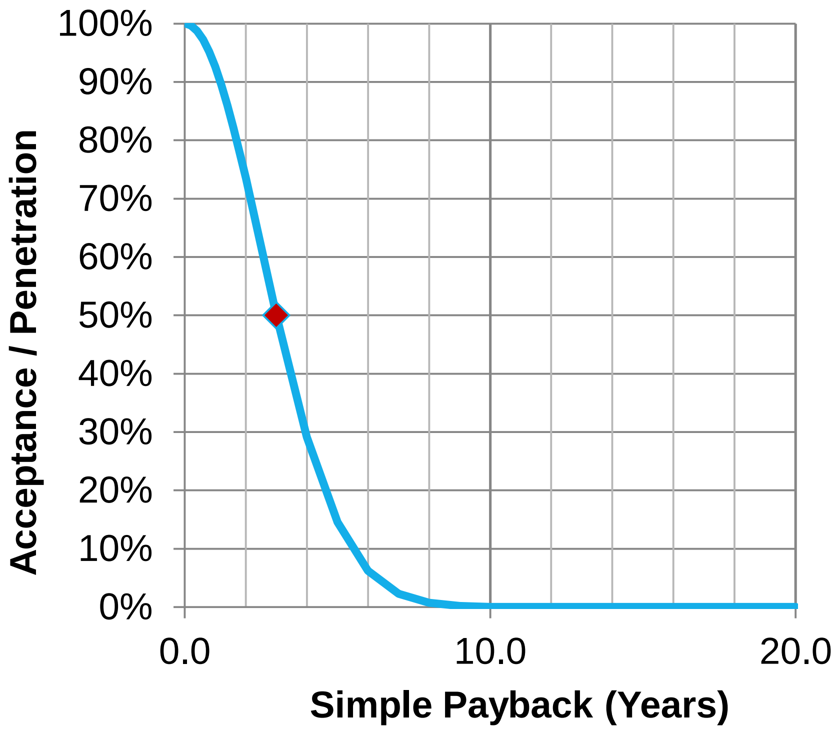
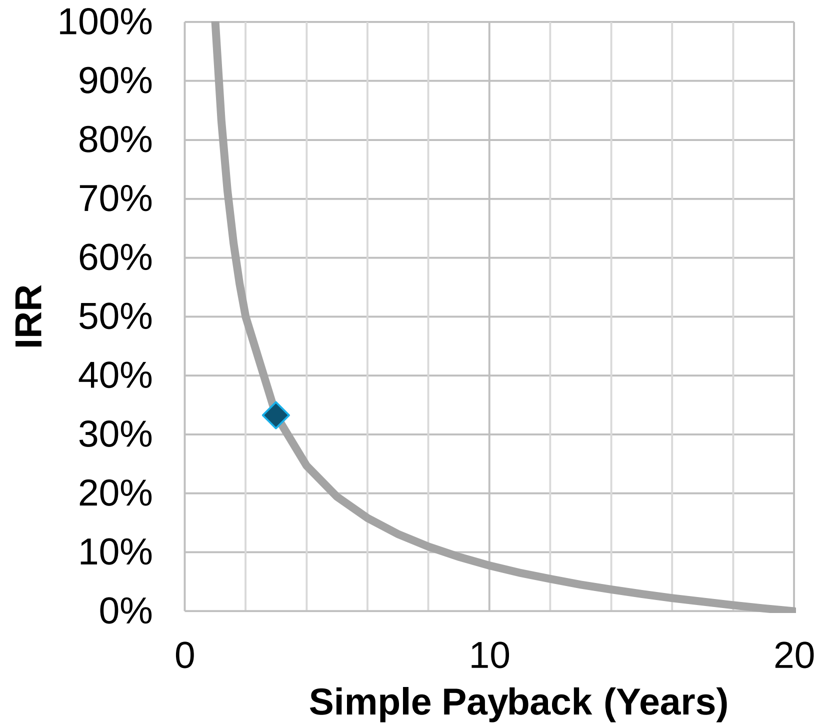
Market Requirements: Financial Return

Compelling financial return required for wide acceptance

- Customer Acceptance / Market Penetration Model





Compelling Financial Return → Simple Payback < 3 years → IRR > 33%

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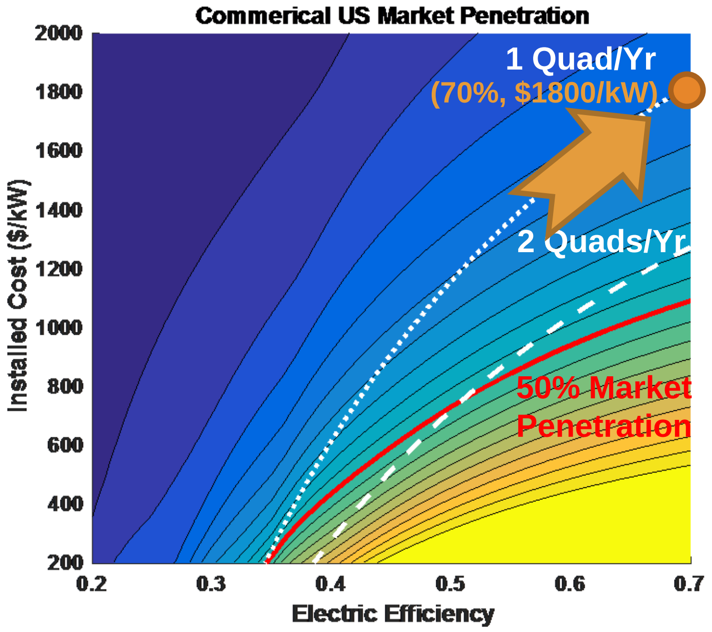
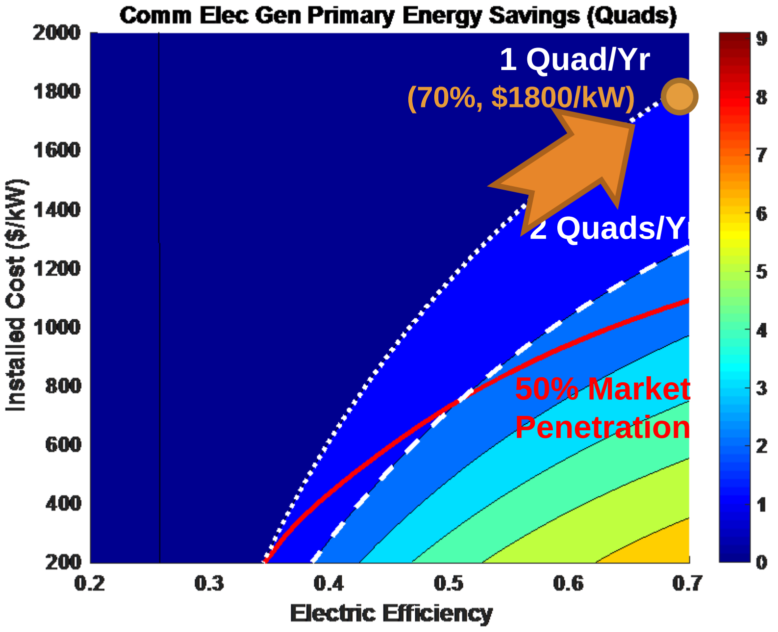
Market Performance Requirements

Where are we going? ($1800/kW, η_e=70%)

Estimated US Commercial Market Penetration & Primary Energy Savings





Assumptions

- $0.02/kWh$_e$ maintenance
- $\eta_t=(1-\eta_e)/2$
- Capacity utilizations: 85% electric, 50% thermal

Program Concept Synopsis

Opportunity

Economic & environmental value propositions afforded by the potential to locally generate electricity in a highly efficient and fully dispatchable manner.

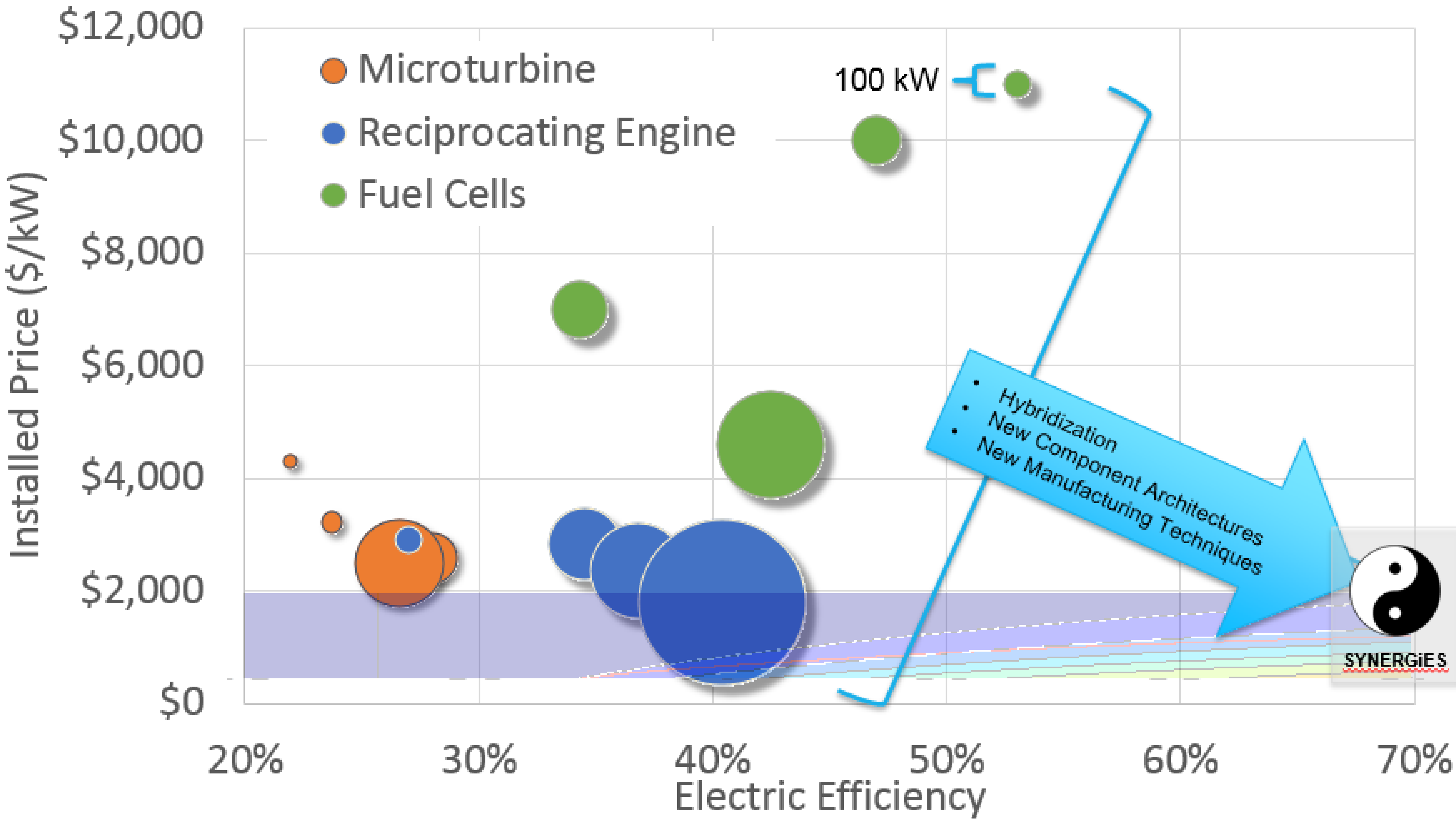
Challenge

Realization of the thermodynamic potential of hybrid systems at a price† afforded by their energy cost savings.*

** $\eta_{elec} \geq 70\%$*

† Installed Cost ≤ $1800/kW, Maintenance ≤ $0.02/kWh

Challenge



Ref:
1. EPA Catalog of CHP Technologies, March2015.
2. CA SGIP Installation Report Downloaded 4/18/16

Is there hope?

Perhaps . . . Toyota Prius Example

57 kW, η=40%

MSRP: $24,200 (with wheels, etc.)
MPG: 58 city, 53 highway

$420/kW

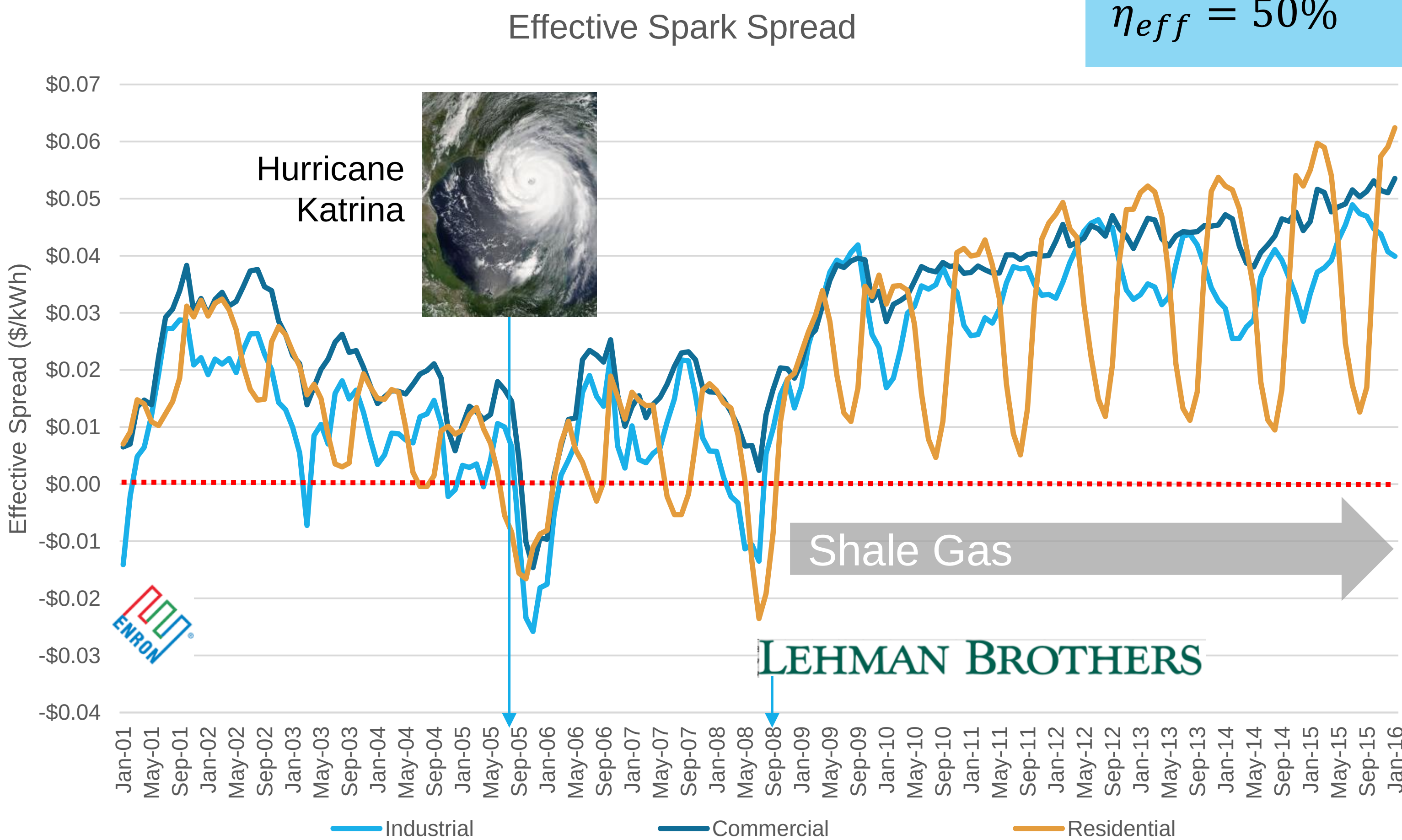
(Engine only → $3689 → $65/kW)

Is there hope?

Perhaps . . . Positive Spark Spread Trend

$$s_{eff} = c_{elec} - \frac{c_{gas}}{\eta_{eff}}$$

$$\eta_{eff} = 50\%$$



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Workshop Goals

Bring together leading experts from the engine & fuel cell communities to

1. Refine and enable the identified **Opportunity** by developing technical solutions to the **Challenge**.
   a) System Concepts
   b) Component Concepts
   c) Manufacturing Approaches
   d) …

2. Meet some new friends

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Workshop Agenda – Day 1

Thursday, January 26, 2017

Time	Event
11:30AM– 12:30 PM	Registration and Lunch
12:30 - 12:45 PM	**Welcome and Introduction to ARPA-E** *Eric Rohlfing, ARPA-E*
12:45 - 1:20 PM	**Introduction: Workshop Goals, Hybrid System Value Proposition & Challenges** *David Tew, ARPA-E*
1:20 – 1:45 PM	**Participant Introductions**
1:45 – 2:15 PM	**Hybrid System Thermodynamics** *Rob Braun, Colorado School of Mines*
2:15 – 2:35 PM	**State of the Art: High Temperature (> 400 °C) Fuel Cells** *Hossein Ghezel-Ayagh, Fuel Cell Energy*
2:35 – 2:55 PM	**State of the Art: Microturbines** *Tony Lorentz, Capstone Turbine*
2:55 – 3:15 PM	**State of the Art: Integrated Systems** *Andy Shapiro, GE Fuel Cells*
3:15 - 3:30 PM	Break/Networking
3:30 – 5:00 PM	**Breakout Session 1: Opportunities, Challenges & Potential Solutions**
5:30 – 7:00 PM	One-on-one meetings with Dr. David Tew, *Program Director*
7:00 PM	**Informal Networking – Organize on Your Own**

Workshop Agenda – Day 2

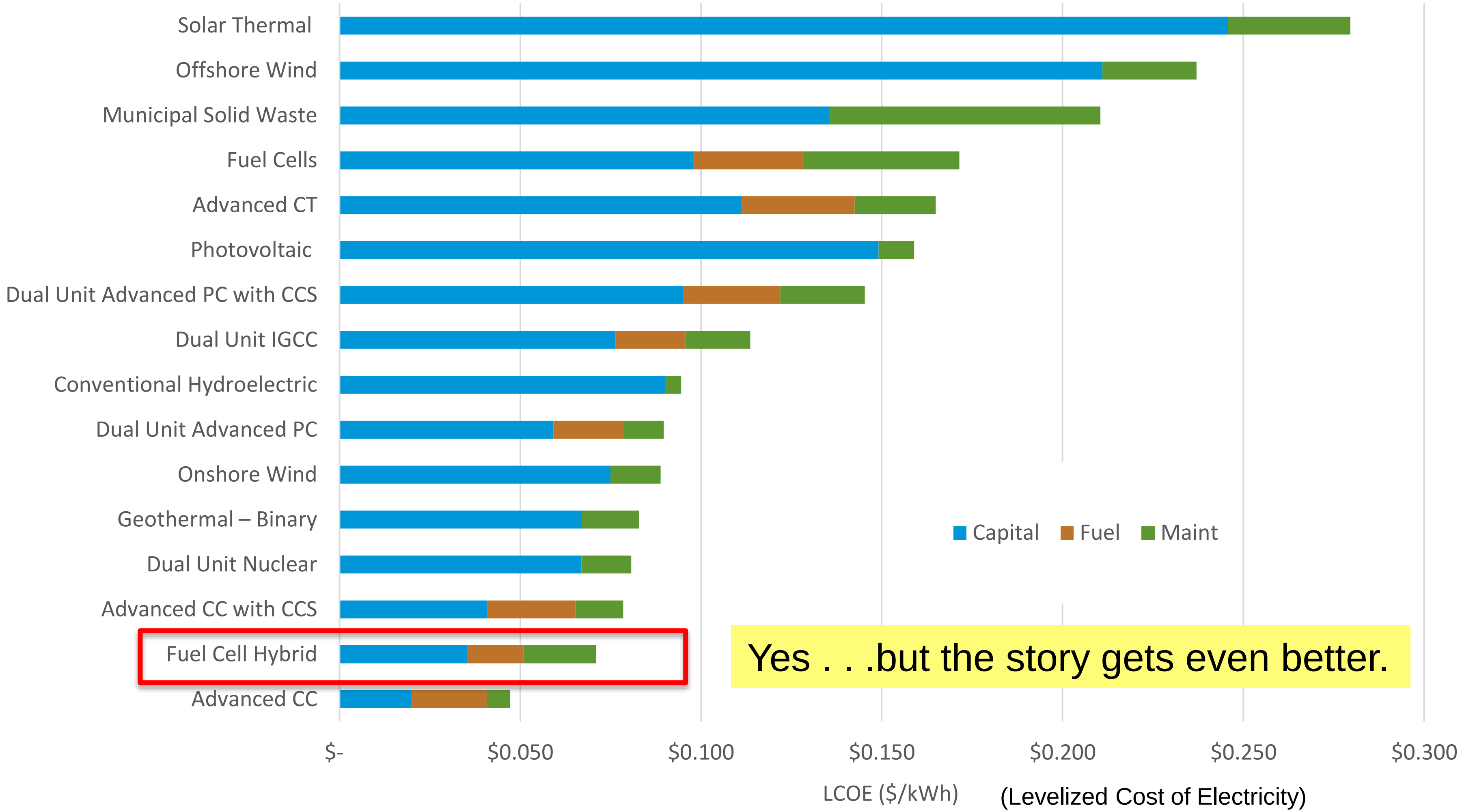
Friday, January 27, 2017

Time	Event
8:00 – 9:00 AM	Breakfast
9:00 – 9:20 AM	**Day 1 Summary/Readout and Day 2 Objectives**
9:20 – 10:00 AM	**Prior Hybrid System Experience: Panel Discussion** *Jim Kesseli, Brayton Energy; Shailesh Vora, DOE NETL; Jack Brouwer, UC Irvine; Hossein Ghezel-Ayagh, Fuel Cell Energy*
10:00 – 10:20 AM	**Research and Development of Hybrid (Electricity and Heat) System Utilizing SOFC in Japan** *Akira YABE, NEDO Technology Strategy Center*
10:20 – 10:30 AM	Break/Networking
10:30 AM – 12:00 PM	**Breakout Session 2: Hybrid System Potential Program Scope**
12:00 – 1:00 PM	Lunch
12:30 – 2:30 PM	One-on-one meetings with Dr. David Tew, *Program Director*

BACKUP

Would Hybrid Systems Be Competitive?

70%, $1800/kW→ Competitive with most cost effective next gen. grid-scale plants



Ref: EIA 2012 Utility Plant Overnight Costs (Non-hybrid plant capital & operating costs)
EIA 2015 US Average Coal & Natural Gas Rates, CO2 Emission Factors & Capacity Factors (CF)
Hybrid System Assumptions: CAPEX=$1800/kW, η=70%, Maintenance = $0.02/kWh, CF= 56% (same as CC)

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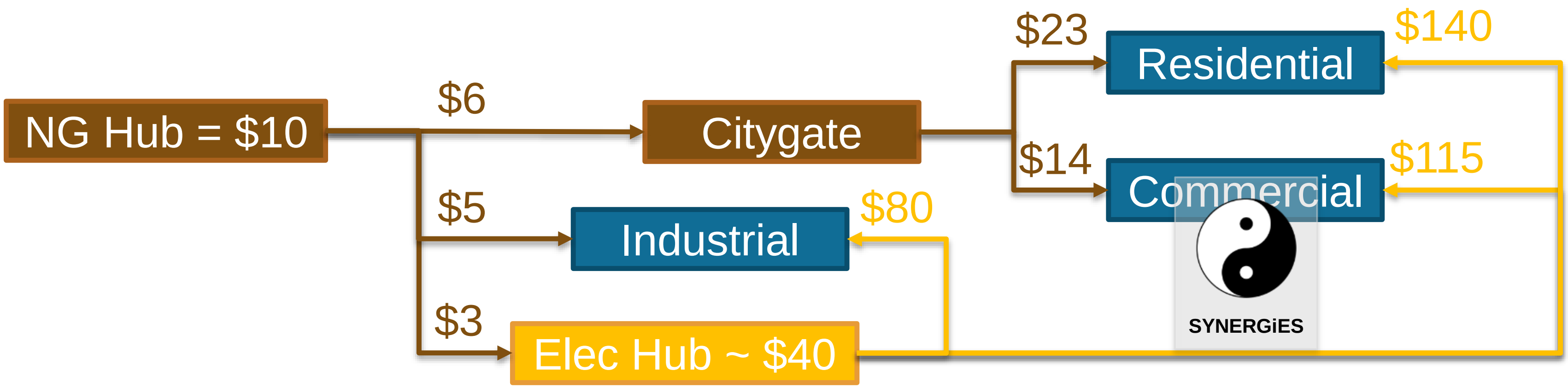
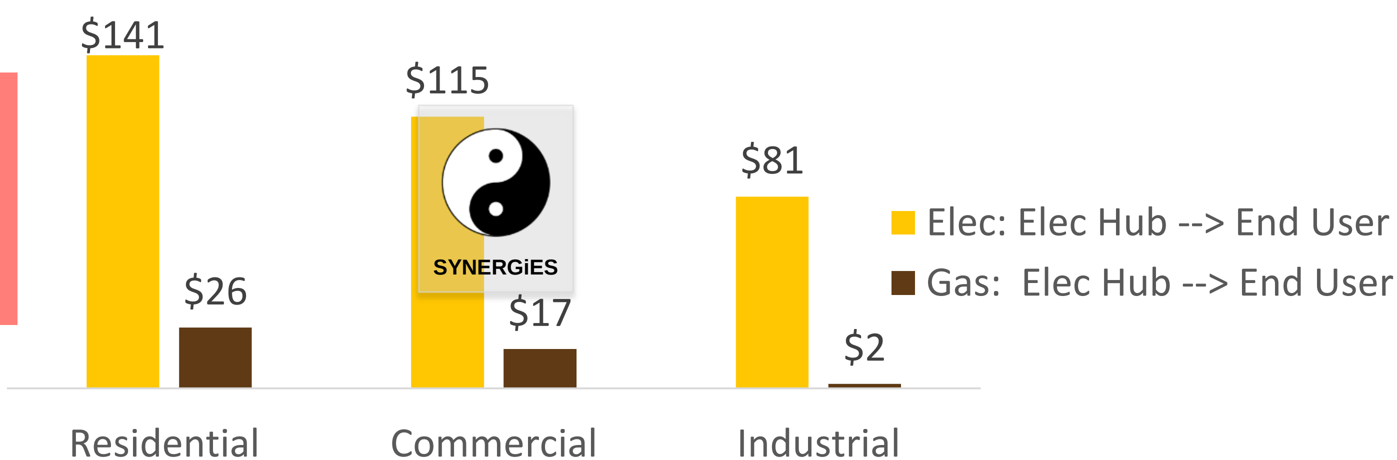
Hybrid Systems: GW-Scale Efficiency @ kW-Scale

Attractive kW-Scale Efficiency & Low NG Transportation Costs → DG Arbitrage Opportunity

Electricity & Natural Gas Flows & 2015 Costs ($/MWh)



Cheaper to move NG than electricity



*costs associated with transportation of energy (gas or electricity)

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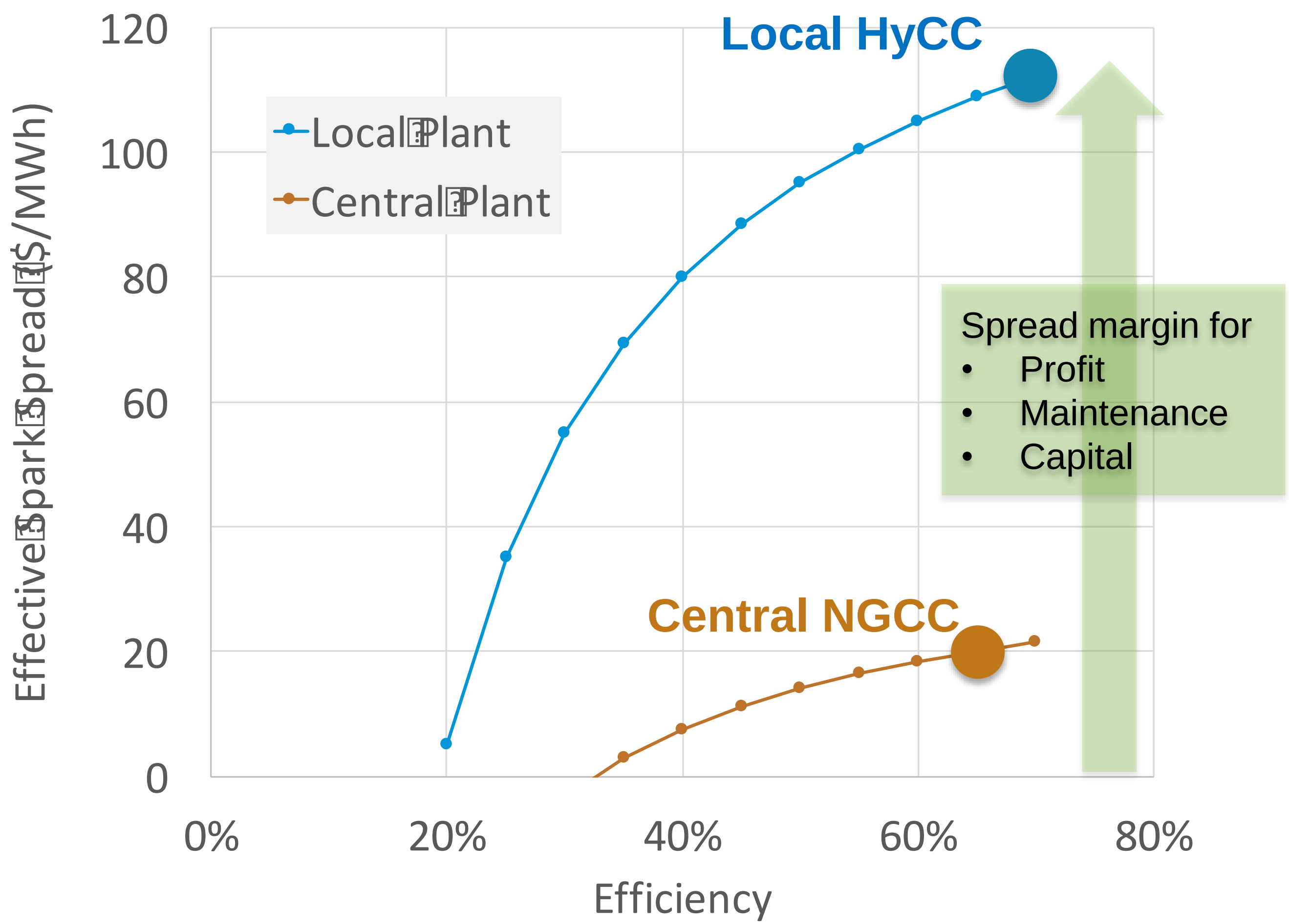
Illustration of DG Arbitrage Opportunity

Local & efficient generation → cleaner & lower cost electricity with potential for heat recovery

Central Plant	
Efficiency	60%
Quantity	Cost ($/MWh)
Gas (LHV)	$13
Elec	$40
Eff Spread	$18

Transportation Costs	
Quantity	Cost ($/MWh)
Gas (LHV)	17
Elec	115

Local Plant	
Efficiency	70%
Quantity	Cost ($/MWh)
Gas (LHV)	$30
Elec	$155
Eff Spread	$112*



$$c_{eff} = c_{elec} - \frac{c_{gas}}{\eta_{elec}}$$

*Not inclusive of waste heat recovery benefits for thermal loads

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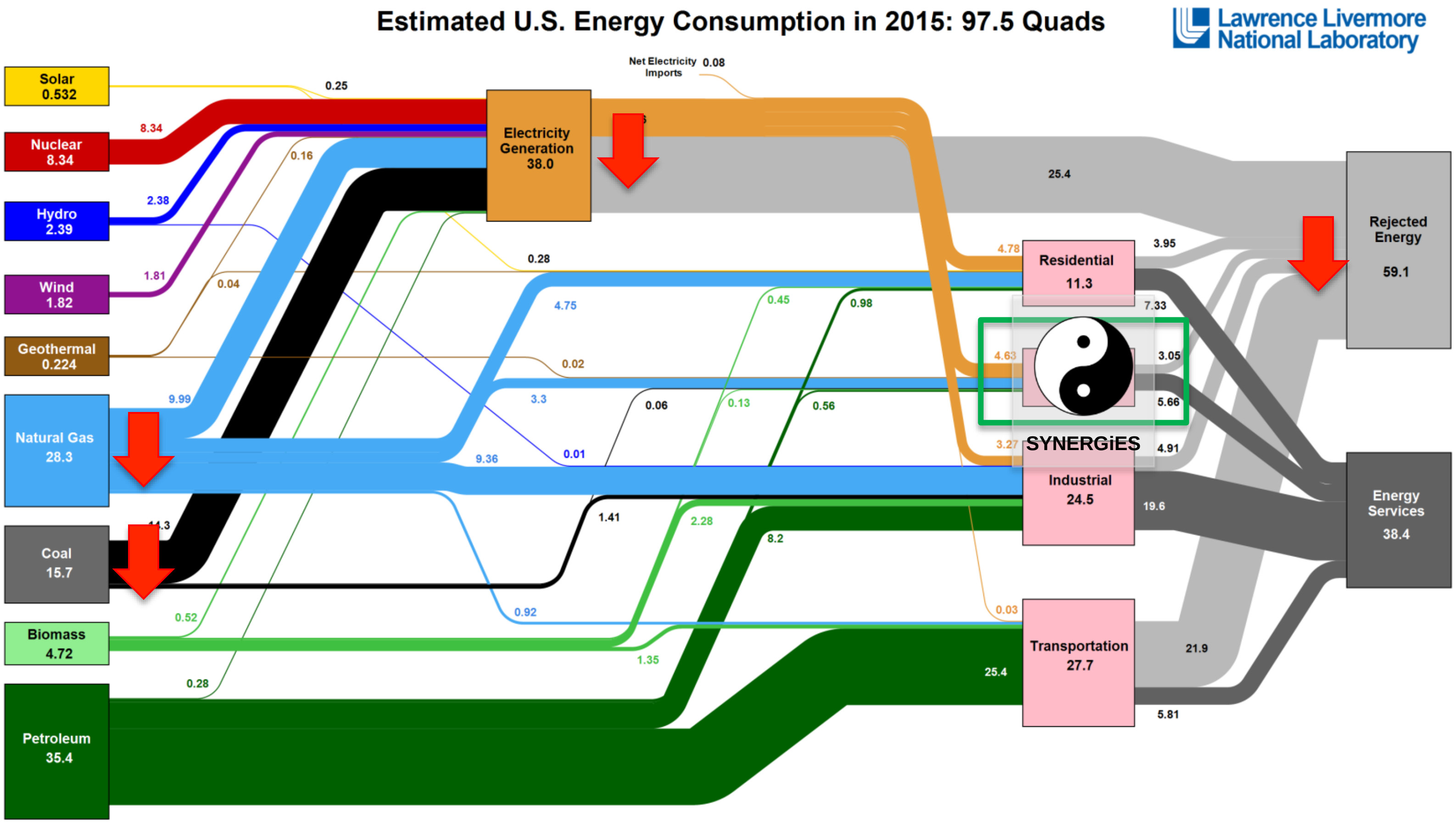
Impact

Initial Focus on Commercial-Scale DG Application



Source: LLNL March, 2016. Data is based on DOE/EIA MER (2015). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

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Breakout Session #1 Strategy

Objectives	Approach
Refine Definition of Opportunity (15 min)	Present hypothesis and encourage debate on merits (or lack thereof)
Refine Definition of Challenge (15 min)	
Develop Solutions to Challenge (60 min)	Seek answers to questions posed. Seed discussion with HW assignments or ideas from table if needed/appropriate.

Breakout Session #1

Opportunities & Challenges (with potential solutions)

Hypotheses

1. Hybrid systems offer the potential to be highly efficient (≥70%) & cost-effective (Installed Cost ≤ $1800/kW) electric power generation systems @ scales ≥ 100 kW

2. If the above-mentioned efficiency & cost targets can be achieved, hybrid systems could offer attractive economic, energy consumption &/or emissions generation value propositions in multiple markets:
    a) Distributed/Remote Generation (Challenge: Life/Durability)
    b) Utility-Scale Generation (Challenge Δ: None)
    c) Transportation Power (Challenge Δ: -Life, +Fuel, +Weight, +Volume)
    d) Military Power (Additional Challenges Δ: None)
    e) Other?

Discussion Topics: Validity (or not) of Hypotheses, Market Opportunities for Technology

Breakout Session #1

Opportunities & Challenges (with potential solutions)

- What are the major technical challenges associated with the attainment of the target
  1. Efficiency (>65%),
  2. Installed Cost (<$1800/kW),
  3. Maintenance Cost/Durability/Life (<$0.02/kWh)?

- What are potential technical solutions to these challenges?

Breakout Session #1

Opportunities & Challenges (with potential solutions)

Challenges & Solutions Discussion Starters

Efficiency	Cost	Durability
Area-specific stack cost	High temperature recuperator materials	Anode catalyst coarsening/surface area reduction
Thermal management	Recuperator manufacturing labor	Interdiffusion of Electrolyte & Electrode Materials
Integration & Controls	Fuel cell stack manufacturing labor	
	Fuel cell stack materials	

If needed . . .

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Breakout Session #2 Strategy

Objectives	Approach
Seek Recommendations on Program Scope	Present technology options (e.g. microturbine, reciprocating engines, o-SOFCs, MCFCs, p-SOFCs, etc.*) and debate the pros/cons of their use in hybrid systems. (30 minutes)
	Present program options and encourage debate of the pros/cons of the various options and associated metrics for each options. (45 minutes)
	Solicit new technology &/or program approaches (15 minutes)

*Identified in Breakout #1

Market Approach

- What are the pros/cons of the proposed "Market Approach"?
  - Are there "easier" first markets than DG?
  - What are the major barriers to a "successful" (Market Penetration > 25%) commercial DG product?
  - If a 70% electric efficiency can be achieved, is heat recovery likely to be worth the additional capital investment?

Hybrid System Demonstration -- Direct

Siemens PH-220: First test of a hybrid SOFC/gas turbine generator (2000-2003)

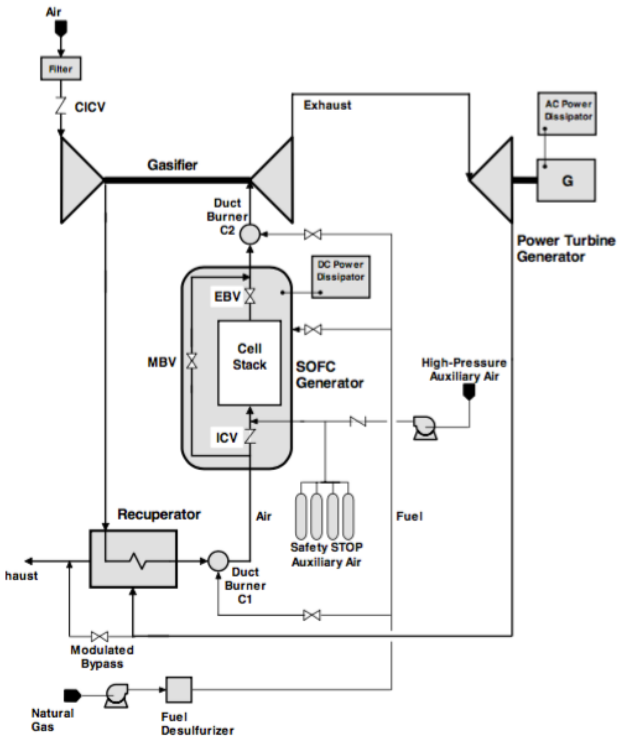

Figure 8-2 – PH-220 Simplified Process Flow Diagram

Figure 8-3 – Photograph of the SCE PH-220 Power System

P = 193 kW, η=52%, 3256 hrs

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