"Through investment in high risk, high reward ideas, ARPA-E strives to be the global leader in transformative energy technology."

ARPA-E™

REEACH Program Summary

Range Extenders for Electric Aviation with low Carbon and High efficiency

ARPA-E Mission

REDUCE imports

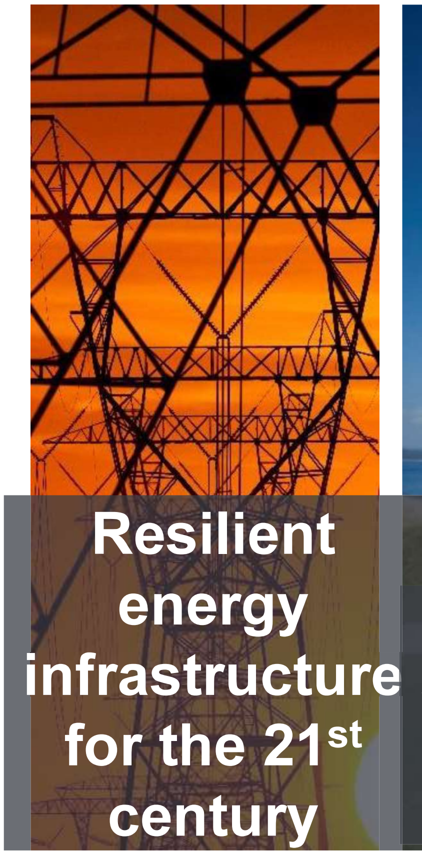
IMPROVE efficiency

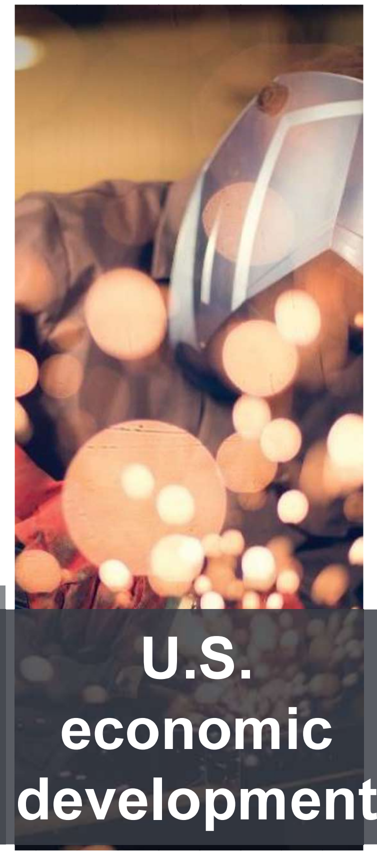
REDUCE emissions

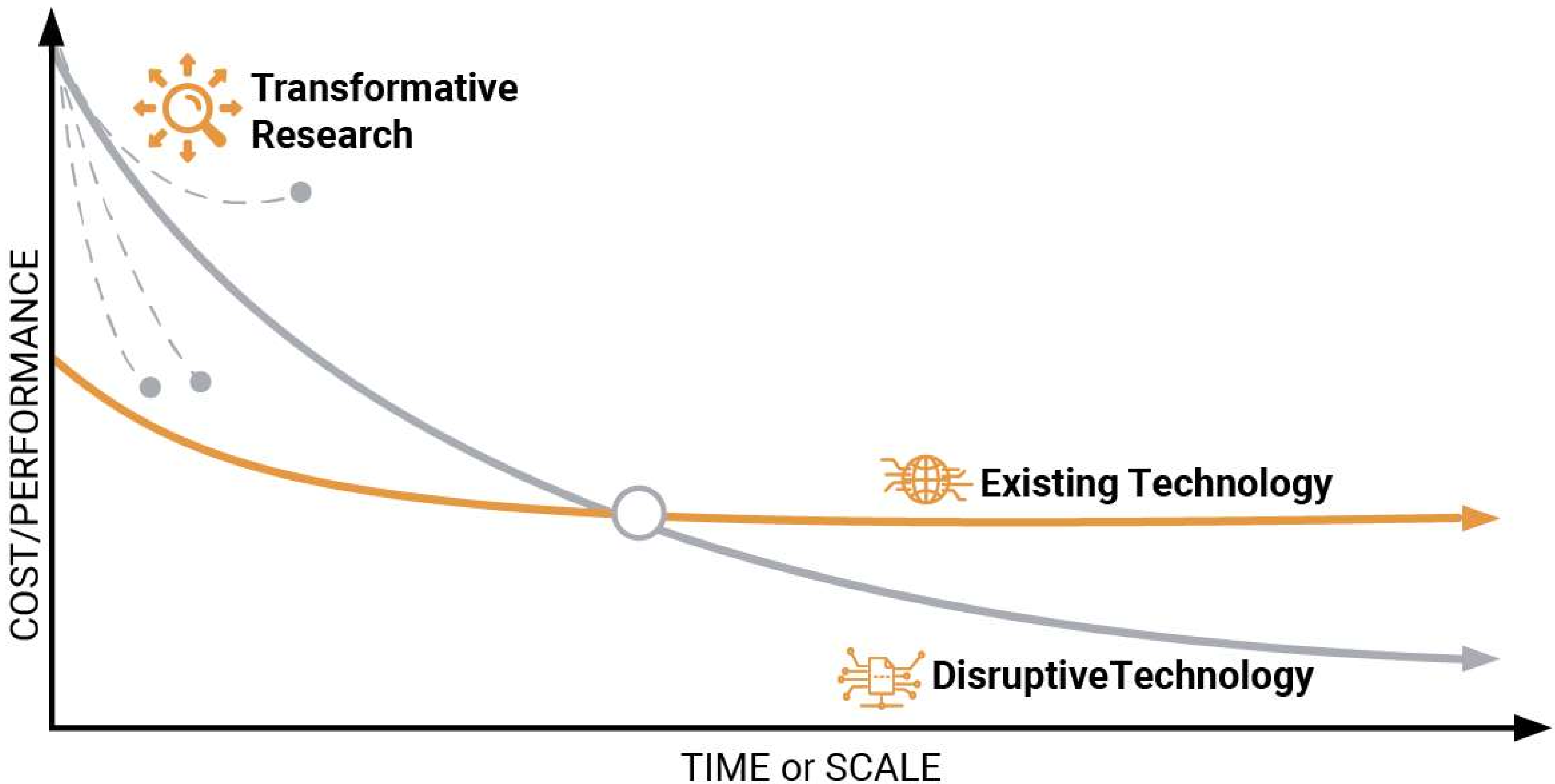
IMPROVE radioactive waste management

IMPROVE energy infrastructure resilience

What Problems are We Trying to Solve?






Transformative
Research
Existing Technology
DisruptiveTechnology
COST/PERFORMANCE
TIME or SCALE

ARPA-E Impact Indicators 2023

Since 2009
ARPA-E has provided
$3.58 billion
in R&D funding to
more than **1,500 projects**
+ 42 selected projects

212 projects
have attracted more than
$11.5 billion
in private-sector follow-on funding

149 companies
formed by
ARPA-E projects

27 exits
market valuations worth
$21.8 billion
from mergers, acquisitions, and IPOs

300 projects
have **partered with other government agencies**
for further development

6,797
peer-reviewed
journal articles
from ARPA-E
projects

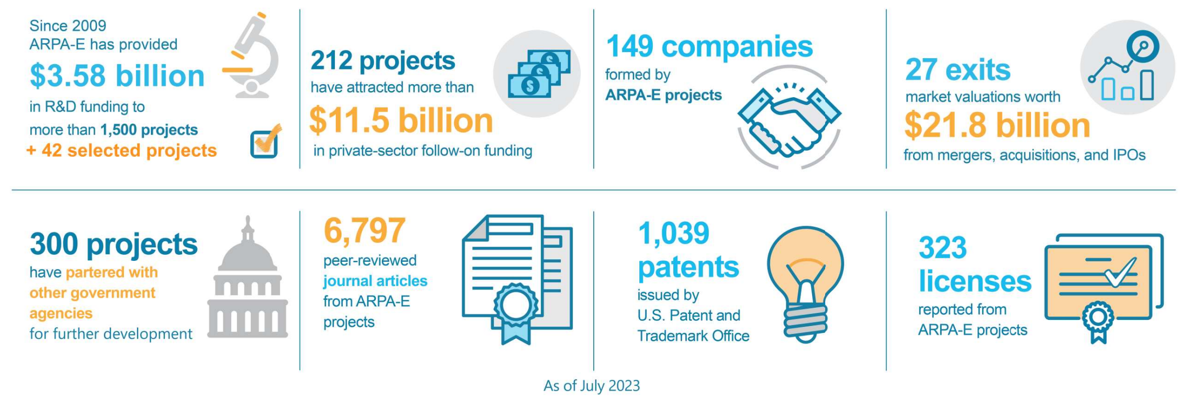
1,039
patents
issued by
U.S. Patent and
Trademark Office

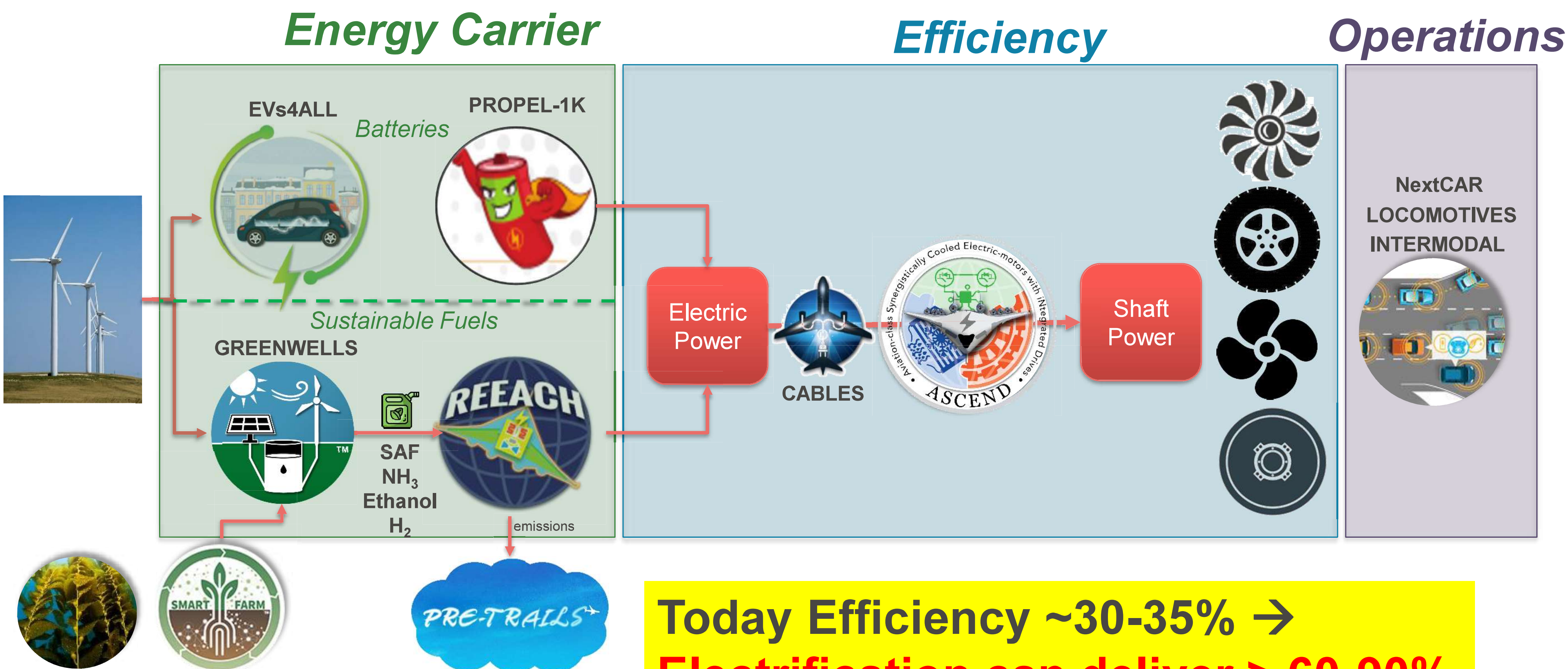
323
licenses
reported from
ARPA-E projects

As of July 2023

REEACH Indicator additions

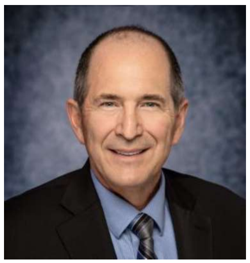
- $ 55M program spend
- 42+ patents
- 12+ papers
- 2 startup companies
- Several licenses under review





Today Efficiency ~30-35% →
Electrification can deliver > 60-90%

ARPA-E



James Seaba
Program Director

Vivien Lecoustre
Tech/T2M SETA

Colin Gore
Tech SETA

Performers

Dr. Malcolm MacDonald,
RTX Technology Research Center,
Compact Propulsion Engine Optimized with Waste Heat Recovery (CO-POWER)

Mr. Subir Roychoudhury,
Precision Combustion, Inc.,
SOFCS for Flight

Performers

Professor Christopher Cadou, University of Maryland,
Hybrid SOFC-Turbogenerator for Aircraft

Dr. John Hong,
GE Aerospace Research Center,
FueL CelL Embedded ENgine (FLyCLEEN)

Professor Xiao-Dong Zhou,
University of Connecticut,
High Performance Metal-Supported SOFC System for Range Extension of Commercial Aviation

Aviation

- Is/will be **critical** to our **economy** and **quality of life**

- Is/would be a significant contributor to **fuel consumption**– if we don't act
  - Passenger-miles-traveled forecast to nearly double between 2016 & 2040 [1]
  - Approx. 25% of flying costs is fuel

- Need lightweight **economically-attractive climate-friendly propulsion** options
  - Carbon-Neutral Liquid Fuels (CNLF): e.g., Synthetic Aviation Fuel, CH_3OH, NH_3,H_2
  - High specific-energy batteries
  - **High-efficiency chemical- to thrust- power conversion systems**

1. *EIA Annual Energy Outlook 2020*

Airliner Economics – Cost per Available Seat Mile

Cost per Available Seat Mile (CASM)

- Essential metric in airline industry for measuring cost of operating an aircraft

$$\frac{\textit{Total Operating Expenses}}{\textit{Total Seat Miles Available to Passengers}} = \textit{Cost per Available Seat Mile}$$

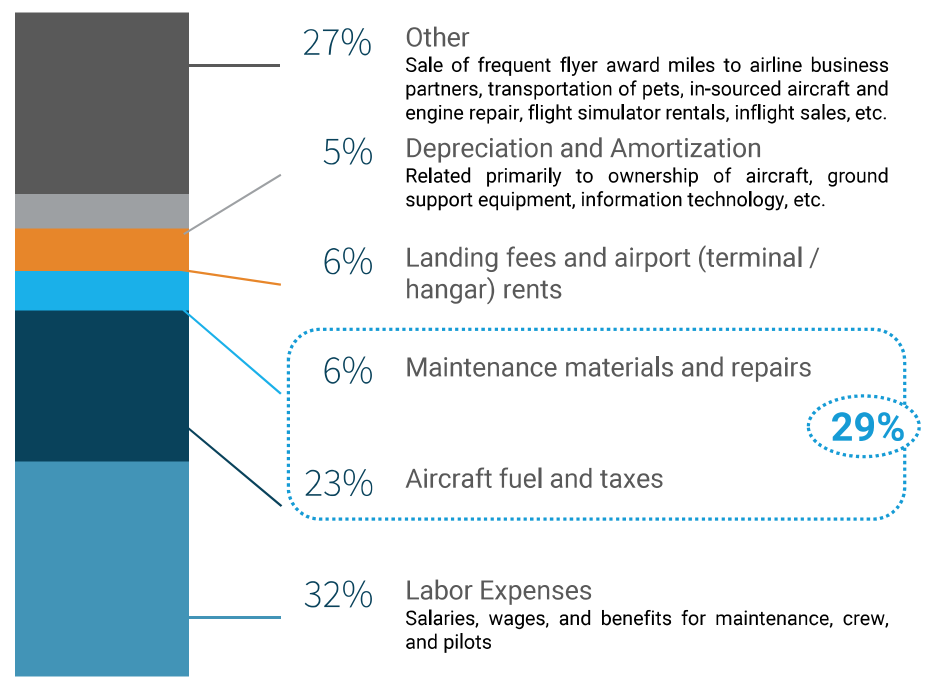
- **Primary Factors that affect CASM:**
  - **Fuel prices:** Jet A exhibits high price volatility
  - **Labor costs:** Airlines with higher labor costs must cut other services
  - **Aircraft maintenance costs:** Older fleets incur higher maintenance costs

Reducing CASM

- **Investment:** Newer, more fuel-efficient aircraft require less maintenance and fuel
- **Fuel Prices:** Negotiating better fuel prices and hedging schemes
- **Flight Scheduling:** Optimizing schedules reduces idle time and aircraft utilization

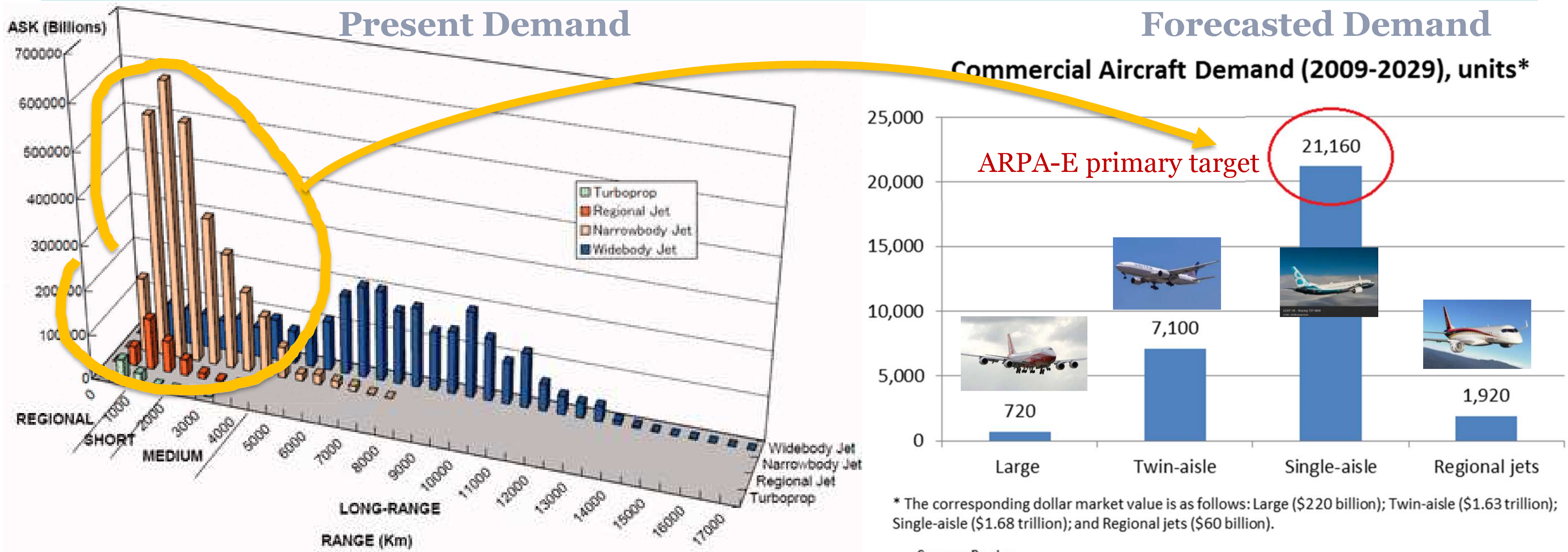
Airliners' Average Cost per Available Seat Mile[1]

(Q1 2024)



[1] A4A: Recovery from COVID (airlines.org

Narrow-body Aircraft Will Keep Dominating the Sky & the Market

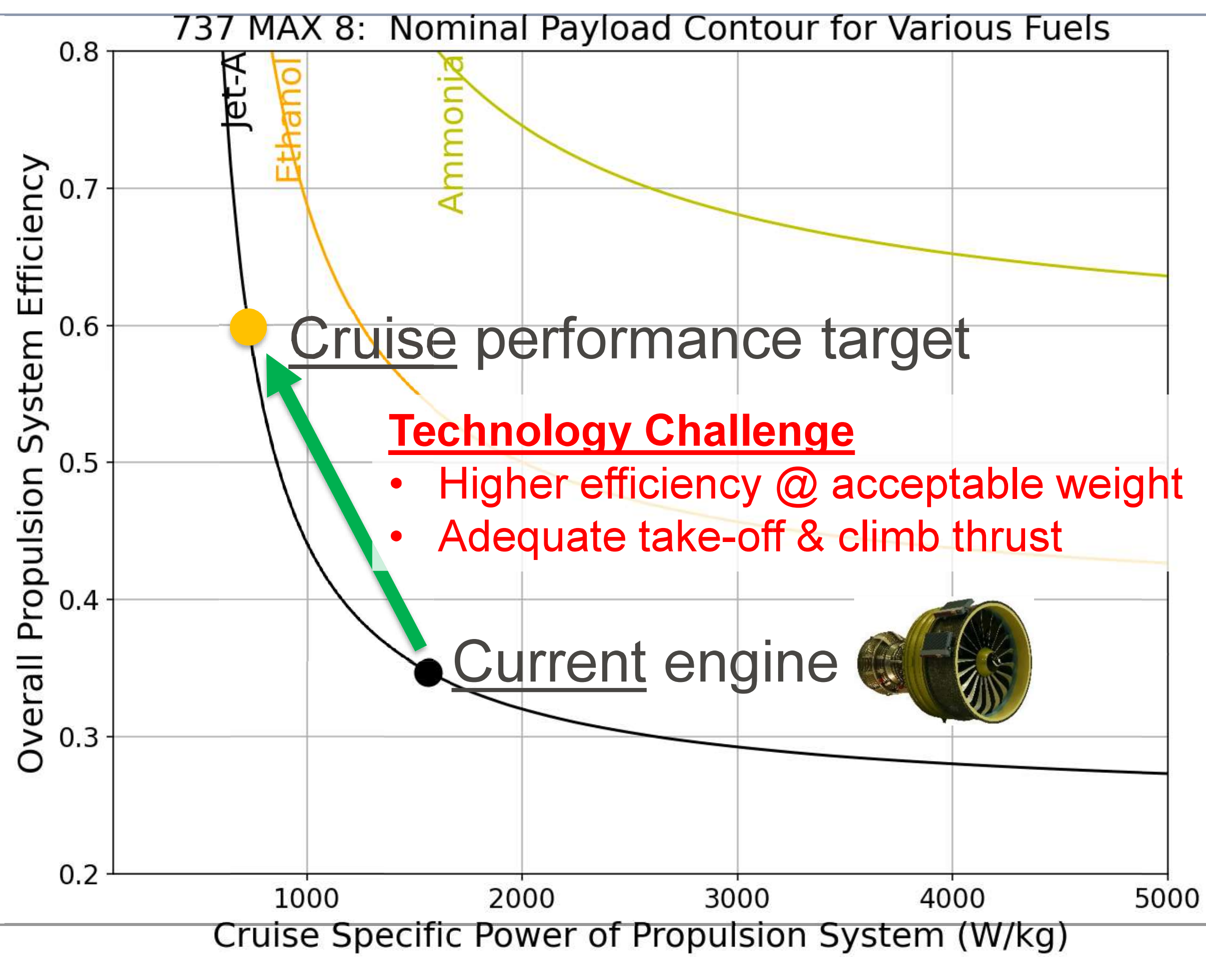


* The corresponding dollar market value is as follows: Large ($220 billion); Twin-aisle ($1.63 trillion); Single-aisle ($1.68 trillion); and Regional jets ($60 billion).

Source: Boeing

Asian demand will be the largest at 6,710 planes, followed by Europe (5,380), North America (5,180), and Latin America (1,800)

Must Achieve High Efficiency at an Acceptable Weight



Technology Challenge

- Higher efficiency @ acceptable weight
- Adequate take-off & climb thrust

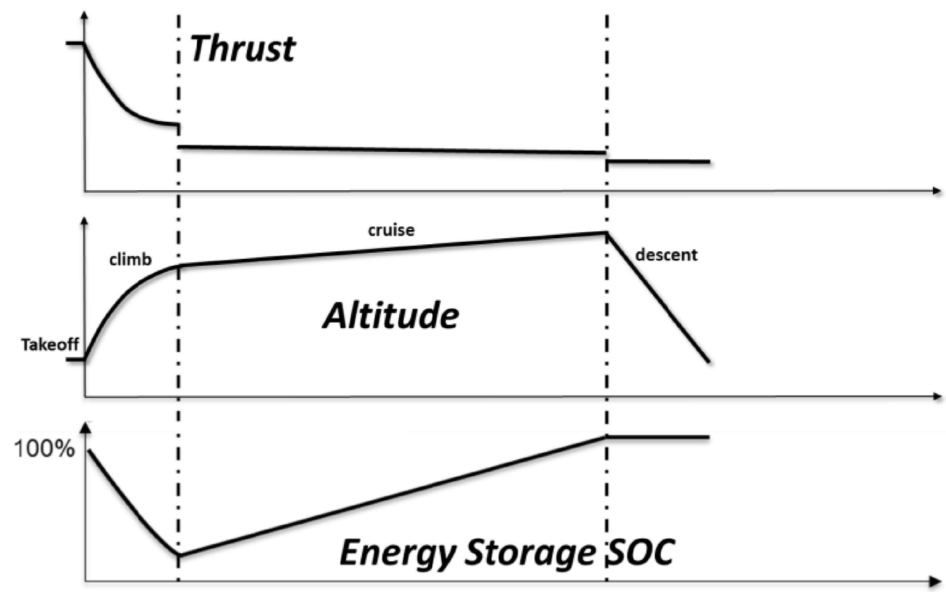
REEACH Program- Metrics & Results

Description	Target
System specific energy	> 3000 Wh/kg
Powertrain system specific power	> 0.75 kW/kg
Cost of fuel for delivered electric energy	< $0.15/kWh
Initial capital system cost	< $1000/kW

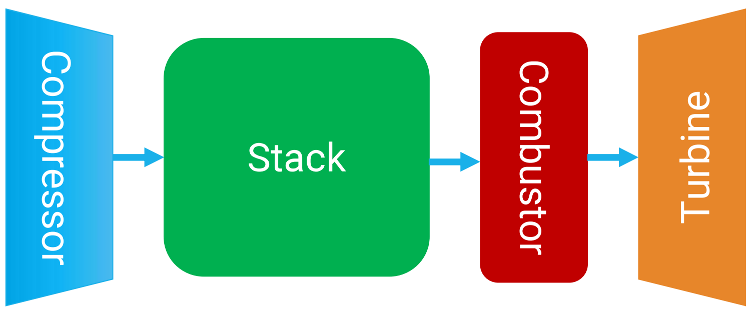
Executive Technical Summary:

- MS-SOFC is a huge success; met all system targets
- SAF processing integrated successfully with MS-SOFC
- Bottom cycle heat recovery pending

Mission Profile for Modeling

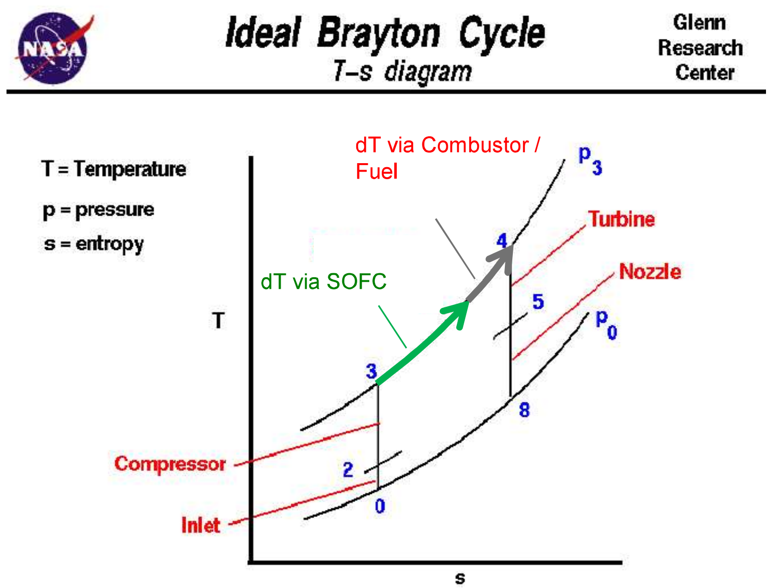


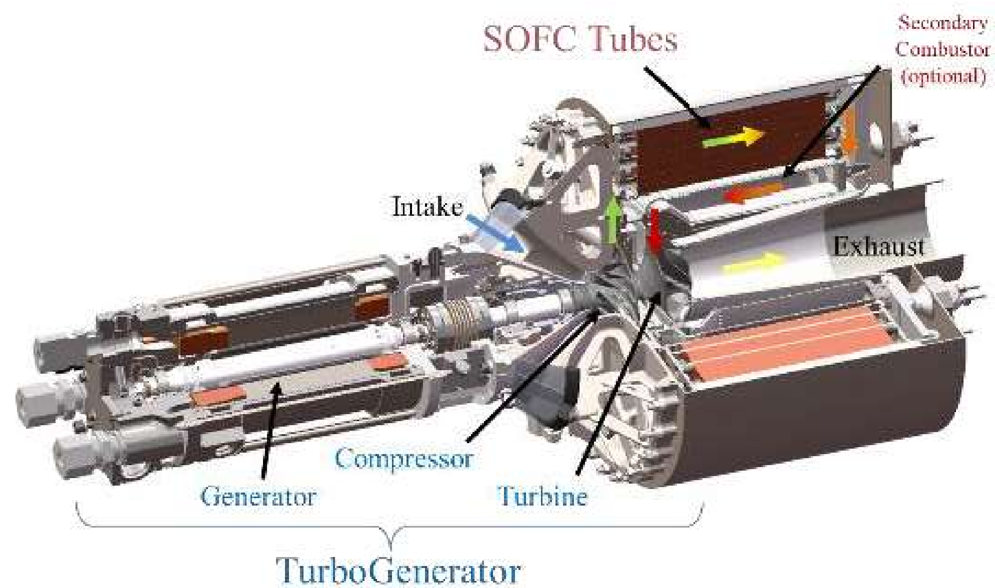
SOFC/Gas Turbine Hybrids



DARPA SHEPARD (Serial Hybrid Electric Propulsion AiRcraft Demonstrator)

SOFC system integration for HEVP





REEACH Program Structure

Today's Discussion

Phase I

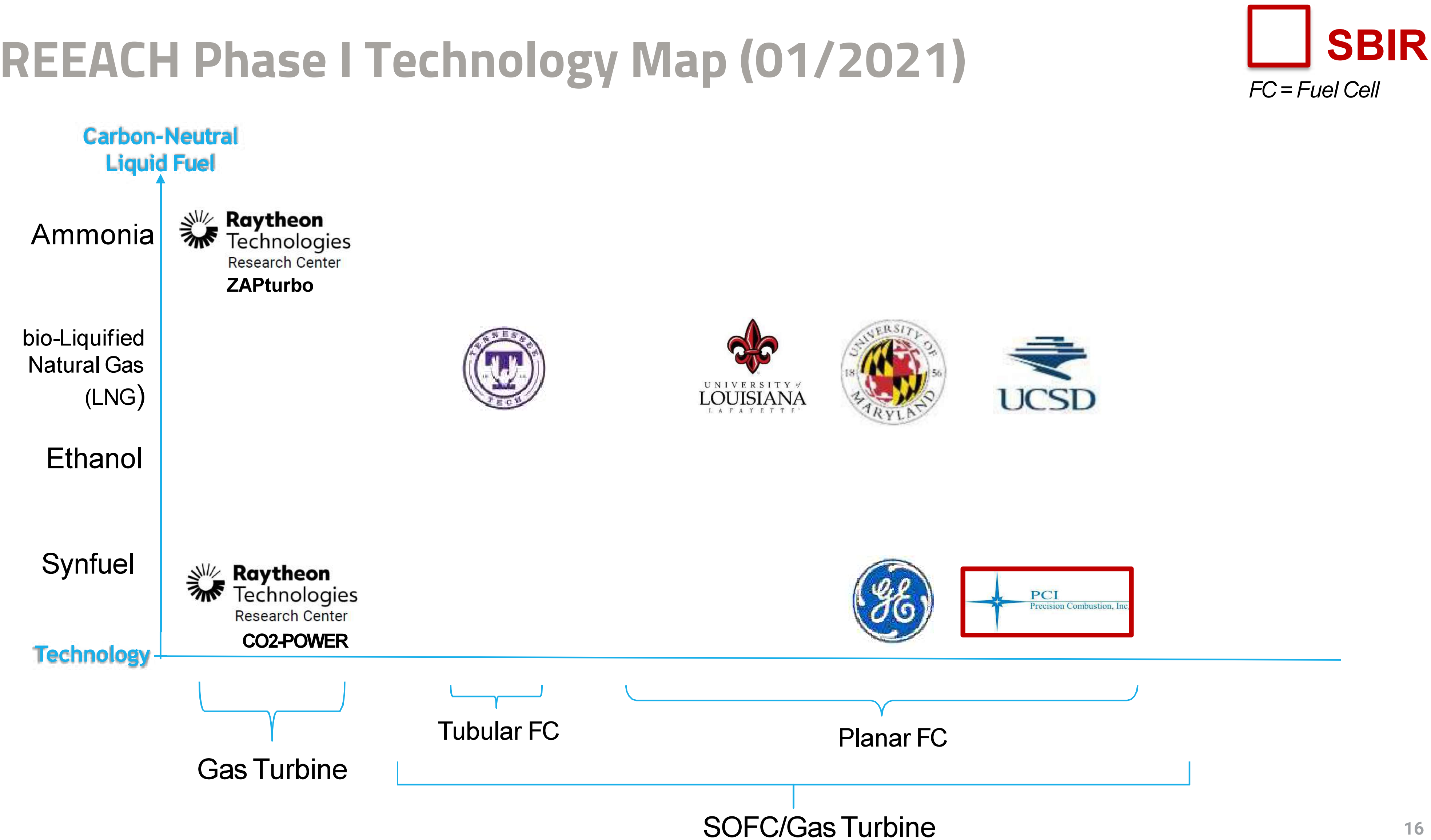
System Conceptual Design → Component Risk Reduction

Phase II

Sub-scale System Demo

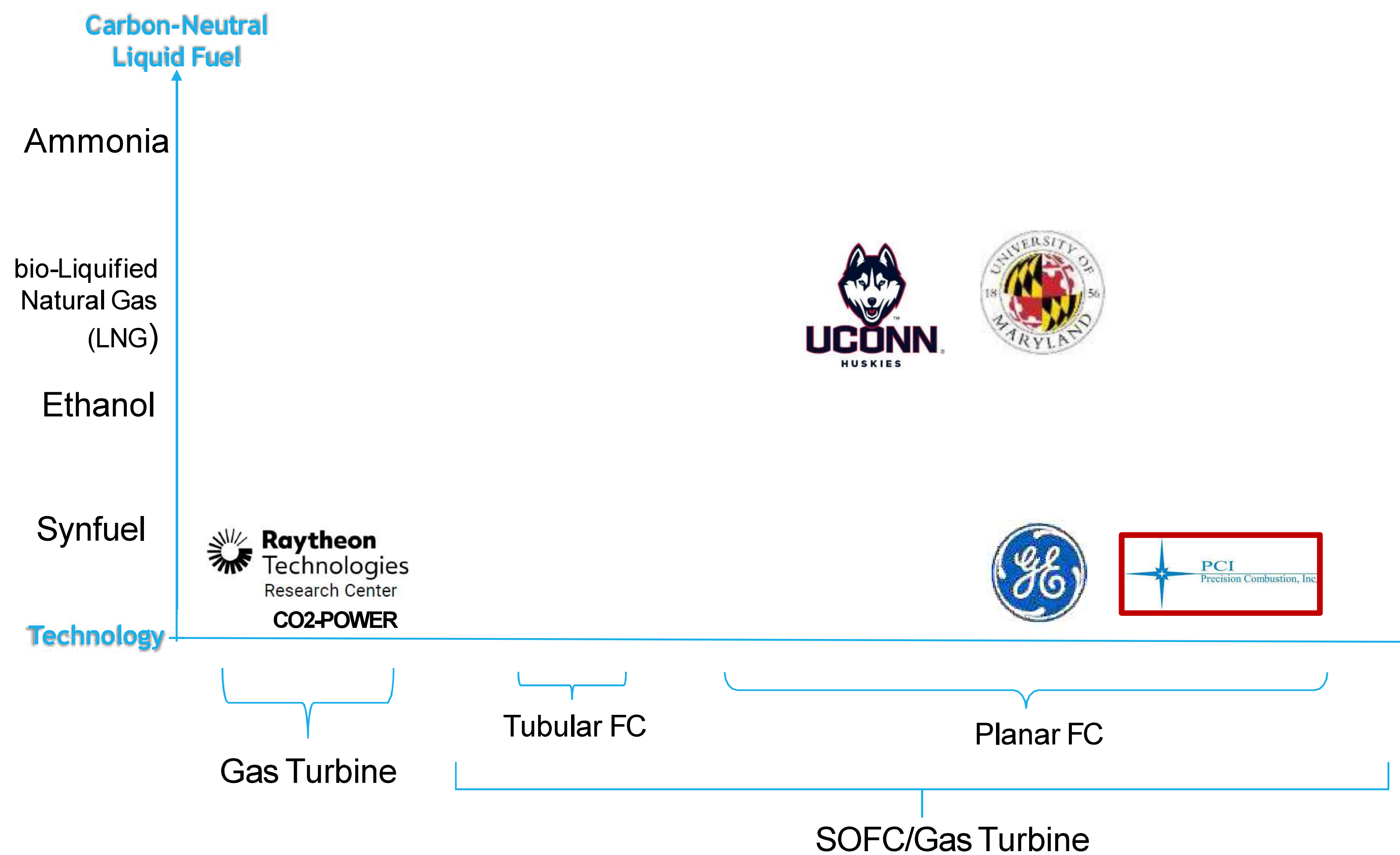
Item	Phase I	Phase II
Program Funding	$20M	$35M
# of Projects	9	5
Start Date	January to July 2021	2024
Duration	36 Months	24 – 36 mo.

REEACH Phase I Technology Map (01/2021)



REEACH Phase II Technology Map (1/2024)

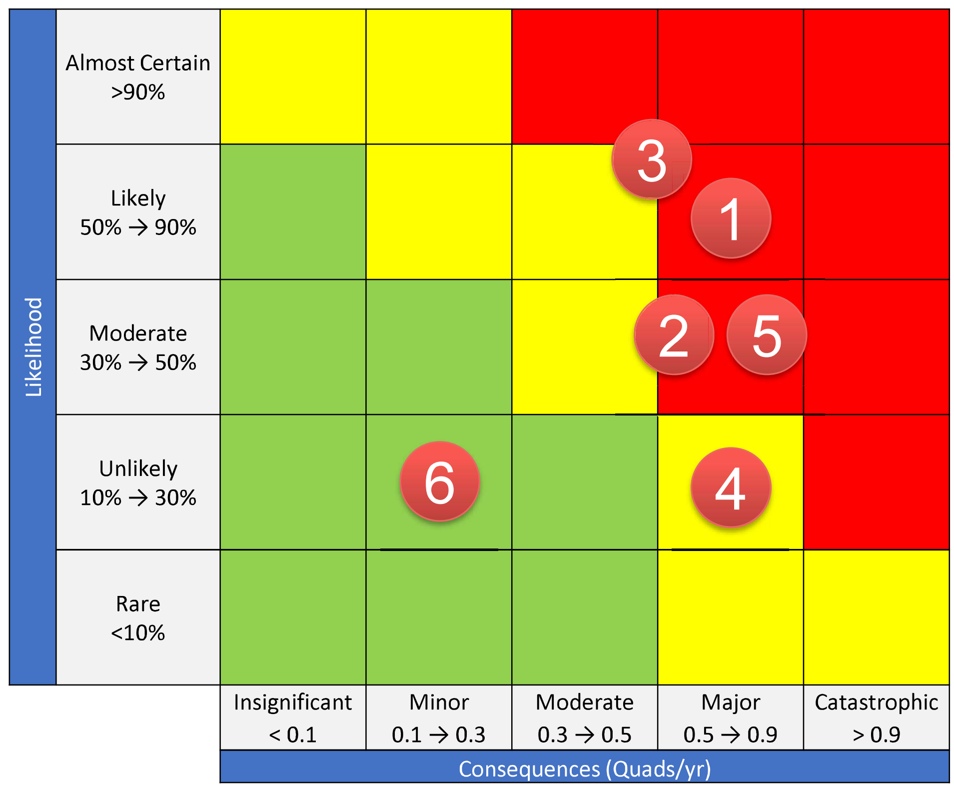
SBIR
FC = Fuel Cell



Technical Risks & Potential Mitigations 11/2023

Risks to ultra-high efficiency at an acceptable specific power (weight)

Risk	#
Specific Power (W/kg)	1
Power Density (W/L)	2
Durability (SOFC)	3
Efficiency	4
Propulsion System Integration	5
Energy Storage System	6



Technical Risks & Potential Mitigations 08/2025

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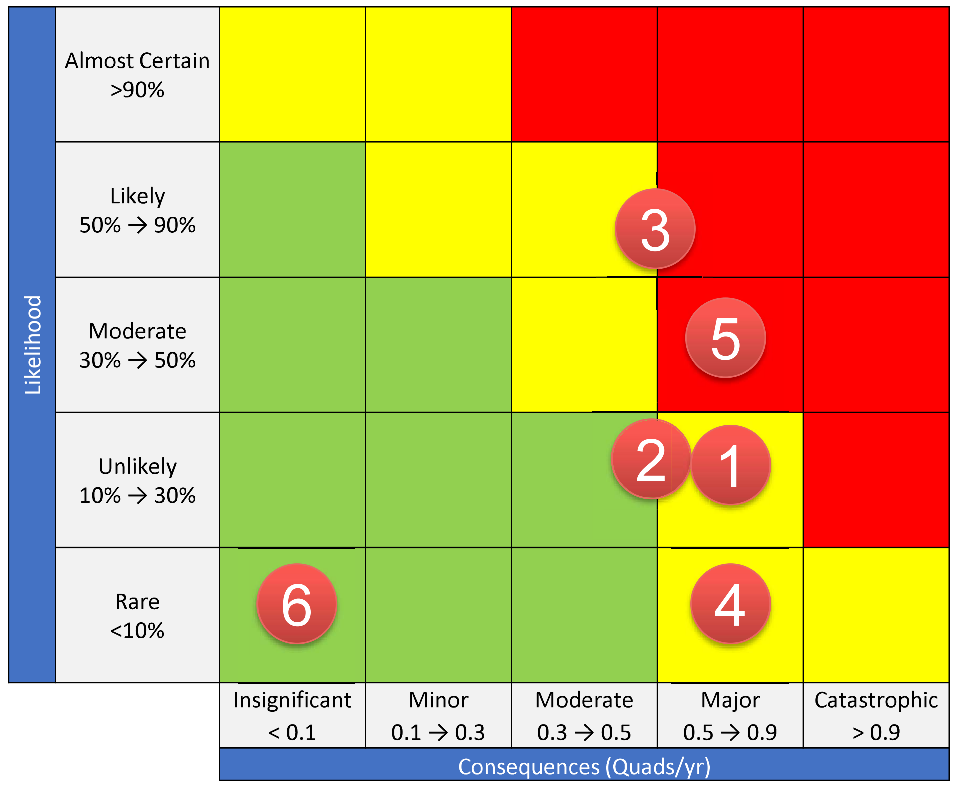


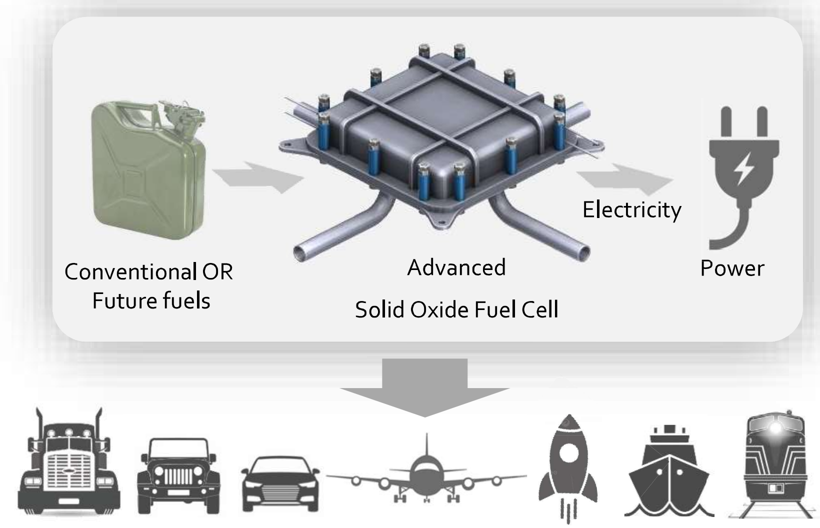
SOFC Performer Details

SOFC's for *FLIGHT*

PI: Subir Roychoudhury
PI's email: sroychoudhury@precision-combustion.com

Fuel-flexible, Lightweight, Internally-reformed, Gas-turbine Hybridized SOFC for Transportation (*FLIGHT*)

Parameter	Unit	Full Scale Design	Phase II Test Article
Technology Type		Solid Oxide Fuel Cell	
Fuel		Synfuel, kerosene, etc.	
Powertrain specific power (peak)	kW/kg	1.05	0.5
Volumetric power density (peak)	kW/l	TBD	TBD
Peak power rating	kW	Application Specific	10 (SOFC)
Fuel to electricity efficiency	%	>70%	>50%
Output voltage & type (AC/DC)	V	TBD	100 VDC
Start-up time	min.	<30 min	<60 min
Estimated ESPG MTBF	Hrs.	10,000 [TBR]	
Predicted ESPG CAPEX	$/kW$_e$	<1000	

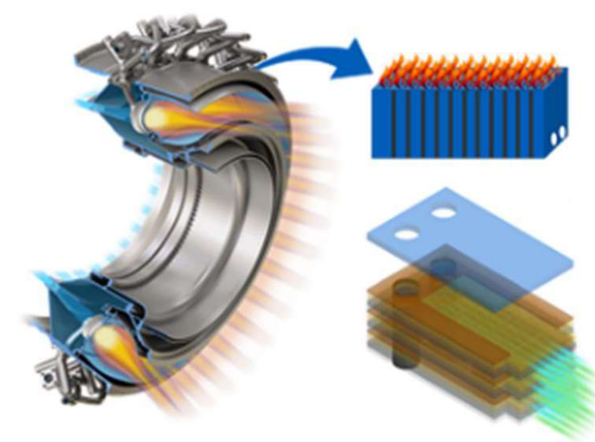


FueL CelL Embedded ENgine (FLyCLEEN)

PI: Dr. John Hong (Senior Engineer, GE Aerospace)
PI's email: John.Hong@GEAerospace.com

INNOVATIVELY INTEGRATING HIGH POWER DENSITY METAL-SUPPORTED SOLID OXIDE FUEL CELL (MS-SOFC) WITH GAS TURBINE (GT) GENSET, FOR FUEL-FLEXIBLE & HIGH-EFFICIENCY THRUST AND POWER GENERATION

Parameter	Unit	Full Scale Design	Phase II Test Article
Technology Type		SOFC-GT Hybrid	
Fuel		H_2, CH_4, Kerosene-based fuel (e.g., Jet-A), SAF (e.g., HEFA-SPK)	
Powertrain specific power (peak)*	kW/kg	> 1	~1
Volumetric power density (peak)*	kW/l	TBD	~4
Peak power rating*	kW	> 1000	5
Fuel to electricity efficiency*	%	> 80%	> 70%
Output voltage & type (AC/DC)*	V	TBD	> 70V DC
Start-up time*	min.	Start with GT	
Estimated ESPG MTBF*	Hrs.	Gas Turbine Standard	
Predicted ESPG CAPEX*	$/kW	~940	



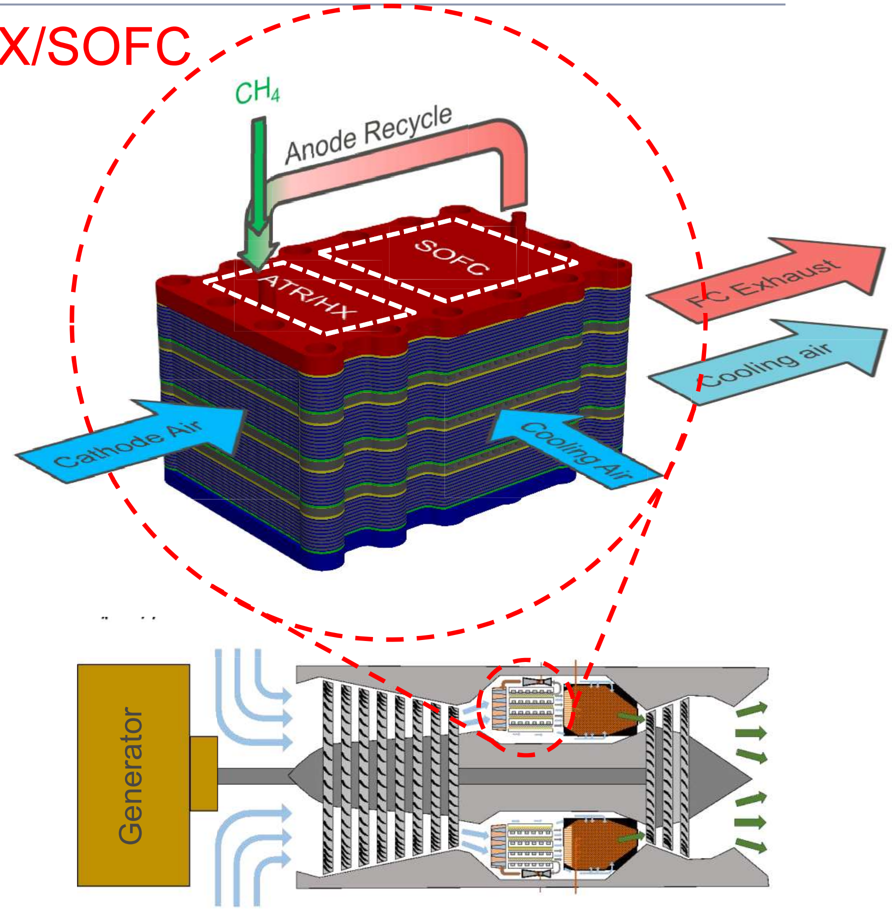
*Current engineering estimates or targets

Hybrid SOFC-Turbogenerator for Aircraft

PI: Christopher Cadou
PI's email: cadou@umd.edu

Integrated ATR/HX/SOFC

Parameter	Unit	Full Scale Design	Phase II Test Article
Technology Type		Hybrid Fuel Cell / Turbogenerator	
Fuel		LNG/Methane	
Powertrain specific power (peak)	kW/kg	3.2	2.5*
Volumetric power density (peak)	kW/l	3.2	2.7*
Peak power rating	kW	35,000	2.5
Fuel to electricity efficiency	%	51	48*
Output voltage & type (AC/DC)	V	Arbitrary	22.5V
Start-up time	min.	Cold: 106 Normal: 15	40
Estimated ESPG MTBO	Hrs.	10k service/30k overhaul	
Predicted ESPG CAPEX	$/kW$_e$	586	



High Performance Metal-Supported SOFC System for Range Extension of Commercial Aviation

PI: Xiao-Dong Zhou
PI's email: xiao-dong.zhou@uconn.edu

BREAKTHROUGH EFFICIENCY AND PERFORMANCE IN NATURAL GAS-POWERED METAL-SUPPORTED SOFCS

The University of Connecticut has achieved significant milestones in the development of metal-supported solid oxide fuel cells (MS-SOFCs), demonstrating unprecedented levels of efficiency and performance. Leveraging liquefied natural gas (LNG), propane, and other readily available fuels, these next-generation fuel cells offer enhanced reliability and are well-positioned to serve as a clean, high-efficiency power source for future applications in aviation, data centers, maritime transport, heavy-duty trucking, and beyond.

Parameter	Unit	Full Scale Design	Phase II Test Article
Technology Type		Next Generation SOFC	
Fuel		Natural Gas, Propane, Jet Fuels & H2	
Powertrain specific power (peak)	kW/kg	1.5	1.5
Volumetric power density (peak)	kW/l	3.5	3.5
Peak power rating	kW	2500	5
Fuel to electricity efficiency	%	80	80
Output voltage & type (AC/DC)	V	1,000	8V (DC) for 1 kW stack
Start-up time	min.	< 30	< 15
Estimated ESPG MTBF	Hrs.	12,000	
Predicted ESPG CAPEX	$/kW$_e$	$125	

Thank You

James Seaba

Program Director

ARPA-E

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