National Aeronautics and Space Administration

IA012 NASA Fuel Cell and Hydrogen Activities

Department of Energy
Annual Merit Review
Interagency Track

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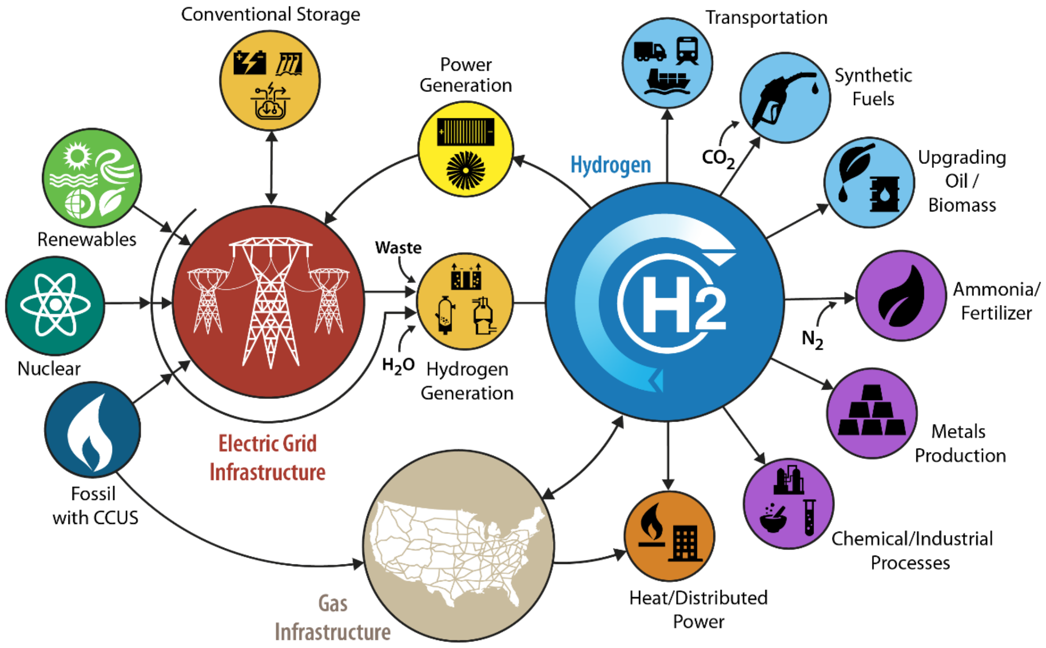
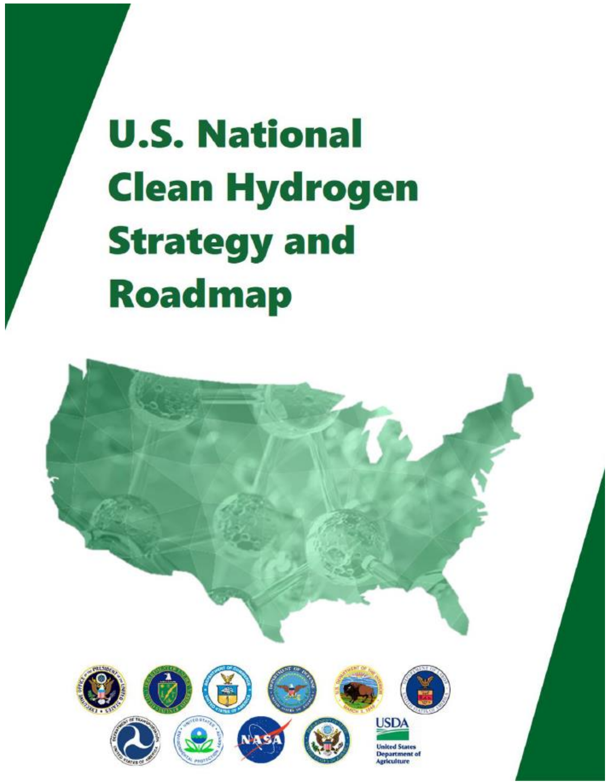
U.S. National Clean Hydrogen Strategy and Roadmap

- U.S. National Clean Hydrogen Strategy and Roadmap outlines the Administration's plan to implement the Carbon-reduction activities outlined in the Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA) https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf
- Department of Energy (DOE) leads an "all-of-government" Hydrogen Interagency Taskforce (HIT) to guide the implementation of the Hydrogen Strategy and Roadmap https://www.hydrogen.energy.gov/interagency.html

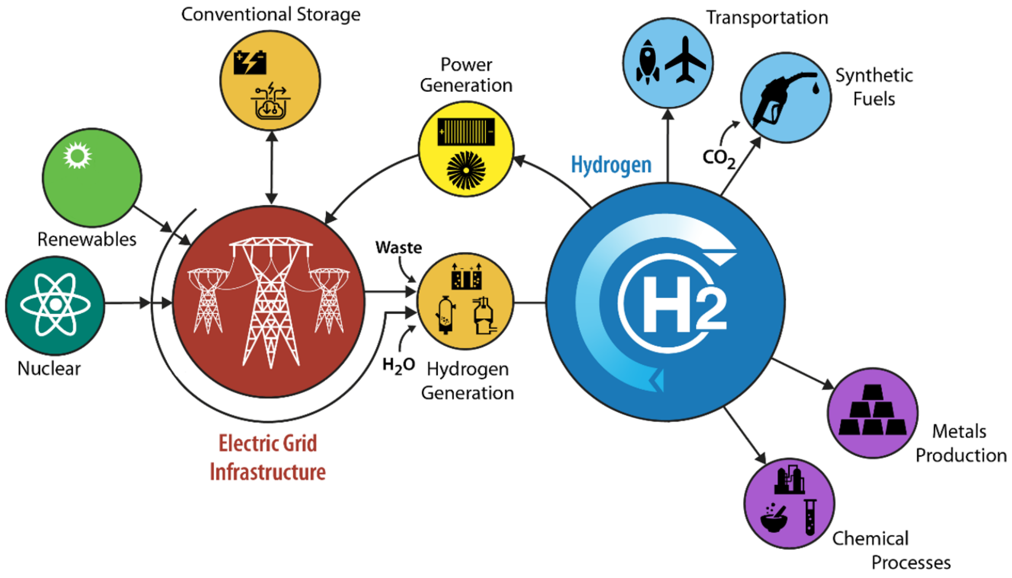


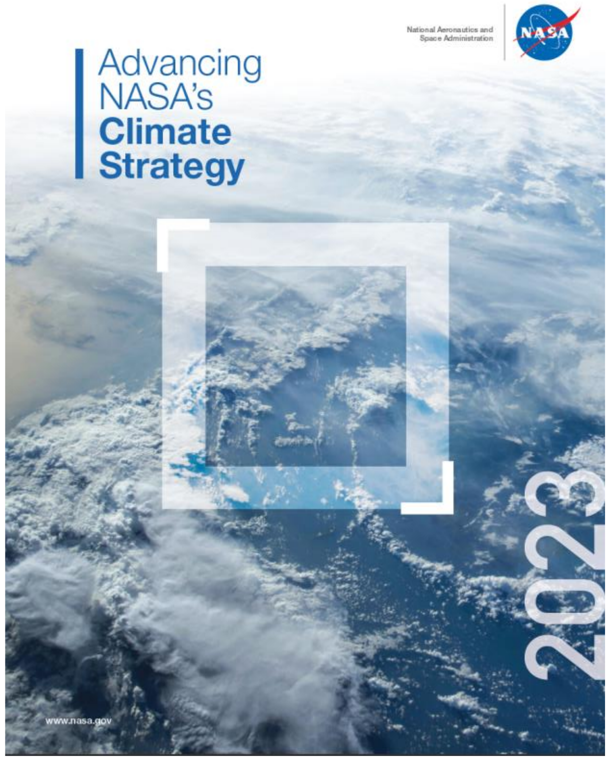


NASA Climate and Space Sustainability Strategies

- NASA actively participates in the DOE Hydrogen Interagency Taskforce (HIT)
  - Supports all Working Groups and some Cross-cutting Teams
  - Hydrogen Training available to participating HIT agencies
- DOE HIT activities align with NASA Climate Strategy released last year

https://www.nasa.gov/wp-content/uploads/2023/04/advancing-nasas-climate-strategy-2023.pdf





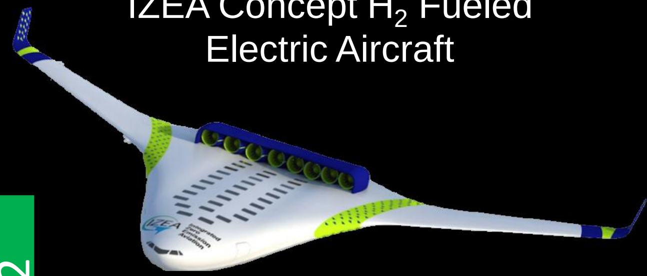
Fuel Cell and Hydrogen Applications Within NASA

LH2 Tank at Pad 39B

Energy Storage

Long-term storage and management of H_2, O_2 and water

IZEA Concept H_2 Fueled Electric Aircraft



O_2 ↑ H_2 ↑

On the Ground
In the Air
In Space

H_2 ↓ O_2 ↓

Water Electrolysis

Generate H_2 and O_2 from water

← H_2O

Power Generation

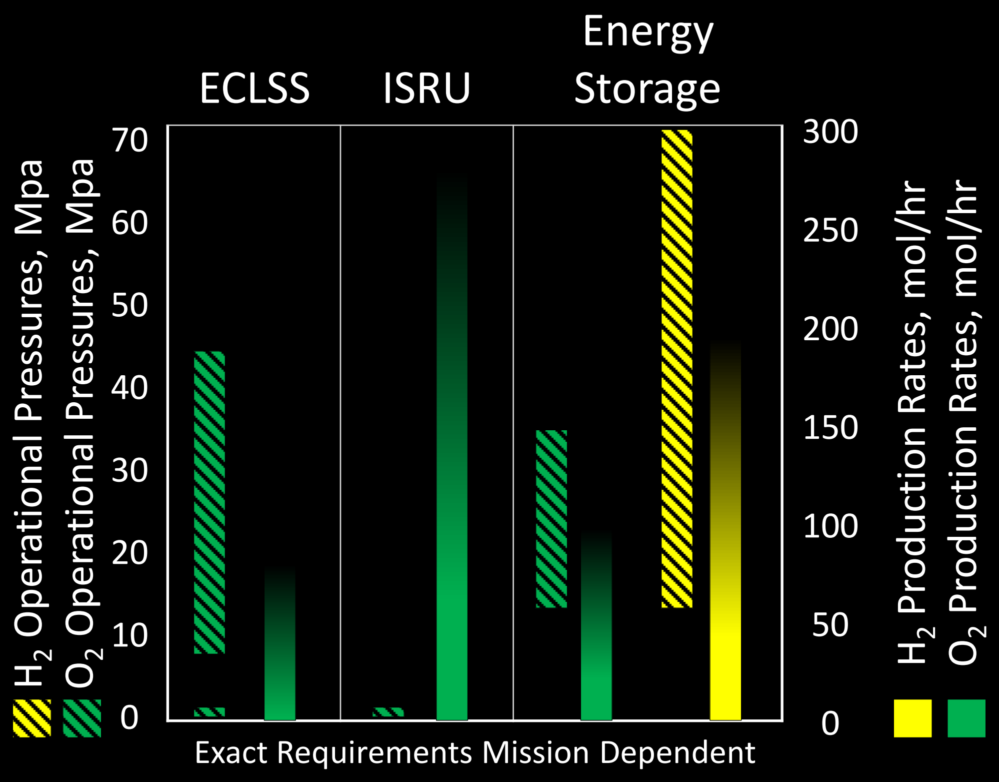
- *Electrochemically combine H_2 and O_2 into H_2O, heat, & electricity*
- *Combust H_2 to generate thrust*

Water Electrolysis

H2 and O2 Reactant Generation

- *Electrochemically dissociate water into gaseous H_2 and O_2*
  - *Balanced and Unbalanced designs*
  - *Low Pressure (< 0.3 MPa, < 45 psia)*
  - *Medium Pressure (<1.7 MPa, < 250 psia)*
  - *High Pressure (> 10 MPa, > 1,500 psia)*
  - *Contaminated Water Sources for ISRU*
- *ECLSS*
  - *Unbalanced Design ($H_2 << O_2$)*
  - *Unmet long-term requirements for reliability, life, or H_2 sensors stability*
- *Energy Storage*
  - *Balance Design ($H_2 \approx O_2$)*
  - *Unmet long-term requirements for performance, reliability, life, sensors availability, sensor stability*
- *In-situ Resource Utilization (ISRU)*
  - *Balance Design ($H_2 \approx O_2$)*
  - *Unmet long-term requirements for performance, reliability, or life*
  - *Tolerate contaminated water sources to minimize pre-conditioning requirements*

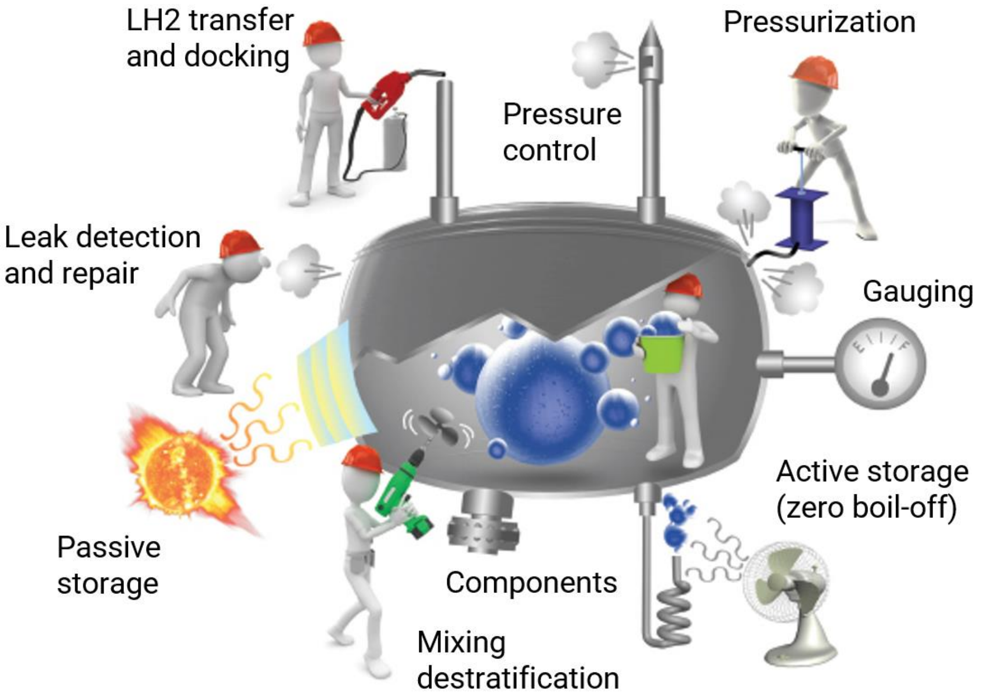
Notional Electrolysis Requirements



All applications Power and Mass Constrained

Energy Storage

- NASA stores Hydrogen as compressed gas, cryo-compressed fluid, and cryogenic liquid
- NASA participates in developing and maintaining industry Codes and Standards
- Systems safely provide fuel to user systems at desired pressure, temperature, and flow rates through multiple system operational modes and mitigate potential failures



800,000 gal (3,3028 m^3)
LH2 Tank at Pad 39B
(NASA Image KSC-20191108-PH-JBS01_0001)

Tanker trucks deliver liquid hydrogen (LH2) to replenish the large sphere at NASA's Kennedy Space Center in Florida, Launch Pad 39B.
(NASA Image NHQ202208310013)

Fuel Cell Power Generation

Fuel cells provide primary direct current (DC) electrical power

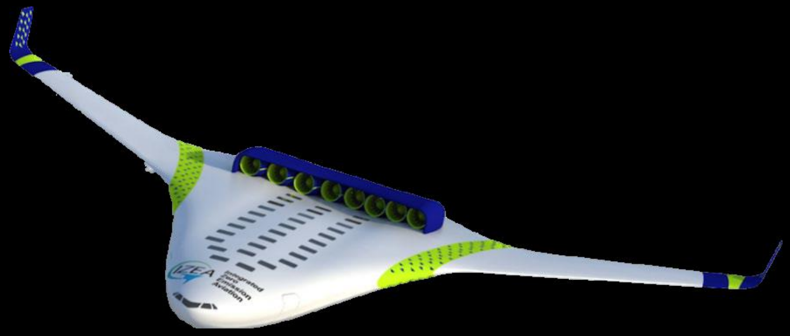
- *Use pure to propellant-grade O_2 / H_2 or O_2 / CH_4 reactants*
- *Uncrewed experiment platforms*
- *Crewed/uncrewed rovers*
- *Electric aircraft / Urban Air Mobility (UAM)*

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)
Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage

Applications

- *Electric Aircraft / Urban Air Mobility: 120 kW to > 20 MW*
- *Lunar / Mars Landers: ~ 2 kW to ≤ 10 kW*
- *Lunar / Mars surface systems: ~ 2 kW to ≤ 10 kW modules*

Blue Origin Lunar Lander Baselined Fuel Cell Power as primary power source



Concept H_2-fueled Aircraft for the Integrated Zero Emission Aviation (IZEA) ULI activity led by the University of Kentucky

ARMD and Hydrogen-Related Investment

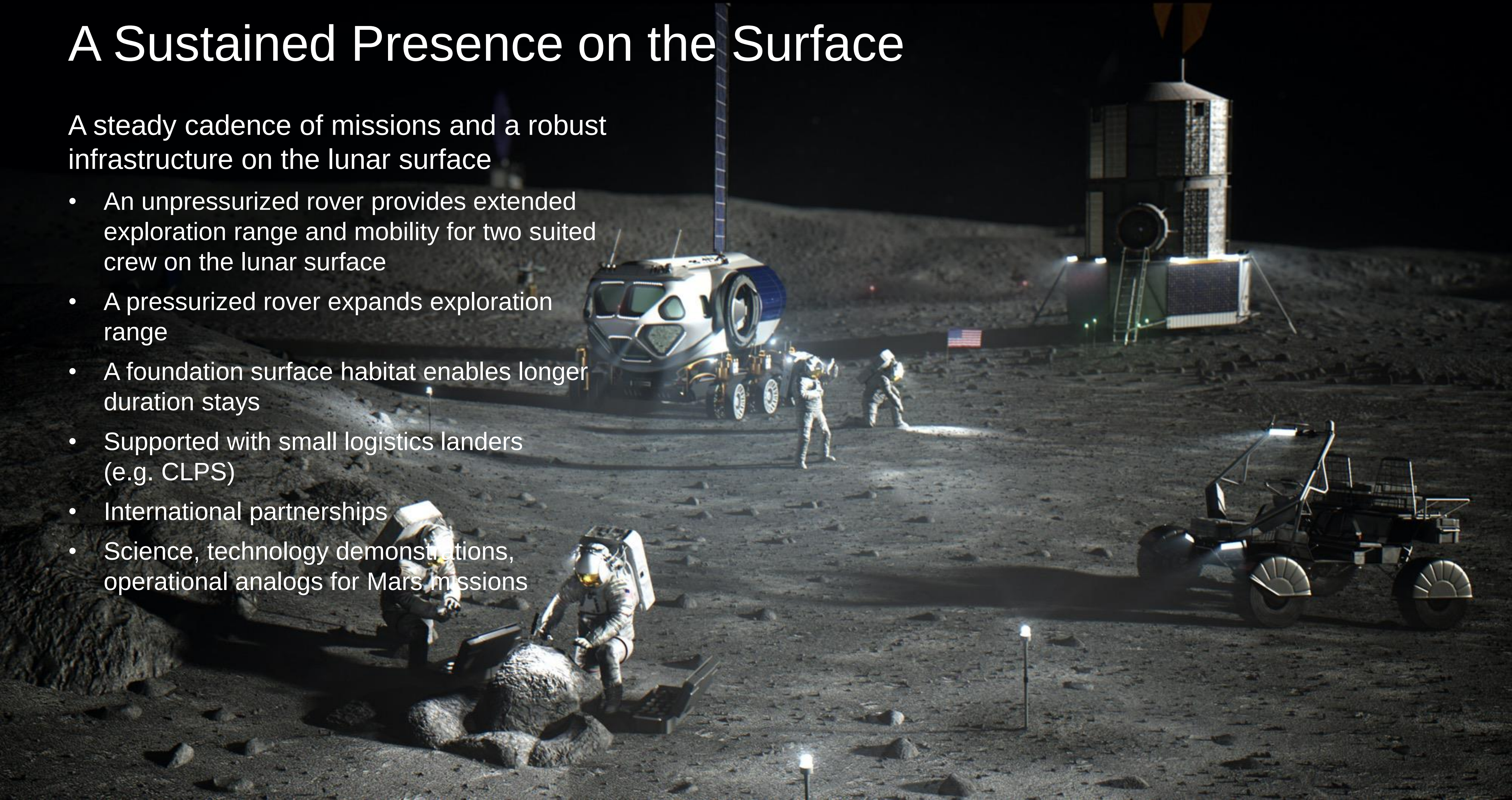
- ARMD invests broadly in technologies for a sustainable aviation future. The use of hydrogen as an aviation fuel through direct burn combustion or fuel cell-electric application is being explored at a low level amongst other options; there is no directed funding for hydrogen-specific technology development, and such ideas compete with other alternatives. *Current investment $7-8M/year, mostly to university-led teams.*

- Transformative Aeronautics Concepts Program (TACP)
  - University Leadership Initiative: These recipient defined efforts total approximately $7M/year in FY2024 and FY2025
    - **University of Illinois:** CHEETA - Develop cryogenic & hydrogen technologies for a hydrogen aircraft
    - **University of Central Florida:** ALFA - Technologies for using ammonia for a hydrogen powered aircraft
    - **Florida State University**: IZEA - Hydrogen powered hybrid electric power system that uses turboelectric generators and fuel cells
    - **Tennessee Technological University:** CLEAN - Integrated propulsion, power, and thermal management system for an ammonia-based aircraft
  - Transformational Tools and Technologies Project
    - **Exploration of Hydrogen-based Concepts**: $0.5M per year in FY2024 and FY2025
- Advanced Air Vehicles Program (AAVP)
  - Approximately $100k (internal labor) effort on H2 aircraft design exploration (AATT/SA&I)
  - AACES 2050 advanced concepts solicitation (currently in proposal evaluation phase)
    - Hydrogen-based research within scope, but not a requirement nor pre-determined selection – investment is TBD
- Integrated Aviation Systems Program (IASP) & Airspace Operations and Safety Program (AOSP)
  - None
- No specific investments in aeronautical facilities related to hydrogen at this time.
- NASA ARMD and DoE leadership have periodic engagement on collaboration and monitor future opportunities

A Sustained Presence on the Surface

A steady cadence of missions and a robust infrastructure on the lunar surface

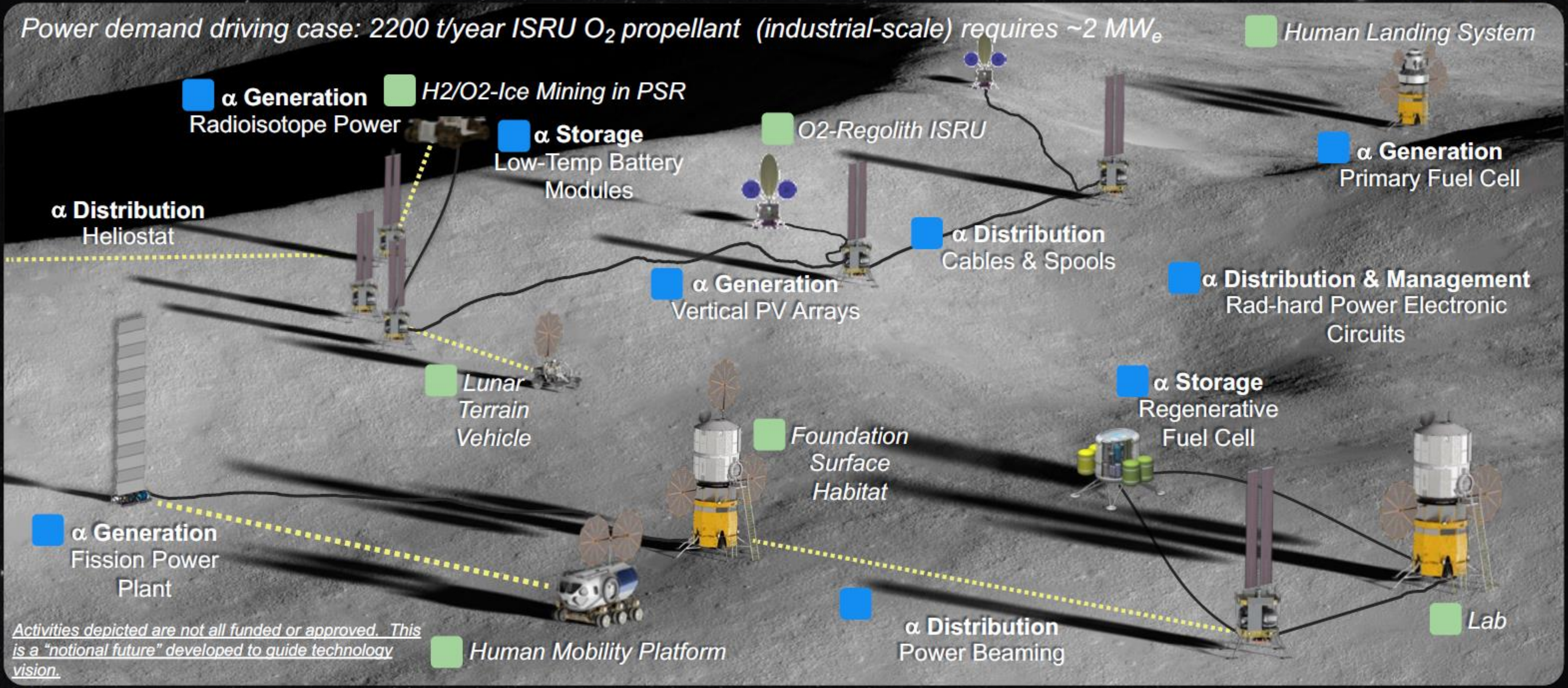
- An unpressurized rover provides extended exploration range and mobility for two suited crew on the lunar surface
- A pressurized rover expands exploration range
- A foundation surface habitat enables longer duration stays
- Supported with small logistics landers (e.g. CLPS)
- International partnerships
- Science, technology demonstrations, operational analogs for Mars missions



Power Architecture Building Blocks

Phase α South Pole Facilities: Handoff from Artemis Base Camp to Industry (~2030+)

- Power system
- Load



NASA TechPort

Website for the public to find:

- Latest Space Technology News
- Potential collaboration partners
- Funding opportunities / Solicitation announcements

https://techport.nasa.gov/dashboards

Questions?


Thank you for your attention.

Back-up

Integrated Zero-Emission Aviation using a Robust Hybrid Architecture (IZEA)

The project goals and broader impacts:

- Figure out how to use liquid hydrogen as fuel
  - Burning hydrogen to produce electricity has water vapor as exhaust.
  - Solving challenges related to safety, engineering, electrical, thermal, infrastructure, and societal acceptance helps aviation.
- Increase power and efficiency without increasing weight
  - Liquid hydrogen is very cold (cryogenic), which enables using superconductors to greatly increase power density.
  - Fuel cells and electric motors provide cruise thrust instead of heavy batteries and turbofans.
- Research tasks
  - Evaluate potential for global warming reduction across passenger aviation fleet
  - Use multi-disciplinary design, analysis and optimization approach to identify and model hydrogen-fueled aircraft for the fleet
  - Develop feasible power generation and energy conversion subsystem
  - Develop feasible power electronics, distribution and motor-driven propulsion subsystem
  - Develop thermal management system to optimize efficiency
- Unify all tasks with real demonstrations on a system testbed

IZEA Integrated Zero Emission Aviation

NASA

Grant Number: 80NSSC22M0068

Principal Investigator: Lance Cooley
Lead Organization: Florida State University (FSU)
Supporting Organizations:

- Advanced Magnet Lab, Inc. (AML)
- Florida Agricultural and Mechanical University (FAMU)
- Georgia Institute of Technology-Main Campus (GA Tech)
- Illinois Institute of Technology
- Raytheon Technologies Research Center
- SUNY Buffalo State
- The Boeing Company (Boeing)
- University of Kentucky

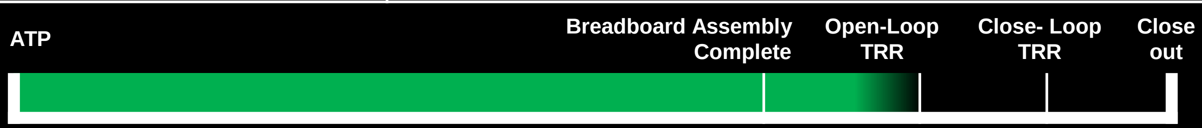
Funded by:
Aeronautics Research Mission Directorate (ARMD) Transformative Aeronautics Concepts Program (TACP) University Leadership Initiative (ULI, https://uli.arc.nasa.gov/)

Regenerative Fuel Cell Project

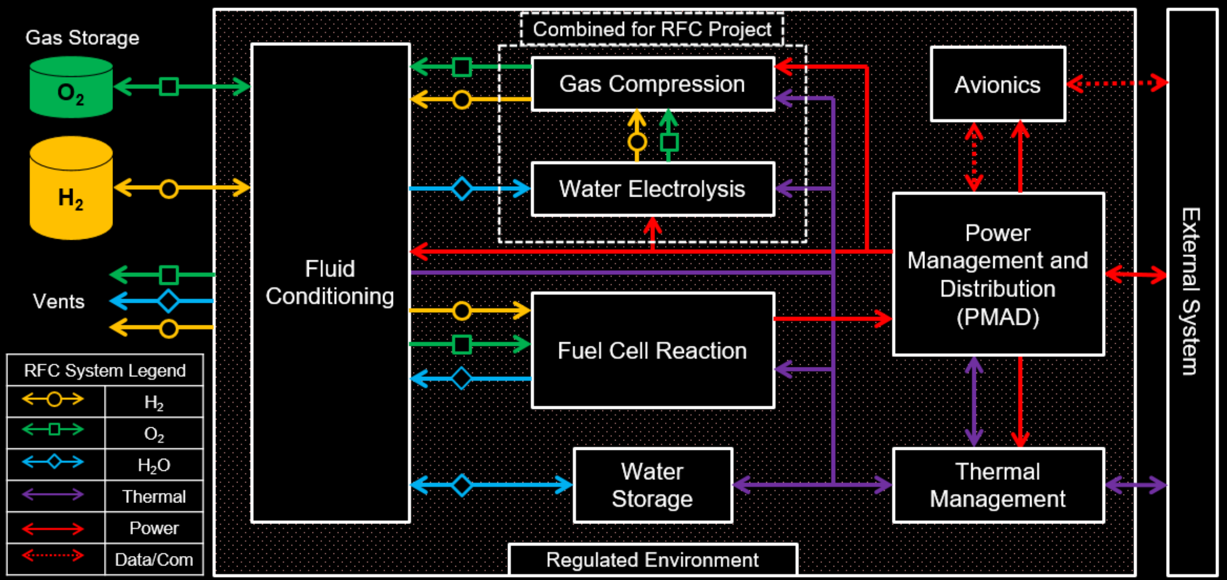
- Available energy storage technologies have low specific energies (W·hr/kg) imposing unacceptable mass onto lunar surface missions
- NASA funds research of multiple technologies to maximize specific energy, including hydrogen (H_2) / oxygen (O_2) regenerative fuel cell (RFC) energy storage technology
- RFC project to assess viability of optimized discrete *system* technology for potential inclusion into lunar surface missions

Regenerative Fuel Cell Project Overview

Design & Build H_2 / O_2 RFC System	• 50 psia Fuel Cell stack (Infinity Fuel Cell and Hydrogen) • 1800 to 2500 psia Electrolyzer (Giner) • Self-supporting sub-systems • Automated control system
≥ 2 month autonomous closed-loop test under laboratory conditions	• Full system pressures and multiple cycles • Open-loop operation for system functional verification • Closed-loop operation for reactant purity verification



Simplified RFC Functional Block Diagram



<u>Open Loop Testing</u>
- Component Verification Testing
- Breadboard System Assembly
- Breadboard System Verification
- Breadboard Open-loop Testing

<u>Closed Loop Testing</u>
- RFC Breadboard System Closed-loop Testing

Hydrogen Interagency Taskforce (HIT)

- NASA supporting all Working Groups and some Cross-cutting teams
- Proposed mechanism for improved inter-agency collaboration

WH and Deputies Group Co-Chairs → **Enable National Goals**

- 10 MMT/yr supply and end use by 2030
- 20 MMT/yr supply and end use by 2040
- 50 MMT/yr supply and end use by 2050

HIT Director (Deputy Director(s))

Secretariat — **Program Leadership Group**

Working Groups

Supply and Demand at Scale

- Enabling large scale production and demand creation
- Financing, incentives, and compliance tools for commercial scale up
- Metrics for deployment and USG as off-taker
- Supply chains and resiliency (critical materials, strategic reserve)
- R&D to accelerate cost reductions and end use commercialization (JST interface)

Infrastructure, Siting, Permitting

- Siting, permitting, pipelines, storage, and infrastructure
- Harmonized codes and standards
- Interoperability and global standardization
- Safety, emissions (including secondary), sensors, risk mitigation, environmental impact
- Environmental review and best practices (NEPA, etc.)
- Pipeline and blending test facilities

Analysis and Global Competitiveness

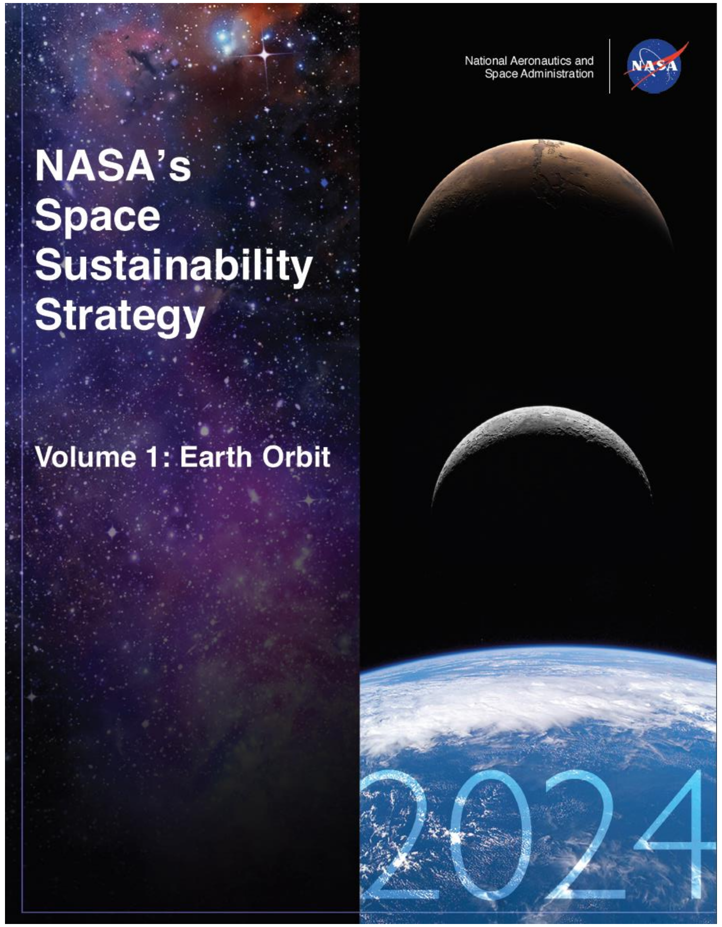
- National strategy and commercial liftoff analysis
- Impacts and gap assessments (technoeconomic analysis, incentives, resource/water availability, emissions, jobs, manufacturing, etc.)
- Intellectual property and global landscape assessment
- Export market analysis
- Systems integration and optimization

DOE JSC Tech Teams: Production, Delivery, Storage, Conversion, Applications H2 Hubs, Workforce, Equity, and Justice

Cross-cutting Teams

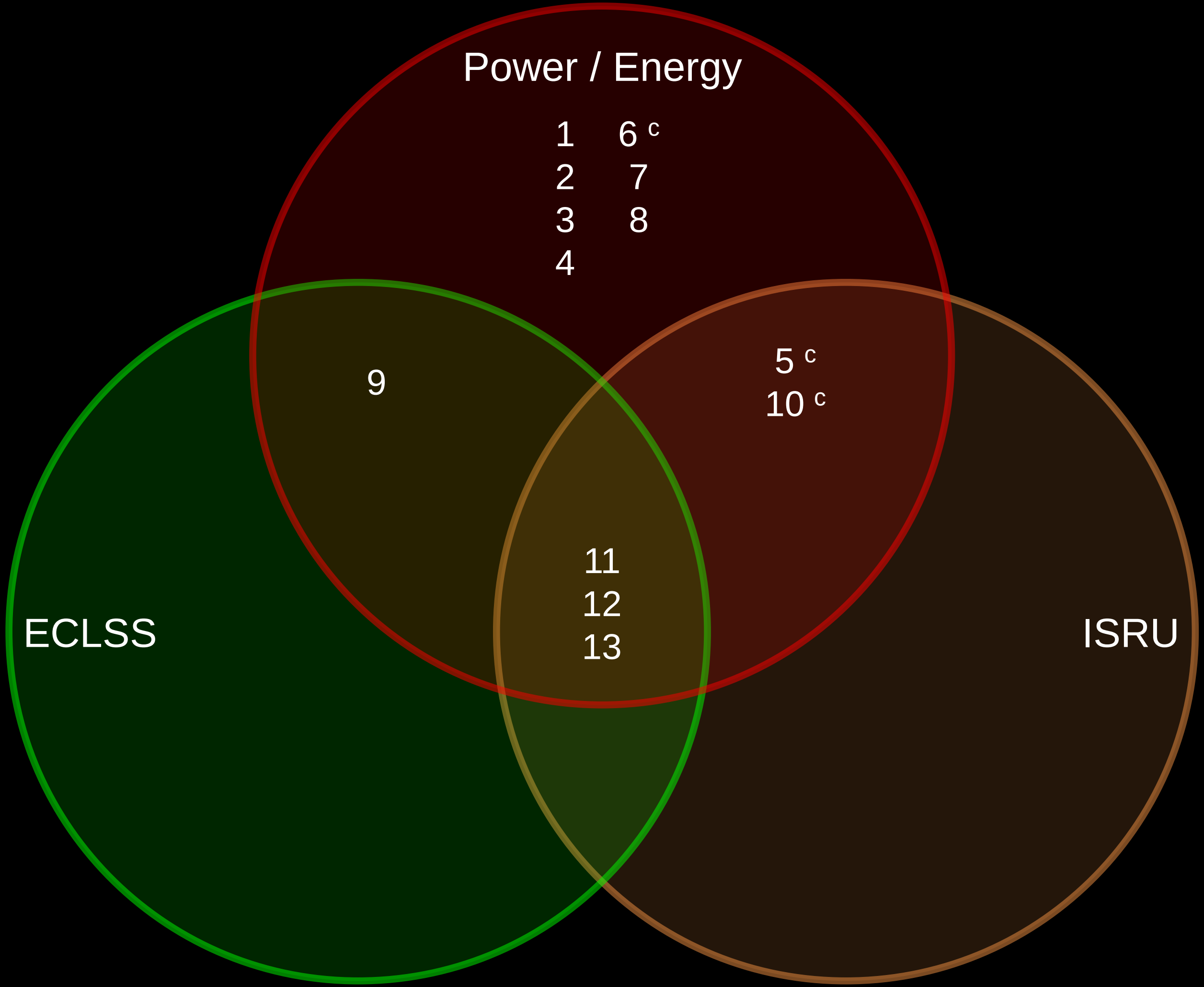
NASA's Space Sustainability Strategy

- NASA defines space sustainability as the ability to maintain the conduct of space activities indefinitely into the future in a manner that is safe, peaceful, and responsible to meet the needs of the present generations while preserving the outer space environment for future activities and limiting harm to terrestrial life.
- The Agency will increase its role as a global leader in space sustainability by fulfilling the following key responsibilities.
  - Provide science and technology leadership in the United States and the global space community on space sustainability topics.
  - Support equitable access to and use of space now and in the future.
  - Ensure that NASA's missions and operations—including those it undertakes with non-NASA entities—maintain or enhance space sustainability.



https://www.nasa.gov/wp-content/uploads/2024/04/nasa-space-sustainability-strategy-march-20-2024-tagged3.pdf?emrc=d1885c

Active FY24 Fuel Cell and Hydrogen Projects



	Tag	Activities [a]	Funding Source	Description
Power	1	CH_2RGE	ARMD	Electrification of single-aisle aircraft
Power	2	HEPS	TDM	Sub-orbital μg flight demonstration
Power	3	HLS Appendix P GTA	HLS	Primary fuel cells for lunar landers
Power	4	IZEA	ULI	Electrification of single-aisle aircraft
Power	5 [c]	MOWS / NITE	GCD	Combined Thermal/Power for lunar night
Power	6 [c]	PaCeSS	JSC (IRAD)	Passive fuel cell thermal management
Power	7	PropFC	GCD	SOFC power from LOX/CH_4 propellant
Power	8	WVU-NASA IV&V Fuel Cell	DOE	Facility SOFC CH&P demonstration
Electrolysis	9	AOGA	ESDMD	Next Gen. Crew O_2 supply system
Electrolysis	10 [c]	Co-electrolysis Methanation	GCD	Generate CH_4 & O_2 from ECLSS
Storage	11	BRACES	STMD	Lunar surface URFC energy storage
Storage	12	PR	EHP	Lunar surface mobility
Storage	13	RFC	GCD	Lunar surface RFC energy storage

Notes

a	Excludes SBIR activities
b	Excludes SME support for reviews / consulting
c	Scheduled to end in FY24

Legend

ECLSS = Environmental Control and Life Support Systems
ISRU = In Situ Resource Utilization (On-site Production)
PMAD = Power Management and Distribution

Terrestrial vs Aerospace Fuel Cell Systems

Aerospace

Differentiating Characteristics

- Pure Oxygen (stored, stoichiometric)
- Water Separation in reduced gravity

≠

Terrestrial

Differentiating Characteristics

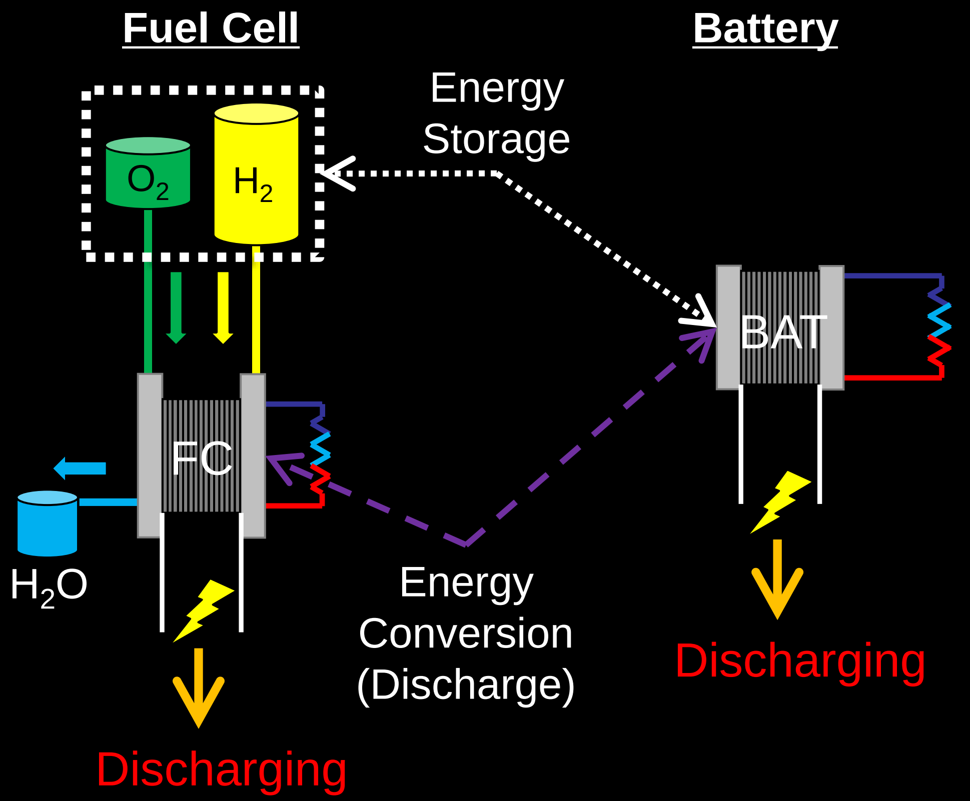
- Atmospheric Air (conditioned, excess flow)
- High air flow drives water removal

Fluid management issues make aerospace and terrestrial fuel cells functionally dissimilar

Fuel Cells vs Batteries

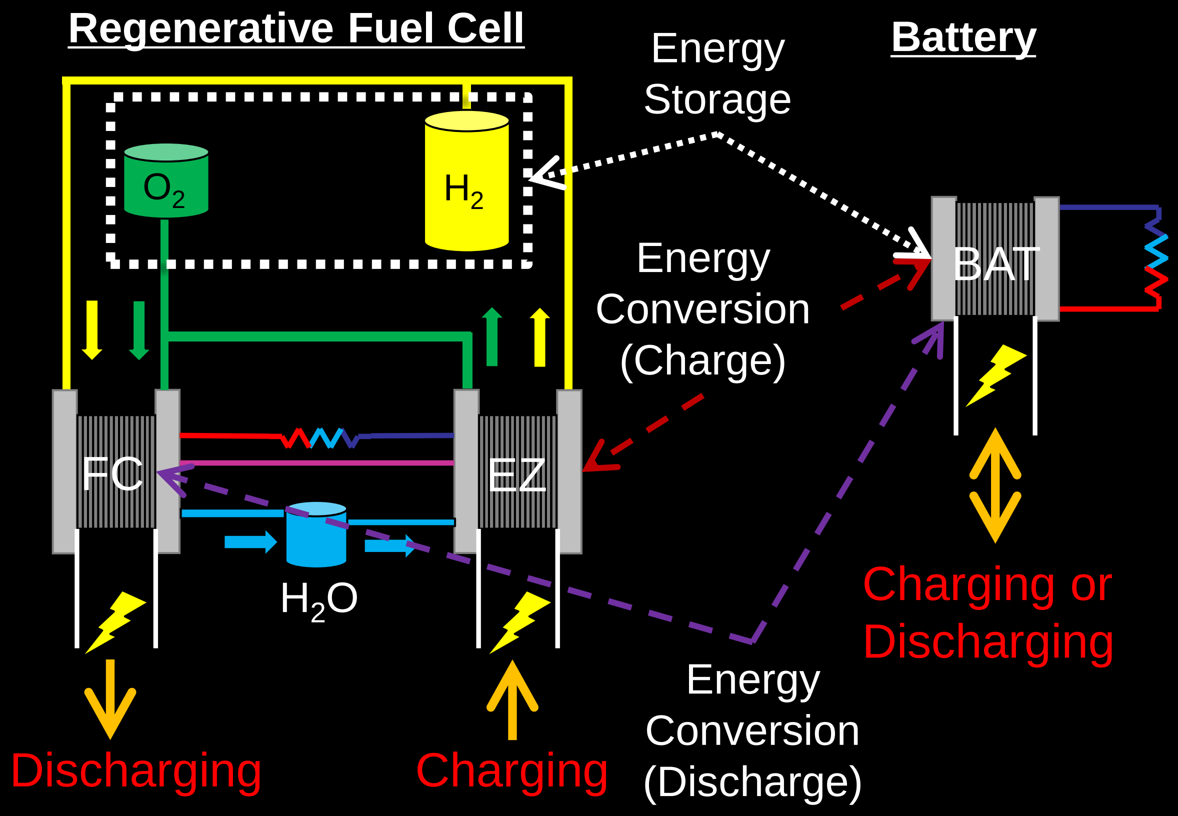
Primary Fuel Cell vs. Primary Battery

Discharge Power Only



RFC vs. Rechargeable Battery

Charge + Store + Discharge



Legend
BAT = Battery
EZ = Electrolyzer
FC = Fuel Cell Stack

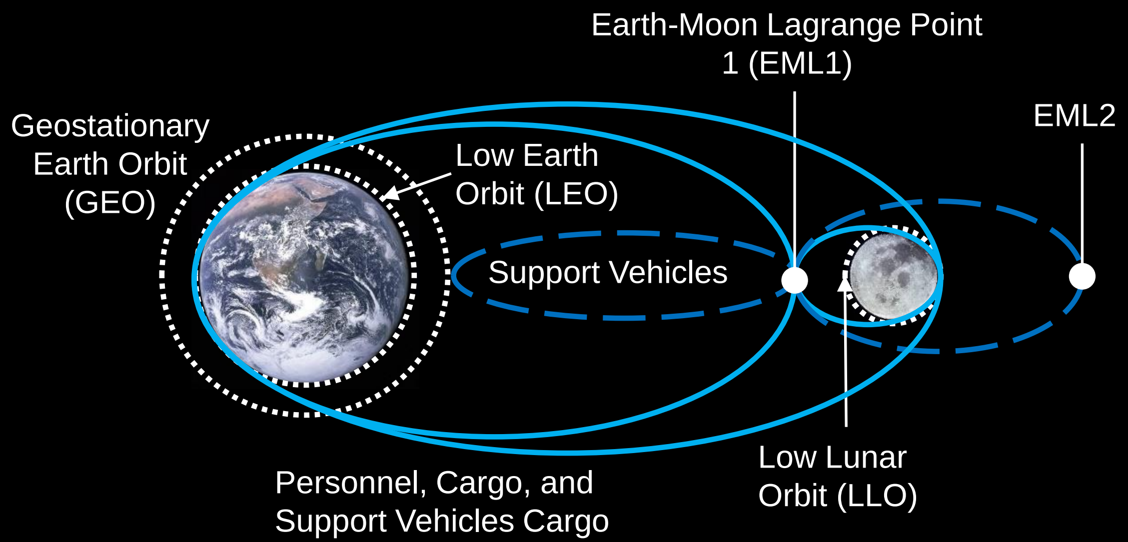
Fuel cells and Batteries ***Convert*** and ***Store*** Energy differently, resulting in:

- ***Different*** Safety Hazards
- ***Different*** Voltage response to State-of-Charge (SoC)
- ***Different*** Specific Power and Specific Energy

Making Propellants on Planetary Surfaces Saves on Launches and Cost (Gear Ratio Effect)

Every 1 kg of propellant made on the Moon or Mars saves 7.5 to 11.2 kg in LEO

- Enable exploration by staging required resources in forward locations
  - Earth Orbit (LEO, GEO)
  - LaGrange Points (EML1 and EML2)
  - Lunar Orbit
  - Lunar Surface
- Resources include propellant depots, propellant production facilities (initially H_2 and O_2), and consumable storage

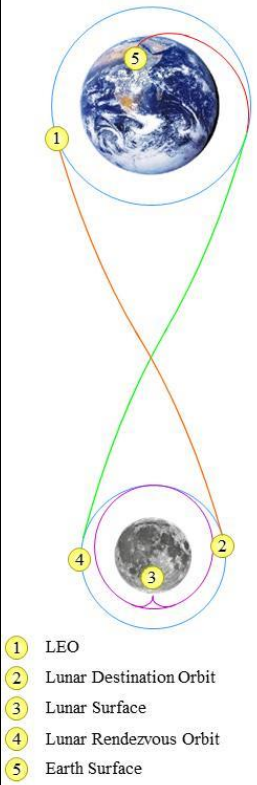


Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

- Savings depend on in-space transportation approach and assumptions; previous Mars gear ratio calculations showed only a 7.5 kg saving
- 25,000 kg mass savings from propellant production on Mars for ascent = 187,500 to 282,500 kg launched into LEO

Moon Lander: Surface to NRHO

- Crew Ascent Stage (1 way): 3 to 6 mT O_2
- Single Stage (both ways): 40 to 50 mT O_2/H_2



A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

In-situ Resource Utilization (ISRU)

Modular Power Functions/ Elements

- Power Generation
- Power Distribution
- Energy Storage (O_2 & H_2)

Support Functions /Elements

- ISRU
- Life Support & EVA
- O_2, H_2, and CH_4 Storage and Transfer

Shared Hardware to Reduce Mass & Cost

- Solar arrays/nuclear reactor
- Water Electrolysis
- Reactant Storage
- Cryogenic Storage
- Mobility