CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY
An Initiative of the Clean Energy Ministerial

Hydrogen 101

Hydrogen and Analytical Tools Webinar Series

February 7, 2024

Housekeeping - Zoom

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- We will be launching a **survey** when the event ends. Your feedback is highly valuable to us!

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Introduction to Hydrogen and Analytical Tools Workshop Series

Presented by Daniella Rough, National Renewable Energy Laboratory

Overview of Workshop Series

Title	Description	Proposed Date
#1: Hydrogen 101	- Hydrogen Considerations Tree - US National Hydrogen Strategy and Roadmap - Key considerations and tools used for hydrogen market analysis	7 February
#2: Hydrogen to Support Climate Targets	- Potential for hydrogen, and its derivatives to decarbonize domestic, commercial, and hard-to-decarbonize sectors. - Overview of the "Greenhouse gases, regulated emissions, and energy use in technologies" (**GREET**) Model	21 February
#3: Technical Considerations	- Technical considerations and challenges of hydrogen production, storage, and transport - Application of the Hydrogen Analysis Production (**H2A**) tool: Transparent cost analysis methodology for hydrogen production at centralized and distributed facilities	March
#4: Hydrogen Markets	- Techno-economic considerations for near- and long-term hydrogen (+ derivatives) markets - Example analysis and tools for demand projections	March
#5: International Hydrogen Landscapes	- Policy and regulatory enabling conditions (e.g. standards, certifications, incentives) to support hydrogen markets - Environmental, social, health and safety considerations - Life cycle analysis for certification and compliance purposes (**GREET**)	April
#6: Analytical Tools	- Analytic tools and datasets to support hydrogen analysis (regional, technical, economic, social), and decision-making - Overview and application of the Revenue, Operation, and Device Optimization (**RODeO**) tool: Explores optimal system design and operation - Overview and application of the Scenario Evaluation and Regionalization Analysis (**SERA**) tool: Provides insights that can guide hydrogen infrastructure development and transportation investment decisions (city to national levels).	April
#7: Applying Knowledge	- Integrated exercises to apply acquired knowledge into country-specific structure, roadmap, and prioritization framework - Summary of key takeaways from training program and next steps - Application of the Hydrogen Financial Analysis Scenario Tool (**H2FAST**) tool: Provides a quick and convenient in-depth financial analysis for hydrogen projects	May

Webinar Speakers

Aaron Ng
International Relations Specialist

U.S. Department of Energy

Campbell Howe
Senior Strategy Consultant

U.S. Department of Energy

Daniella Rough
International Program Manager

National Renewable Energy Laboratory

Misho Penev
Senior Analyst

National Renewable Energy Laboratory

Neha Rustagi
Program Manager

U.S. Department of Energy

Omar Guerra Fernández
Research Engineer

National Renewable Energy Laboratory

Today's Agenda

Speaker	Topic	Duration
Daniella Rough	Introduction to Hydrogen and Analytical Tools Workshop Series	5 minutes
Aaron Ng	Introduction to the Clean Energy Solutions Center	3 mins
Daniella Rough & Omar Guerra	Introduction to the Hydrogen Considerations Tree, developed through the USAID-NREL Partnership	25 mins
Neha Rustagi	U.S. National Hydrogen Strategy and Roadmap	20 mins
Campbell Howe	Takeaways from Report "Pathways to Commercial Liftoff - Clean Hydrogen"	20 mins
Misho Penev	Overview of DOE Laboratory Tools for Hydrogen Supply Chain Analysis	30 mins
Wrap-up, final questions, and next steps		Remaining time

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Overview of the Clean Energy Solutions Center

Presented by Aaron Ng, U.S. Department of Energy

The Clean Energy Solutions Center

CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY

CLEAN ENERGY MINISTERIAL
Advancing Clean Energy Together

OBJECTIVE

To accelerate the transition of clean energy markets and technologies.

RATIONALE

Many developing governments lack capacity to design and adopt policies and programs that support the deployment of clean energy technologies.

AMBITION/TARGET

Support governments in developing nations of the world in strengthening clean energy policies and finance measures

ACTORS

Leads:

Operating Agent:

NREL
Transforming ENERGY

Partners:

More than 40 partners, including UN-Energy, IRENA, IEA, IPEEC, REEEP, REN21, SE4All, IADB, ADB, AfDB, and other workstreams etc.

ACTIONS

- **Deliver** dynamic services that enable *expert assistance, learning, and peer-to-peer sharing of experiences. Services are offered at no-cost to users.*
- **Foster** dialogue on emerging policy issues and innovation across the globe.
- **Serve** as a first-stop clearinghouse of clean energy policy resources, including policy best practices, data, and analysis tools.

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UPDATES

Website:
www.cleanenergyministerial.org/initiatives-campaigns/clean-energy-solutions-center

Factsheet:
www.nrel.gov/docs/fy22osti/83658.pdf

Requests: Now accepting Ask an Expert requests!

The Clean Energy Solutions Center

CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY

CLEAN ENERGY MINISTERIAL
Advancing Clean Energy Together

Ask an Expert Service

- Ask an Expert is designed to help policymakers in developing countries and emerging economies identify and implement ***clean energy policy*** and finance solutions.
- The Ask an Expert service features a network of more than **50** experts from over **15** countries.
- Responded to **300+** requests submitted by **90+** governments and regional organizations from developing nations since inception

Training and Capacity Building

- Delivered over **300** webinars training more than **20,000** public & private sector stakeholders.

Resource Library

- Over **1,500** curated reports, policy briefs, journal articles, etc.

For additional information and questions, reach out to Jal Desai, NREL, jal.desai@nrel.gov

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Navigating Key Considerations for Developing a Clean Hydrogen Landscape

7 February 2024

Guiding Sustainable Hydrogen Integration: USAID-NREL Partnership's Capacity-Building Approach

- **Background:** Growing need from Missions and country partners to respond to requests related to hydrogen, and key considerations in costs, benefits and tradeoffs when making strategy, policy and investment decisions.
- **Objective:** Build understanding and capacity of USAID Missions and country partners to make informed decisions, as they look to potentially support hydrogen and its derivatives.
- **Format:** Key topics are organized into a "considerations tree" to help stakeholders think through technical, regulatory, economic, environmental, social, and analytical questions.

1. End-Use Application Considerations
   - Energy Generation
   - Industrial and Chemical
   - Transport and Agriculture
2. Production and energy source Considerations
   - Electrolysis Technological Advancements
   - Feedstock
   - Energy Sources: Renewable, Nuclear, Fossil
3. Infrastructure Considerations
   - Production and Conversion
   - Storage and Distribution
   - Clusters or hubs
4. Costs and Economic Viability Considerations
   - Capital Expenditure/ Operating expenditure Viability
   - Markets
   - Technology Availability
5. Environmental Considerations
   - Greenhouse Gases & Life Cycle Assessments
   - Local/Regional/ Country-Level Environmental Impacts
   - Resource competition
6. Social Considerations
   - Stakeholder Engagement
   - Workforce Opportunities
   - Health and Safety
7. Policy and Regulatory Considerations
   - Policy and regulatory framework
   - Incentives and Enabling Conditions
   - Standards and Certifications
8. Considerations Tree Exercises
   - Case Study: Large-scale wind powered hydrogen & ammonia project
   - SWOT Analysis (Strengths, Weaknesses, Opportunities, Threats)

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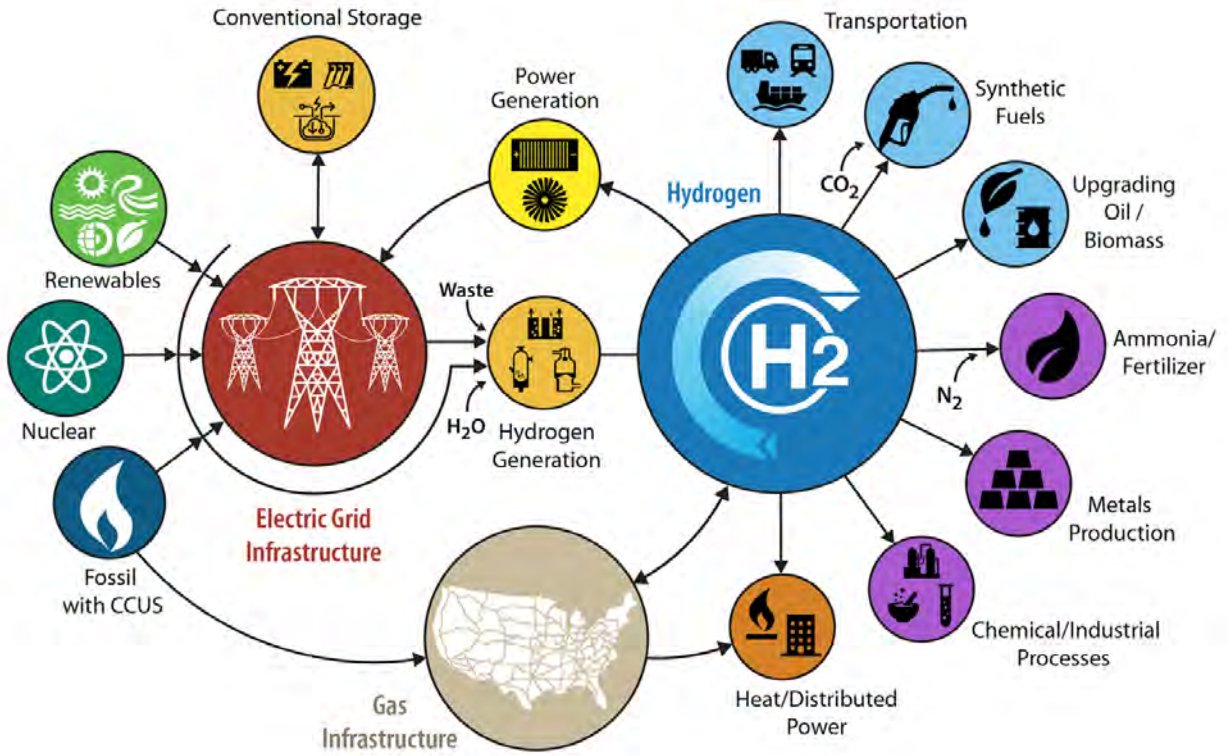
Hydrogen is a versatile energy carrier.

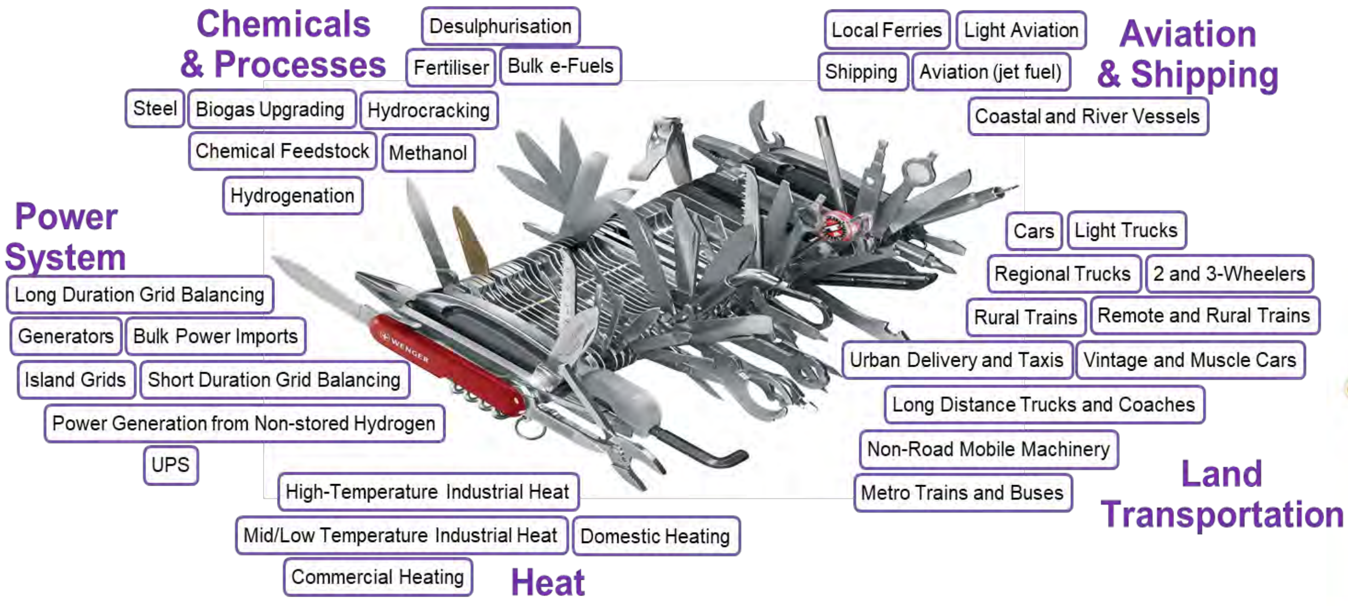
- Hydrogen can be produced via **electrolysis** using electricity from renewable energy (e.g. wind and solar), hydropower, or nuclear energy, it can be found naturally in **geologic reserves**, produced from **gasification** of biomass, or other more conventional production pathways (e.g. **steam methane reformation** from natural gas)
- Electrolysis of water using 100% renewable energy produces **zero direct carbon emissions**
- Hydrogen can be used in different sectors of the economy. For example, the transport sector, **refineries**, **fertilizer** production, **chemical** production, **steel**, **cement kilns**, and other industrial applications



Source: DOE Hydrogen and Fuel Cell Technologies Office. H2@Scale. https://www.energy.gov/eere/fuelcells/h2scale.

Hydrogen – Climate's Swiss Army Knife?

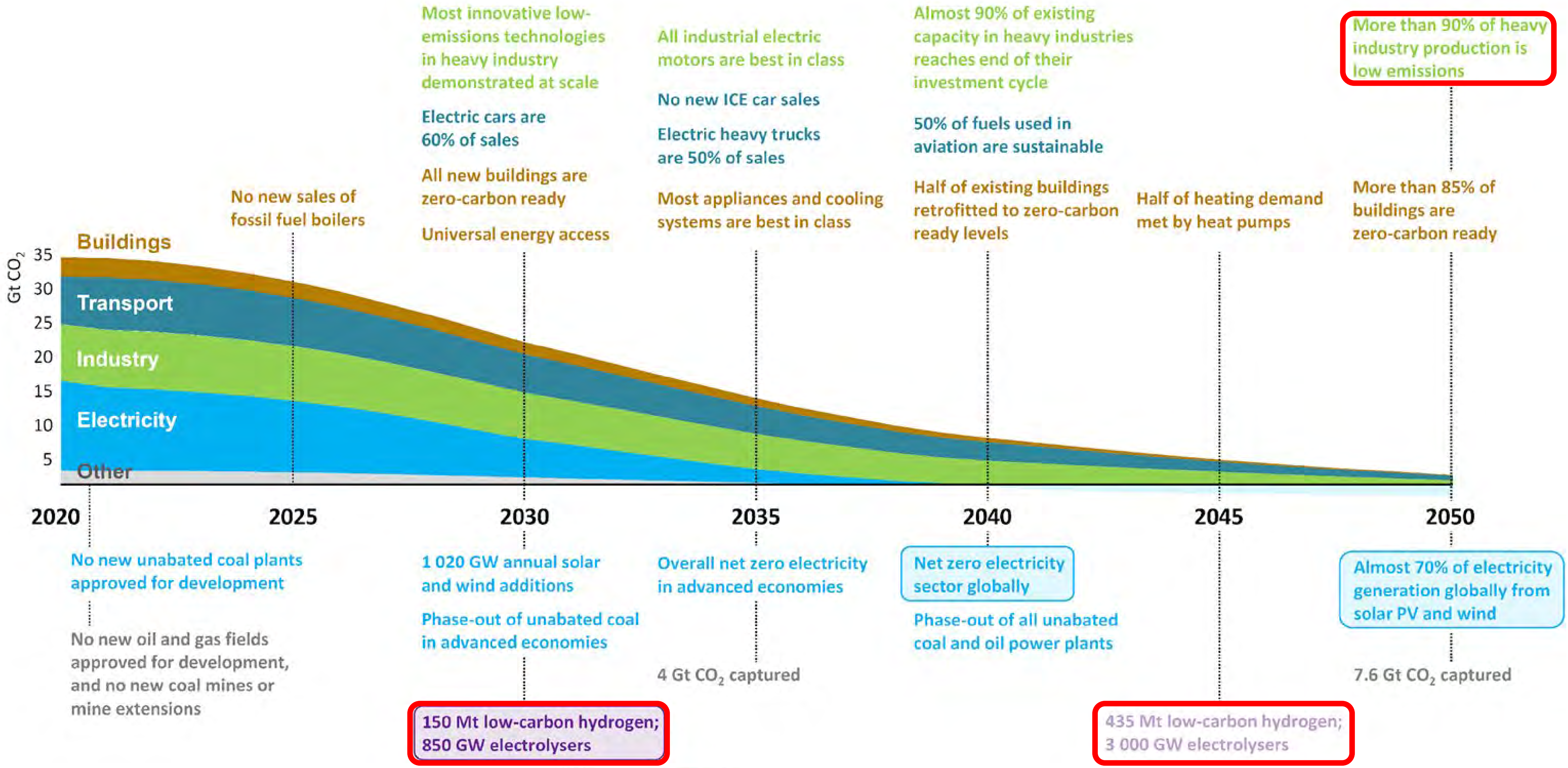
You can do almost anything with a Swiss Army Knife…



Source: Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 5.0, 2023.Concept credit: Adrian Hiel, Energy Cities. Image: Wenger (concept credit: Paul Martin). *CC-BY 4.0*

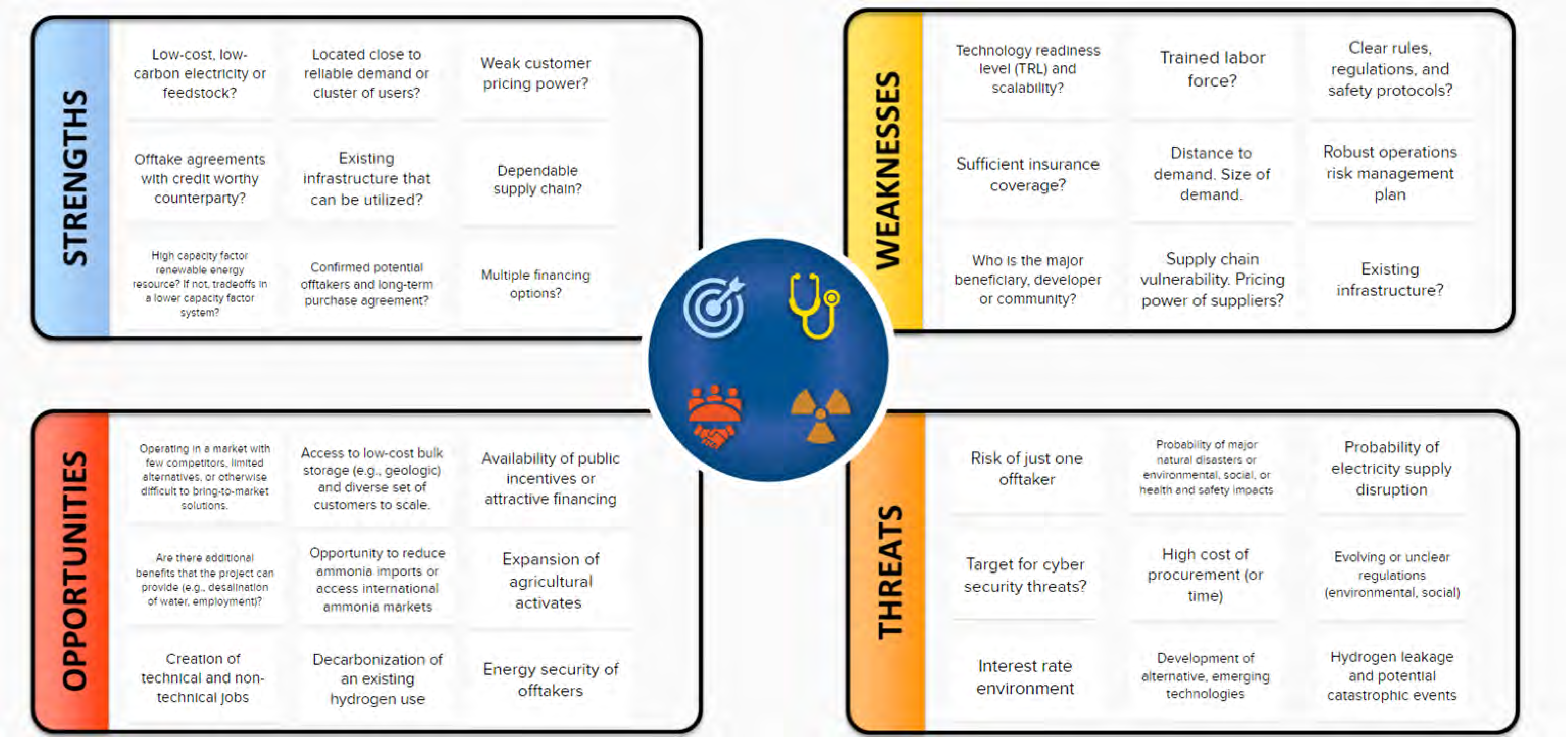
But would you build your house with one?

The Path Toward a Net-Zero Emissions Energy Sector by 2050



Ref: https://unfccc.int/sites/default/files/resource/NZE2050_Worsdorfer_IEA.pdf

SWOT Analysis - Guiding Questions



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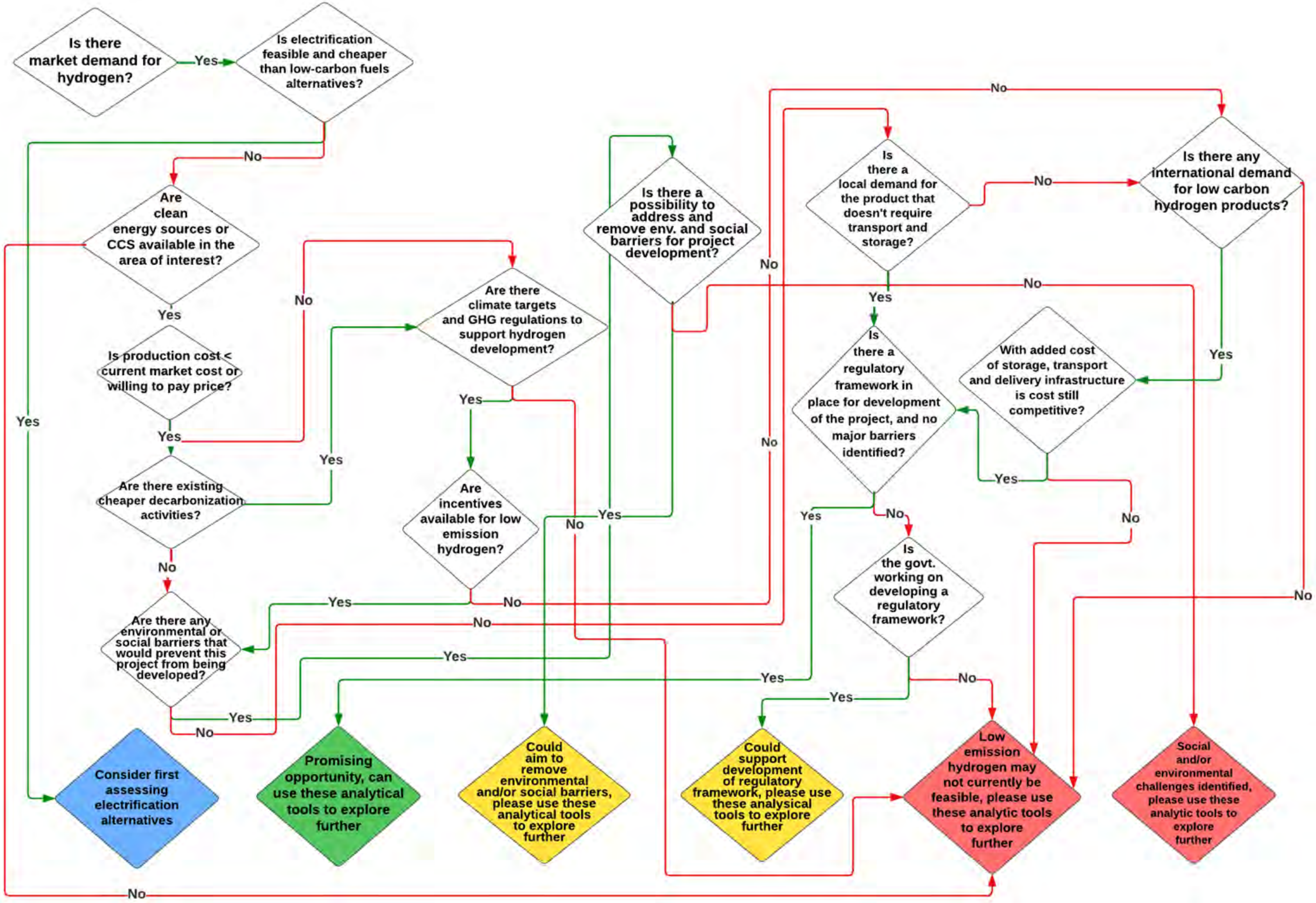
Navigating Hydrogen Considerations Tree Flow Chart for Potential Projects

Start Here:



Note: This flow chart is intended to provide a very high-level overview of considerations and questions, to be used for qualitative discussion purposes.

It should not be used to make investment decisions.

Promising Opportunity to Explore Further

Start here

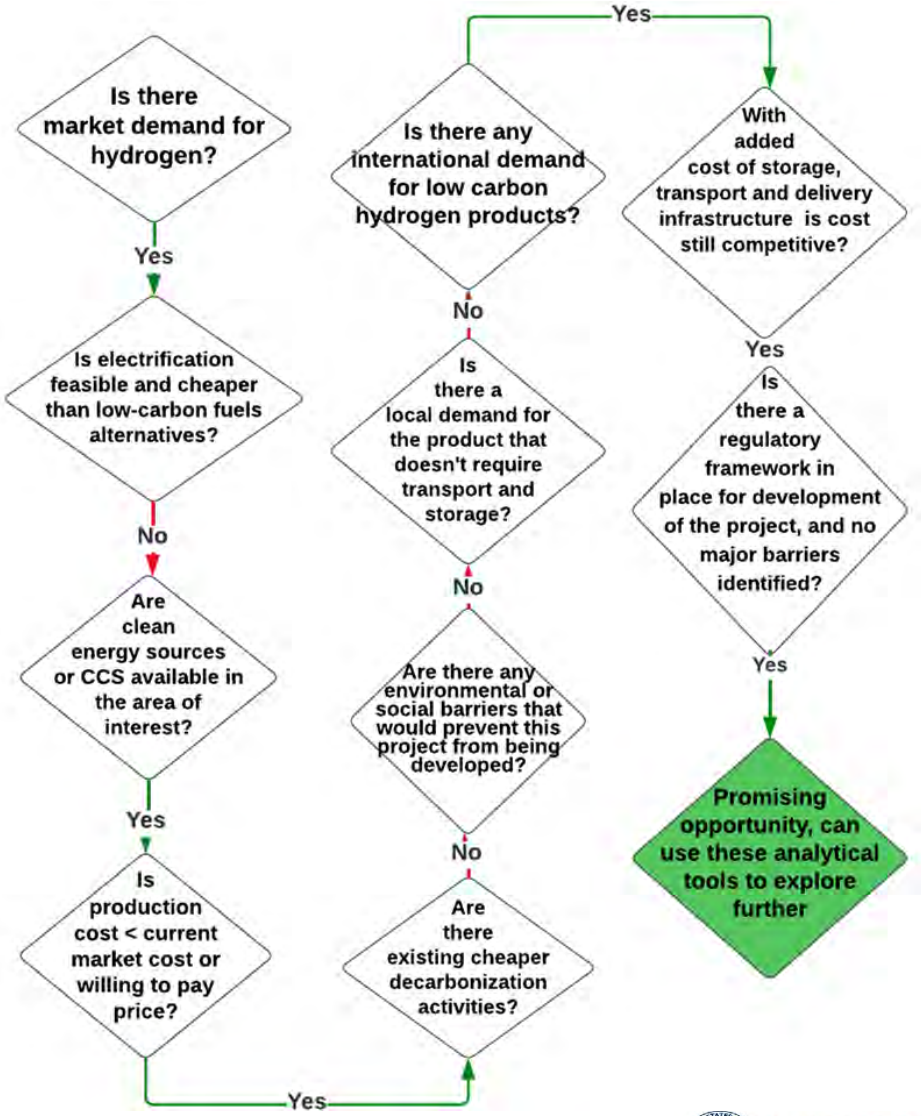


Image from Getty Images 1395775131

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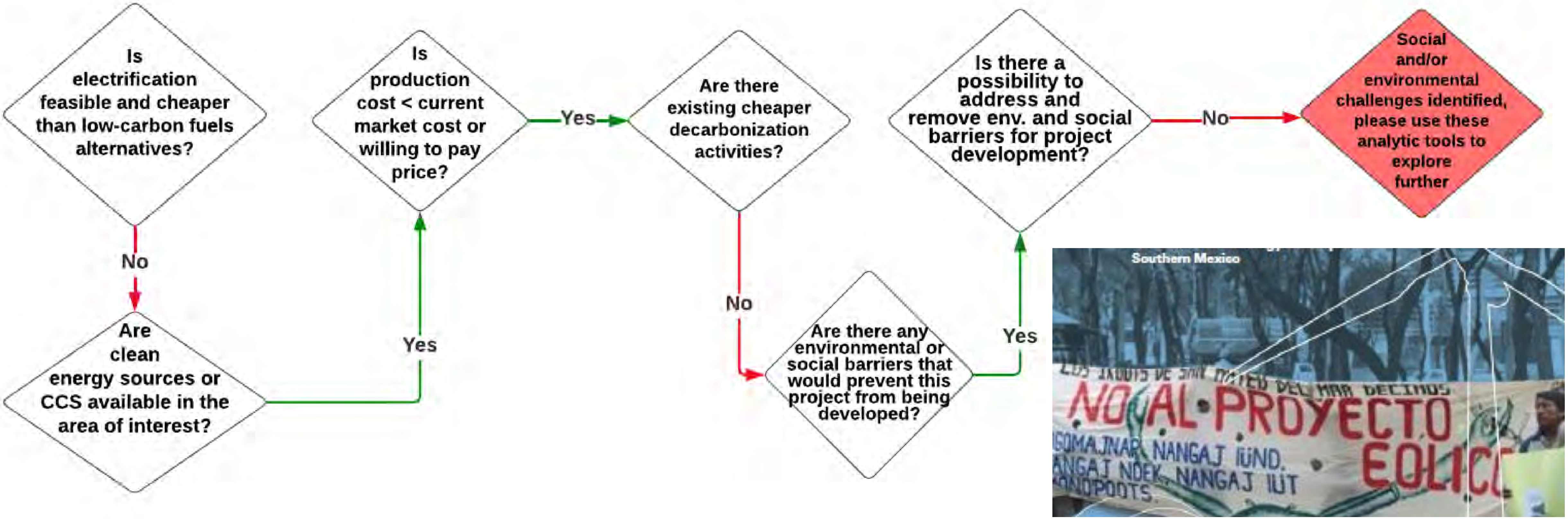
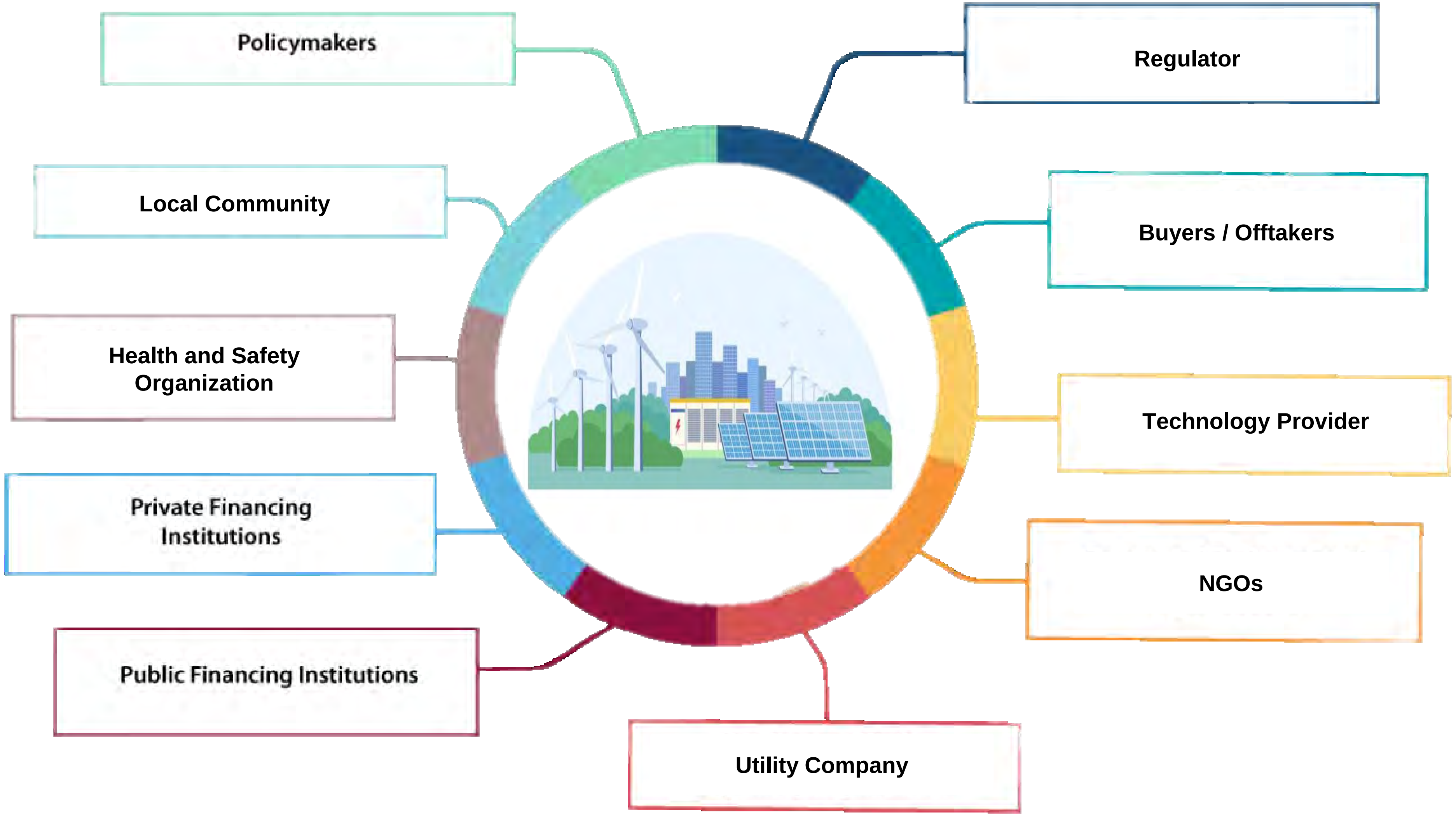
Significant Barrier(s) Identified

Start here



Integrating Diverse Stakeholders



Hydrogen decision-making requires review of social considerations.

- **Land use and access:**
  - Land ownership models (leasing versus purchasing)?
- **Stakeholder engagement**
  - What is the local perception of the project?
  - Have local workforce opportunities been identified and supported?
  - Value chain & supply chain risks?
- **Water usage:**
  - Is there water competition with agriculture, human consumption, or productive uses?
  - Does the project contribute to fresh water supply with a desalinization plant?
- **Human health and safety:**
  - Have human safety risks been mitigated?
- **Regulatory framework for successful stakeholder engagement:**
  - Existing regulations for stakeholder engagement?

Source: United Nations Sustainable Development Goals. https://sdgs.un.org/goals

Image from Getty Images 1314214863

Hydrogen decision-making requires review of environmental considerations.

- **Land Use and Access:**
  - Land availability for infrastructure?
  - Resource utilization and land disruption?
- **Water Usage:**
  - Water requirements for hydrogen production considered?
  - Potential impacts on ecosystems and local communities?
- **Waste:**
  - Is there a waste disposal plan in place?
  - How is brine and other discharge being managed?
- **Sustainability:**
  - Are renewable energy resources being utilized where possible?
- **Carbon Emissions and LCA:**
  - Calculated reductions in carbon emissions and air pollutants?
  - 3rd party verification (e.g., LCA and CCUS)?
  - Potential for leakage (GWP of hydrogen >10 x CO_2)?

Photo from Getty Images 508752705

Hydrogen decision-making requires a thorough review of end-use applications and considerations.

- **Analysis of alternatives:**
  - Hydrogen or e-fuels, versus electrification, biofuels, or other alternative?
- **Transport:**
  - Heavy or long-distance transport fleets?
  - Decarbonizing shipping, aviation, or other specialty and hard-to-abate sectors?
- **Industrial:**
  - Industrial clusters nearby?
  - Are there premiums or incentives? (e.g. for green steel or concrete)
- **Chemical industry:**
  - Proximity to an ammonia market or port?
- **Agriculture:**
  - Proximity to agricultural regions or clusters?
- **Need for storage:**
  - High variable renewable energy (VRE) targets?
  - High seasonal variability of renewable energy resources?

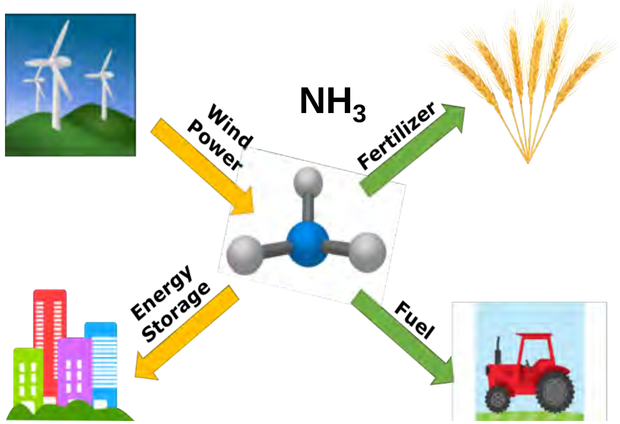
Image from Getty Images 465393520

Green ammonia offers near-term opportunities for the deployment of clean hydrogen.

- **Key opportunity:**
  - High energy intensity and hydrogen content
  - Liquefaction at near room temperature (20^{o}C at 7.5 bar)
  - Already produced large-scale and traded globally
  - Near-term domestic market and existing infrastructure
  - Energy security, especially where ammonia is imported
  - Can be used directly in some applications (e.g. fertilizers, power generation, maritime fuel)
  - High economic opportunity for domestic use versus export

- **Co-located systems – multiple benefits:**
  - Desalination plant
  - Renewable energy generation
  - Hydrogen production
  - Ammonia production

- **Key considerations:**
  - Low TRL of dynamic operation and cracking (NH_3 as energy carrier)
  - Not yet competitive with conventional sources
  - Toxic and corrosive gas



Source: UMN, Michael Reese and Jennifer King (NREL)

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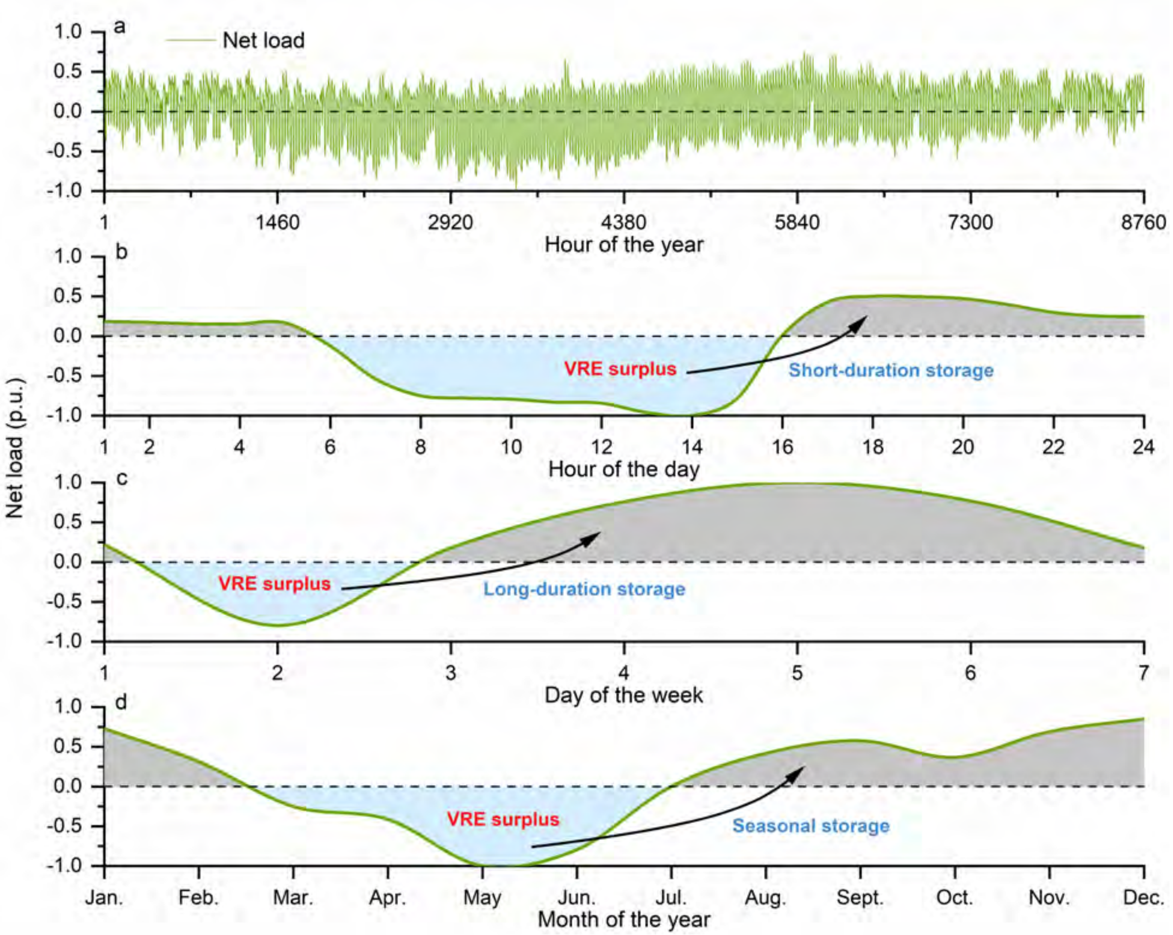
Seasonal energy storage for the power sector is a potential future application for clean hydrogen, especially with high integration of variable renewable energy.

Multi-scale energy storage needs for 95% carbon-free CAISO power system
(28.4% wind and 51.5% solar PV energy share)



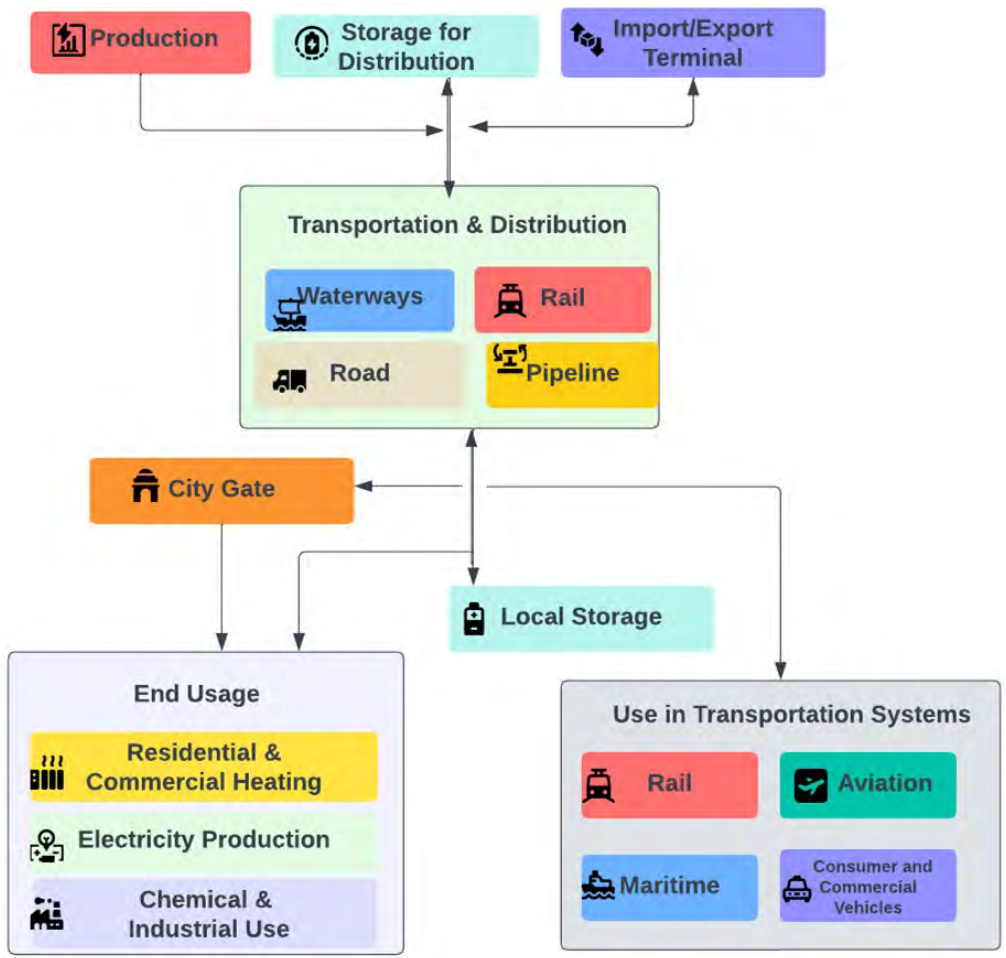
Definitions:

- **Net load**: electricity demand minus variable renewable energy (VRE), e.g., wind plus solar PV power.
- **Short-duration storage**: up to 10 hours of discharge duration at rated power before the energy capacity is depleted (typically lithium-ion batteries)
- **Long-duration energy storage**: discharge duration >10 hours and <100 hours (e.g. compressed air energy storage (CAES), pumped hydro storage (PHS), flow batteries)
- **Seasonal energy storage**: discharge duration >100 hours (e.g. hydrogen, methanol, etc.)

Ref : Guerra, O. J. Beyond short-duration energy storage. Nature Energy 6, 460–461 (2021).

Hydrogen decision-making requires review of policy and regulatory considerations.

- **Policy landscape and regulatory frameworks:**
  - Regulatory framework for production, storage, transportation?
  - Emissions reduction targets that can drive greater adoption?
- **Incentives and Support Programs:**
  - Government incentives or subsidies available for hydrogen?
  - Carbon market or pricing mechanisms available?
- **Regulations:**
  - Safety standards developed?
  - National and/or international certification schemes?
- **Safety and Handling:**
  - Safety protocols and programs for handling, storing, distribution and operation of hydrogen and its derivatives?
- **International Collaboration:**
  - International cooperation supporting the project(s)?
  - Established standardization to enable cross-border trade?



Source: Baird, Austin R., Brian D. Ehrhart, Austin M. Glover, and Chris B. Lafleur. 2021. *Federal Oversight of Hydrogen Systems.* SAND2021-2955. Albuquerque, NM: Sandia National Laboratory. https://energy.sandia.gov/wp-content/uploads/2021/03/H2-Regulatory-Map-Report_SAND2021-2955.pdf.

Hydrogen decision-making requires review of costs and economic viability considerations.

- **Capital Costs:**
  - Costs of infrastructure, land, new hydrogen production facilities?
  - High interest rates or costs of capital?
- **Operational Costs:**
  - Costs of energy, maintenance, water, land, insurance?
- **Economic viability:**
  - Available financing options?
  - Attractive revenue streams?
  - Investment and tax incentives available?
- **Market Demand:**
  - Existing market?
  - Domestic demand versus international export?
- **Market dynamics:**
  - Changing regulatory or certification requirements?
  - Reliable pricing projections for products?
  - Supply chain risks?

Hydrogen markets require reliable energy sources and technology readiness.

- **Energy Source:**
  - High local availability and quality of renewable energy?
  - Competitive costs of power generation ($/MWh)?
  - Climate change risk? (e.g., hydropower)
  - Risk of stranded assets?
- **Feedstock sustainability and supply chain risks:**
  - Sustainable supply of water?
  - Sustainable source of CO_2 for e-fuels?
  - Supply chain limitations, e.g. critical minerals and platinum for PEM electrolyzers?
  - Carbon capture and storage potential for “blue hydrogen”
- **Technological Advancements:**
  - Recent advances in production technologies?
  - High / low technology readiness level (TRL)?
  - Efficiency of production technologies and catalysts?

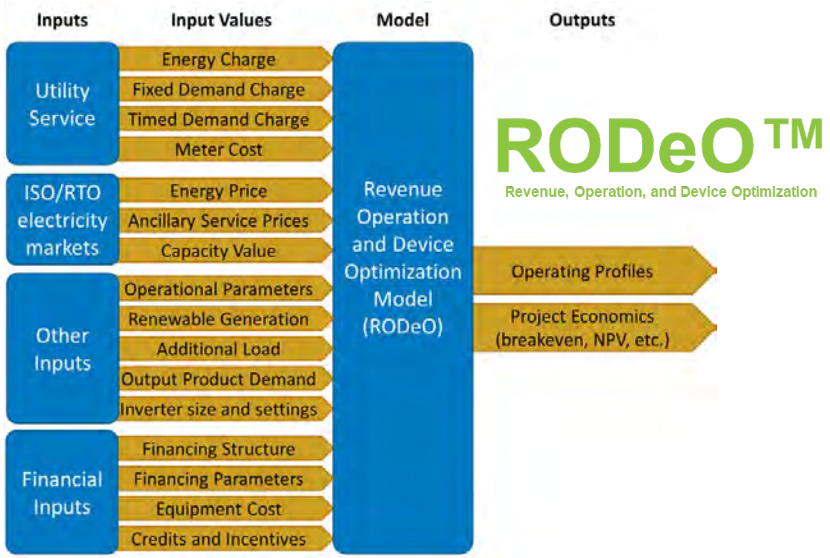


Image from Getty Images 1395775131

Hydrogen decision-making requires a thorough review of infrastructure considerations.

- **Hydrogen/Derivative Production**
  - Available infrastructure for renewable energy electricity generation?
  - Co-located infrastructure (e.g. desalination plant)?

- **Storage:**
  - Storage opportunities in the area (e.g. underground)?

- **Transportation and Distribution:**
  - Material adequacy of existing pipelines for natural gas blending?
  - Refueling stations, transportation corridors?

- **End-use:**
  - Proximity to clusters or potential hubs?
  - Industrial/chemical sectors, ports, trucking operations, mining nearby?
  - Potential for retrofitting existing production facilities (e.g. ammonia, steel)?

SERA

Photo by Dennis Schroeder, NREL 40080

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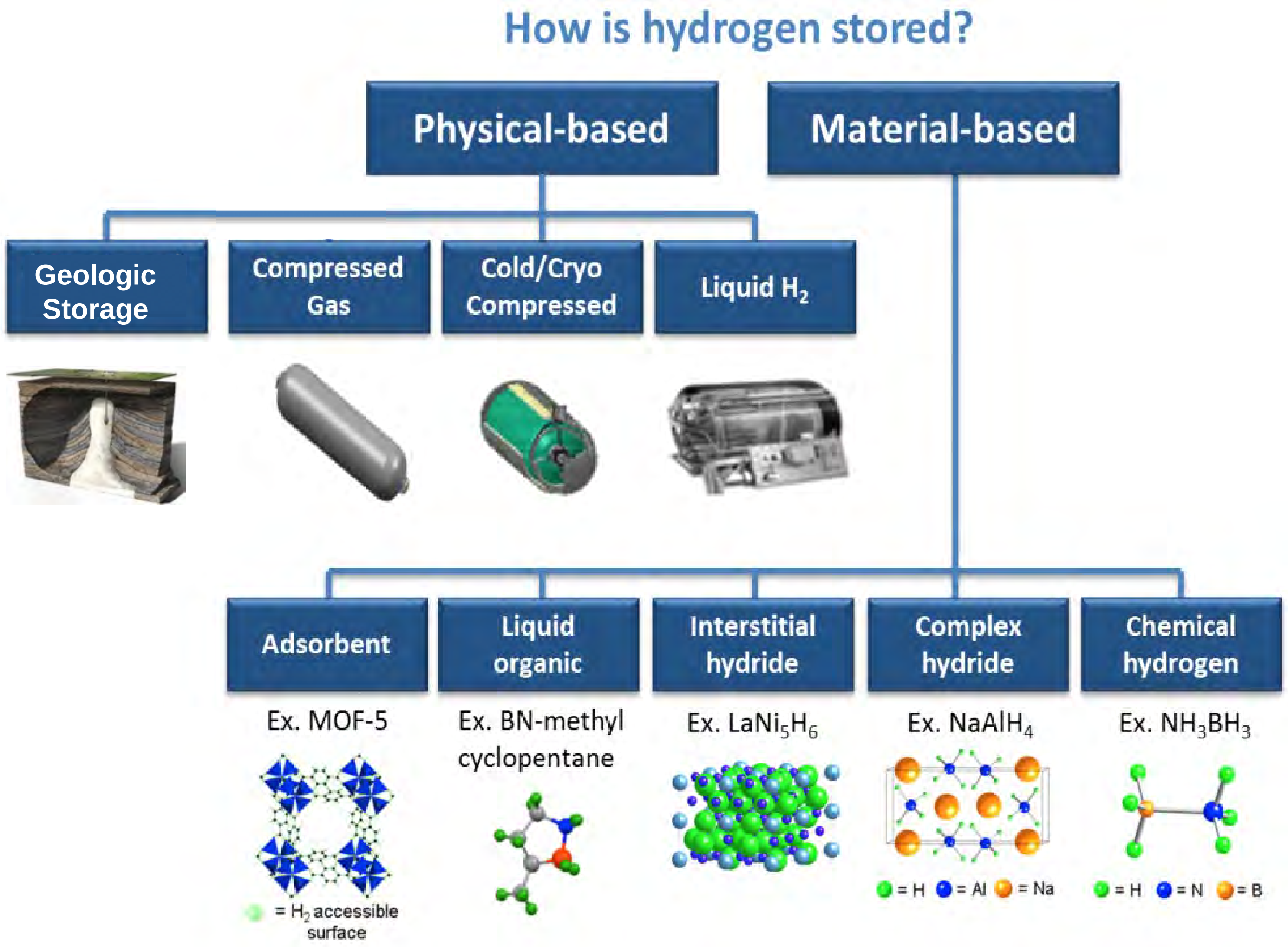
There are various options for hydrogen storage and conversion.



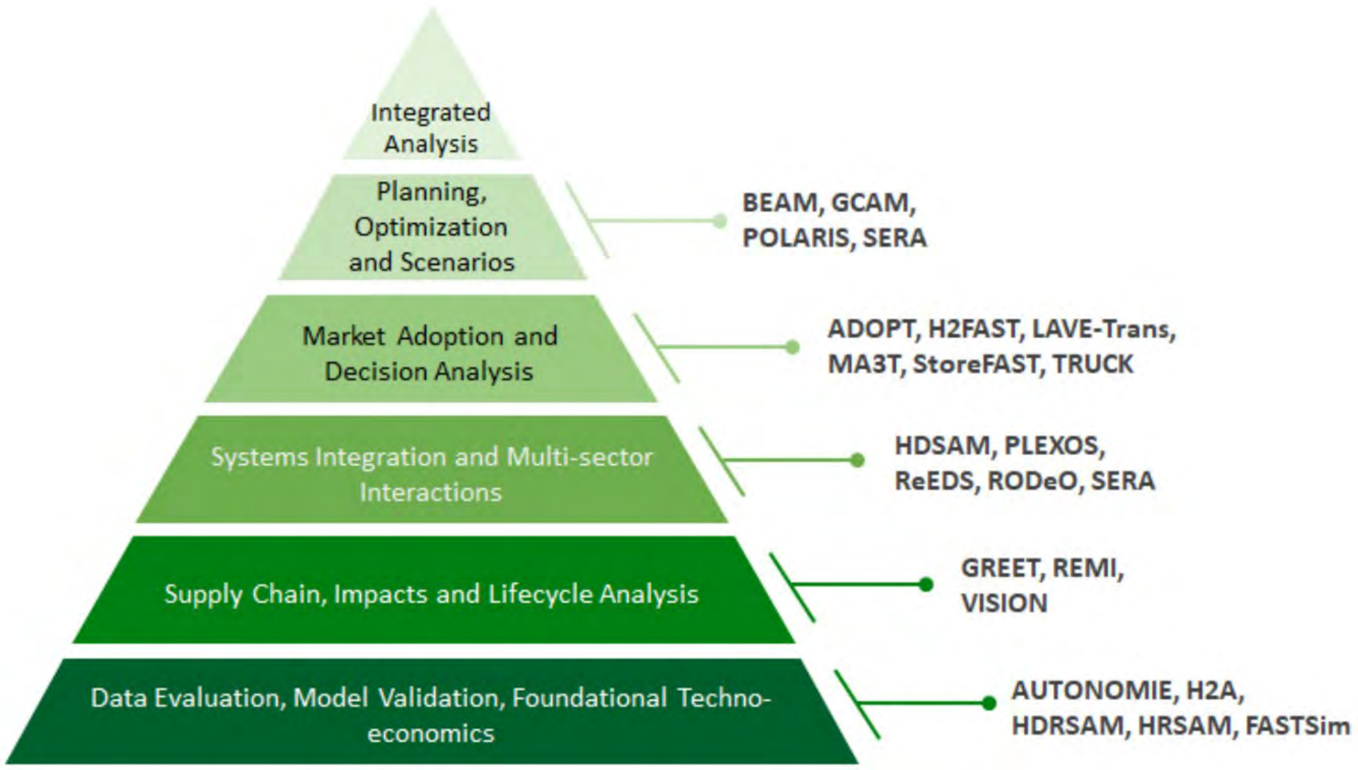
Challenges in Storage:

- Low energy density = **high volume**
- **Leakage** due to small molecular size and **embrittlement** of metal
- **Limited availability** of geological storage sites
- **Additional cost** and **low efficiency** of conversion and reconversion to electricity or hydrogen-based fuels

Source: EERE. "Hydrogen Storage." https://www.energy.gov/eere/fuelcells/hydrogen-storage.

Tools Spotlight: Supporting decision making

Decision-making workflow for hydrogen deployment



ADOPT: Automotive Deployment Options Projection Tool, Autonomie: (a vehicle system simulation tool), BEAM: Behavior, Energy, Autonomy, and Mobility, FASTSim: Future Automotive Systems Technology Simulator, GCAM: Global Change Assessment Model, GREET: Greenhouse gases, regulated emissions, and energy use in Technologies Model, H2A: The Hydrogen Analysis Project, H2FAST: Hydrogen Financial Analysis Scenario Tool, HDRSAM: Heavy-Duty Refueling Station Analysis Model, HDSAM: Hydrogen Delivery Scenario Analysis Model, HRSAM: Hydrogen Refueling Station Analysis Model, LAVE-Trans: Light-Duty Alternative Vehicle Energy Transitions, PLEXOS: (an integrated energy model), POLARIS: (a predictive transportation system model), ReEDS: Regional Energy Deployment System, REMI: Regional Economic Models, Inc., RODeO: Revenue Operation and Device Optimization Model, SERA: Scenario Evaluation and Regionalization Analysis, StoreFAST: Storage Financial Analysis Scenario Tool, VISION: (a transportation energy use prediction model).

Source: https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

- **Hydrogen Analysis Production (H2A)**: Transparent reporting of process design assumptions and a consistent cost analysis methodology for hydrogen production at central and distributed (forecourt/filling-station) facilities. H2A includes biomass, coal, electrolysis, natural gas, and emerging production pathways.

- **Revenue, Operation, and Device Optimization (RODeO)**: Explores optimal system design and operation considering different levels of grid integration, equipment cost, operating limitations, financing, and credits and incentives.

- **Scenario Evaluation and Regionalization Analysis (SERA)**: Provides insights that can guide hydrogen infrastructure development and transportation investment decisions and accelerate the adoption of hydrogen technologies (city to national levels).

- **Hydrogen Financial Analysis Scenario Tool (H2FAST)**: Provides a quick and convenient in-depth financial analysis for hydrogen fueling stations and hydrogen production facilities.

Explore the Hydrogen Considerations Tree

Executive Deck

Fact Sheet

Reach out if interested in more information for your country or project: **daniella.rough@nrel.gov.**

Questions?

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The U.S. National Clean Hydrogen Strategy

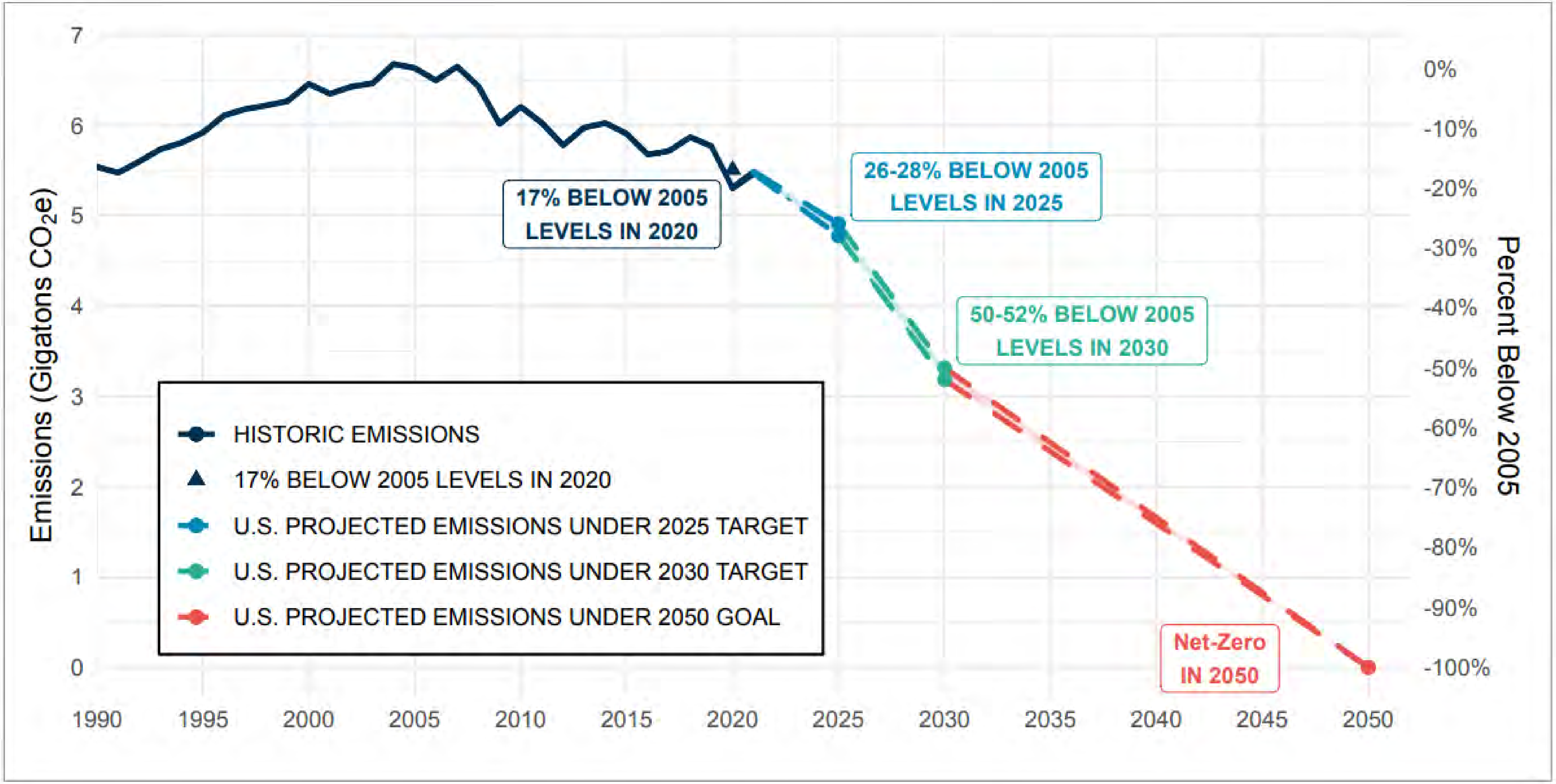
Neha Rustagi, Program Manager

Hydrogen and Fuel Cell Technologies Office

U.S. Department of Energy

Hydrogen 101 Webinar
February 7, 2024

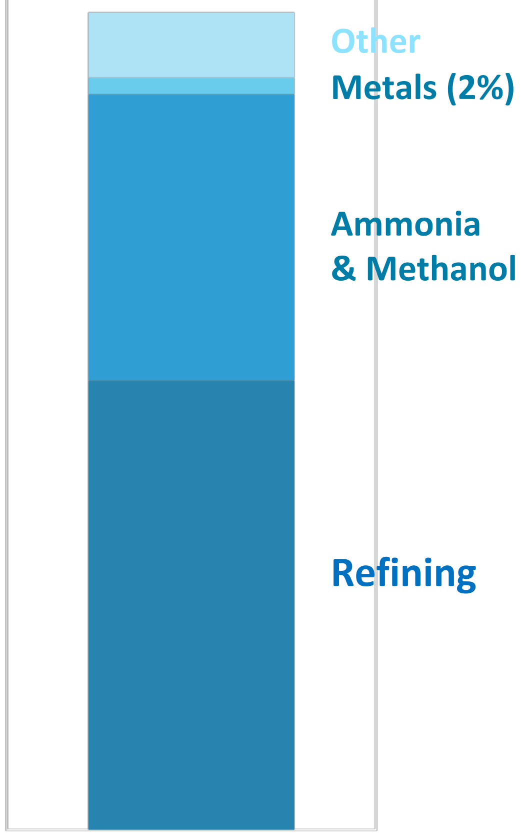
U.S. Decarbonization Goals and Targets vs. Historic Emissions



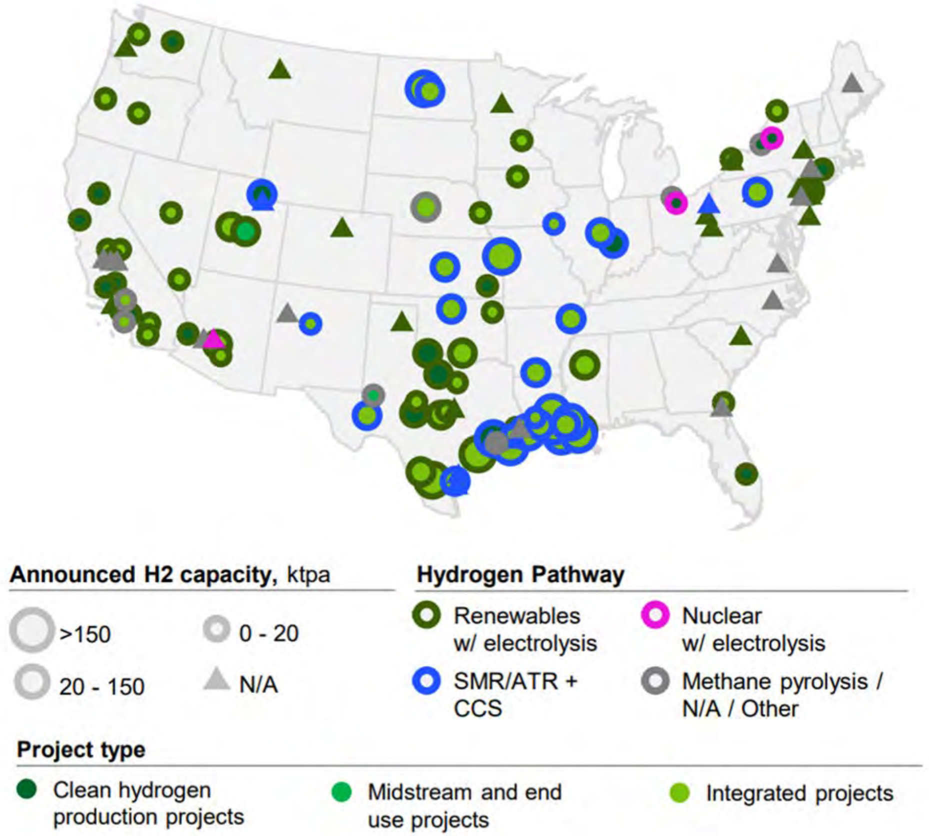
Snapshot of Hydrogen and Fuel Cells in the U.S.

- 10 million metric tons produced annually
- More than 1,600 miles of H_2 pipeline
- World's largest H_2 storage cavern

Use of Hydrogen in the U.S. Today

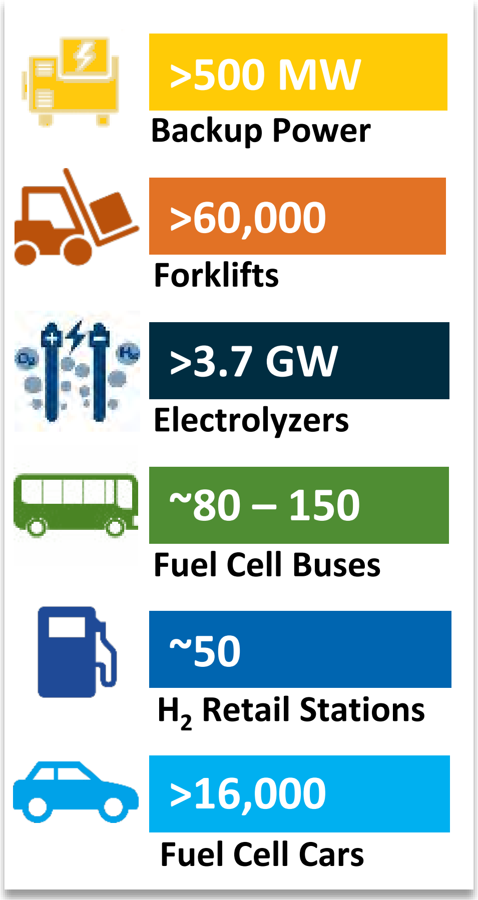


Current publicly announced clean hydrogen production projects*



*as of EOY 2022, DOE Commercial Liftoff Report

Examples of Deployments



DO NOT CITE OR REFERENCE.

Legislation Highlights: BIL and IRA

Bipartisan Infrastructure Law

- **Includes $9.5B for clean hydrogen**:
  - $1B for electrolysis
  - $0.5B for manufacturing and recycling
  - $8B for at least four regional clean hydrogen hubs
- **Requires** developing a **National Clean Hydrogen Strategy and Roadmap**

President Biden Signs the Bipartisan Infrastructure Bill into law on November 15, 2021. Photo Credit: Kenny Holston/Getty Images

Inflation Reduction Act

- **Includes significant tax credits** (e.g., up to $3/kg for production of clean hydrogen)

U.S. National Clean Hydrogen Strategy

Strategy

1. **Target strategic, high-impact end uses**
   Achieve 10 MMT/year of clean hydrogen by 2030

2. **Reduce the cost of clean hydrogen**
   Enable $2/kg by electrolysis by 2026 and $1/kg H_2 by 2031

3. **Focus on regional networks**
   Deploy regional clean hydrogen hubs and ramp up scale

Vision:
Affordable clean hydrogen for a net-zero carbon future and a sustainable, resilient, and equitable economy

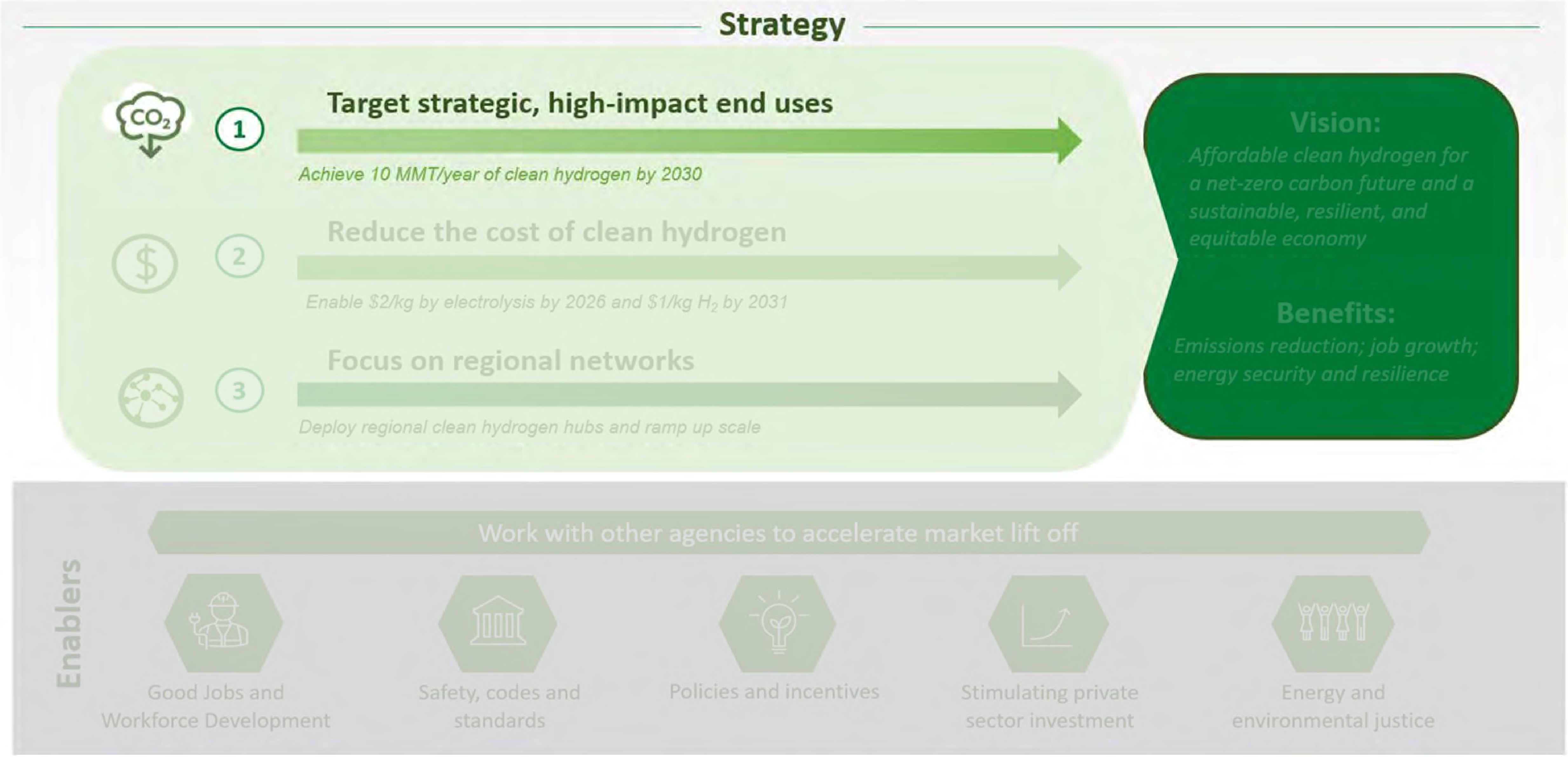
Benefits:
Emissions reduction; job growth; energy security and resilience

Enablers

Work with other agencies to accelerate market lift off

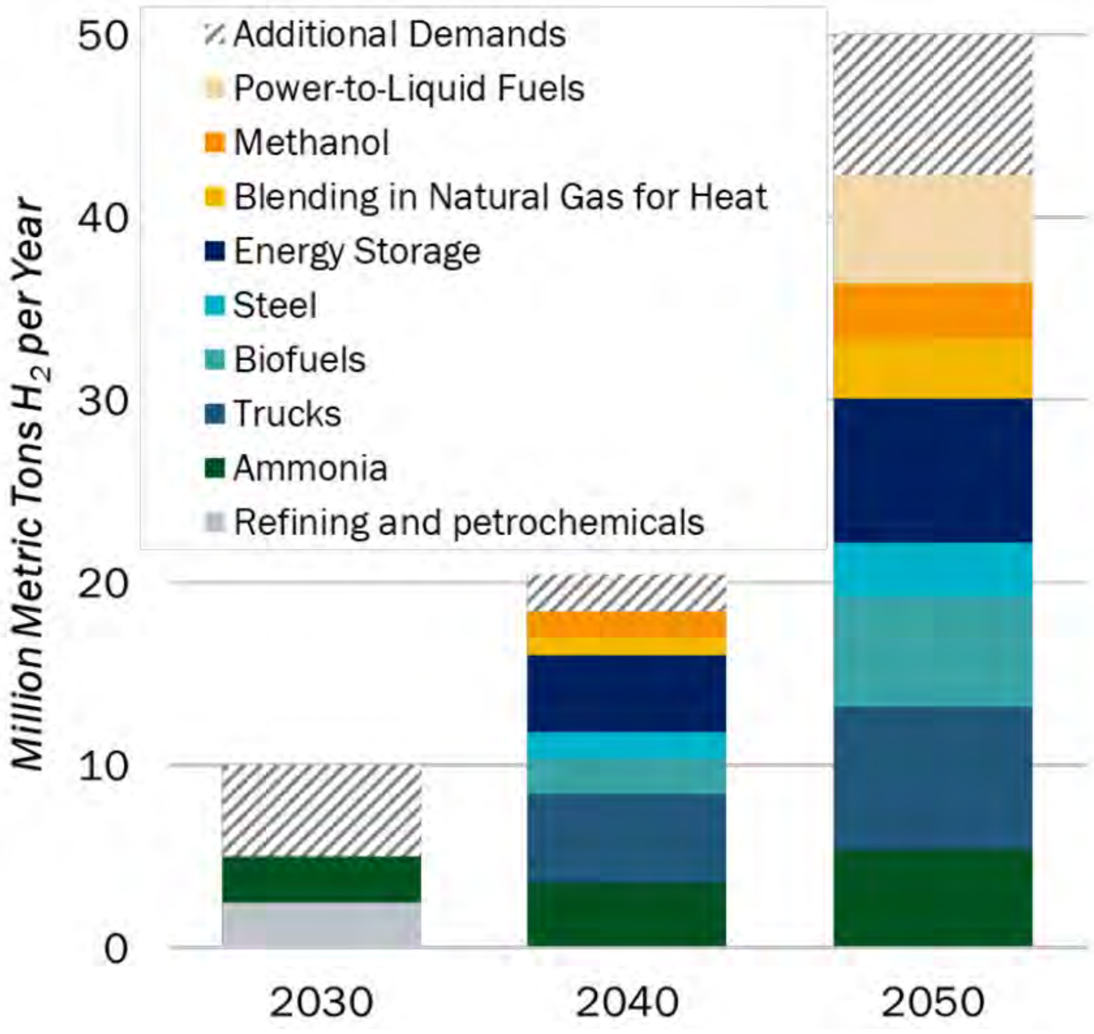
- Good Jobs and Workforce Development
- Safety, codes and standards
- Policies and incentives
- Stimulating private sector investment
- Energy and environmental justice

U.S. National Clean Hydrogen Strategy



Strategy 1: Target High-Impact Uses of Hydrogen

Opportunities for Clean Hydrogen Across Applications

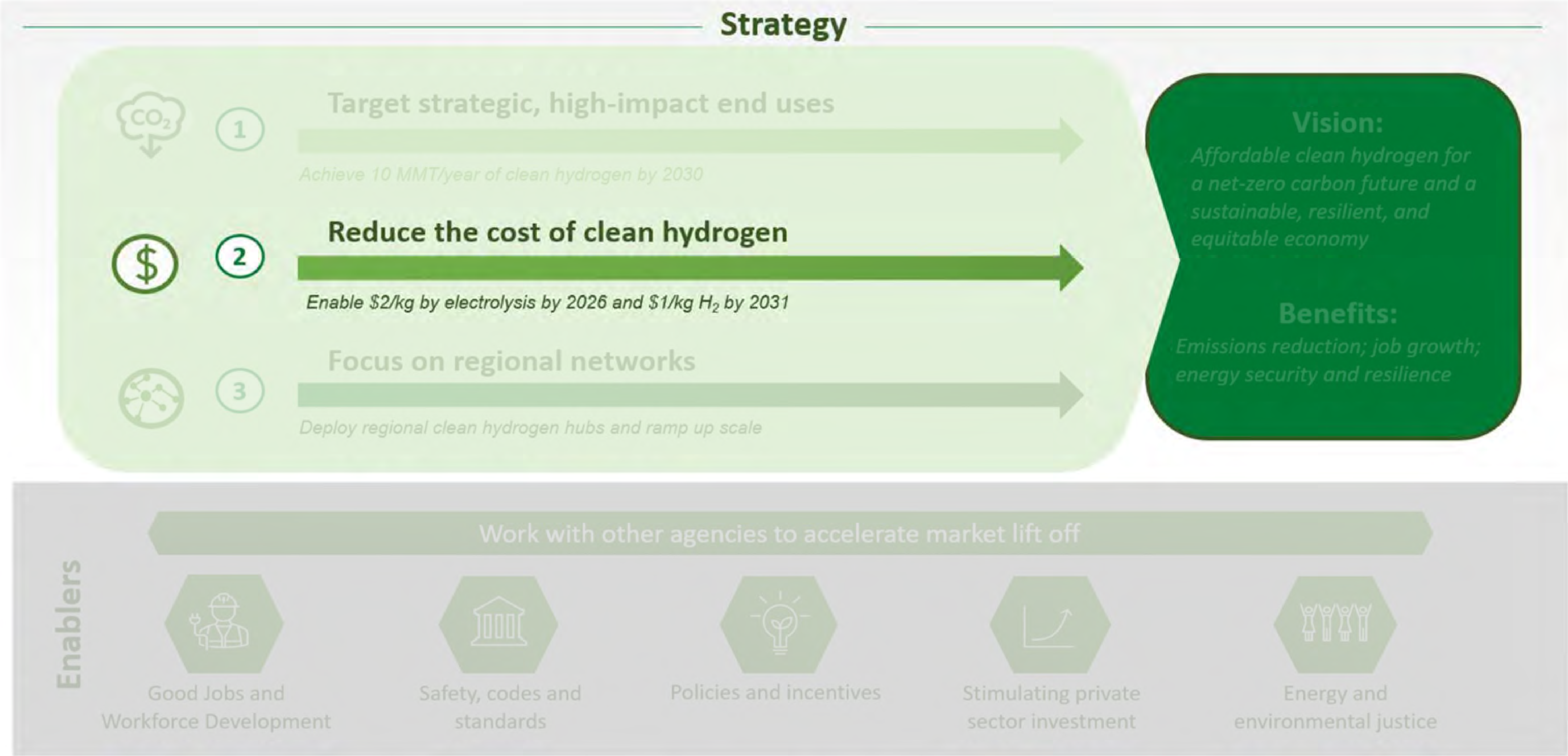


Clean Hydrogen Use Scenarios

- Catalyze clean H_2 use in existing industries (ammonia, refineries), initiate new use (e.g., sustainable aviation fuels (SAFs), steel, potential exports)
- Scale up for heavy-duty transport, industry, and energy storage
- Market expansion across sectors for strategic, high-impact uses

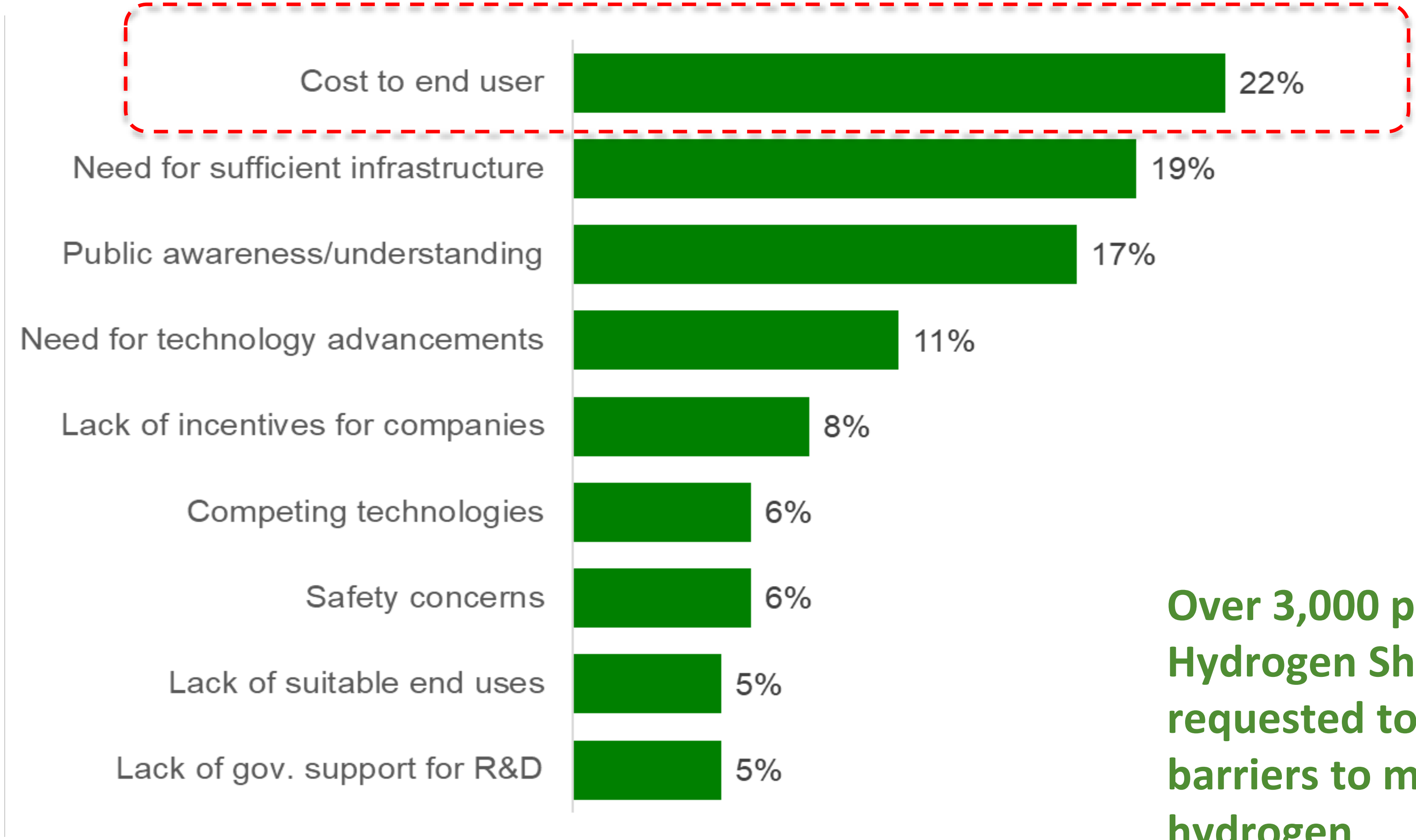
U.S. Opportunity: 10MMT/yr by 2030, 20 MMT/yr by 2040, 50 MMT/yr by 2050
~10% Emissions Reduction.
~100K Jobs by 2030

U.S. National Clean Hydrogen Strategy



Strategy 2: Focus on Cost-Reduction

Stakeholder Reported Barriers to Hydrogen Market Adoption



Over 3,000 participants at DOE Hydrogen Shot Summit were requested to provide feedback on key barriers to market adoption of hydrogen

https://www.energy.gov/eere/fuelcells/hydrogen-shot-summit

Source: Hydrogen Shot Summit, Sept 2021

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

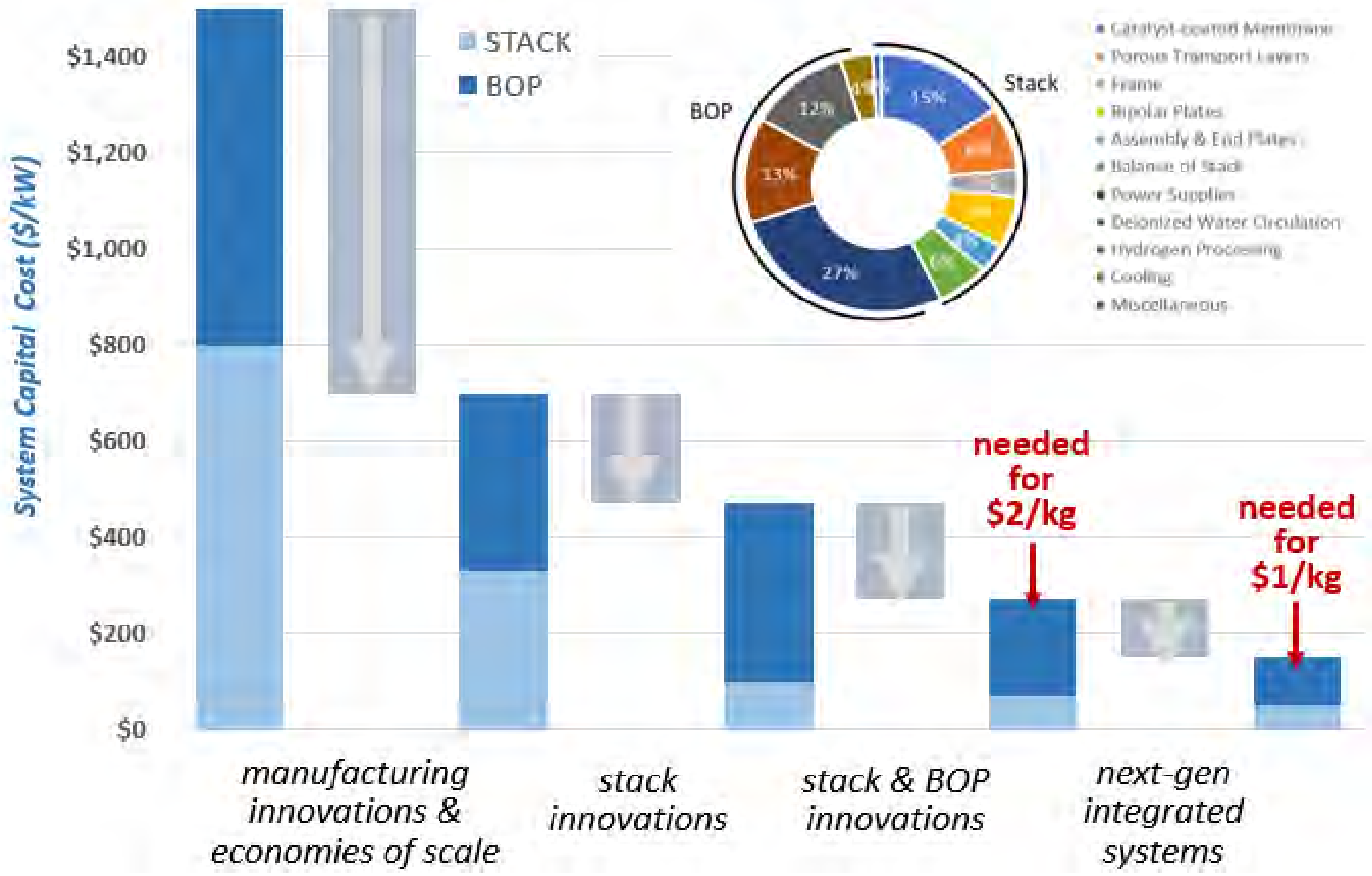
Hydrogen Energy Earthshot

“Hydrogen Shot”

“1 1 1”
$1 for 1 kg clean hydrogen in 1 decade

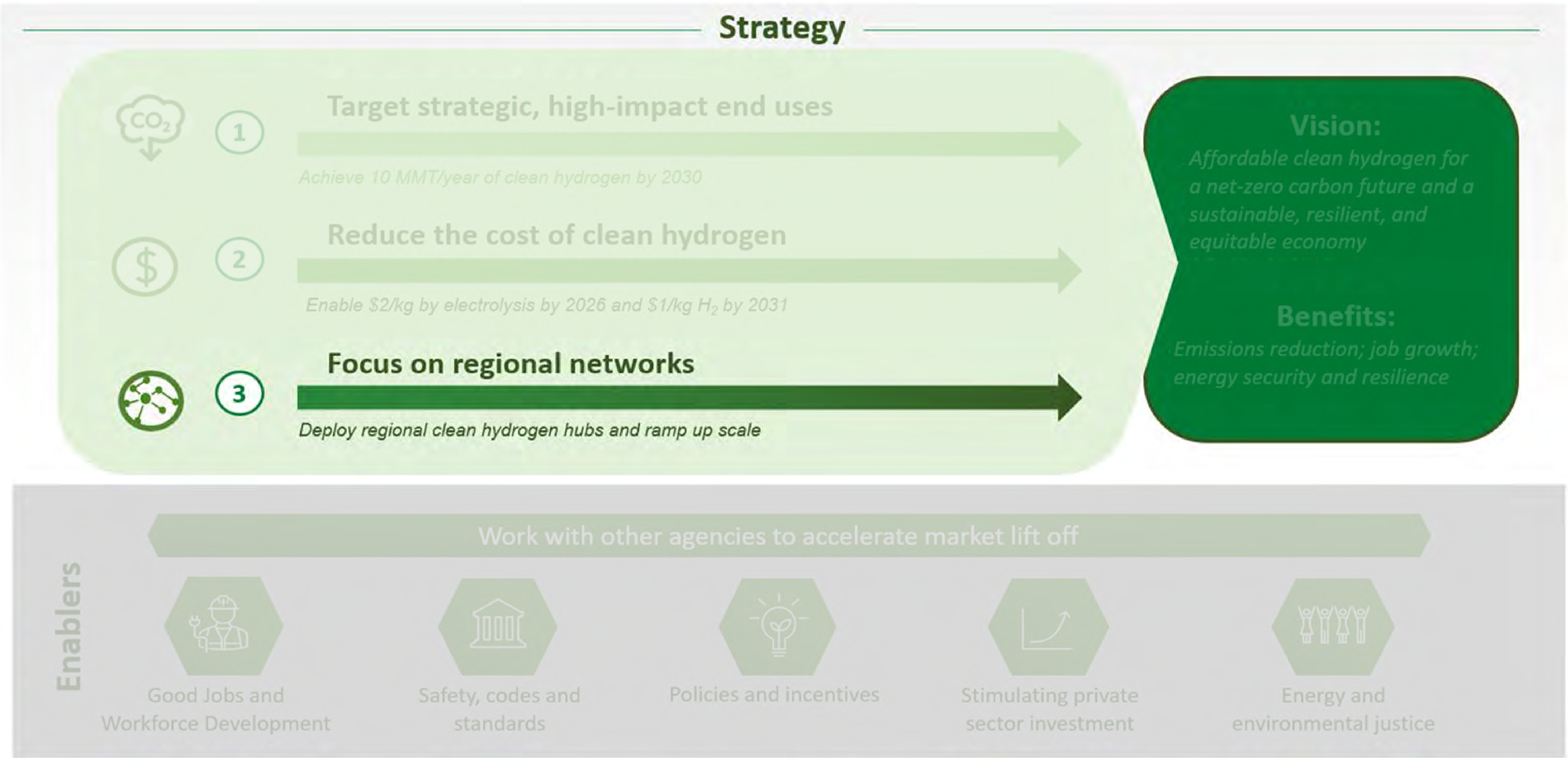
Launched June 7, 2021

How to reduce cost? Examples across multiple pathways



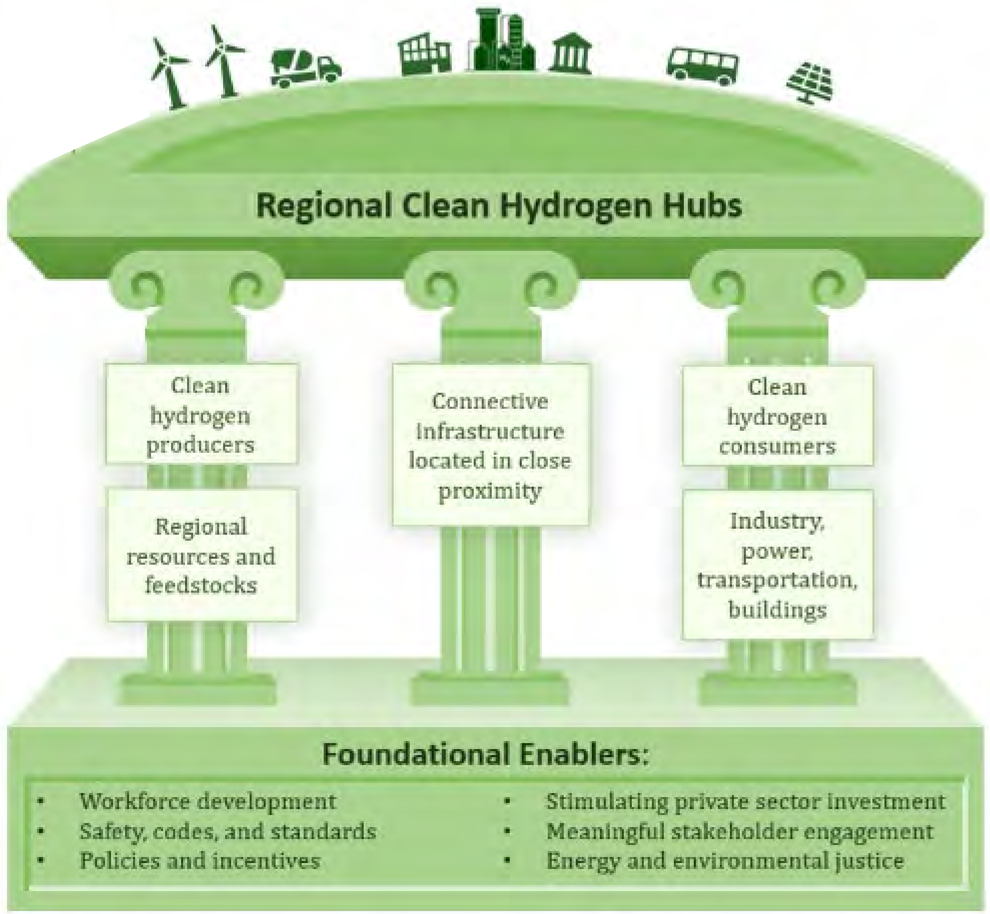
Analysis shows pathways to reduce cost require both manufacturing scale-up and continued R&D

U.S. National Clean Hydrogen Strategy

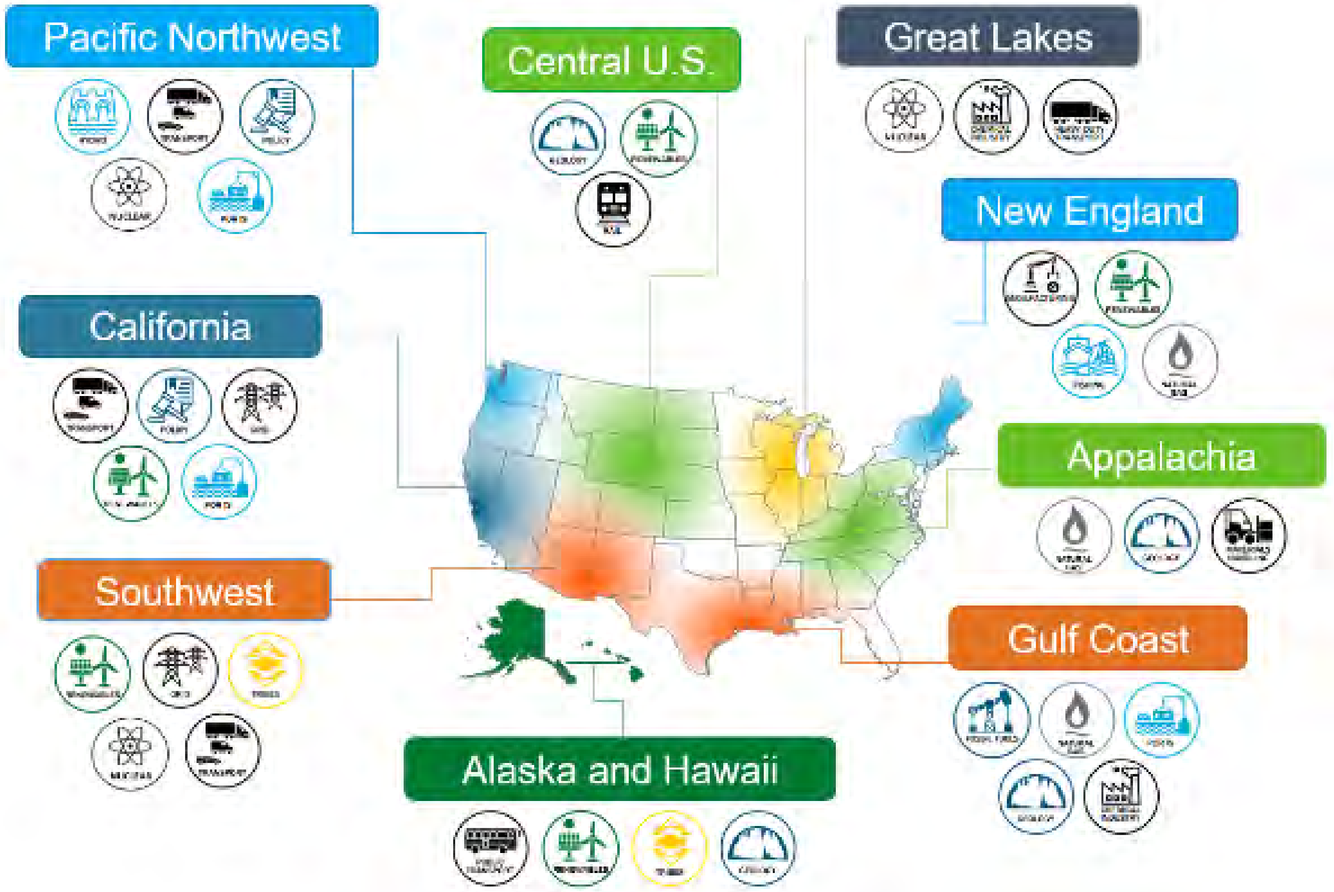


Strategy 3: Focus on Regional Networks and Ramp up Scale

Build Regional Networks through "Clean Hydrogen Hubs"



Examples of Stakeholder and RFI Input

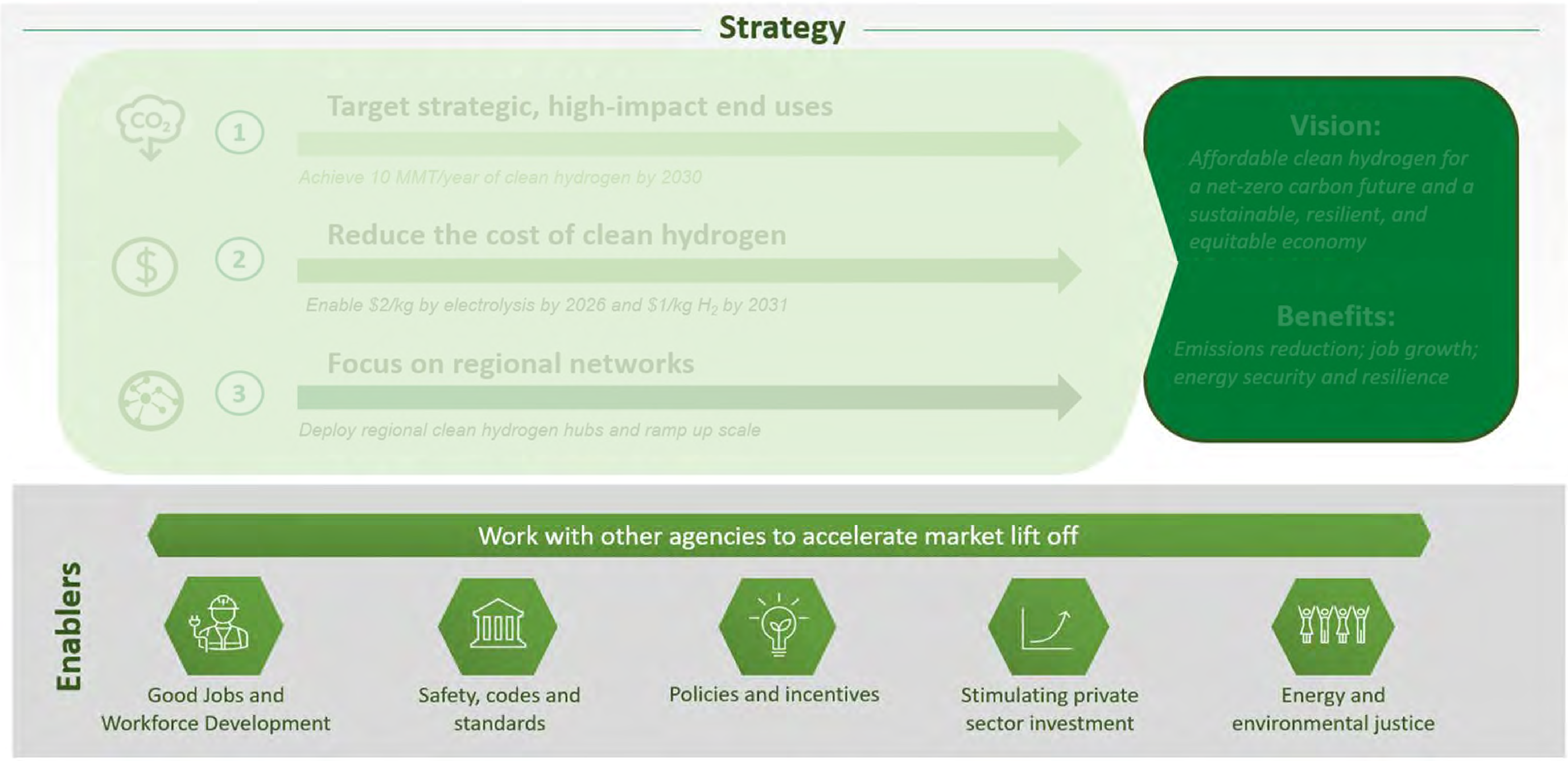


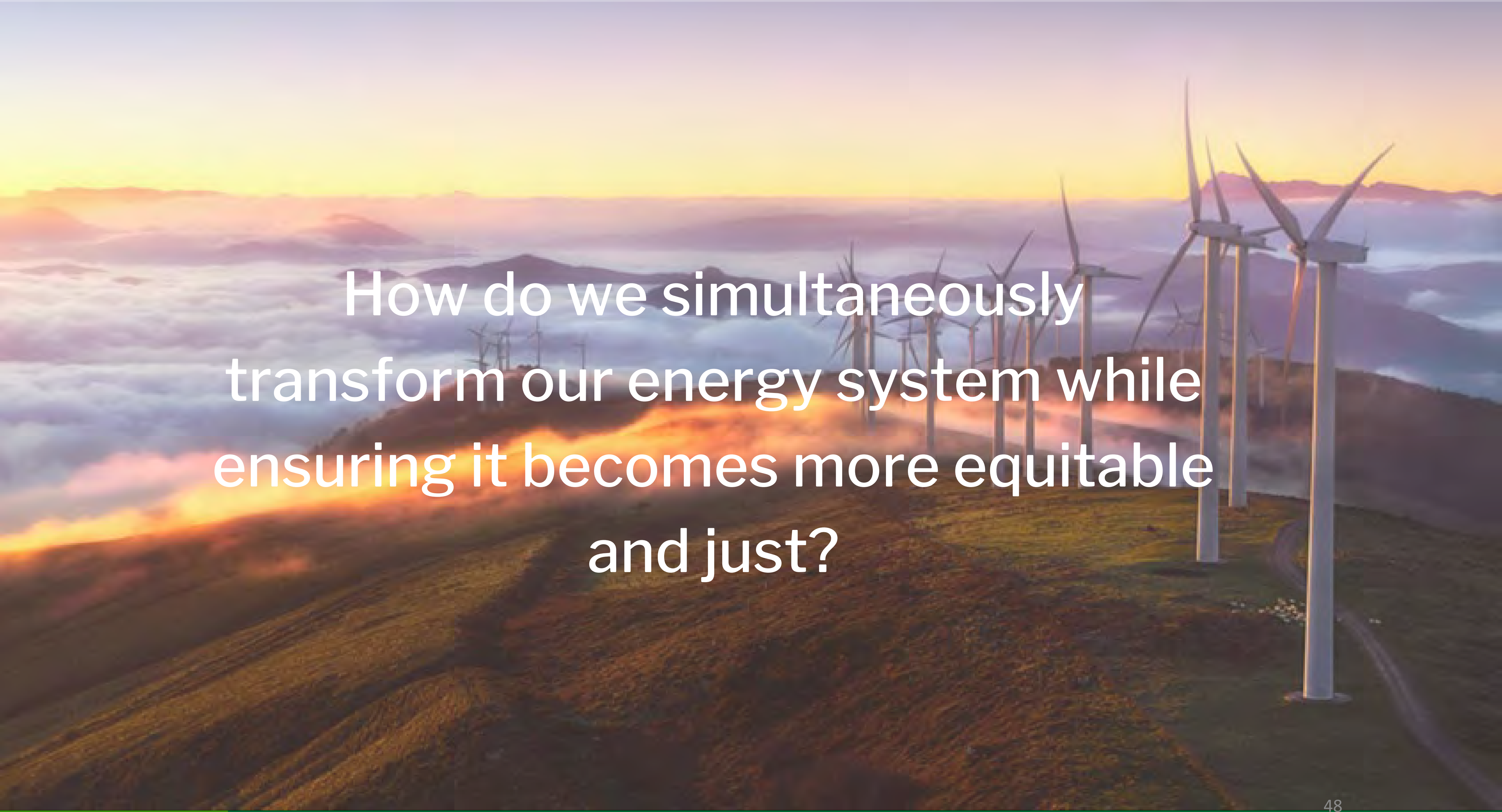
Seven Regional Clean Hydrogen Hubs Selected

Bipartisan Infrastructure Law Clean H_2 Hubs Leveraging:

- Natural gas resources with carbon management;
- Renewable and nuclear power generation coupled with electrolysis
- Other regional resources supporting H_2 production, distribution, and end use

U.S. National Clean Hydrogen Strategy





How do we simultaneously transform our energy system while ensuring it becomes more equitable and just?

48

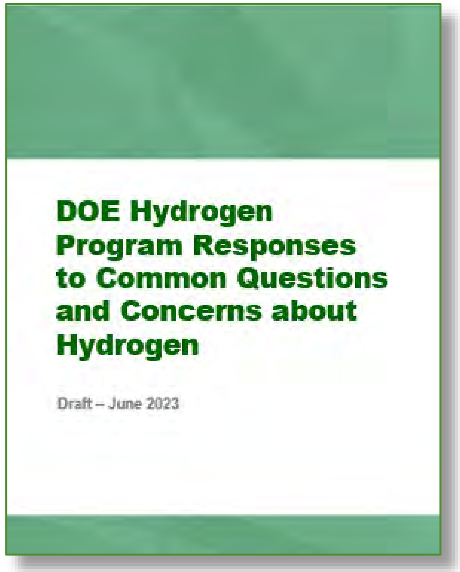
Equity and Environmental Justice in the Hydrogen Office

Strategy

- I. Listening, Engaging & Increasing Transparency
- II. Prioritizing Safety and Positive Impacts
- III. Lowering Barriers
- IV. Diversifying the Clean Hydrogen Workforce
- V. Building Capacity & Skills
- VI. Environmental Justice in Permitting and Siting

Community Benefit Plans

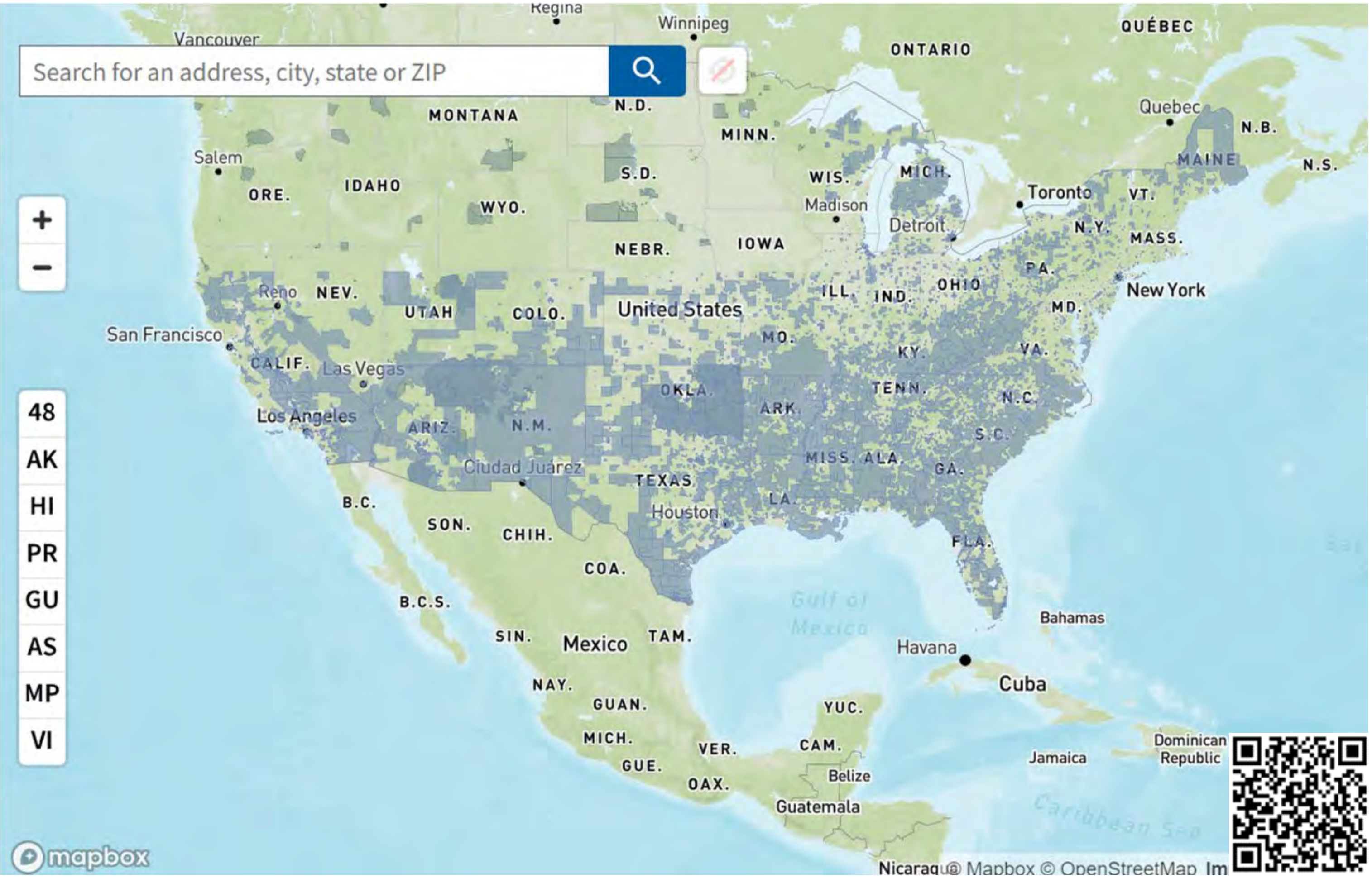
Resources


DOE Hydrogen Program Responses to Common Questions and Concerns about Hydrogen

Draft – June 2023

Justice 40 & Disadvantaged Communities

Distribution of census tracts identified as DACs



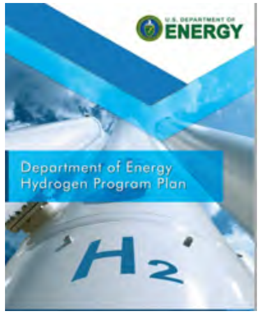
[Explore the map - Climate & Economic Justice Screening Tool (geoplatform.gov)]

INDICATORS:
CLIMATE CHANGE
ENERGY
WATER & WASTERWATER
HEALTH
HOUSING
TRANSPORTATION
LEGACY POLLUTION
WORKFORCE DEVELOPMENT

Census tracts that are overburdened and underserved are highlighted as being **disadvantaged** on the map. Federally Recognized Tribes, including Alaska Native Villages, are also considered disadvantaged communities.

Resources and Opportunities for Engagement

Key Publications



www.hydrogen.energy.gov

Save the date!

2024 DOE Annual Merit Review May 6-9, 2024

Hydrogen and Fuel Cells Day October 8

- Held on hydrogen's very own atomic weight-day

1
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1.008
Hydrogen

INCREASE YOUR H2IQ
hydrogen.energy.gov

Join Monthly
H2IQ Hour Webinars

Download
H2IQ For Free

Visit H2tools.Org For Hydrogen Safety And Lessons Learned

https://h2tools.org/

CENTER FOR Hydrogen SAFETY
Connecting a Global Community

www.aiche.org/CHS

Sign up to receive hydrogen and fuel cell updates

www.energy.gov/eere/fuelcells/fuel-cell-technologies-office-newsletter

Learn more at: energy.gov/eere/fuelcells AND www.hydrogen.energy.gov

Thank you

Neha Rustagi
Hydrogen and Fuel Cell Technologies Office
U.S. Department of Energy

Neha.Rustagi@ee.doe.gov

www.hydrogen.gov

Pathways to Commercial Liftoff: Clean Hydrogen Takeaways

Campbell Howe

Hydrogen 101 Webinar
February 7, 2024

Pathways to Commercial Liftoff Overview

Accelerating the commercialization and deployment clean energy technologies to achieve net-zero emissions by 2050

- The clean energy transition represents an **investment opportunity of ~$30T in the US and ~$200T globally**
- The scale up of the technologies to enable this transition in the US will be **private sector-led, government-enabled** centered on **deep & continuous engagement** between the private and public sectors
- Liftoff Reports are **living documents that serve as a common fact base**, pulling information from market data, industry feedback, and progress from DOE investments, **establishing critical signposts and pinpoint both challenges and opportunities for public and private investment**

8 Reports Published to Date

Clean Hydrogen

Long Duration Energy Storage

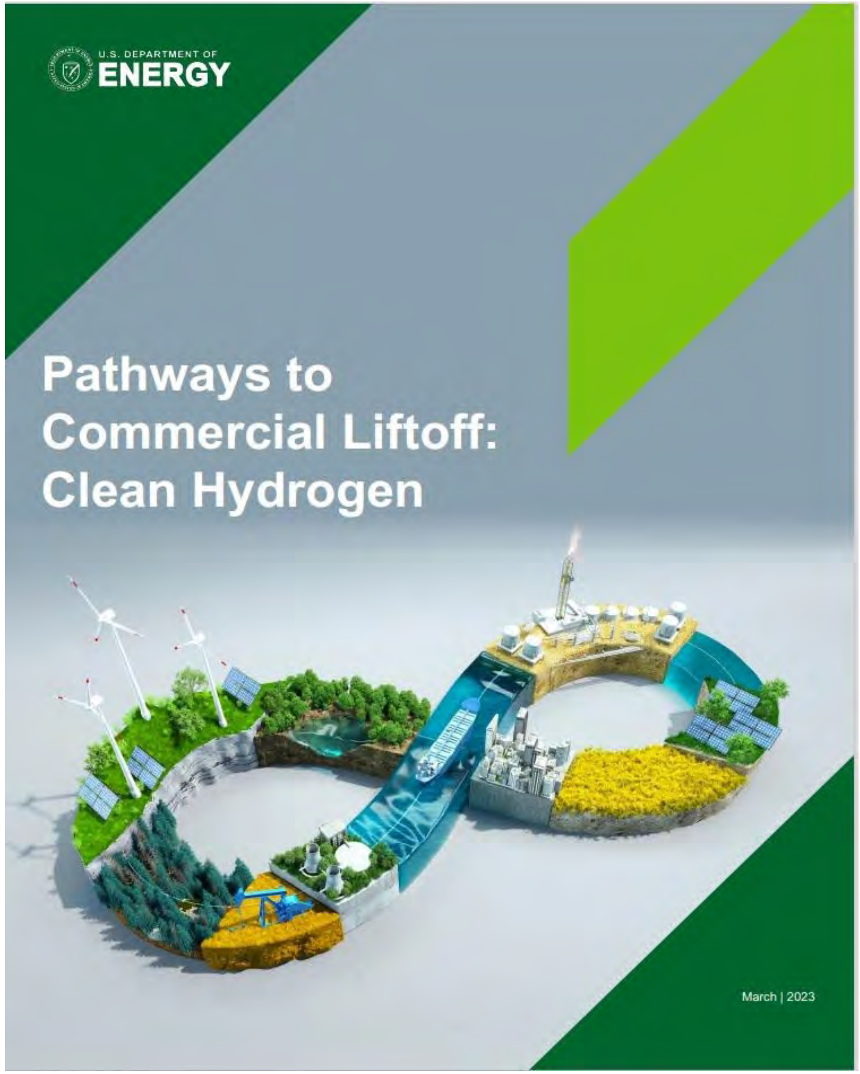
Advanced Nuclear

Carbon Management

Industrial Decarb *(Chemicals & Refining + Cement)*

Virtual Power Plants

Clean Hydrogen Liftoff Overview (March 2023)



- **Clean hydrogen has the potential to decarbonize 10-25% of global emissions**, often in sectors with the fewest other decarbonization options (e.g., ammonia, heavy-duty transport, etc.)
- **$15B of projects have been announced which could represent up to 12 MMTpa of production capacity by 2030**, but only ~1.5 MMTpa of this capacity has reached final investment decision
- Growing the U.S. clean hydrogen economy to over 10 MMTpa by 2030 **requires $85-215B**, ~50% of which for midstream and end-use infrastructure, and ~33-50% for the build out net new low carbon energy production
- **Barriers to scale remain** – including off-taker hesitancy, insufficient storage and distribution infrastructure, a nascent trained hydrogen workforce, and constrained supply chains for electrolyzers and renewable energy, etc.
- R&D is needed to bring down the cost of electrolyzer stacks and to improve CCS cost and performance (critical dependency for SMR with CCS)

liftoff.energy.gov/clean-hydrogen

Recent Developments in the U.S. Clean Hydrogen Economy

Hydrogen production costs have increased driven by increases in capex costs, financing costs, and other factors

Increase in clean hydrogen production plans in the U.S. following the passage of the Inflation Reduction Act and the announcement of the DOE Clean Hydrogen Hubs representing up to 3 MMTpa of clean hydrogen production volume in 7 regions

45V draft guidance was released in December 2023 based on the "three pillars" (time-matching, incrementality, and regionality)

The DOE announced the launch of **demand-side support mechanism with the remaining Hydrogen Hubs funding** to bridge the gap between delivered costs and offtaker willingness to pay

Key Messages from the Original Clean Hydrogen Liftoff Report

PTC reduces production costs to kick-start the transition from high carbon intensity (CI) to low CI hydrogen for existing uses

DOE H2Hubs and open access infrastructure will bolster the project economics for more nascent use cases

In addition to industrial/chemicals use cases, transportation use cases will be critical for market liftoff

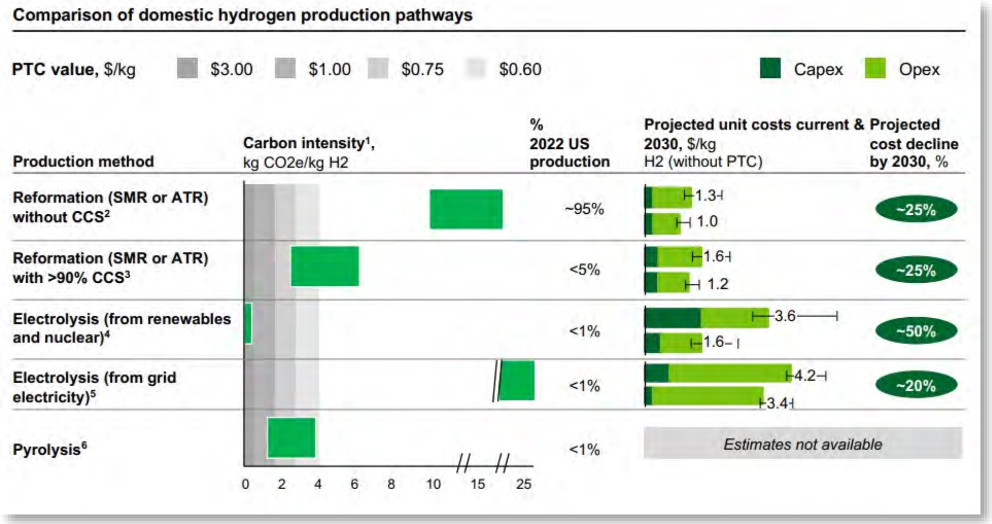
Without sustained long-term offtake or merchant markets, domestic market acceleration could slow

Foregrounding energy and environmental justice mitigates project risk, improves health and safety in surrounding communities, and generates social acceptance

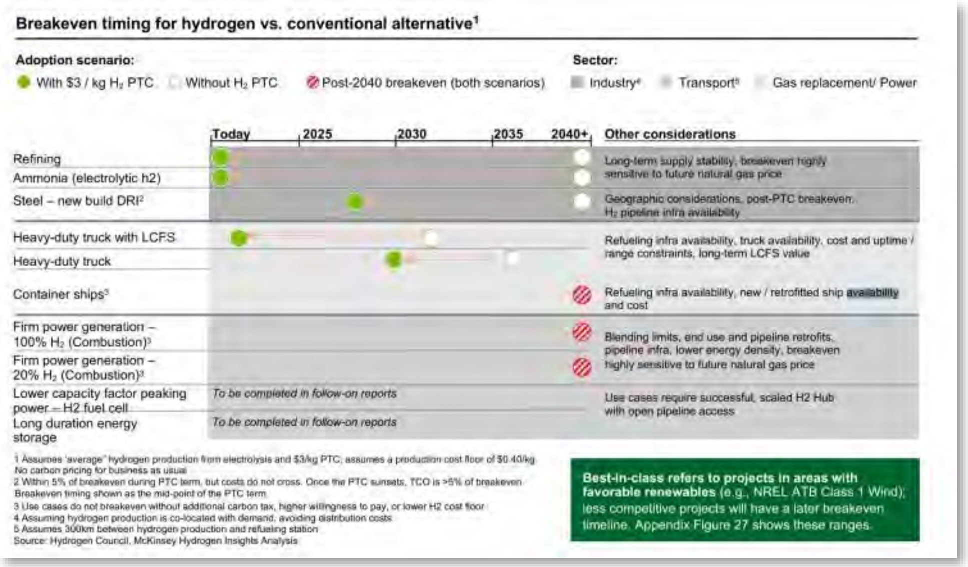
Providing quality jobs and investing in worker development is essential to recruit and retain a sufficient, appropriately skilled hydrogen workforce

Original Liftoff Report Sample Analyses (not exhaustive)

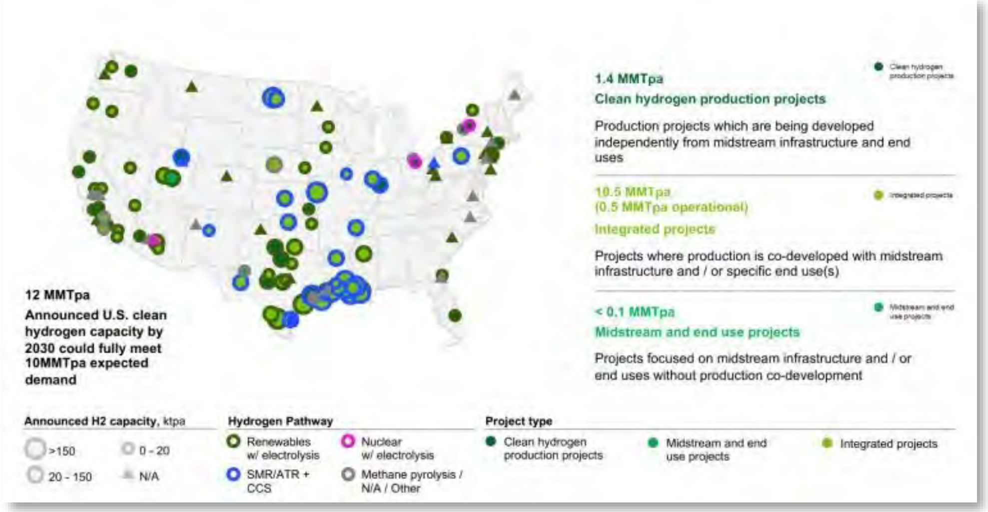
Carbon Intensities



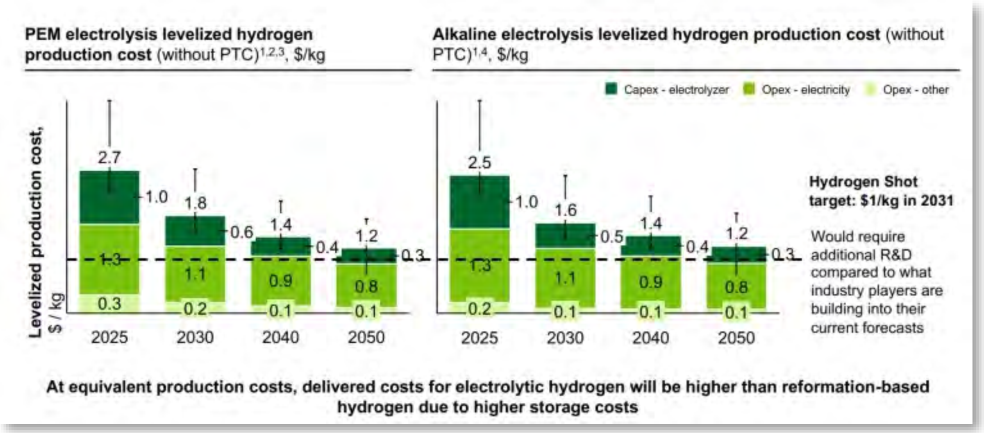
Total Cost of Ownership



Project announcements



Production Costs



Midstream: Delivered costs of hydrogen vs. end use willingness to pay (March 2023)

2030 costs across the value chain if advances in distribution and storage technology are commercialized[1]

Industry | Gas replacement | Transport

Upstream: Hydrogen production

Reformation-based production

w/ $0.75/kg PTC: LCOH = $0.4-0.85/kg

CO2 transport/ sequestration

Water electrolysis

w/ $3/kg PTC: LCOH < $0.4/kg[3]

Midstream: Hydrogen distribution and storage assuming state-of-art technology at scale[2]

Commercialized, best-in-class gas compression

$0.2-0.4/kg at 500 bar, 10 tpd (tank storage, truck distribution)

$0.1/kg at 80-120 bar, 50 + tpd (pipeline, co-located electrolysis)

Salt cavern storage: $0.1/kg at 80 bar for 7 days, 600 tpd

Compressed gas tank storage: $0.8 / kg at 500 bar for 7 days

H2 pipeline: $0.1/kg at 600 tpd, 300 km, 12” OD; $0.1/kg at ~5000 tpd, 1000 km, 42” OD

Gas phase trucking: $0.7-1.5/kg at 10 tpd, 250 km

Liquefaction: $2.7/kg at 50 tpd

Liquid hydrogen storage: $0.2/kg for 7 days, 50 tpd scale

Liquid hydrogen trucking: $0.2-0.3/kg at 50 tpd, 250 km

Next generation fuel dispensing at high utilization[6]: $1 -3.6/kg ≥700 kg/day, 700 bar

Downstream: End use applications

End use willingness to pay[4]

End use	Willingness to pay
Ammonia	$0.9-2.3/kg
Refining	$1-1.3/kg
Steel	$1.25-2.3/kg
Chemicals	$0.9-2.3/kg
NG blending	$0.4-0.5/kg
Industrial heat	$0.7-1.5/kg
Power gen. (high-capacity firm)	$0.4-0.5/kg
Aviation and maritime fuels[5]	$0.7-3/kg
HDMD road transport	$4-5/kg

1. See appendix for calculation details
2. Data based on cost-downs shared from leading-edge companies who have deployed at demonstration scale (or larger)
3. Range based on varying renewables costs and electrolyzer sizes/technologies
4. Defined as the price an off-taker will pay for clean hydrogen
5. Represents delivery of hydrogen to aviation and maritime fuel production facilities
6. Greater than or equal to 70% utilization, assumes line fill at high pressure

Sources: HDSAM, Argonne National Laboratory; DOE National Hydrogen Strategy and Roadmap, Hydrogen Council

Readers should sum (1) Upstream costs and (2) Midstream costs to arrive at a potential delivered cost of clean hydrogen, based on production pathway and storage/distribution method selected. Hydrogen production costs shown take an upper bound of production costs (~2MW (450 Nm3/ h) PEM electrolyzer with Class 9 NREL ATB wind power) and then subtract the PTC at point-in-time. A wider range of LCOH values, without the PTC credit applied, are described in Figures 11 and 12 in the Clean Hydrogen Liftoff report.

Regional Clean Hydrogen Hubs

DOE H2Hubs: Building regional clean H2Hubs across the country to create networks of clean hydrogen producers, consumers, and local connective infrastructure to accelerate use of clean hydrogen

H2Hubs Demand-Side Support Initiative

- January 2024: Consortium announced in response to $1B RFP. Design phase initiated.
- Learn more about the initiative here: https://www.youtube.com/watch?v=QgOL_Xg7K1Q

H2Hubs Current Status

- October 2023: DOE announced 7 projects selected for award negotiations.

U.S. DEPARTMENT OF ENERGY

CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY
An Initiative of the Clean Energy Ministerial

Hydrogen 101

Hydrogen and Analytical Tools

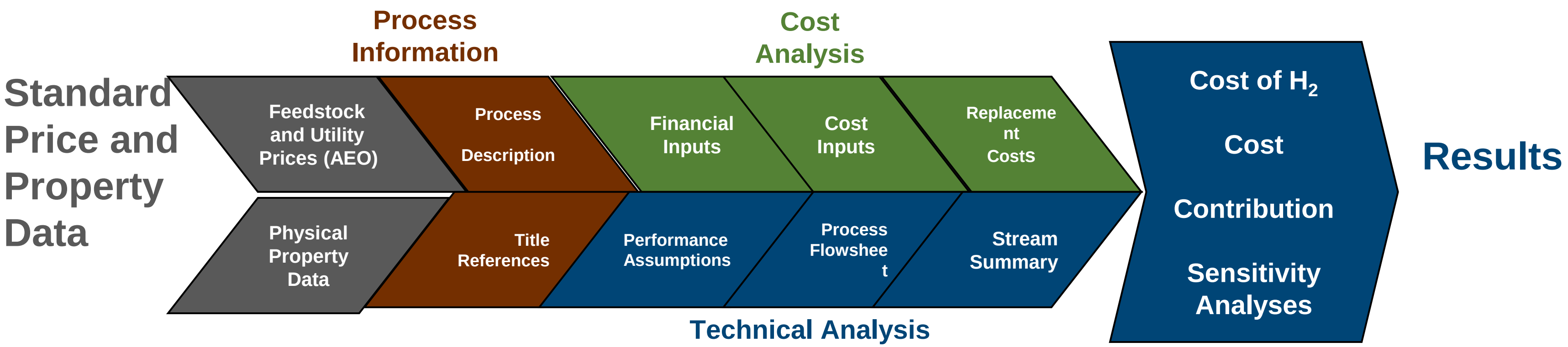
Michael (Misho) Penev

February 7, 2024

Hydrogen Specific Model Suite

1. Production models (H2A & Lite)
2. HDSAM
3. H2FAST
4. SERA
5. GREET
6. StoreFAST
7. RoDEO

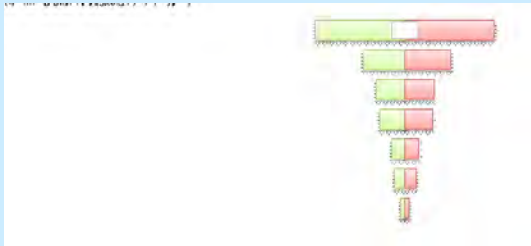
H2A (H2 Production Analysis Tool)

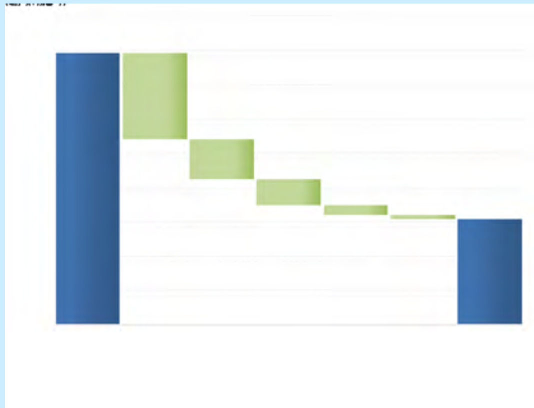


Spreadsheet Examples

AEO_2017_Reference_Case
Year
Feedstock Type
Residential Natural Gas
Commercial Natural Gas
Industrial Natural Gas
Electric Utility Natural Gas
Woody Biomass
Electric Utility Steam Coal
Commercial Electricity
Industrial Electricity
Residential Electricity

Technical Operating Parameters and Specifications	
Operating Capacity Factor (%)	90.0%
Plant Design Capacity (kg of H2/day)	379,387
Plant Output (kg/day)	341,448
Plant Output (kg/year)	124,628,630
Financial Input Values	
Reference year	2016
Assumed start-up year	2015
Basis year	2005
Length of Construction Period (years)	3
% of Capital Spent in 1st Year of Construction	8%
% of Capital Spent in 2nd Year of Construction	60%
% of Capital Spent in 3rd Year of Construction	32%
% of Capital Spent in 4th Year of Construction	
Start-up Time (years)	1
Plant life (years)	40
Analysis period (years)	40
Depreciation Schedule Length (years)	20
Depreciation Type	MACRS
% Equity Financing	40%
Interest rate on debt, if applicable (%)	3.70%
Debt period (years)	Constant debt
% of Fixed Operating Costs During Start-up (%)	75%
% of Revenues During Start-up (%)	50%
% of Variable Operating Costs During Start-up (%)	75%
Decommissioning costs (% of depreciable capital investment)	10%
Salvage value (% of total capital investment)	10%
Inflation rate (%)	1.9%
After-tax Real IRR (%)	8.0%
State Taxes (%)	6.0%
Federal Taxes (%)	21.0%
Total Tax Rate (%)	25.74%
WORKING CAPITAL (% of yearly change in operating costs)	15%





Central production pathways:
- Biomass gasification
- Coal gasification
- Electrolysis
- Natural gas SMR
- Natural gas SMR+CCS
- Natural gas ATR+CCS

Distributed production pathways:
- Electrolysis
- Ethanol reforming
- Natural gas SMR

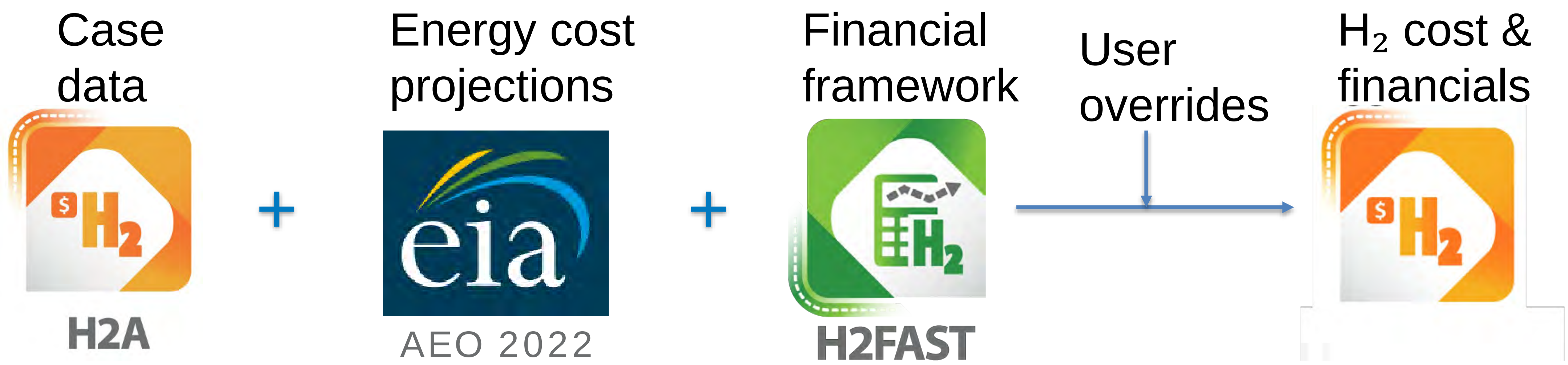
Emerging technologies:
- Photo-electrochemical
- Solar thermochemical ferrite cycle

https://www.nrel.gov/hydrogen/h2a-production-models.html

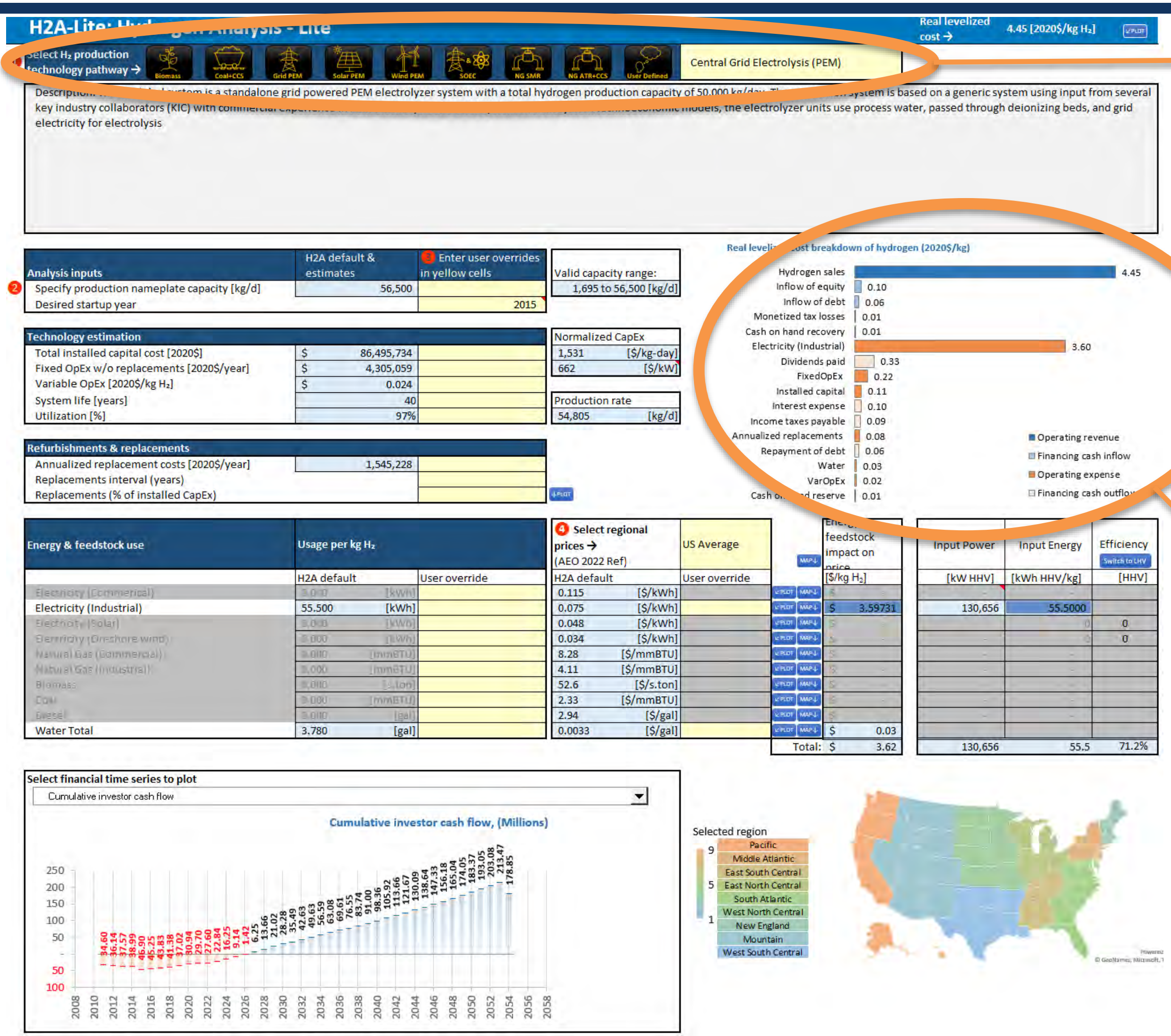
H2A-Lite: Overview

Based on Hydrogen Financial Analysis Scenario Tool (H2-FAST)

- Uses Generally Accepted Accounting Principles (GAAP) financial analysis
- Also compatible with International Financial Reporting Standards (IFRS)
- Articulates standard financial reports for duration of analysis
    - Income statements
    - Cash flow statements
    - Balance sheets
- Analysis performed on real 2020$ basis (for consistency with H2A –future methodology)



H2A-Lite Layout



Central production pathways:

- Biomass gasification
- Coal gasification
- Electrolysis
- Natural gas SMR
- Natural gas SMR+CCS
- Natural gas ATR+CCS

Cost Breakdown

All yellow cells allow user overrides

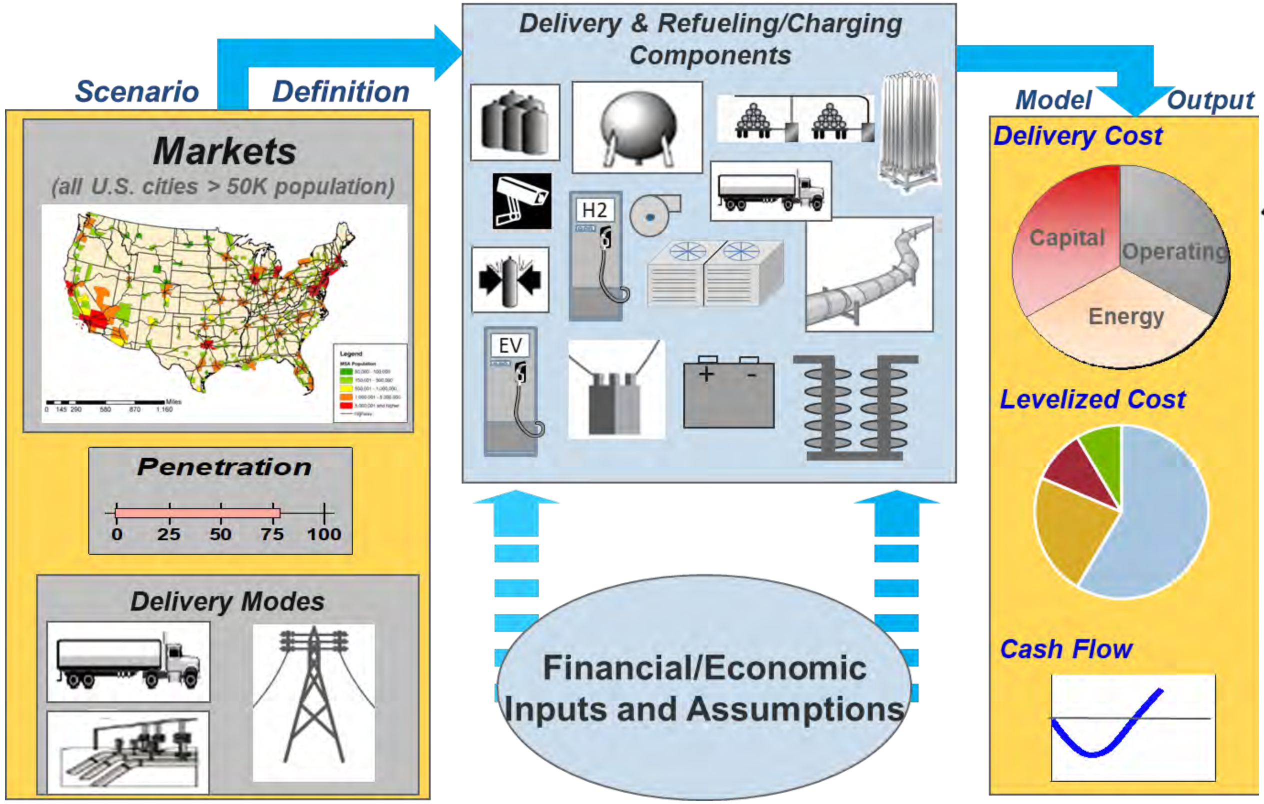
Hydrogen Specific Model Suite

1. Production models (H2A & Lite)
2. HDSAM
3. H2FAST
4. SERA
5. GREET
6. StoreFAST
7. RoDEO

Hydrogen Delivery Scenario Analysis suite of Models (HDSAM)

Argonne's HDSAM and its derivatives evaluate the economic performance and market acceptance of hydrogen delivery technologies and fueling infrastructure for FCEVs

- Publicly available with >5,250 users, including major gas and energy companies, in more than 25 countries
- Supported by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) since 2004



Hydrogen Specific Model Suite

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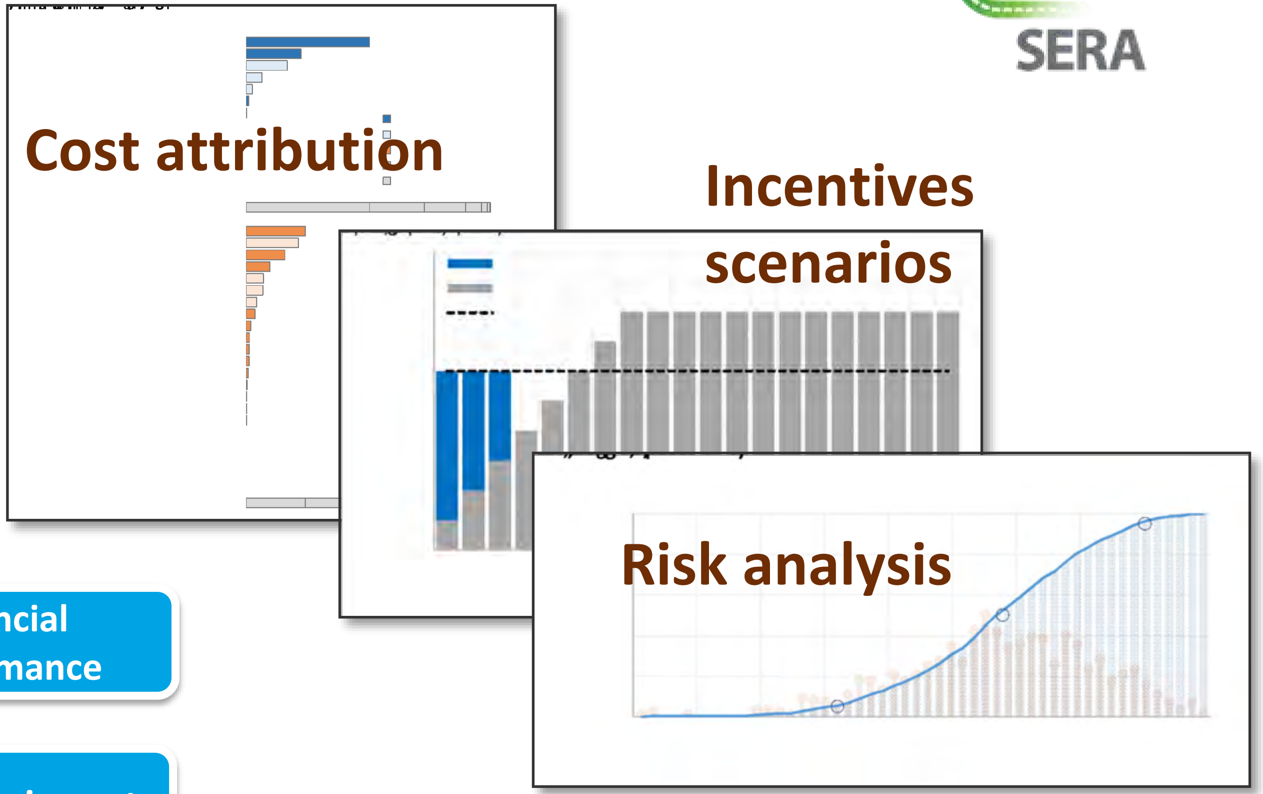
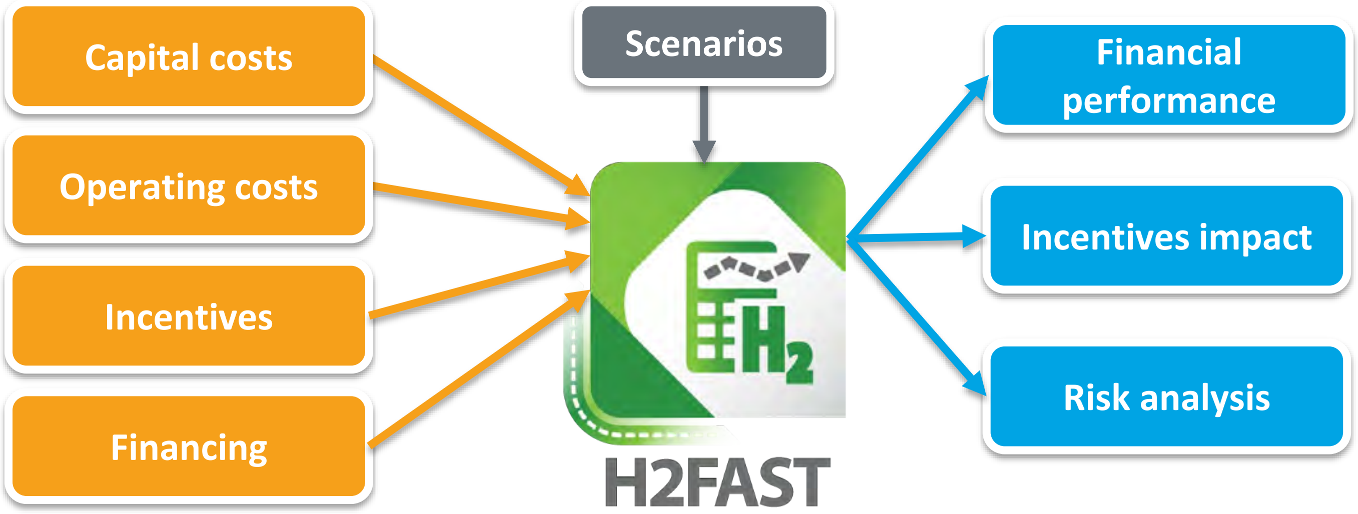
7. RoDEO

H2FAST – Corporate Finance Framework Analysis

The ***Hydrogen Financial Analysis Scenario Tool*** **(H2FAST)**

- Generally accepted accounting principles (GAAP) analysis of individual hydrogen infrastructure projects (production, distribution, retail dispensing stations)
- Compatible with International Financial Reporting Standards (IFRS)
- Annual computation of income statements, cash flow statements, balance sheets.
- Cost attribution by category
- Incentive policy analysis
- Risk analysis





https://www.nrel.gov/hydrogen/h2fast.html

Hydrogen Specific Model Suite

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5. GREET
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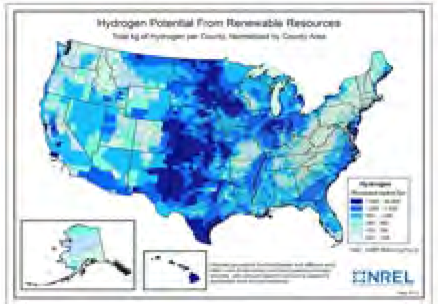
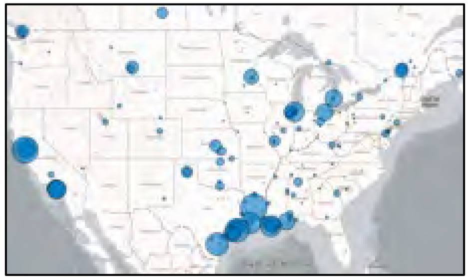
7. RoDEO

Overview of Hydrogen Supply Chain Modeling In SERA

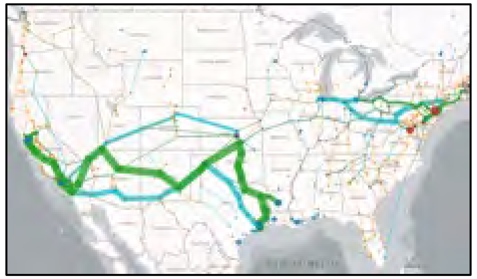
Energy Resources → **Hydrogen Production** → **Storage & Delivery** → **Retail Station Networks**



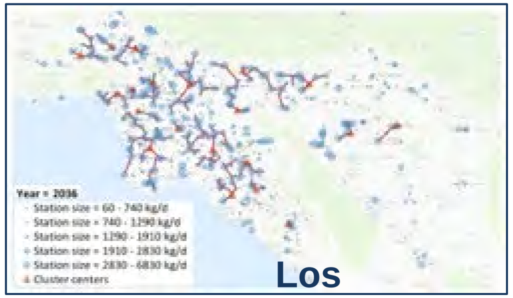
- Energy prices (natural gas, electricity, etc.)
- Renewables (biomass, solar, wind)
- Terrain, rights of way, etc.



- Central and onsite production facilities
- Capacity sized to meet forecasted demand
- Economies of scale balanced with delivery costs



- Truck delivery, rail, and pipeline.
- Cost is sensitive to volume, distance
- Seasonal and weekly storage
- Networked supply to multiple cities



Los Angeles

- Coverage stations for FCEV introductions
- Station sizes increase with market growth
- Liquid and pipeline delivery networks compete for large stations

The SERA model simulates least-cost hydrogen infrastructure supply systems for industrial & transportation markets

https://www.nrel.gov/hydrogen/sera-model.html

Hydrogen Specific Model Suite

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2. HDSAM
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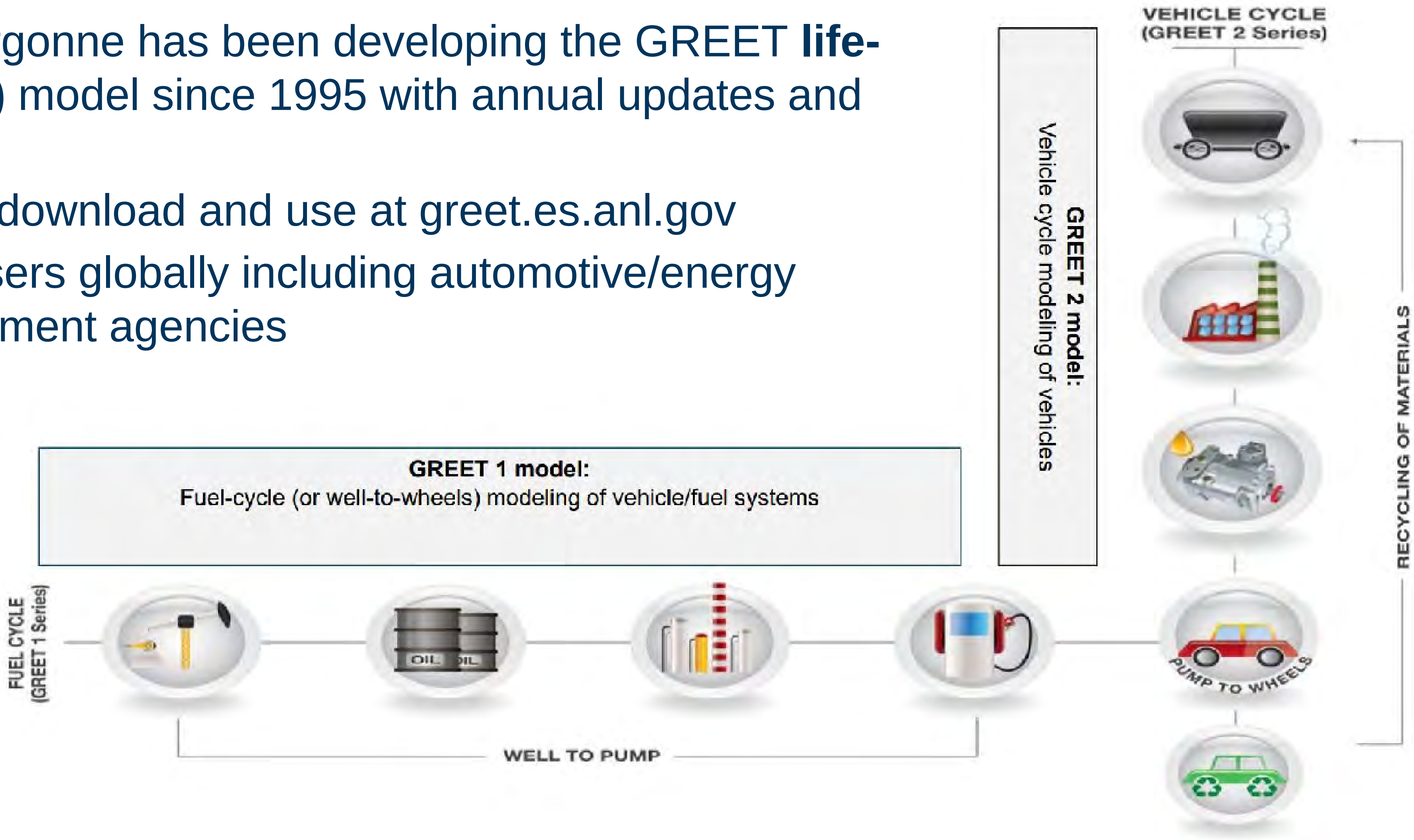
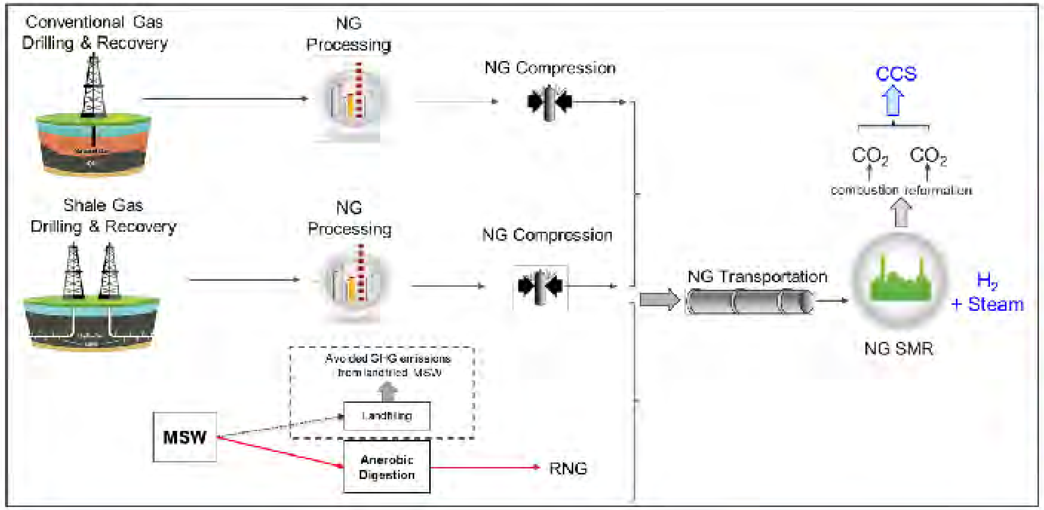
7. RoDEO

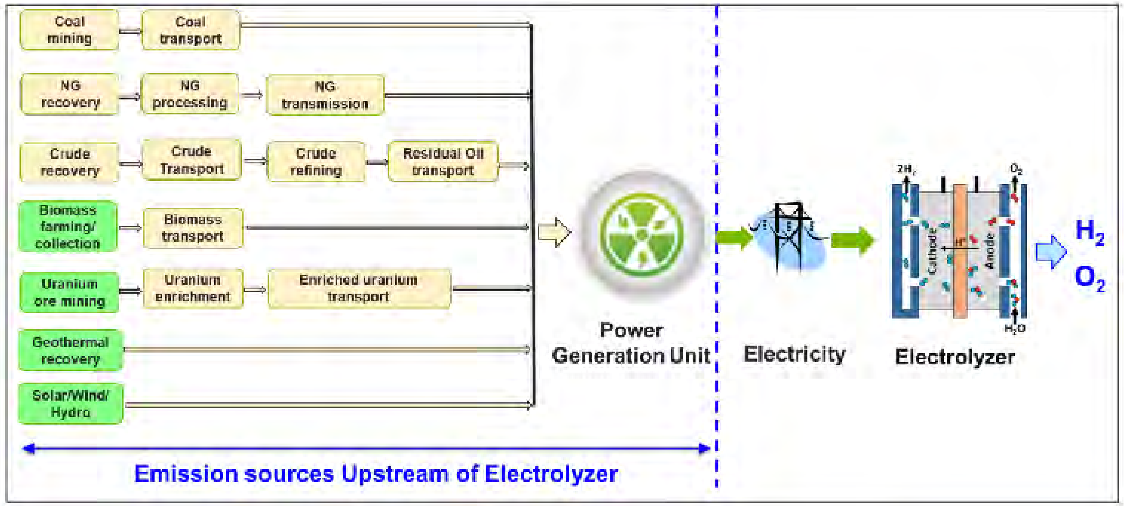
The GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model

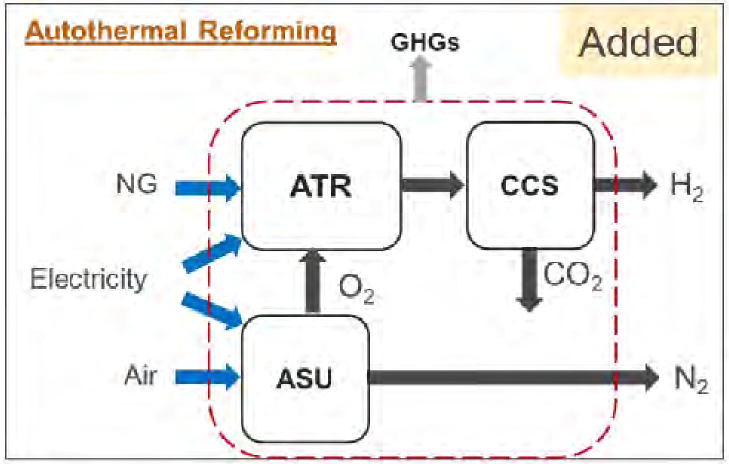
- With DOE support, Argonne has been developing the GREET **life-cycle analysis (LCA)** model since 1995 with annual updates and expansions
- It is available for free download and use at greet.es.anl.gov
- >50,000 registered users globally including automotive/energy industries and government agencies

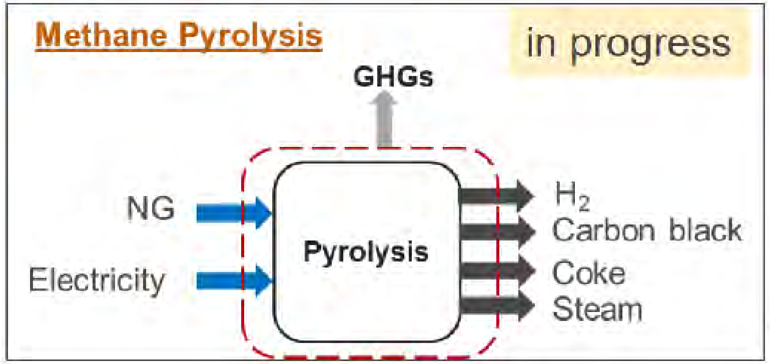


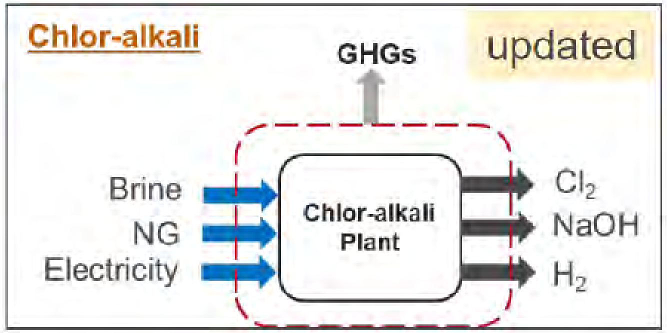
Conventional and emerging H_2 production technologies in GREET





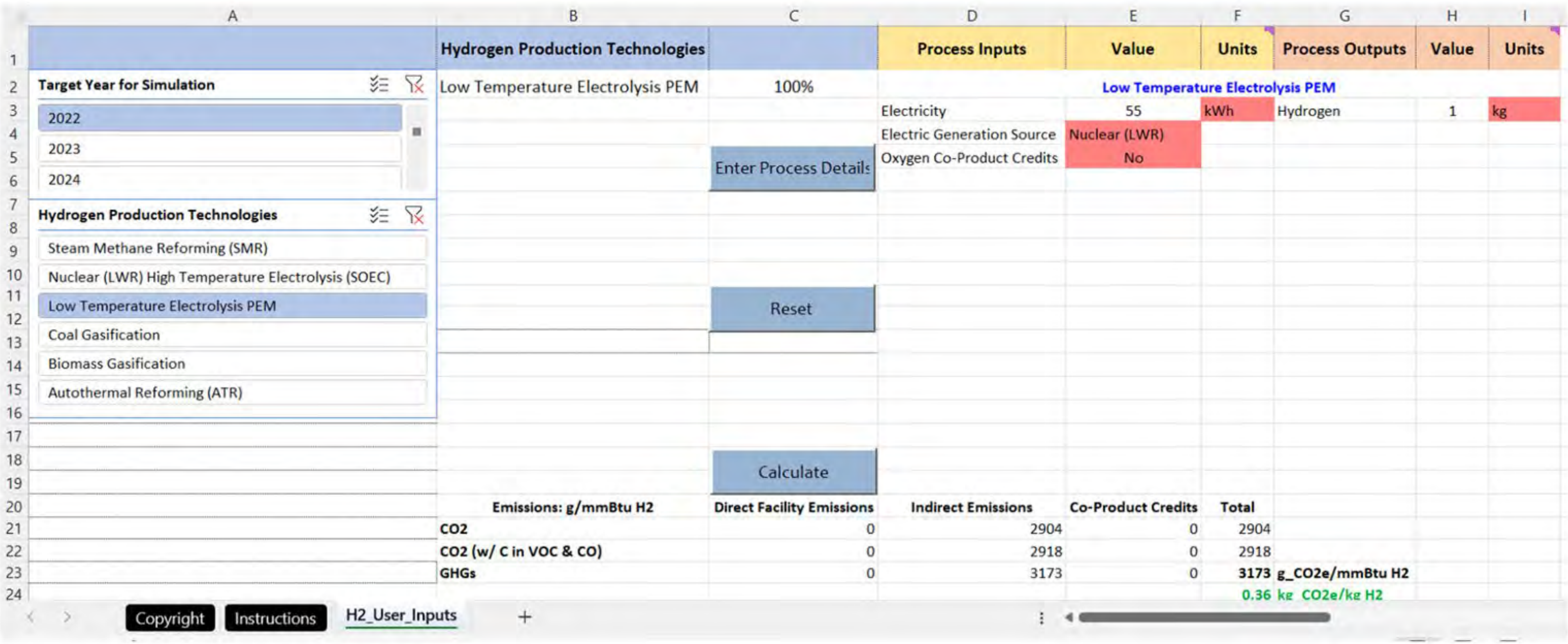






NG = natural gas
RNG = renewable NG
SMR = steam methane reforming
ATR = autothermal reforming
MSW = municipal solid waste

Developed a H_2 module user interface with simple process inputs and outputs



Simple process data input, output and various levels of emissions results in the same worksheet

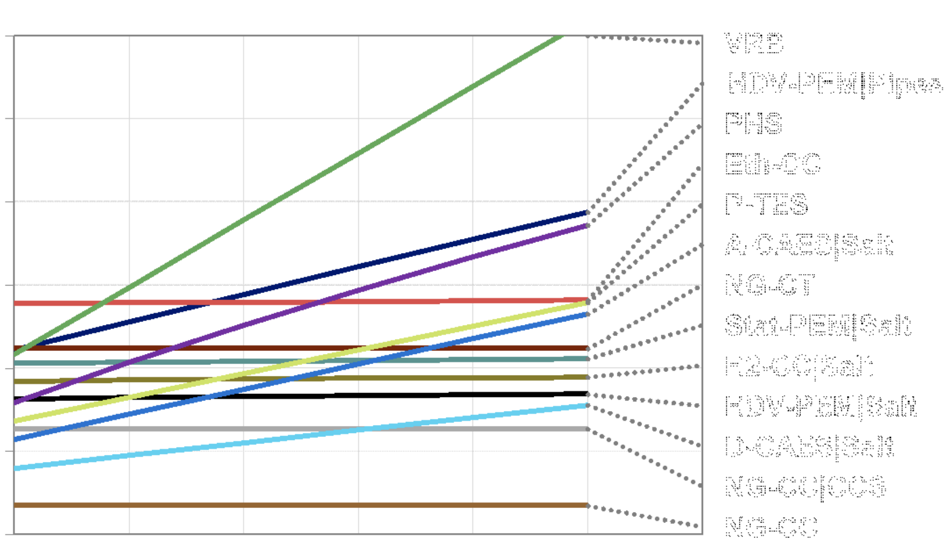
- GREET with H2 Interface model and publication: https://greet.es.anl.gov/greet_hydrogen
- H2 Interface Tutorial: https://www.youtube.com/watch?v=0NakQjCUSoQ

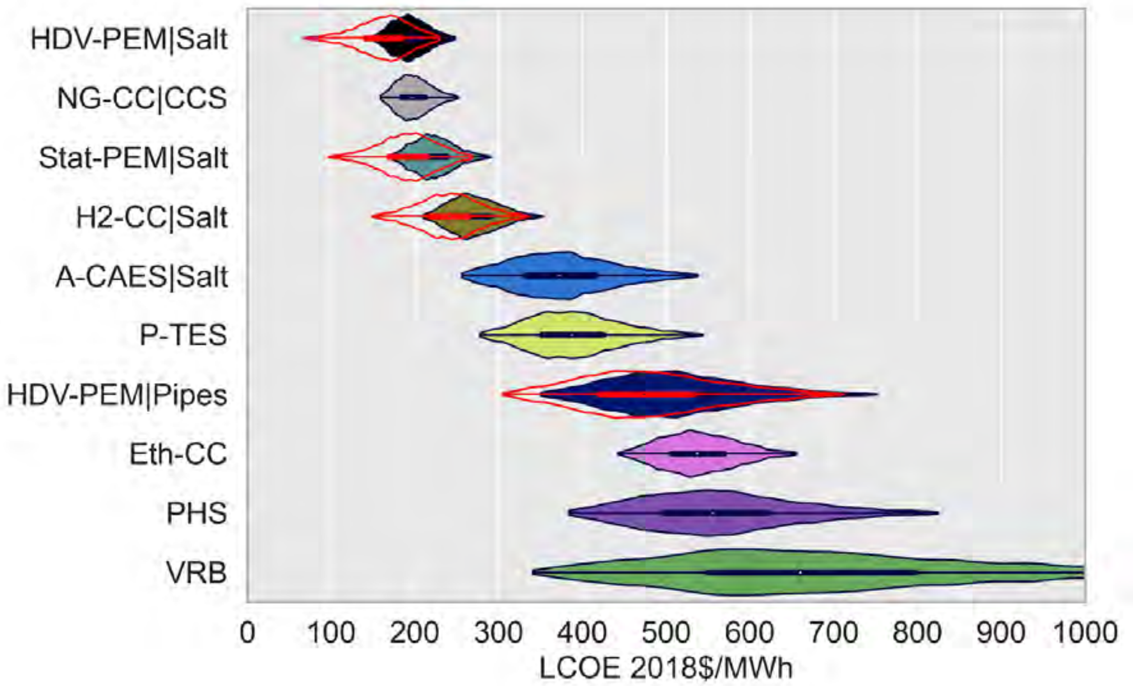
Hydrogen Specific Model Suite

1. Production models (H2A & Lite)
2. HDSAM
3. H2FAST
4. SERA
5. GREET
6. StoreFAST
7. RoDEO

StoreFAST – A tool for techno-economic analysis of energy storage technologies

- **Long-duration energy storage is not well understood** but essential for deep decarbonization of the electricity grid
- NREL created and **published a free spreadsheet tool** for anyone to quickly analyze long-duration and flexible power generation technology systems
- This tool is unique as it **analyzes up to 15 technology systems simultaneously** and uses operating data based on PLEXOS grid modeling done by NREL
- This tool is based on a **Joule publication** https://www.cell.com/joule/fulltext/S2542-4351(21)00306-8
- Learn more at: https://www.nrel.gov/storage/storefast.html





Hydrogen Specific Model Suite

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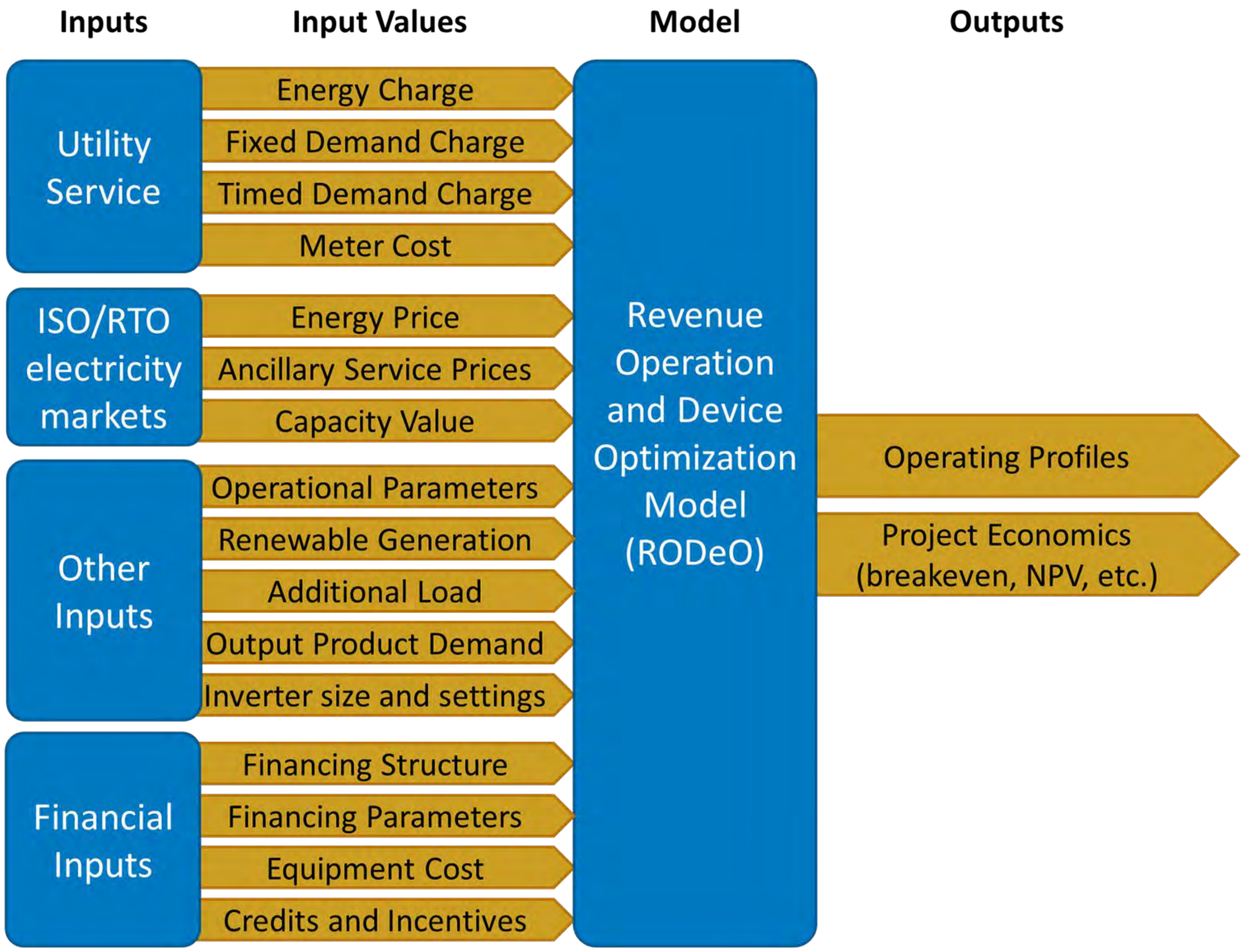
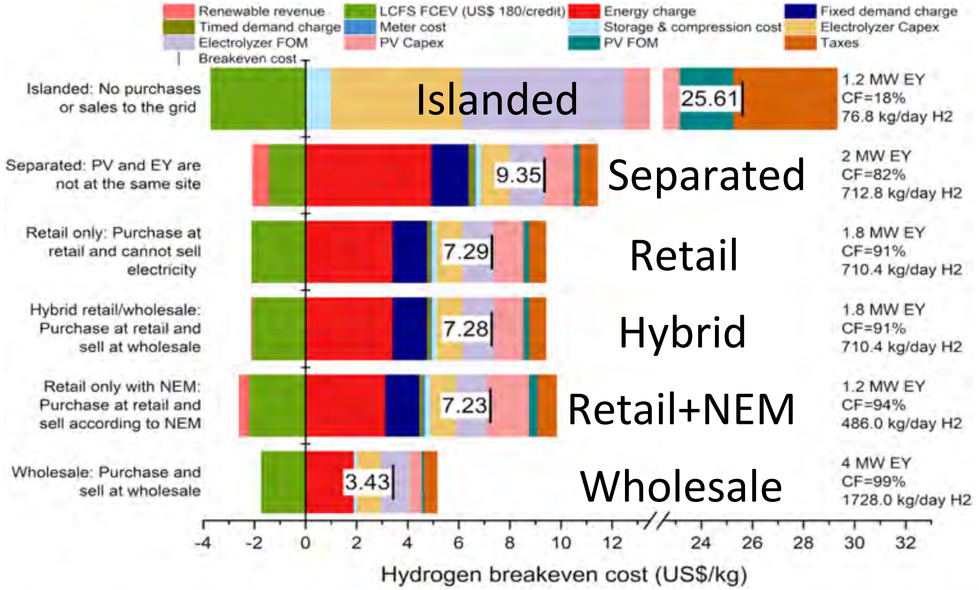
Dispatch optimization using RODeO can determine the best operating strategy for hydrogen production systems

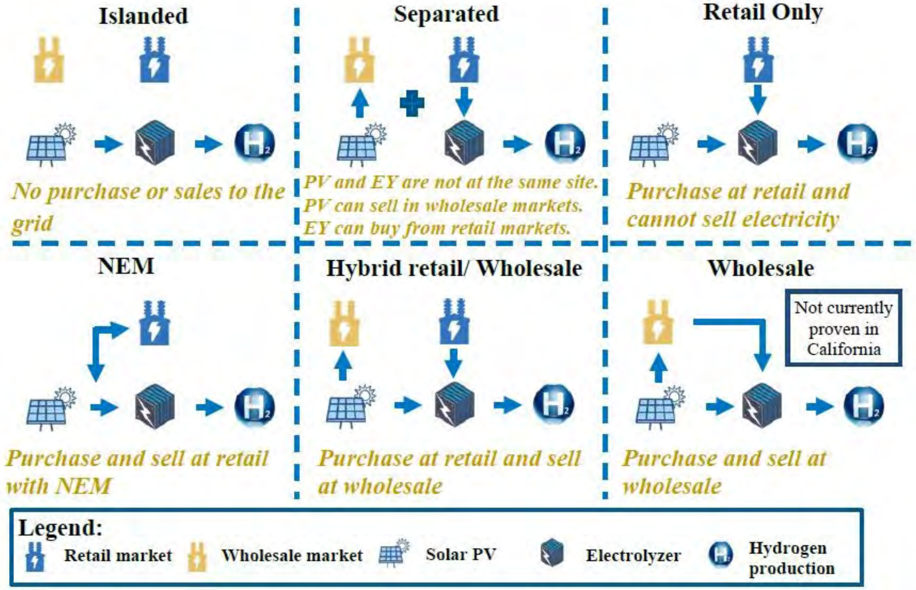
- RODeO is a price-taker model formulated as a mixed-integer linear programming (MILP) model
- Open source; written in Generic Algebraic Modeling Software (GAMS) platform
- Objective: minimize the levelized cost of hydrogen for a collection of equipment at a given site
- Potential equipment
  - Generators (gas turbine, steam turbine, solar, wind, fuel cells, etc.)
  - Storage (batteries, pumped hydro, hydrogen, etc.)
  - Flexible loads (EVs, electrolyzers, buildings)

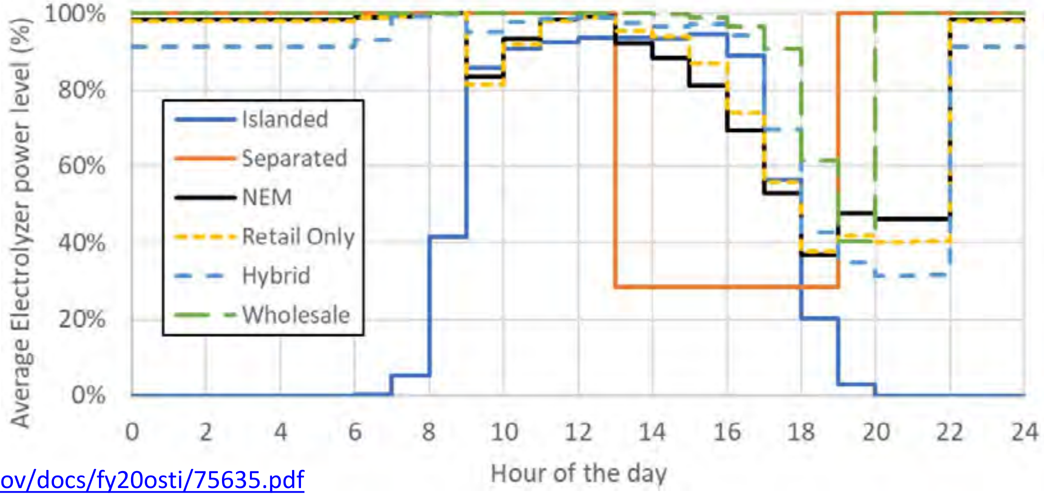


Optimized Hydrogen Production Cost Analysis with RODeO

- RODeO can be used to estimate the break-even price of hydrogen for different energy input scenarios
- It optimizes the hourly dispatch of the electrolyzer based on renewables output and grid electricity costs
- Can also be used to analyze hydrogen energy storage with tanks/geological caverns and fuel cells/H2 turbines







[7] Eichman et al. “Optimizing an Integrated Renewable-Electrolysis System”. NREL/TP-5400-75635. March 2020. https://www.nrel.gov/docs/fy20osti/75635.pdf

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An Initiative of the Clean Energy Ministerial

Thank you!

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Next Steps

- **Please take our survey! It will surface as soon as the event ends. Your feedback is highly valued!**

- **Register for our next workshop installment:**
  Hydrogen to Support Climate Targets - February 21, 2024 | 9:00 – 11:00 am EST

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Thank you for joining!

Questions? Contact Expert@CleanEnergySolutions.org.