Solid Oxide Electrolysis Cells (SOEC) integrated with Direct Reduced Iron (DRI) plants for producing green steel

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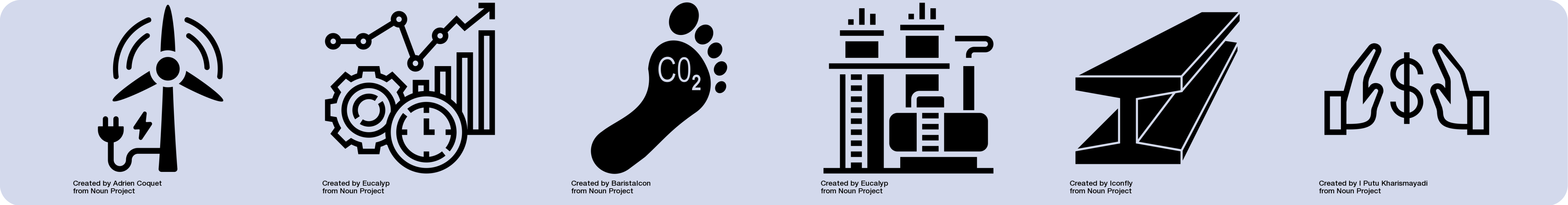
DOE project award #DE-EE0009249
August 31st, 2021

UCI University of California, Irvine

Project Goals

Advance, demonstrate and optimize a thermally and chemically integrated Solid Oxide Electrolysis Cell (SOEC) system, as co-producer of H_2 and O_2, with a Direct Reduction Iron (DRI) plant at 1 ton/week of product scale.

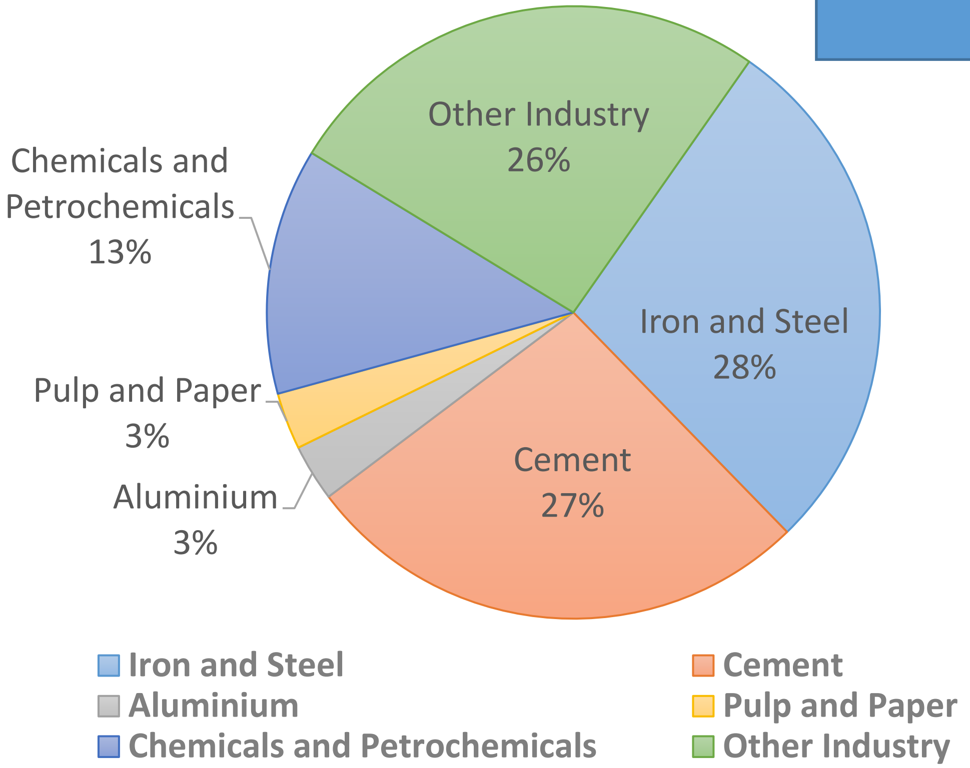


Specific primary energy consumption <8 GJ/t_{DRI}	Electric-to-hydrogen efficiency for an SOEC stack of <35 kWh/kg of H_2 produced	Specific CO_2 emissions rate < 90 kg CO_2/ton DRI product w/o oxyfuel	Pilot system at production capacity of 1 ton/week and TRL 4	Scale-up design for a 2 Mton/year DRI product capacity	Total capital specific cost < $200/ton equivalent pig-iron per year

Total Project Budget: $5,664,862.00 – Total DOE Share: $4,043,993.00 – Total Cost Share: $1,620,869.00

Relevance/Potential Impact

Direct Industrial CO2 emissions



WorldSteel association – World steel in figures 2020
International Energy Agency (IEA)

Steel industry:
World total 1869 $Mton_{steel}$
6-6.5% of total anthropogenic CO_2 emissions

Blast Furnace + Basic Oxygen Furnace (BF+BOF)
Hydrogen Direct Reduction (HDR)
Hybrid Hydrogen Direct Reduction (Hybrid HDR)

	Units	BF+BOF	HDR	Hybrid HDR
Energy intensity	$GJ/ton_{crude\ steel}$	19-20	<8	<9
Specific emissions	$ton_{CO2}/ton_{crude\ steel}$	1.8-1.9	<0.09	<0.09
Specific cost	$\$/ton_{eq\ pig\text{-}iron}\ yr$	210	200*	200*
Electric load	$GJ_{el}/ton_{crude\ steel}$	-	<7	<7
*At 2 Mton/yr scale				

	Units	Ref SOEC	HDR	Hybrid HDR
Hydrogen Eff.	kWh/kg	40	35	-
Syngas Eff.	kWh/kg	45	-	40
Oxygen Eff.	kWh/kg	6.5	<5	<5

Project Work Packages

WP1: System integration and thermodynamic analysis

- *Plant conceptualization and thermodynamic analysis*
- *DRI kinetics at high H_2 concentrations*
- *Assessment of product quality*

WP2: SOEC module design and control

- *SOEC module sizing and nominal load design*
- *SOEC thermal management*
- *SOEC control strategy development*

WP3: SOEC prototype design, construction and testing

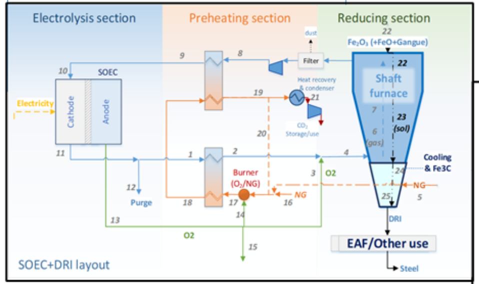
- *Testing in relevant conditions for DRI operation*
- *SOEC prototype design*
- *SOEC prototype fabrication*

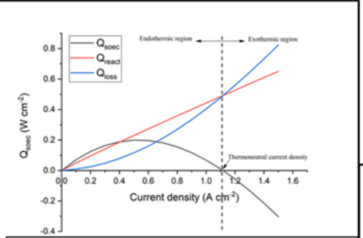
WP4: Design and characterization of pilot-scale SOEC+DRI process

- *Design and commissioning of DRI simulator*
- *Integration and commissioning of SOEC module into DRI test bench*
- *Characterization and testing of integrated SOEC+DRI system*

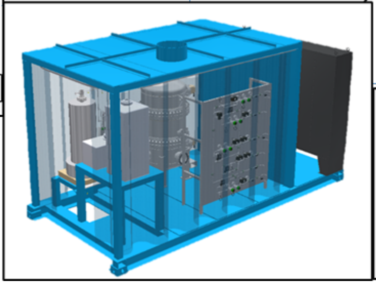
WP5: Techno-economic optimization of full scale SOEC+DRI layouts

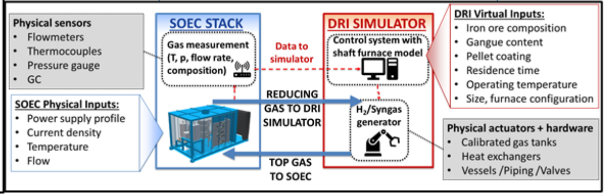
- *Economic and market background build-up*
- *Design and Techno-economic assessment of full-scale system*
- *Comparative assessment with state-of-the-art*
- *Sector coupling assessment*

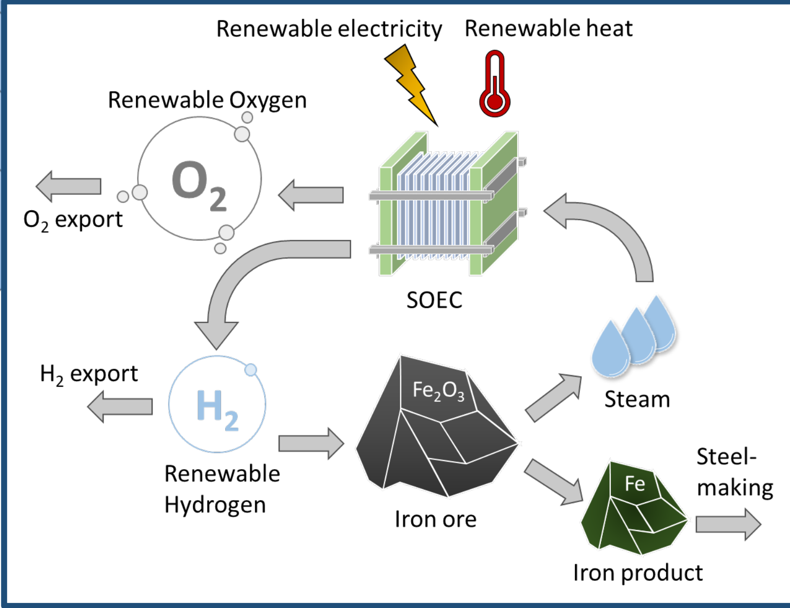




Mastropasqua et al., 2020, Applied Energy 261, 114392



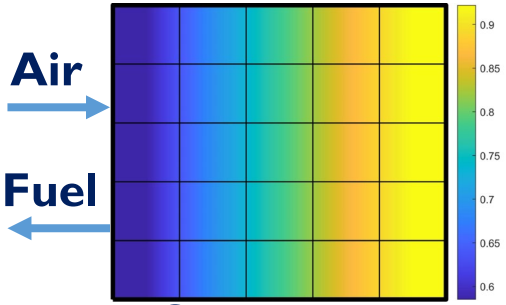




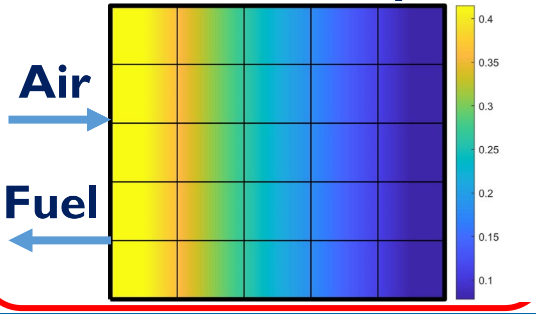
Hydrogen Direct Reduction (HDR) concept

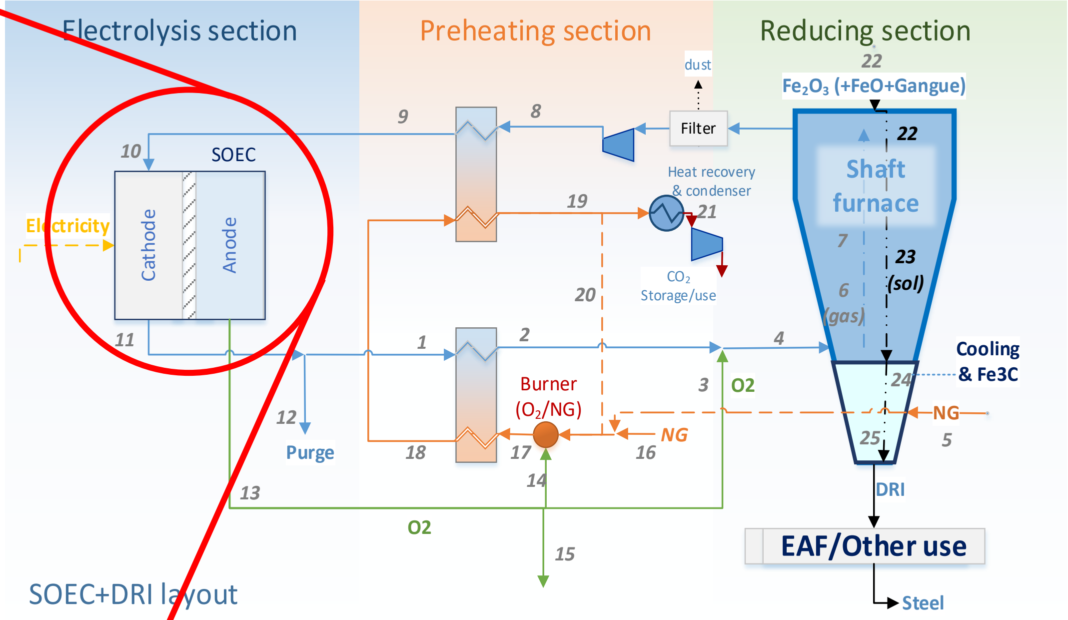
Voltage = 1.206 V
Current Density = 829 A/m2
Operating Power = 495 MW
Steam Utilization = 0.8936
Pressure = 7 bar
Efficiency = 95%

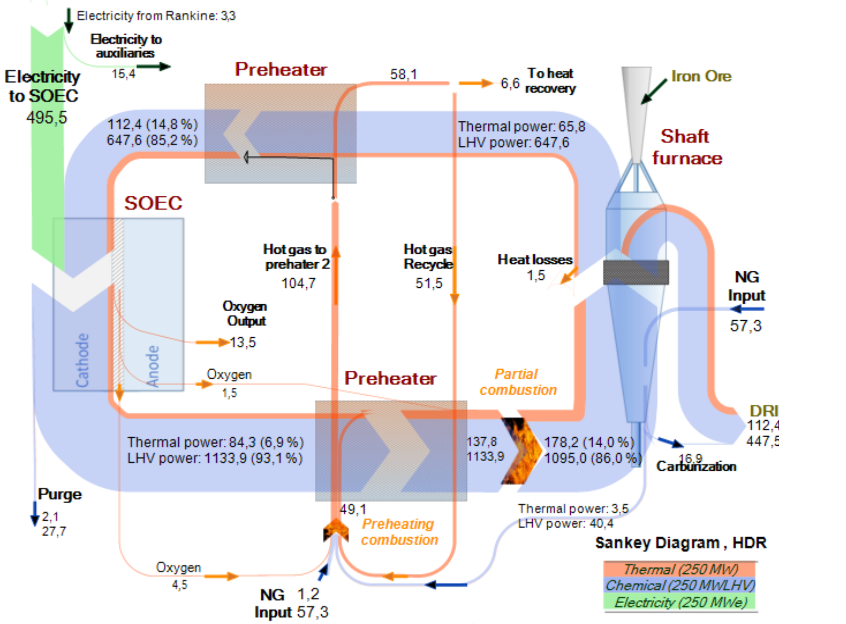
Hydrogen map



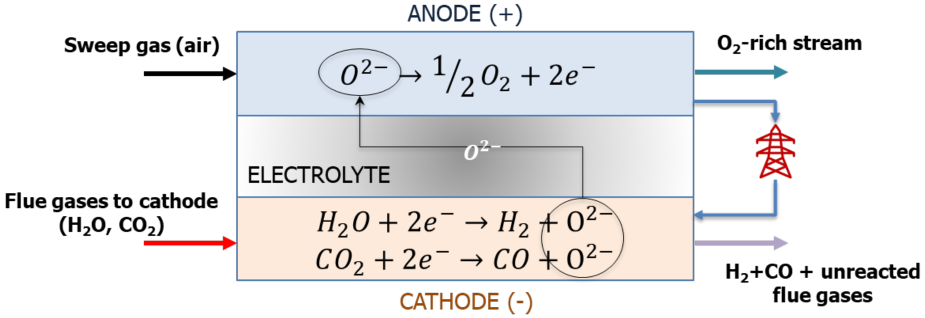
Steam map

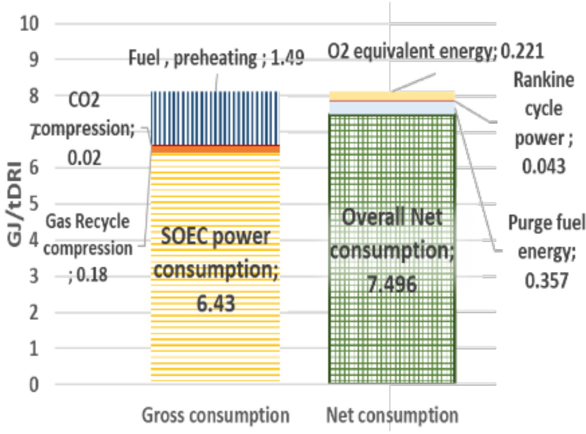






Steam and co-electrolysis



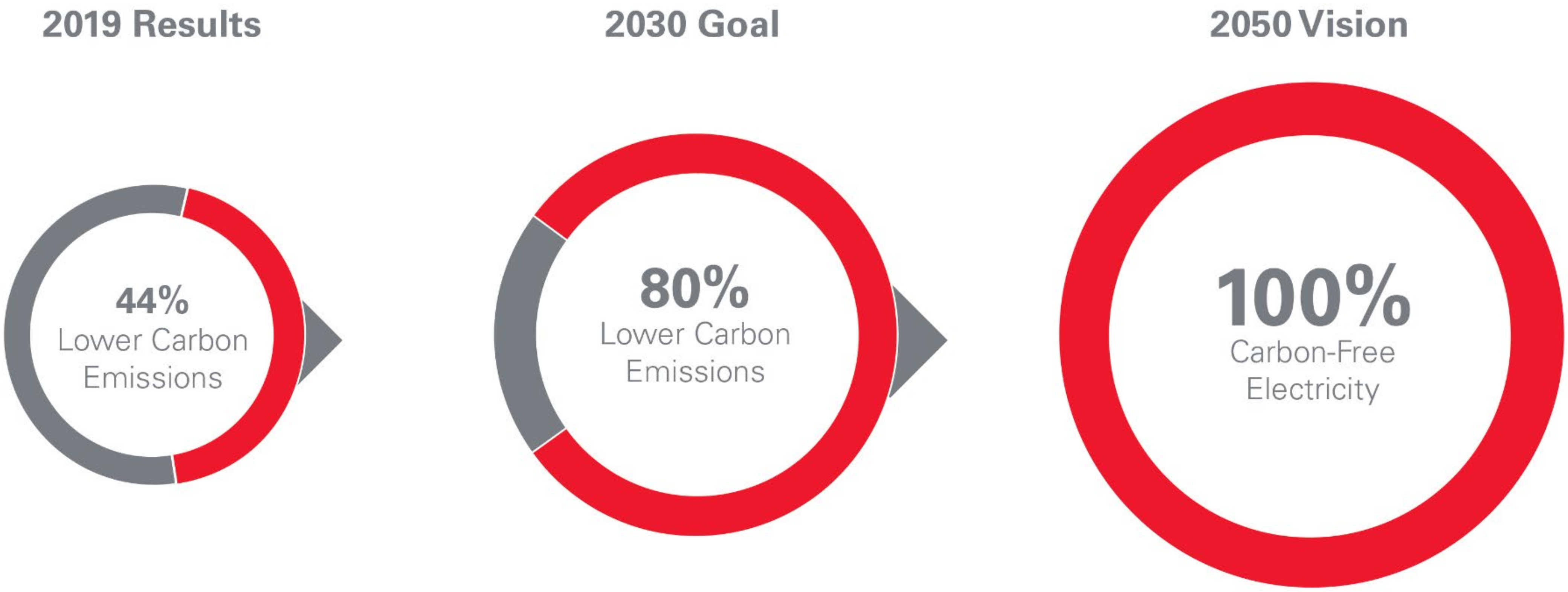


Carbon Free Hydrogen from Nuclear Power

9/2/2021

Leading the Clean Energy Transition

A bold vision for a carbon-free future



Company-wide emissions reductions from the electricity serving our customers, compared to 2005

NUCLEAR CONSORTIUM:
WORKING FOR THE FUTURE OF NUCLEAR

Xcel Energy®

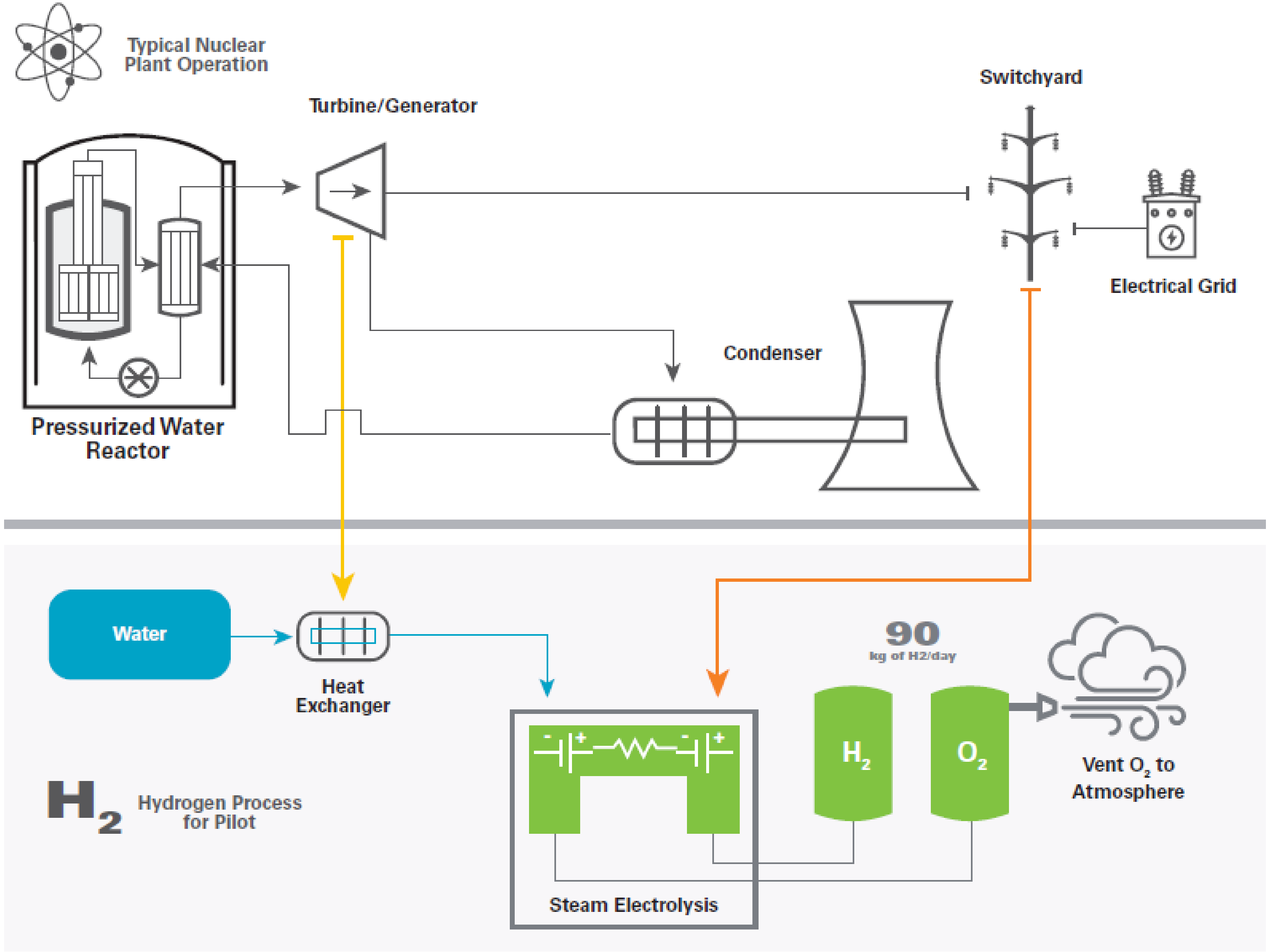
energy harbor

aps®

INL Idaho National Laboratory

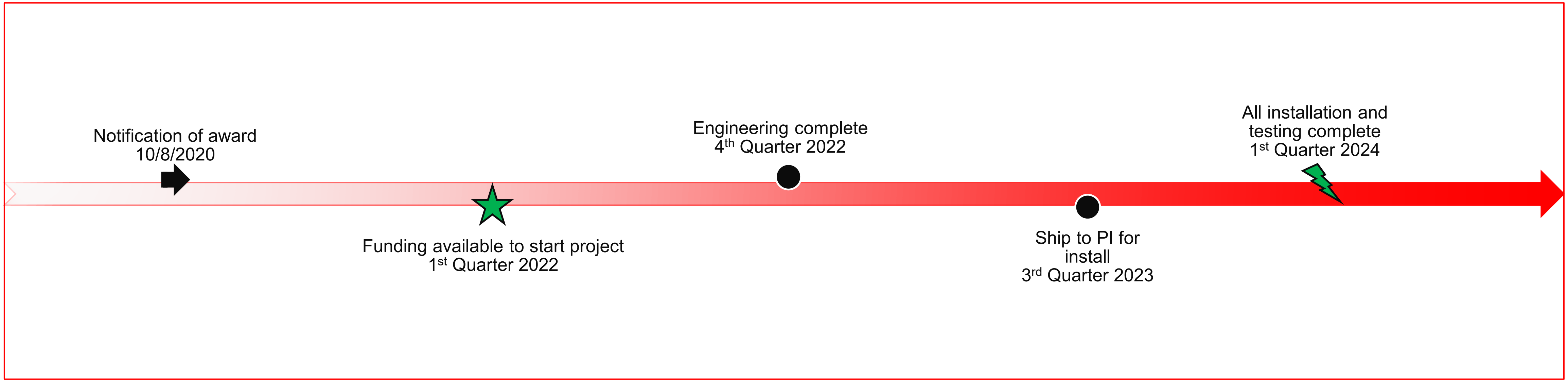
Phased Approach - DOE Funded Scope
Phase 1 Install Low Temperature Electrolysis (LTE) Skid ***[Energy Harbor]*** Technical and Economic Assessments (due mid-2021) ***[Xcel Energy & APS]***
Phase 2 Installation of High Temperature Steam Electrolysis (HTSE) Skid ***[Xcel Energy]*** Complete design work for Reversible HTSE skid ***[APS]***
Phase 3 – Future Expansions on Phase 2 work, hydrogen storage, use demonstration, other. ***[TBD]***

Producing Hydrogen From Carbon-free Nuclear Energy



Pilot Project Schedule

- Project must be completed within 2 years of funding receipt
- All dates pending receipt of funding



Hydrogen & Integrated Electrolyzer Systems Panel

Noah D. Meeks, Ph.D., P.E.
R&D

For: Hydrogen Shot Summit
September 1, 2021

Southern Company

Research & Development

Roadmap for Emerging Hydrogen Applications

Increase utilization of existing infrastructure

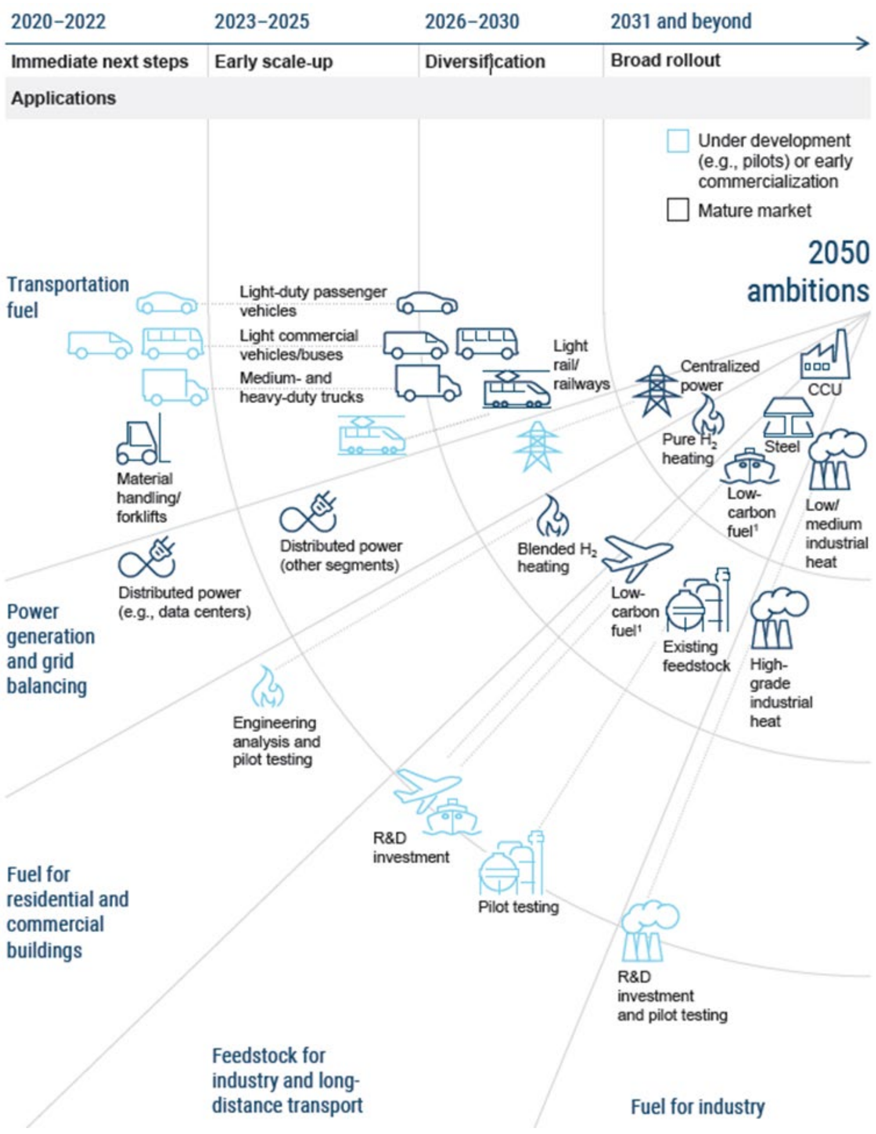
- “Indirect Electrification” and value stacking
- Hydrogen competes against petrol

Scale decarbonized energy for transportation and industrial sectors

- Expand to chemical and thermal potential

Deep decarbonization of electricity operations and delivered gas

- Bulk energy storage
- Central station H_2-based power



Transportation and resilient / peak shaving power are early mover markets

Power → Electrolysis → Hydrogen → Fuel Cells → Resilient and High-value Power

Transportation: logistics, employees, customers, off-road **Future:** shipping, aviation

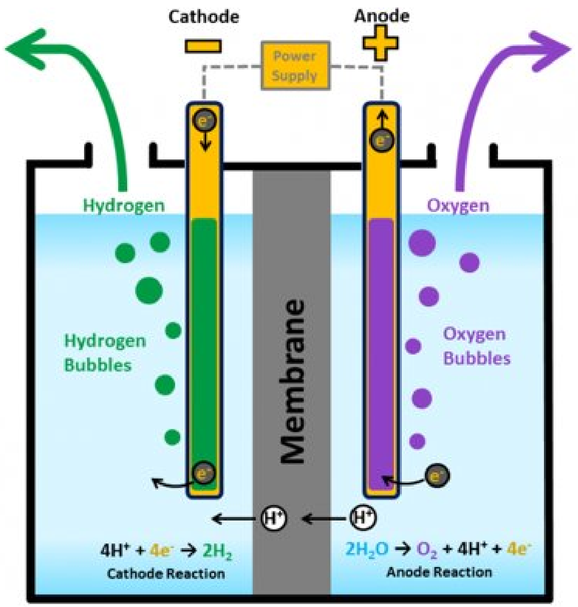
PowerSecure Demo
- Demonstrate equipment performance
- Understand storage and scaling
- Develop strategic partnership with Plug Power

OPCO Distribution Center
- Integrate vehicle energy loads
- Develop strategic partnership with auto OEM
- Showcase customer opportunity for OPCO

Customer Sites
- Demonstrate value for customer
- Provide win-win-win-win for customer, Company, partners, and environment

Hydrogen Production - Electrolysis

- Hydrogen production via electrolysis is currently <5% current US hydrogen market (not using clean electricity)
- Overall cost of hydrogen primarily a function of power price & capacity factor
- Technological cost drivers are efficiency, capital cost, and lifetime



Non-technology issues:

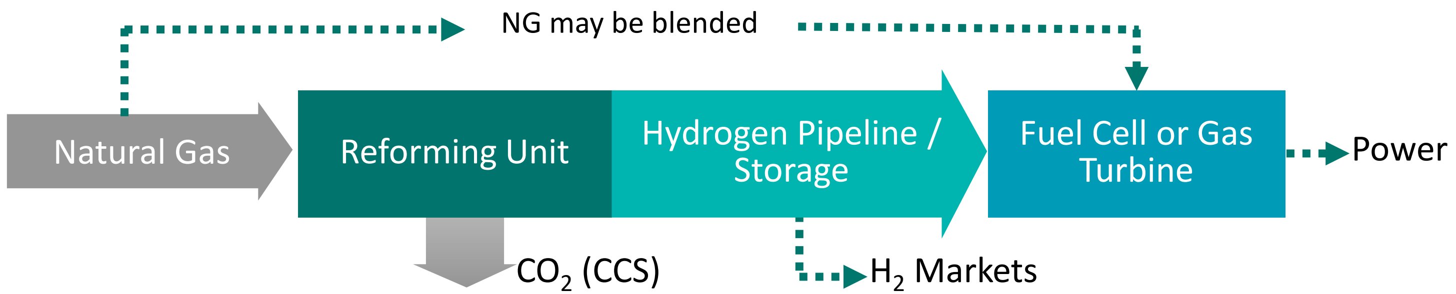
- Regulatory treatment of electrolysis uncertain
- "Indirect electrification" viewed as competing with "electrification" efforts
- Geographic deployment of fuel cell electric vehicles uncertain

Target H_2 Cost ($/kg)	Target System Capex ($/kW)	Target System Efficiency (kWh/kg)	Average Power Price ($/kWh)	Capacity Factor	Lifetime (years)
4	1,000	70	0.05	0.8	20
2	400	60	0.03	0.7	20
1	200	54	0.015	0.3	20

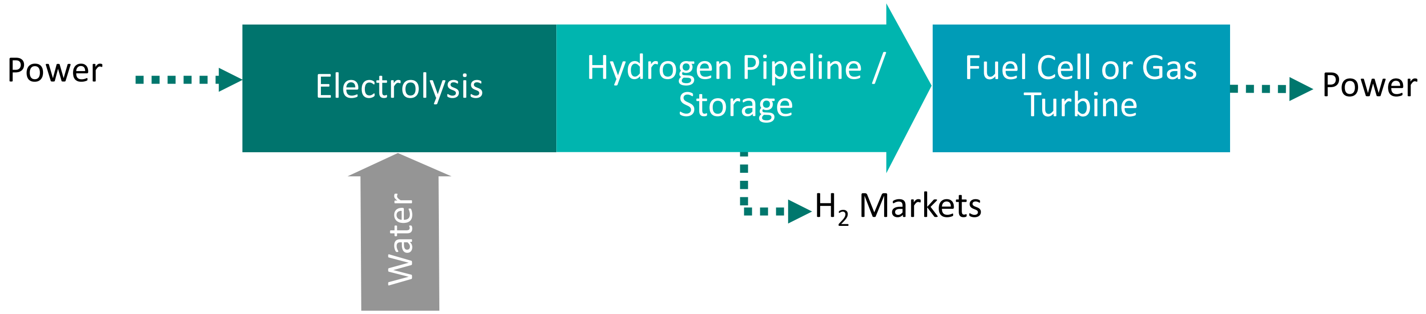
Note: $1/kg is target for power generation → The capacity factor looks like energy storage.

Hydrogen-based power generation is likely part of energy storage.

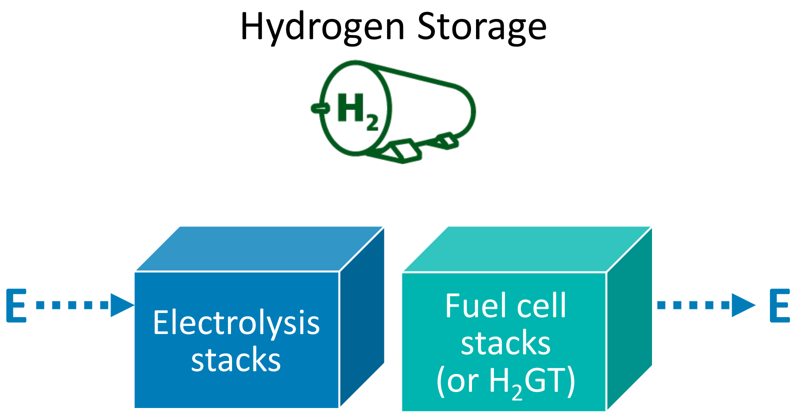
Pre-combustion carbon capture



Energy Storage

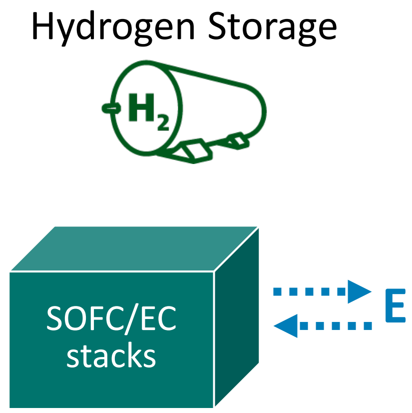


Cost reductions in energy storage are possible with technology.



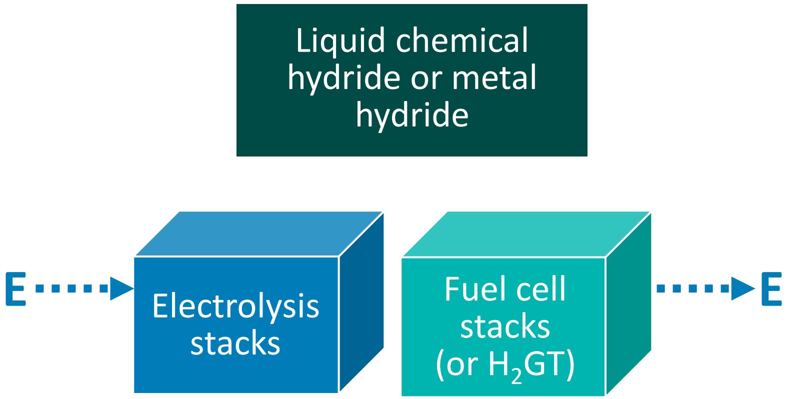
Conventional concept with separate electrolysis and fuel cell systems

- Degrees of freedom around multiple units
- Higher CAPEX
- More flexibility



Unitized FC/EC Concept

- Lower CAPEX
- Simplified operation
- Less flexibility



Integrated storage Concept

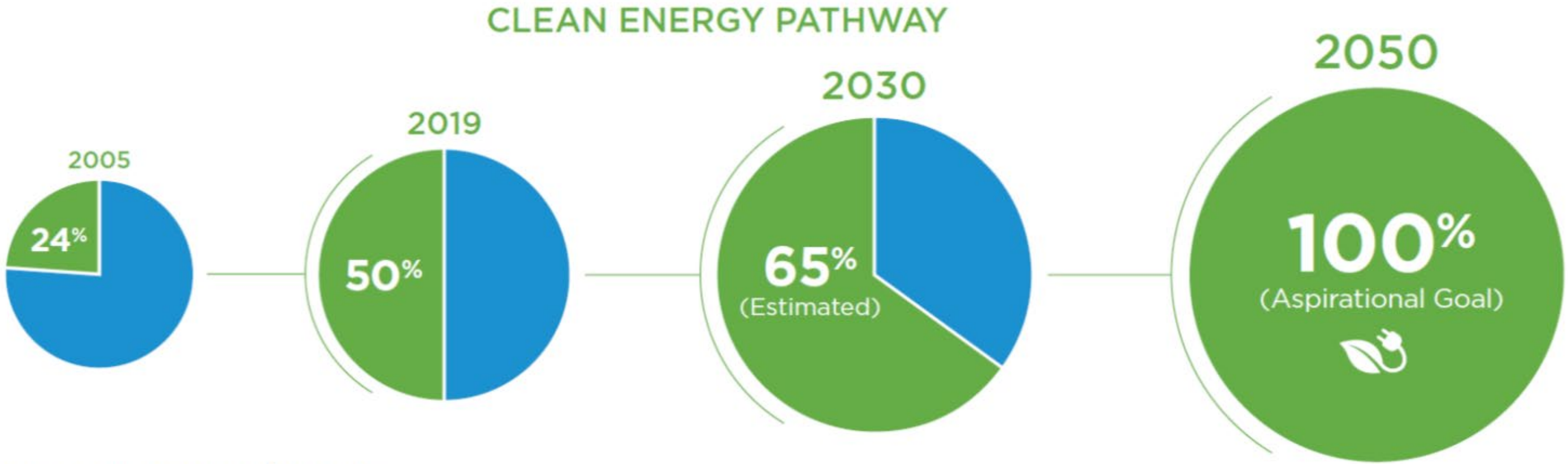
- Lower CAPEX
- Improved efficiency with heat integration

Hydrogen Shot Summit
Hybrid and Integrated Electrolyzer Systems Panel

Michael G. Green

September 1, 2021

Our Clean Energy Pathway



Clean energy commitments

Consortium: *The Future of Nuclear*

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Phase 2 Installation of High Temperature Steam Electrolysis (HTSE) Skid ***[Xcel Energy]*** Complete design work for Reversible HTSE ***[APS]***
Phase 3 – Future Scale up LTE demonstration for hydrogen/natural gas co-firing and synthetic hydrocarbon production. ***[APS]***

Project Summary and Status

- ~20 MW low temperature electrolysis with on-site compression and storage
- Objectives
  - Co-fire up to 30% hydrogen / 70% natural gas blend in natural gas fired power plant
  - Synthetic hydrocarbon production
- Status
  - Submitted funding application in April 2021
  - Anticipate work to begin first quarter 2022

aps

Electrolysis – How does it plug in on the grid?

Brittany Westlake, Ph.D.
Sr. Technical Leader, Low-Carbon Resources Initiative
EPRI
bwestlake@epri.com

Hydrogen Shot Summit
September 1, 2021

Decarbonization Pathways Enabled by Innovation

Decarbonization

~10-15 years

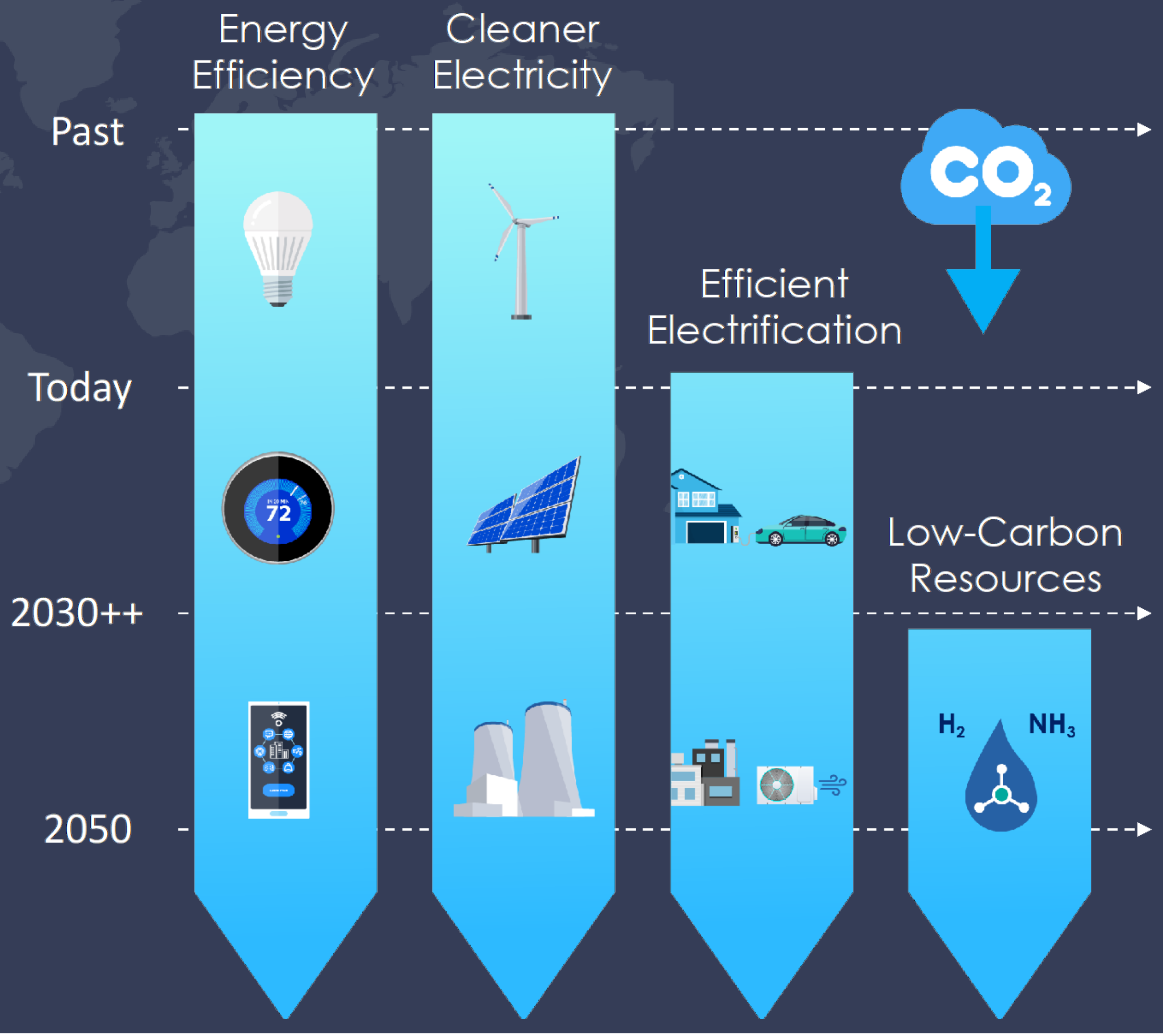
Accelerate economy-wide, low-carbon solutions

- Electric sector decarbonization
- Transmission and grid flexibility: storage, demand, EVs
- Efficient electrification

~15-30 years

Achieve a net-zero clean energy system

- Ubiquitous clean electricity: renewables, advanced nuclear, CCUS
- Negative-emission technologies
- Low-carbon resources: hydrogen and related, low-carbon fuels, biofuels, and biogas



The **Low-Carbon Resources Initiative** (LCRI) is a five-year R&D commitment focused on the advancement of low-carbon technologies for large-scale deployment across the energy economy. This initiative is jointly led by **EPRI and GTI**.

LCRI LOW-CARBON RESOURCES INITIATIVE

FOCUS

Multiple options and solutions to establish viable low-carbon pathways

Technologies for hard-to-decarbonize areas of the energy economy

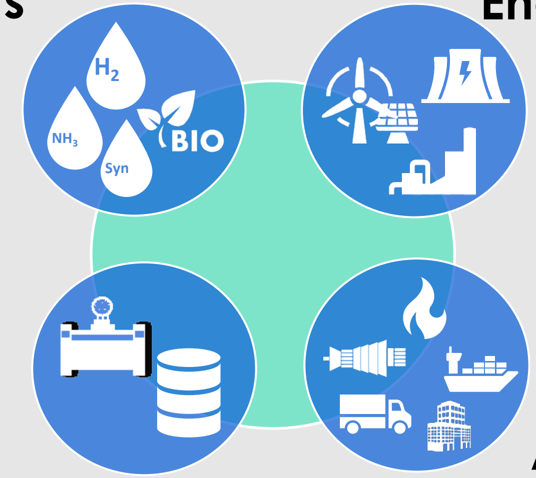
Affordable, reliable, and resilient integrated energy systems for the future

RESEARCH AREAS

Hydrogen | Ammonia | Synthetic/ Derivative Fuels | Biofuels

Production Pathways

Integrated Energy Systems



Storage & Delivery

End Use Applications

VALUE

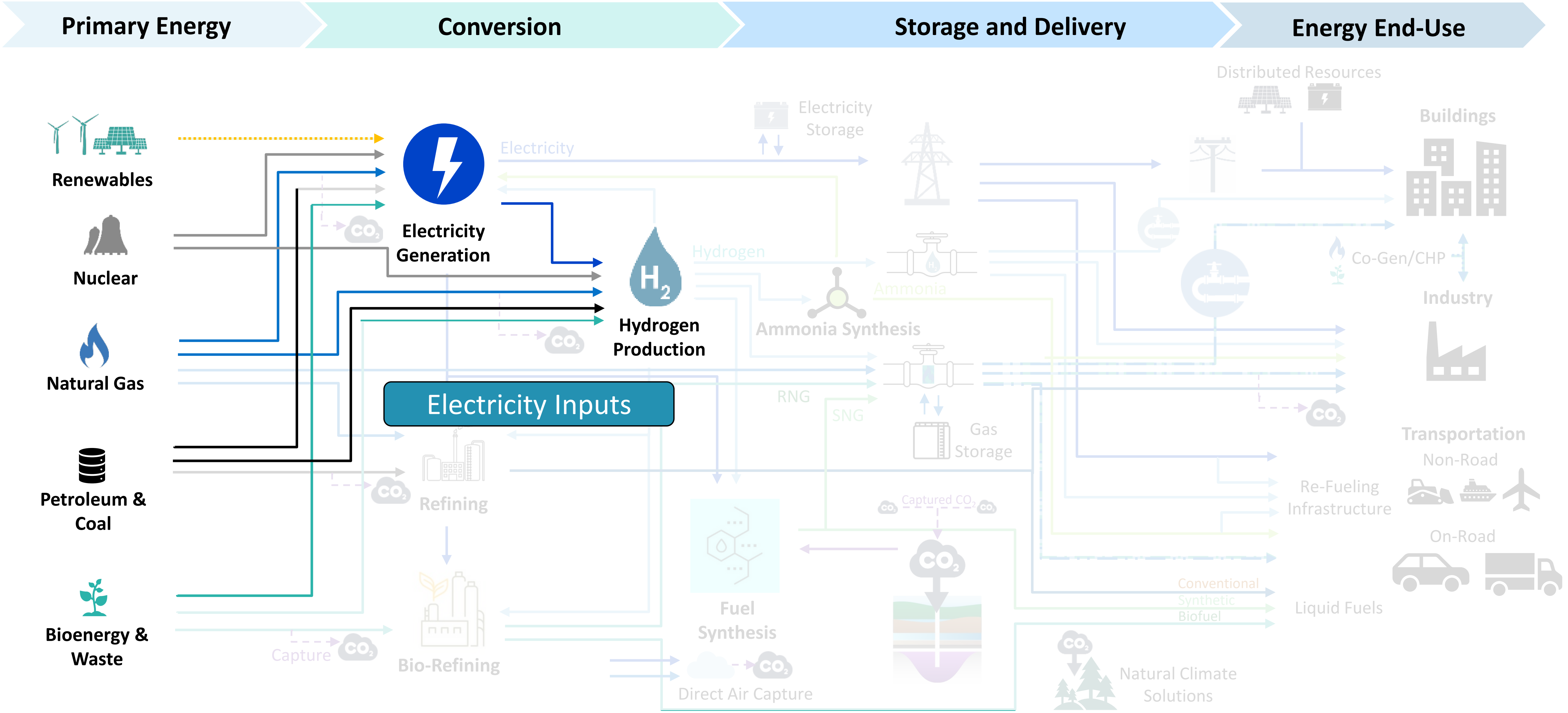
Independent, objective research leveraged by global engagement and collaboration

Comprehensive value chain approach across adjacent sectors

High-impact results that accelerate technology time to market

www.LowCarbonLCRI.com

Economy-Wide Low-Carbon Energy Pathways



Integration of Alternative Energy Carriers

LCRI
LOW-CARBON RESOURCES INITIATIVE

H_2 Production

Nuclear

Electrolysis

Clean Generation

Natural Gas CCS

H_2 Delivery

Utilize Existing or Develop New Pipelines

H2 Storage and Transport

H_2 End-Use

Boiler

Heavy Duty Transportation

Electric Generation

Advanced Fuel Cell

Large Industry

Chemical Process