Reimaging Deployment and Application of Nuclear Energy for Clean Energy at Scale

Vision for 2050 and Beyond

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NAS Committee Briefing for Study: Laying the Foundation for New and Advanced Nuclear Reactors in the US
July 20, 2021

Flexible Operations of Nuclear Plants – Departure from Full Power

Pre-Planned
100 - 70 -100% Power

- >12 hour duration - daily basis
- Ramp rate 0.5-1% per minute

Most frequent mode of FPO in the US to manage high renewable integration

Pre-Planned
50% Power

- 2-8 week duration
- Seasonal

Extended low power operation under consideration by some plant operators

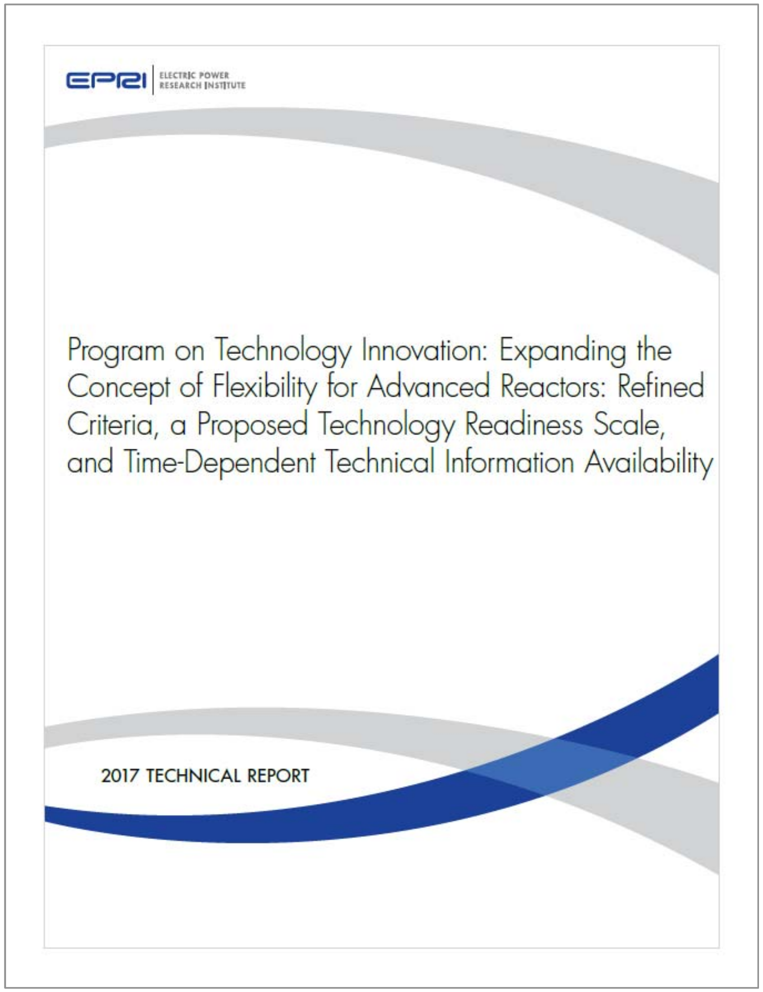
Extreme
100-30-100%

- Ramp rate 2-5% per minute
- Response to Grid - short notice, no defined duration

EXTREME - Response to grid transient; requires modification to plant and design basis (R&D needed)

Categorization of flexible operations for nuclear power plants in the United States by ramping requirements, frequency, and duration

Expanding Nuclear Flexibility Beyond Load Following



- An expanded flexibility paradigm and associated (measurable) technology criteria are warranted to better capture and categorize key attributes and applications of advanced nuclear energy systems

- Three flexibility categories proposed:
  - Operational flexibility (traditional definition +)
  - Deployment flexibility
  - Product flexibility

Expanding the Concept of Flexibility for Advanced Reactors. November 2017. Report 3002010479. https://www.epri.com/#/pages/product/3002010479/

Expanded Concept of Flexibility for Advanced Reactors

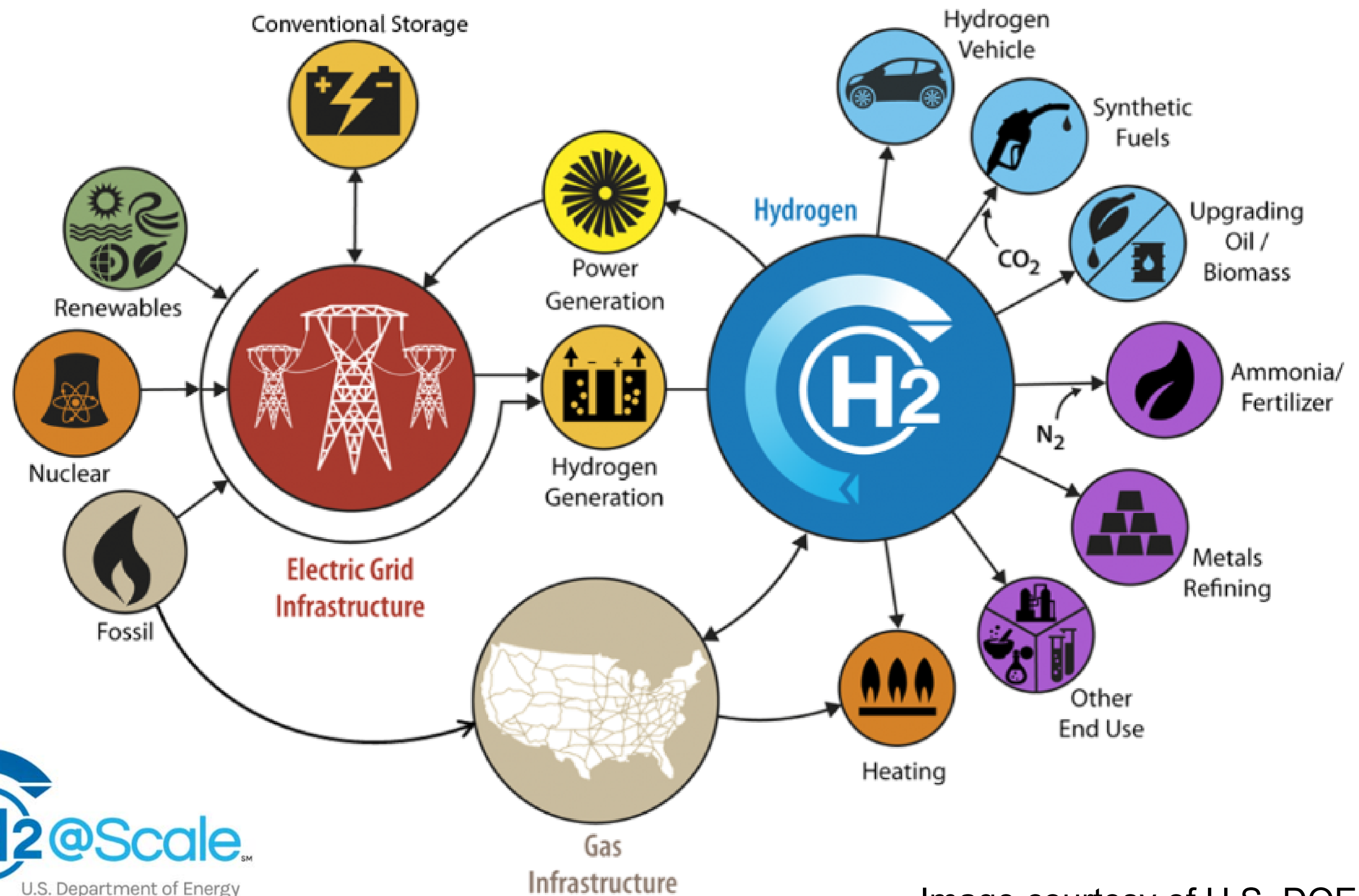
EPRI Report No. 3002010479, November 2017

Attribute	Sub-Attribute	Benefits
Operational Flexibility	Maneuverability	Load following
	Compatibility with Hybrid Energy Systems and Polygeneration	Economic operation with increasing penetration of intermittent generation, alternative missions
	Diversified Fuel Use	Economics and security of fuel supply
	Island Operation	System resiliency, remote power, micro-grid, emergency power applications
Deployment Flexibility	Scalability	Ability to deploy at scale needed
	Siting	Ability to deploy where needed
	Constructability	Ability to deploy on schedule and on budget
Product Flexibility	Electricity	Reliable, dispatchable power supply
	Process Heat	Reliable, dispatchable process heat supply
	Radioisotopes	Unique or high demand isotopes supply

Product Flexibility: Hydrogen as a Second Energy Carrier

Hydrogen offers an alternate path for:

- Deep decarbonization of industrial and transportation sectors
- Energy storage



H2@Scale
U.S. Department of Energy

Image courtesy of U.S. DOE

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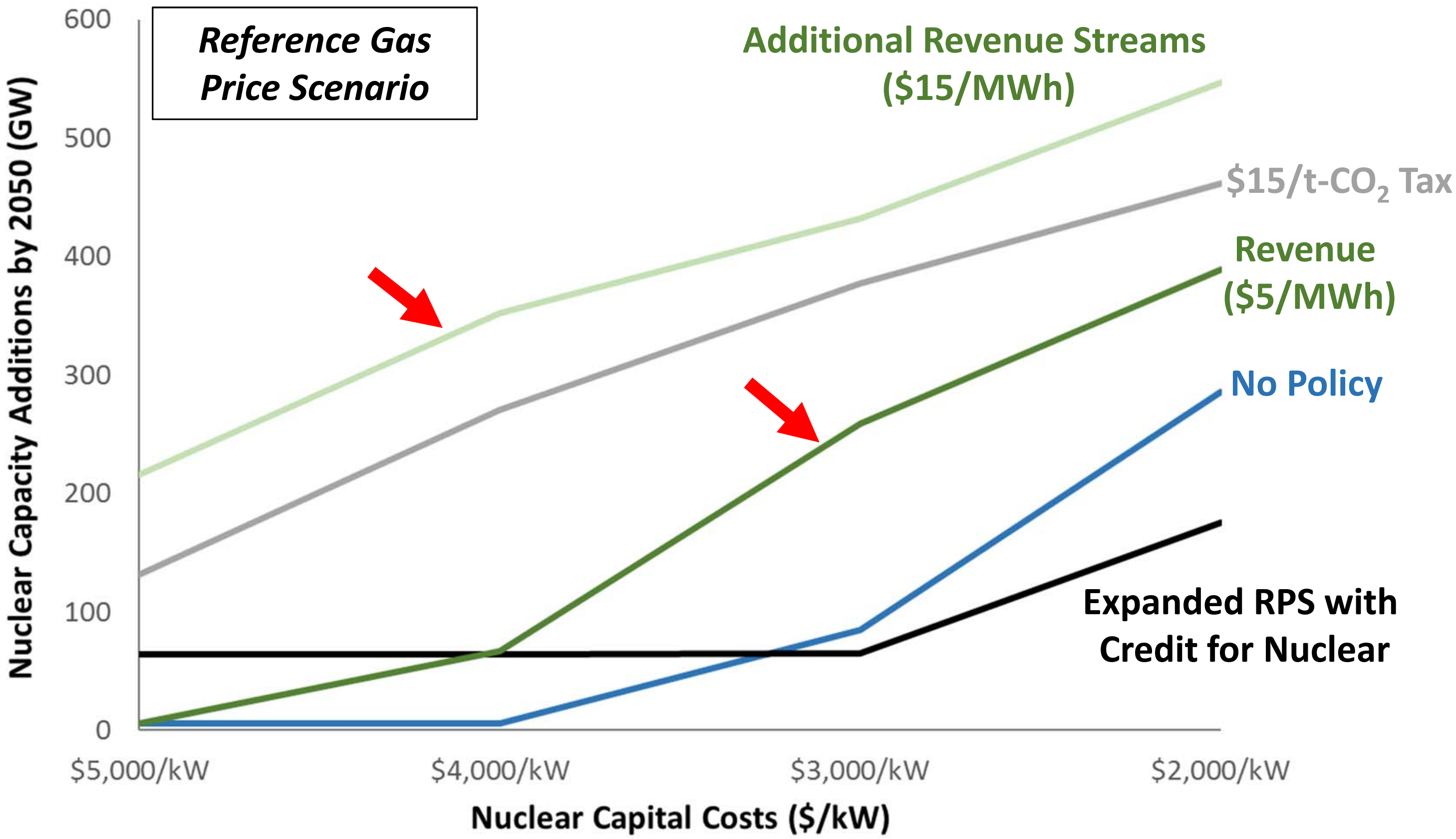
Increased Revenue Changes Nuclear Competitiveness Picture

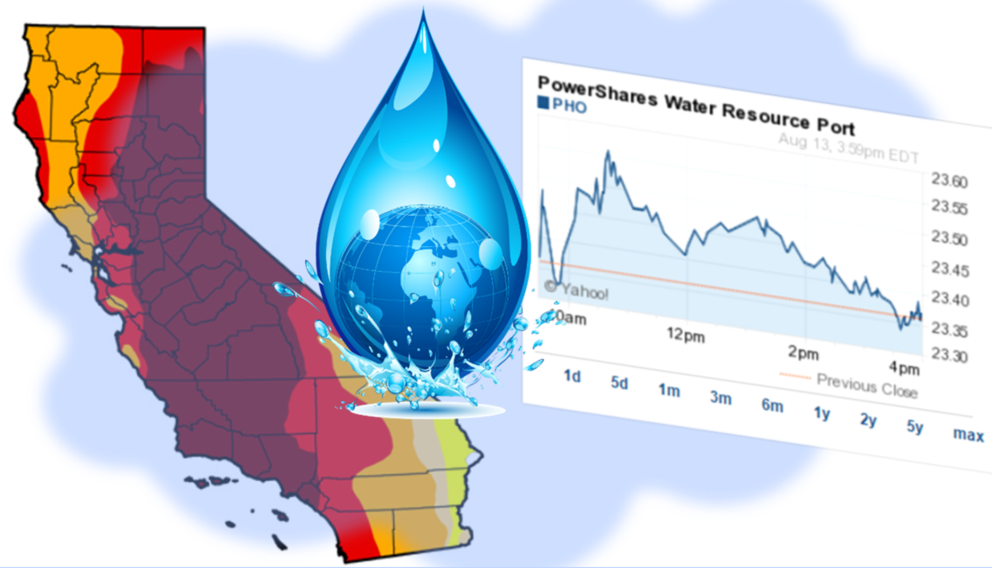
EPRI Report No. 3002011803, March 2018



Scenario analysis using EPRI's REGEN-US capacity expansion model

Vision: Scalable, Dispatchable, Zero-Carbon Energy from Nuclear

- Hydrogen-based and synthetic fuels to decarbonize heavy transportation
  - scalable drop-in substitute for liquid fossil fuels
  - overcomes challenges of battery technology from fundamental energy density limits



- Potable water as the “oil” of the 21st century
  - 50% of world’s population within 200 km of coast
  - Fresh water comprises only 2.5% of earth’s water
  - Only 1% of fresh water is accessible for use
  - Supplies under pressure by growth, climate change
  - Water already recognized as a bankable commodity

2021 EPRI *Visioneering* Study

Rethinking Deployment Scenarios to Enable Large-Scale, Demand-Driven Non-Electricity Markets for Advanced Reactors. EPRI Whitepaper No. 3002022311 June 2021.
https://www.epri.com/research/products/000000003002022311

- **Deployment Architectures**
  approaches, systems, and components common to scenarios
- **Decarbonized Fuel Production Deployment Scenarios**
  four narratives elaborating market opportunities, delivery models, and value for investors, owner-operators, and consumers

Coming Soon:

- **Target Cost and Cost Reduction Potential**
  indicative economics for scenarios based on known costs and high-level estimates

Key Tenets of Study

For a New Advanced Reactor Deployment Model

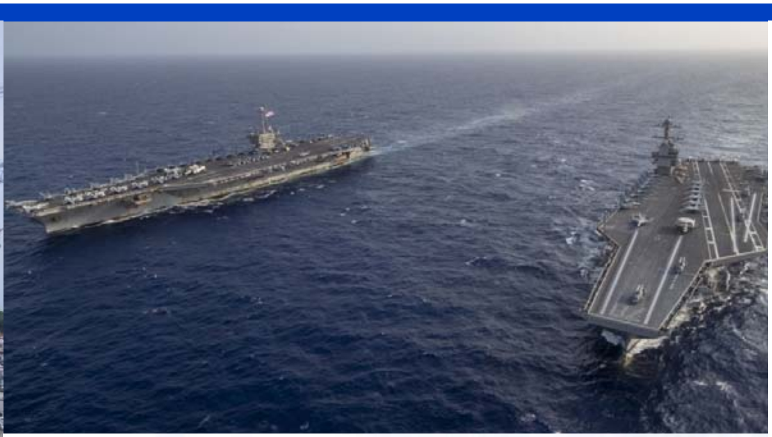
- Fabricate the entire (standardized) plant in a shipyard
- Deliver the plant to the point of use via marine conveyance
- Produce high-value, storage, conveyable commodities for large, established markets…on a *like-for-like* basis if possible
- Described with traceable techno-economic analyses based on public data and proprietary commercial cost estimates and quotes

Four Scenarios

	Scenario	Product	Resource Being Substituted	Infrastructure Changes Required	Deployment Setting & Model	Compatibility with Existing Infrastructure
I	Ammonia Production for Marine Shipping Fuel	Ammonia (NH_3)	Shipping fuel	Ammonia burning engines (in development)	Offshore (FPSO)	High
II	Commercial Airline Fuel Production	Carbon-Neutral Jet A	Fossil Jet A	None	Offshore (FPSO)	High
III	Ammonia, Power, and Desalinated Water Production for Coastal Cities	Ammonia, Electricity & Desalinated Water	Multiple	None	Offshore (FPSO)	Medium - High
IV	Blending H_2 into Existing Gas Network	Hydrogen Gas	Natural Gas	Infrastructure upgrades needed for >15-20%	Onshore (coastal with port and rail access)	High if <20% of blend concentration

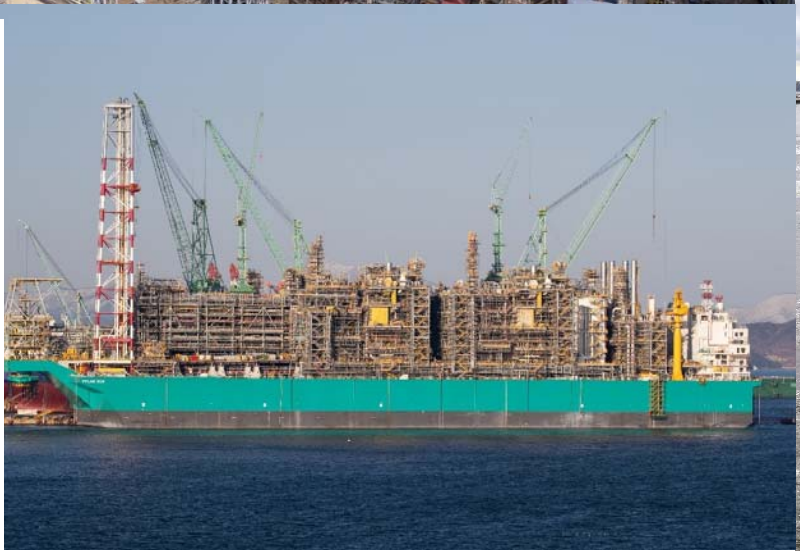
Four Lines of Evidence

The world already builds ships this way.
Image courtesy of US Navy.



Seven decades of nuclear naval propulsion starting with USS Nautilus (SSN-571) in 1954.
Image courtesy of US Navy

The petroleum industry has moved to floating production, storage, and offloading platforms (FPSOs).
Photographer: SeongJoon Cho/Bloomberg via Getty Images. Used with permission.



Floating nuclear power plants for commercial grid-connected power are being developed, deployed ***and operated.***
Photographer: Lev Fedoseyev via Getty Images. Used with permission.

Benchmarks for Competitive Product Pricing

Without Carbon Abatement

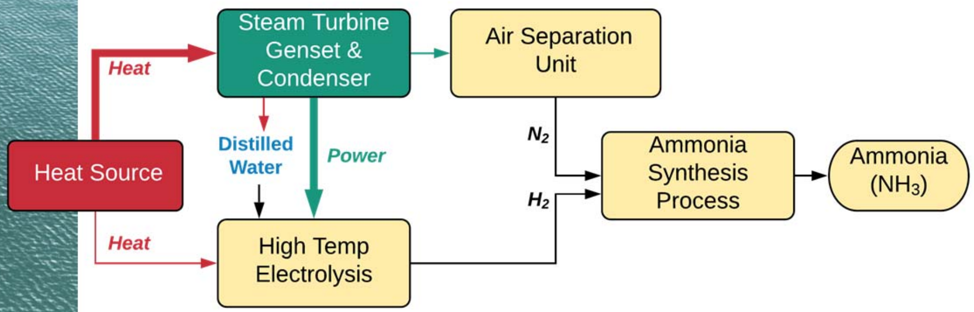
Product	Price	Units	Basis	Reference
Jet A (Kerosene-Type Jet Fuel)	94	USD/bbl	2010 – 2019 average wholesale price	USEIA, 2020
Ammonia (NH_3)	200	USD/tonne	Estimated pre-shipment cost of ammonia produced with \$3/MMBtu natural gas	Ammonia Energy Association, 2020
Hydrogen	0.7 – 1.6	USD/kg	2019 levelized production cost from natural gas	IEA, 2020
Electricity	68.3 – 185 102 - 334	USD/MWh	2019 OECD industry 2019 OECD residential	IEA, 2020
Desalinated Water	0.64 – 2.86	USD/m^3	2016 prices for reverse osmosis technology	World Bank Group, 2019

Carbon Neutral Substitute for Marine Shipping Fuel

Marine shipping conveys 90% of global trade and represents one of the most difficult industry sectors to decarbonize

NH_3 as fuel for global shipping

- Plants needed: 2020 (324); 2050 (617)
- Low sulfur fuel oil (LSFO) trades at $400-600/T ($9.24-13.86/GJ)
- Ship-based nuclear-powered platform production estimated as low as $230/T ($10.22$/GJ)
- Can be sited close to use
- Offers industry-friendly, competitive means to meet IMO decarbonization targets
- Ammonia-burning engines under development

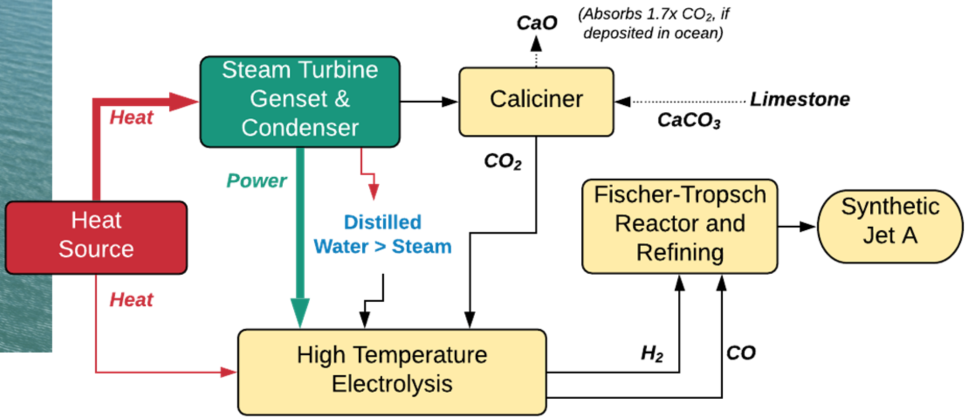


Zero- or Negative-Carbon Commercial Jet Fuel at Scale

Commercial air-miles traveled could triple by 2050—with associated emissions

Scalable, zero-or negative-carbon commercial-grade jet fuel (Jet A)

- Biofuel alternatives challenging to scale
- Future consumer and regulatory demand likely to increase beyond carbon offsets
- 2019 airline expenditure for Jet A: \$188 B at market average of \$79/bbl
- Ship-based nuclear-powered platform Jet A production estimated at \$82/bbl
- May offer more stable long-term pricing



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Summary

- Innovative technology configurations combined with efficient delivery and deployment models for hydrogen and synthetic fuels production facilities could improve global prospects for **achieving a clean energy transition within a reasonable timeframe**.

- Pull from these markets could drive transformational changes in how liquid fuels are produced without disrupting cost, storage, distribution, or use.

- Commodities produced for these non-electricity markets, e.g., hydrogen and zero-carbon liquid fuels, could rapidly accelerate decarbonization of the global energy system while minimizing cost and disruption to producers or consumers.

- Publicly available report coming soon:
  - ***Rethinking Deployment Scenarios to Enable Large-Scale, Demand-Driven Non-Electricity Markets for Advanced Reactors.*** EPRI, Palo Alto, CA: 2021. Report 3002018348.


Together…Shaping the Future of Electricity