Flexibility from Hydrogen

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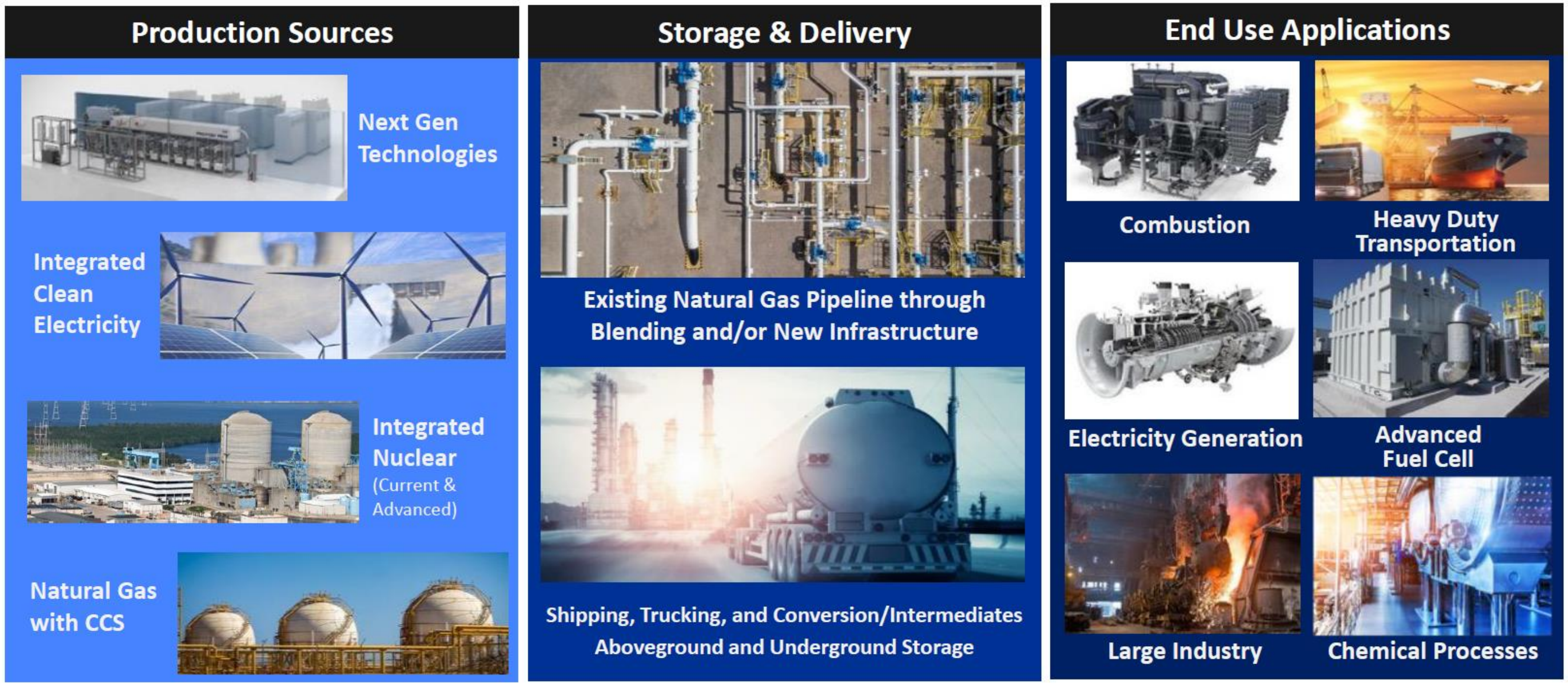
ESIG Webinar: Flexibility from Hydrogen
April 25, 2024 @ 4:00 pm - 5:00 pm EDT

Today's Discussion

1. Why the interest in hydrogen?
2. What could the growth in electrolytic hydrogen mean for the power sector?
3. Assessing flexibility from hydrogen and possible Participation Models
4. Representation of Hydrogen Plants

Why the interest in hydrogen?

Hydrogen can play many roles in a low-carbon economy, making it challenging to discern how it will be used in the electricity sector



There is a burgeoning interest in hydrogen **across the entire energy sector**

Electricity generation is **one of many end-use applications**

How **hydrogen will produced, stored, and delivered** for electricity generation is not yet certain

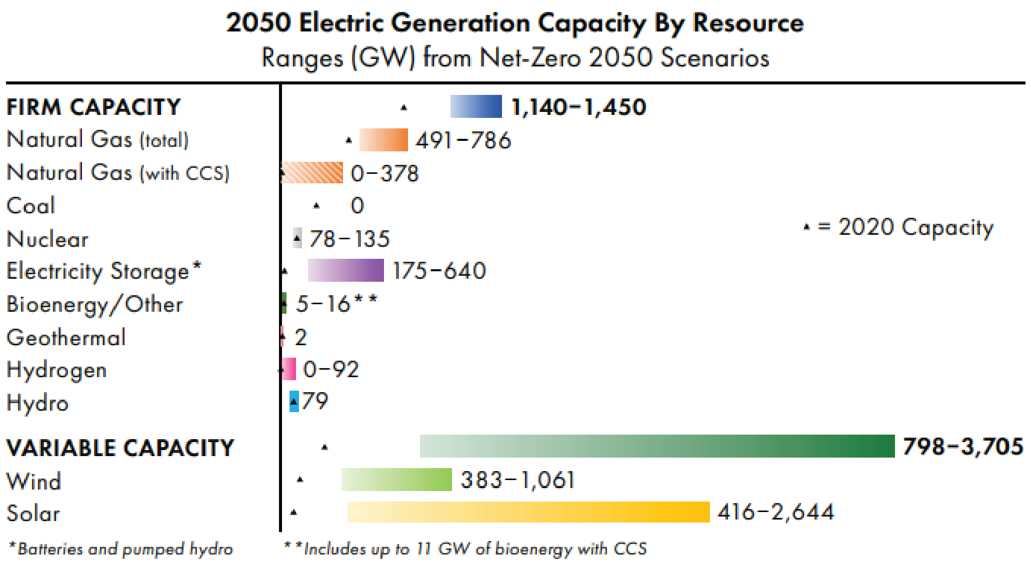
Slide adapted from: Cross-Sector Webcast on EPA Power Plant Rules: Insights from EPRI Research. July 6, 2023. Available: https://epri.webex.com/epri/ldr.php?RCID=836f60af0265ce70aa2d7989faec4532

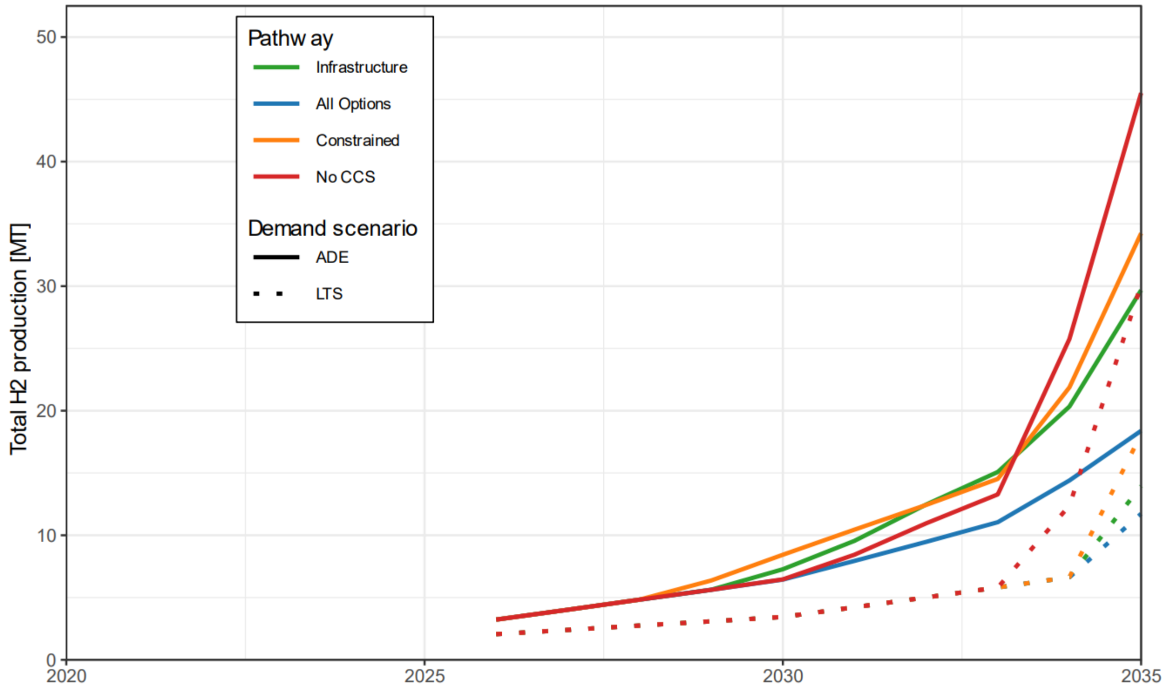
Large, national-scale studies suggest that the penetration of hydrogen in the electricity sector varies greatly by scenario

According to the IEA, hydrogen may be an increasingly important piece of the net zero emissions by 2050 puzzle

EPRI Net Zero 2050: US Economy-Wide Deep Decarbonization Scenario Analysis

Generation capacity from hydrogen (of all types) could vary from 0 GW to 92 GW depending on the scenario studied.





NREL Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035

Hydrogen production for the electricity sector could vary from 4 MT to 46 MT, depending on the scenario studied.

Sources: https://lcri-netzero.epri.com/ and https://www.nrel.gov/docs/fy22osti/81644.pdf

Hydrogen is one of many technology options that can be valuable in a decarbonized economy

Clean Electricity	Hydrogen Direct	Hydrogen Derivatives & Biofuels	Carbon Capture
Buildings	Refining & Chemicals	Aviation	Power Generation
Transportation	Ammonia	Marine Shipping	Cement & Concrete
Industrial Processes	Steel	MD/HD Vehicles	Ammonia
Short and Medium Duration Energy Storage	High Temp Process Heating	Power Generation & Seasonal Storage	Industrial Process Heating
Electrolytic Hydrogen	Power Generation & Seasonal Storage	Bulk Import / Export	Carbon Offset Technologies
	MD/HD Vehicles		

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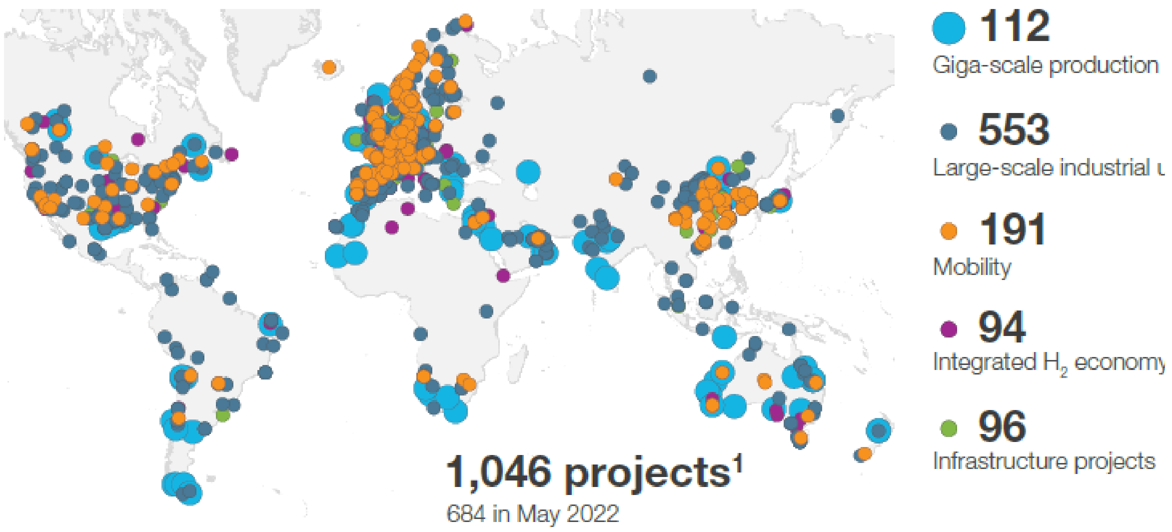
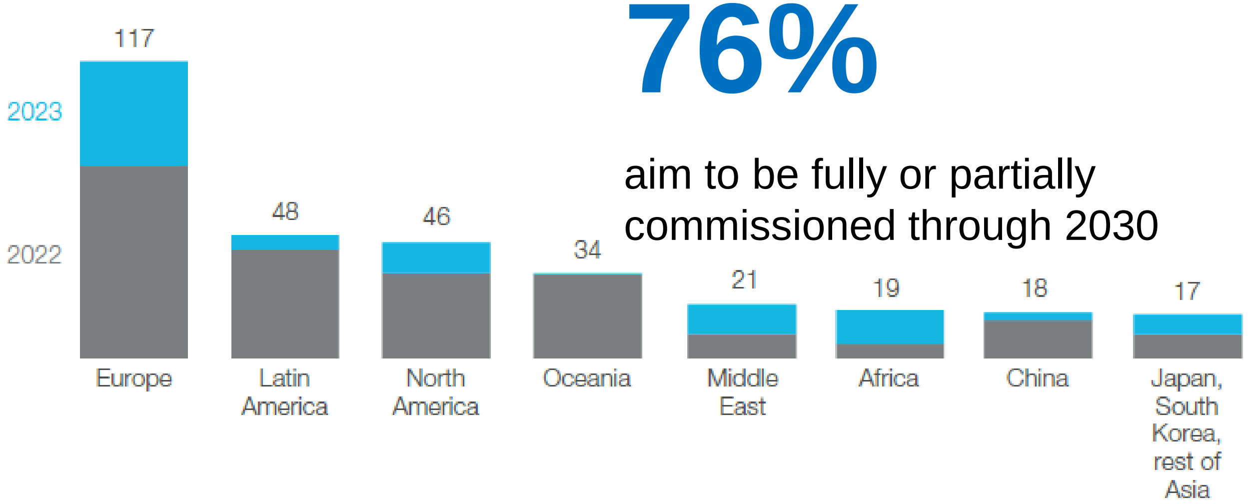
Hydrogen momentum is strong: more than 1,000 project proposals have been announced globally



Source: Hydrogen Insights 2023. Hydrogen Council and McKinsey&Company

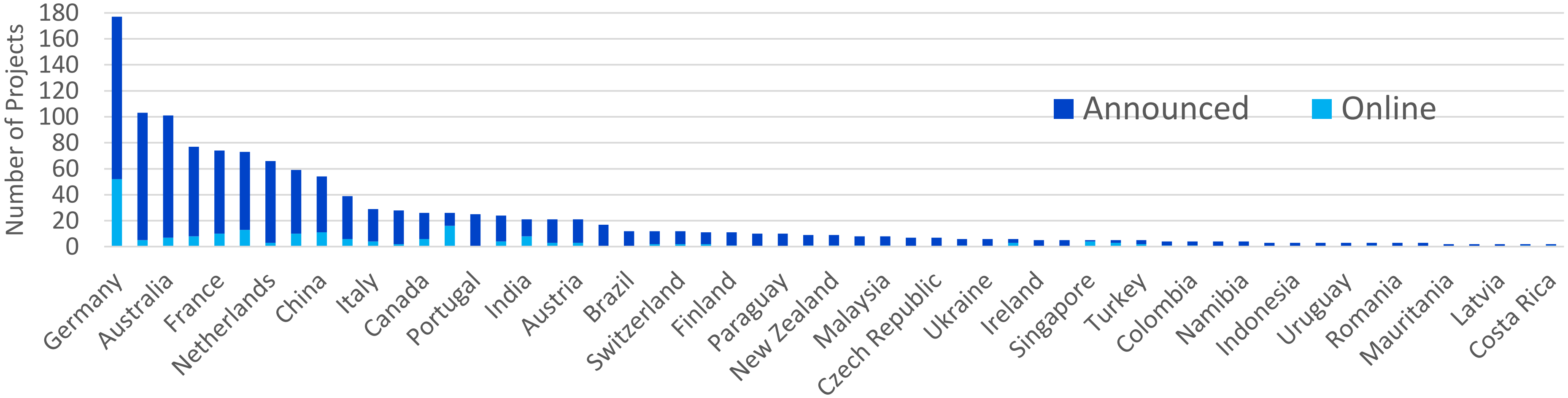


76%

aim to be fully or partially commissioned through 2030

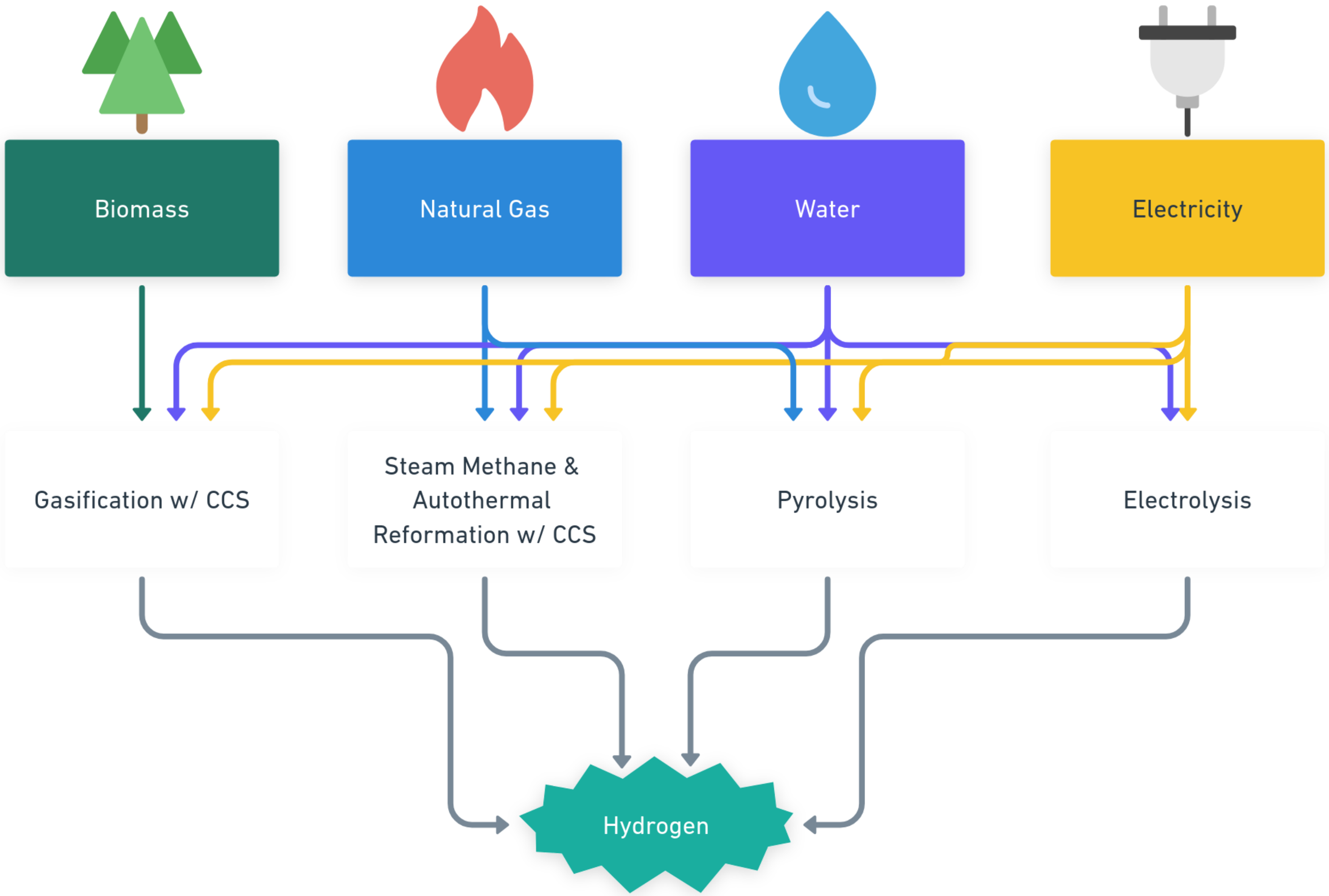
Source: Hydrogen Insights 2023. Hydrogen Council and McKinsey&Company

Number of Announced Hydrogen Projects



Source: IEA Hydrogen Projects Database. Paris, France: 2022. Available: https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database. Accessed: January 27, 2023.

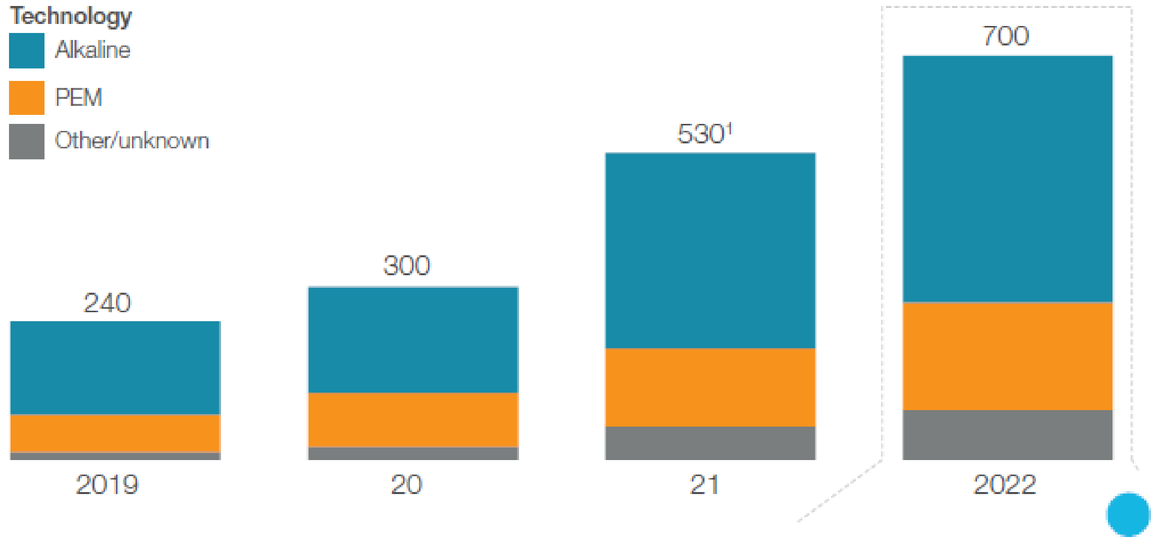
Project proposals can span several pathways



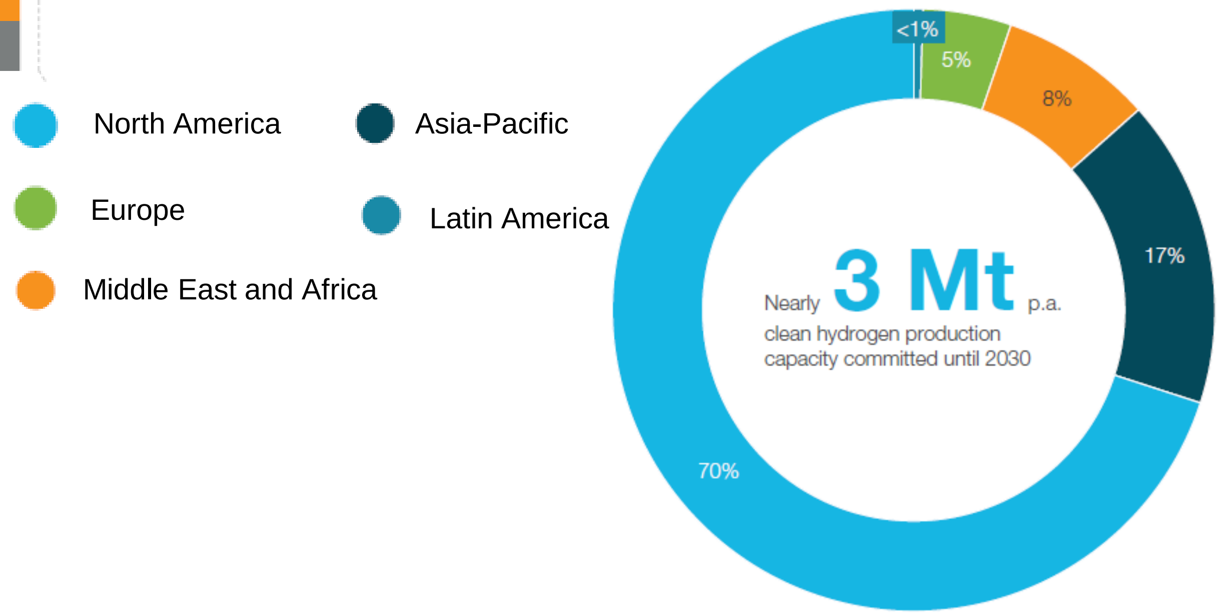
Low-Carbon Hydrogen Production Pathways

Deployments of electrolysis are anticipated to continue to grow

Global Cumulative Installed Electrolysis Capacity, MW (EOY)



Committed production capacity until 2030



Source: Hydrogen Insights 2023. Hydrogen Council and McKinsey&Company

What could the growth in electrolytic hydrogen mean for the power sector?

Today's IRPs are in the earliest stages of incorporating hydrogen

Of 115 U.S. Integrated Resource Plans (IRPs), 33 are planning or considering hydrogen capable generators. Of those, the predominant value proposition for hydrogen is to replace coal or natural gas facilities.

12

Number of IRPs that refer to the potential for hydrogen to replace coal or gas units

10

Number of IRPs that assume new gas units are hydrogen capable

Other use cases/benefits identified:

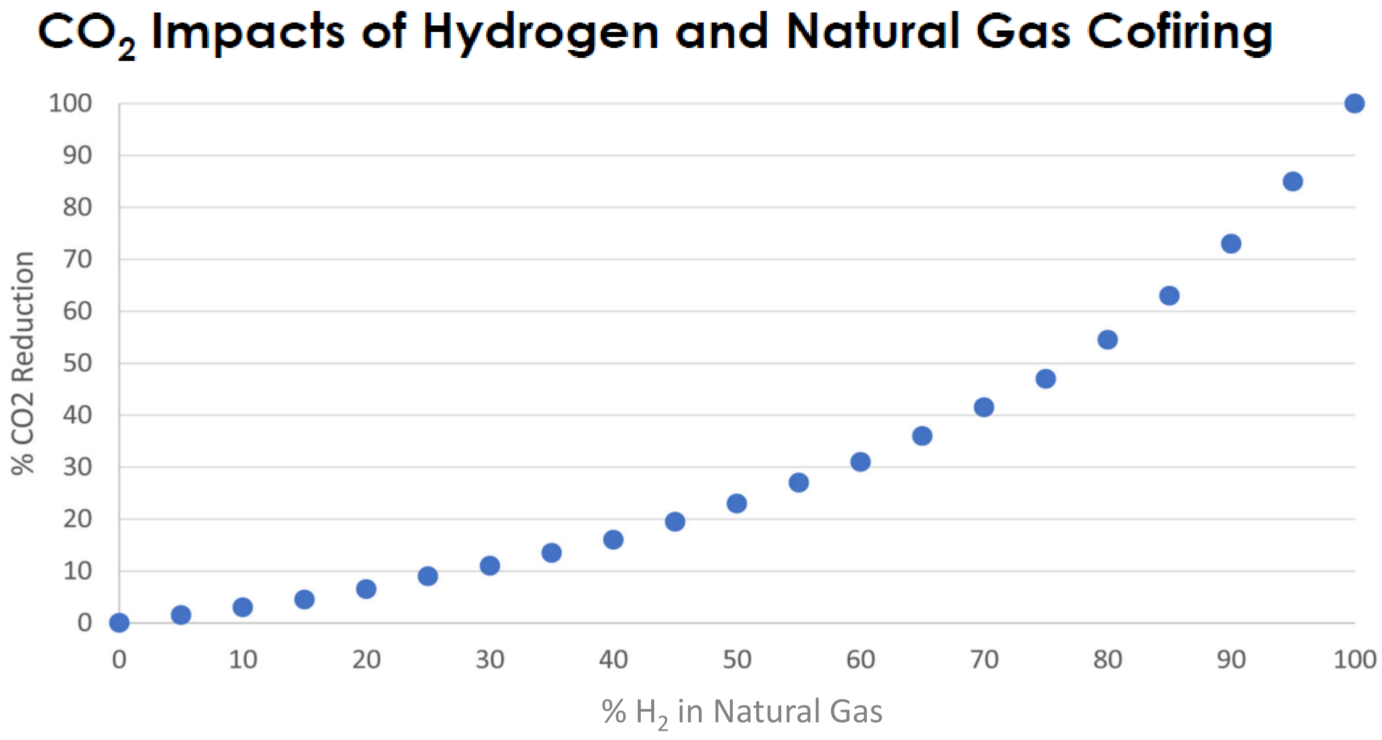
- **Fuel Diversity**
- **Resilience**
- **Long-duration energy storage**
- **Load following and operational flexibility**
- **Baseload**

In interviews with three electricity companies, the most common motivation for assessing hydrogen in an IRP is to **reduce emissions** while ensuring **dispatchable** resources are available to support system reliability.

Source: State of Hydrogen Modeling in Electric Company Integrated Resource Planning (epri.com)

Motivated by emissions reductions goals, some IRPs refer to the potential for hydrogen and natural gas cofiring (blending)

- Although blending is mentioned in some IRPs, the published modeling assumptions were very limited
- Current turbines can blend up to 30% H_2; equipment providers expect to provide 100% H_2 capable combustion turbines by 2030
- A potential challenge is CO_2 reductions are not linear; shown to the right, the lower volumetric energy density of H_2 means that 20% H_2 by volume reduces CO_2 emission by ~7%
- This relationship is notably absent in most IRPs



Source: Technology Insights Brief: Hydrogen-Capable Gas Turbines for Deep Decarbonization (epri.com)

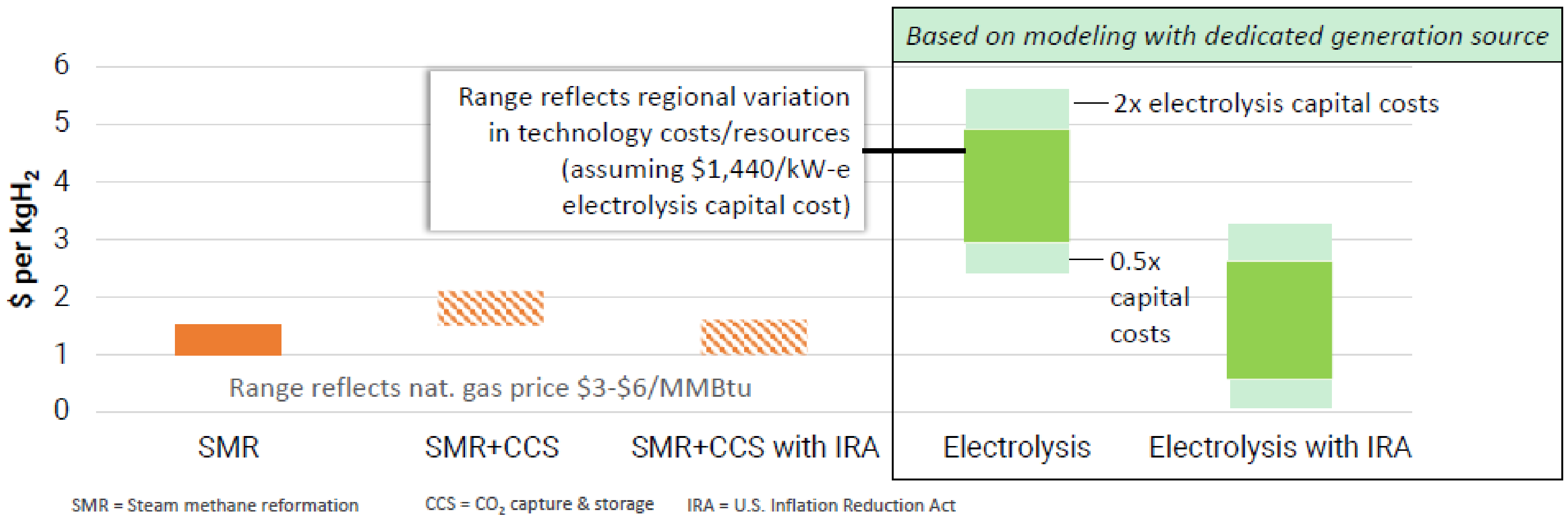
Policies, tax incentives, and stakeholder interest might accelerate interest for the power sector

Looking ahead in the U.S., the IRA could have a significant impact on costs and opportunities relating to hydrogen.

Incentives for zero-carbon electrolysis in the IRA may provide a potential pathway for lower costs than natural gas reforming.

In some jurisdictions, stakeholders have expressed interest in utility plans with no natural gas. Furthermore, CCS technology is still maturing.

Initial estimates of U.S. IRA hydrogen price impacts



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Hydrogen's value to the power sector should be contextualized with other market potentials

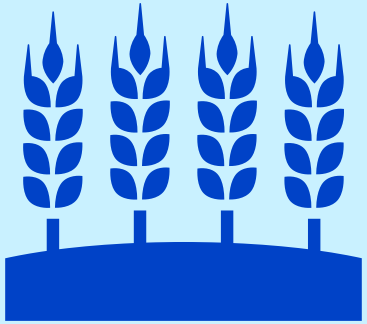
Largest Hydrogen Market Potentials by 2050

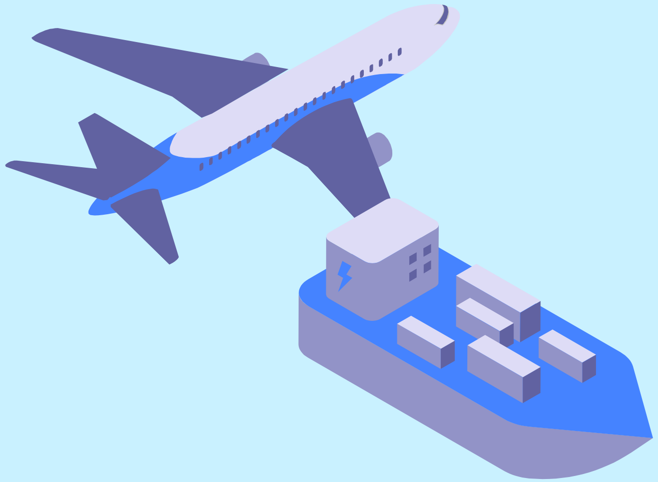
MD/HD Trucking

$40-160B

Ammonia

$5-12B



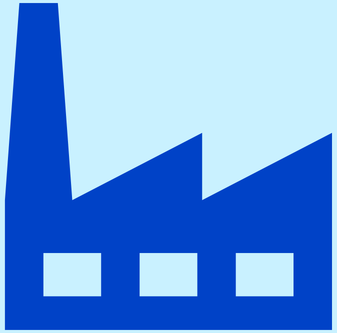


Marine & Aviation

$18-50B

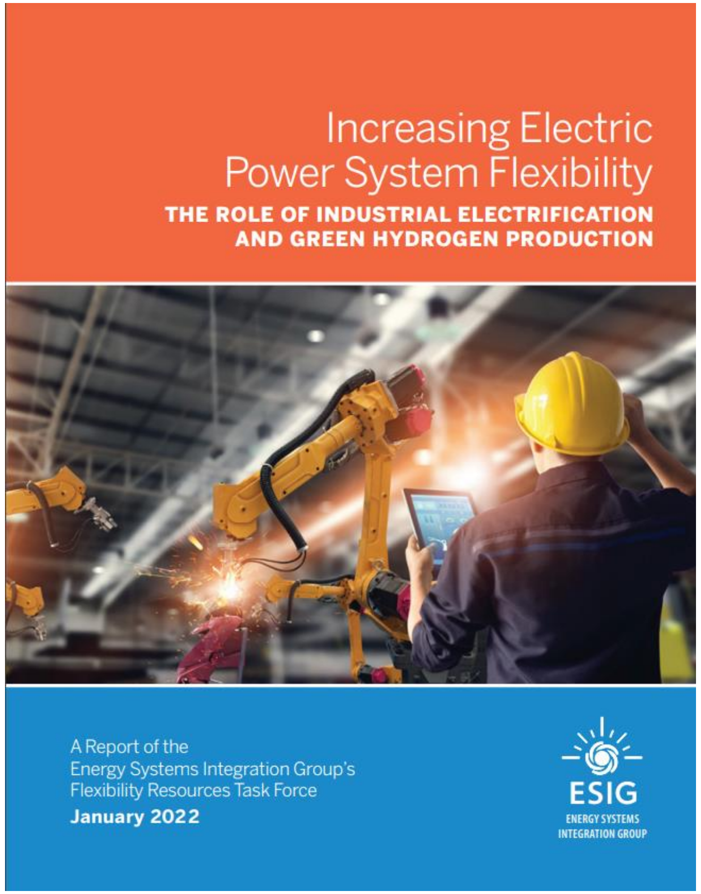
Steel

$20-40B



Data Source: US DOE Pathways to Commercial Liftoff: Clean Hydrogen, March 2023. https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf

Macroeconomic studies (including pathways studies) and integrated resource plans might not fully describe the potential role of hydrogen

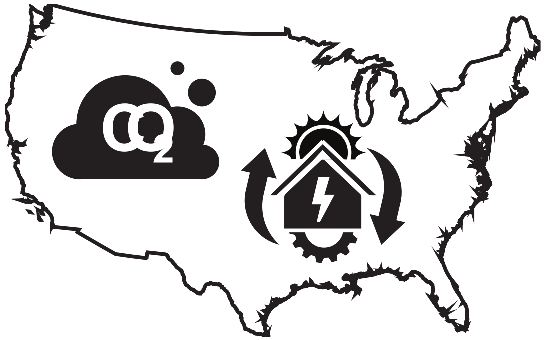


- Hydrogen resources may provide much-needed **capacity and flexibility to the system during periods when other carbon-free resources are not available, analogous to gas peakers today.**
- **On the demand side, [hydrogen] production can be a flexible load that aids in balancing the grid.**
- Hydrogen fuel cells or gas turbines powered by stored hydrogen could be used to serve load during such long-duration shortfalls in renewable generation.
- **Hydrogen may very likely be the key to reaching a 100 percent net-zero electric power supply.**

See https://www.esig.energy/wp-content/uploads/2022/01/ESIG-Industrial-Elec-Hydrogen-report-2022.pdf

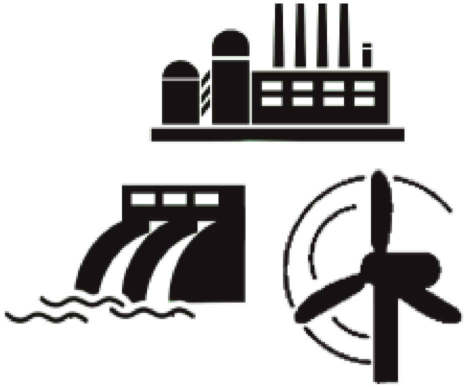
Assessing flexibility from hydrogen and possible Participation Models

Model fidelity is important to value hydrogen and represent flexibility



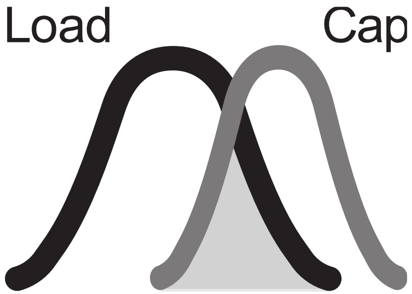
Regional Decarbonization Technology Pathways Modeling

- Large-scale regional model
- Ensures the system can meet decarbonization and technology targets and policies
- Representation of customer heterogeneity across end-use sectors, and end-use technology trade-offs
- Includes a detailed analysis of electrification and efficiency opportunities



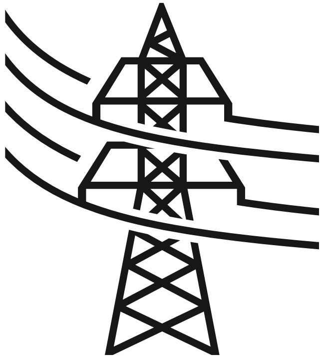
Bulk System Capacity Expansion Model

- Has a selected geographical area of focus
- Includes nodal generation and transmission capacity expansion
- Includes detailed unit-level costs and engineering constraints



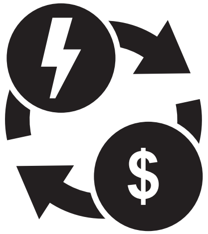
Bulk System Reliability Model

- Ensures steady-state reliability (reduce load shed, meet reserves) and that the system has adequate capacity



Power Flow and Stability Model

- Ensures the system is stable; the system has sufficient reactive resources, voltage control, frequency response, inertia, and system strength



Production Cost Model

- Examines detailed operating costs, and market, environment, and revenue impacts

Distribution Grid Model

- Incorporates distribution infrastructure needs and better understanding of DER share of resources

The tool you select may be informed by the grid service/form of flexibility of interest

Grid Services provided will depend on hydrogen's role in the power system

Regulation

To manage, on a second-to-second basis, uncertainty from forecast errors and generator responsiveness

Balancing

To manage variability and uncertainty within an hour and across hours

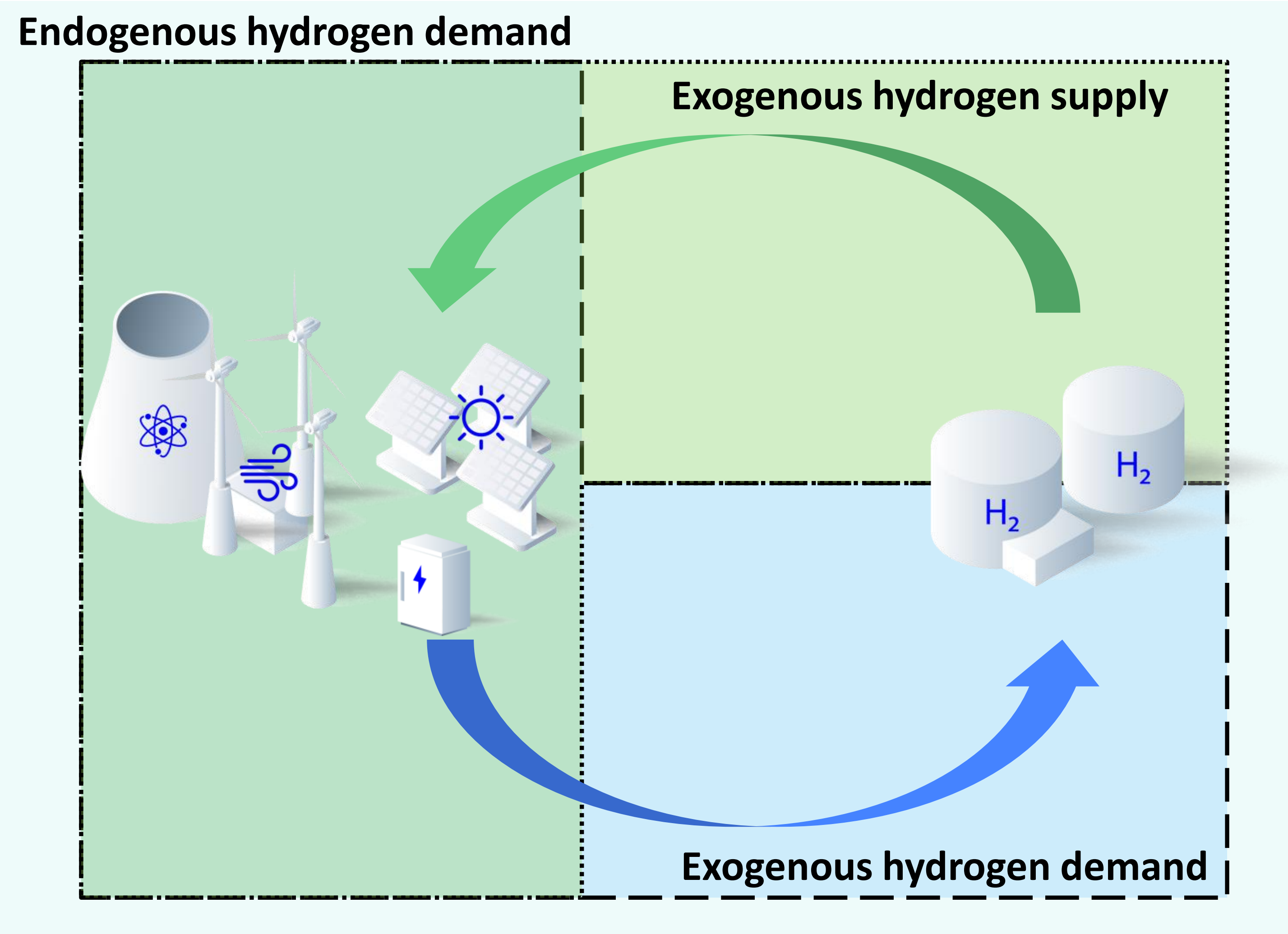
Operating Reserve

To manage contingencies or operational events—such as any combination of forced outages and periods of low wind or solar

Seasonal Energy Arbitrage

To manage the mismatch of resource availability and load across seasons.

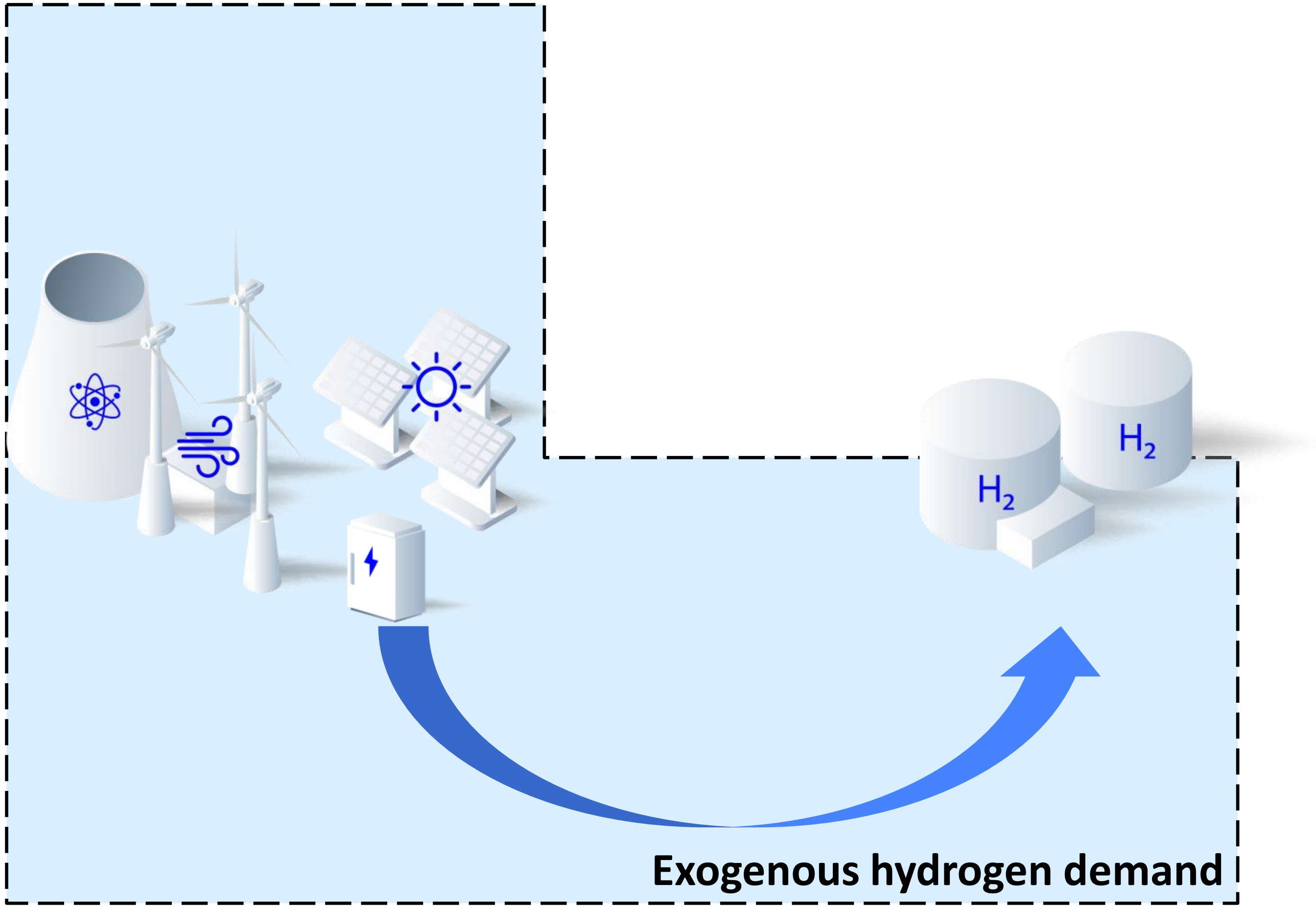
The role of hydrogen from a power systems perspective



- Depending on **system design** and **study scope**, representation of hydrogen from a power system perspective may differ
- **Exogenous hydrogen demand**:
  - Hydrogen is produced through electrolysis and used elsewhere
- **Exogenous hydrogen supply**:
  - Hydrogen is considered an input fuel (similar to e.g., natural gas)
- **Endogenous hydrogen demand**:
  - Hydrogen is produced through electrolysis, stored and/or transported, and re-electrified at later point in time

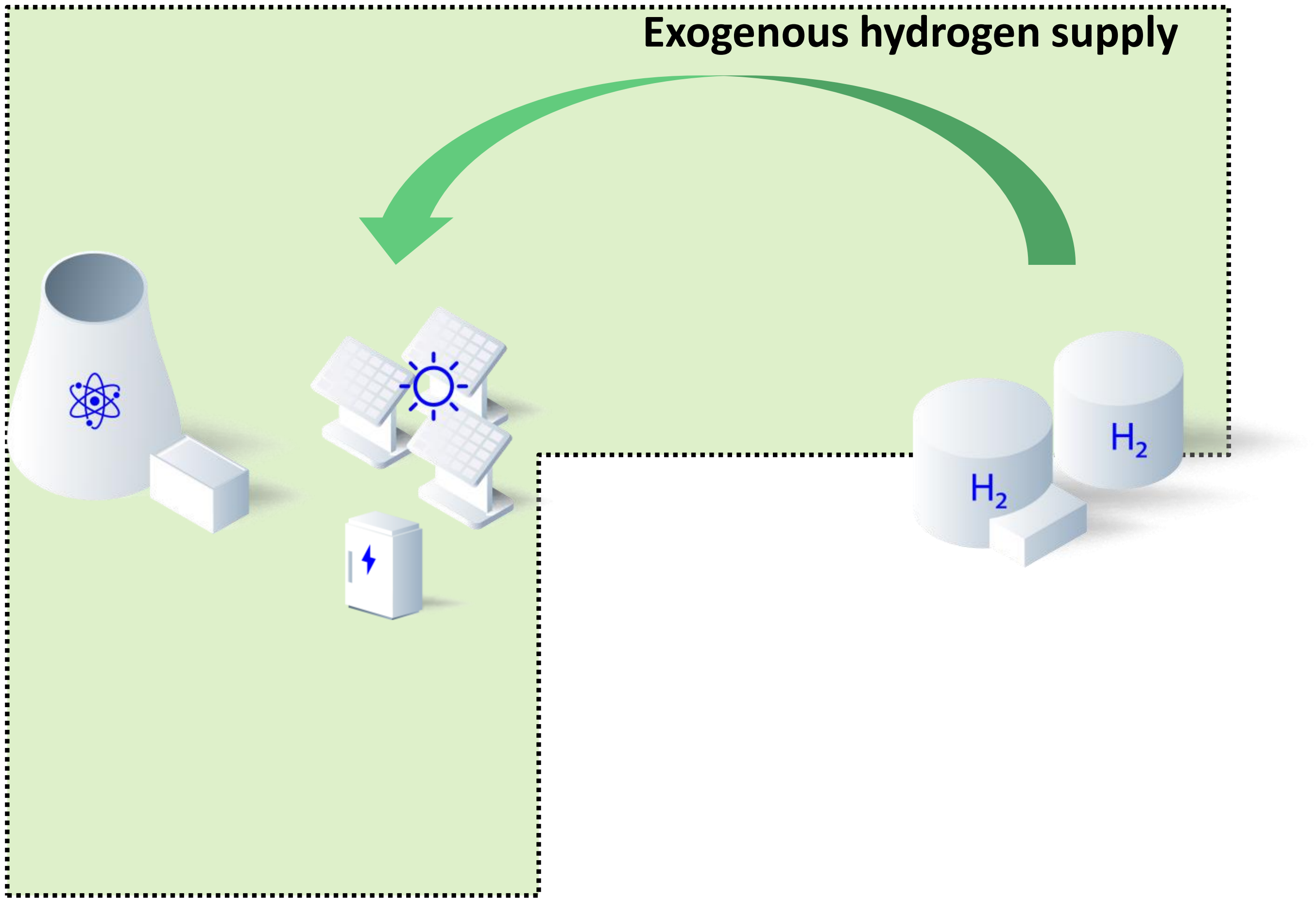
Exogenous hydrogen demand

- Electrolytic hydrogen is produced to satisfy hydrogen demand outside of the system boundaries
  - Hydrogen demand is either imposed through a demand timeseries or predefined price profile
- Electrolysis may act as a **Flexible Load** providing regulation, balancing services, and operating reserves services
  - Downward: by increasing hydrogen production, i.e., more power offtake
  - Upward: by decreasing production of hydrogen
- Flexibility depends on electrolyzer type and elasticity of downstream hydrogen demand
  - Important to identify a balanced representation of electrolyzer operating characteristics



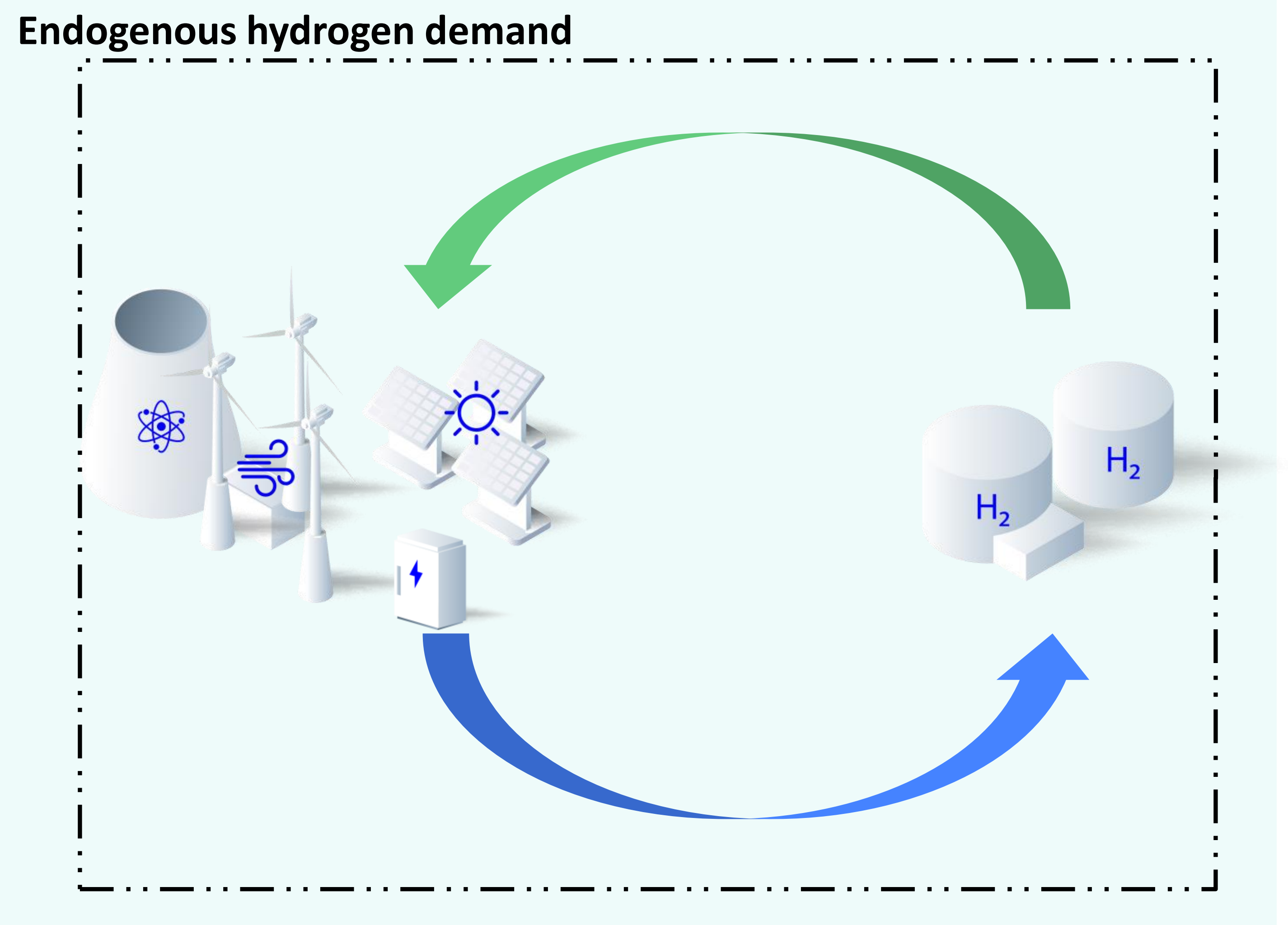
Exogenous hydrogen supply

- Hydrogen may also be considered as exogenous fuel supply
  - E.g., similar to natural gas
- Found in integrated planning models
- Hydrogen turbines or fuel cells can act as firm capacity providing grid services
- Currently mostly envisioned as blend with natural gas
  - Important to track hydrogen concentration when existing infrastructure is used



Endogenous hydrogen demand

- Hydrogen is produced through electrolysis **and** serves as fuel supply to the electric power system
  - Hydrogen demand is therefore **endogenous**
- Hydrogen is used as energy carrier and utilized and long-duration energy storage
  - Combination of prior concepts
- Need to represent long-horizon (to capture seasonal arbitrage)
- Capture hydrogen network, processes, transport, storage



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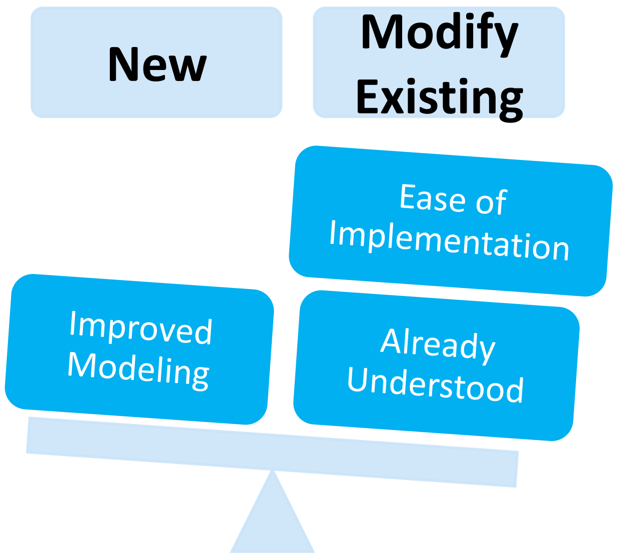
Additional modeling considerations

Representing Uncertainties	Short-term uncertainty: Variability of renewable generation and load and how electrolysis system can provide flexibility (regulation, balancing, operating reserves) Long-term uncertainty: Seasonal uncertainties impact possibility for seasonal arbitrage, costs, market design
Locational Detail and Transmission Networks	Locational price of hydrogen: Depending on availability of low-cost electricity and deliverability
Modeling the Transportation of Hydrogen	Transport of hydrogen through existing pipelines: Tracking of hydrogen concentration Representation through transport models and multi-energy/multi-sector models
Modeling Hydrogen End-Use Demand	Representing multi-energy and sector coupling

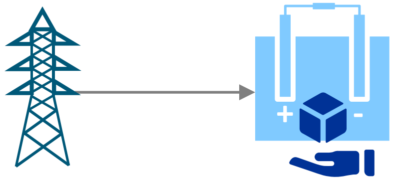
Possible Participation Models for Hydrogen Resources

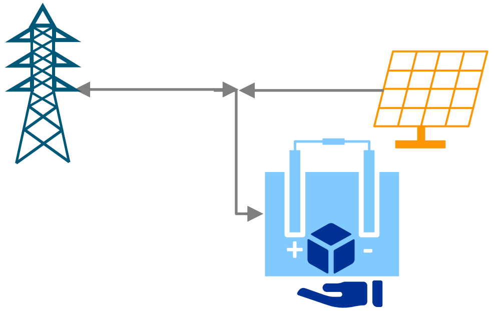
Participation Model - What does it mean?

- **FERC NOPR:** Defined as "a set of **tariff provisions** that **accommodate the participation of resources with particular physical and operational characteristics** in the organized wholesale electric markets of the RTOs and ISOs."
- **FERC Order 841:** Tariff revisions that consist of **market rules** that, recognizing the **physical and operational characteristics** of the resource, **facilitates** their participation in RTO/ISO markets
- **ERPI**: Definition of a participation model also includes the **set of market clearing software provisions required to represent the physical and operational characteristics** of the resource.



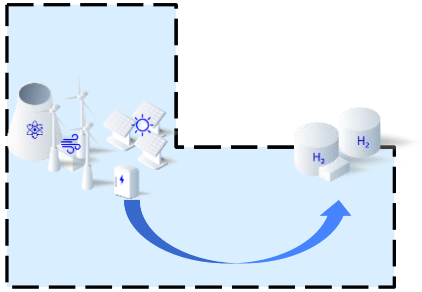
Exogenous demand
Analogy: Flexible load participation model





Linking constraint:
$P_{el,demand_{H_2}} \leq P_{VRES}$

- Exogenous hydrogen demand may participate in the market analogous to a flexible load participant
- Key considerations:
  - Intuitive interpretation of flexible demand
  - Lack of ability to represent technical characteristic of Electrolyzers (minimum up/down times, ramps, min. operating point, start-up/shut-down)
  - Lack of linking constraints between flexible demand and VRES



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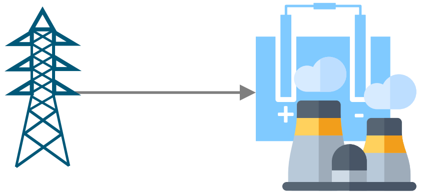
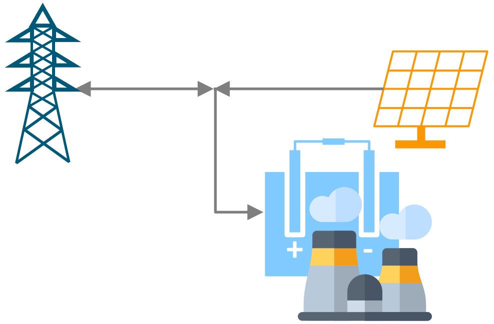
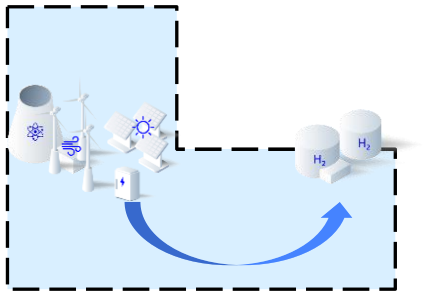
Exogenous demand
Analogy: Thermal resource participation model



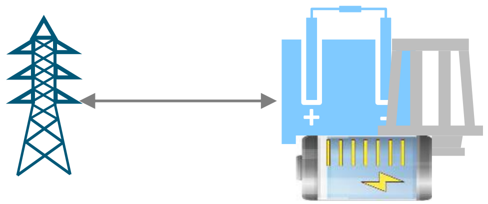


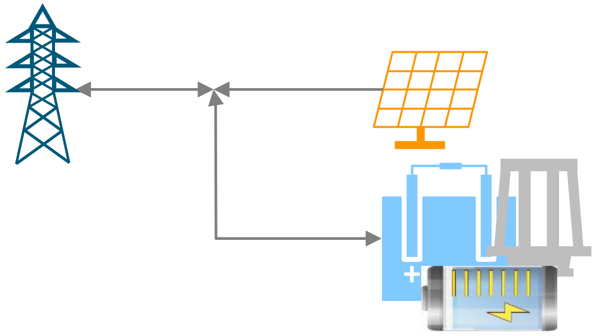
Linking constraint:
$-P_{el,inj_{H_2}} \leq P_{VRES}$

- Exogenous hydrogen demand may participate in the market analogous to (negative) conventional generators
- Key considerations:
  - Ability to represent technical characteristic of Electrolyzers (minimum up/down times, ramps, min. operating point, start-up/shut-down)
  - Less intuitive (offtake rather than injection)
  - Lack of linking constraints between VRES and thermal generators



Endogenous demand
Analogy: Battery participation model

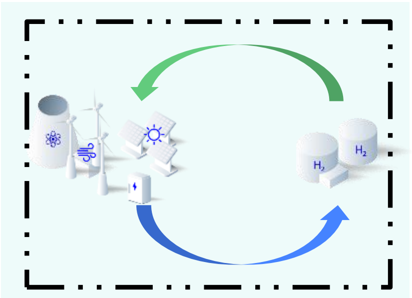




Linking constraint:

$P_{el,charge_{H_2}} \le P_{VRES}$

- Endogenous hydrogen demand may participate in the market analogous to a battery storage resource
- Key considerations:
  – Linking constraints between charging and VRES
  – Hydrogen inventory ≅ State of Charge
  – Lack of ability to represent technical characteristic of Electrolyzers (minimum up/down times, min. operating point, start-up/shut-down)



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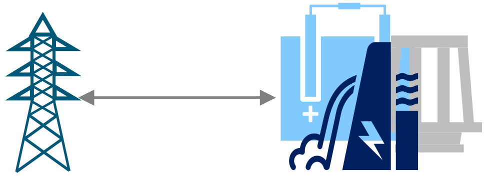
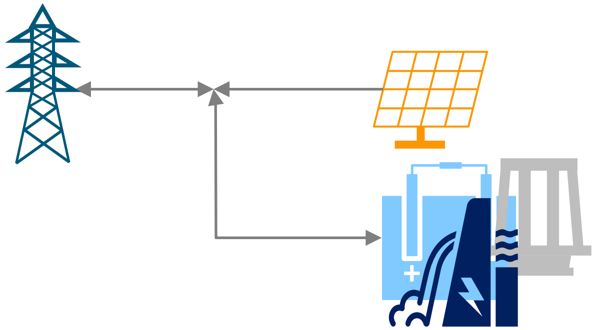
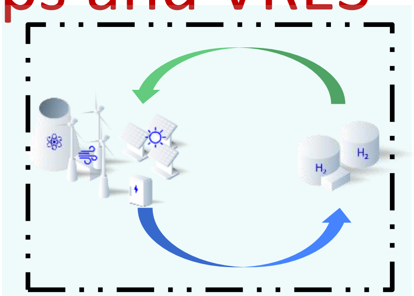
Endogenous demand
Analogy: Pumped hydro participation model





Linking constraint:
$P_{el,pump_{H_2}} \le P_{VRES}$

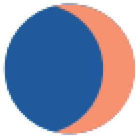
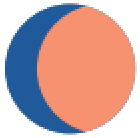
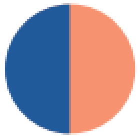
- Endogenous hydrogen demand may participate in the market analogous to pumped hydro resources
- Key considerations:
  - Ability to represent technical characteristic of Electrolyzers (minimum up/down times, ramps, min. operating point, start-up/shut-down)
  - Hydrogen inventory ≅ Water level
  - Lack of linking constraints between pumps and VRES



Representation of Hydrogen Plants

The representation varies by electrolysis technology type

Electrolysis Technology Types

Category	Technology Type	Description	Technology Maturity
Low-temperature electrolysis	Alkaline electrolysis	Uses nickel alloy electrodes submerged in an alkaline solution separated by a diaphragm	
	Polymer electrolyte membrane electrolysis (PEM)	Uses precious metal catalysts and a solid polymer membrane without a liquid electrolyte	
	Anion exchange membrane electrolysis (AEM)	Uses a design similar to PEM, but its electrolyte conducts anions rather than protons (the same reaction as in alkaline)	
High-temperature electrolysis	Solid oxide electrolysis cell (SOEC)	Has catalyst layers separated by a gas-tight ceramic electrolyte and uses steam as an input rather than liquid water	

The four main types of electrolysis described and compared in this report. The blue indicates greater technological maturity.

Adapted from EPRI Low-Carbon Energy Supply Technology Cost and Performance Study (3002023656)

Capital costs also vary by technology type. Electricity costs are the most significant operational cost.

Capital Costs of Electrolysis Systems

Blue shading indicates lower cost, and orange shading indicates higher cost. Due to the early-stage development of SOEC and AEM electrolysis, their costs could remain high for the foreseeable future and remain highly uncertain. Capital costs for AEM electrolysis are not available.

Notes: AEM = anion exchange membrane; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolysis cell.

Source: Adapted from EPRI (2023).

Adapted from EPRI
Low-Carbon Energy Supply Technology Cost and Performance Study (3002023656)

Stack lifetime for electrolysis systems impacts the total cost in the long-run

Stack Lifetime for Electrolysis Systems

Alkaline electrolysis has the longest stack lifetime, and it may be possible to refurbish rather than replace the stack. SOECs' ceramic materials cause shorter stack lifetimes. Blue shading indicates a longer stack lifetime, and orange shading indicates a shorter stack lifetime. Gray shading indicates that information was not available.

Notes: AEM = anion exchange membrane; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolysis cell.

Especially when assessing balancing or load-following, the range and response rate is important

Operating or Dynamic Range of Electrolysis Systems

Of the four main electrolyzer types, alkaline systems have the narrowest operating range. The other three technologies provide a broad operating range that can be beneficial for providing operational flexibility. Blue shading indicates a larger range and orange indicates a narrower range.

Notes: AEM = anion exchange membrane; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolysis cell.

System Response of Electrolysis Systems

The rapid response rate of AEM and PEM systems makes them ideally suited for providing operational flexibility. Blue shading indicates faster response, and orange shading indicates slower response.

Notes: AEM = anion exchange membrane; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolysis cell.

Adapted from EPRI Low-Carbon Energy Supply Technology Cost and Performance Study (3002023656)

Salient Questions for Study Design

Modeling Framework for Assessing Flexibility

Needs Assessment

- What grid services are needed in this geographical area?
- What time horizon is being studied?
- What operating regime and other end uses might a given hydrogen facility provide?
- What electrolysis system is best suited for providing the grid service(s) and time horizon being studied?

Tools Assessment

- What tools have the right level of detail to assess grid services?
- Can my tools sufficiently consider the dynamics between hydrogen and electric power markets?
- Can my tools consider the availability and uncertainties of supporting infrastructure?

Inputs Assessment

- What inputs are most critical for the grid service(s) being studied?
- What are the characteristics of electrolysis system that affect flexibility?
- What data sources are available to develop modeling inputs?

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