Hydrogen economics in Texas

Aurora Public Webinar | March 23, 2023

REDACTED VERSION

Agenda

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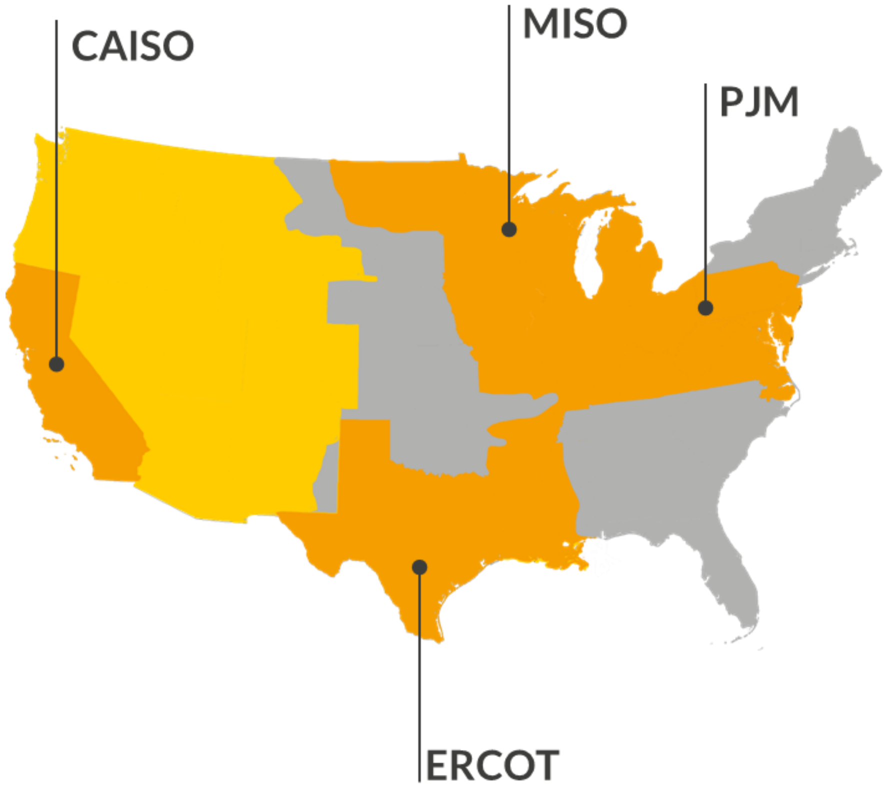

Regular detailed coverage | Analytics on demand

2023-2024 Coverage Expansion: NYISO, ISONE, Alberta, WECC, SPP

Grid-Scale Battery Storage in PJM: Introduction and Outlook

- In depth look at the value proposition of batteries and the ROI
- Pipeline of projects across ERCOT and CAISO and analysis of historical battery returns
- Favorable investment landscape for batteries in ERCOT and CAISO with varying IRRs

March 15th, 2023

Hydrogen Economics in Texas

- Analysis of hydrogen landscape in the United States and current policies driving interest
- Deep-dive on clean hydrogen business models in Texas, benchmarked against the cost of producing blue hydrogen
- Additional analysis on the cost of hydrogen transportation and storage

March 23rd, 2023

US Commodities Forecast, 2023 Update

- Aurora's in-house commodity forecast update for Natural Gas, Oil, and Coal prices
- Global commodity markets have calmed in the short term
- Prices remain elevated following Russia's invasion of Ukraine amid economic turmoil and shifting supply chains
- CAISO Weather-Year Analysis Webinar upcoming May 2023

April, 2023

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Aurora provides market-leading forecasts & data-driven intelligence for the global energy transition

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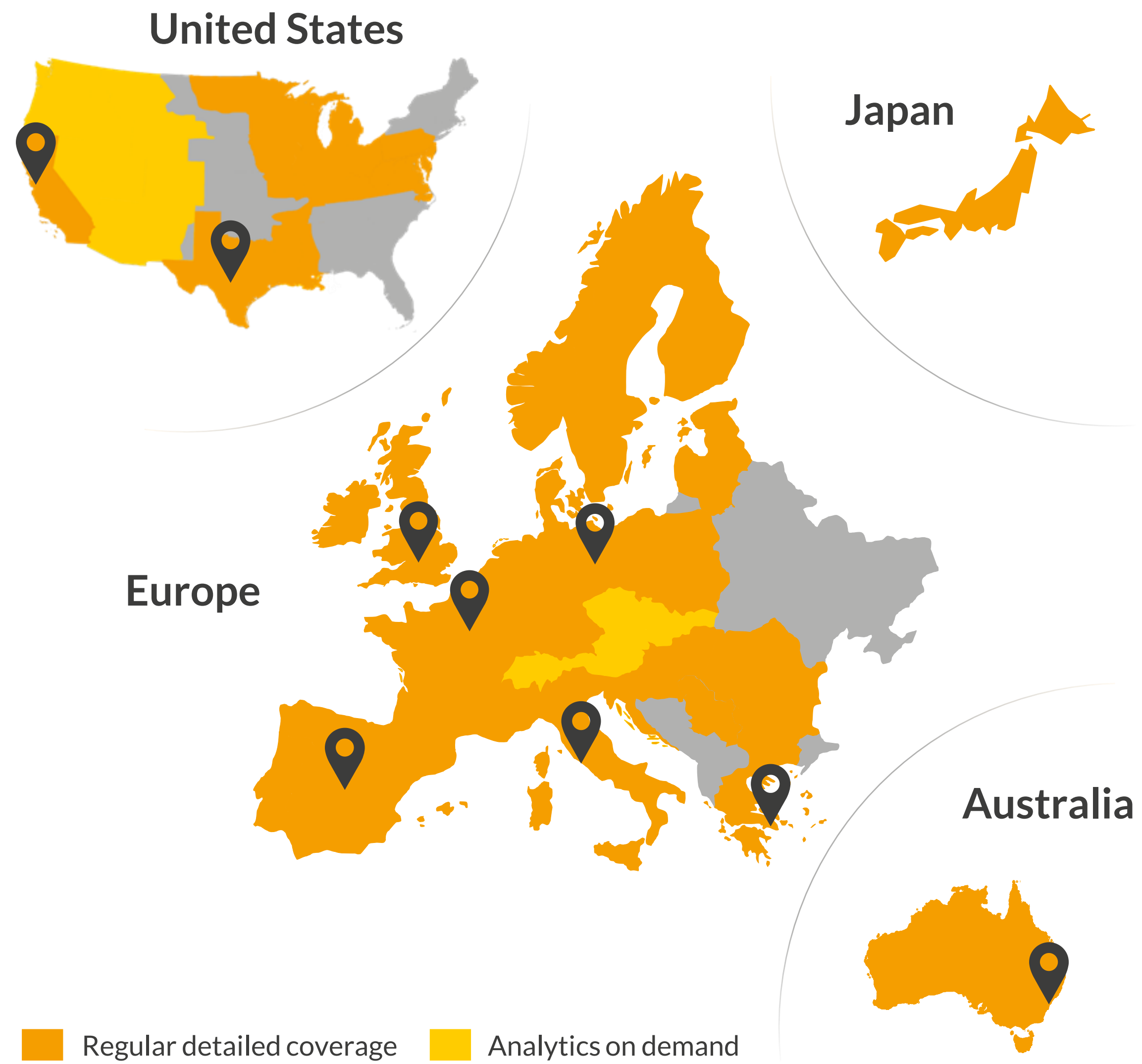
- Power markets
- Renewables
- Storage
- Electric vehicles
- Hydrogen H_2
- Carbon CO_2
- Natural gas



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350+
market experts, 40+ in the US

600+
subscribing companies

120+
transactions supported in 2021

Source: Aurora Energy Research

Our market leading models underpin a comprehensive range of seamlessly integrated services to best suit your needs

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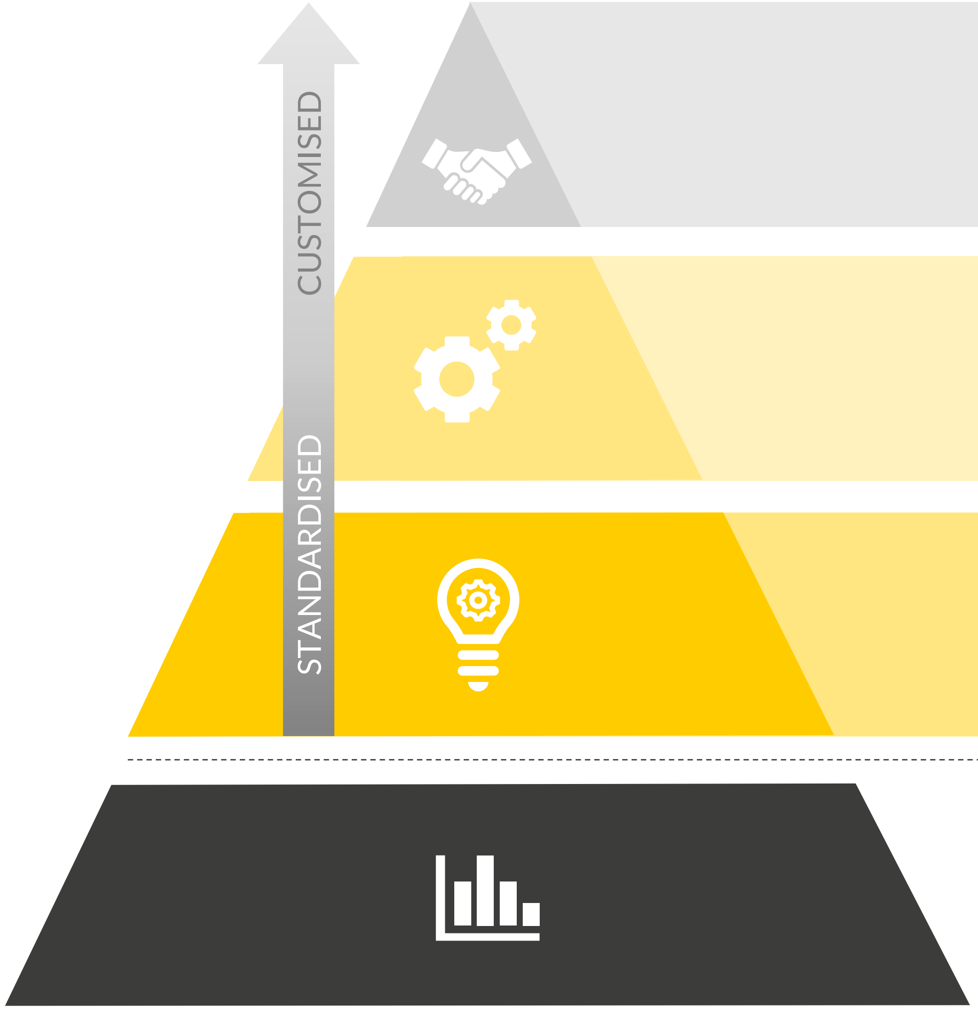

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Developed over 10 years, 40+ dedicated modellers

Source: Aurora Energy Research

Modelling storage is complex. Aurora's forecasts have underpinned the deployment of over 1.5 GW of operational battery assets globally

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What is the challenge?

- Modelling a consistent set of day-ahead, real-time and Ancillary service prices accounting for opportunity costs
- Understanding and modelling detailed rules in AS markets, including responding to market changes
- Capturing the role of weather in driving scarcity and AS procurement – annual averages are irrelevant to storage economics, esp. as renewables penetration increases

Future of the market (*difficult to model*)

- Dispatching assets against multiple price series accounting for imperfect foresight, degradation, warranties, route to market, and asset characteristics

Future of the asset in the market (*easier to model*)

How do we address it?

- ✓ Offer valuations for a range of standard and bespoke market scenarios
- ✓ Work closely with clients to ensure the valuation is specific to their asset or portfolio characteristics
- ✓ Model storage margins for all major business models including arbitrage, Ancillary Services, and hybrid
- ✓ Dispatch against consistent day-ahead, real-time and AS prices
- ✓ Account for degradation and imperfect foresight
- ✓ Present results in slides and cashflow model at monthly, quarterly and annual granularity

Example transactions

2017	UK	Sell-side advisory for UKPR's 500+ MW portfolio of peakers and battery storage, sold to Sembcorp for £216m
2018	UK	Banked by Santander on first project financing of battery storage in the UK for 100 MW Zenobe portfolio
	Germany	Sell-side market advisory for then-largest operational battery storage portfolio in Europe, STEAG's 90 MW bid into the FCR market
2019	UK	Supported Pivot Power on sale of company and 2GW portfolio to EDF
	Ireland	Supported PE fund on \$50m acquisition of storage developer; bidding support for large developer for DS3 auctions
2020	Australia	AUS \$50m in debt financing for 50MW extension of Neoen's Hornsdale battery – first battery project financing in Australia
2021	UK	Debt and equity raise for 100 MW battery portfolio
	Australia	Development/financing of 150MW Hazelwood BESS project
2022	USA	Buy-side advisor on multiple equity transactions for over 1GW of battery storage projects across Texas
	USA	Sell-side advisor for 1.1 GW of battery storage from BMES to UBS Asset Management and Cypress Creek Renewables

Source: Aurora Energy Research

Aurora is trusted as a bankable lender's advisor across US and European power markets

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Aurora's price forecasts have been relied upon by lenders in recently completed transactions:

- $568MM debt financing of a 300MW Solar + Storage facility in CAISO
- $568MM debt financing of a 350MW Storage portfolio in CAISO
- $650MM debt financing of a 215MW Solar + Storage facility in CAISO
- $130MM debt financing of a 150MW Solar project in ERCOT
- Market advisor for debt financing of Gresham House's 400+MW battery storage portfolio
- Debt financing of a 826MW CCGT asset
- €28MM debt financing
  First subsidy-free wind financing in Poland
- £192MM debt financing
  Saltend CCGT with CHP. LMA for regular forecasts
- Market advisor for the financing of a portfolio of hydro and PV assets
- Sell side advisor for the largest operational battery storage portfolio within the frequency containment reserve in Europe (90 MW)
- Market advisor for first project financing of battery storage in the UK
- €48MM debt financing
  220MW Potegowo onshore wind farm of Israel Infrastructure Fund

Source: Aurora Energy Research

Aurora's battery forecasts utilize both our long-term market model and the battery asset dispatch model

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Step 1: Model the wholesale and ancillary markets

Wholesale market assumptions
- Technology, commodity, demand, policy assumptions etc.

PJM Power Market Model
- Simultaneously models wholesale, ancillary, capacity, and REC markets
- Hourly granularity
- Iterative modelling
- Capacity build / exit / mothballing
- IRR / NPV driven
- Detailed technology assessments

Continuous iteration until an equilibrium is reached

Wholesale prices
- DA prices at 1-hour granularity
- RT prices at 1-hour granularity derived from DA prices

Ancillary service prices
- All main services consistent with DA prices

Capacity market prices
- Internally consistent with wholesale and ancillary service prices

All additional revenue streams
- E.g., RECs based on revenue requirements and shortfall dynamics

Step 2: Model the battery asset dispatch

Asset business models
- Business model: Energy only, Ancillary service only, optimized across markets
- Connection: Standalone/ co-located with solar/thermal/wind asset with/without DC coupling
- Location: Relevant hub price and LMP bonus

Storage asset dispatch model
- Model trading strategy against hourly prices in sequence
- Lifetime impact of degradation

Storage asset dispatch model
- Monthly and yearly granularity
- Gross margins by market

Storage technical parameters and constraints
- Technology: lithium ion/ pumped storage/ flow
- Size
- Duration
- Degradation
- Cycling constraints
- Round trip efficiency
- Co-location charging
- Location and LMP bonus

In-house model | Input | Output

Source: Aurora Energy Research

Agenda

Several challenges exist in the uptake of clean hydrogen, though its potential for decarbonization could be vast

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1 The role of hydrogen for decarbonization could be vast in scale and scope

- Hydrogen (H_2) has emerged as a leading option to reduce economy-wide emissions due to the versatility of its application across sectors and the broad range of production sources
- H_2 can decarbonize harder-to-abate sectors where electrification will not suffice

1 Production

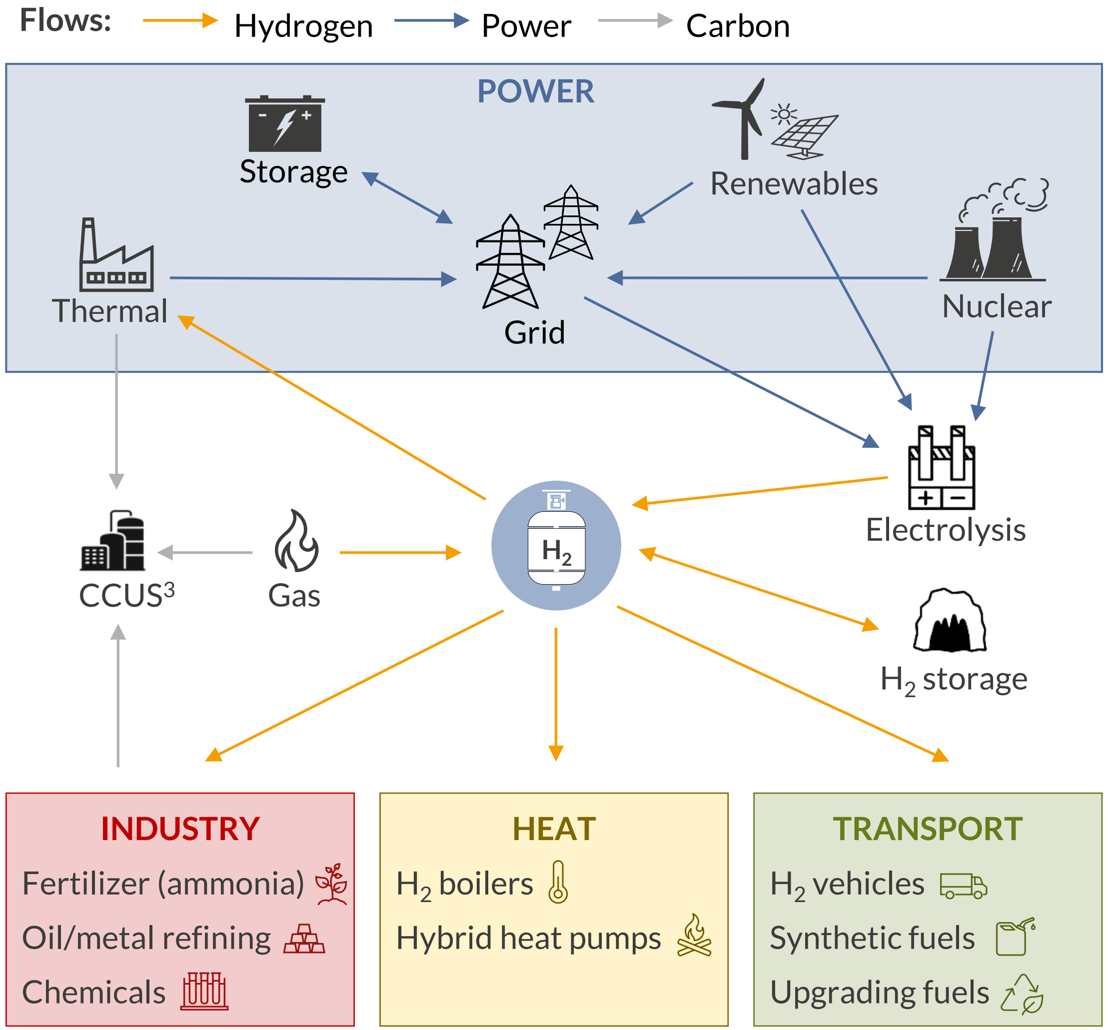
- Hydrogen can be produced from different sources, including natural gas and electricity
- Increased supply will largely come from electrolysis or gas reformation

2 Consumption

- Hydrogen will see extensive application in sectors with limited clean alternatives e.g. heavy duty transport, shipping, steel manufacturing, etc.
- It may also play a role in the US power sector where it can be blended with natural gas to create lower emission electricity

2 Several challenges remain to the uptake of clean hydrogen in the US

- **Commercial readiness** – clean hydrogen and hydrogen-ready technologies are still nascent, and the economics of commercial-scale rollout are still unclear
- **Efficiency** – low efficiencies are typical of production processes[1] and of consumption[2]
- **Infrastructure** – a fully fledged transport and storage network will be required to untap the full potential of hydrogen



1) Due to conversion losses, losses resulting from further compression or cooling, 2) I.e. hydrogen boilers are less efficient than electric alternatives. 3) Carbon capture, utilization, and storage.

Sources: Aurora Energy Research

There are many ways to produce hydrogen though gas reformation is dominant in practice, making up 82% of total production in 2021

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1 The hydrogen "rainbow" consists of various feedstocks and processes

Color	Input	Process
Green	Electricity - Renewables	Electrolysis
Pink	Electricity - Nuclear	Electrolysis
Yellow	Electricity – pulled from grid	Electrolysis
Turquoise	Natural gas	Methane pyrolysis
White	Byproduct of industrial processes[6]	Biomass conversion
Grey	Natural gas	Gas reformation
Blue	Natural gas	Gas reformation with CCS
Brown[1]	Coal/lignite	Gasification

2 Two main processes – electrolysis and gas reformation with CCUS[3] – are of primary interest for federal subsidies

Hydrogen production through electrolysis

$H_2O \xrightarrow{\text{Electrolysis}} H_2 + O_2$

Water → Hydrogen + Oxygen

- Electricity goes through a process called electrolysis which splits water molecules to produce hydrogen and oxygen
- Green hydrogen, using electricity from renewables, is expected to be the highest in demand for meeting decarbonization targets

Hydrogen production through gas reformation

$CH_4 \xrightarrow{\text{Gas reformation}} H_2 + CO_2$

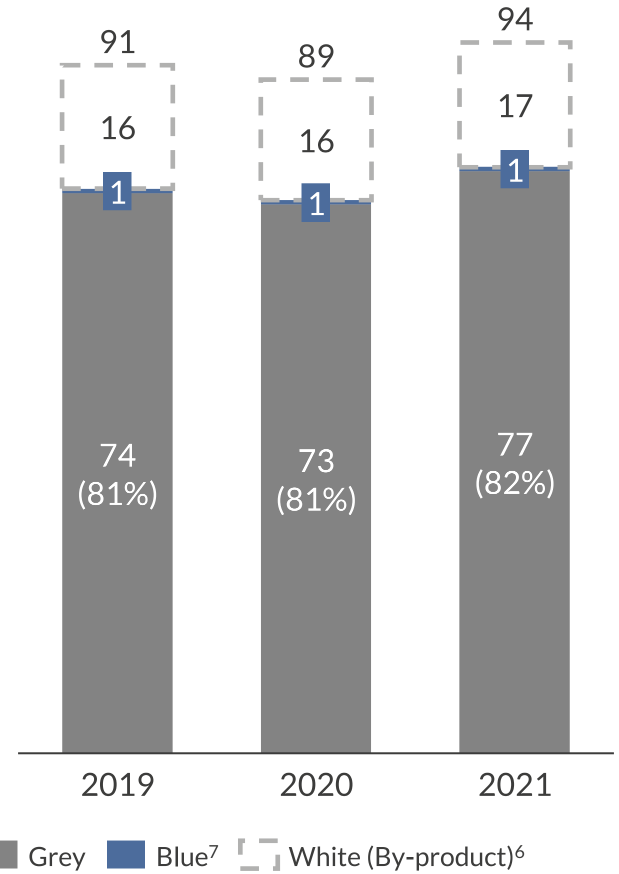
Methane → Hydrogen + Carbon dioxide (captured via CCUS[3])

- Methane (natural gas) goes through a process called gas reformation to produce hydrogen and carbon dioxide – with CCUS it is blue hydrogen, without CCUS it is grey hydrogen
- Production costs will be determined by the natural gas price
- Processes include SMR[4] and ATR[5]

3 Though current hydrogen demand is met primarily with grey H_2

Annual global H_2 production by type

Million metric tons H_2



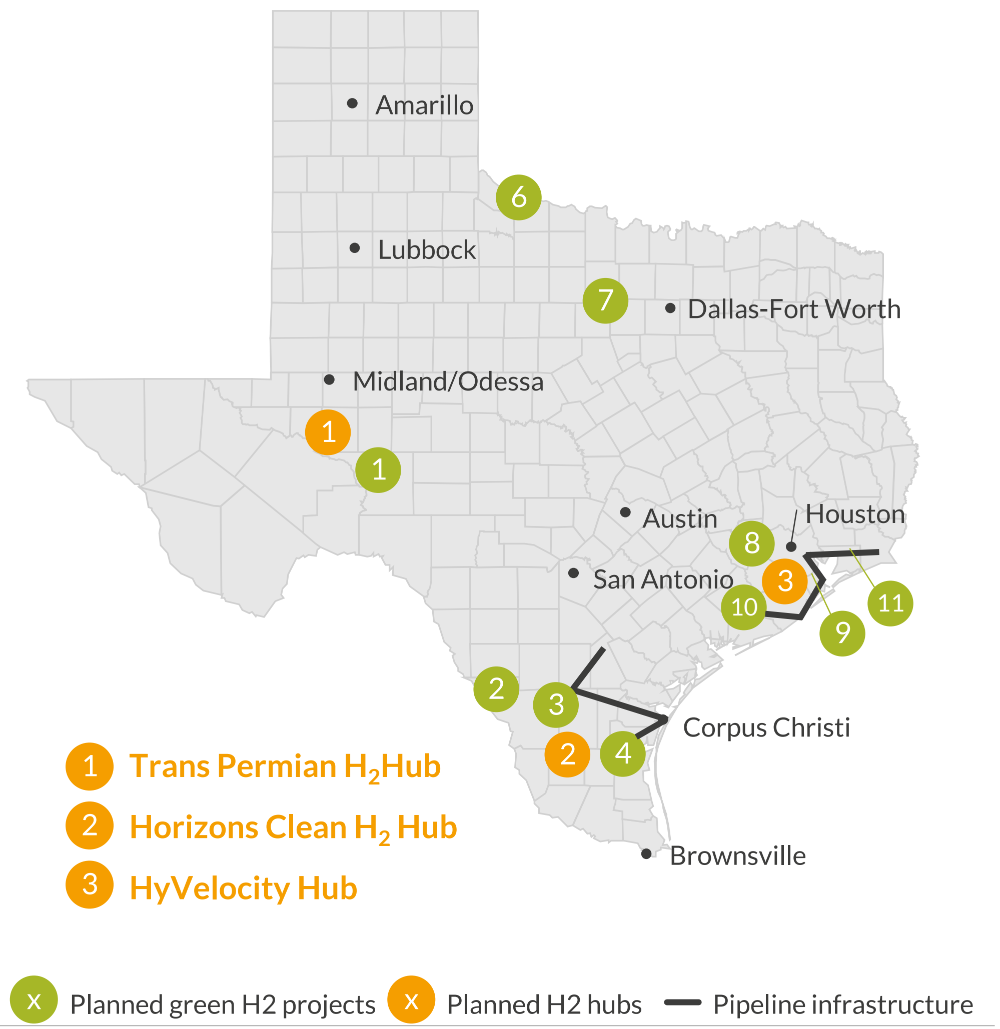
1) Also referred to as black hydrogen. 2) Inflation Reduction Act, for construction start years 2022-2032. 3) Carbon capture, utilization and storage. 4) Steam Methane Reforming. 5) Autothermal Reforming. 6) Primarily from processes in the petrochemical industry. 7) As of April 2021, there were seven active blue hydrogen plants globally, producing a combined ~4,000 metric tonnes of hydrogen per day.

Sources: Aurora Energy Research, EIA, Global CCS Institute.

Texas' characteristics make it an attractive state for clean hydrogen investment; 90% of all US hydrogen pipelines are along the Gulf Coast

Topic	Blue hydrogen	Green hydrogen
Production	Abundant natural gas production and low gas prices	Windy areas, high irradiance, relatively fast interconnection, competitive market, cheap and abundant land
Transport	**Existing natural gas and hydrogen pipeline infrastructure** – 60% of all US hydrogen is already produced and moved along the Texas and Louisiana coasts where there is also 90% of US hydrogen pipeline infrastructure **Coastal access for exports** – in the form of ammonia, liquid H_2, etc.	
Storage	Depleted conventional oil and gas wells for sequestration of carbon dioxide	Natural salt caverns in South Texas and along the Gulf Coast for hydrogen storage
End-use	**Existing hydrogen demand** along the Gulf Coast from oil refining, petrochemicals, fertilizer production, and aerospace operations	
Culture	**Texas' economy is historically tied up in energy**, strong labor force in oil and gas and an educated workforce. Blue hydrogen serves as a transition fuel for oil and gas, green hydrogen as a new fuel	

Key locations in Texas for hydrogen production[1]



1) Most planned blue hydrogen projects are along the coast near demand.

Sources: Aurora Energy Research, Department of Energy, Congressional Research Service, Pipeline Transportation of Hydrogen: Regulation, Research, and Policy

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We have identified four business models for hydrogen production via electrolyzers to benchmark against grey and blue production

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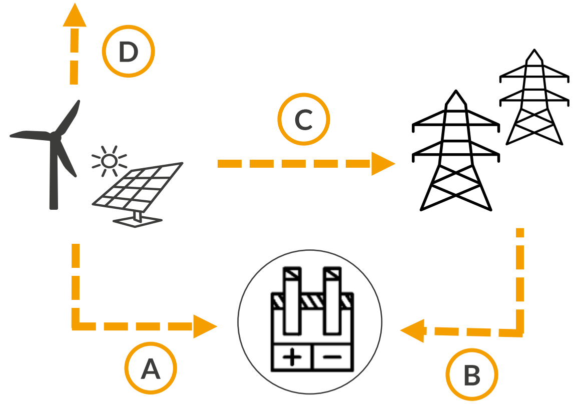
0 Blue/grey hydrogen

- Calculated for benchmarking green hydrogen prices

Overview of connections we considered in our electrolyzer business models

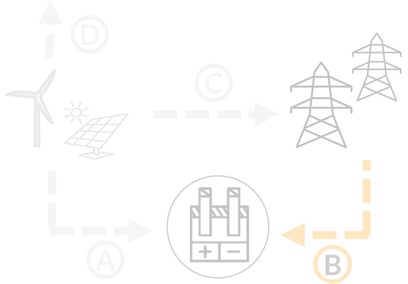


- A Electrolyzer imports power from renewables
- B Electrolyzer imports power from grid
- C Renewables exports power to grid
- D Renewables spills power

Grid connected

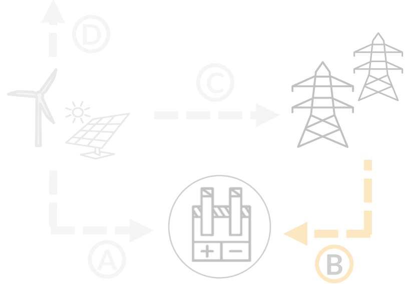
1 Grid connected (inflexible)

- Grid electricity **only** and runs at **95%** load factor



2 Grid connected (flexible)

- Grid electricity **only** and ability to choose operating hours to minimize LCOH

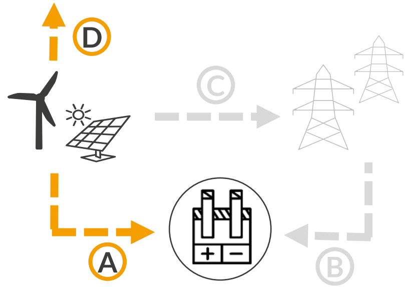


Not considered today

Co-located

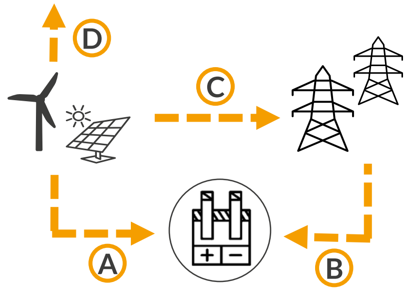
3 Co-located (island)

- Electrolyzer connected to renewable asset only (no grid connection)



4 Co-located (with grid connection)

- Direct connection between electrolyzer and renewable asset; both connected to grid



Sources: Aurora Energy Research

We use the levelized cost of hydrogen production (LCOH) to compare across different types and output levels of hydrogen

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Schematic of hydrogen production plant lifetime

Construction and development phase → **Commissioning** → Operational phase → **End of life** → Decommissioning

Cost of hydrogen production	Capital cost of plant, construction costs, permitting costs, grid connection, other costs	Operating costs (fuel, maintenance, grid charges and power prices, rent, water) Production Tax Credits (PTC) for clean hydrogen Hydrogen production	Decommissioning costs

1 LCOH definition

The Levelized Cost of Hydrogen (LCOH) production represents the lifetime average production costs for a plant commissioned in a certain year

2 Why we use LCOH

The LCOH allows us to compare different modes of hydrogen production by considering the production costs over the whole lifetime. Using LCOH, one can set benchmarks below which production of green hydrogen becomes cost competitive with blue and grey hydrogen

3 How is it calculated?

- LCOH is calculated by dividing the net present value (NPV) of the total lifetime costs and subsidies of the asset by the discounted total hydrogen production over the lifetime of the electrolyzer
- This gives one value of LCOH for the lifetime of the asset (in any given year the actual production costs may vary, depending on the fuel and other variable costs)

Cost Subsidy

Sources: Aurora Energy Research

Hydrogen produced via electrolysis can receive a PTC of \$3/kg H_2 and business models co-located with renewables can stack tax credits

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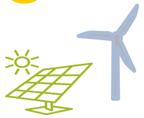
Tax credit stackability — Expectation that both the electricity-generating asset and the electrolyzer may get a PTC

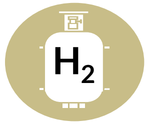
Potential lifecycle benefits for hydrogen production

1 Renewable energy generation for electrolysis



Wind and solar generation qualifies for the Production Tax Credit or Investment Tax credit (as much as \$32/MWh for ten years or 60% of capital expenditure, respectively)

2 Clean hydrogen production



Clean hydrogen production is eligible for Section 45V PTC. Alternatively, blue hydrogen can opt for Section 45Q PTC for carbon sequestration

3 Zero-emission electricity generation

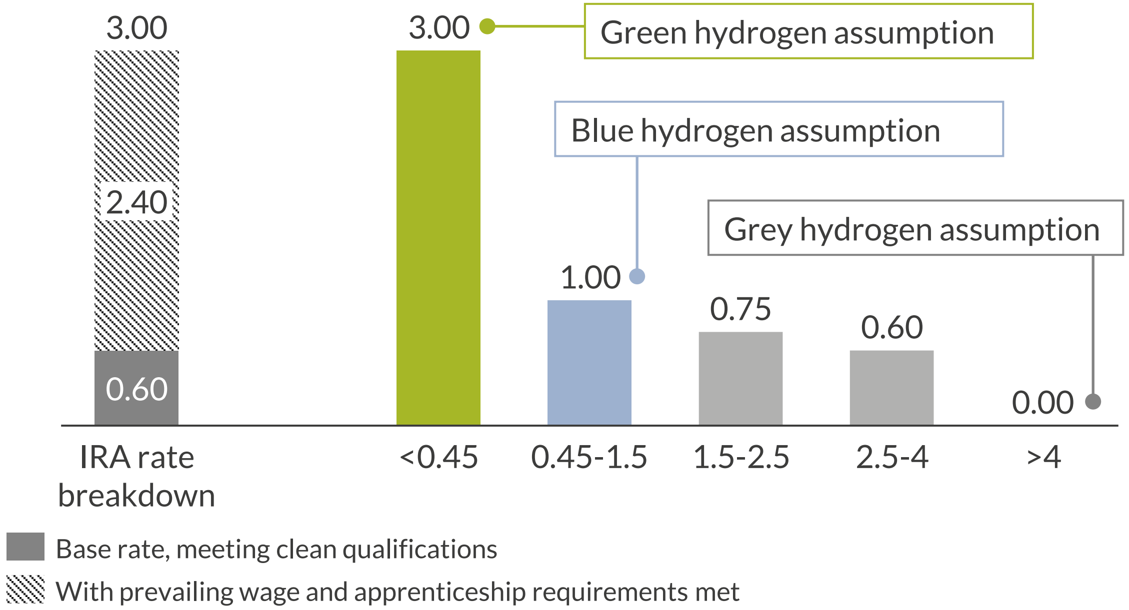
If the hydrogen is used as a feedstock for electricity production, the facility is eligible for PTC or ITC as zero-carbon electricity generation

- Stacked credits are possible for an electrolyzer co-located with a wind or solar asset. Tax credit rates for electricity generation vary by meeting a range of criteria: wage and apprenticeship requirements, use of domestic content, low income or energy community siting, etc.
- This effectively reduces costs, reducing the overall cost of H_2 production

Tax credit availability — Electrolyzers can receive a maximum of \$3/kg H_2 PTC, blue hydrogen receives \$1/kg PTC

Applicable 45V PTC rate based on CO_2e kg to H_2 kg ratio

\$/kg H_2



- The Inflation Reduction Act introduced a direct pay Production Tax Credit (PTC) for low-emission hydrogen production
- The applicable credit rate is based on a tiered system of labor and emissions requirements. If i) wage requirements are met and ii) the ratio of emissions created to hydrogen produced is 1:1, a facility would receive a PTC of \$1/kg H_2

Sources: Aurora Energy Research, The White House

For a 2030 commissioning, the co-located models achieve a competitive LCOH with blue and grey hydrogen thanks to the PTC

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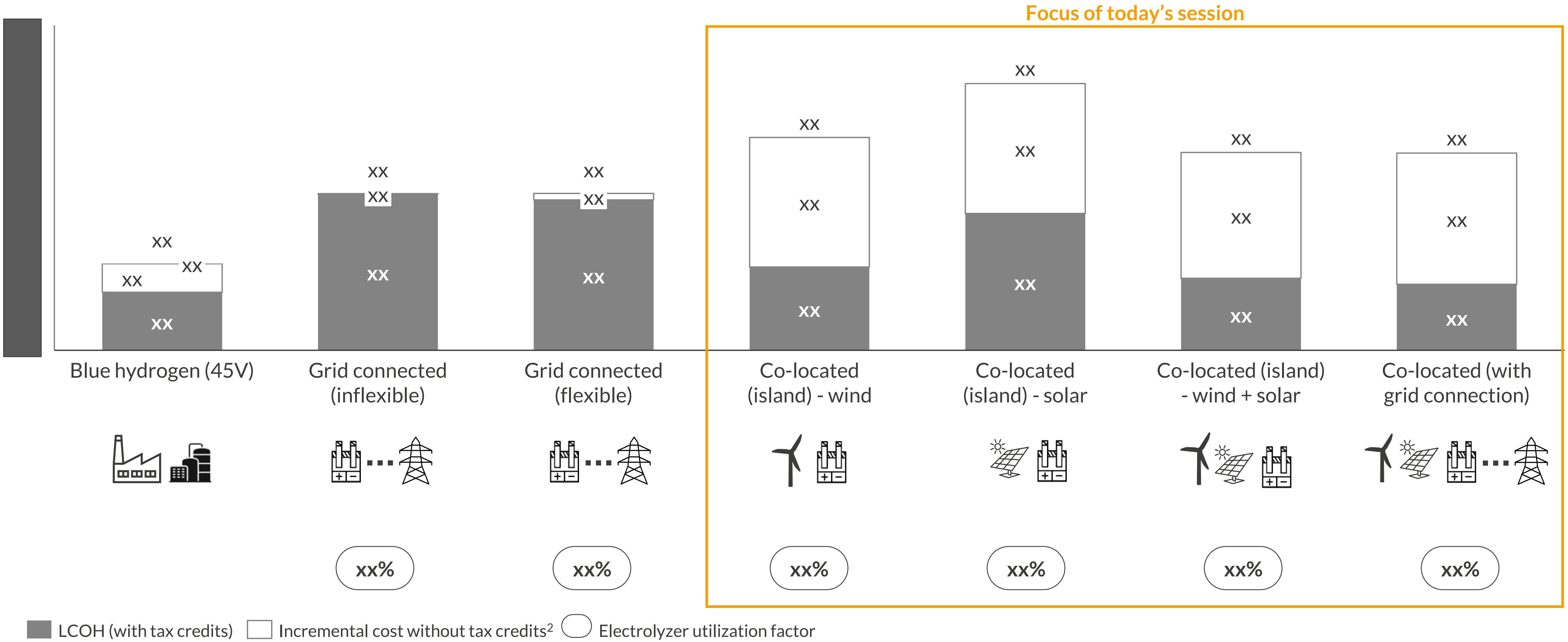
Levelized cost of electrolyzer H_2 production, 2030 commissioning, South hub
$/kg H_2 (real 2021)



1) Inflexible model using an alkaline electrolyzer; all other models using PEM. 2) Tax credits for clean hydrogen production, tax credits from co-located renewables assets. For grid-connected business models, value of tax credits for electricity in the wholesale market remains.
Sources: Aurora Energy Research

For electrolyzers co-located with renewables, optimal sizing of wind and solar is critical to maximize load factor and minimize spillage

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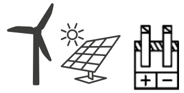
3 Co-located (island)



The key consideration for this business model is the size of the electrolyzer relative to the renewable asset, which can take three forms:

1 Under-utilized electrolyzer

If the renewable asset is not sized optimally, the hydrogen costs can be high due to a low utilization of the electrolyzer

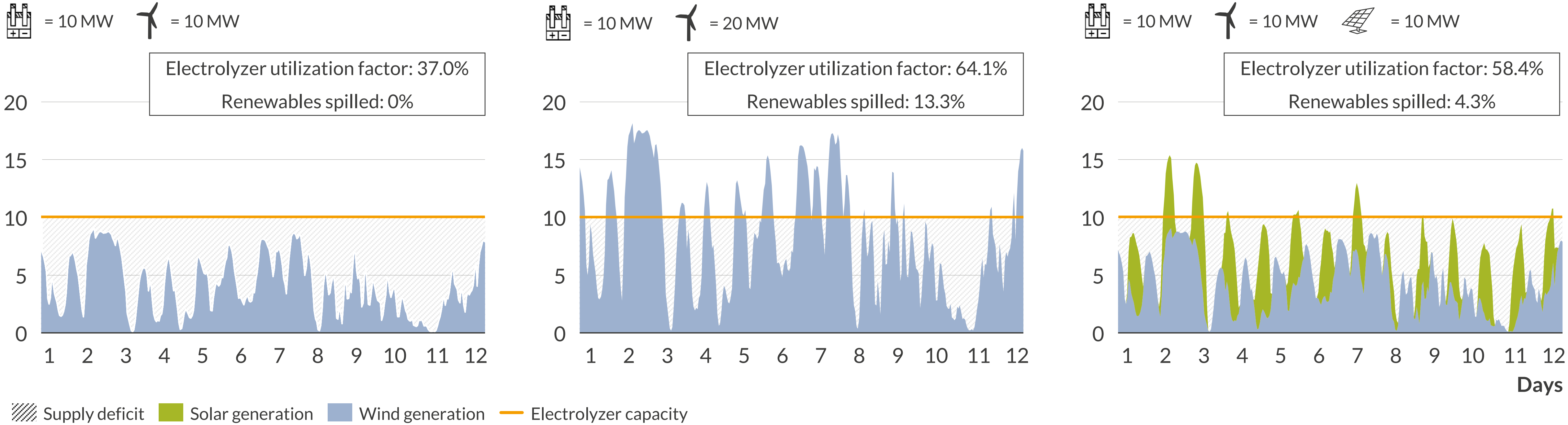
2 Over-sized renewable asset

If the renewable asset is too oversized relative to the electrolyzer capacity, this can lead to significant energy spillage and a high LCOH as the renewable costs are also taken into account[1]

3 Hybrid renewables

Hybrid wind and solar co-location can help to achieve a higher ratio of electrolyzer utilization factor to spilled power

Example electricity generation profiles for various renewable sizings, MW



1) Curtailment is reflected in the LCOH, as energy spillage leads to a higher average cost of energy, increasing renewable hydrogen production costs.

Sources: Aurora Energy Research

For 2030 commissioning, [redacted] MW wind is optimal for [redacted] MW electrolyzer while solar co-location is less attractive due to lower electrolyzer utilization

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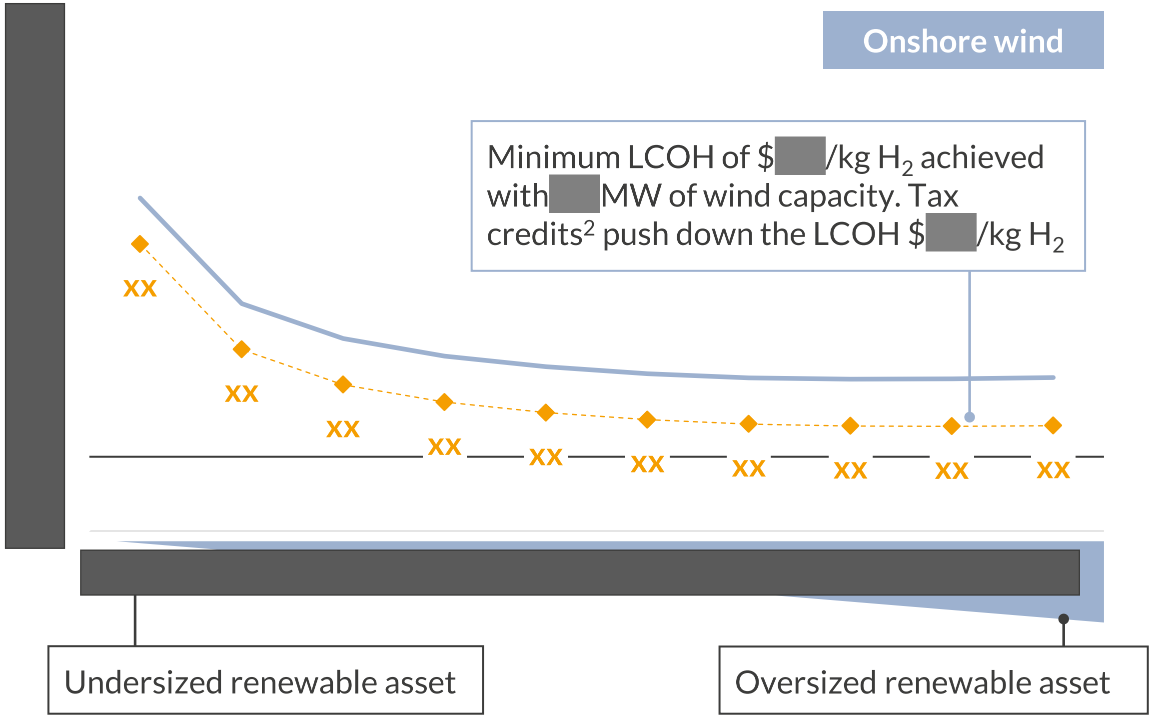
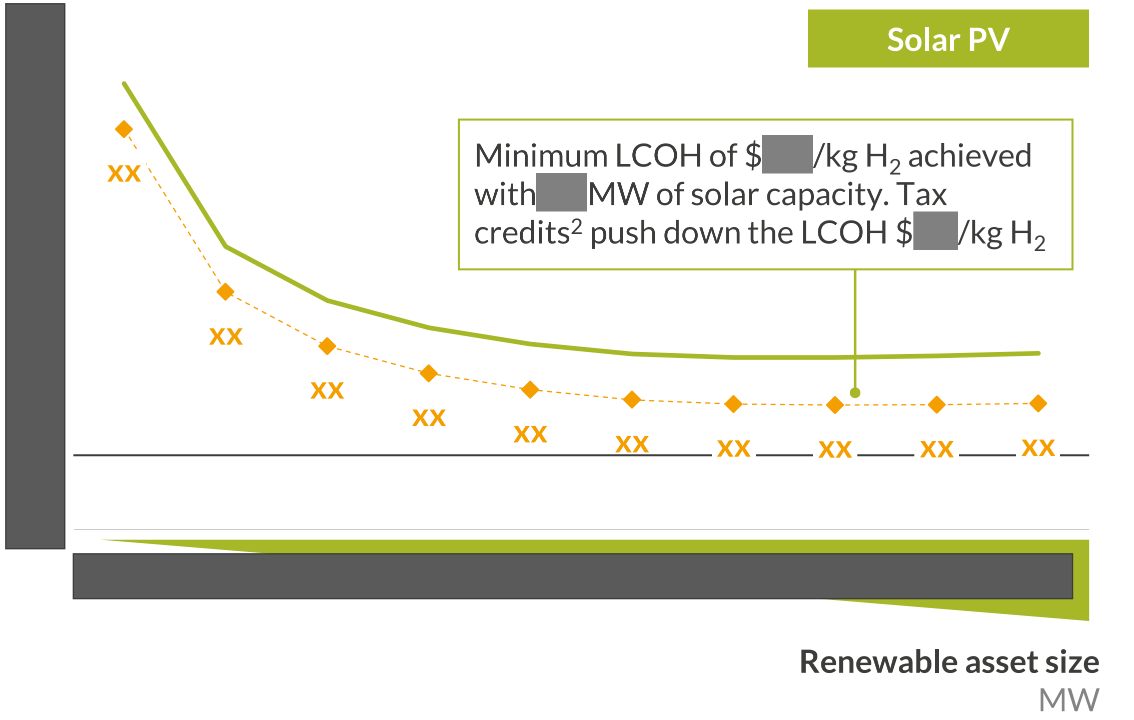
3 Co-located (island)

LCOH of a 100 MW electrolyzer, South Hub, 2030

$/kg H_2





- The LCOH reaches a minimum of $[redacted]/kg H_2 with a [redacted] MW wind asset. Wind has relatively high load factor compared to solar[1]; the electrolyzer reaches [redacted]% utilization with [redacted] MW of wind capacity
- When wind is undersized, the low electrolyzer output results in a higher hydrogen price due to not sharing out CAPEX and fixed costs

- Low solar load factors lead to limited utilization of the electrolyzer[1], resulting in high LCOH relative to co-location with onshore wind. The electrolyzer reaches [redacted]% utilization at [redacted] MW, [redacted] p.p. less than wind at same capacity
- The inflection point in the LCOH curve for solar occurs at a [redacted] MW. Beyond this size, spilled electricity and higher CAPEX cause the LCOH to increase

LCOH (with hydrogen and renewables tax credits) — LCOH (no tax credits)[2]

1) Using average annual load factors of [redacted]% for wind and [redacted]% for solar. 2) Showing the impact of removing the [redacted]V PTC for both power and hydrogen production.

Sources: Aurora Energy Research

A combination of [redacted] MW wind and [redacted] MW solar lowers LCOH to $[redacted] /kg H_2 at an electrolyzer utilization factor of [redacted] %

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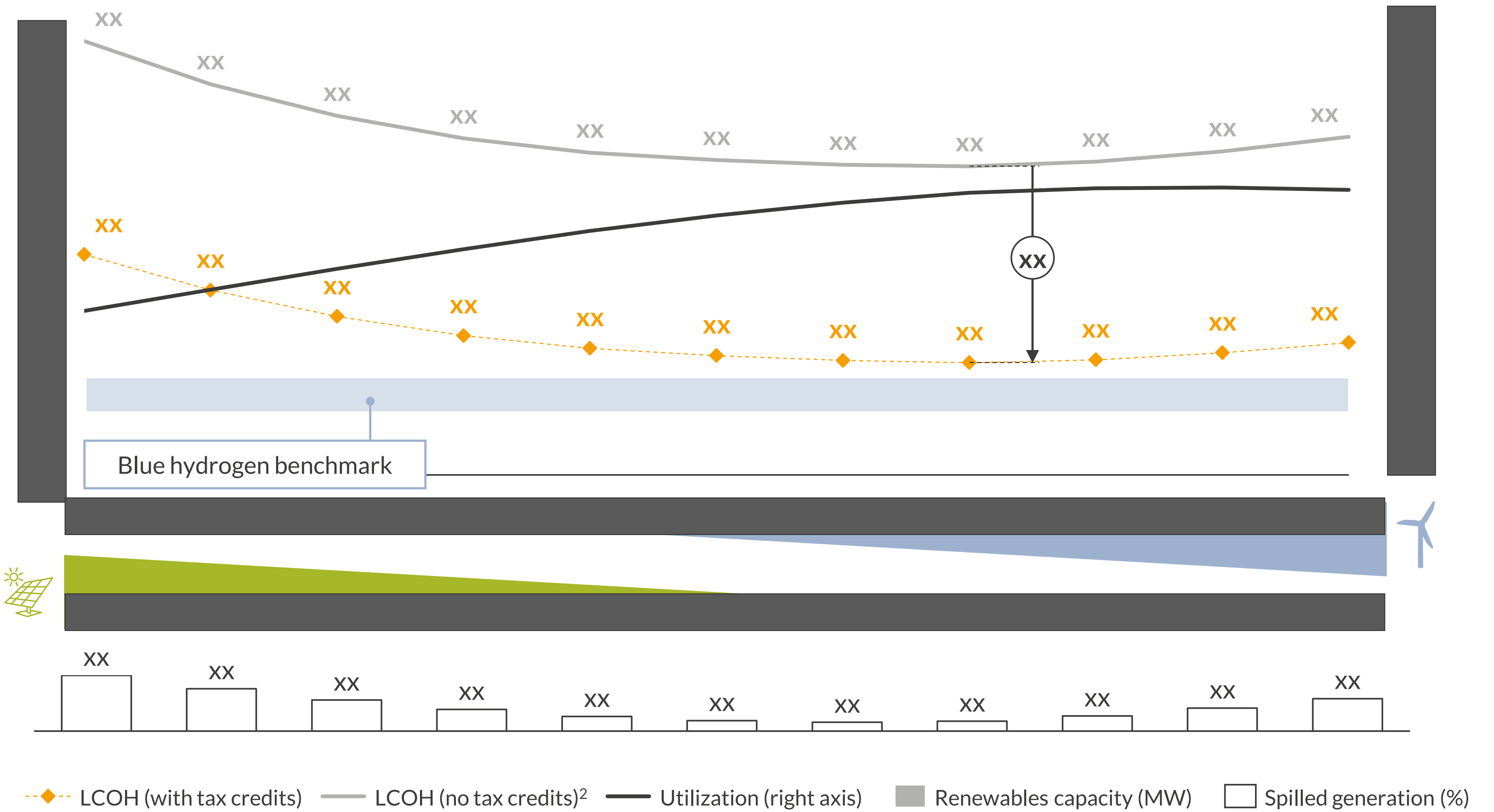
3 Co-located (island)

LCOH of a [redacted] MW electrolyzer with combined renewables assets, 2030[1]
$/kg H_2

Electrolyzer utilization factor
%



1) Commissioned in 2030 in the South hub using a PEM electrolyzer. 2) Showing the impact of removing the [redacted] V PTC for both power and hydrogen production.

Sources: Aurora Energy Research

- Complementary production profiles of solar PV and onshore wind help increase electrolyzer utilization, thereby reducing the cost of the project
- The economic optimal asset sizing can reduce the LCOH to $[redacted] /kg H_2, comprised of [redacted] MW of wind and [redacted] MW of solar with only [redacted] % of generation spilled. However, this does not take into account storage, transportation, or the offaker's preferred production profile
- Combining wind and solar technologies improves the business case compared to co-location with a single renewable asset, reductions totalling $[redacted] /kg H_2 for solar and only $[redacted] /kg H_2 for wind
- The availability of hydrogen and electricity PTCs drive down LCOH by $[redacted] /kg H_2 in the optimal configuration

Adding a grid connection to a co-located electrolyzer can increase electrolyzer utilization and adds another source of revenue

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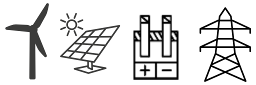
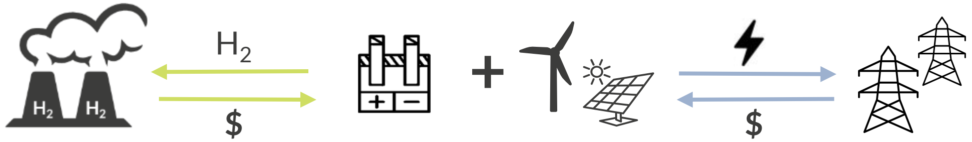
4 Co-located (with grid connection)



Under this business model, revenue come from two sources:



1 Hydrogen exports

- The electrolyzer produces hydrogen with power from the renewables assets or the grid
- Produced hydrogen is sold to offtakers, e.g. industry

2 Electricity exports

- The renewables assets generate electricity and sell to the grid at wholesale prices
- Or it supplies power to the electrolyzer if hydrogen is more valuable

- A Co-located (with grid connection) business model expands on the Co-located (island) electrolyzer model. Adding a grid connection allows for greater flexibility in hydrogen production
- With a grid connection, the electrolyzer can choose to purchase grid electricity to increase its production when renewables generation is insufficient and it is still profitable to produce hydrogen
- The model can also sell any excess renewable generation (minimizing spill) and sell power generated from co-located renewables to the grid when prices are high

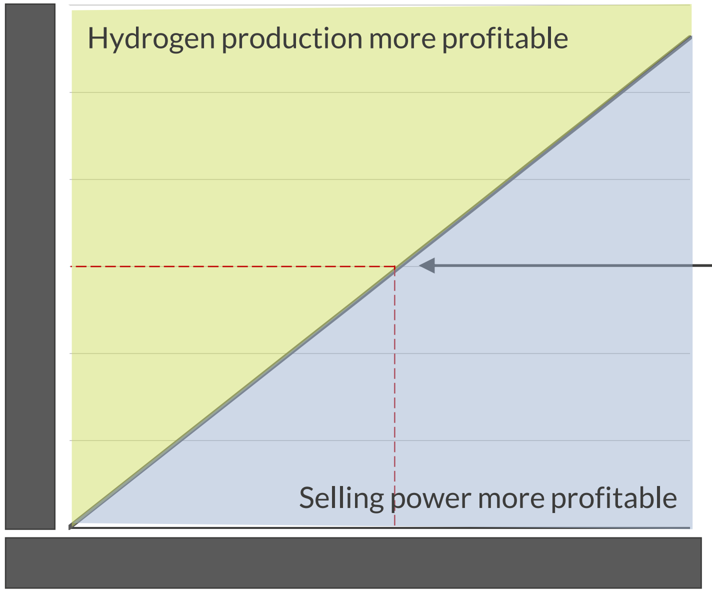
Revenue optimization

To maximize revenues, the electrolyzer will need to optimize its operations based on the profits from both sources, which is dictated by:

i. Hourly power price – we use Aurora Central scenario for the analysis

ii. Hydrogen price – we assume a fixed purchase price of $3/kg H_2 by industrial offtakers

Hydrogen price, $/kg H_2



At a power price of $[redacted] /MWh, a hydrogen offtake price of at least **$[redacted]/kg H_2** would be required to incentivize hydrogen production over selling power to grid[1]

Power price, $/MWh

1) Assuming no hydrogen PTC.

Sources: Aurora Energy Research

A grid connection can decrease LCOH by an additional $[redacted]/kg H_2 and provide an additional secure revenue stream from power sales

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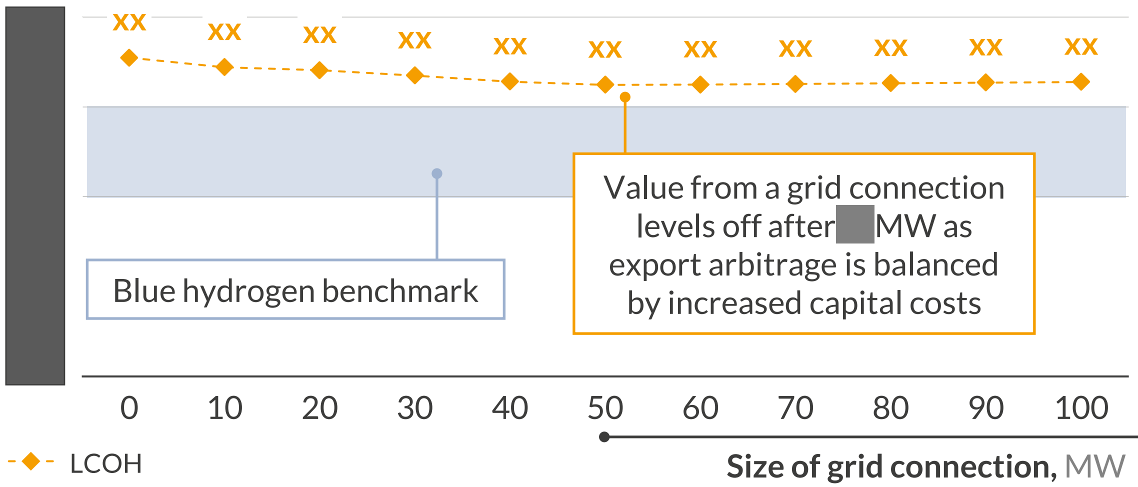
4 Co-located (with grid connection)

1 Adding a grid connection to a co-located model is the most competitive electrolyzer business model, reaching $[redacted]/kg H_2 at [redacted] MW connection…

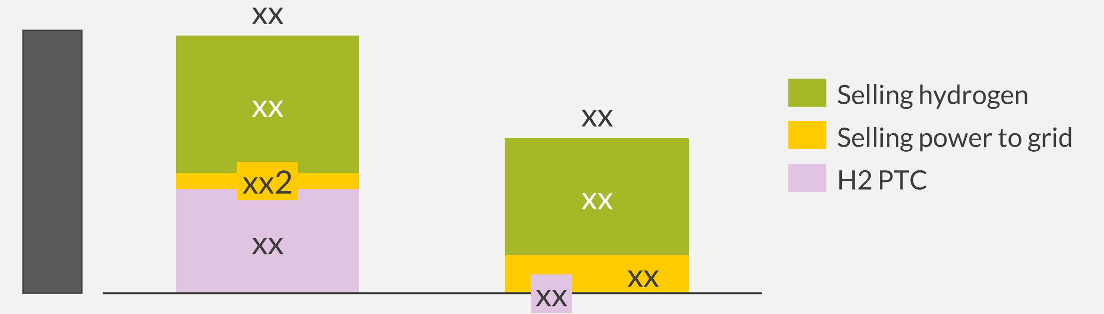
LCOH by varying grid connection[1]
$/kg H_2



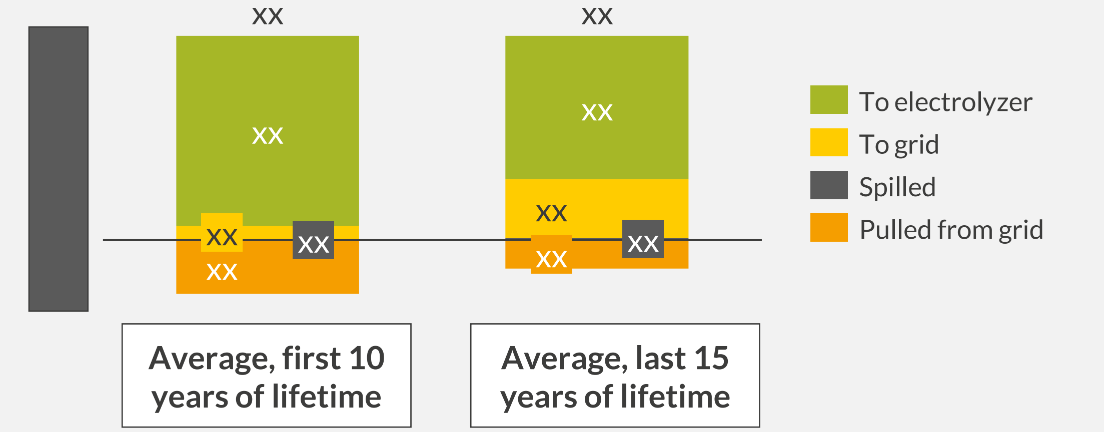
- Revenue from the clean H_2 PTC makes up [redacted]% of revenue in the first ten years of operation (assuming a fixed $[redacted]/kg H_2 offtake price). After PTC expiration, a growing share comes from exporting power to the grid as the assets engage in arbitrage without factoring the opportunity cost of the hydrogen PTC
- Imported power from grid for H_2 production steadily declines as wholesale prices increase and offtake remains steady - $[redacted]/MWh is the breakeven
- Renewables spill increases in later years, occurring when generation is sufficient to fully power the electrolyzer and wholesale prices are negative

2 …although most H_2 produced is from the co-located assets, the additional revenue stream from selling power cushions revenues in later years

Annual revenue with [redacted] MW grid connection (with $[redacted]/kg H_2 offtake price)
$ million (real 2021)



Flow of power from co-located renewables (with $[redacted]/kg H_2 offtake price)
GWh



1) 50 MW electrolyzer with [redacted] MW onshore wind asset and [redacted] MW solar asset. For 2030 commissioning, South hub using PEM electrolyzer.

Sources: Aurora Energy Research

In addition to asset sizing, transportation and storage costs will play a critical role in delivering hydrogen at a competitive price

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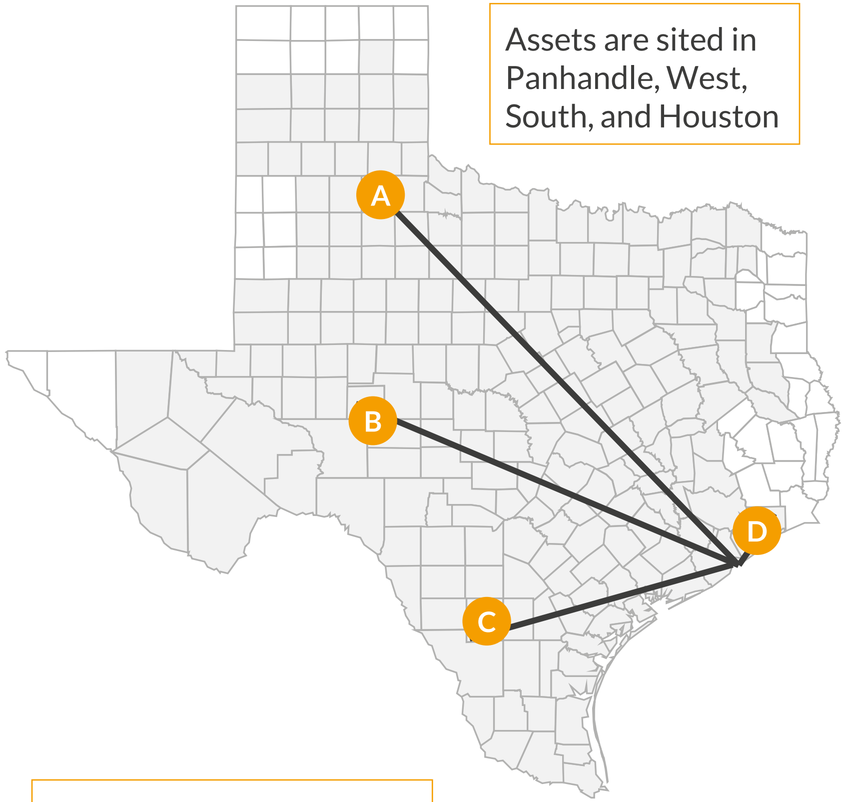
1 **With assets sited in the Panhandle, West, South, and Houson, we applied transport costs**

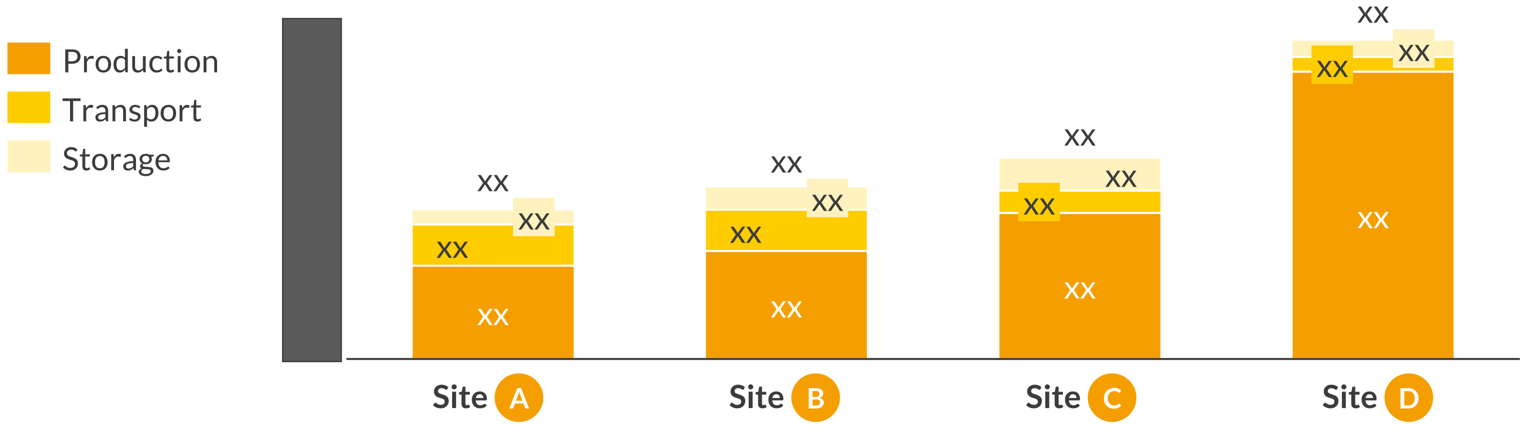
Assets are sited in Panhandle, West, South, and Houston



Hydrogen is transported via pipeline to the Gulf

2 **Assuming high pipeline utilization, siting for renewables assets is more dependent on maximizing renewables production at minimal cost than being located close to demand centers**

Levelized cost of hydrogen production, storage, and transportation, 2030[1], $/kg H_2



Assumptions

	Site A		Site B	Site C	Site D
Renewables sizing, MW	XX	*Solar*	XX	XX	XX
	XX	*Wind*	XX	XX	XX
Pipeline distance, miles	500		400	150	40
Pipeline diameter, inches	20		20	20	12
Pipeline utilization[2], %	57		57	57	70

1) 2030 commissioning, [redacted] MW electrolyzer with [redacted] MW renewables capacity. Co-located (island) model 2) Assuming an aggregation of supply upstream of pipeline corresponding to [redacted] GW of electrolyzer capacity for sites A,B,C and approximately [redacted] GW for site D

Sources: Aurora Energy Research, International Journal of Hydrogen Energy

Key takeaways from Aurora's Group Meeting on hydrogen in the ERCOT market

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1. Hydrogen can be produced in several ways and used in many applications; globally over 80% of hydrogen produced is grey and most is used in industrial applications

2. The Gulf Coast currently produces 60% of the US' hydrogen and is poised to expand further. The Bipartisan Infrastructure Deal will establish 6-10 hydrogen hubs in the US; at least three proposed hubs are located in Texas

3. For green hydrogen to take off at scale it will need to be competitive with blue hydrogen production. With IRA tax credits, blue hydrogen production costs in 2030 are between $[redacted] to $[redacted]/kg H_2

4. Electrolyzers co-located with renewables can reach a $[redacted] - $[redacted]/kg H_2 range (island and grid connected). Grid-connected business models without co-located renewables remain uncompetitive

5. In addition to asset sizing, transportation and storage costs will play a critical role in delivering hydrogen at a competitive price. Siting hydrogen next to demand will reduce costs, but may lower renewables resource

Sources: Aurora Energy Research

Details and disclaimer

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