BOSTON CONSULTING GROUP

Green Hydrogen: An assessment of near-term power matching requirements

Tradeoffs between annual and hourly matching approaches

APRIL 2023

Context for these materials

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Executive summary

❯ **U.S. Inflation Reduction Act (IRA) legislation made a strong commitment to decarbonization via clean hydrogen but did not fully define qualification for the production tax credit (PTC)**

- Green hydrogen (produced from electrolysis) has a decarbonization potential of 9-30+ kg CO_2/kg H_2
- Realization of this decarbonization potential in the near term is contingent on PTC requirements

❯ **Temporal power matching requirements (annual vs hourly) evaluated here against four principles:**

I. Ensure total **carbon emissions** from green H_2 production do not exceed IRA specified limit on a lifetime basis
II. Foster clean H_2 **industry growth** to drive decarbonization, jobs creation, and technology leadership
III. Protect energy consumers from adverse **externalities** of green H_2 buildout (e.g., power cost and reliability)
IV. Enable **simplicity** in PTC qualification/criteria to support equitable outcomes and access to the incentive

❯ **(I. Carbon emissions) While achieving long-term decarbonization will ultimately require hourly matching, analysis suggests an annual matching approach with modest conditions can produce green hydrogen aligned to IRA limit across the U.S. for new green hydrogen assets through 2032**

- Includes base assumptions of additionality and same-grid deployment of supporting renewable energy
- Analysis calculates anticipated emissions for annual matching on an hour-by-hour basis across the U.S.
- Incorporating modest conditions for renewables overbuild capacity, resource mix, and electrolyzer shutdown during peak-load hours, annual matching is expected to yield net negative emissions (-0.5 to -1.8 $kgCO_2/kgH_2$)

❯ **(II. Industry growth) A near-term hourly matching requirement expected to result in higher costs, slowing deployment and technology maturation**

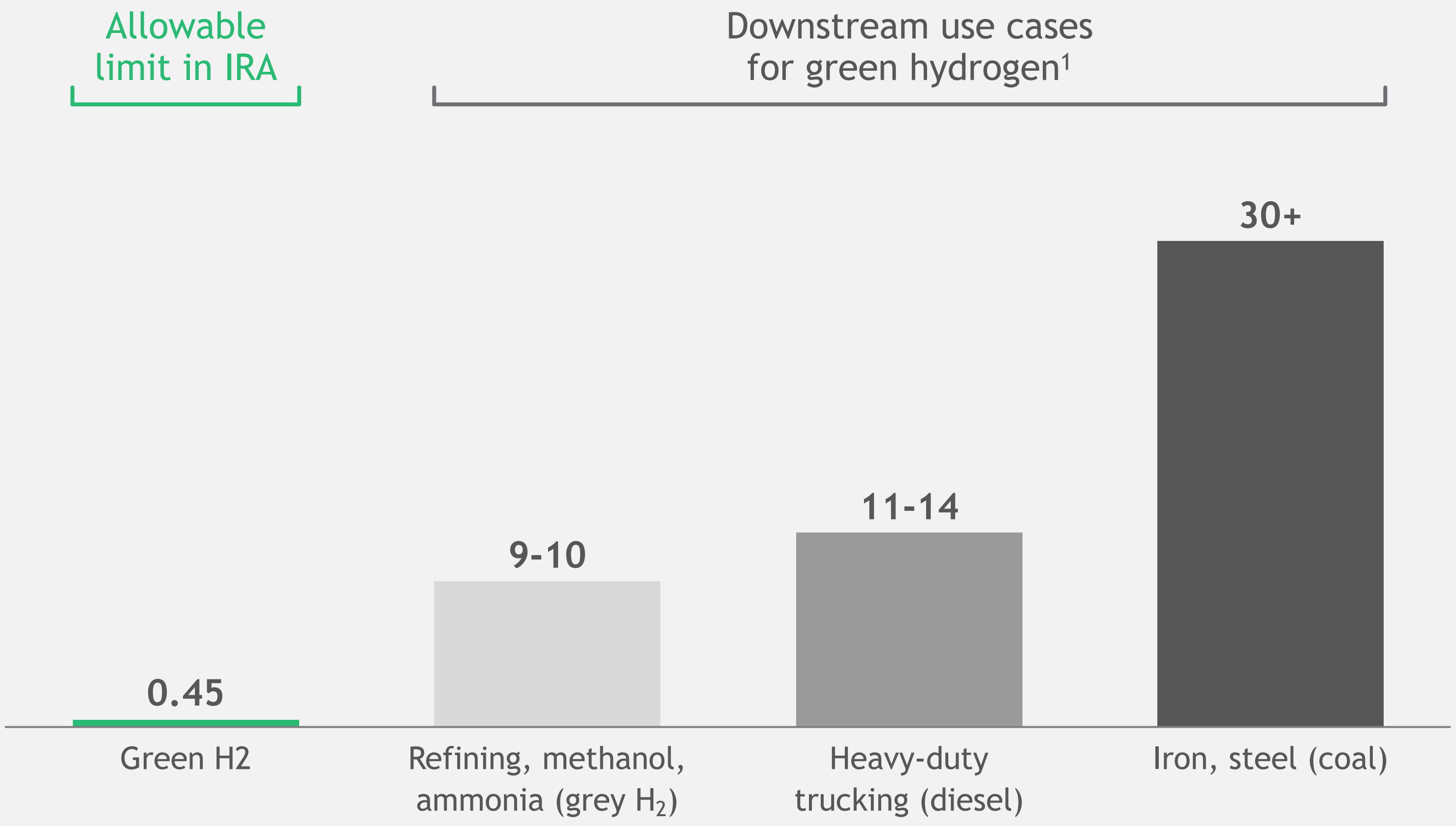
- Costs to achieve hourly matching expected to more than double green H_2 price net of PTC in 2030
- Price premium for hourly matching likely to make green H_2 non-economical for most applications through 2030
- Each Mtpa of new green hydrogen production capacity anticipated to yield $20-22 billion in investments, 40-60,000 jobs, and 6-10 Mtpa abated CO_2 emissions

❯ **(III. Externalities) Basic annual matching is disadvantaged on cost and reliability externalities while annual with conditions and hourly matching mitigate challenges of increased variable renewable energy**

❯ **(IV. Simplicity) Annual matching is simplest and in practice today; hourly matching requires complex optimization to implement and hourly resolution to validate**

Green hydrogen (H_2) is a significant decarbonization opportunity

Emissions intensity (kg CO_2/kg H_2)



1. Displacement of grey hydrogen for processes already using hydrogen today (refining, methanol, ammonia, etc.) expected to transition first given highest breakeven cost and simplicity of the transition

Note: IRA = Inflation Reduction Act

Source: U.S. Gov.; IEA; SP Global; BCG analysis

U.S. Inflation Reduction Act (IRA) builds on prior commitments to green H_2

Hydrogen Earthshot

June 7, 2021 - The first U.S. DoE Energy Earthshot launched: Hydrogen Shot

- Seeks to reduce cost of clean hydrogen by 80% to $1/kg by 2030
- Provides framework and foundations for clean hydrogen development in the American Jobs Plan
- Supports demonstration projects

Infrastructure Investment & Jobs Act (IIJA)

Nov. 15, 2021 - legislation includes:

- $8 billion to establish at least four regional clean hydrogen hubs (incl. one dedicated to nuclear energy)
- $1 billion toward R&D, demonstration, commercialization and deployment of hydrogen from electrolyzers
- $500 million for advanced clean H_2 manufacturing and recycling R&D
- $30 billion in overall clean energy R&D to cut emissions across the economy

Inflation Reduction Act

Aug. 16, 2022 - Climate tax package with a **significant H_2 production tax**:

- Ten (10) year PTC duration
- Full credit eligibility requires meeting apprenticeship and prevailing wage requirements

- Credit scaled by GHG reduction relative to grey H_2[1]:
- ~60-75%: $0.6/kg H_2
- ~75-85%: $0.75/kg H_2
- ~85-95%: $1.0/kg H_2
- ~95%+ : $3/kg H_2

Rules[2] governing qualification and validation will have significant impact on clean hydrogen trajectory in the U.S.

1. Grey hydrogen carbon intensity typically in the range of ~9-10 kg CO_2 / kg H_2; Taking the lower limit of the range, 95% corresponds to 0.45 kg CO_2 / kg H_2 which is the limit listed in the U.S. 45V legislation. 2. At the time of this report, US treasury in the process of defining nuanced rules for distribution of PTC
Note: PTC = Production Tax Credit ; H_2 = Hydrogen
Source: U.S. Government

Option space for near-term U.S. green H_2 PTC qualification/validation

Significant implications for end cost of H_2 and focal point of this analysis

Additionality

Should the electricity source be newly constructed?

New capacity ✓

Carbon-free energy capacity built specifically for the clean hydrogen project

New or existing

Supports repurposing of existing assets for greater carbon impact but can leave gaps that are filled by carbon intensive power

Location

Should the electricity be deliverable to the electrolyzer?

Local grid connection ✓

Ensures deliverability such that the clean energy added in part offsets the new electrolyzer load[1]

In the United States

Supports emissionality[2] approach and investment in the American economy and infrastructure

Anywhere

Focuses on global decarbonization and fully supports emissionality[2]

Matching[3]

Does the electricity need to be produced when it is consumed?

A Annual

Total MWh of renewable energy produced over one year matches total MWh used to produce hydrogen

B Annual w/ conditions

Annual matching with some added assumptions, e.g., overbuild, targeted shutdown, resource mix[4]

C Hourly

For each hour of the year, MWh of renewable energy generation equal MWh used to produce hydrogen

In future state, hourly matching will be necessitated by high grid penetration of RE

Legend ✓ Base assumption for this analysis

1. Lack of physical connection requirement could lead to unfavorable buildout of new fossil generation 2. Emissionality concept focuses on realized decarbonization benefit via the highest rate of kg CO_2 displaced per USD spent rather than decarbonizing any one specific power load 3. Other time resolutions (e.g., quarterly, monthly) are under consideration in the EU; this analysis focuses on the 'bookends' that are the focus of current U.S. debate. 4. Further defined on subsequent page

Note: Pertains to individual green H_2 production facilities seeking to claim IRA PTC

Source: BCG analysis

Additional conditions considered for annual matching approach

Rational actors may naturally implement overbuild and shutdown conditions

Targeted **shutdown** of hydrogen production	✓	**Cost benefit to producers** to shutdown H_2 production during peak grid load hours when cost of power and carbon intensity are higher
Overbuild of renewables	✓	Modest overbuild of renewables **reduces risk of under-generation** created by seasonal/annual variability in generation
Renewable **resource mix**	?	Building a mix of wind, solar resources may **reduce generation variability** risk, but may **increases costs and complexity**

Legend ✓ Rational actor incentivized to do ? Competing interests for rational actor

Source: BCG analysis

Principles to consider when setting green H_2 qualification requirements

I. CO_2 emissions

Ensure total carbon emissions from green H_2 production do not exceed IRA specified limit of 0.45 kg CO_2/kg H_2 on a lifetime basis[1]

II. Industry growth

Foster clean hydrogen industry growth in the U.S. to drive decarbonization, jobs creation, and global technology leadership

III. Externalities

Protect energy consumers from adverse externalities of green H_2 buildout (e.g., power cost and reliability)

IV. Simplicity

Enable simplicity in PTC qualification/criteria to support equitable outcomes and access to the incentive

To be effective, policy should consider impacts across all four principles

1. Assumes that graduated IRA PTC credit already accounts for differential benefit of downstream decarbonization when displacing other energy forms

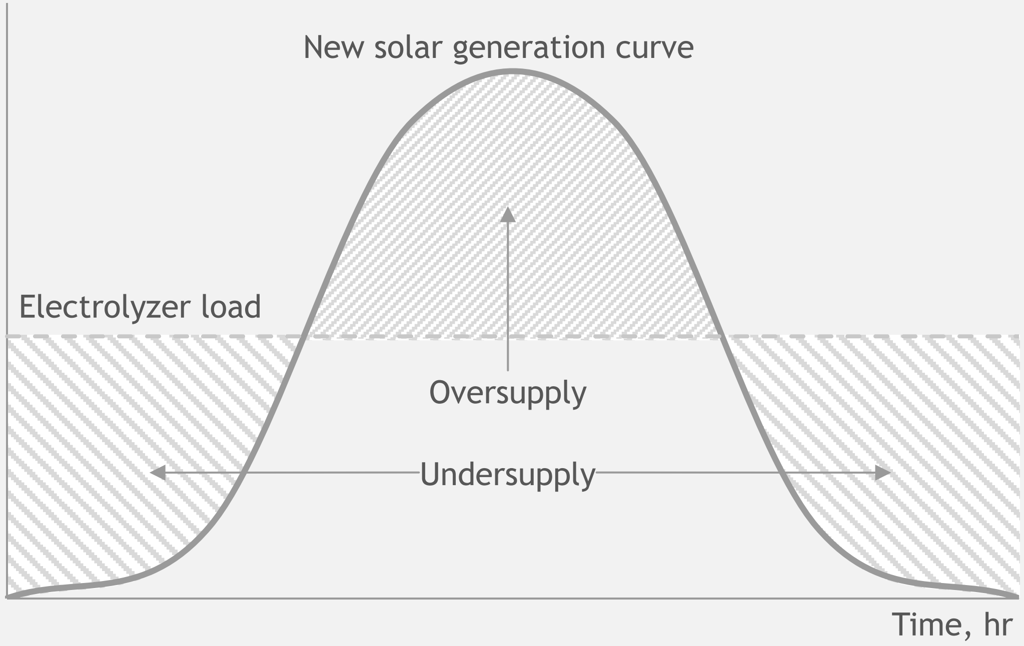
Source: BCG analysis

Annual matching emissions impacts assessed based on hourly grid mix

Annual matching decarbonization approach relies on decarbonizing other loads on the grid

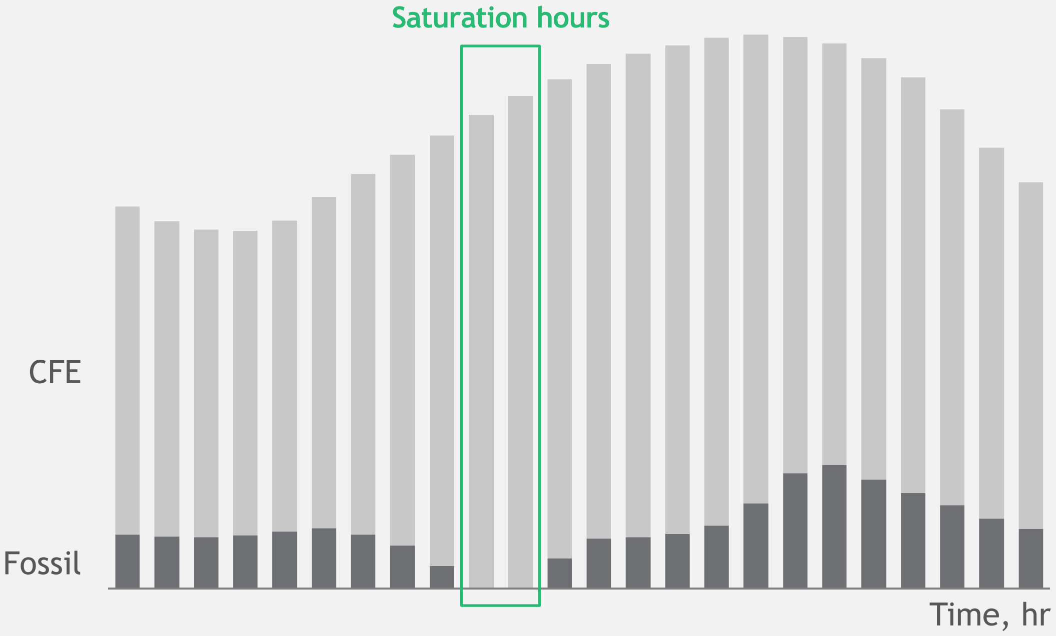
Oversupply assumed to displace equivalent amount of CO_2 to amount added during undersupply periods

New green H_2 project power balance, MW



Imbalances emerge from lack of carbon displacement in Carbon-Free Electricity (CFE) saturation hours[1]

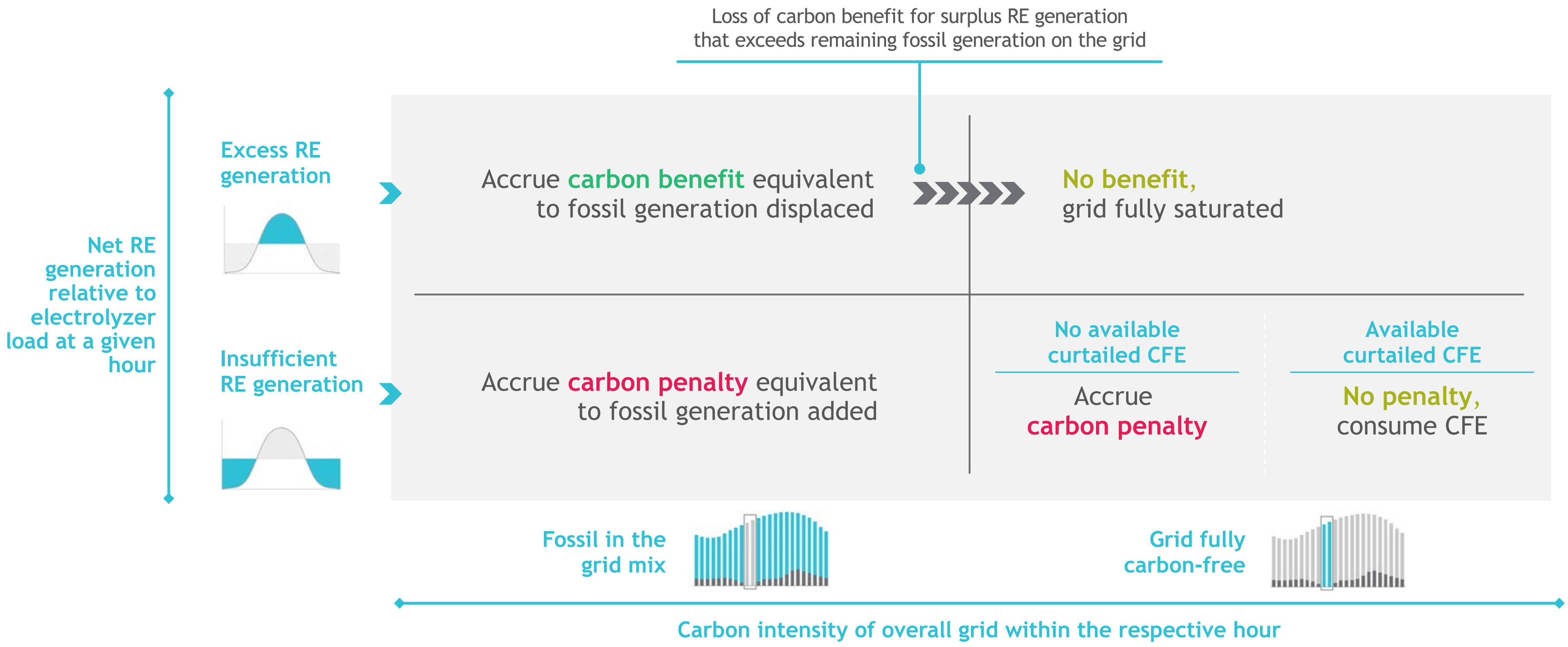
Existing grid power mix, MW



1. Carbon imbalances may also emerge from second-order effects such as differences in carbon intensity of the fossil generators being displaced during periods of net generation vs net load for the green H_2 project

Source: BCG analysis

Modeling framework used to assess emissions impact on an hour-by-hour basis



1. Neglects any local transmission constraints and focuses on full region fossil generation, assuming that interconnection and curtailment costs will be sufficient to make installations non-economical where such constraints exist

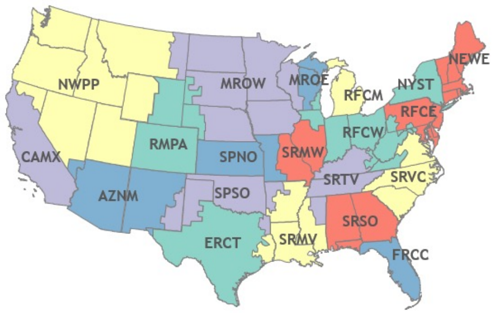
Note: RE = Renewable energy; CFE = Carbon-free energy (CFE)

Source: BCG analysis

Evaluated emissions impacts at the regional level across various conditions

Analyzed emissions impacts at the regional level U.S.-wide

- Grid mix, generation forecasts through 2040[1]
- 20 unique sub-regions
- Full 8760 hourly data



A Annual matching
Base case

Assumed…

- 10-year project lifetimes consistent with duration of PTC
- 2030 Commercial Operating Date (COD)
- 500 MW electrolyzer capacity added per region
- 100% solar capacity added to support electrolyzer load

B Annual matching
(with conditions)

Assessed impacts of…

- **Targeted shutdown** (5%) of green H_2 electrolyzer, removing load in expensive, carbon intensive hours
- **Overbuild** of renewables (10%), adding excess renewable energy to the grid to cover impacts of "saturation hours”
- **Wind-solar resource mix**[2] (i.e., 100% wind, 50-50% wind-solar) to better distribute generation throughout the day

Emissions investigation focused on annual matching; by default, hourly matching assumed to have negligible carbon emissions

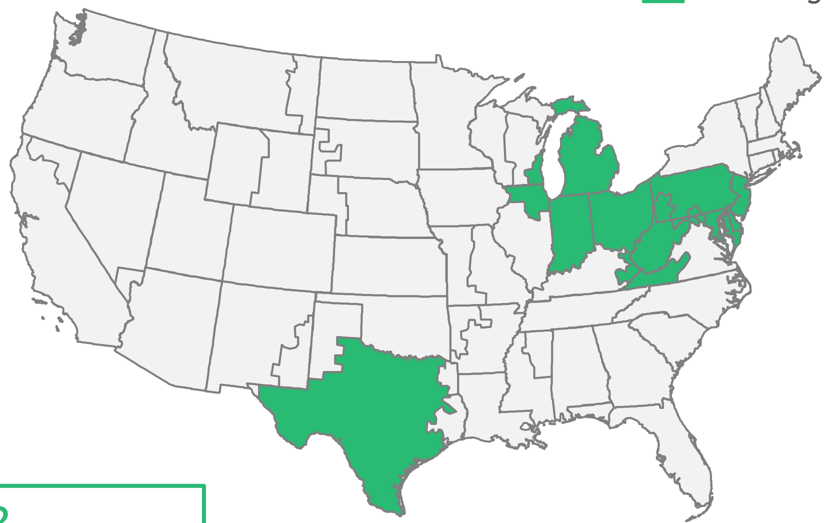
1. Forecasts from NREL Cambium, mid-case; include anticipated impacts of IRA on wind solar deployment, but do not include anticipated impacts of clean H_2 PTC 2. Some regions not forecast to have wind resources based on resource quality: FL, GA, AL, MS, LA, AR, TN, KY
Note 8760 = number of hours in a year
Source: NREL (https://www.nrel.gov/disclaimer.html); BCG analysis

Base case annual matching predominantly yields H_2 above IRA threshold

Emissions intensity by region (2030)

A Base Case

>0.45 kg CO_2/kg H_2
< 0.45 kg CO_2/kg H_2



2.8
Avg. kg CO_2/kg H_2

-6
Avg. kg CO_2/kg H_2
Accounting for downstream decarbonization from displacement of grey H_2

Average CO_2 abatement
U.S. average based on results from all 20 regions

Commercial Online Date (COD) and Electrolyzer Size (MW)

Scenario assumptions
2030 COD | 500 MW

0%

Electrolyzer Shutdown
Percentage of hours that production is shutoff (i.e., curtailed)

0%

Renewables Overbuild
Percentage of capacity beyond minimum required to meet annual electrolyzer load at 100% capacity factor

0%

100%

Solar and Wind Mix
Percentage of capacity build to power H_2 production

- 100% solar generation used in base case (shown)
- When a wind/solar mix is specified, assumes onshore
- If a region[1] has insufficient wind resources to make resource mix feasible, model defaults to 100% solar

Blue icons and data points (XX%) represent **conditions** that place **constraints** on **base case**

1. Regions with insufficient wind resources: FL, GA, AL, MS, LA, AR, TN, KY)
Source: NREL CAMBIUM 2022 (https://www.nrel.gov/disclaimer.html); BCG analysis

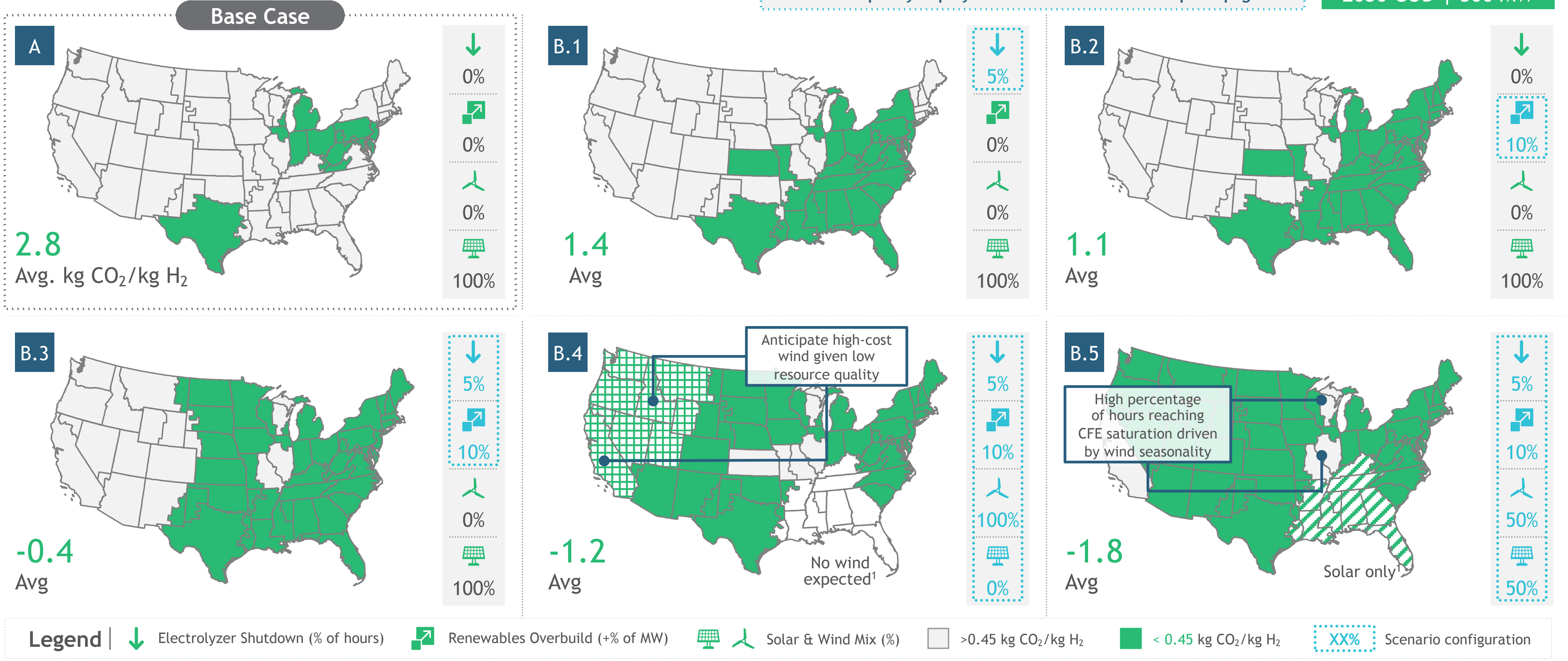
With conditions, several scenarios with net negative average H_2 emissions

Emissions intensity by region ($kgCO_2/kgH_2$) - 2030

Scenario assumptions

Viable capacity deployment for full PTC on subsequent pages

2030 COD | 500 MW

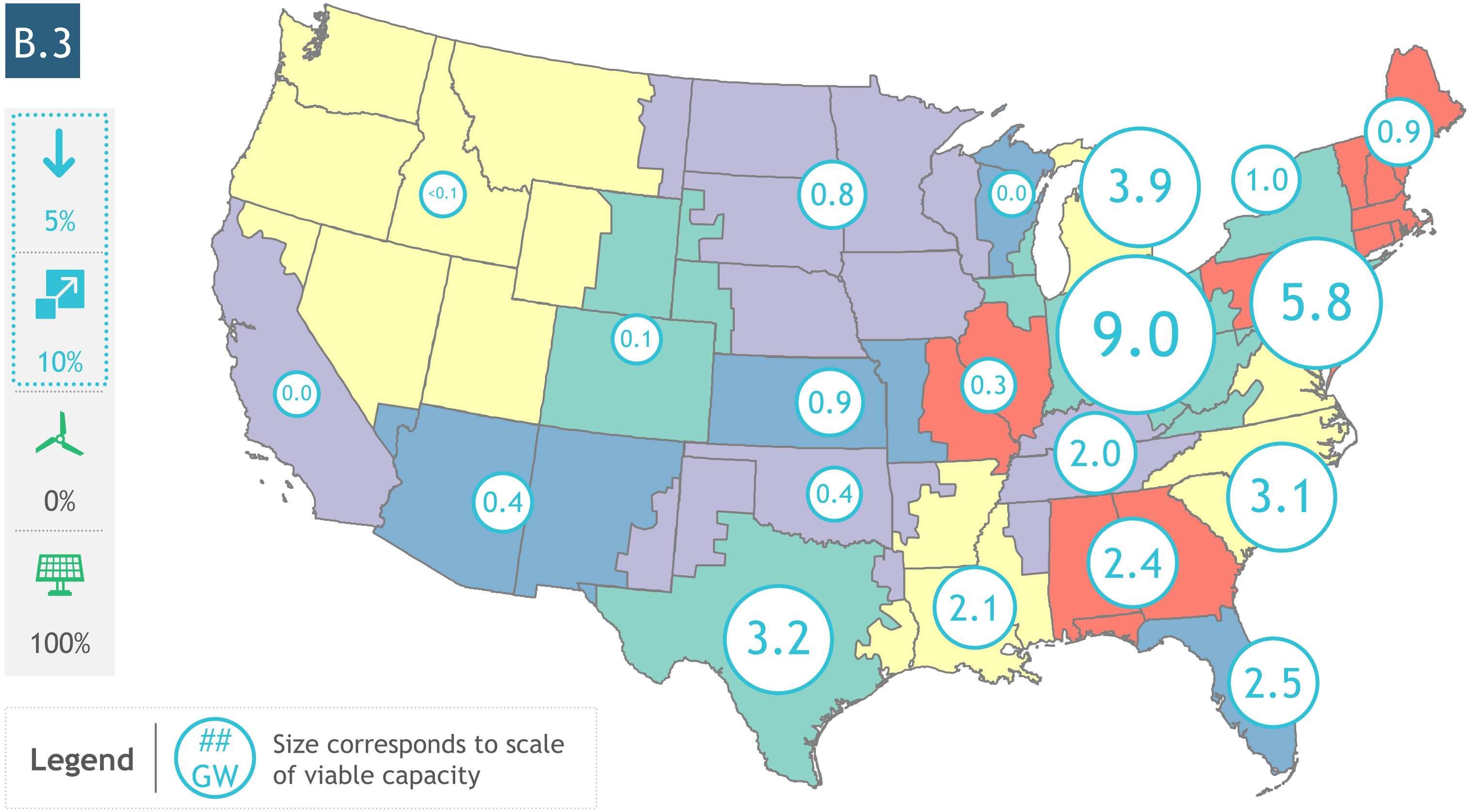


1. NREL model forecasts no wind buildout in: FL, GA, AL, MS, LA, AR, TN, KY. 2. Defaults to 100% solar for regions with no predicted wind resources
Note: Analysis assumes 70% electrolyzer efficiency and LHV H_2 of 120 MJ/kgH_2 (48 kWh / kg H_2)
Source: NREL CAMBIUM 2022 (https://www.nrel.gov/disclaimer.html); BCG analysis

Achievable H_2 capacity for annual matching with conditions

Green hydrogen production capacity before exceeding 0.45 kg CO_2/kg H_2
(Viable capacity in GW, 2030)

Scenario



Aggregate capacity corresponds to…

~7 Mtpa green H_2
(40 GW of electrolyzer capacity)

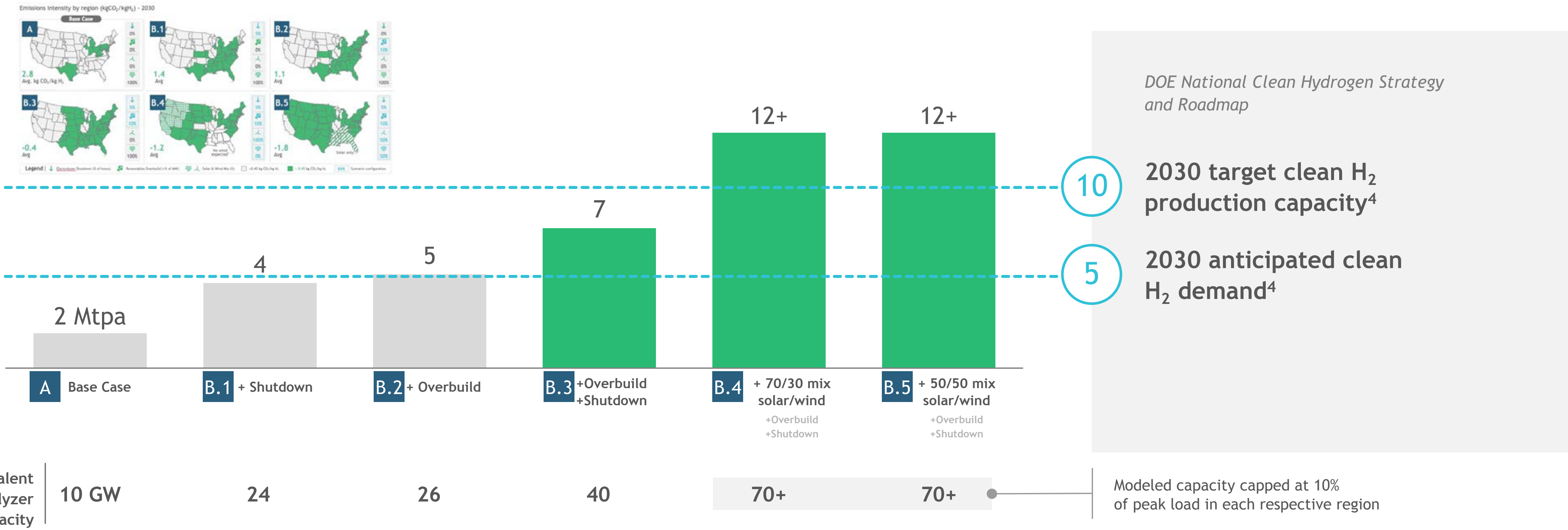
With opportunity for…

~60 Mtpa abated downstream carbon emissions[1]

1. Assuming carbon abatement of ~9 kg CO_2/kg H_2 produced consistent with displacing grey H_2; opportunity for higher carbon impact in some applications
Source: NREL CAMBIUM 2022 (https://www.nrel.gov/disclaimer.html); BCG analysis

Model indicates available capacity for low carbon H_2 under 'annual matching with conditions' exceeds anticipated 2030 demand[1]

Total green H_2 capacity that can be built below 0.45 kg CO_2/kg H_2 (Mtpa)[2,3]



1. Viable capacity of electrolyzer deployment constrained by 0.45 kg CO_2 / kg H_2 requirement for full PTC 2. Estimated green H_2 capacity at which annual matching approach crosses 0.45 kg CO_2/kg H_2 for the present model in each region independently 3. Assumes 2030 COD 4. Total inclusive of blue H_2 (via fossil fuels with accompanying carbon capture and sequestration, CCS) and electrolytic green hydrogen;

Source: DOE National Clean Hydrogen Strategy & Roadmap, BCG analysis

Deep dive | Observations and implications of emissions analysis

A **Base Case: Annual matching policy with no conditions creates significant geographic constraints for green hydrogen deployment in the U.S. (based on 500 MW electrolyzer capacity supported by 100% solar in each region)**

- In 16 of 20 regions[1] analyzed, 2030 COD projects do not qualify for full PTC (\$3/kg H_2) for emissions below 0.45 kg CO_2/kg H_2
- Overall average projected emissions intensity of 2.8 kg CO_2/kg H_2 (3.5 kg CO_2/kg H_2 average in 16 regions that do not qualify)
- Across advantaged regions, U.S. may be able to deploy up to ~10 GW[2] of electrolyzer capacity (~2 MTPA of H_2) at/under 0.45 kg CO_2 / kg H_2
- Top five emissions intensive regions include RMPA (7.9 kg CO_2/kg H_2), NWPP (7.6), CAMX (6.4), MROE (6.4), and SRMW (3.0) - no level of green hydrogen production is viable in these regions if targeting full PTC under annual matching

B.1 **B.2** **Shutdown OR Overbuild: Stipulating either a 5% targeted electrolyzer shutdown during peak load hours or 10% renewable capacity overbuild can cut overall average emissions intensity in half to 1.4 and 1.0 kg CO_2 / kg H_2, but still falls above the 0.45 kg CO_2/kg H_2 IRA PTC target**

- Of the 20 regions, 8 remain above the 0.45 kg CO_2/kg H_2 limit under both conditions; NEWE is the only differential region between both scenarios, falling below 0.45 kg CO_2/kg H_2 for 10% overbuild but not for 5% shutdown
- U.S. may be able to deploy up to ~24 GW (~4 MTPA of H_2) for 5% shutdown or ~26 GW (~5 MTPA of H_2) for 10% overbuild at/under 0.45 kg CO_2/kg H_2

B.3 **Shutdown AND Overbuild: Combination of 5% shutdown and 10% overbuild results in a nationwide average carbon displacement of -0.4 kg CO_2/kg H_2, unlocking deployment in all regions east of Rockies except for MROE and SRMW**

- Six regions remain above the 0.45 kg CO_2/kg H_2 limit with an average expected emissions in those 6 regions of 3.0 kg CO_2/kg H_2
- Projected 2030 COD U.S. electrolyzer capacity rises to ~40 GW (~7 MTPA of H_2)

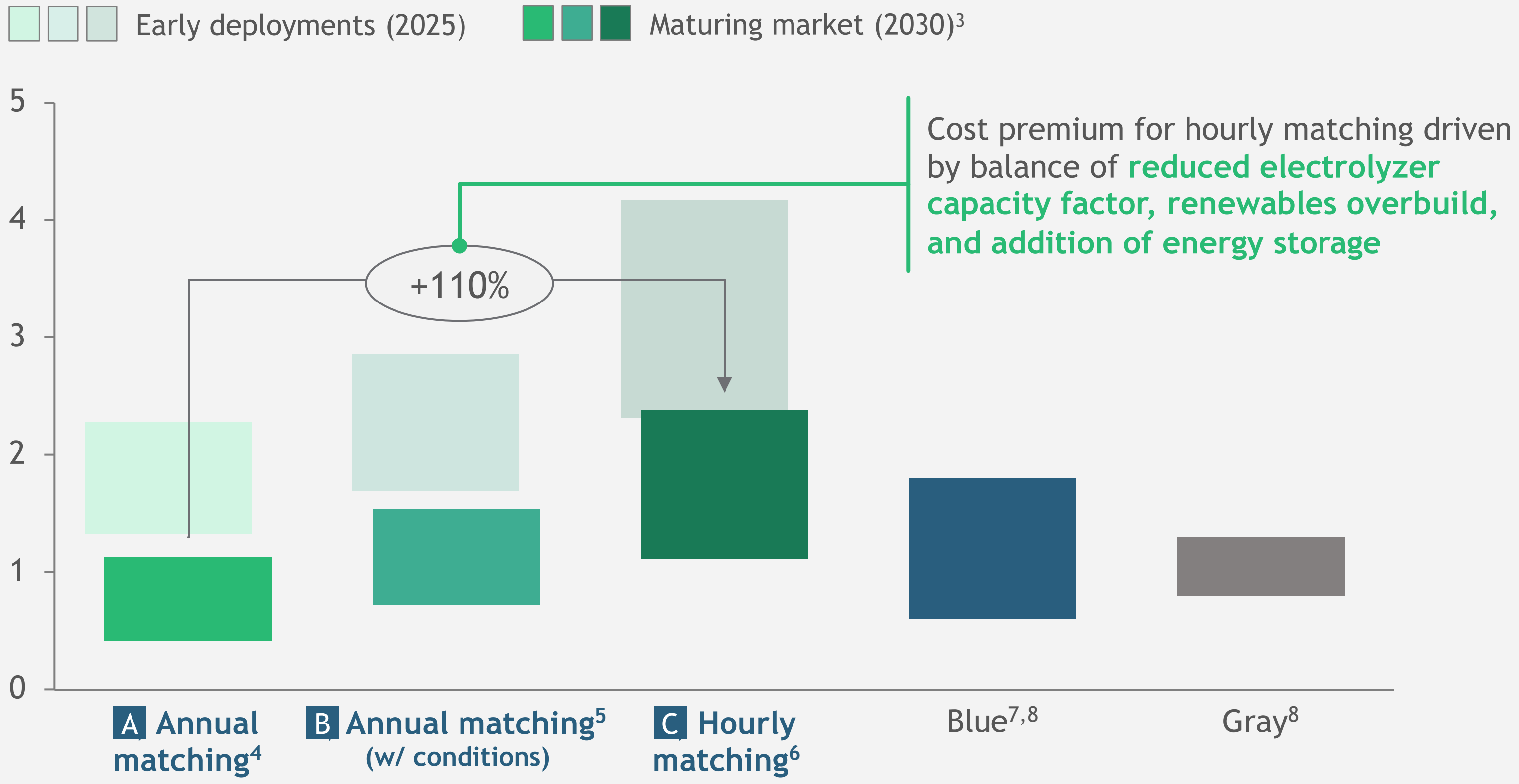
B.4 **B.5** **Resource Mix (+ Shutdown + Overbuild): Adding resource mix conditions to mitigate intermittency with complementary resources (e.g., wind + solar) lowers projected nationwide average emissions intensity to -1.8 kg CO_2/kg H_2 for 50/50 wind and solar**

- Southeastern U.S. forecasted to have little to no wind resource availability but already below the 0.45 threshold with 100% solar
- Projected 2030 COD U.S. electrolyzer capacity rises to 70+ GW[3] (12+ Mtpa of H_2) given stabilizing effect of resource mix
- Wind is needed to bring Pacific Northwest below the 0.45 threshold

1. Generating and Emissions Assessment regions (NREL) 2. Assumes each region is loaded with the maximum amount of electrolyzer capacity before exceeding 0.45 kg CO_2/kg H_2 3. Modelling assumptions/limitations for local linearity of emissions impacts anticipated to breakdown at >10% of peak load
Note: COD = Commercial operation date; PTC = Production tax credit
Source: NREL (https://www.nrel.gov/disclaimer.html); BCG analysis

Expected net cost of green H_2 vs alternatives

Net H_2 production cost[1] (USD/kg H_2) including 45V PTC[2]



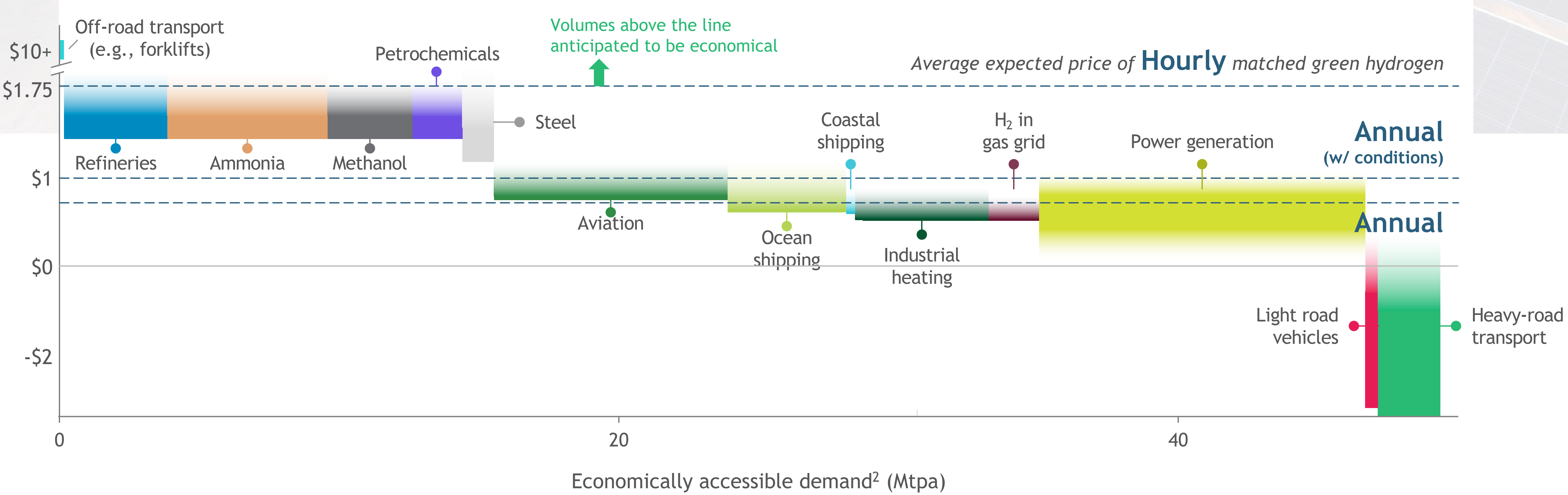
Key takeaways:

- Hourly matching **more than doubles the cost of green H_2** in 2030 by limiting electrolyzer capacity factor and requiring renewables overbuild
- After 2030, hourly matched green H_2 will approach **cost competitiveness with blue and grey H_2**

1. Plant gate costs, does not include transport and storage; based on PEM electrolyzer CAPEX ($1,800 in 2025 and $1,200 in 2030), OPEX (2% of CAPEX), and energy costs. Ranged by PJM (high) and ERCOT (low) electricity costs 2. Assuming $3 PTC for green H_2 and $0.60 for blue H_2 3. Contingent on realization of scale effects on production costs 4. CAPEX based on 100% capacity factor, energy cost based on projected minimum PPA price for renewables 5. 5% curtailment and 10% overbuild, assuming 2023 REC price reported by S&P 6. CAPEX based on 80% capacity factor, energy cost based on solar, wind, and storage mix 7. Assuming annual matching; hourly matching would result in 50-100% increase in cost 8. Costs expected to stagnate due to technology maturation
Source: LBNL, NREL (https://www.nrel.gov/disclaimer.html), BCG analysis

Implications of green H_2 matching approaches on economically viable demand

Breakeven production[1] cost of hydrogen by application ($/kg H_2, 2030)



Power matching approach expected to be the difference between limited green H_2 deployment and significant cross-industry applications in 2030

1. Excludes hydrogen delivery costs associated with transportation, storage, etc. 2. Represents total economically viable demand; does not account for technology readiness, deployment time, supply chain limitations, etc.
Source: BCG NAMR H_2 Applications Economics Model

Economic impacts of each matching strategy

Anticipated impacts of green hydrogen buildout…

	Economically accessible demand[1]	Capital investment[2]	Direct & indirect jobs[3]	Abated emissions[4]
Scale		$0 – $1T	0 – 3,000k	0 – 400 Mtpa
A Annual matching	20-45 Mtpa	$400-990B	800k-2,700k	120-270 Mtpa
B Annual matching (w/ conditions)	15-40 Mtpa	$300-880B	600k-2,400k	140-380 Mtpa
C Hourly matching	0.02-15 Mtpa	$0.4-330B	0.8k-900k	0.2-140 Mtpa

1. Represents total economically viable demand. Does not account for technology readiness, deployment time, supply chain limitations, etc. 2. Assuming 50-50 wind-solar mix with wind capacity factors of 40% and 25% for wind and solar respectively, 48 kWh/kg H_2 electrolyzer efficiency, unit capex of $1200/kW, $1000/kW, and $800/kW for electrolyzers, wind, and solar respectively; total capital investment of $20-22B per Mtpa of H_2 3. Per Mtpa of H_2, estimates 40-60k direct and indirect jobs creation of which ~20k are direct construction jobs, ~1k are direct O&M jobs, with the balance as indirect jobs; uses construction and O&M jobs factors of 0.7 and 0.1 for hydrogen and 1 and 0.05 for supporting wind/solar, and indirect jobs factor of 1-2 4. Highly dependent on end use case and lifecycle emissions; if displacing grey H_2 with fully carbon free H_2, yields downstream decarbonization of ~6 Mtpa CO_2/Mtpa H_2 for base annual matching, ~9.5 for annual with conditions, and ~9 for hourly matching

Source: Los, B., et al. (2020). The Employment Impact of the NorthH2 Project; BCG NAMR H_2 Applications Economics Model

Reliability and cost externalities associated with green H_2 buildout

Reliability externalities

Effect of increased variable renewable energy sources on grid performance

Generation variability
Variability in wind/solar generation increases magnitude of need for dispatchable generation to cover fluctuation in load/supply

Network congestion
High resource regions attract concentration of renewable generation and can overload grid in peak generation hours

Cost externalities

Effect of increased load and generation capacity on end price for power customers

Compensation for dispatchable generation
Increased capacity payments required to maintain sufficient amounts of dispatchable generation to cover increased variability

Higher peak load
Added load during peak load hours drives up marginal price of power and overall costs

Grid infrastructure buildout
Additional transmission and distribution infrastructure required to connect new generation sites to load centers

Source: BCG analysis

Relative impact on externalities across matching strategies

		A Annual matching	B Annual matching (w/ conditions[1])	C Hourly matching
Reliability externalities	Generation variability	Detrimental: Incentivizes development of cheapest renewable resource available with no incentive for adding storage	Partially mitigated: Conditional mix of wind/solar generation yields a more consistent generation profile	Mitigated: Matches load to generation dynamically so as not to impact normal grid supply demand balance[1]
	Network congestion	Detrimental: Adds load and generation capacity to the network	Detrimental: Adds load and generation capacity to the network	Detrimental: Adds load and generation capacity to the network
Cost externalities	Compensation for dispatchable generators	Detrimental: Increase in payments necessary to maintain dispatchable generation availability	Partially mitigated: Resource mix lessens need for dispatchable generation with more stable profile	Mitigated: No net impact on existing generation profiles and load balancing
	Higher peak load	Detrimental: Increases total load on grid during peak demand hours without adding a balance of RE	Mitigated: Shutdown of the electrolyzer during periods of peak load relieves grid pressure	Partially mitigated: Load/generation balancing does not increase net need for generation
	Grid infrastructure buildout	Detrimental: New grid infrastructure to support geographically diverse generation sites and new loads	Detrimental: New grid infrastructure to support geographically diverse generation sites and new loads	Detrimental: New grid infrastructure to support geographically diverse generation sites and new loads

Legend: Mitigated | Partially mitigated | Detrimental

1. Hourly matching may not mitigate effects of intra-hour variability in demand/generation on reliability
Source: BCG analysis

Matching approaches assessed against implementation and validation simplicity

	A Annual matching	B Annual matching (w/ conditions[1])	C Hourly matching
Implementation *What is the complexity of execution in practice?*	**Low complexity** • Technology: Required technology (load/generation metering) already in use • Data: Annual load and generation data readily accessible	**Moderate complexity** • Technology: Required technology (dynamic load shifting) still in development • Data: Hourly grid load/cost not reported by some regulated utilities	**Moderate - high complexity** • Technology: Required technology (resource mix optimization, dynamic load shifting, etc.) still in development • Data: Hourly load and generation data not widely reported • Crediting: No standardized crediting instruments for hourly generation
	• Crediting: Annual generation crediting standardized through RECs Default additionality assumption precludes the exchange of credits since purchased credits would not be from new renewables	(spans A and B)	
Validation *What is the complexity of proving compliance?*	**Low complexity** • Uses existing annual consumption and generation statistics	**Moderate complexity** • Requires hourly reporting to validate shutdown timing	**Moderate complexity** • Requires hourly load and generation profiling • Requires enhanced data management/reporting

1. Constraints primarily related to implementation of targeted shutdown during high-cost / peak load hours
Note: REC = Renewable Energy Certificate; Validation for hourly matching may take place at a periodic cadence (e.g., annually)
Source: BCG analysis

Summary | Evaluation of matching options against principles

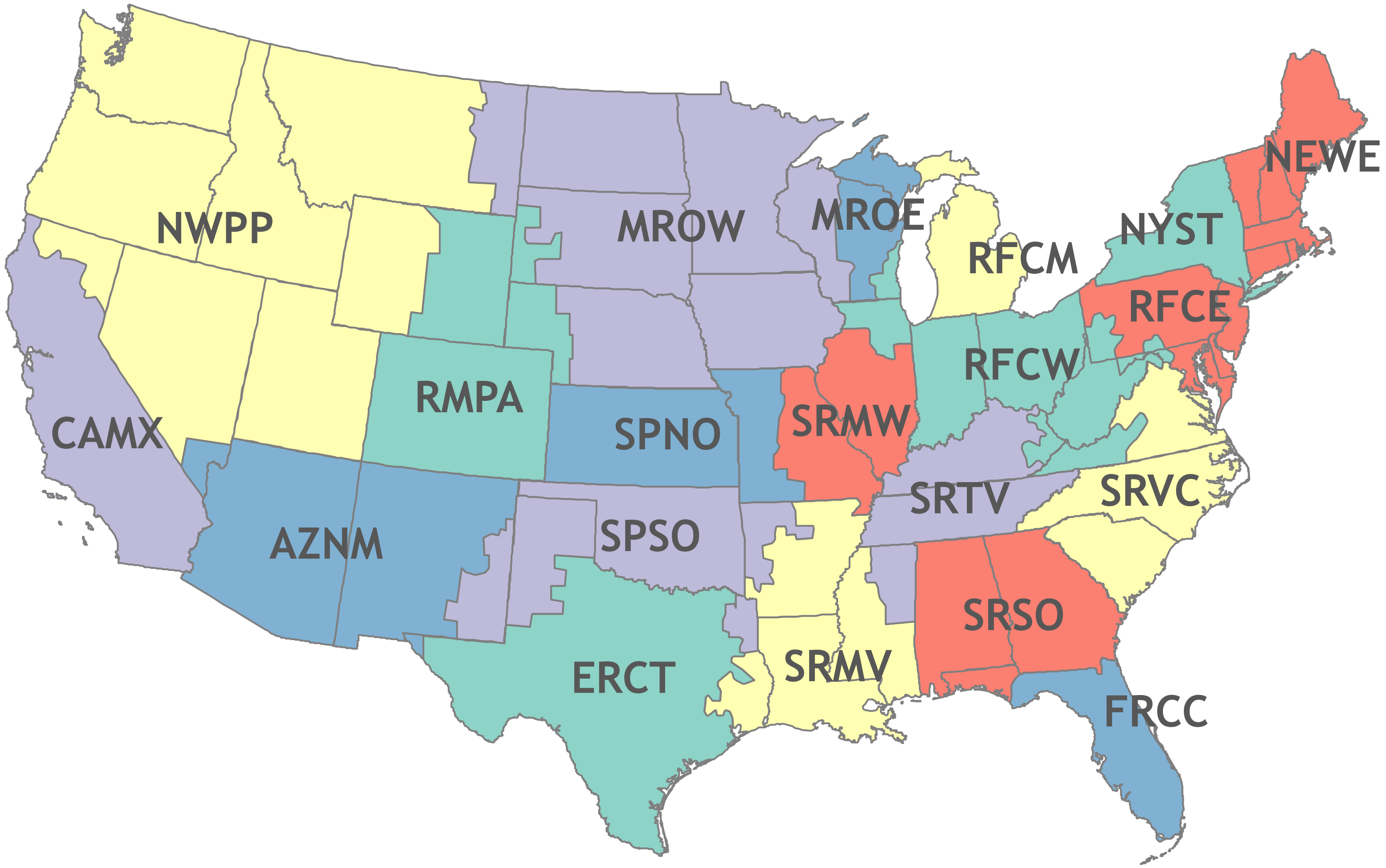
Legend: (+) Pro (−) Con

	A Annual matching	B Annual matching (w/ conditions)	C Hourly matching
I. CO_2 emissions	(−) Yields CO_2 above IRA limit in most geographies	(+) Meets IRA limit nationwide with all three conditions (overbuild, shutdown, resource mix) (−) Breaks down in efficacy at high grid penetration of RE[1]	(+) Ensures no net load or incremental carbon emissions Total decarbonization impact may be limited by realized deployment[2]
II. Industry growth	(+) Roughly doubles economically viable green hydrogen demand (vs hourly) (+) Supports U.S. technology leadership in green H_2	(+) Accesses nearly the same aggregate demand as base annual matching despite modest increase to H_2 price (+) Supports U.S. technology leadership in green H_2	(−) Results in higher cost than fossil-based blue, grey hydrogen prior to 2030 (−) Amplifies regional disparities in deployment based on resource quality
III. Externalities	(−) Creates greatest risk for grid reliability challenges and cost increases	(+) Helps reliability and cost by shutting down during peak load and balancing generation with resource mix	(+) Avoids most reliability and cost issues via load and generation balancing
IV. Simplicity	(+) Uses present day processes and procedures (e.g., REC system) (+) Is validated via currently measured annual values	(+) Uses present day processes and procedures (−) Relies on flexible shutdown based on hourly grid load/power price	(−) Requires complex dynamic load management and renewables portfolio optimization capabilities to achieve (−) Requires hourly generation and load data for validation

1. For example, in California, which is forecast to have ~90% carbon free generation by 2030 2. On an aggregate annual basis, decarbonization potential under annual matching with and without conditions is likely larger than hourly given the lower cost and thus creates more economically viable demand to generate realized downstream decarbonization
Source: BCG analysis

Appendix

Generating and Emissions Assessment (GEA) regions in NREL Cambium model



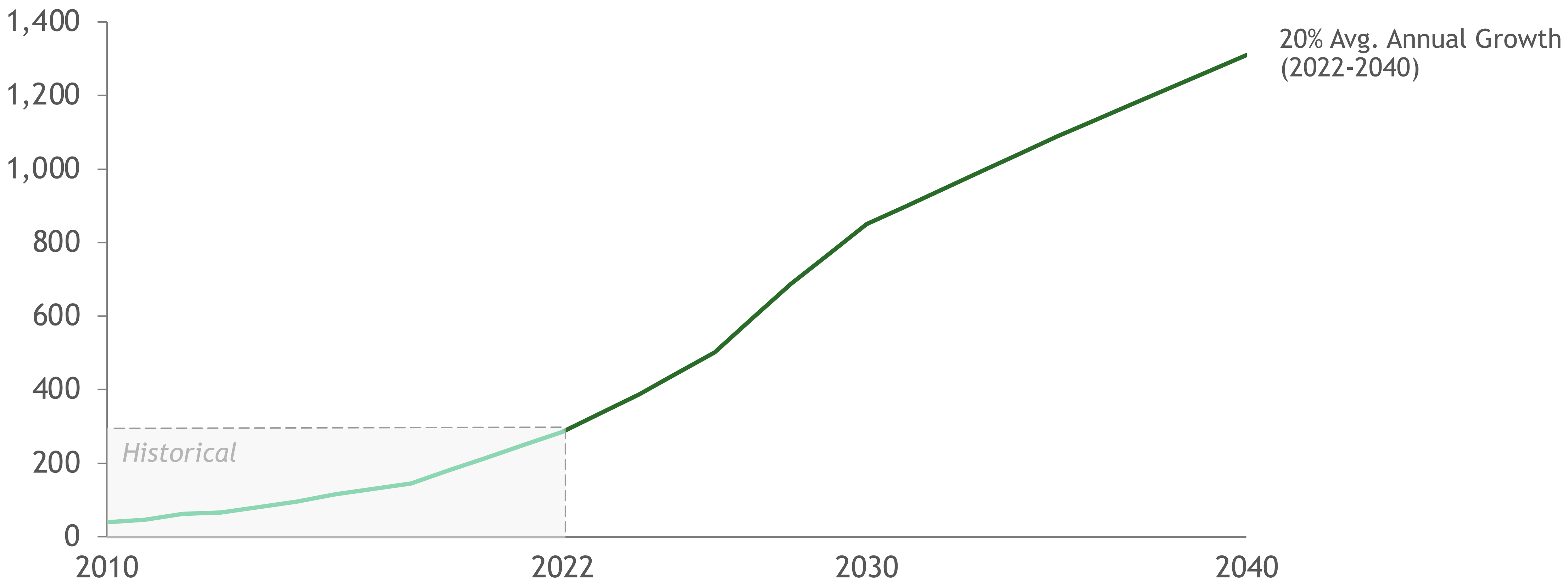
> Cambium's GEA regions are 20 regions covering the contiguous United States. They are based on the EPA's eGRID regions, but they are not identical to them due to the geographic structure of the models in the Cambium workflow"

Source: NREL CAMBIUM 2022 (https://www.nrel.gov/disclaimer.html)

NREL mid-case renewables capacity forecast through 2040

Total installed capacity of wind and solar in the U.S., 2010-2040 (GW)

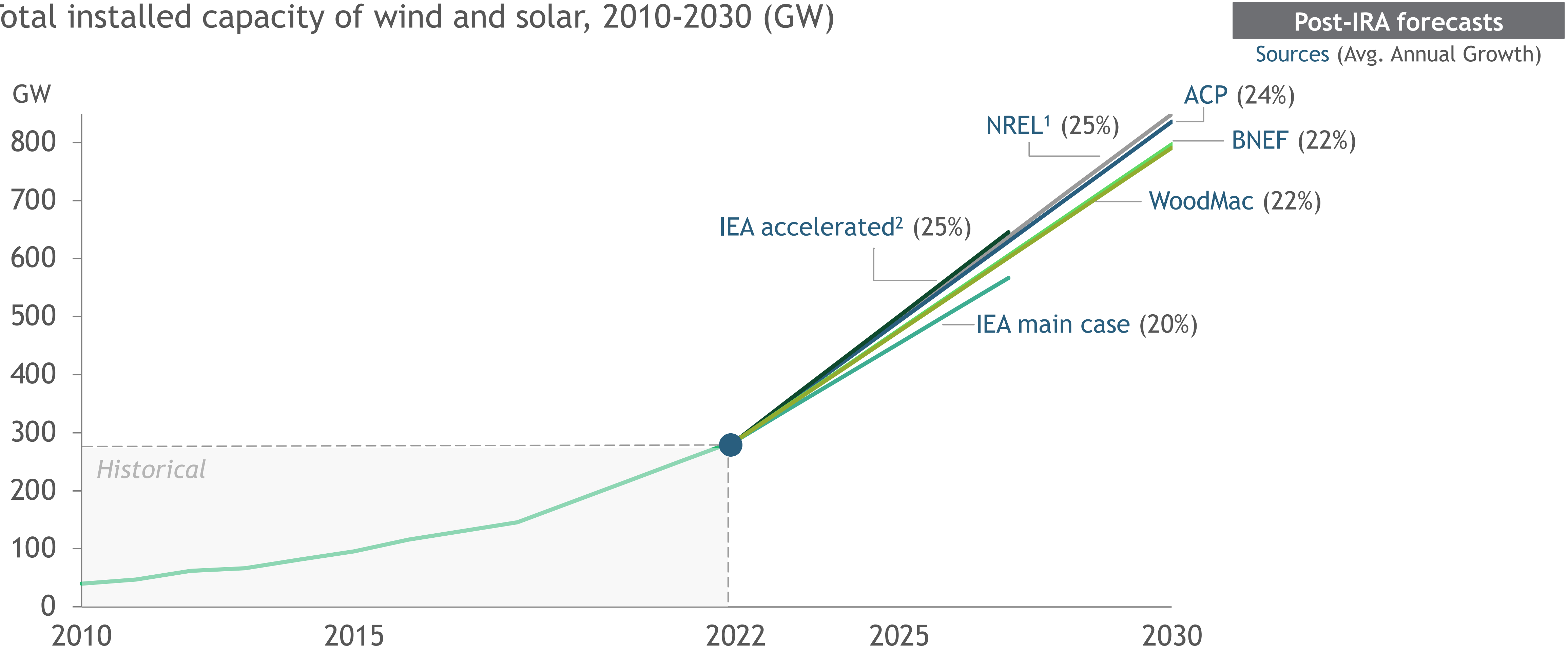
Post-IRA forecast



Note: Historical data from EIA Annual Energy Outlook
Source: EIA, SEIA, NREL CAMBIUM 2022 (https://www.nrel.gov/disclaimer.html)

Renewables forecast comparison (I of II)

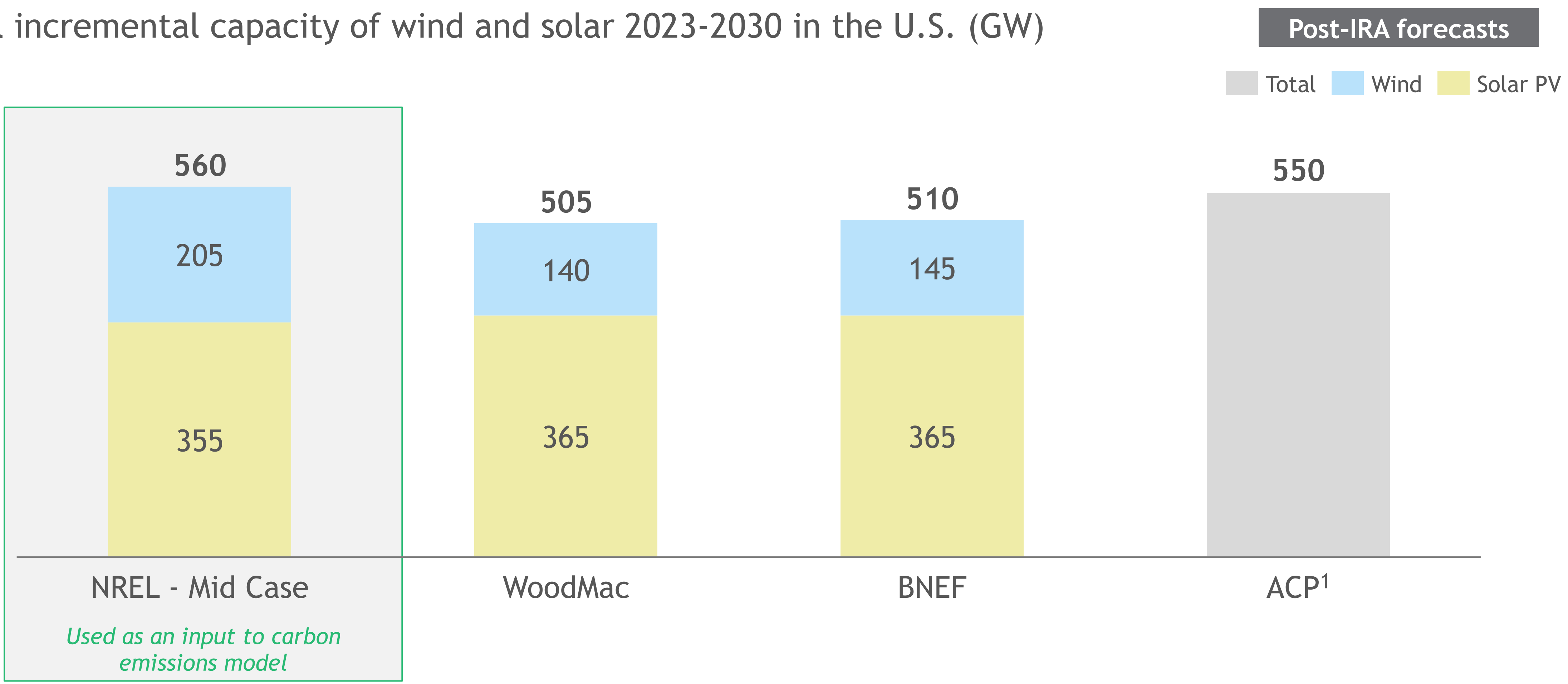
Total installed capacity of wind and solar, 2010-2030 (GW)



1. NREL mid-case forecast 2. Assumes that governments address policy, regulatory, and implementation challenges within the 12-24 mo. report publication;
Note: Historical data from EIA. Total 2030 capacity calculated by summing annual additional capacity reported for 2023-2030 for some sources; linearized for simplicity of comparison
Source: ACP, BloombergNEF (BNEF), EIA, SEIA, IEA, NREL CAMBIUM (https://www.nrel.gov/disclaimer.html), Wood Mackenzie (WoodMac)

Renewables forecast comparison (II of II)

Total incremental capacity of wind and solar 2023-2030 in the U.S. (GW)



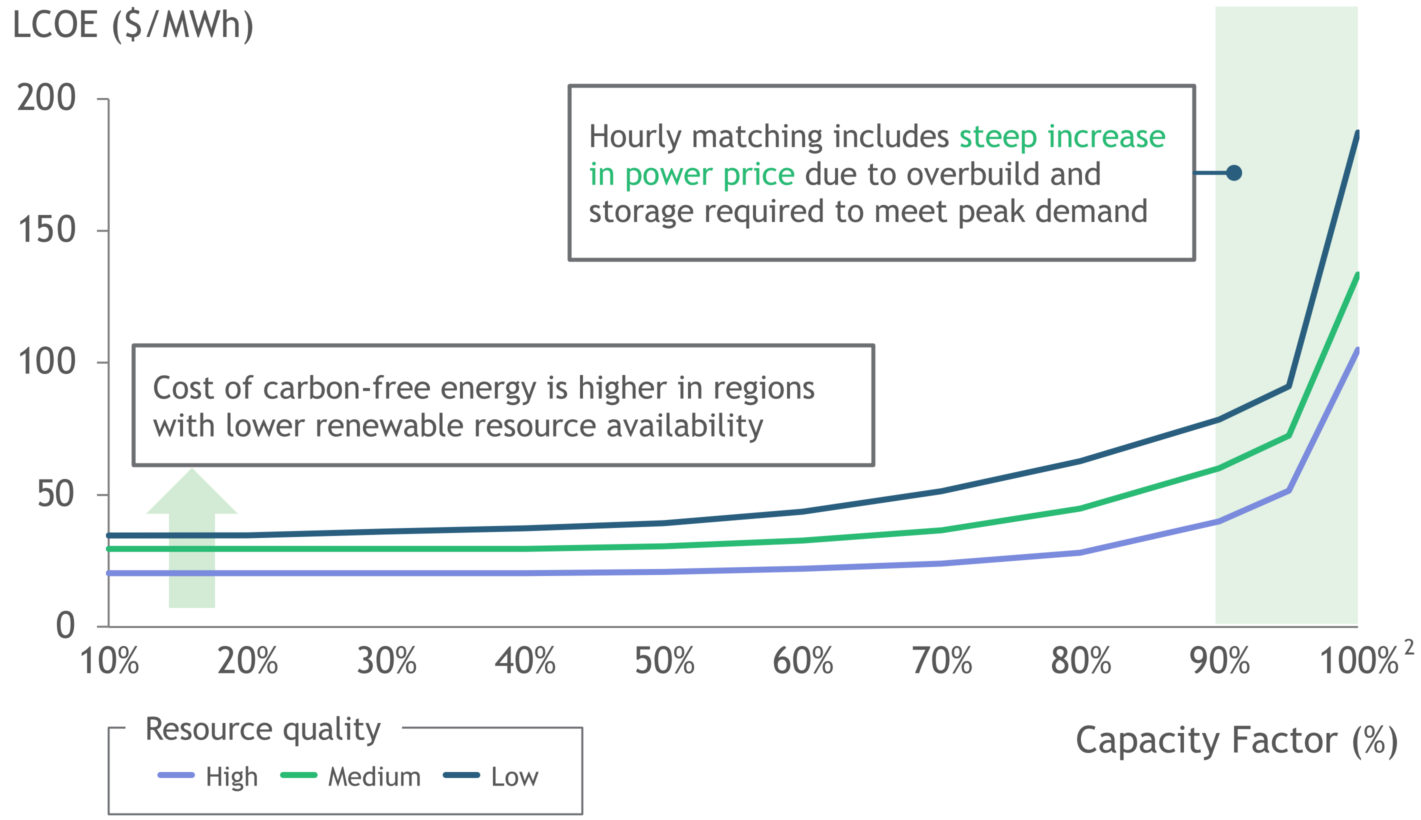
1. Solar and wind split unavailable

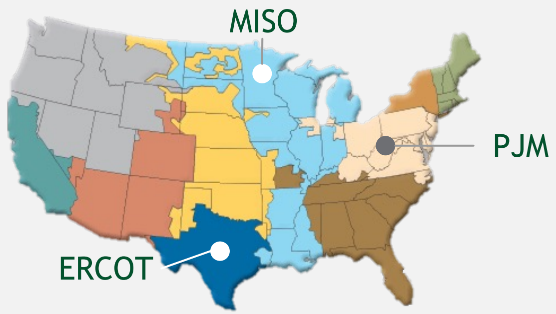
Note: ACP = American Clean Power

Source: ACP, BloombergNEF, WoodMac, NREL CAMBIUM (https://www.nrel.gov/disclaimer.html)

Hourly matching requirement significantly increases power cost

Hourly matching, carbon-free energy price vs. electrolyzer capacity factor[1]





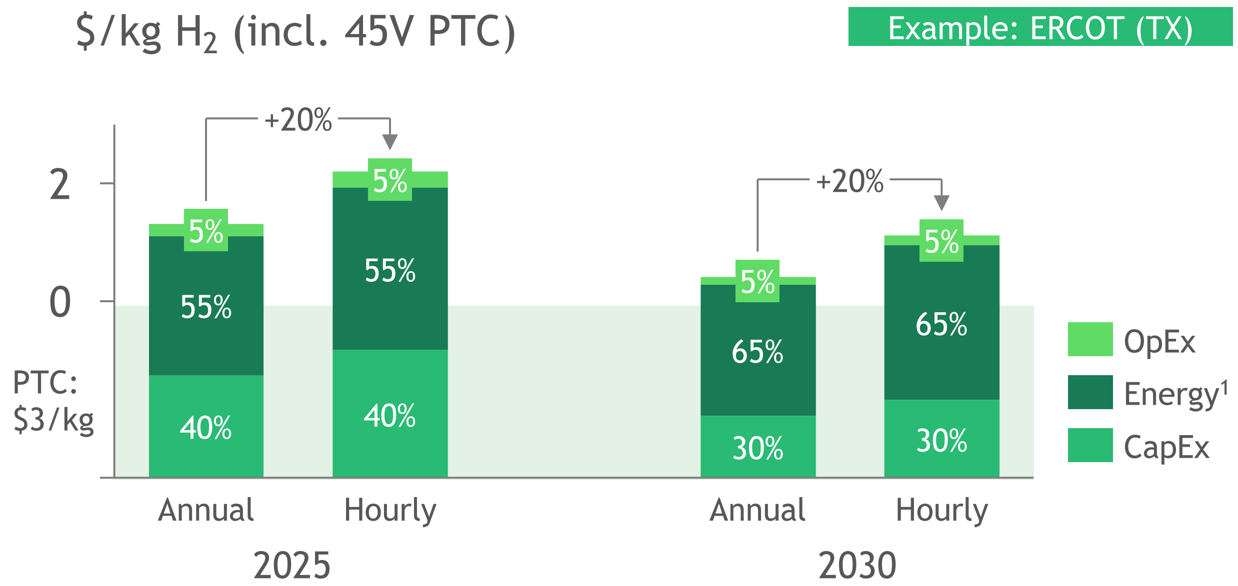
High Resource Region - ERCOT
- High solar and wind availability

Medium Resource Region - MISO
- Low solar, high wind availability

Low Resource Region – PJM
- Low solar and wind availability

1. Linear optimization of wind, solar, and storage based on full 8760 profile data to assess effective coverage 2. Difficult to achieve in practice due to scale of storage required
Source: LBNL, NREL (https://www.nrel.gov/disclaimer.html), BCG analysis

Deep dive | Green hydrogen cost assumptions and breakdown



Assumptions

$1,800/kW	No change	$1,200/kW	No change	**CapEx[2]**
$36/kW	No change	$24/kW	No change	**OpEx**
52 kWh/kg	No change	47 kWh/kg	No change	**Efficiency**
100%	80%	100%	80%	**CF[3]**

Hourly matching has higher capital and energy costs than annual matching

- Running electrolyzers at less than full capacity increases the marginal capital cost per kg H_2
- Renewables overbuild and curtailment required for hourly matching raises energy costs

Capital and energy costs will decrease within the next decade

- The learning rates of electrolyzer technologies will be realized as scale increases, reducing capital costs
- Continued development of renewables technology will decrease energy costs

1. Based on 2021 PPA price for solar and wind in ERCOT, including transmission and delivery charges, projected for 2025 and 2030 2. Assuming PEM electrolyzer
3. Optimization performed to balance CapEx against higher energy costs for higher capacity factors
Source: NREL (https://www.nrel.gov/disclaimer.html), LBNL, BCG analysis

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