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

Tradeoffs between annual and hourly matching approaches

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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 CO₂/kg H₂
- 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 H₂ production do not exceed IRA specified limit on a lifetime basis
II. Foster clean H₂ industry growth to drive decarbonization, jobs creation, and technology leadership
III. Protect energy consumers from adverse externalities of green H₂ 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 kgCO₂/kgH₂)

(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 H₂ price net of PTC in 2030
- Price premium for hourly matching likely to make green H₂ 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 CO₂ 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.

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 H₂

**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

**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 H₂ manufacturing and recycling R&D
- $30 billion in overall clean energy R&D to cut emissions across the economy

**Aug. 16, 2022** - Climate tax package with a significant H₂ 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 H₂:¹
    - -60-75%: $0.6/kg H₂
    - -75-85%: $0.75/kg H₂
    - -85-95%: $1.0/kg H₂
    - >95%: $3/kg H₂

Rules² governing qualification and validation will have significant impact on clean hydrogen trajectory in the U.S.

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1. Grey hydrogen carbon intensity typically in the range of ~9-10 kg CO₂ / kg H₂; Taking the lower limit of the range, 95% corresponds to 0.45 kg CO₂ / kg H₂ 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 ; H₂ = Hydrogen

Source: U.S. Government
Option space for near-term U.S. green H₂ PTC qualification/validation

**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

- **In the United States**
  Supports emissionality approach and investment in the American economy and infrastructure

- **Anywhere**
  Focuses on global decarbonization and fully supports emissionality²

**Matching³**
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

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

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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 CO₂ 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 H₂ production facilities seeking to claim IRA PTC

Source: BCG analysis

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In future state, hourly matching will be necessitated by high grid penetration of RE
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 H₂ 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 increase costs and complexity.

**Legend**
- ✓ Rational actor incentivized to do
- ❓ Competing interests for rational actor

Source: BCG analysis
Principles to consider when setting green H₂ qualification requirements

I. CO₂ emissions
Ensure total carbon emissions from green H₂ production do not exceed IRA specified limit of 0.45 kg CO₂/kg H₂ on a lifetime basis¹

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 H₂ 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 CO₂ to amount added during undersupply periods

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

New green H₂ project power balance, MW

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 H₂ project

Source: BCG analysis
Modeling framework used to assess emissions impact on an hour-by-hour basis

I. Carbon emissions

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 2040¹
• 20 unique sub-regions
• Full 8760 hourly data

Assumed...

A Annual matching
Base case

• 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 H₂ 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 mix² (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 H₂ 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
I. Carbon emissions

Base case annual matching predominantly yields H₂ above IRA threshold

Emissions intensity by region (2030)

**Scenario assumptions**
- **2030 COD | 500 MW**
- **Electrolyzer Shutdown** Percentage of hours that production is shutoff (i.e., curtailed)
- **Renewables Overbuild** Percentage of capacity beyond minimum required to meet annual electrolyzer load at 100% capacity factor
- **Solar and Wind Mix** Percentage of capacity build to power H₂ production
  - 100% solar generation used in base case (shown)
  - When a wind/solar mix is specified, assumes onshore
  - If a region¹ has insufficient wind resources to make resource mix feasible, model defaults to 100% solar

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

**Average CO₂ abatement** U.S. average based on results from all 20 regions

1. Regions with insufficient wind resources: FL, GA, AL, MS, LA, AR, TN, KY

Source: NREL CAMBIM 2022 (https://www.nrel.gov/disclaimer.html); BCG analysis
With conditions, several scenarios with net negative average H\textsubscript{2} emissions

Emissions intensity by region (kgCO\textsubscript{2}/kgH\textsubscript{2}) - 2030

**Scenario assumptions**

<table>
<thead>
<tr>
<th>Scenario configuration</th>
<th>2030 COD</th>
<th>500 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>2.8</td>
<td>1.4</td>
</tr>
<tr>
<td>B.1</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>B.2</td>
<td>1.8</td>
<td>0.4</td>
</tr>
<tr>
<td>B.3</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>B.4</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>B.5</td>
<td>5%</td>
<td>10%</td>
</tr>
</tbody>
</table>

**Legend**

- **Electrolyzer Shutdown (% of hours)**
- **Renewables Overbuild (+% of MW)**
- **Solar & Wind Mix (%)**
- >0.45 kg CO\textsubscript{2}/kg H\textsubscript{2}
- < 0.45 kg CO\textsubscript{2}/kg H\textsubscript{2}

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\textsubscript{2} of 120 MJ/kgH\textsubscript{2} (48 kWh / kg H\textsubscript{2})

Source: NREL CAMBIUM 2022 (https://www.nrel.gov/disclaimer.html); BCG analysis
Achievable H₂ capacity for annual matching with conditions

Green hydrogen production capacity before exceeding 0.45 kg CO₂/kg H₂
(Viable capacity in GW, 2030)

Scenario

B.3

Aggregate capacity corresponds to...
~7 Mtpa green H₂
(40 GW of electrolyzer capacity)

With opportunity for...
~60 Mtpa abated downstream carbon emissions¹

1. Assuming carbon abatement of ~9 kg CO₂/kg H₂ produced consistent with displacing grey H₂; 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 H₂ under ‘annual matching with conditions’ exceeds anticipated 2030 demand\(^1\)

Total green H₂ capacity that can be built below 0.45 kg CO₂/kg H₂ (Mtpa)\(^2,3\)

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1. Viable capacity of electrolyzer deployment constrained by 0.45 kg CO₂/kg H₂ requirement for full PTC
2. Estimated green H₂ capacity at which annual matching approach crosses 0.45 kg CO₂/kg H₂ for the present model in each region independently
3. Assumes 2030 COD
4. Total inclusive of blue H₂ (via fossil fuels with accompanying carbon capture and sequestration, CCS) and electrolytic green hydrogen

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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 analyzed, 2030 COD projects do not qualify for full PTC ($3/kg H₂) for emissions below 0.45 kg CO₂/kg H₂
- Overall average projected emissions intensity of 2.8 kg CO₂/kg H₂ (3.5 kg CO₂/kg H₂ average in 16 regions that do not qualify)
- Across advantaged regions, U.S. may be able to deploy up to ~10 GW² of electrolyzer capacity (~2 MTPA of H₂) at/under 0.45 kg CO₂ / kg H₂
- Top five emissions intensive regions include RMPA (7.9 kg CO₂/kg H₂), 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 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 CO₂ / kg H₂, but still falls above the 0.45 kg CO₂/kg H₂ IRA PTC target

- Of the 20 regions, 8 remain above the 0.45 kg CO₂/kg H₂ limit under both conditions; NEWE is the only differential region between both scenarios, falling below 0.45 kg CO₂/kg H₂ for 10% overbuild but not for 5% shutdown
- U.S. may be able to deploy up to ~24 GW (~4 MTPA of H₂) for 5% shutdown or ~26 GW (~5 MTPA of H₂) for 10% overbuild at/under 0.45 kg CO₂/kg H₂

B.2 Shutdown AND Overbuild: Combination of 5% shutdown and 10% overbuild results in a nationwide average carbon displacement of -0.4 kg CO₂/kg H₂, unlocking deployment in all regions east of Rockies except for MROE and SIRMW

- Six regions remain above the 0.45 kg CO₂/kg H₂ limit with an average expected emissions in those 6 regions of 3.0 kg CO₂/kg H₂
- Projected 2030 COD U.S. electrolyzer capacity rises to ~40 GW (~7 MTPA of H₂)

B.3 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 CO₂/kg H₂ 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+ GW³ (12+ Mtpa of H₂) 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 CO₂/kg H₂ 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\textsubscript{2} vs alternatives**

**Net H\textsubscript{2} production cost\textsuperscript{1} (USD/kg H\textsubscript{2}) including 45V PTC\textsuperscript{2}**

- Early deployments (2025)
- Maturing market (2030)\textsuperscript{3}

Cost premium for hourly matching driven by balance of reduced electrolyzer capacity factor, renewables overbuild, and addition of energy storage

+110%

**Key takeaways:**

- Hourly matching more than doubles the cost of green H\textsubscript{2} in 2030 by limiting electrolyzer capacity factor and requiring renewables overbuild.

- After 2030, hourly matched green H\textsubscript{2} will approach cost competitiveness with blue and grey H\textsubscript{2}.

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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\textsubscript{2} and $0.60 for blue H\textsubscript{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.
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.

Implications of green H₂ matching approaches on economically viable demand

Breakeven production¹ cost of hydrogen by application ($/kg H₂, 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 H₂ Applications Economics Model

Power matching approach expected to be the difference between limited green H₂ deployment and significant cross-industry applications in 2030
II. Industry growth

Economic impacts of each matching strategy

Anticipated impacts of green hydrogen buildout...

<table>
<thead>
<tr>
<th>Matching Strategy</th>
<th>Economically accessible demand</th>
<th>Capital investment</th>
<th>Direct &amp; indirect jobs</th>
<th>Abated emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong> Annual matching</td>
<td>20-45 Mtpa</td>
<td>$400-990B</td>
<td>800k-2,700k</td>
<td>120-270 Mtpa</td>
</tr>
<tr>
<td><strong>B</strong> Annual matching (w/ conditions)</td>
<td>15-40 Mtpa</td>
<td>$300-880B</td>
<td>600k-2,400k</td>
<td>140-380 Mtpa</td>
</tr>
<tr>
<td><strong>C</strong> Hourly matching</td>
<td>0.02-15 Mtpa</td>
<td>$0.4-330B</td>
<td>0.8k-900k</td>
<td>0.2-140 Mtpa</td>
</tr>
</tbody>
</table>

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\textsubscript{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\textsubscript{2}. 3. Per Mtpa of H\textsubscript{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\textsubscript{2} with fully carbon free H\textsubscript{2}, yields downstream decarbonization of ~6 Mtpa CO\textsubscript{2}/Mtpa H\textsubscript{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 North2 Project; BCG NAMR \textsubscript{H2} Applications Economics Model
Reliability and cost externalities associated with green H₂ buildout

### Reliability externalities
Effect of increased variable renewable energy sources on grid performance

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

#### 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

#### 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
## II. Externalities

### III. Relative impact on externalities across matching strategies

<table>
<thead>
<tr>
<th>Reliability externalities</th>
<th>Cost externalities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Generation variability</strong></td>
<td>- Incentivizes development of cheapest renewable resource available with no incentive for adding storage</td>
</tr>
<tr>
<td><strong>Network congestion</strong></td>
<td>- Adds load and generation capacity to the network</td>
</tr>
<tr>
<td><strong>Compensation for dispatchable generators</strong></td>
<td>- Increase in payments necessary to maintain dispatchable generation availability</td>
</tr>
<tr>
<td><strong>Higher peak load</strong></td>
<td>- Increases total load on grid during peak demand hours without adding a balance of RE</td>
</tr>
<tr>
<td><strong>Grid infrastructure buildout</strong></td>
<td>- New grid infrastructure to support geographically diverse generation sites and new loads</td>
</tr>
</tbody>
</table>

| Source: BCG analysis |

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

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**Legend**

- 🔄 Mitigated
-.green; ⬆️ Partially mitigated
- red; ⬇️ Detrimental

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Matching approaches assessed against implementation and validation simplicity

### 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
- **Crediting**: Annual generation crediting standardized through RECs

#### 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

### 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

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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

A) Annual matching

- Yields CO\textsubscript{2} above IRA limit in most geographies
- Roughly doubles economically viable green hydrogen demand (vs hourly)
- Creates greatest risk for grid reliability challenges and cost increases
- Uses present day processes and procedures (e.g., REC system)
- Supports U.S. technology leadership in green H\textsubscript{2}
- Helps reliability and cost by shutting down during peak load and balancing generation with resource mix
- Uses present day processes and procedures
- Requires complex dynamic load management and renewables portfolio optimization capabilities to achieve
- Is validated via currently measured annual values
- Relies on flexible shutdown based on hourly grid load/power price

B) Annual matching (w/ conditions)

- Meets IRA limit nationwide with all three conditions (overbuild, shutdown, resource mix)
- Accesses nearly the same aggregate demand as base annual matching despite modest increase to H\textsubscript{2} price
- Helps reliability and cost by shutting down during peak load and balancing generation with resource mix
- Uses present day processes and procedures
- Requires hourly generation and load data for validation

C) Hourly matching

- Ensures no net load or incremental carbon emissions
- Results in higher cost than fossil-based blue, grey hydrogen prior to 2030
- Amplifies regional disparities in deployment based on resource quality

I. CO\textsubscript{2} emissions

- Yields CO\textsubscript{2} above IRA limit in most geographies
- Roughly doubles economically viable green hydrogen demand (vs hourly)
- Creates greatest risk for grid reliability challenges and cost increases
- Uses present day processes and procedures (e.g., REC system)
- Supports U.S. technology leadership in green H\textsubscript{2}
- Helps reliability and cost by shutting down during peak load and balancing generation with resource mix
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- Requires complex dynamic load management and renewables portfolio optimization capabilities to achieve
- Is validated via currently measured annual values
- Relies on flexible shutdown based on hourly grid load/power price

II. Industry growth

- Meets IRA limit nationwide with all three conditions (overbuild, shutdown, resource mix)
- Accesses nearly the same aggregate demand as base annual matching despite modest increase to H\textsubscript{2} price
- Helps reliability and cost by shutting down during peak load and balancing generation with resource mix
- Uses present day processes and procedures
- Requires hourly generation and load data for validation

III. Externalities

- Breaks down in efficacy at high grid penetration of RE\textsuperscript{1}
- 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

- Ensures no net load or incremental carbon emissions
- Total decarbonization impact may be limited by realized deployment\textsuperscript{2}

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.”

NREL mid-case renewables capacity forecast through 2040

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

Note: Historical data from EIA Annual Energy Outlook
I. Carbon emissions

Renewables forecast comparison (I of II)

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

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.

Sources (Avg. Annual Growth)
- ACP (24%)
- BNEF (22%)
- IEA accelerated\(^2\) (25%)
- IEA main case (20%)
- NREL\(^1\) (25%)
- WoodMac (22%)

1. NREL mid-case forecast
2. Assumes that governments address policy, regulatory, and implementation challenges within the 12-24 mo. report publication;

Post-IRA forecasts

Sources:
- 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)

Post-IRA forecasts

<table>
<thead>
<tr>
<th>Source</th>
<th>Total</th>
<th>Wind</th>
<th>Solar PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>NREL - Mid Case</td>
<td>560</td>
<td>205</td>
<td>355</td>
</tr>
<tr>
<td>WoodMac</td>
<td>505</td>
<td>140</td>
<td>365</td>
</tr>
<tr>
<td>BNEF</td>
<td>510</td>
<td>145</td>
<td>365</td>
</tr>
<tr>
<td>ACP1</td>
<td>550</td>
<td></td>
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</tbody>
</table>

1. Solar and wind split unavailable
Note: ACP = American Clean Power
Hourly matching requirement significantly increases power cost

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

LCOE ($/MWh)

0  50  100  150  200

10%  20%  30%  40%  50%  60%  70%  80%  90%  100%

Capacity Factor (%) 

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

Cost of carbon-free energy is higher in regions with lower renewable resource availability

Hourly matching includes steep increase in power price due to overbuild and storage required to meet peak demand

II. Industry growth

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

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>CapEx $/kW</td>
<td>$1,800</td>
<td>$1,200</td>
</tr>
<tr>
<td>OpEx $/kW</td>
<td>$36</td>
<td>$24</td>
</tr>
<tr>
<td>Efficiency</td>
<td>52 kWh/kg</td>
<td>47 kWh/kg</td>
</tr>
<tr>
<td>CF</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

30 kWh/kg No change 47 kWh/kg No change

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

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 H₂.
- 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.