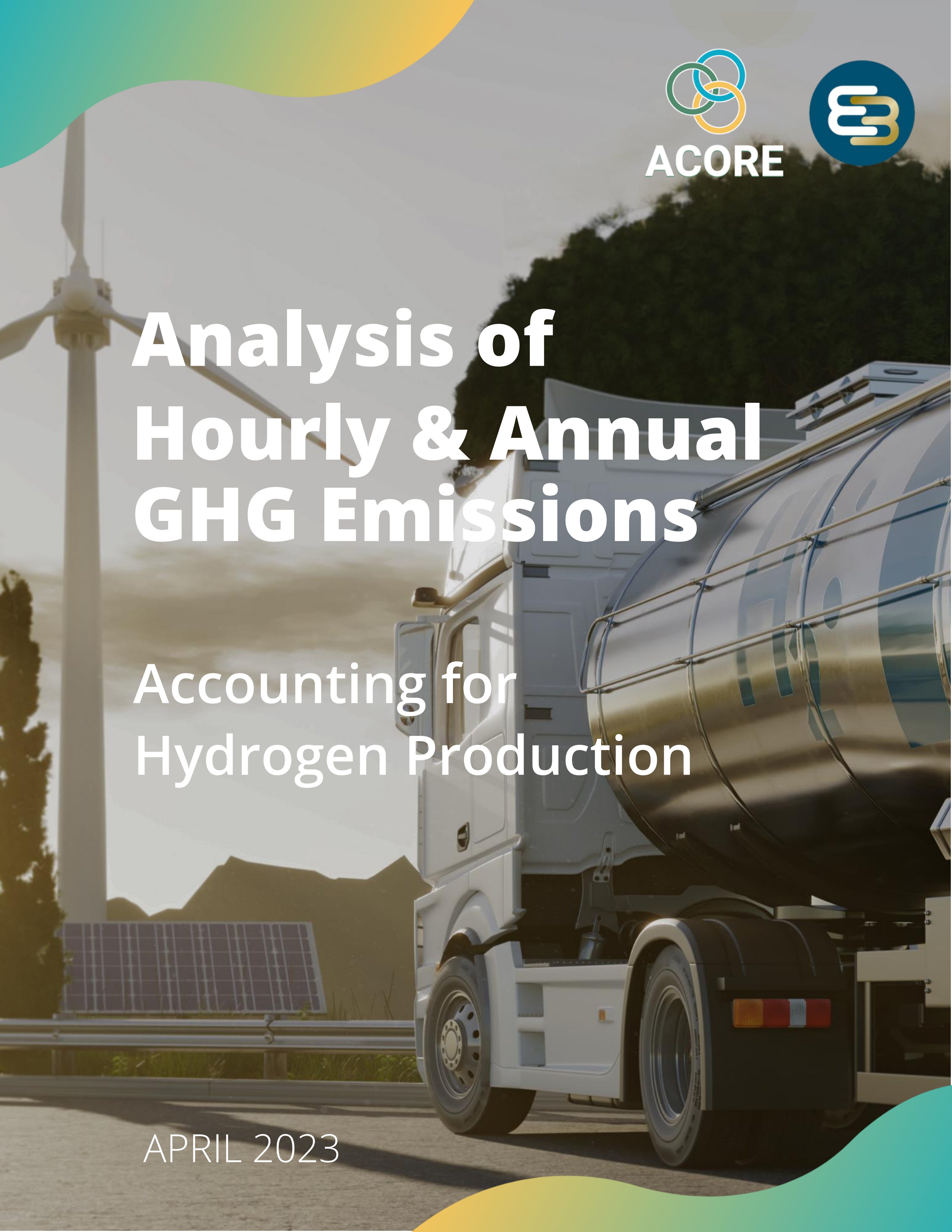

ACORE

Analysis of Hourly & Annual GHG Emissions

Accounting for Hydrogen Production

APRIL 2023

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About E3:

E3 is a leading economic consultancy focused on the energy industry, with an emphasis on electricity and the clean energy transition. E3 provides advisory services and energy systems modeling to investor-owned utilities, public power agencies, project developers, energy consumers, regulators, grid operators, government agencies, and public interest advocacy groups across North America. For more information, please visit www.ethree.com.

About ACORE:

The American Council on Renewable Energy (ACORE) is a 501(c)(3) national nonprofit organization that unites finance, policy and technology to accelerate the transition to a renewable energy economy. For more information, please visit www.acore.org.

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Acronym Definitions

Acronym	Definition
ACORE	American Council on Renewable Energy
ATB	Annual Technology Baseline
ATR	Autothermal reforming
CCS	Carbon capture and storage
CETA	Clean Energy Transformation Act (Washington)
CI	Carbon intensity
CO_2 or CO2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DOE	Department of Energy
E3	Energy and Environmental Economics
ERCOT	Electric Reliability Council of Texas
ESG	Environmental, Social, and Governance
GHG	Greenhouse gas
IRA	Inflation Reduction Act
IRS	Internal Revenue Service
ITC	Investment tax credit
kg	kilogram
LBNL	Lawrence Berkeley National Laboratory
LCOE	Levelized cost of electricity
LSE	Load serving entity
MISO	Midcontinent Independent System Operator
MWh	Megawatt-hour
NREL	National Renewable Energy Laboratory
PJM	PJM Interconnection
POX	Partial oxidation
PPA	Power purchase agreement
PTC	Production tax credit
ReEDS	Regional Energy Deployment System
REC	Renewable energy certificate
RPS	Renewable Portfolio Standard
SMR	Steam methane reforming
SPP	Southwest Power Pool
VOM	Variable operations and maintenance
VPPA	Virtual power purchase agreement

Executive Summary

Low-carbon hydrogen production has become an important component of many plans for reducing economy-wide greenhouse gas (GHG) emissions, including in the electricity sector. Hydrogen can be a valuable resource to decarbonize hard-to-electrify sectors of the economy, such as high-heat industrial processes and medium- and heavy-duty transportation. Power generation from hydrogen can also provide firm zero-carbon capacity to the electric grid. The attention paid to hydrogen has only increased in the United States since the passage of the Inflation Reduction Act (IRA) in 2022, which included a 10-year Production Tax Credit (PTC) for clean hydrogen (45V) produced with less than 4 kilograms (kg) of CO_2e per kg of hydrogen. Additionally, the U.S. Department of Energy (DOE) published a draft "National Clean Hydrogen Strategy and Roadmap" in September 2022.

Energy and Environmental Economics, Inc. (E3) was commissioned by the **American Council on Renewable Energy (ACORE)** to study implementation scenarios for 45V and focus on a key question: **how should we account for the carbon content of the electricity supply used to produce hydrogen**? This study analyzes the incremental GHG emissions impacts of hydrogen when clean energy used for electrolytic hydrogen production is accounted for on an annual versus an hourly basis, and analyzes the potential impacts of each accounting method on the cost of producing hydrogen.

Some entities have proposed an 'hourly matching' accounting requirement, under which specified clean electricity production would need to be equal to electricity consumption for hydrogen production on an hourly basis. Such a requirement could, setting aside complicating factors such as real power losses and locational differences in marginal grid emissions rates, provide a high degree of confidence that hydrogen production would not result in any increase in grid CO_2 emissions.

An annual matching requirement, in which hydrogen producers would need to procure specified clean energy production to match their consumption on an annual basis, would allow electrolyzers to more cost-effectively operate at a higher capacity factor, reducing the cost of hydrogen production. Critics of this approach express the concern that an annual matching requirement would result in incremental CO_2 emissions relative to an hourly matching approach. To determine whether this concern is well-founded, this report analyzes the clean energy, emissions, and cost implications of annual matching requirements relative to hourly matching requirements using simulated electricity market operations for four markets – the Electric Reliability Council of Texas (ERCOT), the Midcontinent Independent System Operator - North (MISO-North), the PJM Interconnection (PJM), and the Southwest Power Pool (SPP) – in 2025 and 2030.

Due to the nature of networked electricity systems, electrolytic production of hydrogen is met physically with grid electricity from a mix of generating resources that, all else being equal, results in higher emissions. Similarly, in both the hourly and annual matching approaches, clean energy generation is injected into the grid that, all else being equal, reduces energy production from emitting resources. The difference between the two approaches is the timing of hydrogen production and clean energy generation, which results in differences in the carbon intensity of the emitting resources whose production is reduced. Thus, whether hydrogen production results in net CO_2 emissions depends on the marginal emissions factors during hours of hydrogen production relative to hours of renewable generation.

E3’s analysis assumes clean energy supply is additional and is located within the same market footprint as hydrogen production. This study therefore models only the question of hourly versus annual matching and does not directly examine related questions of ‘additionality’ (ensuring clean energy generation procured by hydrogen producers is ‘new’ rather than ‘existing’) and ‘deliverability’ (whether there should be restrictions on the physical location of clean electricity supplies). We discuss these issues qualitatively and note that such restrictions on clean energy supplies may not result in lower emissions from hydrogen production, but almost certainly result in higher costs.

E3 compares the clean energy production requirement, carbon emissions in kgCO_2e / kgH_2, and cost of hydrogen production in $/kg under annual and hourly matching approaches for two scenarios:

1. **Energy Match**:
   For annual matching, a portfolio of wind and solar generation is procured in a quantity equal to the annual energy demand of the electrolyzer during hours when the marginal emissions rate of grid electricity is positive. For hourly matching, hydrogen production is restricted based on the hourly quantity of renewable generation available under the same portfolio.
2. **Emissions Match With 0.45 kg CO_2 Target**:
   For annual matching, a sufficient quantity of wind and solar generation is procured to limit incremental emissions to 0.45 kg CO_2e / kg H_2, the maximum allowed under the IRA to qualify for the full 45V PTC. For hourly matching, hydrogen production is restricted based on the hourly quantity of renewable generation available under the same portfolio.

The analysis is repeated across clean generation mixes, markets, and time periods to capture a range of current and future grid dynamics. The analysis assumes a utility-scale, 500 MW electrolyzer with a 90% utilization rate under annual matching to maximize hydrogen production and 70% production efficiency.

E3’s analysis finds that:

- An annual energy matching requirement results in emissions intensities between -1.23 and +1.18 kg CO_2e / kg H_2, depending on the market, time period, and renewable generation mix. Under 34 out of 40 scenarios evaluated by E3, CO_2 emissions are less than 0.45 kg CO_2e / kg H_2. In 25 scenarios, emissions are reduced (the matched clean energy production saves more emissions than the hydrogen load causes). Emissions are reduced relative to an hourly matching approach because the carbon intensity during hours of hydrogen production is lower than the carbon intensity during the hours of new renewable energy production.

- Modest changes in the renewable generation portfolio – i.e., changes in the total quantity of annual renewable generation or changes in the mix of renewable resources – can entirely eliminate the incremental emissions observed under annual matching for those few scenarios where emissions are higher. Specifically, changes in the total quantity of renewable resources required to achieve the 0.45 kg CO_2e / kg H_2 threshold range from -10% (i.e., the quantity of renewable generation procured could be reduced) to +3%.

- For all scenarios, across all markets, years, and renewable portfolio assumptions, hydrogen production costs are higher under an hourly matching requirement than under an annual matching requirement. Hydrogen production costs under an hourly approach are 14% to 108% higher than under an annual approach with the same renewable generation portfolio.

Figure 1. Incremental Emissions by Market and Renewable Mix, Annual Energy Match Scenario[1]

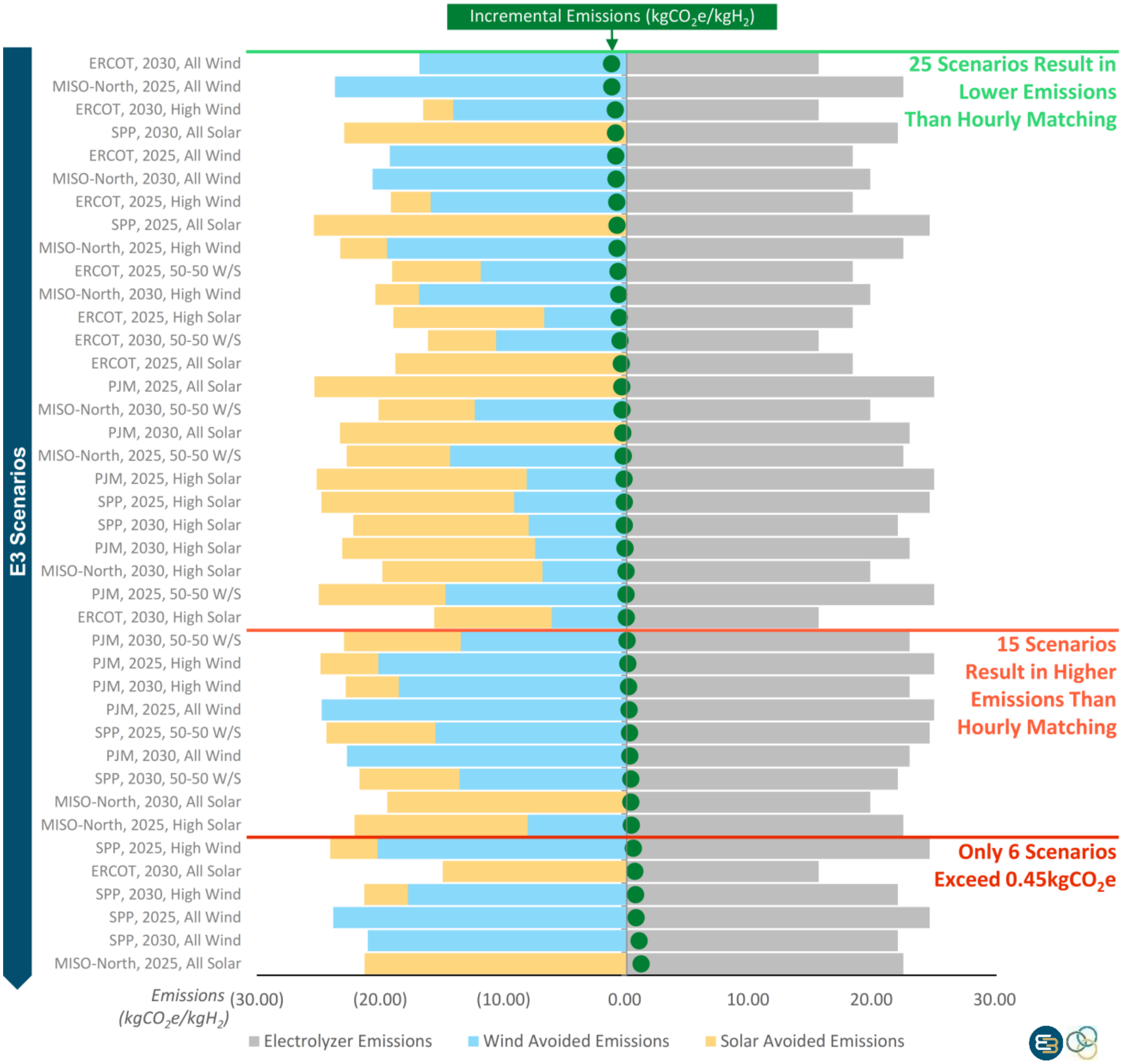

Figure 1 summarizes the emissions results under the Energy Match scenario. CO_2 emissions are lower under the annual matching approach than the hourly matching approach for 25 out of 40 scenarios, and less than the minimum value of 0.45 kg CO_2e / kg H_2 for 34 out of 40 scenarios.

Discussion of energy matching requirements often assumes an exact match between the quantity of energy consumed by hydrogen producers and the quantity of clean energy produced by matching supplies. However, there is no inherent reason or market logic for these quantities to be equal. Indeed, there are many sound reasons for renewable energy supplies to be different in quantity than hydrogen production

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[1] 50-50 W/S refers to a renewable generation portfolio with 50% wind and 50% solar capacity. High Solar denotes a mix of 25% wind and 75% solar capacity. High Wind denotes a generation mix of 75% wind and 25% solar capacity. Renewable capacity is translated into generation using region-specific capacity factors. See later sections for more details.

load, including but not limited to hedging of financial risk, annual variability in renewable production, real power losses, and ensuring that any increases in emissions are offset. This study uses a deliberate 'overbuild' as a means for eliminating any residual CO_2 emissions under an annual matching approach.

Figure 2. Over / (Under) Build for 0.45 kgCO_2e/kgH_2 Incremental Emissions[2]

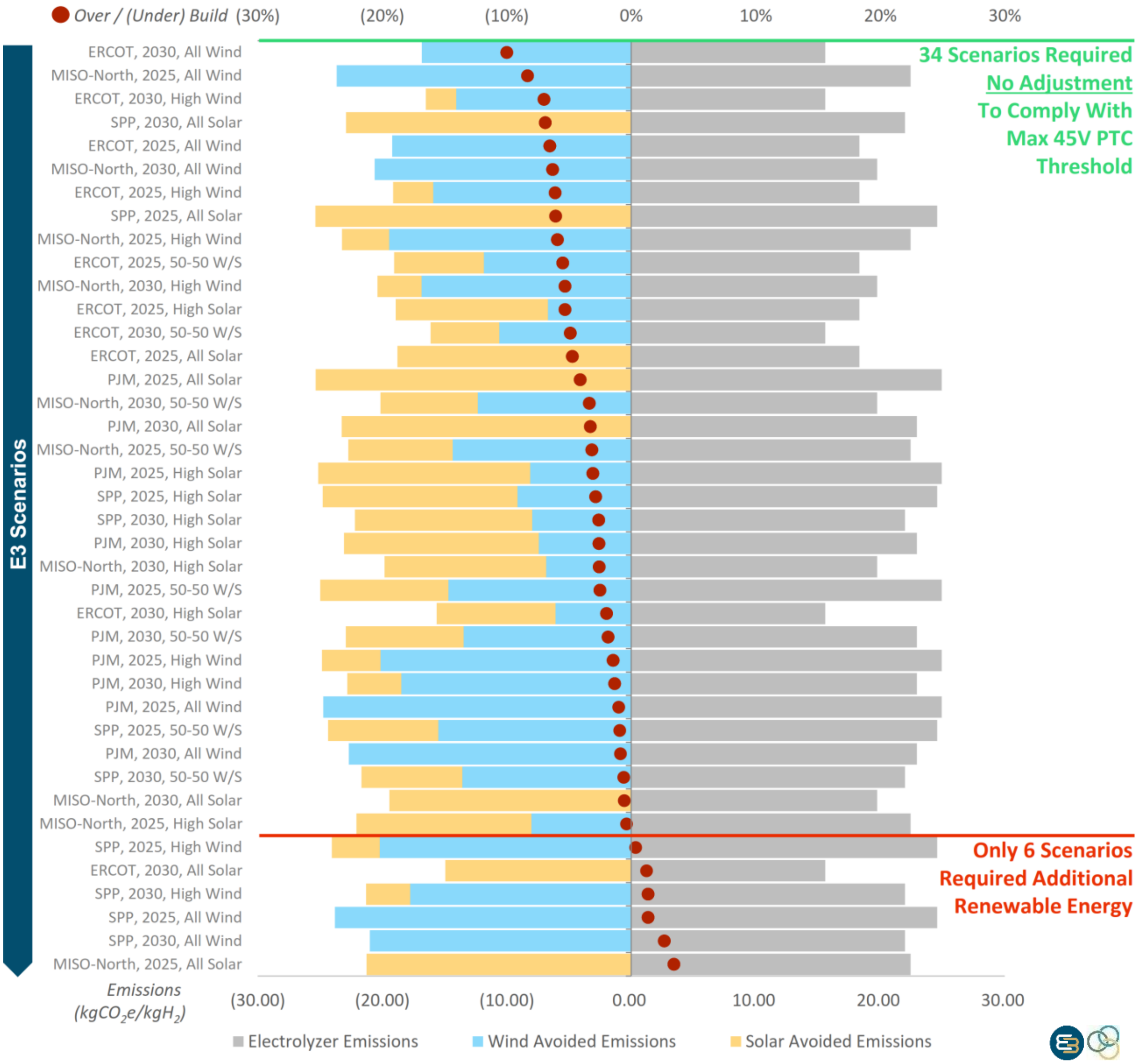

Figure 2 summarizes the increase (overbuild) or decrease (underbuild) in renewable generation that limits incremental emissions to 0.45 kg CO_2e / kg H_2. In the majority of scenarios, renewable generation can decrease after meeting the energy requirement and still meet the 0.45 kg CO_2e target. Only six of 40 scenarios require an overbuild of the renewable portfolio.

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[2] High Solar denotes portfolios with 25% wind and 75% solar capacity. High Wind is 75% wind, 25% solar. Renewable capacity is translated into generation using region-specific capacity factors. See later sections for more details.

Figure 3. Incremental Cost Under Hourly Matching With 0.45 kg CO_2e Emissions Target[3]

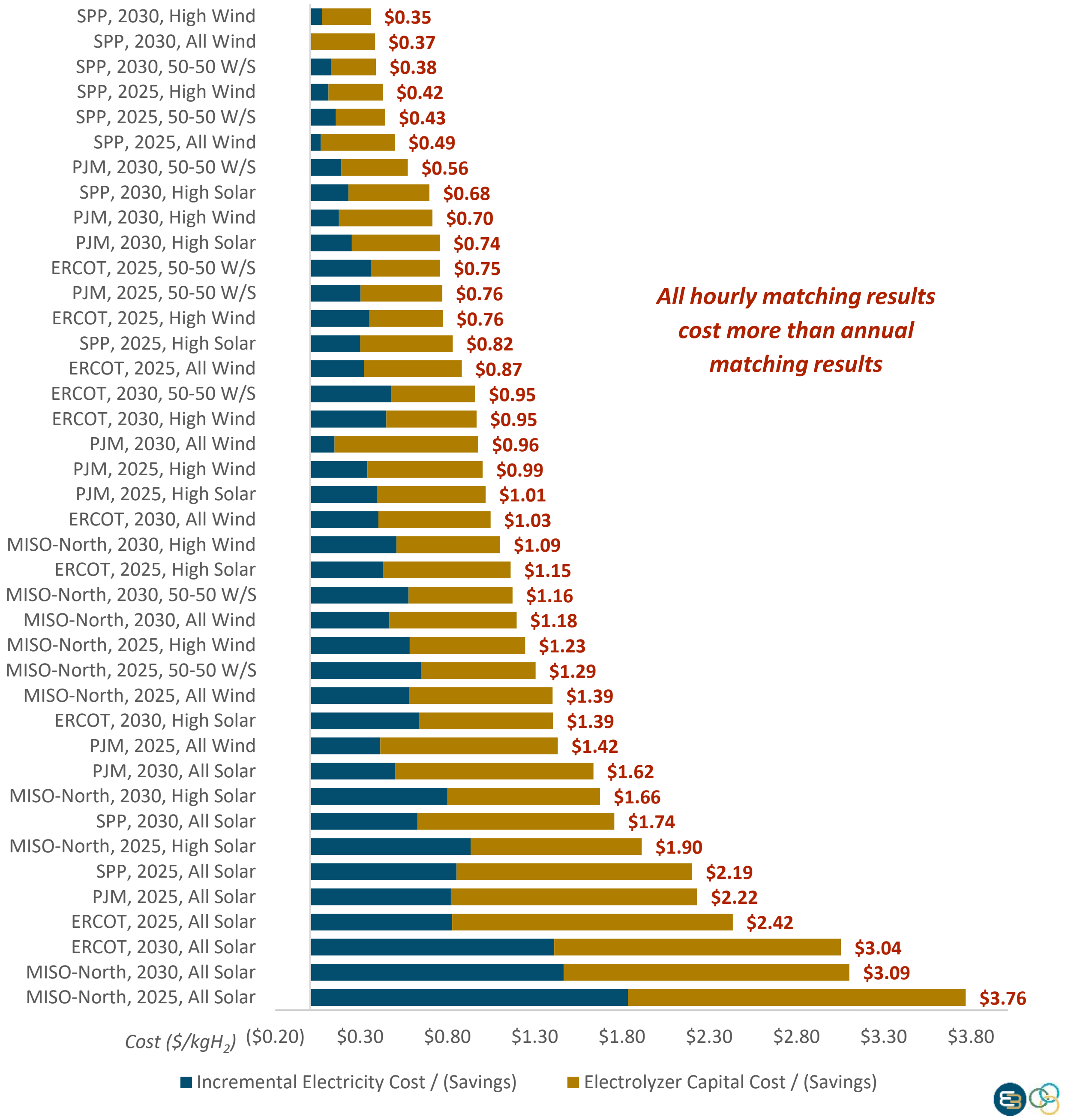

Figure 3 summarizes incremental increases in H_2 cost per kilogram under an hourly matching requirement. Hourly matching results in significantly higher costs for hydrogen production than annual matching for all 40 scenarios.

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[3] High Solar denotes portfolios with 25% wind and 75% solar capacity. High Wind is 75% wind, 25% solar.

Figure 4. Cost Premium for Hourly Matching Relative to Annual Matching (%)[4]

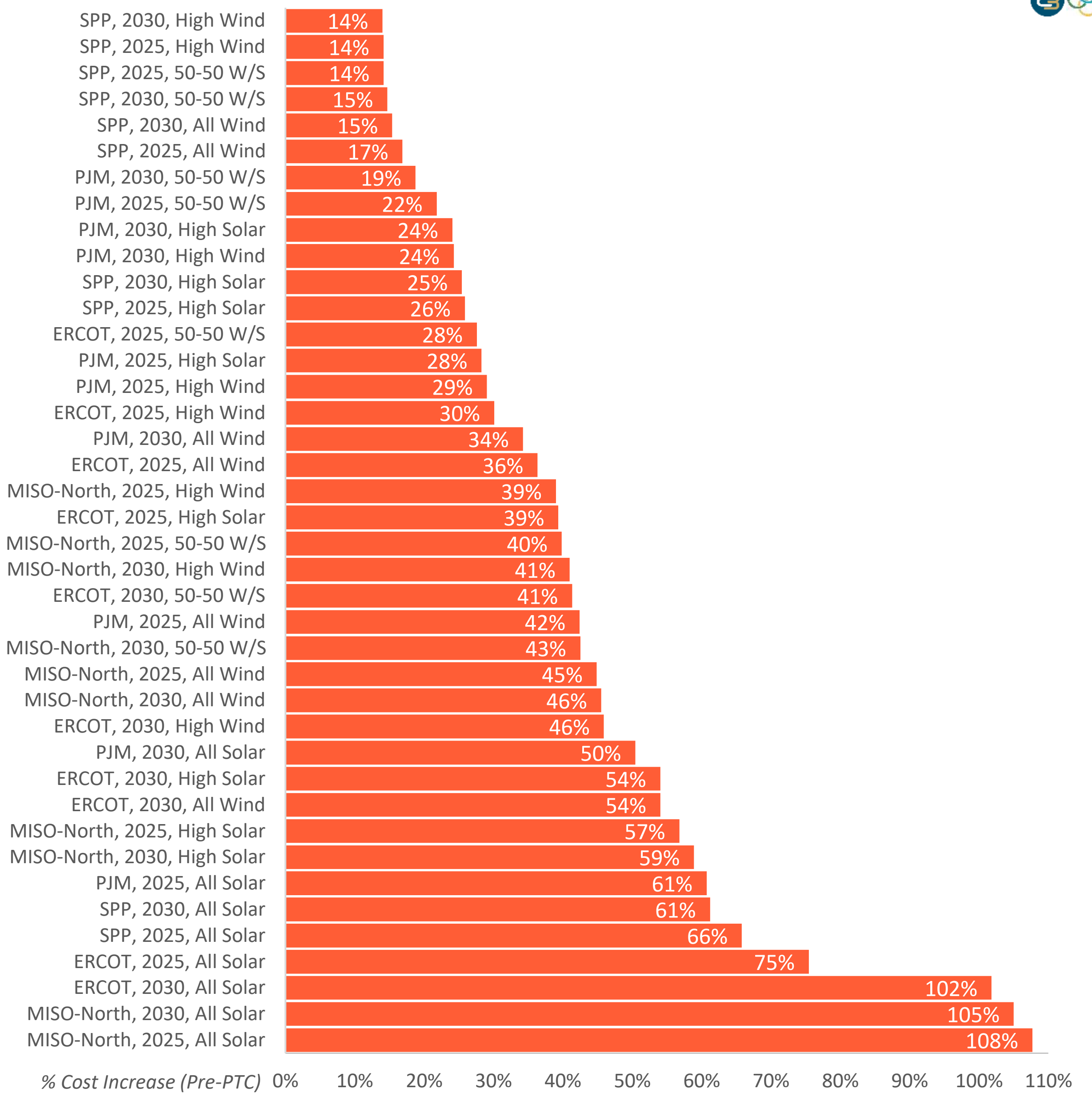

Figure 4 summarizes percentage increases in production cost under an hourly matching requirement, before accounting for the Production Tax Credit applicable to each scenario. When the Production Tax Credit is reflected, the resulting percentage cost increases are significantly higher, reflecting significantly higher hydrogen prices when viewed from the perspective of the final consumer.

An hourly matching requirement with the same net CO_2 emissions as an annual matching requirement produces higher hydrogen production costs across markets:

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[4] High Solar denotes portfolios with 25% wind and 75% solar capacity. High Wind is 75% wind, 25% solar.

- In ERCOT, hydrogen produced under the hourly matching requirement could cost up to 102% more than hydrogen produced under the annual matching requirement;
- In MISO-North, production costs increase by up to 108% under an hourly matching requirement;
- In PJM, production costs increase by up to 61% under an hourly matching requirement; and
- In SPP, production costs increase by up to 66% under an hourly matching requirement.

Based on the analysis described above, E3 draws the following key conclusions:

1) An hourly matching requirement does not ensure lower GHG emissions relative to an annual matching requirement, and in many cases is less effective at eliminating carbon emissions than annual matching;

2) With modest changes to the size and composition of the renewable portfolio to meet electrolyzer demand, hydrogen produced under an annual renewable energy matching requirement results in incremental emissions less than the threshold for the maximum Production Tax Credit under the Inflation Reduction Act; and

3) An hourly matching requirement results in significantly higher costs for hydrogen production than an annual matching requirement with the same GHG intensity across a wide range of renewable energy and wholesale electricity market assumptions.

Introduction

Purpose of Study

Energy and Environmental Economics, Inc. (E3) was commissioned by the American Council on Renewable Energy (ACORE) to determine the incremental GHG emissions impact of hydrogen when clean energy used for electrolytic hydrogen production is accounted for on an annual versus an hourly basis, and to conduct an initial analysis of the potential production cost impacts of hourly versus annual accounting.

E3's analysis begins with the assumption, embedded in the IRA, that hydrogen must be produced using low- or zero-carbon electricity. Policy recommendations for the sector, and hence this study, therefore focus on a key question: **how should we account for the carbon content of the electricity supply used to produce hydrogen?**

Role of Hydrogen in a Decarbonized World

Low-carbon hydrogen production has become an important component of many plans for reducing economy-wide greenhouse gas (GHG) emissions including in the electricity sector. Hydrogen can be a valuable resource to decarbonize hard-to-electrify aspects of the economy, such as high-heat industrial processes and medium- and heavy-duty transportation. Power generation from hydrogen can also provide firm zero-carbon capacity to the electric grid.

The attention paid to hydrogen has only increased in the United States since the passage of the Inflation Reduction Act (IRA) in 2022, which included a 10-year Production Tax Credit (PTC) for clean hydrogen (45V) produced with less than 4 kilograms (kg) of carbon dioxide equivalent (CO_2e) per kg of hydrogen (H_2). Additionally, the U.S. Department of Energy (DOE) published a draft "National Clean Hydrogen Strategy and Roadmap" in September 2022.[5]

Low-Carbon Hydrogen Definition

Hydrogen is the lightest and simplest element on our planet. Hydrogen has the highest energy per mass and lowest energy content by volume of any fuel, resulting in technical challenges related to storage and distribution. Although hydrogen releases no GHG emissions when combusted to produce electricity or heat, hydrogen requires relatively high volumes of production to achieve similar levels of emission reductions compared to other low-carbon gases.

Hydrogen can be produced in a variety of ways. The majority of global hydrogen production today is derived from fossil fuels without the capture and storage of released carbon dioxide (CO_2) emissions, and therefore is not carbon-free. This hydrogen production is used primarily as a feedstock for oil refining,

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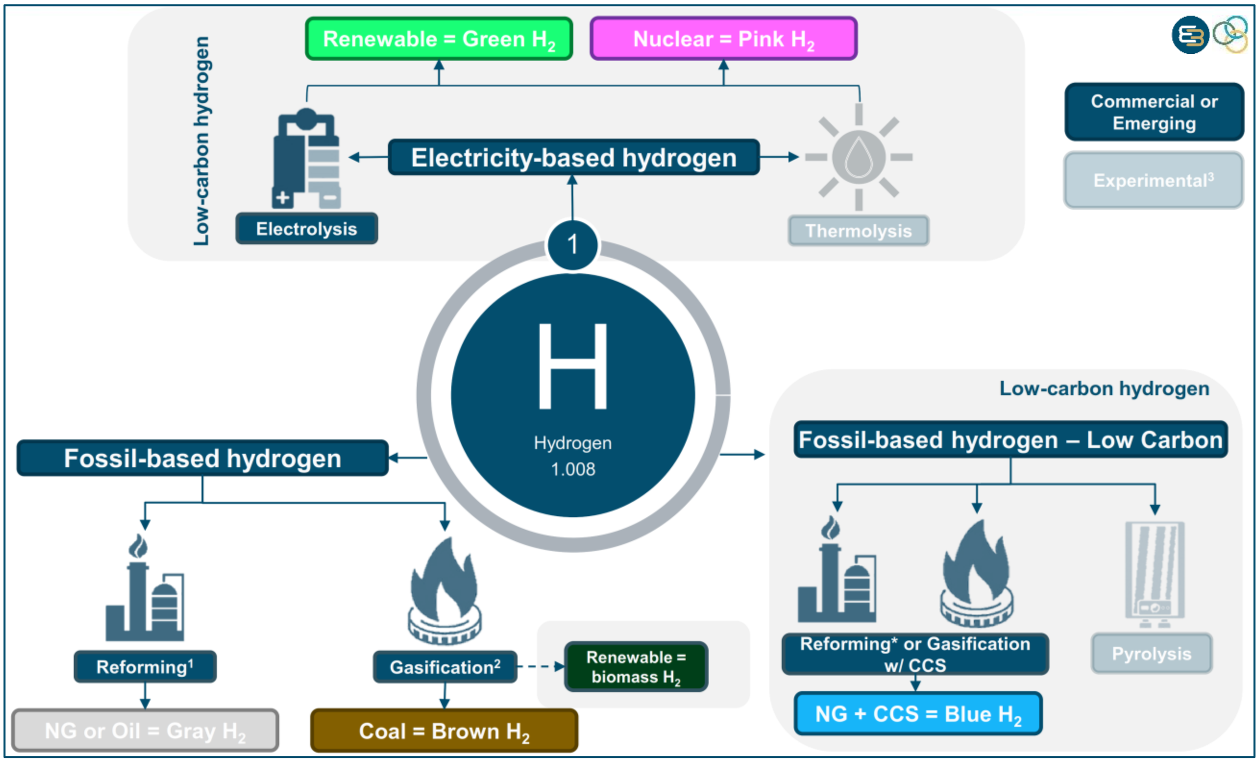
[5] https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf

ammonia and methanol production. Alternatively, hydrogen can be produced from electricity in a process that results in no direct carbon emissions but may indirectly create emissions if the incremental electricity is not generated by carbon-free resources.

A spectrum of colors is frequently used to distinguish hydrogen produced from the variety of different means. For example, hydrogen production from natural gas is commonly referred to as ‘gray hydrogen.’ Low-carbon hydrogen can be fossil-based in production, with Carbon Capture and Storage (CCS), a process often referred to as ‘blue hydrogen,’ or produced using bioenergy feedstocks. This study considers hydrogen produced from renewable electricity, often referred to as ‘green hydrogen.’[6]

The hydrogen industry is attempting to move away from these ‘color-wheel’ definitions of hydrogen as policy tools including the IRA are technology agnostic, with the key defining factor being the carbon intensity (CI) of hydrogen production. This study focuses on renewable electricity as the most likely means of minimizing emissions associated with hydrogen production in the near to medium term.

Figure 5. Hydrogen Production Overview



1) Includes catalytic reforming, SMR, ATR, and POX.
2) Hydrogen through gasification can be derived from bio feedstocks. This would be considered low-carbon hydrogen.
3) This overview includes commonly cited methods to break apart hydrogen, but is not intended to be exhaustive.

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[6] While some sources differ on colors for different hydrogen production methods, hydrogen produced from electricity that includes fossil fuel generation sources is sometimes referred to as “yellow.” For more details on hydrogen colors, see: Ahmet Kusoglu 2021 Electrochem. Soc. Interface 30 44. Link.

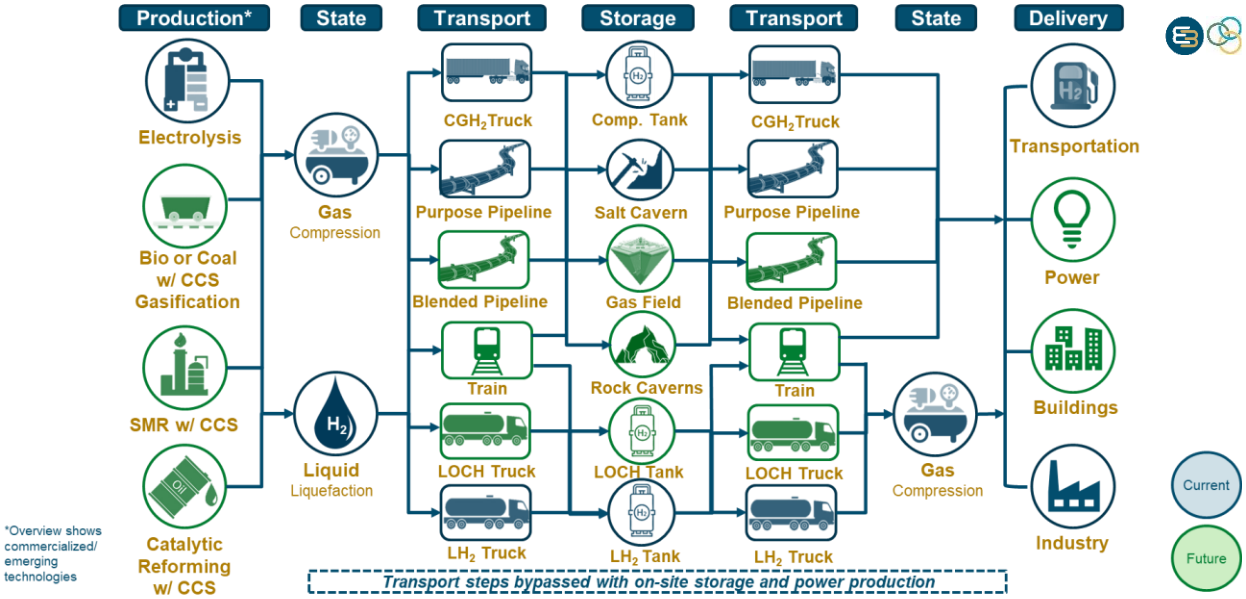
Green and blue hydrogen are eligible for incentives under the IRA, which uses the term “clean hydrogen,” but will remain more expensive than gray hydrogen in all relevant applications once the IRA incentives expire post-2032, and gas offtake from plants built to comply with the deadline becomes fully subscribed. There are two broad use cases for green hydrogen moving forward:

1) Direct hydrogen use as fuel, or as feedstock for fuel generation, to offset use of fossil fuels.
2) Green hydrogen use in place of existing demands for gray hydrogen such as oil refining, ammonia production, and industrial applications.

Hydrogen Production and the General Supply Chain

Figure 6 provides an overview of the low-carbon hydrogen supply chain. The schematic distinguishes between current supply chain options (in blue) and potential future supply chain options (in green). Potential future supply chain options are defined as commercialized or emerging technologies that have a relatively high chance of becoming cost competitive.

Figure 6. Schematic Overview of Low-Carbon Hydrogen Supply Chain



As the figure illustrates, there are many potential supply chain paths for hydrogen production, transport, storage, and delivery. The most promising near-term options circumvent the need for a complete hydrogen delivery supply chain, and would instead use utility on-site production of hydrogen, coupled with on-site storage and use, for example, through combustion in electric generation turbines or as feedstock in industrial processes. Additional details on hydrogen production can be found in the Appendix.

Hydrogen-Related Aspects of the Inflation Reduction Act

In the IRA, the Clean Hydrogen Fuel Credit (45V) provides a new 10-year PTC for facilities that begin construction before 2033 and for clean hydrogen produced from qualifying facilities. However, a qualified facility must produce hydrogen that results in greenhouse gas (GHG) emissions up to the point of fuel production of not greater than 4 kg of CO_2e per kilogram (kg) of hydrogen. The exact value of the 45V credit depends on the lifecycle GHG emissions of the production pathway:

- Credit is $3/kg for emissions less than 0.45 kg CO_2e/kg H_2
- 33.4% of full credit value for emissions between 0.45-1.5 kg CO_2e/kg H_2
- 25% of full credit value for emissions between 1.5-2.5 kg CO_2e/kg H_2
- 20% of full credit value for emissions of 2.5-4 kg CO_2e/kg H_2
- Note to receive any of these credits, the IRA's wage and apprenticeship requirements[7] must be satisfied, otherwise facilities are only eligible to receive 20% of the above credits.

While it is possible to claim the Investment Tax Credit (ITC) in lieu of the PTC, initial analysis suggests the ITC is not as valuable for green hydrogen applications, since it is feasible to separately claim upstream ITCs or PTCs for green electricity production and then claim the PTC specific to hydrogen (45V) as described here. However, it is not possible to claim both the 45V credit and the separate tax credit associated with carbon capture (45Q) for the same hydrogen that is produced. There are various areas of implementation and guidance associated with the 45V credit that have yet to be clarified or confirmed by the U.S. Treasury Department's Internal Revenue Service (IRS), including the specific methodology by which emissions associated with hydrogen production will be defined for tax credit qualification purposes.

Separate from the IRA, the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law) contains roughly $9.5 billion in federal funding and incentives for clean hydrogen initiatives. Funding is allocated to the development of Regional Clean Hydrogen Hubs ($8 billion), a program intended to reduce the cost of hydrogen produced from zero-emissions electricity ($1 billion), and to provide support for domestic manufacturing related to the hydrogen supply chain ($0.5 billion).[8]

Accounting for Emissions from Hydrogen Production

Rationale for Discussion

The 45V credit has raised associated questions about the emissions impact of increased hydrogen production. As utilities, regulators, policy makers, developers, and investors have sought to identify

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[7] To meet the:

- Prevailing wage requirement: laborers and mechanics employed in the construction, alteration, or repair of the facility must be paid wages no less than prevailing wages (determined by Labor Department and varying by job type and location, as specified on www.sam.gov). There is a penalty of $5,000 for every employee paid below the prevailing wage (intentional disregard is a fine of $10,000/employee).
- Apprenticeship requirement: certain labor hours for the work must be performed by apprentices. 12.5% of hours worked must be performed by apprentices if construction begins before 1/1/2024 (15% if construction begins after 12/31/2023). Failure penalty is $50 x total labor hours or $500 x total labor hours if intentional disregard is established. Good faith effort may be proven if the project requested qualified apprentices from a registered apprenticeship program but request has been denied or there was a failure to respond within five business days.

[8] For more details, see: https://www.energy.gov/articles/doe-establishes-bipartisan-infrastructure-laws-95-billion-clean-hydrogen-initiatives

opportunities and obstacles associated with the IRA, third-party analyses of the potential impact of hydrogen production on electric sector GHG emissions have become significant. The goal of such analysis, including this study, is to identify an appropriate methodology for measuring emissions associated with hydrogen production and to use that methodology to estimate emissions impacts of hydrogen production for the purpose of establishing qualification for tax credits under the IRA.

Current Perspectives on Hourly Versus Annual Accounting

Underlying the current literature on this topic are five potential criteria for evaluating different approaches to measuring compliance with emissions reductions targets:

1) Additionality of any new clean energy generation
2) Deliverability of any clean electricity generated to the demand source of hydrogen production
3) Cumulative GHG emissions (either in association with additionality and deliverability constraints, or independent of these constraints)
4) Impact of the preceding criteria on quantity of hydrogen produced
5) Impact of the preceding criteria on the cost of hydrogen produced

A number of studies have approached the topic of hydrogen production's emissions and cost impacts using the criteria above, with divergent results.[9] Recently, multiple parties have submitted comments to the Department of the Treasury and other relevant U.S. government entities regarding the potential implementation methods for the 45V tax credits in the IRA. This has included parties advocating for an annual matching requirement, parties advocating for an hourly matching requirement, and parties advocating for implementation of an hourly matching requirement in phases.

Some academics, companies, and non-governmental organizations have proposed an 'hourly matching' requirement, under which specified clean electricity production would need to be equal to electricity consumption for hydrogen production on an hourly basis. Such a requirement could, setting aside complicating factors such as real power losses and locational differences in marginal grid emissions rates, provide a high degree of confidence that hydrogen production would not result in any increase in grid CO_2 emissions.[10]

There are two key areas of uncertainty in the discussion of this topic. First, the emissions target or goal used in different studies is not always consistent. In this report, E3 assumes the standard of 0.45 $kgCO_2e/kgH_2$ to align with the IRA full value PTC. Second, while emissions reduction is one of the core

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[9] For example:

- Wilson Ricks et al 2023 Environ. Res. Lett. 18 014025.
- https://www.iea.org/reports/the-future-of-hydrogen
- https://rmi.org/wp-content/uploads/2020/01/hydrogen_insight_brief.pdf
- https://rmi.org/hydrogen-reality-check-1-hydrogen-is-not-a-significant-warming-risk/
- https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/
- https://acp.copernicus.org/articles/22/9349/2022/
- https://crsreports.congress.gov/product/pdf/R/R46436
- https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2023/02/EFI-Hydrogen-Hubs-FINAL-2-1.pdf

[10] For more details on these arguments, see Canary Media: https://www.canarymedia.com/articles/hydrogen/the-great-green-hydrogen-battle

goals of the IRA, and the phase-out of tax credits for new zero-emission generation is accordingly tied to a power sector emissions reduction target, other goals are economic in nature such as the wage and apprenticeship requirements for tax credit incentives for new zero-emission generation, among other aspects of the Act.

In this study, E3 responds directly to the arguments that annual matching will result in an increase in GHG emissions. The study also examines the argument that hourly matching imposes only minor economic costs on hydrogen production. It does not directly address related questions of additionality or deliverability – E3's analysis assumes clean energy supply is additional and is located within the same market footprint as hydrogen production.

Modeling Assumptions

Scenario Design Considerations

Years of Analysis

The simulated year of analysis has a significant impact on the emissions associated with consumption of electricity from the grid due to changes in the resource mix for each market studied. E3 used two years of analysis in its scenarios:

- **2025:** Near-term year representing today's grid portfolio with minor adjustments.
- **2030:** Medium-term year with more significant renewable additions as well as expected and announced retirements.

Markets for Analysis

The resource mix and availability of high-quality wind and solar resources (i.e., resources with high capacity factors) will have a significant impact on the clean resource build required to meet electrolyzer load as well as the cost of producing that hydrogen. To capture a range of potential outcomes, E3 considers the renewable-rich areas of the Electric Reliability Council of Texas (ERCOT), the Midcontinent Independent System Operator - North (MISO-North), and the Southwest Power Pool (SPP), as well as the more renewable resource-limited region of the PJM Interconnection (PJM).

Clean Energy Resource

E3 models only wind and solar as the resources built to meet the electrolyzer's load. While other technologies can be considered 'clean,' wind and solar are the universal qualifying REC resources and are the resources most likely to be constructed at scale over the time period studied.

'Overbuild' or 'Underbuild' as a Portfolio Design Strategy

Discussion of energy matching requirements often assumes an exact match between the quantity of energy consumed by hydrogen producers and the quantity of clean energy produced by matching supplies. However, there is no inherent reason or market logic for these quantities to be equal. Hydrogen should be produced at times, in locations, and in quantities where it is economic and environmentally beneficial to do so. Similarly, clean energy should be generated at times, in locations, and in quantities where it is economic and environmentally beneficial to do so.

Indeed, there are many sound reasons for renewable energy supplies to be different in quantity than hydrogen production load:

- Hydrogen producers may wish to hedge their financial risk from producing hydrogen and procuring clean energy. The quantity of clean energy that provides the optimal hedge may be different from the exact quantity it consumes.
- Annual variability in renewable production may require annual adjustments to the REC procurement required to comply with an annual matching requirement. Some renewable developers plan their portfolios to have a surplus of energy during most years, to ensure they can continue to meet their contractual REC delivery obligations during a low production year.
- Proponents of 'deliverability' requirements have proposed that renewable energy supplies be increased to account for real power losses using an industry-wide average loss factor.
- Most directly for the purposes of this analysis, procuring slightly more renewable energy than is consumed for hydrogen production may be sufficient to offset any increase in net CO_2 emissions associated with an annual matching approach relative to hourly matching.

To reflect this ability to modulate the emissions impacts by changing the quantity of renewable energy procured, E3 models an 'Emissions Match' approach where the quantity of renewable energy is varied in order to meet an annual emission target of 0.45 kg CO_2e/kg H_2.

Matching Approach

E3 considers two approaches to annual matching for comparison to hourly matching results:

1. **Energy Match**:
   For annual matching, a portfolio of wind and solar generation is procured and built in a quantity equal to the annual energy demand of the electrolyzer during hours when the marginal emissions rate of grid electricity is positive. For hourly matching, hydrogen production is restricted based on the hourly quantity of renewable generation available under the same portfolio.
2. **Emissions Match With 0.45 kg CO_2 Target**:
   For annual matching, a portfolio of wind and solar generation is procured and built to produce incremental emissions equal to 0.45 kgCO_2e / kgH_2, the maximum allowed under the IRA to qualify for the full 45V PTC. For hourly matching, hydrogen production is restricted based on the hourly quantity of renewable generation available under the same portfolio.

Electrolyzer Characteristics

The traditional method of hydrogen production is via extraction from hydrocarbons, most commonly through steam methane reforming (SMR) as detailed in the Appendix. The advantage of using electrolysis is that hydrogen production occurs via extraction from water, offering an emission-free production process if paired with a clean source of electricity. Second, an electrolyzer can be a flexible load that can rapidly increase or decrease its consumption of electricity (i.e., 10% of capacity/second).

In the context of this study E3 assumes a 500 MW electrolyzer that operates at a 90% utilization rate for the year, with an hourly load shape based on E3's forecasted prices for the regions examined. E3 assumes that cost-conscious electrolyzer operators will avoid the top 10% of highest-priced hours within a given year, as measured by hourly prices. These hours are also more likely to include higher marginal emissions. E3 assumes a production efficiency of 70%, and assumes a lifetime of 10 years to represent the period of qualification for the 45V PTC.

Renewable Resource and Portfolio Profiles

Each scenario includes an assumed buildout of incremental solar and wind resources to support electrolyzer operations under the 90% capacity factor as described above. The capacity factors of the generation resources used in each region are summarized below. The resources are chosen based on the lowest levelized cost of electricity (LCOE) and available potential. E3 did not develop optimized portfolios because one goal of the study is to explore the impact of alternative matching approaches under a range of different renewable resource mixes.

Table 1. Capacity Factor of Regional Clean Energy Resources

Region	Wind Capacity Factor	Solar Capacity Factor
SPP	45%	25%
MISO North	45%	21%
ERCOT	46%	30%
PJM	33%	22%

Wind output shapes are from the National Renewable Energy Laboratory (NREL) Wind Toolkit[11] and solar shapes are from the NREL System Advisory Model (SAM) version 2017.9.5.[12] Each market consists of distinct regions as defined by NREL (referred to as ‘p’ regions), with each region containing a characteristic solar and wind shape produced by averaging the shapes of hundreds of sample points within that region. These regions are mapped to the appropriate market region. Wind production shapes use historic wind speed data from 2009 - 2012, and solar production shapes use historic solar insolation data from 2000 - 2018.

Renewable Resource Costs

The Levelized Cost of Electricity (LCOE) for each resource in each region is summarized below. The LCOEs are based on the resource capacity factors above and E3’s forecasted fixed costs of these resources. Expected upfront fixed costs of new solar and wind resources are updated to reflect current market conditions based on the latest E3 Pro Forma, which sources capital expenditure cost data from the 2022 NREL Annual Technology Baseline (ATB). Regional multipliers from NREL’s Regional Energy Deployment System (ReEDS) are applied to capital costs. Costs incorporate the effects of the IRA’s passage in the form of the ITC and PTC available to wind and solar under the technology-neutral credits. E3 assumes new wind and solar resources meet prevailing wage and apprenticeship requirements, and therefore qualify for the 30% ITC or $26/MWh PTC.

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[11] https://www.nrel.gov/grid/wind-toolkit.html

[12] https://sam.nrel.gov/download/version-2017-9-5.html

Table 2. LCOE of Regional Clean Energy Resources

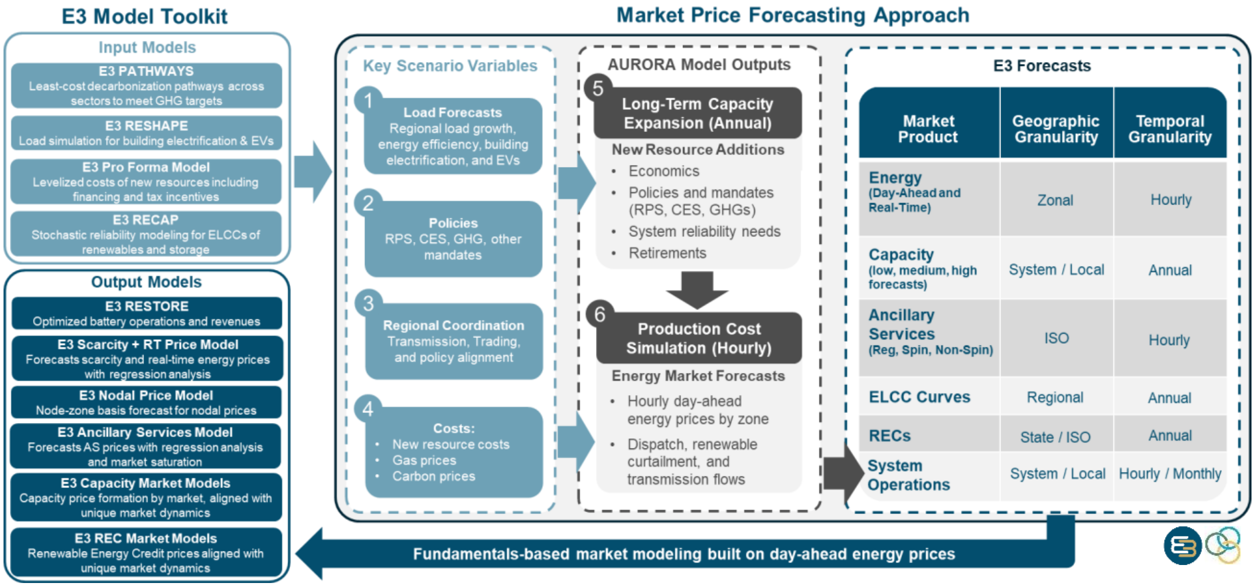
Region	LCOE (2022$/MWh)			
	2025		2030	
	Wind	Solar	Wind	Solar
SPP	$25.76	$41.67	$20.20	$36.53
MISO North	$26.22	$47.90	$20.43	$42.38
ERCOT	$23.27	$32.81	$17.57	$27.91
PJM	$41.93	$45.09	$35.65	$39.36

Production Dispatch Modeling

Due to the nature of networked electricity systems, electrolytic production of hydrogen is met physically with grid electricity from a mix of generating resources that, all else being equal, results in higher emissions. Similarly, in both the hourly and annual matching approaches, clean energy generation is injected into the grid that, all else being equal, reduces energy production and emissions from emitting resources. The difference between the two approaches is the timing of clean energy production, which results in differences in the carbon intensity (generally measured in tCO_2e/MWh) of the emitting resources whose production is reduced. Thus, whether hydrogen production results in net CO_2 emissions depends on the marginal emissions factors during hours of hydrogen production relative to hours of clean energy generation.

The E3 in-house market price model and resulting forecasts of electricity prices and marginal emission rates are used for this study. E3 conducts long-term analysis of power dispatch fundamentals using Energy Exemplar's Aurora production simulation model. This projection method generates relevant scenarios that are applicable to complex and dynamic energy markets. Hourly day-ahead energy price and marginal generation units, with their associated marginal emissions rates, are produced from this modeling and used in this analysis. E3's modeling process is tailored to reflect the changing nature of U.S. energy markets, with customized Aurora production simulation scenarios that consider factors such as forecasted load, resource build-out, and transmission. E3's market production simulation process is visualized below.

Figure 7. E3 Model Ecosystem for Market Price Forecasts



Market Product	Geographic Granularity	Temporal Granularity
Energy (Day-Ahead and Real-Time)	Zonal	Hourly
Capacity (low, medium, high forecasts)	System / Local	Annual
Ancillary Services (Reg, Spin, Non-Spin)	ISO	Hourly
ELCC Curves	Regional	Annual
RECs	State / ISO	Annual
System Operations	System / Local	Hourly / Monthly

Methodology

Build Requirements and Emissions Estimation

The analysis builds sufficient wind and solar generation capacity in each region to match energy consumed for electrolyzer operation under the two match scenarios described above. Under the Energy Match scenario, total energy production of these new resources over the entire year equals the electrolyzer's annual demand when operating for 90% of the year. The analysis ensures incrementality by assuming that no existing renewable energy resources are displaced; this is accomplished by sizing the renewable portfolio such that only generation that occurs during hours with positive marginal emissions rates is counted toward the generation total. This assumption also captures a key market dynamic: curtailed renewable generation does not create a REC and cannot be counted toward renewable energy purchases. When hourly marginal emissions rates are zero in a given market, zero-emitting resources are on the margin and no new clean generation can be delivered to the grid.

To capture the full range of wind and solar that is added to grid to meet electrolyzer demand, the build scenarios in Table 3 are considered.

Table 3. Clean Resource Build Scenarios

Scenario	Wind Capacity Share of New Resource Build	Solar Capacity Share of New Resource Build
50-50 W/S	50%	50%
High Solar	25%	75%
High Wind	75%	25%
All Wind	100%	0%
All Solar	0%	100%

While Energy Match portfolios satisfy the annual energy requirements of the electrolyzer, they do not result in zero net emissions. Incremental emissions are positive in markets where the grid carbon intensity during hours of hydrogen production is higher than the grid carbon intensity during hours of renewable generation. Conversely, incremental emissions are negative in markets where the grid carbon intensity during hours of hydrogen production is lower than the grid carbon intensity during hours of renewable generation.

Under the Emissions Match scenario, E3's model scales the renewable portfolio up ('overbuild') or down ('underbuild') such that the incremental grid emissions from the electrolyzer demand are 0.45 kg CO_2e/kg H_2. The equation below highlights how E3 determines the equivalent build required in this context.

$$a_i = Electrolyzer\ Load\ in\ hour\ i\ (MW)$$

$$b_i = Renewable\ Production\ in\ hour\ i\ (MW)$$

$$c_i = Marginal\ Emissions\ Rate\ in\ hour\ i\ \left(\frac{tCO_2}{MWh}\right)$$

$$[1] = Electrolyzer\ Load\ Emissions = \sum_{i=1}^{8760} a_i\ \times c_i\ \ (tCO_2)$$

$$[2] = Generation\ Avoided\ Emissions = \sum_{i=1}^{8760} b_i\ \times c_i\ \ (tCO_2)$$

$$[3] = Emissions\ Gap = \frac{[2]-[1]}{0.449}\ (\frac{tCO_2}{MWh})$$

$$[4] = Build = \left(\frac{[1]}{[2]} - 1\right) \times \frac{[3] - 0.449}{[3]}\ (\%)$$

Cost of Hydrogen

Hourly and annual accounting for additional renewable generation to meet electrolyzer demands will impact the cost of hydrogen. This cost is driven primarily by two factors: the cost of electricity to supply the electrolyzer and the electrolyzer's utilization (i.e., how much hydrogen the electrolyzer produces).

Across all scenarios, E3 assumes electrolyzer capital costs of $1,500/kW in 2025 and $1,200/kW in 2030 (in 2022 dollars), and a constant variable operations and maintenance (VOM) cost of $10/MWh. E3 assumes a discount rate of 8%.

$$a_i = Electrolyzer\ load\ in\ hour\ i\ (MW)$$ [13]

$$e_i = Forecasted\ electricity\ price\ in\ hour\ i\ (\$/MWh)$$ [14]

$$f = Demand\ Charge\ (\frac{\$}{kW})$$ [15]

$$g = Weighted\ LCOE\ of\ Renewable\ Build\ (\frac{\$}{MWh})$$ [16]

$$h = Electrolyzer\ Size\ (MW)$$

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[13] The load in the annual case is 500 MW every hour except the top 10% highest priced hours.

[14] Sourced from E3's in-house market energy price forecasts.

[15] E3 relied upon data collected by NREL from multiple states contained either entirely or partially within the footprint of each region analyzed in this study, and applies the median demand charge for utilities in these states. https://www.nrel.gov/docs/fy17osti/68963.pdf.

[16] Weighted on the basis of capacity share.

$$i = Electrolyzer\ Utilization\ (\%)$$

$$j = Electrolyzer\ Efficiency\ (\%)$$

$$k = Electrolyzer\ CAPEX\ \left(\frac{\$}{kW}\right)$$

$$l = \ Capital\ Recovery\ Factor\ (\%)$$

$$m = \ Interconnection\ Cost\ (\$)^{17}$$

$$n = VOM\ (\$/MWh)^{18}$$

The cost of hydrogen under annual matching (A) is calculated as follows:

Electricity Cost:

$$[5] = Demand\ Cost = \sum_{i=1}^{8760} a_i \ \times e_i$$

$$[6] = \ Renewable\ Revenue = \sum_{i=1}^{8760} b_i \ \times e_i$$

$$[7] = \ Renewable\ Cost = \sum_{i=1}^{8760} b_i \ \times LCOE$$

$$[8] = \ Demand\ Charge\ Cost = f \times h$$

$$[9] = Hydrogen\ Produced = h \times i \times j \times\ 8760\ hrs$$

$$[\mathbf{10}] = \boldsymbol{Electricity\ Cost} = \frac{[\mathbf{5}] - [\mathbf{6}] + [\mathbf{7}] + [\mathbf{8}]}{[\mathbf{9}]}$$

Capital Cost:

$$[\mathbf{11}] = \ \boldsymbol{Electrolyzer\ Capital\ Cost} = \frac{\boldsymbol{k}\ \times \boldsymbol{h}\ \times \boldsymbol{l} + \boldsymbol{m}}{[\mathbf{9}]}$$

Non-Electricity VOM:

$$[\mathbf{12}] = \ \boldsymbol{VOM} = \frac{\sum_{i=1}^{8760} a_{A,i}\ \times n}{[\mathbf{9}]}$$

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[17] \$4,100,00/plant

[18] \$10/MWh

And the final cost of hydrogen under annual matching is calculated as:

$$\boldsymbol{Cost\ of\ H_{2_A}}\left(\frac{\$}{\boldsymbol{kgH_2}}\right) = [\mathbf{10}] + [\mathbf{11}] + [\mathbf{12}]$$

The cost of hydrogen under hourly matching is calculated similarly to the approach above, but with the following differences:

Electricity Cost:

$$[13] = Hydrogen\ Produced = \sum_{i=1}^{8760} a_i \times j$$

Note that electrolyzer load in the hourly case will never exceed renewable production.

$$[\mathbf{14}] = \boldsymbol{Electricity\ Cost_{hourly}} = \frac{[\mathbf{7}] + [\mathbf{8}]}{[\mathbf{13}]}$$

Capital Cost:

$$[\mathbf{15}] = \boldsymbol{Electrolyzer\ Capital\ Cost_{hourly}} = \frac{\boldsymbol{k} \times \boldsymbol{h} \times \boldsymbol{l} + \boldsymbol{m}}{[\mathbf{13}]}$$

Non-Electricity VOM:

$$[\mathbf{16}] = \boldsymbol{VOM_{hourly}} = \frac{\sum_{i=1}^{8760} a_i \times n}{[\mathbf{13}]}$$

The final cost of hydrogen in hourly matching is calculated as:

$$\boldsymbol{Cost\ of\ H_{2_{hourly}}}\left(\frac{\$}{\boldsymbol{kgH_2}}\right) = [\mathbf{14}] + [\mathbf{15}] + [\mathbf{16}]$$

Summary of Scenarios

Below is a summary of the 40 scenarios that E3 tested across each of the potential annual matching approaches.

Table 4. Summary of E3 Scenarios

Region	Year	Build Scenario	Scenario #
ERCOT	2025	50-50 W/S	1
		High Solar	2
		High Wind	3
		All Wind	4
		All Solar	5
	2030	50-50 W/S	6
		High Solar	7
		High Wind	8
		All Wind	9
		All Solar	10
MISO-North	2025	50-50 W/S	11
		High Solar	12
		High Wind	13
		All Wind	14
		All Solar	15
	2030	50-50 W/S	16
		High Solar	17
		High Wind	18
		All Wind	19
		All Solar	20
PJM	2025	50-50 W/S	21
		High Solar	22
		High Wind	23
		All Wind	24
		All Solar	25
	2030	50-50 W/S	26
		High Solar	27
		High Wind	28
		All Wind	29
		All Solar	30
SPP	2025	50-50 W/S	31
		High Solar	32
		High Wind	33
		All Wind	34
		All Solar	35
	2030	50-50 W/S	36
		High Solar	37
		High Wind	38
		All Wind	39
		All Solar	40

RECs and Additionality

This section discusses the common industry practice for demonstrating the renewable energy content of power purchase agreements. Renewable Energy Certificates (RECs) were designed to allow buyers to substantiate claims of renewable electricity use, given that physical energy consumed on a networked electricity grid is indistinguishable by origin and generation source.

About RECs

What are Renewable Energy Certificates (RECs)?

A REC represents the renewable energy attributes of one megawatt-hour (MWh) of renewable electricity generated and delivered to the electricity grid. RECs are created when a qualifying renewable resource delivers energy to the grid. The sale of RECs provides an important source of revenue to support the development of clean energy projects and has been demonstrated to be a significant factor for growing renewable energy capacity.[19] REC 'retirement' is a universal and indispensable means for demonstrating compliance with both voluntary and mandatory clean energy goals such as state Renewables Portfolio Standards (RPS). Renewable energy purchases cannot be certified without some form of REC.

How Are RECs Tracked?

RECs may be 'unbundled' and transacted separately from the underlying electricity supply, in contrast to a 'bundled' REC where the electricity and REC from a renewable generation resource are transacted together. It is therefore possible and commonplace for a consumer to purchase RECs in a transaction that is separate from their purchase of the electricity commodity. REC creation and transfer is tracked by one of ten regional electronic REC tracking systems in the U.S. These systems register basic information about each megawatt-hour (MWh) of renewable generation in that region and issue RECs to the generator, signifying that a MWh of renewable electricity has been delivered to the grid. RECs generally include certificate data, tracking IDs, fuel type, facility location, capacity, project name, build date, utility interconnection, emissions rate, and other information for tracking purposes. Each REC has a unique ID and can only be owned by one account holder at a time, avoiding ownership disputes and preventing double counting.[20]

There has been an increasing interest in the use of time-stamped hourly RECs, as the '24x7' clean energy goals have grown in popularity. However, this concept has not been widely adopted and most RECs today are not time-stamped.

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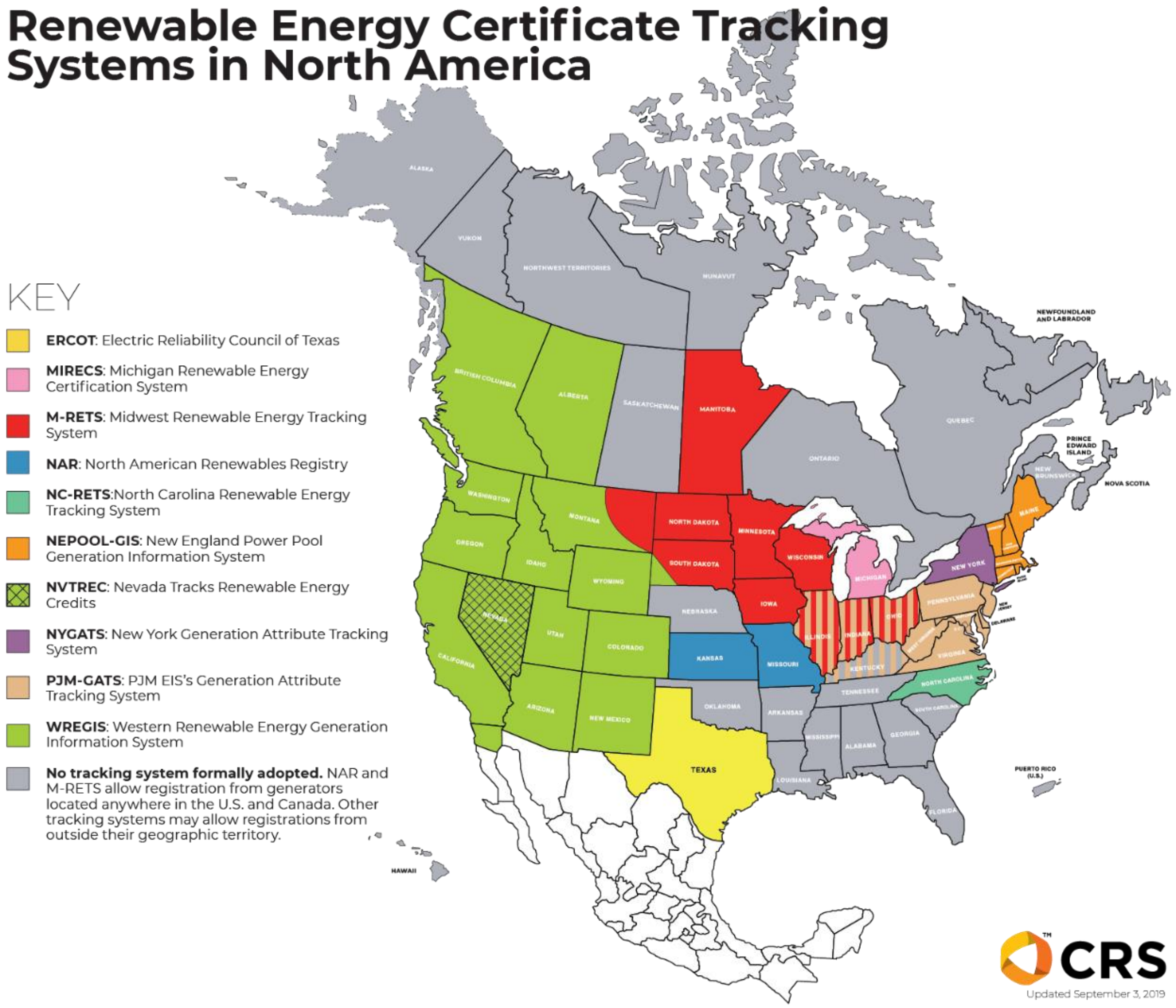
[19] Joshi J. Do renewable portfolio standards increase renewable energy capacity? Evidence from the United States. J Environ Manage. 2021 Jun 1;287:112261. doi: 10.1016/j.jenvman.2021.112261. Epub 2021 Mar 13. PMID: 33721760.

[20] For more details, see CRS: https://resource-solutions.org/wp-content/uploads/2018/02/Tracking-System-Map.png

Figure 8. Renewable Energy Certificate Tracking Systems in North America[21]



REC tracking systems monitor all wholesale transactions. The ability to buy and sell RECs improves the economics of electricity procurement and reduces compliance costs by allowing renewable energy to be generated where it provides the greatest economic and environmental benefits, affording greater geographic reach than the electricity delivery system provides, and avoiding costs of new transmission and distribution where efficient.[22] In addition, the purchase and sale of RECs enables companies to balance their portfolios to match clean energy supplies with compliance requirements.

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[21] https://resource-solutions.org/wp-content/uploads/2018/02/Tracking-System-Map.png

[22] For more details, see https://www.pjm-eis.com/~/media/pjm-eis/documents/rps-comparison.ashx, https://www.nwcouncil.org/2021powerplan_existing-policies_state-rps/, and https://www.green-e.org/faq.

What is the Legal Basis for RECs?

Multiple federal governmental entities, state legislation and regulation, regional electricity transmission authorities, NGOs, trade associations, and market participants have recognized that RECs represent and convey the renewable, environmental and/or social attributes of renewable electricity generation to the owner, along with the legal right to claim usage of that renewable electricity where bundled. Furthermore, they recognize that without RECs, such a claim could not otherwise be substantiated. This includes state laws that recognize the use of RECs for tracking and transacting renewable energy, as the supreme demonstration method, with several states and entities identifying them as property. FERC has also recognized that "environmental attributes" can be traded separately and are not necessarily bound to or conveyed with the "energy or capacity" (i.e., within a Power Purchase Agreement, or PPA). Other notable entities that have recognized the legal basis for RECs include the U.S. Environmental Protection Agency, Department of Energy, Federal Trade Commission, the Western Area Power Administration, the Environmental Markets Association, the American Bar Association, California Energy Commission, the Superior Court of New Jersey, Connecticut Supreme Court, and the Second Circuit Court of Appeals.[23]

Are RECs the Same as Carbon Offsets?

A "carbon offset" is generally defined to mean an action taken to reduce carbon emissions that is then used to offset emissions that occur elsewhere.[24] Carbon offsets are frequently certified and traded by entities that have a need to balance their portfolio of environmental attributes. Clean electricity purchases are distinct from carbon offsets in several ways. Purchase of a REC can be directly tied to renewable electricity from a low or zero-emission resource. A REC purchase represents a premium paid to support 1 MWh of renewable or clean electricity generation for the right to claim its clean energy attribute. Metering, tracking and retirement requirements ensure that RECs are generated only when clean electricity is delivered to the grid, and that no 'double-counting' of clean energy generation occurs. Finally, there is no distinction in this regard between bundled and unbundled RECs, time-stamped vs. annual RECs, or any other flavor of REC. In all cases, a REC is produced when clean energy is generated and delivered to the grid and its ownership is tracked from creation to retirement.

Additionality: Does New Demand for RECs Create New Renewable Electricity Supplies?

The theory behind the development of renewable electricity standards, and the RECs that are needed to demonstrate compliance with them, is that the standards will lead to the development of new renewable resources. Indeed, the United States renewable electricity industry has developed based largely on this premise. REC prices represent a 'green premium' – an additional price that consumers are willing to pay for renewable energy supply relative to conventional supply. REC prices are non-zero because demand for renewable electricity exceeds the quantity of supply that can be offered at the price of conventional

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[23] For more details, see CRS http://resource-solutions.org/wp-content/uploads/2015/07/The-Legal-Basis-for-RECs.pdf.

[24] https://www.offsetguide.org/understanding-carbon-offsets/what-is-a-carbon-offset/

energy. The price premiums that are attached to renewable energy attributes are an important source of revenue to support renewable energy development.

RECs have been criticized because they do not distinguish between ‘existing’ and ‘new’ clean energy supply. As a result, some buyers have taken additional steps to ensure the ‘additionality’ of their renewable energy supplies. A common method for doing so is to procure only from ‘new’ resources, i.e., resources that are not yet online or have come online very recently.

The issues associated with additionality are distinct from the question of hourly-versus-annual energy matching. Additionality-based restrictions on the procurement of clean energy by hydrogen producers could be incorporated into either an hourly or an annual matching requirement. For the purposes of this study, E3 assumes all renewable energy resources procured by hydrogen producers are additional.

However, additionality restrictions may result in higher costs for hydrogen producers and there are several factors that should be considered when evaluating their effectiveness:

+ As long as demand for renewable energy is robust, new renewable energy supplies will be needed. Under market equilibrium, the supply of renewable energy will match the demand over the long run. A temporary shortage of RECs will lead to premium prices, causing more developers to enter the market. A temporary surplus of RECs will create additional demand that, in turn, will more rapidly deplete the surplus and hasten the time when new development is needed. Thus, all new demand ultimately leads to new supply.[25]
+ There is no universal definition of additionality, and indeed it is difficult to draw a durable line between ‘new’ and ‘existing’ resources – all new resources become existing resources as soon as they are placed into operation. Today, each buyer is left to determine for itself which resources it can credibly say are incremental.
+ Many existing renewable resources are exiting their original PPAs and will require ongoing sources of revenue for maintenance or repowering to ensure they can continue to generate carbon-free electricity. From a carbon emissions perspective, a resource that is at threat of retirement is no different from a resource that is seeking to enter the market. The IRA’s provisions for existing nuclear generation are a demonstration of the importance of continuing to support existing resources.
+ In the long run, a market-wide carbon regulatory regime will need to incorporate both new and existing resources.

Deliverability: Must Renewable Supply be Located Near Demand?

Hourly matching of renewable electricity production to hydrogen production does not ensure that the clean energy is consumed by the hydrogen producer. Physically, as long as the hydrogen production facility is connected to the grid, its incremental load is served by a combination of many generators on the system. Factors such as grid congestion and losses mean that hourly matching is only an

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[25] CRS, “RECs and Additionality”, https://resource-solutions.org/wp-content/uploads/2016/03/RECs-and-Additionality.pdf

approximation of the outcome that would obtain if the resource and load were disconnected from the bulk grid.

As a result, some advocates have proposed ‘deliverability’ requirements – geographic restrictions on the clean energy supplies developed to serve hydrogen load. For example, Energy Innovation describes deliverability as “[requiring] electrolyzers to use local sources of clean electricity that are physically deliverable to the electrolyzer, accounting for congestion and transmission line losses.” This is accomplished by “requiring hydrogen electrolyzers and contracted sources of new clean energy to be located in the same defined region (such as power market zones)—with criteria for sourcing electricity from adjacent regions—while purchasing enough clean power to cover transmission line losses.”[26]

For the purposes of this analysis, E3 has adopted these requirements and compared hourly and annual matching of supplies to hydrogen production within the same market. However, it is important to recognize that these requirements do not and cannot guarantee that the contracted clean energy is actually delivered to and consumed by the hydrogen producer. The only means of guaranteeing that hydrogen is produced exclusively with renewable energy is to disconnect the production facility from the grid. Thus, deliverability requirements can be viewed as attempting to improve, not eliminate, the approximation involved in supply and demand matching.

Restrictions on the ability of hydrogen producers to procure an economic supply of clean energy will, all else equal, increase their costs. It is therefore important to understand whether benefits from the gain in precision are sufficient to offset these additional costs. If the goal for clean energy matching requirements is to maximize GHG emissions reductions, a more impactful matching requirement may be to encourage clean energy generation to locate where it will do the most good, i.e., in markets with the highest hourly marginal emissions rates, and to encourage hydrogen production to locate in markets with the lowest hourly marginal emissions rates.

To test this, E3 includes a scenario where deliverability requirements are relaxed and hydrogen producers are allowed to procure clean energy from any of the four markets considered. This is accomplished by pairing the least-carbon intensive market for hydrogen production with the most carbon-intensive market for clean energy supplies.

Projected Demand for Renewable Electricity

Demand for RECs is expected to increase dramatically over the next decade as state RPS targets and voluntary goals ramp up. RPS policies exist in 30 states and the District of Columbia, accounting for 58% of total U.S. retail electricity sales in 2021 (Figure 9). In addition to state mandates, there are also hundreds of electric utilities with emissions reduction targets that will require an increase in the supply of clean and non-emitting generating resources.

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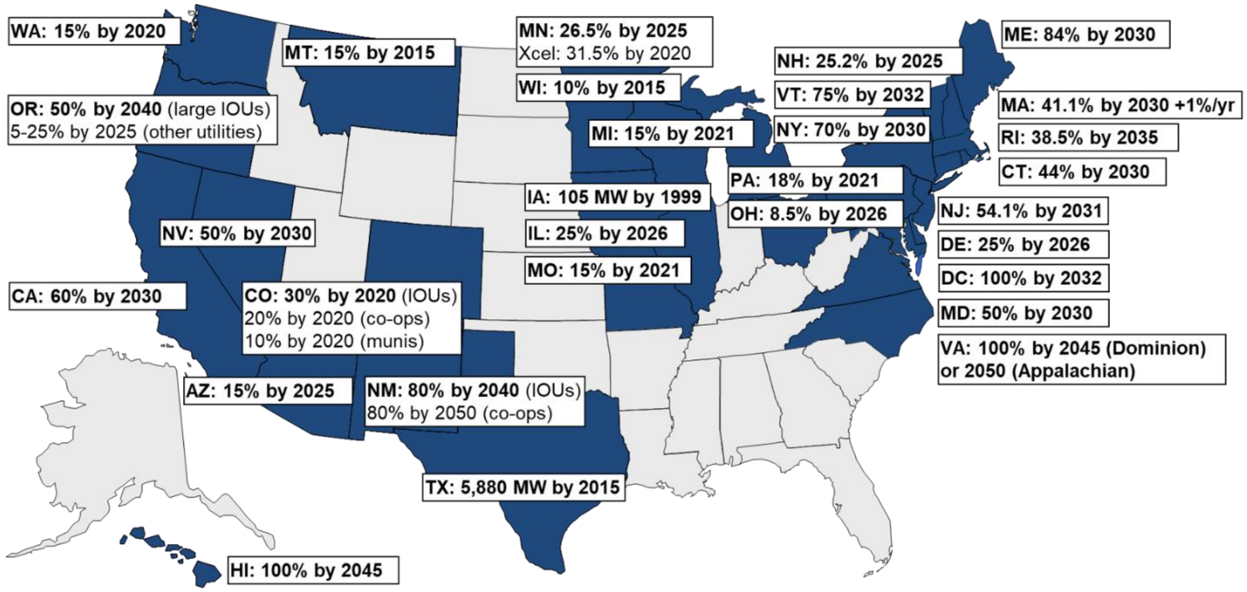
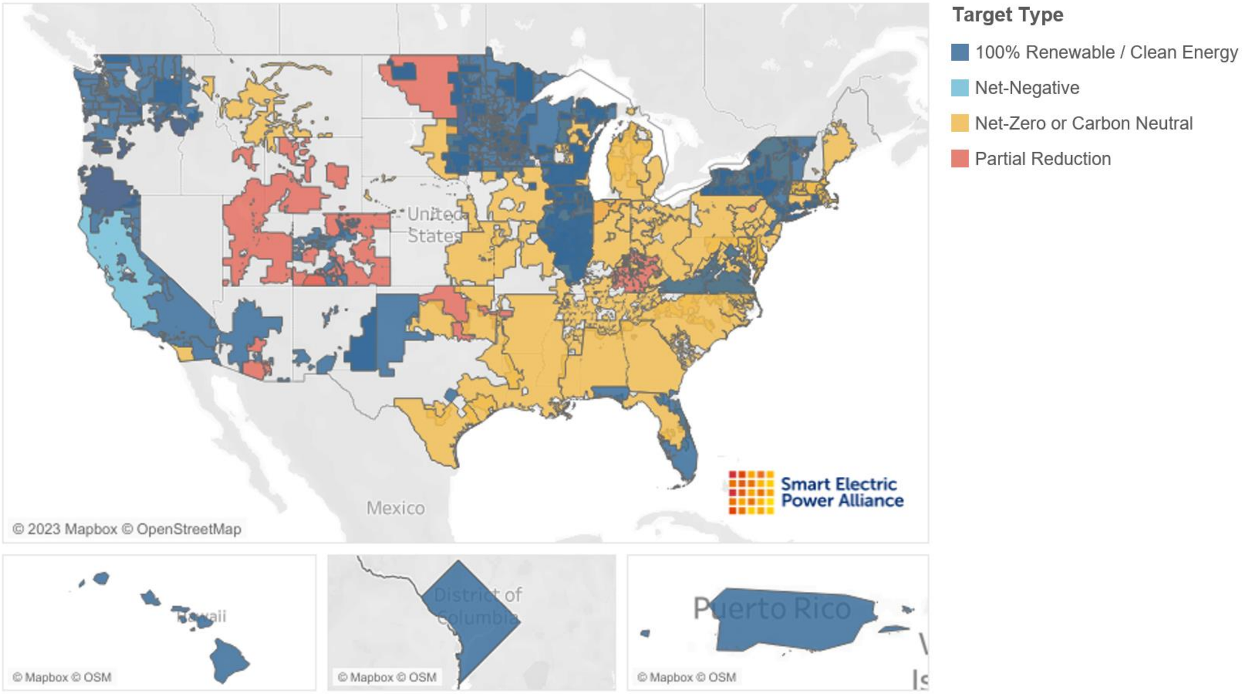
[26] https://energyinnovation.org/wp-content/uploads/2023/04/Smart-Design-Of-45V-Hydrogen-Production-Tax-Credit-Will-Reduce-Emissions-And-Grow-The-Industry.pdf

Figure 9. RPS Policies in the U.S. (as of 2021)



Note: Target percentages represent sum total of all RPS resource tiers where applicable. These targets are distinct from any voluntary renewable energy goals.
Source: Lawrence Berkeley National Laboratory, February 2021. Link.

Figure 10. U.S. Utilities With Emissions Reductions Targets, by Type

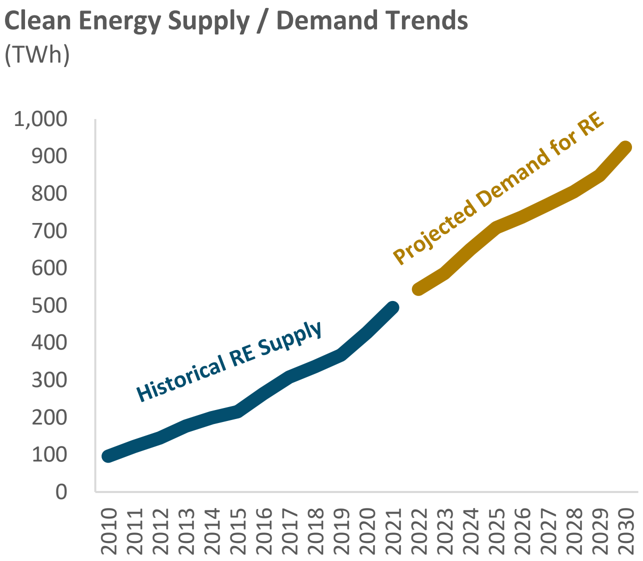


Source: SEPA (https://sepapower.org/utility-transformation-challenge/utility-carbon-reduction-tracker/).

For example, Washington's Clean Energy Transformation Act (CETA) mandates that 100% of electricity supply come from clean or non-emitting generation sources by 2045. Many of these utilities are in states with emissions reductions targets, but many are not. Figure 10 shows utilities with clean energy goals.

Lawrence Berkeley National Laboratory (LBNL) has projected demand for clean energy through mandatory compliance programs to increase by 50% through 2030, after increasing significantly in the three past years, just to meet policies enacted as of the end of 2021 (Figure 11). Voluntary demand for RECs supplements this compliance-driven demand. In sum, renewable energy demand is expected to grow by over 350 TWh between now and 2030 just to meet clean energy goals that have already been announced.

Figure 11. Projected Demand for Clean Energy from Renewable Portfolio Standards



Note: RE refers to wind and solar generation.

Source:

Historical Data: U.S. Energy Information Administration, Monthly Energy Review, Table 7.2a, January 2022 and Electric Power Monthly February 2022, preliminary data for 2021.

Forecast Data: E3 analysis, inclusive of both compliance-based and voluntary demand. Compliance-based demand data from Lawrence Berkeley Laboratory, February 2021 (Link).

Expressed in terms of capacity, the Clean Energy Buyers Association estimates that roughly 17 GW of voluntary clean energy was contracted through power purchase agreements, green tariffs, tax equity investments, and direct project ownership in 2022. This represents roughly 10 times the amount contracted in 2016. Voluntary demand is also expected to increase significantly over the next decade.[27]

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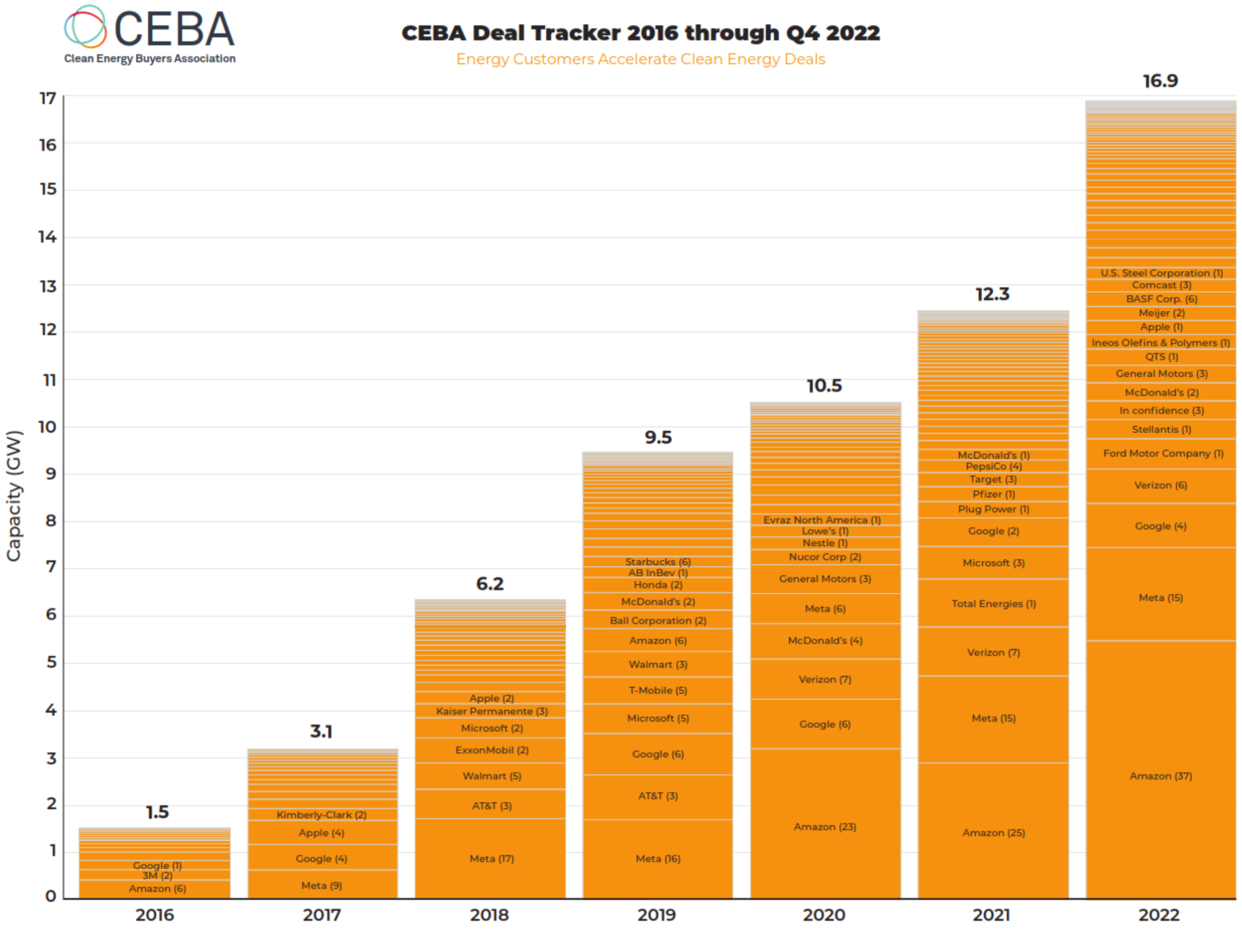
[27] See:

- Clean Energy Buyers Association: https://cebuyers.org/deal-tracker/
- NREL (2021): https://www.nrel.gov/docs/fy22osti/81141.pdf
- 2022 Corporate Renewables Update. S&P Capital IQ (2022). https://www.capitaliq.spglobal.com/web/client?auth=inherit#news/article?KeyProductLinkType=2&id=69190458

Figure 12. Corporate Clean Energy Contracts, 2016 - 2022 (GW)



As of December 31, 2022. Includes publicly announced corporate clean energy procurement through power purchase agreements, green tariffs, tax equity investments, and project ownership in the U.S. from 2016-2022. Excludes onsite generation <20 MW. (#) indicates number of deals each year by individual companies.

Source: Clean Energy Buyers Association.

Results

E3 estimated incremental emissions and production costs for the 40 scenarios summarized earlier in this study for each of the possible matching approaches, resulting in 80 sets of emissions and cost results discussed below.

Energy Match Only

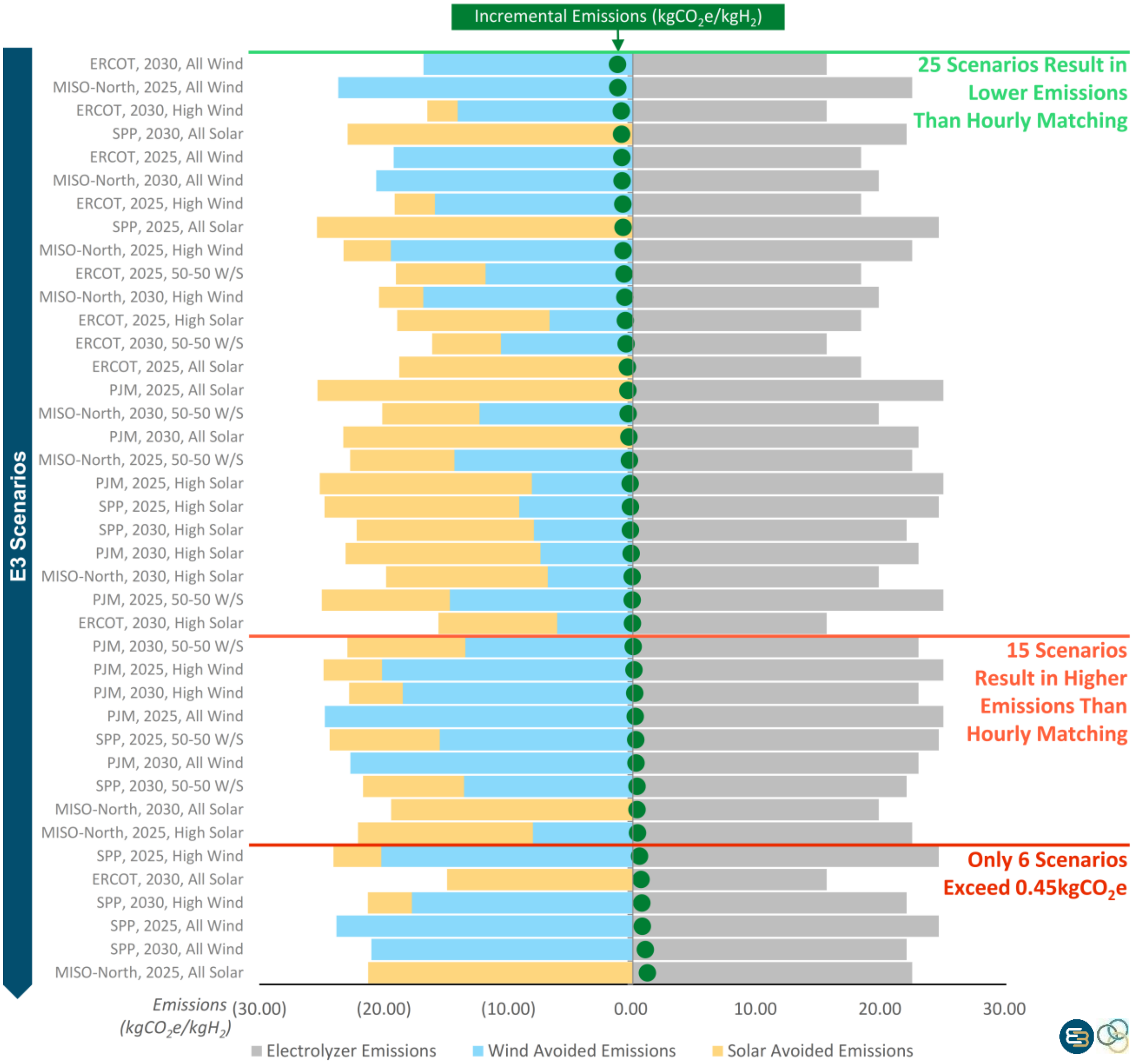
Optimizing the quantity of renewable generation to match the exact demand of the hydrogen electrolyzer results in a range of incremental emissions outcomes, where ‘incremental emissions’ refers to the incremental difference between the emissions associated with hydrogen production demand for electricity and the emissions avoided by renewable generation.

Based on this approach, E3 finds that:

- Under an annual energy matching requirement, 34 of the 40 scenarios (85%) produce incremental emissions less than 0.45 kg CO_2e / kg H_2 without any renewable overbuild;
- 6 out of the 40 scenarios (15%) produce incremental emissions greater than 0.45 kg CO_2e;
- 25 of the 40 scenarios (63%) produce *negative* incremental emissions, meaning the emissions avoided by renewable generation are greater than the emissions associated with hydrogen production without any additional portfolio adjustment; and
- Across all scenarios under the annual energy matching requirement, the cost of hydrogen production is significantly higher under hourly matching than annual matching.

Below is a summary of the emissions results associated with the Energy Match Only approach.

Figure 13. Incremental Emissions, Energy Match Only[28]



Emissions Match

E3 estimates the impact of annual matching such that each renewable portfolio is calibrated (via overbuild or underbuild) to ensure incremental emissions are 0.45 kg CO_2e, the threshold for full PTC qualification. Underbuild implies cost savings from reducing the total cost of renewable supply. In most scenarios, overbuild is not necessary to qualify for the maximum value of the PTC for hydrogen production. Figure 14 summarizes the increase (overbuild) or decrease (underbuild) in renewable generation that limits

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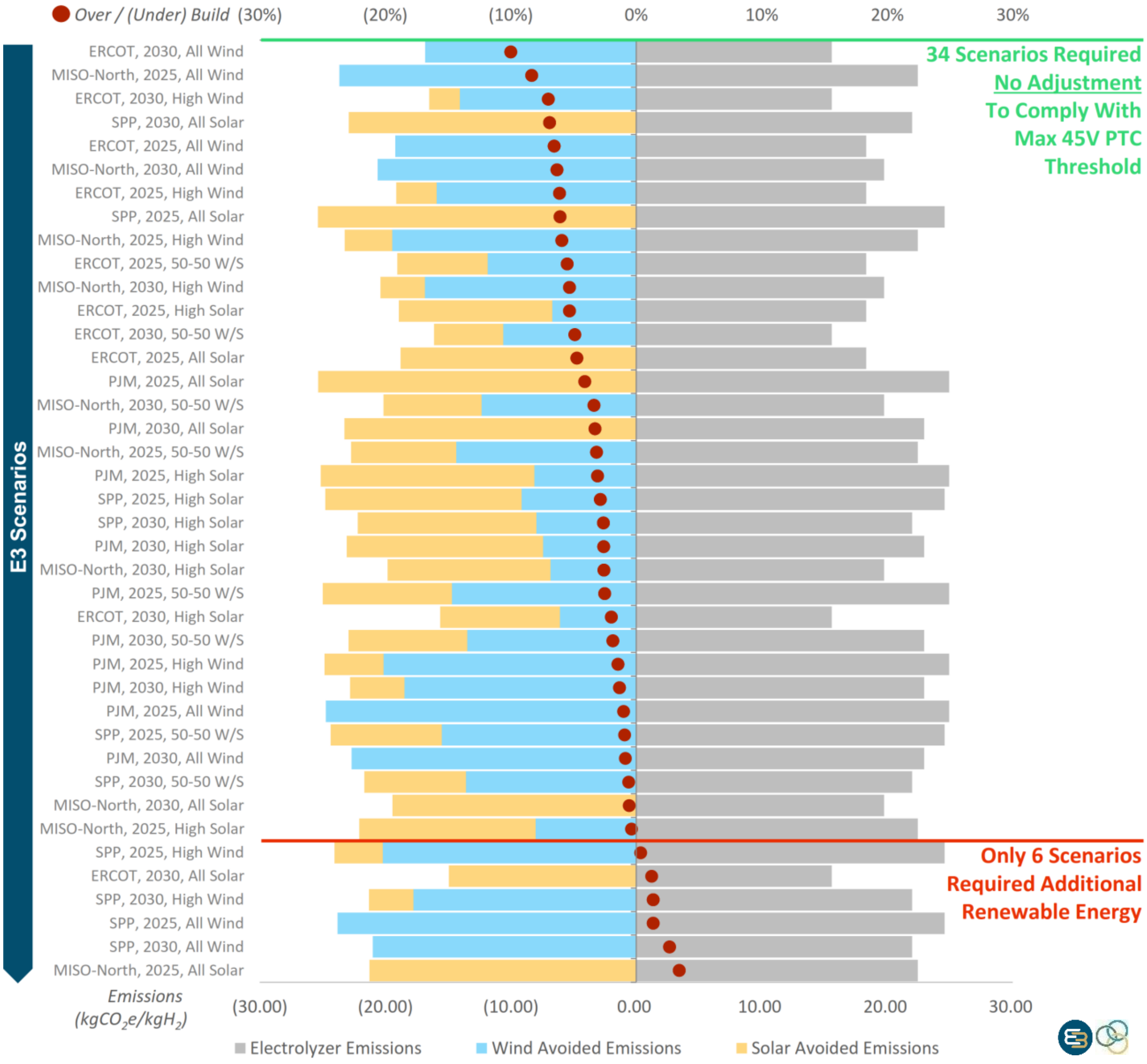
[28] The cost of hydrogen in these scenarios ranged from \$1.86/kgH_2 to \$3.67/kgH_2, all in \$2022. See Appendix for more details.

incremental emissions to 0.45 kg CO_2e / kg H_2. In the majority of scenarios, renewable generation can decrease after meeting the energy requirement and still meet the 0.45 kg CO_2e target.

Figure 14. Overbuild / (Underbuild) for 0.45 $kgCO_2e/kgH_2$ Incremental Emissions[29]



34 Scenarios Required No Adjustment To Comply With Max 45V PTC Threshold

Only 6 Scenarios Required Additional Renewable Energy

Cost Results

The next two figures show how production cost varies under the emissions matching approach. Hourly matching results in significantly higher costs for hydrogen production than annual emissions matching across all 40 scenarios.

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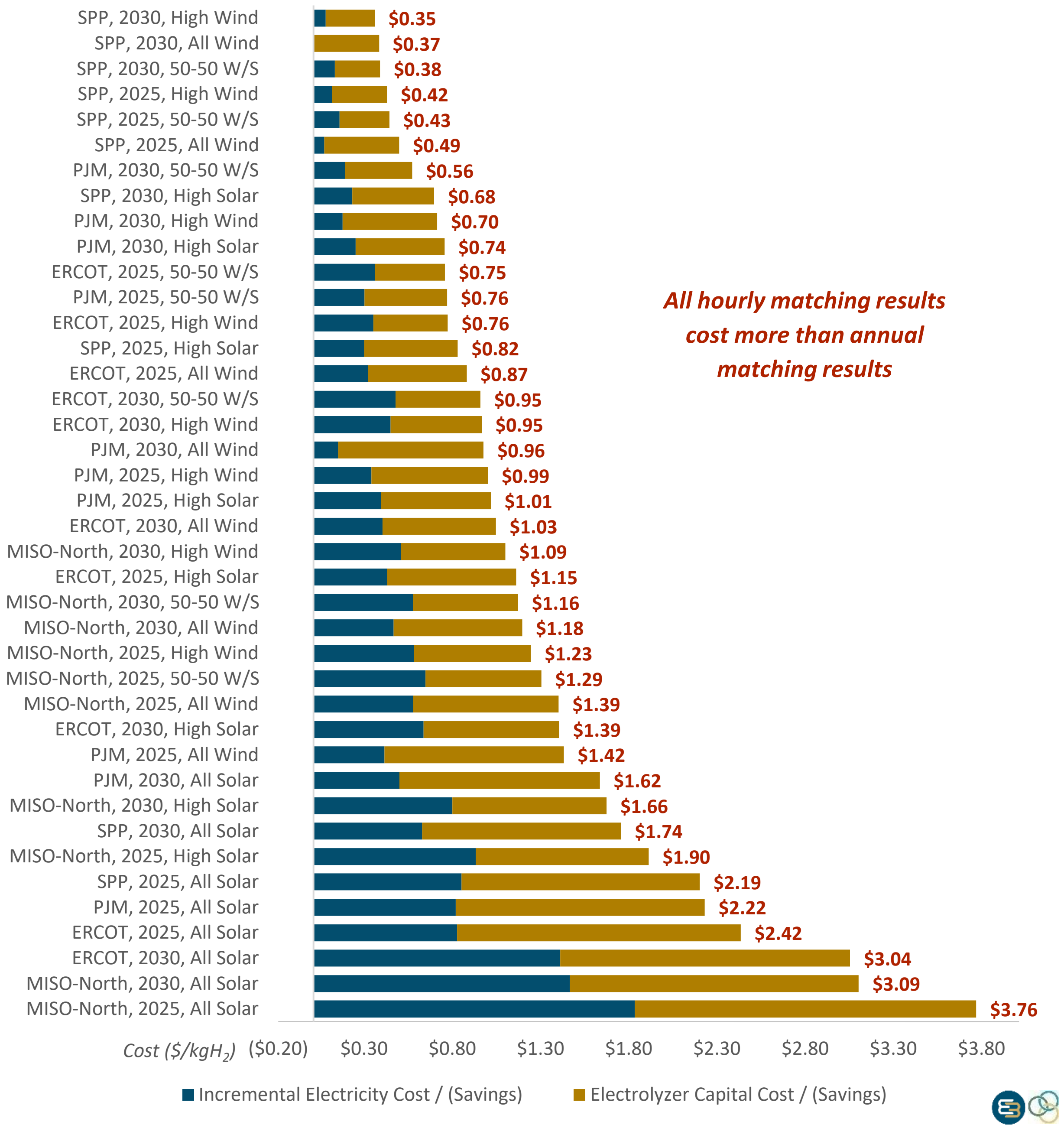
[29] High Solar denotes portfolios with 25% wind and 75% solar capacity. High Wind is 75% wind, 25% solar.

Figure 15. Incremental Cost Under Hourly: Energy Match With 0.45 kg CO_2e Emissions Target[30]



All hourly matching results cost more than annual matching results

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[30] The cost of hydrogen in these scenarios ranged from \$1.91/kgH_2 to \$3.65/kgH_2, all in \$2022. See Appendix for more details.

Figure 16. Cost Premium for Hourly Matching Relative to Annual Matching (%)[31]

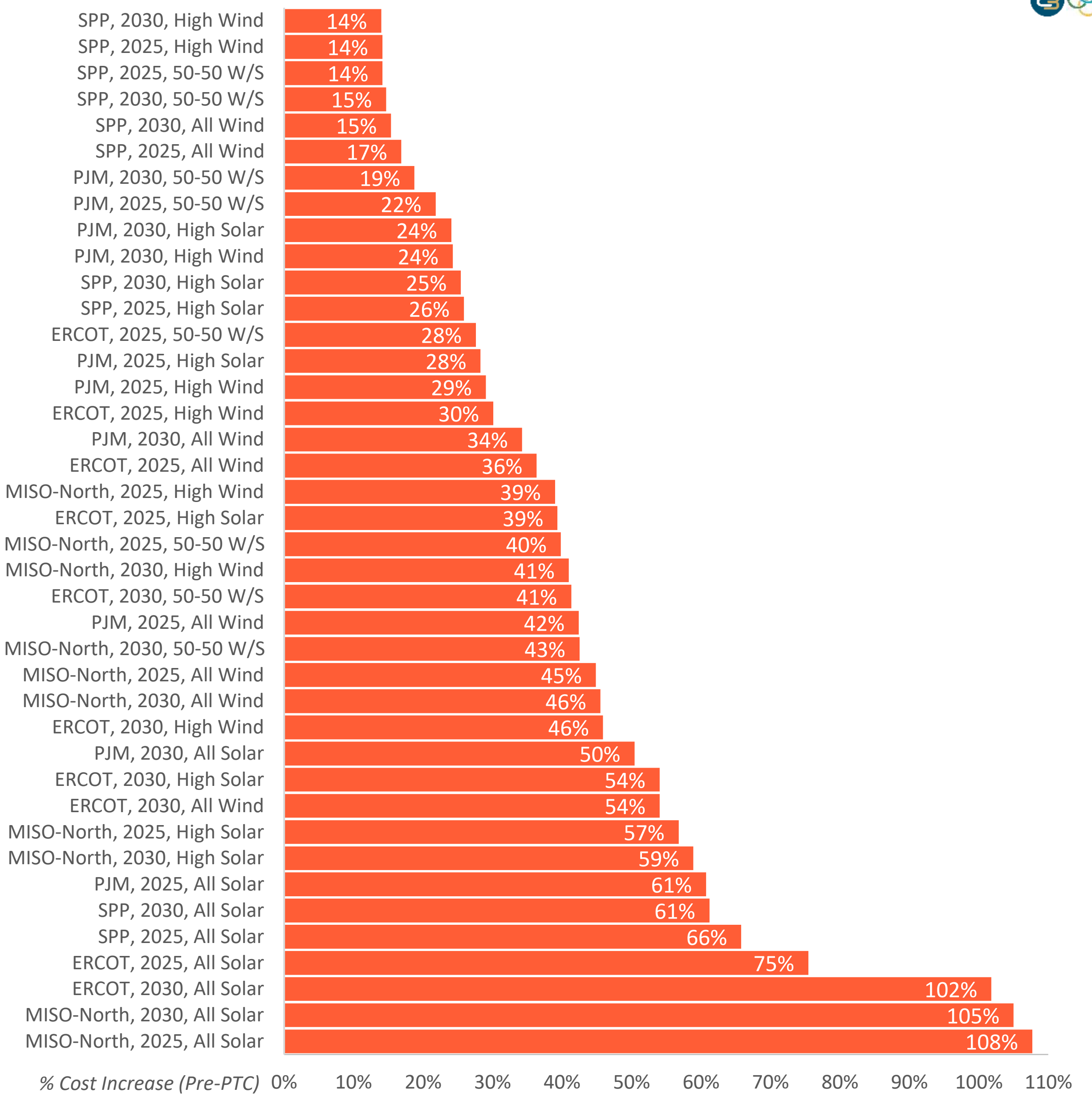

Figure 16 summarizes pre-PTC percentage increases in production cost under an hourly matching requirement. The incremental costs are highest under those scenarios where only solar generation is procured. However, the result is robust to every build scenario E3 tested.

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[31] High Solar denotes portfolios with 25% wind and 75% solar capacity. High Wind is 75% wind, 25% solar.

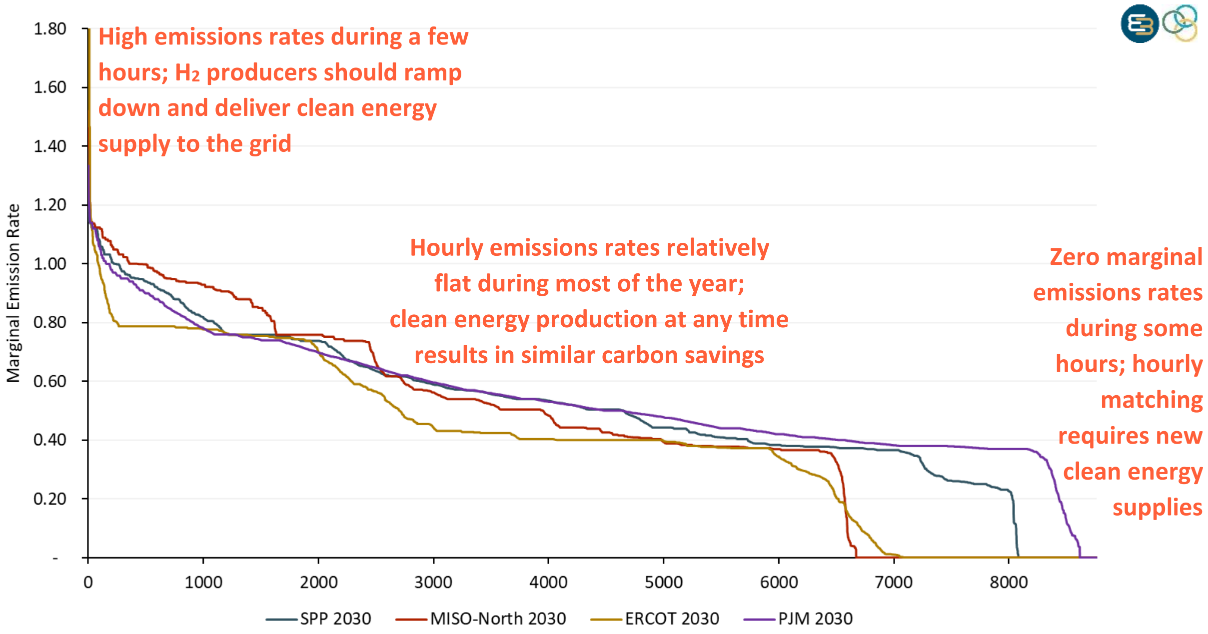
Discussion of Results

To better understand the market dynamics contributing to the results above, E3 investigated the hourly marginal emissions rates across regions and years covered in this study. When marginal emissions rates are visualized using a duration curve, three distinct and meaningful periods become apparent:

1) **High marginal emissions rates occur during a small sub-set of hours (> 1.2 tCO_2/MWh)**. During these hours, hydrogen producers seeking to minimize emissions should ramp down. Annual matching provides a strong incentive for hydrogen producers to reduce their production during hours with high market prices, which generally align with times when the marginal emissions rate is highest. Hourly matching requirements, on the other hand, provide little incentive for hydrogen producers to reduce their load during these periods because their hourly-matched supply sources insulate them from wholesale electricity market dynamics.
2) **Marginal emissions rates are relatively flat during most of the year.** Annual matching provides similar carbon reductions to hourly matching during these periods, because changes in the timing of hydrogen production or clean energy generation do not result in significantly different carbon emissions.
3) **Marginal emissions rates are zero during some hours.** During these hours, hydrogen can be produced using surplus clean energy with no carbon emissions. At the same time, no incremental clean energy deliveries are possible at a time when the grid is already saturated with clean energy. Annual matching facilitates low-cost and low-emission hydrogen production by encouraging hydrogen producers to operate during these hours, and by requiring clean energy generation to be delivered during other hours when it can reduce emissions. By forcing incremental clean energy supplies to be developed to serve hydrogen load during these zero-emissions hours, hourly matching raises the cost of producing hydrogen without necessarily reducing emissions.

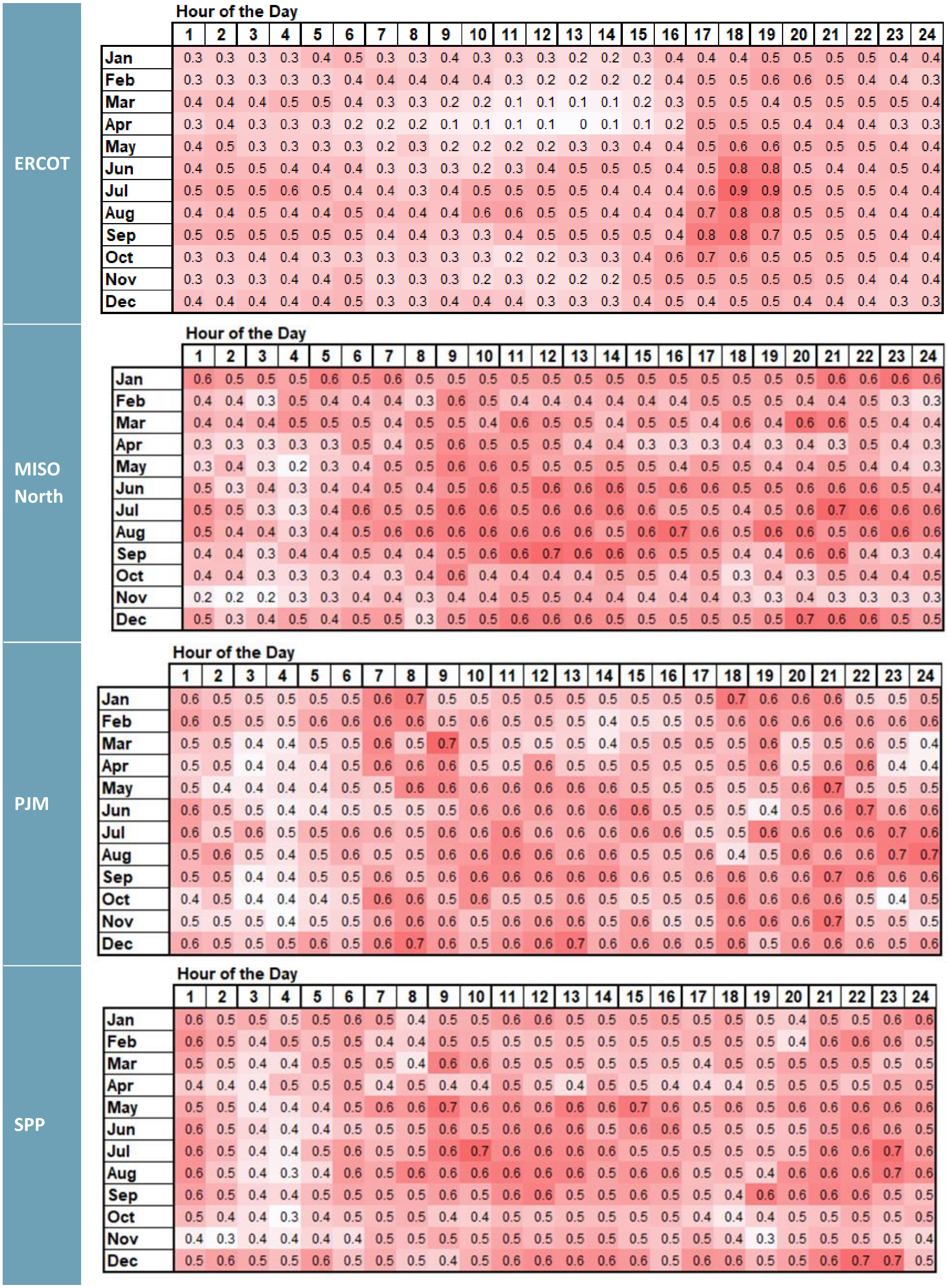
By isolating hydrogen production from wholesale power market dynamics, hourly matching foregoes opportunities to reduce carbon emissions by reducing load, and needlessly adds cost to clean energy supplies without reducing emissions during times when the grid is saturated with clean energy.

Figure 17. Duration Curve of Emissions Rates by Region, 2030



To understand these dynamics for each market, E3 generated the marginal emissions rate heat maps shown below. In these heat maps, we can observe that higher marginal emissions rates are less frequent in ERCOT and more frequent in other markets like PJM. This helps to explain the results because E3 assumes the electrolyzer avoids the 10% of highest-priced hours in a given year under an annual matching requirement, which improves emissions results significantly in ERCOT but does not produce an equivalent relative benefit in other markets.

Figure 18. 2030 Marginal Emissions Rate Heat Maps, by Region (tCO_2 / MWh)



ERCOT

Hour of the Day

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0.3	0.3	0.3	0.3	0.4	0.5	0.3	0.3	0.4	0.3	0.3	0.3	0.2	0.2	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.4	0.4
Feb	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0.4	0.5	0.5	0.6	0.6	0.5	0.4	0.4	0.3
Mar	0.4	0.4	0.4	0.5	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.3	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.4
Apr	0.3	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0	0.1	0.1	0.2	0.5	0.5	0.5	0.4	0.4	0.4	0.3	0.3
May	0.4	0.5	0.3	0.3	0.3	0.3	0.2	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.5	0.5	0.5	0.4	0.4
Jun	0.4	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.2	0.3	0.4	0.5	0.5	0.5	0.4	0.5	0.8	0.8	0.5	0.4	0.4	0.5	0.4
Jul	0.5	0.5	0.5	0.6	0.5	0.4	0.4	0.3	0.4	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.6	0.9	0.9	0.5	0.5	0.5	0.4	0.4
Aug	0.4	0.4	0.5	0.4	0.4	0.5	0.4	0.4	0.4	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.7	0.8	0.8	0.5	0.5	0.4	0.4	0.4
Sep	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.3	0.3	0.4	0.5	0.5	0.5	0.5	0.4	0.8	0.8	0.7	0.5	0.5	0.5	0.4	0.4
Oct	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.4	0.6	0.7	0.6	0.5	0.5	0.5	0.5	0.4	0.4
Nov	0.3	0.3	0.3	0.4	0.4	0.5	0.3	0.3	0.3	0.2	0.3	0.2	0.2	0.2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4
Dec	0.4	0.4	0.4	0.4	0.4	0.5	0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.3	0.4	0.5	0.4	0.5	0.5	0.4	0.4	0.4	0.3	0.3

MISO North

Hour of the Day

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0.6	0.5	0.5	0.5	0.6	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6
Feb	0.4	0.4	0.3	0.5	0.4	0.4	0.4	0.3	0.6	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.4	0.5	0.3	0.3
Mar	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.5	0.4	0.6	0.5	0.5	0.4	0.5	0.5	0.4	0.6	0.4	0.6	0.6	0.5	0.4	0.4
Apr	0.3	0.3	0.3	0.3	0.3	0.5	0.4	0.5	0.6	0.5	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.4	0.3	0.4	0.3	0.5	0.4	0.3
May	0.3	0.4	0.3	0.2	0.3	0.4	0.5	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.4	0.4	0.5	0.4	0.4	0.3
Jun	0.5	0.3	0.4	0.3	0.4	0.4	0.5	0.4	0.5	0.6	0.5	0.6	0.6	0.6	0.5	0.6	0.6	0.5	0.5	0.6	0.6	0.6	0.5	0.4
Jul	0.5	0.5	0.3	0.3	0.4	0.6	0.5	0.5	0.6	0.6	0.5	0.6	0.6	0.6	0.6	0.5	0.5	0.4	0.5	0.6	0.7	0.6	0.6	0.6
Aug	0.5	0.4	0.4	0.3	0.4	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.6	0.7	0.6	0.5	0.6	0.6	0.5	0.6	0.6	0.6
Sep	0.4	0.4	0.3	0.4	0.4	0.5	0.4	0.4	0.5	0.6	0.6	0.7	0.6	0.6	0.6	0.5	0.5	0.4	0.4	0.6	0.6	0.4	0.3	0.4
Oct	0.4	0.4	0.3	0.3	0.3	0.4	0.3	0.4	0.6	0.4	0.4	0.4	0.4	0.5	0.5	0.4	0.5	0.3	0.4	0.3	0.5	0.4	0.4	0.5
Nov	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.3	0.4	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.3
Dec	0.5	0.3	0.4	0.5	0.4	0.5	0.5	0.3	0.5	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.6	0.6	0.5	0.5

PJM

Hour of the Day

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0.6	0.5	0.5	0.5	0.5	0.5	0.6	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.6	0.6	0.6	0.5	0.5	0.5
Feb	0.6	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.5	0.6	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Mar	0.5	0.5	0.4	0.4	0.5	0.5	0.6	0.5	0.7	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.6	0.5	0.4
Apr	0.5	0.5	0.4	0.4	0.4	0.5	0.6	0.6	0.6	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.6	0.6	0.4	0.4
May	0.5	0.4	0.4	0.4	0.4	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.6	0.7	0.5	0.5	0.5
Jun	0.6	0.5	0.5	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.5	0.6	0.7	0.6	0.6
Jul	0.6	0.5	0.6	0.5	0.5	0.6	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.6	0.6	0.6	0.6	0.7	0.6
Aug	0.5	0.6	0.5	0.4	0.5	0.6	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.6	0.4	0.5	0.6	0.6	0.6	0.7	0.7
Sep	0.5	0.5	0.4	0.4	0.5	0.5	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.6	0.7	0.6	0.6	0.6
Oct	0.4	0.5	0.4	0.4	0.4	0.5	0.6	0.6	0.5	0.6	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.5	0.4	0.5
Nov	0.5	0.5	0.5	0.4	0.5	0.5	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.5	0.6	0.5	0.5	0.6	0.6	0.6	0.7	0.5	0.5	0.5
Dec	0.6	0.5	0.5	0.5	0.6	0.5	0.6	0.7	0.6	0.5	0.6	0.6	0.7	0.6	0.6	0.6	0.5	0.6	0.5	0.6	0.6	0.6	0.5	0.6

SPP

Hour of the Day

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0.6	0.5	0.5	0.5	0.5	0.6	0.5	0.4	0.5	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.6	0.6
Feb	0.6	0.5	0.4	0.5	0.5	0.5	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.6	0.6	0.6	0.5
Mar	0.5	0.5	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Apr	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.4	0.4	0.5	0.5	0.4	0.5	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5
May	0.5	0.5	0.4	0.4	0.4	0.5	0.6	0.6	0.7	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.5	0.6	0.5	0.6	0.6	0.6	0.6	0.6
Jun	0.6	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.5	0.6	0.6	0.6	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.5
Jul	0.6	0.5	0.4	0.4	0.5	0.6	0.5	0.5	0.6	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.7	0.6
Aug	0.6	0.5	0.4	0.3	0.4	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.6	0.6	0.5	0.5	0.4	0.6	0.6	0.6	0.7	0.6
Sep	0.6	0.5	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.5	0.6	0.6	0.5	0.5	0.6	0.5	0.5	0.4	0.6	0.6	0.6	0.6	0.5	0.5
Oct	0.5	0.4	0.4	0.3	0.4	0.5	0.5	0.5	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Nov	0.4	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.3	0.5	0.5	0.5	0.5	0.4
Dec	0.5	0.6	0.5	0.5	0.6	0.5	0.5	0.5	0.4	0.5	0.6	0.6	0.6	0.6	0.6	0.5	0.6	0.6	0.5	0.5	0.6	0.7	0.7	0.5

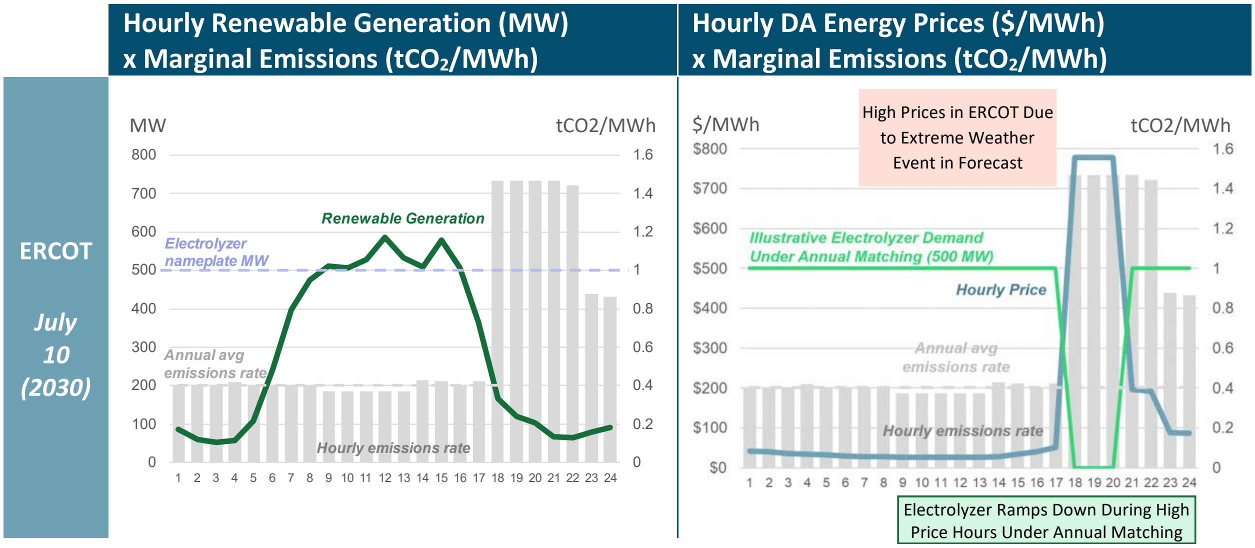
E3 also examined hourly emissions, electrolyzer load, and renewable generation for each region. A sample day for ERCOT is shown below, and other market sample days are shown in the Appendix. Each sample day assumes a 50/50 procurement of wind and solar capacity. Renewable generation shown below represents aggregate output from wind and solar when both resources are present in the portfolio.

From these sample day visualizations, we observe:

- Hourly matching reduces hydrogen production relative to annual matching even under a diversified renewable portfolio, most notably during non-solar hours.
- There are many hours when renewable generation is low but grid carbon intensity is also low – during these hours, hydrogen production under annual matching can be served with grid electricity up to its full capacity, whereas hourly matching requires additional bundled renewable energy supplies to take advantage of these hours.
- The highest-priced 10% of hours overlap significantly with the highest-emissions hours in ERCOT, SPP, and to a lesser extent, PJM, meaning that reducing hydrogen production during these hours results in significant emissions savings under an annual matching scenario. Under hourly matching, hydrogen producers would have little incentive to reduce their production.

These results also capture the importance of a key market dynamic mentioned above: curtailed renewable generation does not create a REC and cannot be counted toward renewable energy purchases. When hourly marginal emissions rates are zero in a given market, zero-emitting resources are on the margin and no new clean generation can be delivered to the grid.

Figure 19. Market Dynamics in ERCOT, 2030 Sample Day



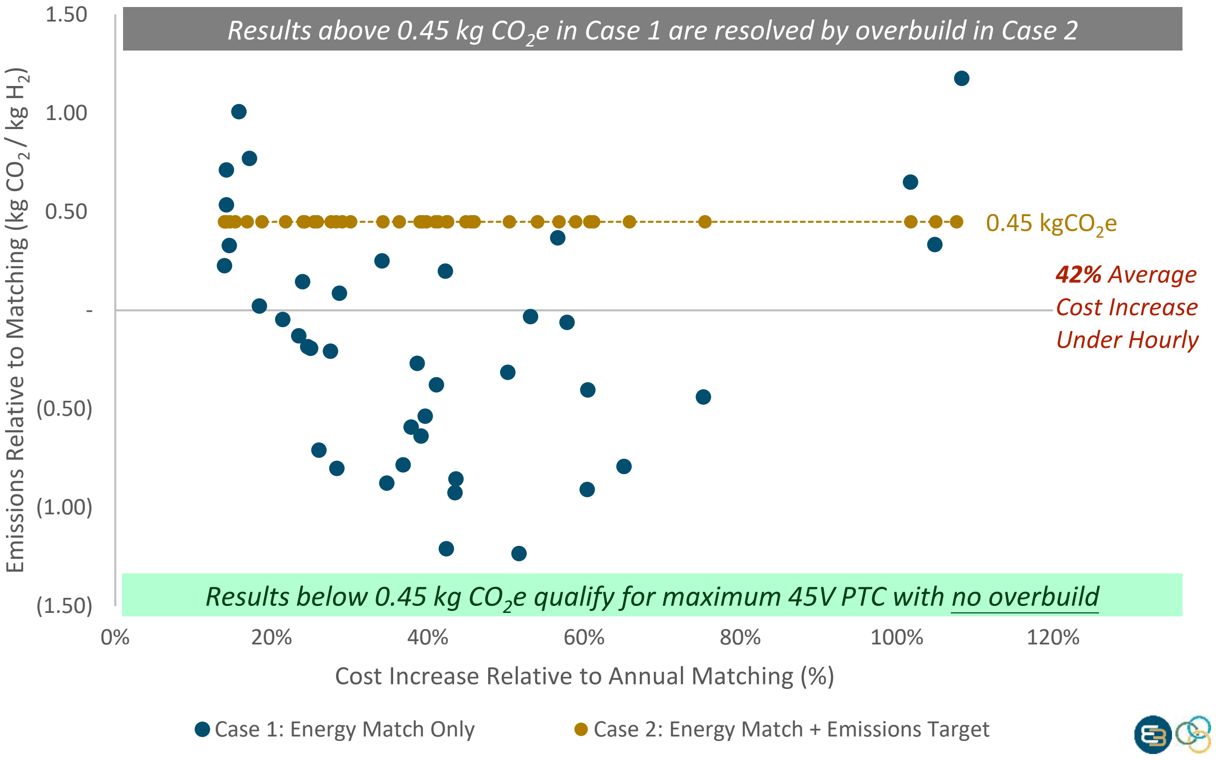
The sample day shown above represents a high-price period in ERCOT, which is driven by extreme weather events in E3's market price forecasts. On these days, the electrolyzer will avoid the highest-priced hours, which occur between 6 pm and 8 pm, under an annual matching approach (right hand side chart). These hours are coincident with the highest hourly emissions rates for the day.

Summary of Results

E3 finds that with only modest changes to the renewable generation portfolio, it is possible to entirely eliminate the incremental GHG emissions observed under an annual energy matching approach. Moreover, hydrogen production costs are higher under an hourly matching requirement than under an annual requirement. Figure 20 shows the incremental emissions under the annual matching requirement relative to the hourly matching requirement along the y axis, and the percentage cost increase (based on $/kg results) associated with meeting the hourly matching requirement. The percentage increases shown below are estimated before accounting for the 45V PTC.

Under the annual matching approach where all but six scenarios meet the threshold for the maximum 45V PTC, we can assume that the cost of hydrogen production should reflect the benefit of the PTC. Under this assumption, the percentage increase in production cost under the hourly matching requirement is significantly higher: on average, the production cost increases by 250% in this context.

Figure 20. Incremental Emissions of Annual Matching Against Incremental Cost of Hourly Matching, Before 45V PTC



An hourly matching requirement with the same net CO_2 emissions as an annual matching requirement produces significantly higher hydrogen production costs across all markets:

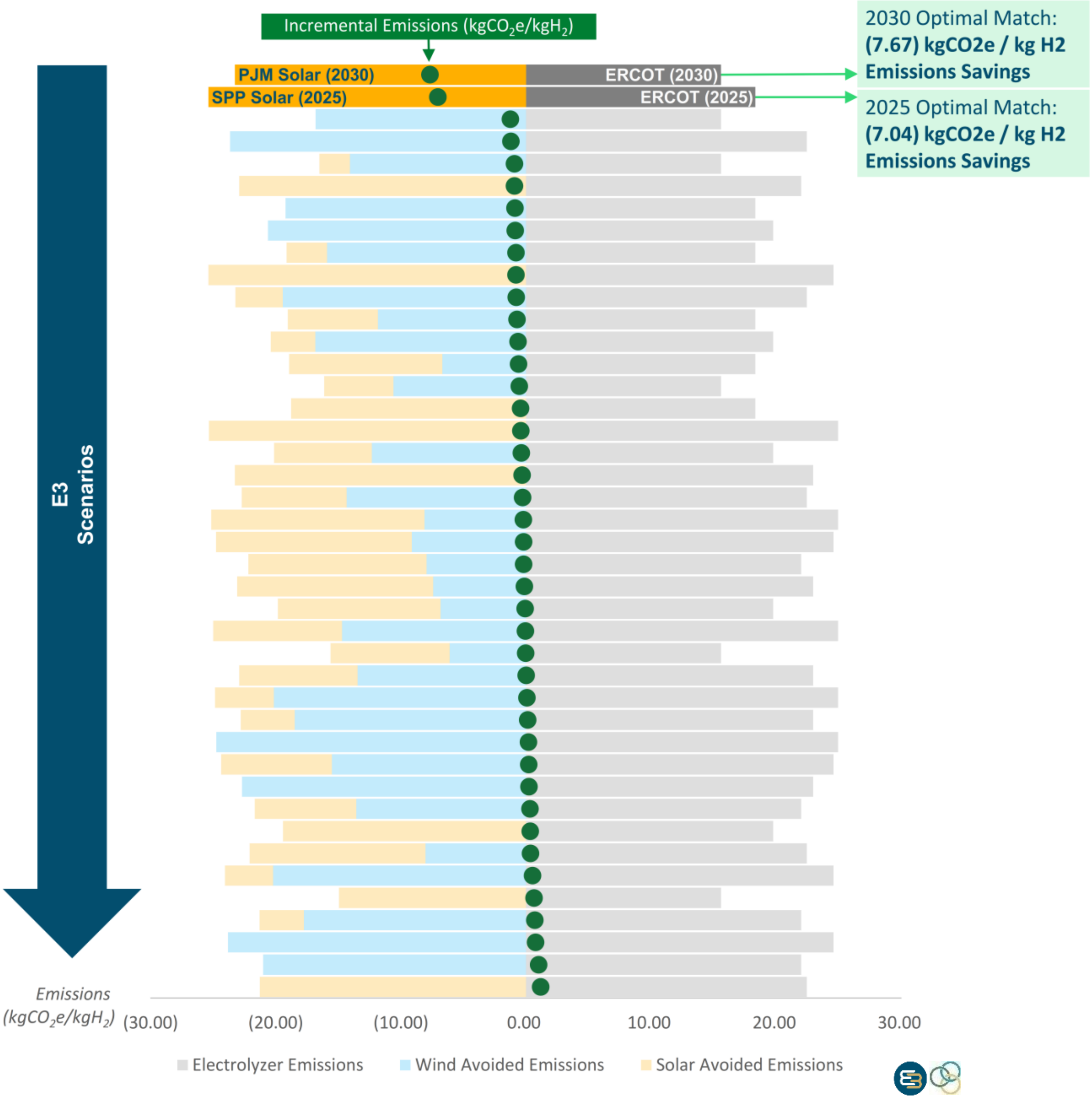
- In ERCOT, hydrogen produced under the hourly matching requirement could cost up to 102% more than hydrogen produced under the annual matching requirement;
- In MISO-North, production costs increase by up to 108% under an hourly matching requirement;

- In PJM, production costs increase by up to 61% under an hourly matching requirement; and
- In SPP, production costs increase by up to 66% under an hourly matching requirement.

Optimal Match Scenario

As a final sensitivity, E3 tests a case for each test year where hydrogen production is located in the market with the lowest grid carbon intensity and renewable energy generation is located in the market with the highest grid carbon intensity. This case represents the most environmentally beneficial combination of hydrogen production and renewable energy generation, based on the data developed for this study. These results are shown in the chart below. This combination of hydrogen production and clean energy generation results in emissions *savings* of 7.67 kg CO_2e / kg H_2 in 2030, relative to an hourly matching approach. This is more than six times the emissions increase observed in the most carbon-intensive scenario.

Figure 21. Incremental Emissions, Energy Match Only With Optimal Matches



2030 Optimal Match:
(7.67) kgCO2e / kg H2 Emissions Savings

2025 Optimal Match:
(7.04) kgCO2e / kg H2 Emissions Savings

Key Conclusions

Based on the results described above, E3 draws the following three key conclusions:

1) An hourly matching requirement does not ensure lower GHG emissions relative to an annual matching requirement, and in many cases is less effective at eliminating carbon emissions than annual matching;

1) With modest changes to the size and composition of the renewable portfolio, hydrogen produced under an annual renewable energy matching requirement results in incremental emissions less than the threshold for the maximum Production Tax Credit under the Inflation Reduction Act;

2) An hourly matching requirement results in significantly higher costs for hydrogen production than an annual matching requirement with the same GHG intensity across a wide range of renewable energy and wholesale electricity market assumptions.

Appendix A.

A.1. Hydrogen Production

As hydrogen is highly reactive, it does not typically occur in its elemental state on Earth. Hydrogen can be produced using a number of different processes, including extraction from water or extraction from hydrocarbons. The methods described below all involve inputting chemical, electrical and/or thermal energy in order to create hydrogen and other byproducts. These byproducts typically consist of oxides of carbon or oxygen.

Extraction from water:

- **Low Temperature Electrolysis**: This method involves breaking liquid water into hydrogen and oxygen using an electrical current. Electricity is most commonly provided from renewables or grid electricity.
- **High Temperature Electrolysis**: Water is heated to high temperature steam, which lowers the amount of electricity that must be used for the electrolytic decomposition of water into hydrogen and oxygen. High-temperature nuclear reactors and waste heat from industrial processes have the best ability to provide the necessary zero-carbon heat.
- **Gasification**: Gasification refers to reacting water with a feedstock of coal or biomass at high pressure and temperature to produce hydrogen, carbon monoxide, and CO_2.

Extraction from hydrocarbons:[32]

- **Steam methane reforming (SMR)**: A process that chemically reforms methane with steam, heat, and pressure to produce hydrogen and CO_2. The reaction is endothermic and requires external heat. Steam methane reforming is currently the highest volume hydrogen production pathway globally.
- **Catalytic reforming**: Chemically reforming petroleum products (hydrocarbons) with a catalyst, heat, and pressure, with hydrogen and CO_2 being produced in the process. The hydrogen produced is often consumed in other processes within a refinery.
- **Partial oxidation (POX)**: An exothermic reaction (does not require external heat) and non-catalytic process in which the hydrocarbon is gasified in the presence of oxygen. Hydrogen and CO_2 are produced.
- **Autothermal reforming (ATR)**: A combination of SMR and POX. This process is similar to partial oxidation, except steam is added during the process. Unlike SMR, autothermal reforming does not require external heat. Hydrogen and CO_2 are produced.

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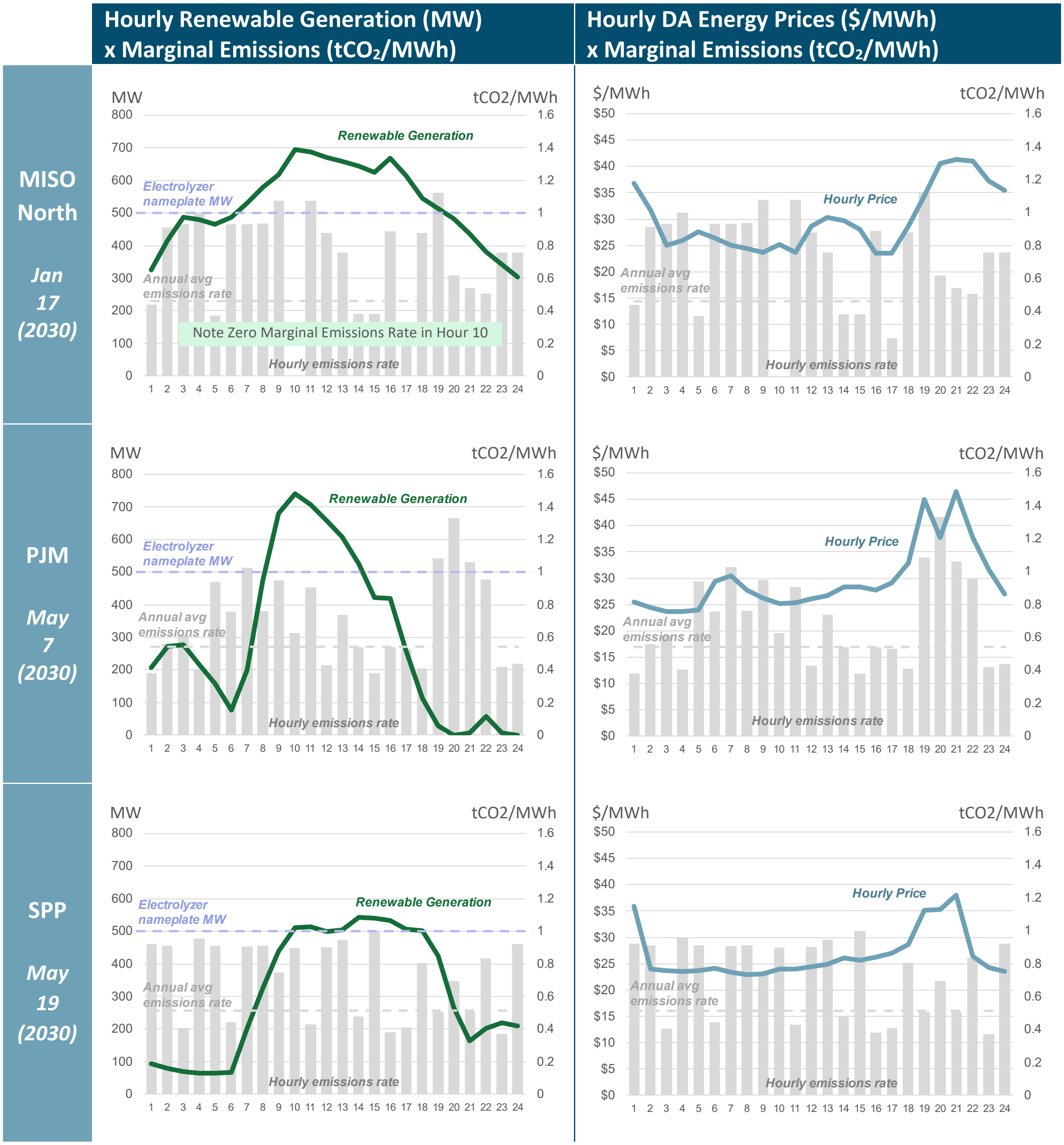
[32] If using fossil-based hydrocarbons, the waste CO_2 would need to be permanently stored or sequestered in order to be considered a low-carbon hydrogen pathway.

A.2. Additional Results Details

Figure 22. Additional Market Dynamics by Region, 2030 Sample Day[33]



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[33] As noted earlier in this study, an electrolyzer operating under an annual matching requirement will avoid the higher-priced hours shown on the charts to the right, assuming these are within the top 10% of highest-priced hours.