Hybrid Energy System to H_2 to Green Steel/Ammonia

Jennifer King and Steve Hammond
National Renewable Energy Laboratory
DOE Contract # or WBS #
June 6, 2023

DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting

Project ID: SDI001a

Project Goal

- **Vision:** Develop a national roadmap and reference designs for GW-scale off-grid, tightly-coupled, hybrid energy systems purpose-built for green H_2 production, in close proximity to or co-located with industry end uses, that can accelerate the path to decarbonization for hard to abate industries.

- **Project Goal:** design and analyze tightly-coupled systems to significantly lower costs for green steel and green ammonia
  - Develop initial cost projections for integrated, wind-H_2 design for GW-scale system at four diverse locations.
  - Compare off-grid approach to steam methane reforming (SMR) and grid-connected designs.
  - Calculate life cycle Greenhouse Gas (GHG) emissions.

Overview: Timeline and Budget

Outcomes:

- Phase 0: Market analysis (August-September 2022)
- Phase 1: Analysis for tightly-coupled, co-located green steel/ammonia systems (October 2022 – April 2023)
- Phase 2: Reference designs for green steel and ammonia (April 2023 – April 2024)

Timeline and Budget

- Project Start Date: 8/1/2022
- FY22 DOE Funding (if applicable): $2.5M
- FY23 Planned DOE Funding (if applicable): $3M
- Total DOE Funds Received to Date**: $2.5M

** Since the project started

Overview: Barriers and Targets

Technical Barriers

- Design and analyze shared components across renewable power, hydrogen, and steel/ammonia
- Integrate tools developed in isolation for individual technologies into one framework to exploit synergies across technologies

Technical Targets

- Targeting systems that reduce costs 10-20%+ due to tight-coupling and co-locating technologies

Five-lab Partnership:

– Project co-leads: Jennifer King and Steve Hammond, **NREL**

– Hanna Breunig/**LBNL**, Pingping Sun/**ANL**, Brian Ehrhart/**SNL**, Joao Pereira Pinto/**ORNL**

Overview: Core Research Questions/Key Insights

Are integrated, tightly coupled, decentralized, near-collocated, non-grid connected [“Integrated H2”], wind-H2-green steel/ammonia designs:

- **Viable and demonstrable** in the immediate, near-term,
- **Enable substantial, rapid H2 deployment**, and are they
- Substantially more **cost effective**

therefore, **enabling significantly more industrial systems-wide GHG reductions** with substantially more rapid deployment than

- Existing fossil SMR-CCUS
- Advanced nuclear/small modular reactors
- Existing siloed grid-H2 pathways (with mixed clean renewable and non-clean electricity generation)?

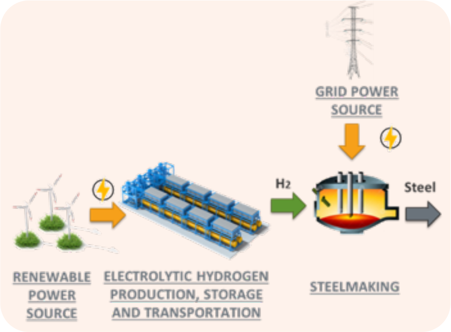
Potential Impact: Key Insights

Key Insight 1: Hybrid system designs with wind+solar can significantly reduce LCOH costs.

- Solar provides a valuable compliment in suboptimal wind resource areas
- Reducing storage requirements and increasing utilization of electrolyzer

Key Insight 2: IRA policy is a game changer for Integrated H2.

- More cost effective than FE-CCUS, advanced nuclear and siloed systems.
- Integrated H2 will fully qualify for the full clean H2 $3/kg credit and wind/Solar can take direct advantage of the full PTC & ITC credits.
- Integrated H2 highly likely to fully satisfy ALL additionality and hourly time matching requirements.



Potential Impact: Key Insights

Key Insight 3: "Integrated H2" costs are highly site specific.

- Diverse **wind resource have a substantial impact on LCOE and therefore LCOH**.
- Off-grid deployment enables massive numbers of potential new locations for integrated H2 deployment at these lower costs, independent of new transmission builds.

Key Insight 4: Costs of H2 storage is a big driver for LCOH-Delivered

- If steady-state end use is required or if storage is needed to buffer between renewable generation and end use for extreme weather events.
- Co-location is key because it avoids the cost of pipelines.

Key Insight 5: Directly coupling renewables to hydrogen can provide a significant cost savings and can accelerate scalability and cost effectiveness.

Potential Impact

Potential Impact: Current grid expansion requirements for new, incremental interconnection capacity, intra-regional transmission and inter-regional transmission to serve demands for:

A. 100% clean grid conversion by 2035, and
B. Direct Electrification for EVs and Heat Pumps -- are massive and far exceed any historical grid installation levels.

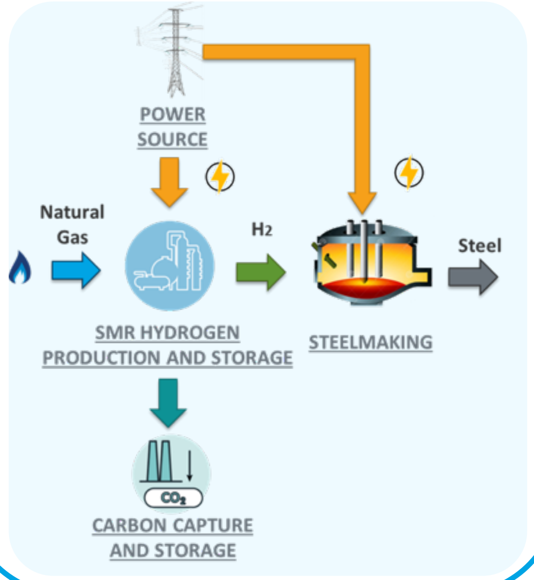
Current transmission development typically takes 5-10+ years to build and currently does not have the grid policies or grid financial incentives needed to reduce this build time period.

Serving grid additionality/expansion capacity for Wind-H2-Green Steel/Ammonia type applications will be low priority and are unlikely.

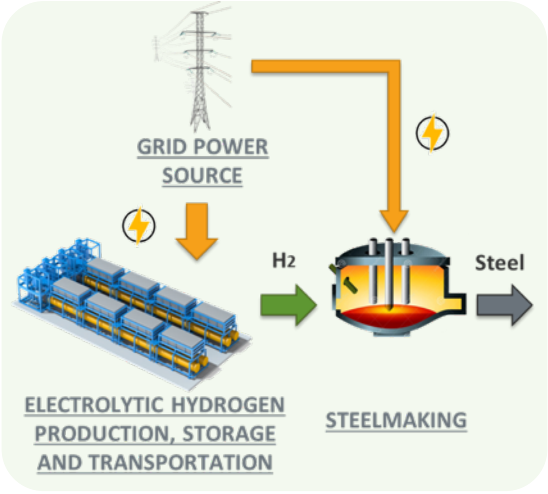
Integrated H2 provides an accelerated deployment pathway.

Approach: Use Case Configurations

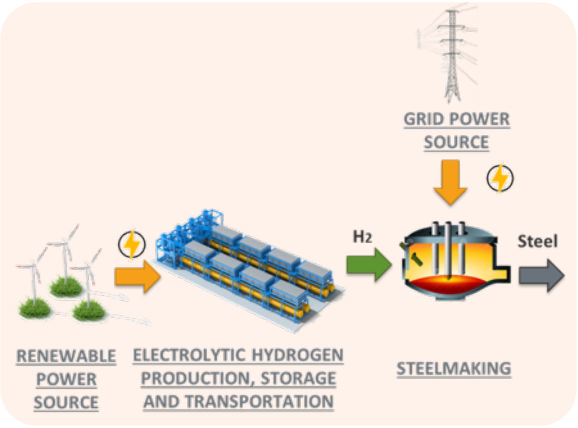
1 Fossil-H2-Steel/Ammonia Production (with CCS option)



2 Grid Connected H2 Production co-located Steel/Ammonia



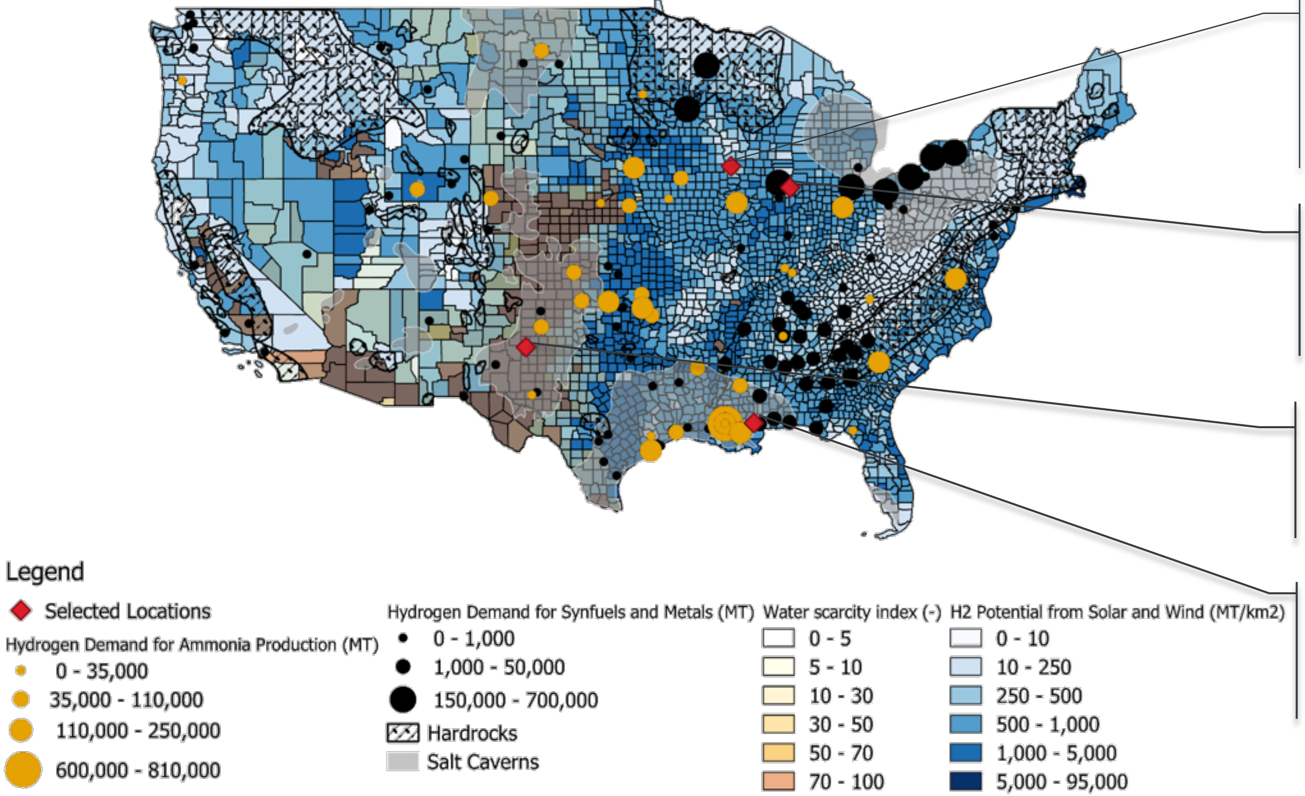
3 **Integrated H2**, Off-grid production co-located with Steel/Ammonia



Determine the cost savings and potential advantages to off-grid, tightly coupled wind-H2-industrial end uses

Approach: Four Land-based Locations for Phase I

- Steel and ammonia production are primarily in central U.S.
- Selected initial four central locations for analysis, with various attributes



IOWA
- Existing ammonia pipeline
- Close to ammonia and steel demand centers
- No geologic storage

INDIANA
- Largest steel mill in the U.S. with 8.2 MMT steel/year capacity
- No geologic storage

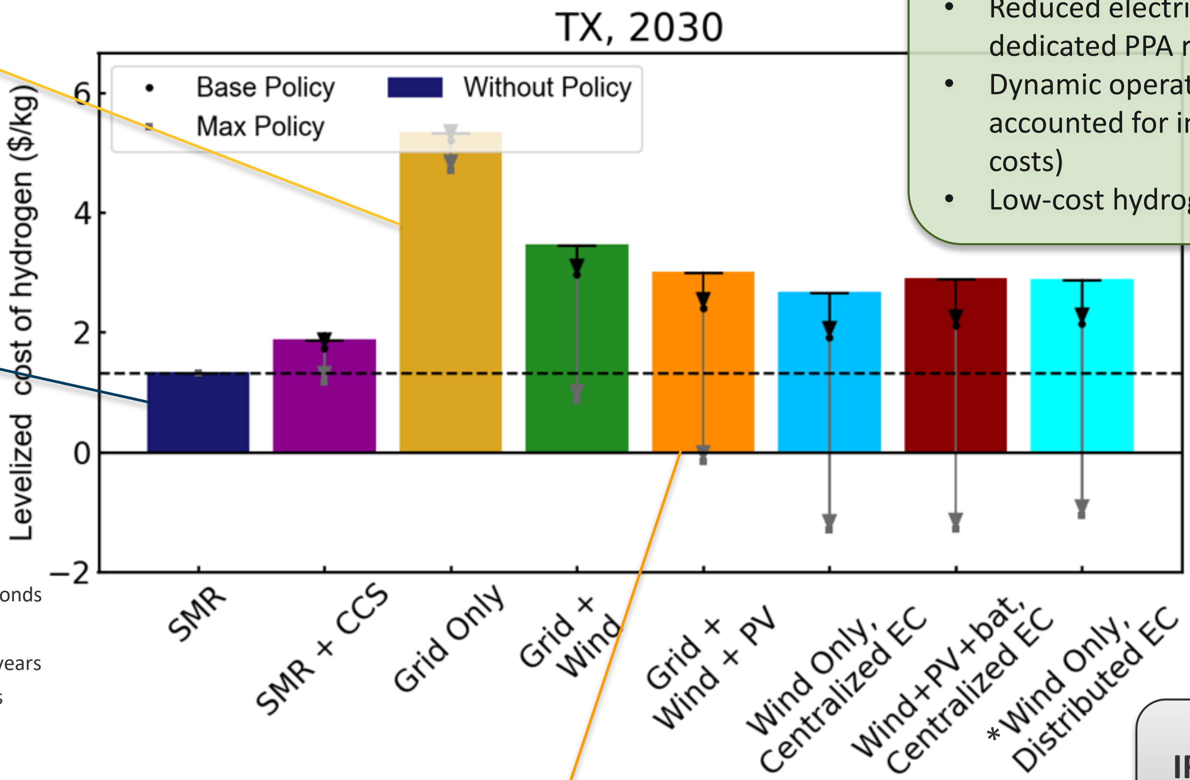
TEXAS
- Salt caverns and water stress region
- Excellent wind resources

MISSISSIPPI
- Close to existing demand
- Salt caverns

Accomplishments: Delivered LCOH in Best Location Analyzed Texas, TY 2030

Dependent on electricity price. This plot includes retail rates at 8.6 cents/kWh

PTC credit considered but CCS credit is the more lucrative credit in the best-case scenario



Off-grid costs less than on-grid:

- Reduced electricity costs (retail vs. dedicated PPA results in decrease)
- Dynamic operation of H2 allowed (and accounted for in increased replacement costs)
- Low-cost hydrogen storage (salt caverns)

*Distributed includes electrical efficiency gains ~4%

*Conversion efficiencies are not included in this slide, addressed in backup (only applies to centralized case)

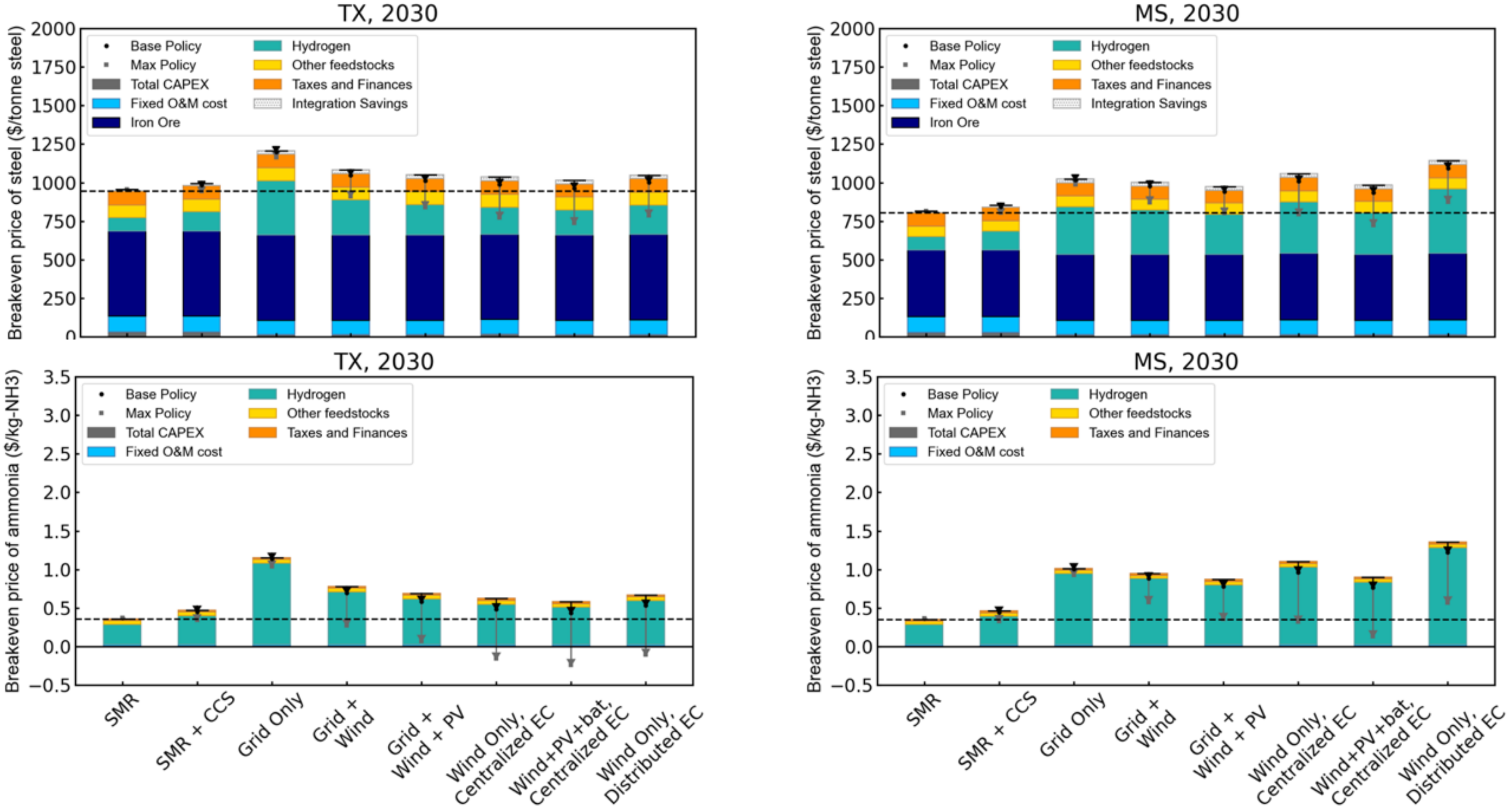
Notes:

- Technology year (TY) 2030 corresponds to operational year 2035
- CCS credit considered for over 12 years
- H2/wind PTC applied over 10 years
- Model does not account for RECs
- **LCOE for TX 2030**
    - Off-grid: 1.3 cents/kWh with PTC
    - On-grid: 8.6 cents/kWh (retail rates), 4.1 cents/kWh (wholesale rates)

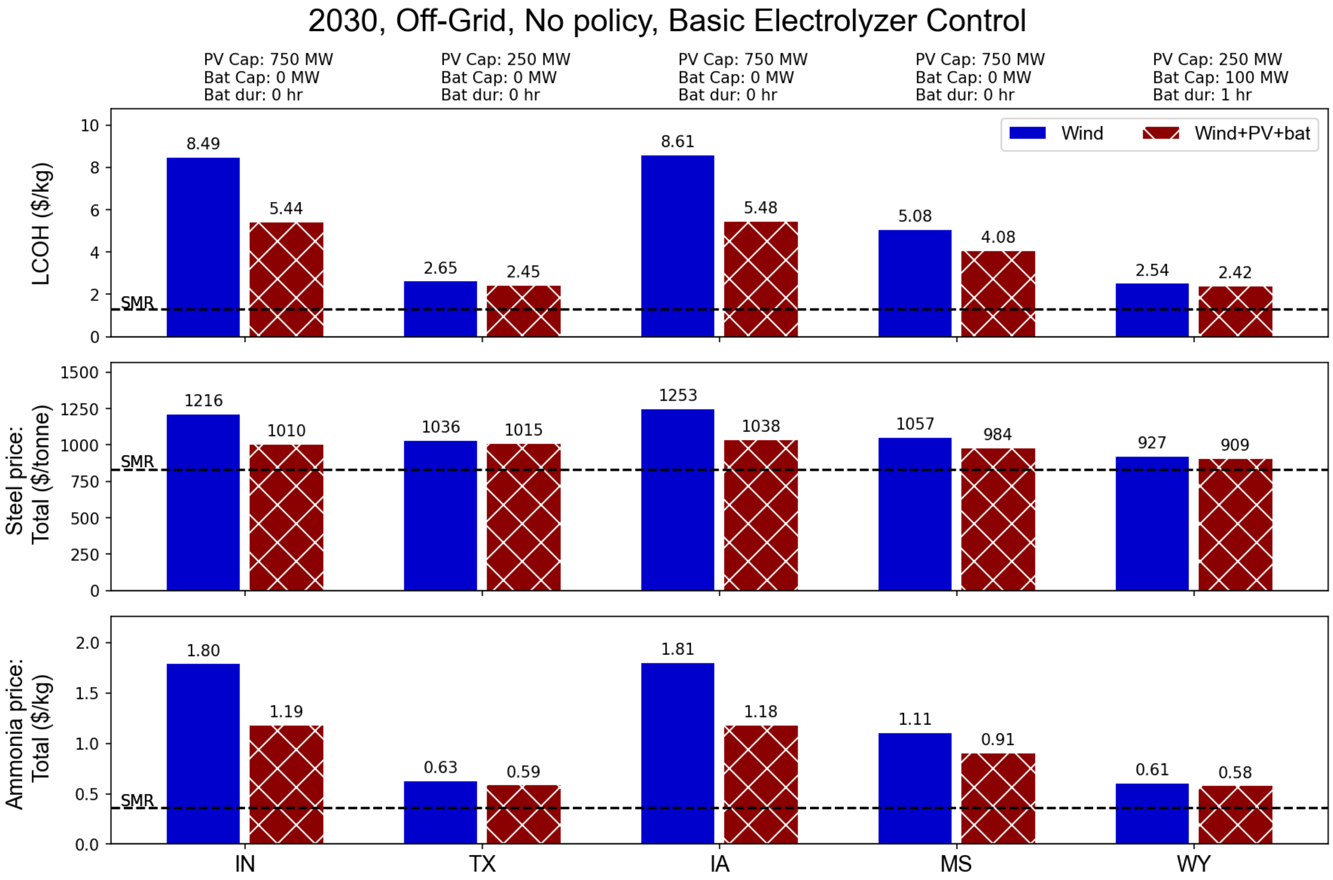
Co-located renewables + electrolyzer backfilled with grid electricity

Key Insight: IRA can be a significant driver for integrated LCOH

Accomplishments: LCOS and LCOA cost competitive with SMR with and without policy



Accomplishments: Steel and Ammonia with Wind-Solar Hybrids, No Policy

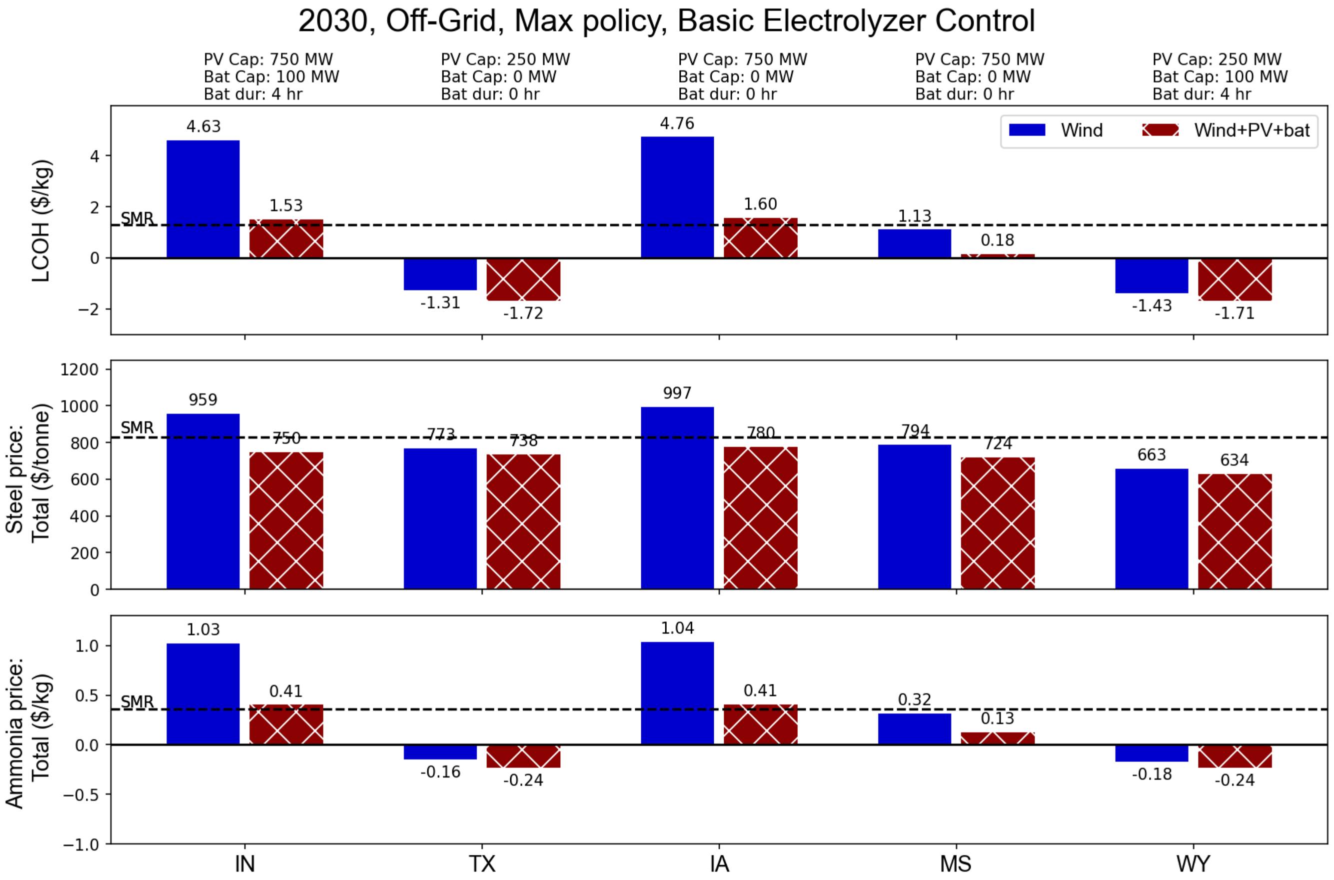


Key Insight:
Hybrids have significant impact on LCOH

Additional Takeaways

1. LCOH is reduced by up to 35%
2. LCOS is reduced by up to 17%
3. LCOA is reduced by up to 35% (mostly driven by LCOH)

Accomplishments: Steel and Ammonia with Wind-Solar Hybrids, Maximum Policy



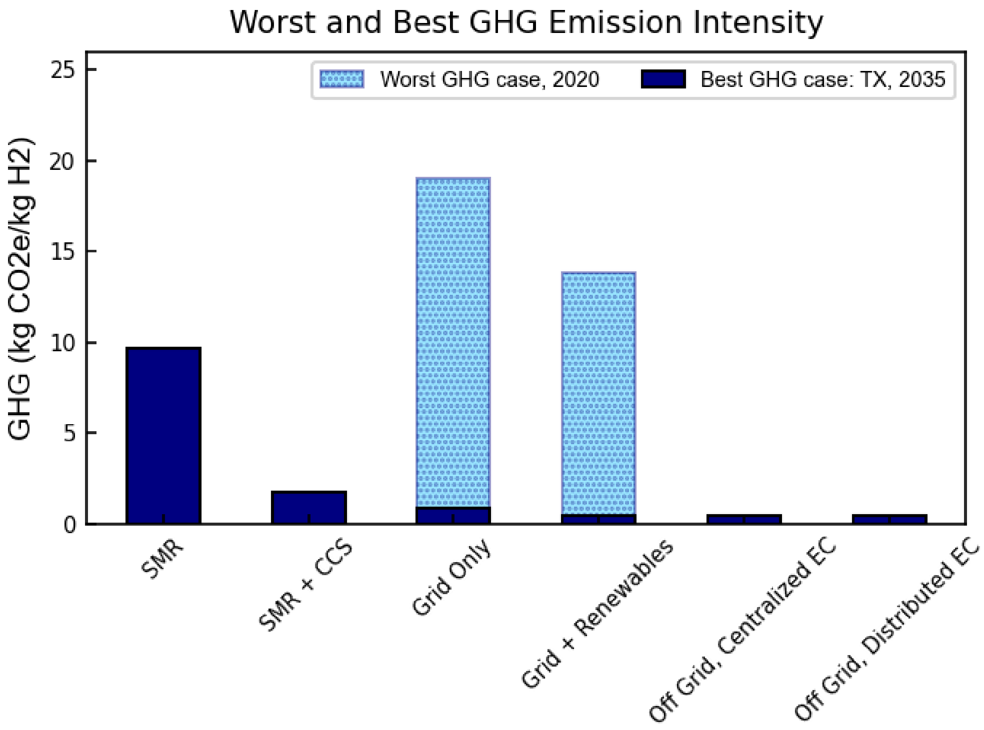
Key Insight:
With max policy, all locations compete with SMR

Additional Takeaways

1. Adding max policy makes **hydrogen cost competitive in all locations** by 2030
2. Steel and ammonia are competitive in all locations

Accomplishments: Best and Worst GHG Emission Intensity Scenarios

- Assuming 95% carbon capture for SMR + CCS process and 95% clean grid by 2035
- Best case scenario is for Texas in 2035, off grid case
- Worst case scenario is for Mississippi in 2020, grid-only case
- Infrastructure embedded emissions result in GHG ~0.5 kg CO2e/kg H2
- Maximum potential reductions amount for over 97% from worst to best case scenario



Collaboration and Coordination

- Collaboration has been a key to achieving our projects goals.
- Lab collaborators include:
  - **LBNL (sub)** – steel TEA model and inputs on hydrogen storage technologies
  - **ANL (sub)** – GREET for LCA and ammonia modeling
  - **ORNL (sub)** – power electronics design and performance for different configurations of wind and electrolyzers.
  - **SNL (sub)** – to come – safety, codes, and standards necessary to realize green steel and green ammonia
- **University collaborator:** Arizona State University (Sridhar Seetharaman)
  - Advise on green steel process and promising integration pathways

Coordination with Key Stakeholders

- Market analysis covering multiple stakeholders to map gaps and tools needed to accelerate industrial decarbonization
    - Database of tools, data, and demonstrations on green steel/ammonia compiled
    - Ensure this project is market relevant and has path to industry impact
- Coordinated with other projects including H2@Scale, H2NEW, DECARB, HyMARC, etc.

Remaining Challenges and Barriers

- **Challenges:**
  - Producing realistic reference designs with enough granularity to pursue tightly coupled systems
  - Need to understand the national impact of off-grid systems
  - Demonstrating the value of tightly or directly coupled systems
  - Understanding the safety challenges with these novel designs

Proposed Future Work

Phase1
Aug ‘22 - Mar ‘23

Complete and presented here.

Phase2
Apr ‘23 - Mar ‘24

Realistic reference designs for GW-scale wind-H2-steel/ammonia systems addressing both onshore and offshore

Phase3
Apr ‘24 - Mar ‘25

Demonstrate key capabilities needed to realize these reference designs, including coordinated controls, direct connections, and co-located resources.

Proposed future work depends on budgets and is subject to change.

Summary

- **Hybrid system designs with wind+solar can significantly reduce LCOH costs**.
- **IRA policy is a game changer for Integrated H2.**
- “Integrated H2” costs are highly site specific.
- **Costs of H2 storage is a big driver** for LCOH-Delivered
- **Directly coupling renewables to hydrogen can provide a significant cost**

Integrated, tightly coupled, decentralized, near-collocated, non-grid connected [“Integrated H2”], wind-H2-green steel/ammonia designs have the potential to **enable significantly more industrial systems-wide GHG reductions** with greatly accelerated deployment

Thank You

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Technical Backup and Additional Information

(Include this "divider" slide before your technical backup slides [maximum 20]. These technical backup slides will be available for oral presenters to use for Q&A and will be included in the published web PDFs for oral and poster presentations.

Note there is ***one required slide*** *in this section and several suggested slides.)*

Project Plan

PROJECT PHASES

PHASE 1: General Design, Model Integration, Initial TEA/LCA Assessments

PHASE 2: Detailed system design/analysis, demo concepts

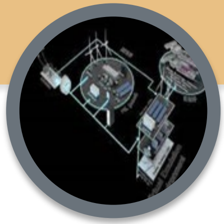
PHASE 3: Demonstration

ACTIVITIES AND GOALS

Phase 1
- Initial end-to-end integrated analysis for renewables-H2-steel/ammonia in an Initial Project Sprint
- Investigate possible advantages to off-grid, tightly coupled GW-scale wind-H2 production for steel/ammonia end uses

Phase 2
- National roadmap + location-specific reference designs
- Detailed system design and control from power electronics to storage technologies to product delivery
- Design possible 10 MW Green Steel Demo at NREL's ARIES

Phase 3
- 10 MW hardware integrated research and demonstration platform at ARIES
- GW-scale emulation of the end-to-end system at ARIES including renewables-H2-steel/ammonia



Phase 1 Focus Areas

- Preliminary **design and cost analysis**
  - Investigate advantages of integrated, renewables-H_2 for GW-scale system at four diverse locations
  - Compare to steam methane reforming (SMR) and siloed utility electricity-based designs.
  - Calculate life cycle Greenhouse Gas (GHG) emissions (no updates from phase 1a)

- Create **integrated software modeling capability**:
  - Integrated, co-located, off-grid renewables-H_2 system
  - Integrating diverse multi-lab sub-component tools

- **Market survey** to assess industry status, pain points, directions, and future needs

- **Explore ~10 MW scale demonstration concepts** at NREL Flatirons, that can be basis for wide range of research innovations and actual, on-site operations and production of green steel/ammonia

Core Research Questions/Key Insights

Are integrated, tightly coupled, decentralized, near-collocated, non-grid connected [“Integrated H2”], wind-H2-green steel/ammonia designs:

- **Viable and demonstrable** in the immediate, near-term,
- **Enable substantial, rapid H2 deployment**, and are they
- Substantially more **cost effective**

therefore, **enabling significantly more industrial systems-wide GHG reductions** with substantially more rapid deployment than

- Existing fossil SMR-CCUS
- Advanced nuclear/small modular reactors
- Existing siloed grid-H2 pathways (with mixed clean renewable and non-clean electricity generation)?

PHASE 1 Modeling and Analysis Key Insights- Viable and Demonstrable

Key Insight 1: Decentralized designs are viable but not substantially beneficial for LBW/Hybrids in deployment scalability or cost effectiveness.

- Off-setting benefits and costs for electrolyzers directly coupled with wind turbines.
- Electrical efficiency gains are around 1-4%.
- Ex: shared power electronics and cabling vs. pipelines are not enough to offset cost of smaller electrolyzers and current O&M costs

Key Insight 2: Full **end-to-end demonstration of integrated H2 at NREL ARIES is viable** and substantially underway.

- Wind Modern Turbine acquisition is underway,
- PV solar, batteries/other electricity storage, and integrated control via CGI are currently deployed and being expanded;
- these components along with on-site PEM H2 production capabilities, plus planned H2 Storage, plus potential award for on-site steel production ("SHREC" AMMTO proposal) would enable a full end-to-end demonstration and research platform.

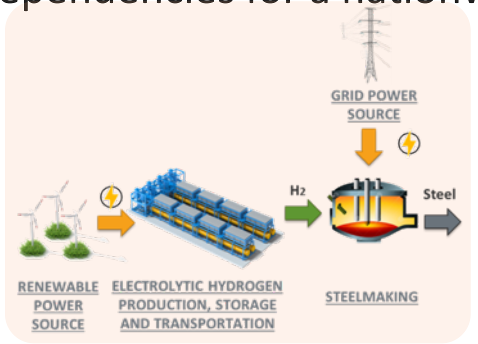
PHASE 1 Modeling and Analysis Key Insights
Cost Effective

Key Insight 3: "Integrated H2" costs are highly site specific.

- Diverse **wind resource have a substantial impact on LCOE and therefore LCOH**.
- Off-grid deployment enables massive numbers of potential new locations for integrated H2 deployment at these lower costs, independent of new transmission builds.

Key Insight 4: Costs of H2 storage is a big driver for LCOH-Delivered

- If steady-state end use is required or if storage is needed to buffer between renewable generation and end use for extreme weather events.
- Integrated H2 also significantly reduces requirements/dependencies for a nationwide H2 pipeline backbone – accelerating deployment.



PHASE 1 Modeling and Analysis Key Insights Cost Effective

Key Insight 5: Hybrid system designs with wind plus solar can significantly reduce LCOH costs.

- Solar provides a valuable compliment in suboptimal wind resource areas
- Reducing storage requirements and increasing utilization of electrolyzer

Key Insight 6: Electrolyzer degradation under dynamic operations has a small impact on LCOH, especially as electrolyzer costs are reduced over time.

Key Insight 7: IRA policy is a game changer for Integrated H2.

- More cost effective than FE-CCUS, advanced nuclear and siloed systems.
- Integrated H2 will fully qualify for the full clean H2 $3/kg credit and wind/Solar can take direct advantage of the full PTC & ITC credits.
- Integrated H2 highly likely to fully satisfy ALL additionality and hourly time matching requirements.

“Integrated H2” supports rapid H2 deployment

Observation: Current grid expansion requirements for new, incremental interconnection capacity, intra-regional transmission and inter-regional transmission to serve demands for:

A. 100% clean grid conversion by 2035, and
B. Direct Electrification for EVs and Heat Pumps -- are massive and far exceed any historical grid installation levels.

Current transmission development typically takes 5-10+ years to build and currently does not have the grid policies or grid financial incentives needed to reduce this build time period.

Serving grid additionality/expansion capacity for Wind-H2-Green Steel/Ammonia type applications will be low priority and are unlikely.

Integrated H2 provides an accelerated deployment pathway.

Phase 1a (December Briefing)

- ***End-to-end modeling capability:***
  - renewable generation technologies (wind and solar),
  - hydrogen production technologies (PEM),
  - hydrogen storage technologies (salt caverns, lined rock caverns, compressed gas, and plans to include hydrogen carriers in Phase 2),
  - end uses (steel and ammonia).
  - On and off-grid configurations compared with SMR
  - *This code is modular and can be adapted to other technologies in this workflow. Leveraged from H2OPP.

- ***Spatially correlated data at high resolution:*** all data is spatially correlated at 2km resolution to increase accuracy
  - Wind, solar, storage, BOS costs
  - Raw material costs
  - Water, land, etc.

- ***Capex/opex savings addressed***
  - pipeline vs. cabling, BOS savings
  - shared power electronics
  - **Projected gains:** 1-3%

- ***Policy included makes LCOH cost competitive with SMR***

Phase 1b Focus Areas

- ***Increased Capacity Factor:*** Phase 1a had wind-only
  - Phase 1b added solar and battery to hybrid system
  - This increases electrolyzer utilization and lifetime, minimizes start/stop, decreases variability.
  - **Result:** 1-35% LCOH savings (dependent on location, mostly beneficial in MS, IA, IN)

- ***Electrical Efficiencies:***
  - Phase 1a included capex savings,
  - Phase 1b incorporates OpEx electrical efficiency gains from shared power electronics (distributed only)
  - **Result:** 1-4% savings on LCOH

- ***Conversion efficiencies:***
  - Phase 1b added advanced controls of electrolyzer stacks (centralized only)
  - This keeps hydrogen production nearly constant and increases the electrolyzer life expectancy.
  - **Result:** 1-3% savings on LCOH (dependent on electrolyzer costs)

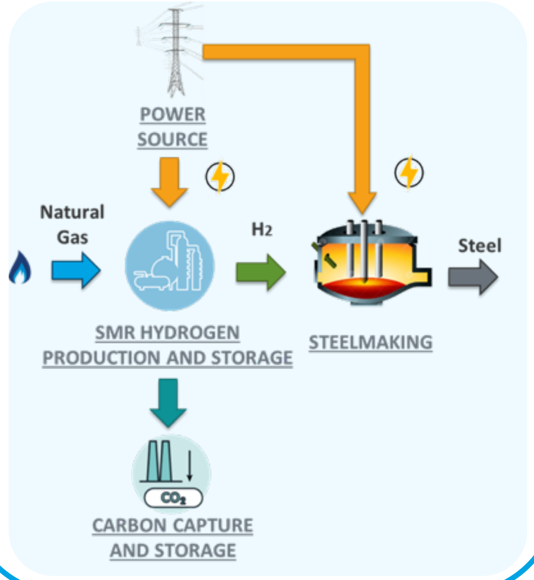
- **We have initial offshore results for fixed bottom (floating under development) in the backup section.**

- *Outside project scope:* nuclear, fossil energy, or CSP. These technologies could be included in future. Focused on production of electricity and fuels; not focused on detailed/optimized methods for heat integration.

Review: Use Case Configurations

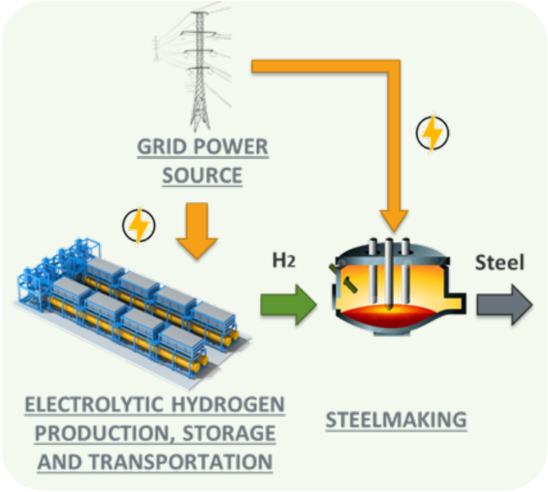
1

Fossil-H2-Steel/Ammonia Production (with CCS option)



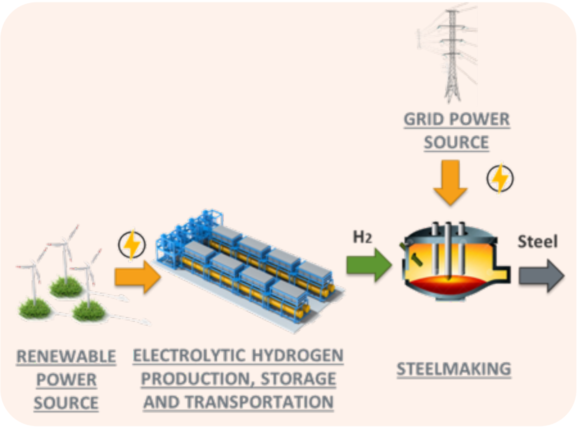
2

Grid Connected H2 Production co-located Steel/Ammonia



3

Integrated, Off-grid H2 Production with co-located Steel/Ammonia



Determine the cost savings and potential advantages to off-grid, tightly coupled wind-H2-industrial end uses

Electrolyzer cost assumptions are determined from literature and HFTO targets

- Costs and credits amortized over 30-year useful lifetime
- Electrolyzer uninstalled system costs are based on literature and HFTO targets
  - Electrolyzer component costs for 2020 taken from EU-funded study[1]; system cost roughly matches HFTO 2022 status of $1,000/kW
  - Low-cost case:
    - Future electrolzyer system costs taken from HFTO targets
    - Distributed system costs calculated using scaling factors from [1]
  - Mid-cost case: future costs calculated using learning rates and estimated future capacities from DOE-funded electrolyzer supply chain report[2]
- Installation and indirect costs taken from H2A

Uninstalled electrolyzer system capital costs ($2019/kW)

Technology year	Low-Cost Case		Mid-Cost Case	
	Centralized	Distributed*	Centralized	Distributed*
2020	1114	1403	1114	1403
2025	450	642	827	1096
2030	200	299	372	537
2035	150	228	308	450

*For a 6 MW turbine. Site-specific cost will depend on turbine rating.

Installation and Indirect Costs

Parameter	Value
Installation cost (% of uninstalled manufacturing price)	12%
Site preparation (% of total installed cost)	2%
Engineering and design (% of total installed cost)	10%
Permitting (% of total installed cost)	15%
Project contingency (% of total installed cost)	15%

[1] Bohm et al. Applied Energy 264 (2020), 114780.
[2]Badgett et al. "Water Electrolyzers and Fuel Cells Supply Chain: Supply Chain Deep Dive Assessment." February 2022

Other Key Assumptions

- Costs and credits amortized over 30-year useful lifetime
- Initial analysis uses detailed wind and solar models, **costs vary spatially and temporally,** e.g. →

Wind plant capital costs ($/kW)

Year	IN	TX	IA	MS	WY
2020	1420	1420	1709	2232	1420
2025	1210	1210	1542	1938	1210
2030	1000	1000	1374	1644	1000
2035	986	986	1348	1613	986

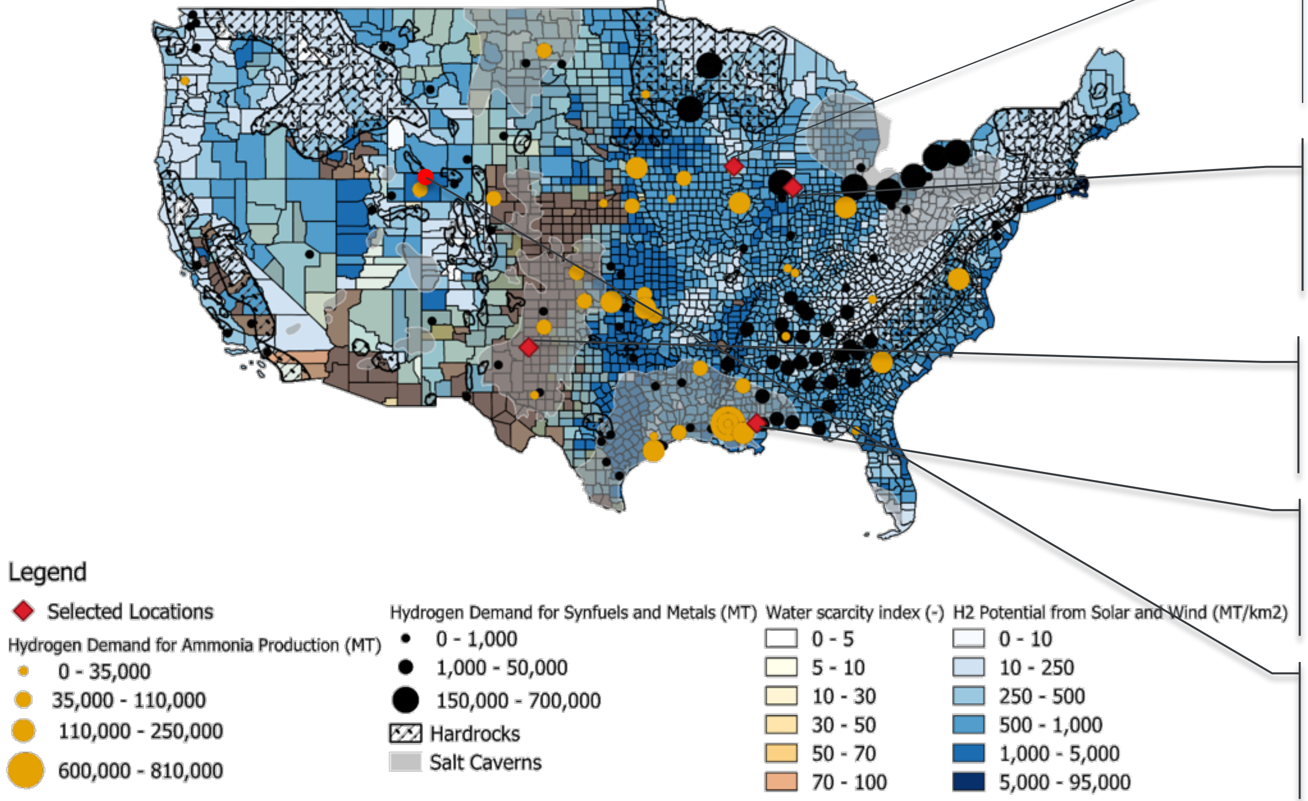
- **Natural gas cost** used for default scenarios is **$5.64/MMBTU** (min: $2.53/MMBTU, max: $11.50/MMBTU)
- Steel & ammonia operated in steady state, sufficient H_2 storage for continuous operation
- Retail rates used for on-grid scenarios – location-specific based on AEO and Cambium database (ReEDS 2021 scenarios)
- H2 storage installed costs:

Storage Type	Storage Cost ($/kg-$H_2$)
Salt cavern	17
Lined-rock cavern	43
Pressure vessel	525

- Compression cost of $39/kW captured separately in the modeling framework

TEA on Five Land-based Locations for Phase I

- Steel and ammonia production are primarily in central U.S.
- Selected initial four central locations for analysis, with various attributes



IOWA
- Existing ammonia pipeline
- Close to ammonia and steel demand centers
- No geologic storage

INDIANA
- Largest steel mill in the U.S. with 8.2 MMT steel/year capacity
- No geologic storage

TEXAS
- Salt caverns and water stress region
- Excellent wind resources

MISSISSIPPI
- Close to existing demand
- Salt caverns

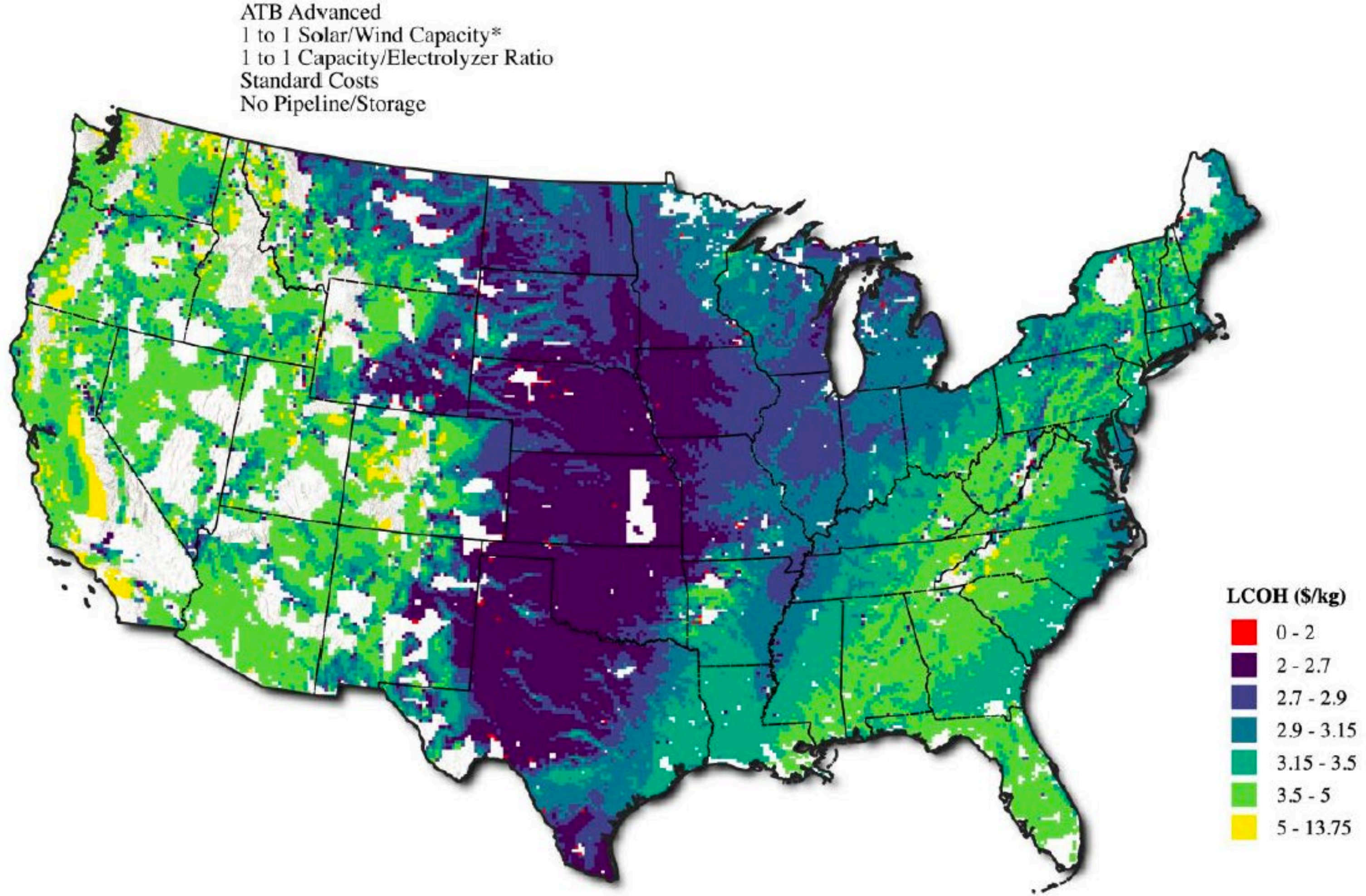
WYOMING
- Best wind resource in the country
- Ammonia production nearby

High Level Insights/Trends

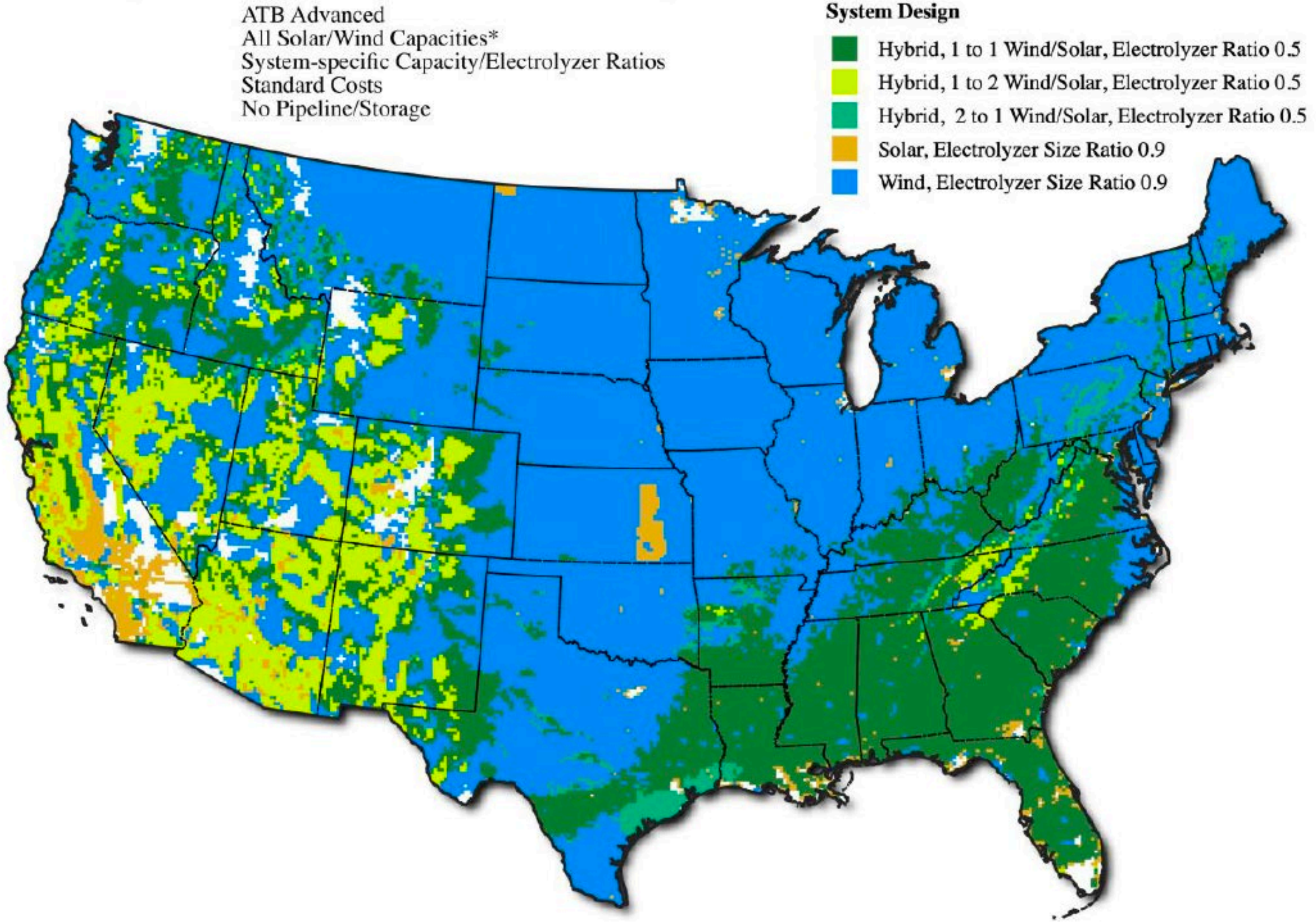
reV Team

Owen Roberts, Travis Williams, Paul Pinchuk

Hybrid System - Levelized Cost of Hydrogen



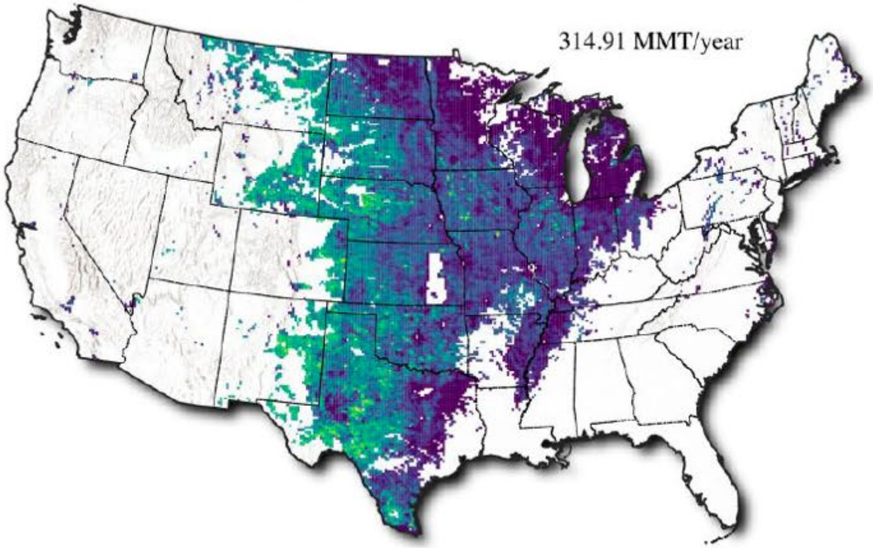
Hybrid System - Least-Cost Systems



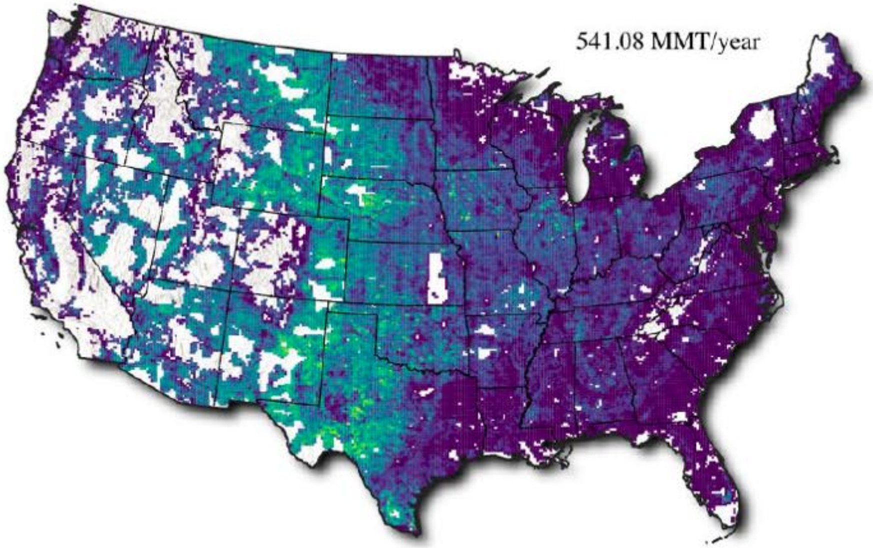
Annual Hydrogen Production Potential - No Pipelines

Hybrid Wind/Solar, 1:1 Capacity Ratio
ATB Advanced
Electrolyzer Ratio 0.5
30 year lifetime

Under $2/kg



Under $3/kg

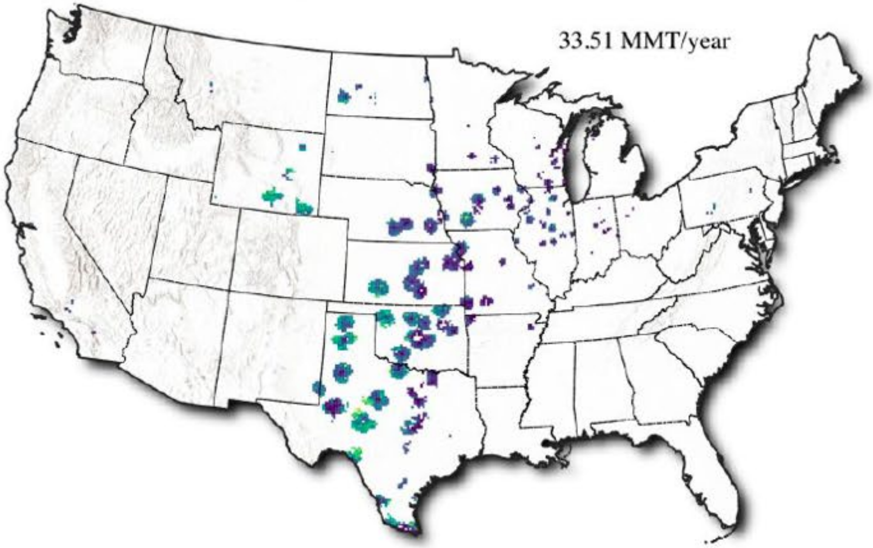


Hydrogen (mt/year)
- 1.144 - 5,000
- 5,000 - 10,000
- 10,000 - 15,000
- 15,000 - 20,000
- 20,000 - 25,000
- 25,000 - 30,000
- 30,000 - 35,000
- 35,000 - 40,000
- 40,000 - 45,000
- 45,000 - 45,513

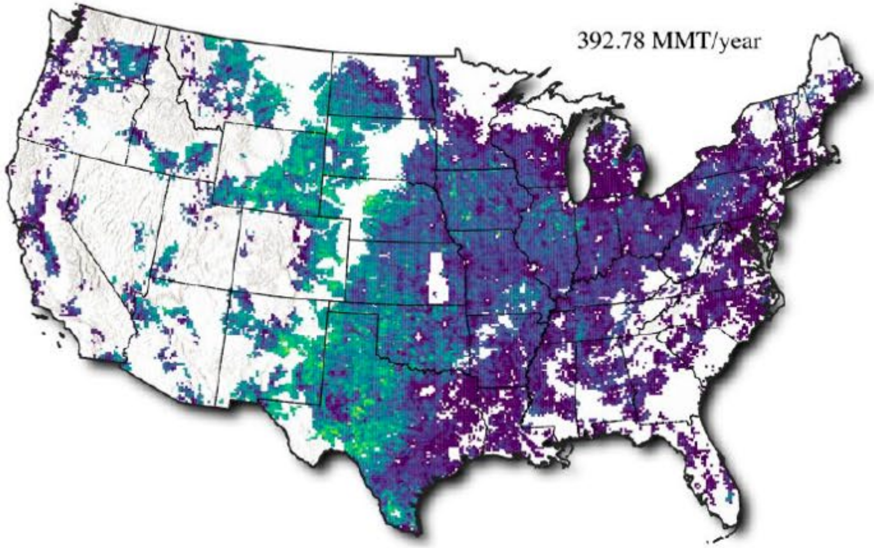
Annual Hydrogen Production Potential - With Pipelines

Hybrid Wind/Solar, 1:1 Capacity Ratio
ATB Advanced
Electrolyzer Ratio 0.5

Under $2/kg



Under $3/kg



Hydrogen (mt/year) 1.144 - 5,000 | 5,000 - 10,000 | 10,000 - 15,000 | 15,000 - 20,000 | 20,000 - 25,000 | 25,000 - 30,000 | 30,000 - 35,000 | 35,000 - 40,000 | 40,000 - 45,000 | 45,000 - 45,513

Key Takeaways – High Level

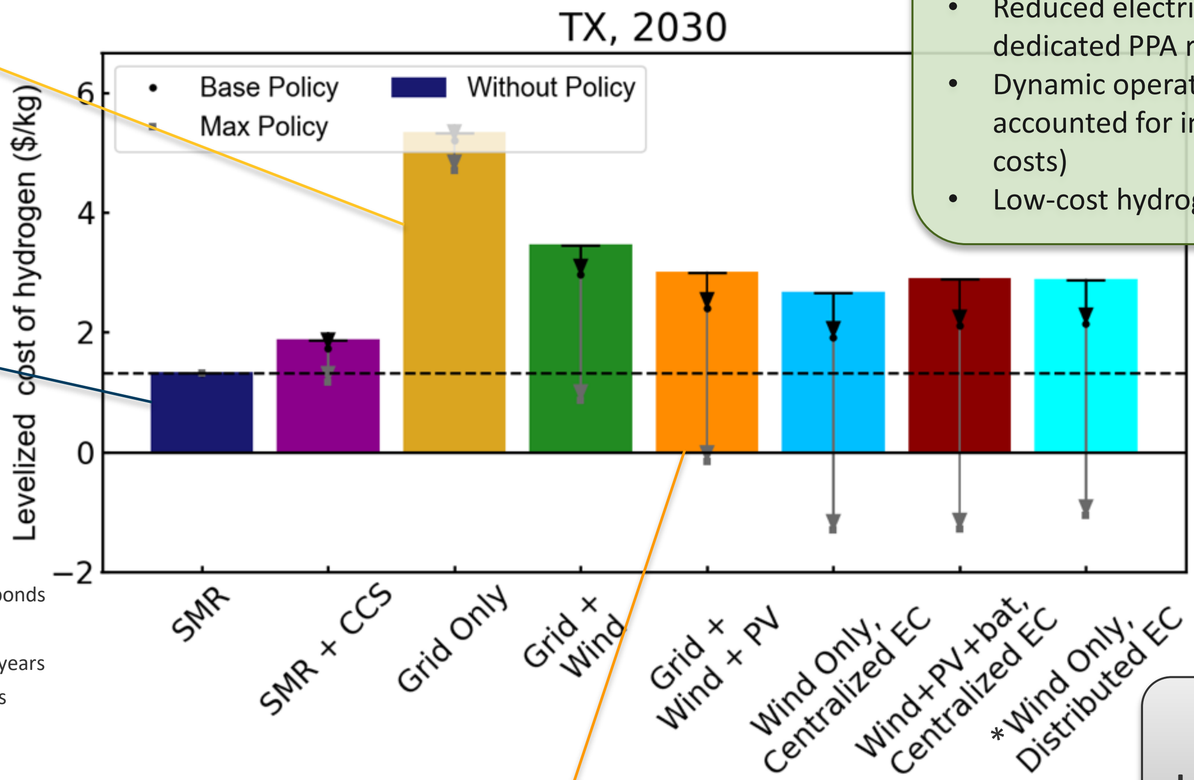
- Hybrid wind-solar PV H_2 systems **reduce LCOH for over 5 TW** of technical potential relative to wind only systems. Assumes 1:1 ratio of wind/PV capacity
- Pipeline use or capacity factor, resource complementarity, and total system cost **drive hybrid cost effectiveness**
- **Reducing or eliminating pipeline costs** increases ECR value resulting in minimum LCOH
- **On site generation applications will likely produce lower LCOH values** with higher ECR values than pipeline connected H2 systems
- Wind generation profile, specific power, and **resource have a large influence** in ideal electrolyzer capacity
- **Lower resource sites result in lower ECR values** due to less wind energy generation at or near rated power
- **High resource sites result in higher ECR values** due to higher energy generation fraction from greater time at rated power
- Sites with LCOH values **<$2/kg show little potential to reduce LCOH by hybridizing**; Some significant exceptions in TX, interestingly at high wind CF sites

Detailed View in 5 Locations

Recall: Delivered LCOH in Best Location Analyzed: Texas, TY 2030

Dependent on electricity price. This plot includes retail rates at 8.6 cents/kWh

PTC credit considered but CCS credit is the more lucrative credit in the best-case scenario



Off-grid costs less than on-grid:

- Reduced electricity costs (retail vs. dedicated PPA results in decrease)
- Dynamic operation of H2 allowed (and accounted for in increased replacement costs)
- Low-cost hydrogen storage (salt caverns)

*Distributed includes electrical efficiency gains ~4%

*Conversion efficiencies are not included in this slide, addressed in backup (only applies to centralized case)

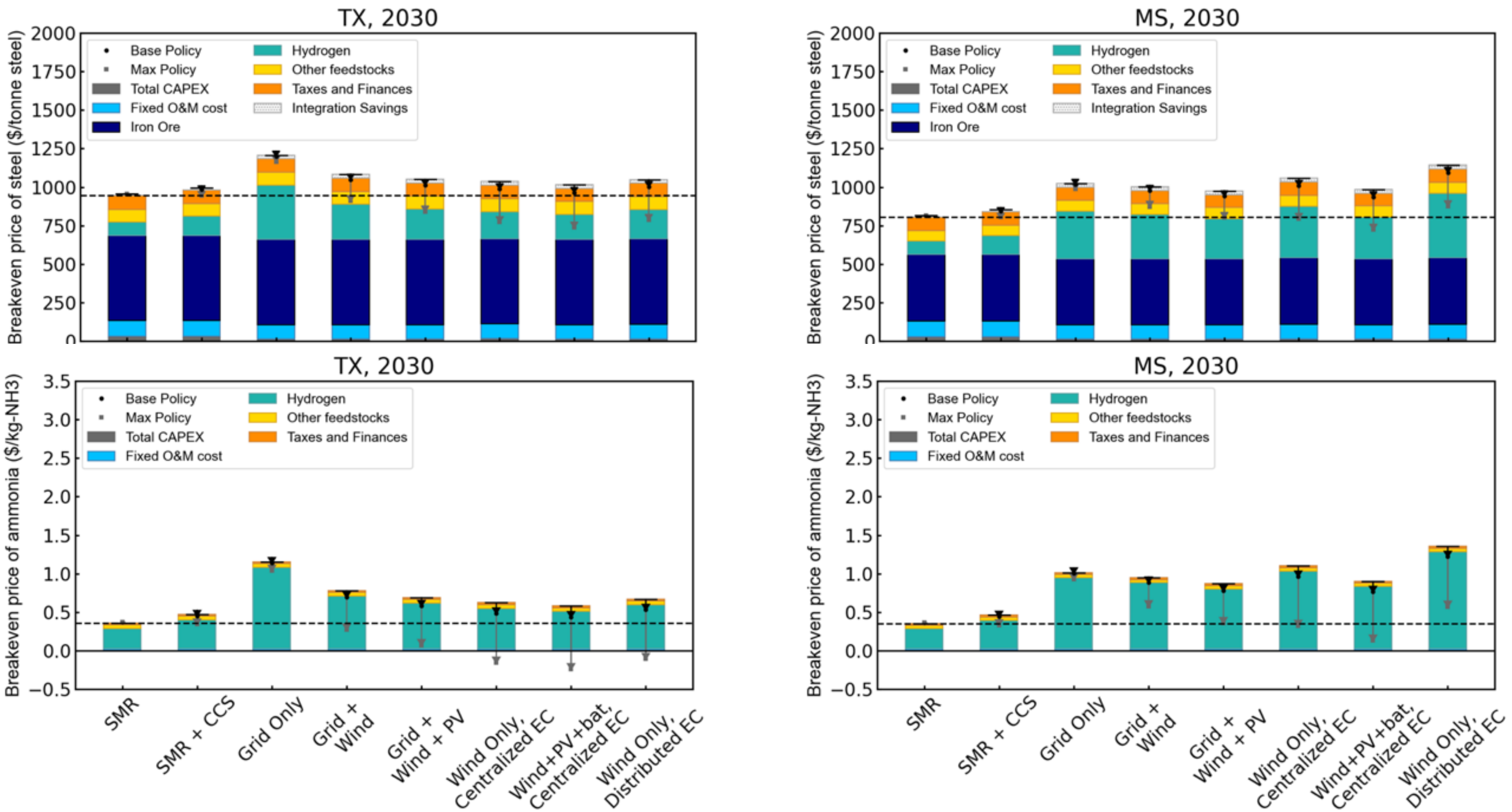
Notes:

- Technology year (TY) 2030 corresponds to operational year 2035
- CCS credit considered for over 12 years
- H2/wind PTC applied over 10 years
- Model does not account for RECs
- **LCOE for TX 2030**
  - Off-grid: 1.3 cents/kWh with PTC
  - On-grid: 8.6 cents/kWh (retail rates), 4.1 cents/kWh (wholesale rates)

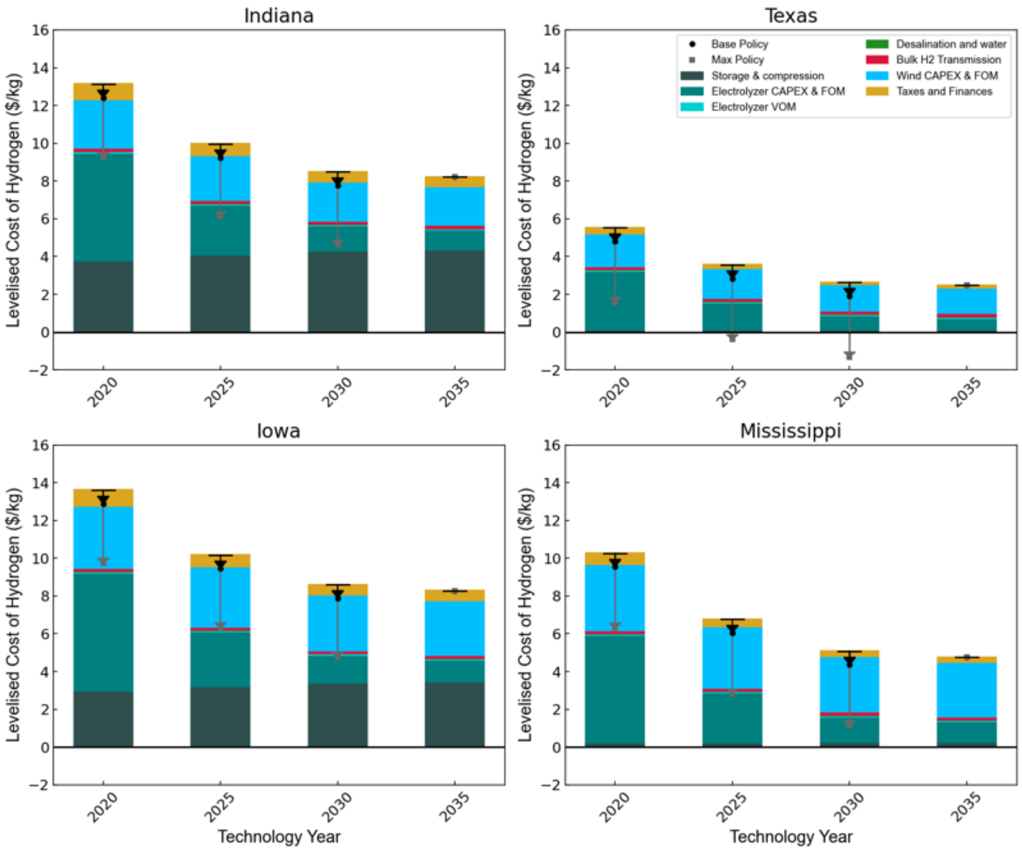
Co-located renewables + electrolyzer backfilled with grid electricity

Key Insight #7: With max policy, all locations compete with SMR

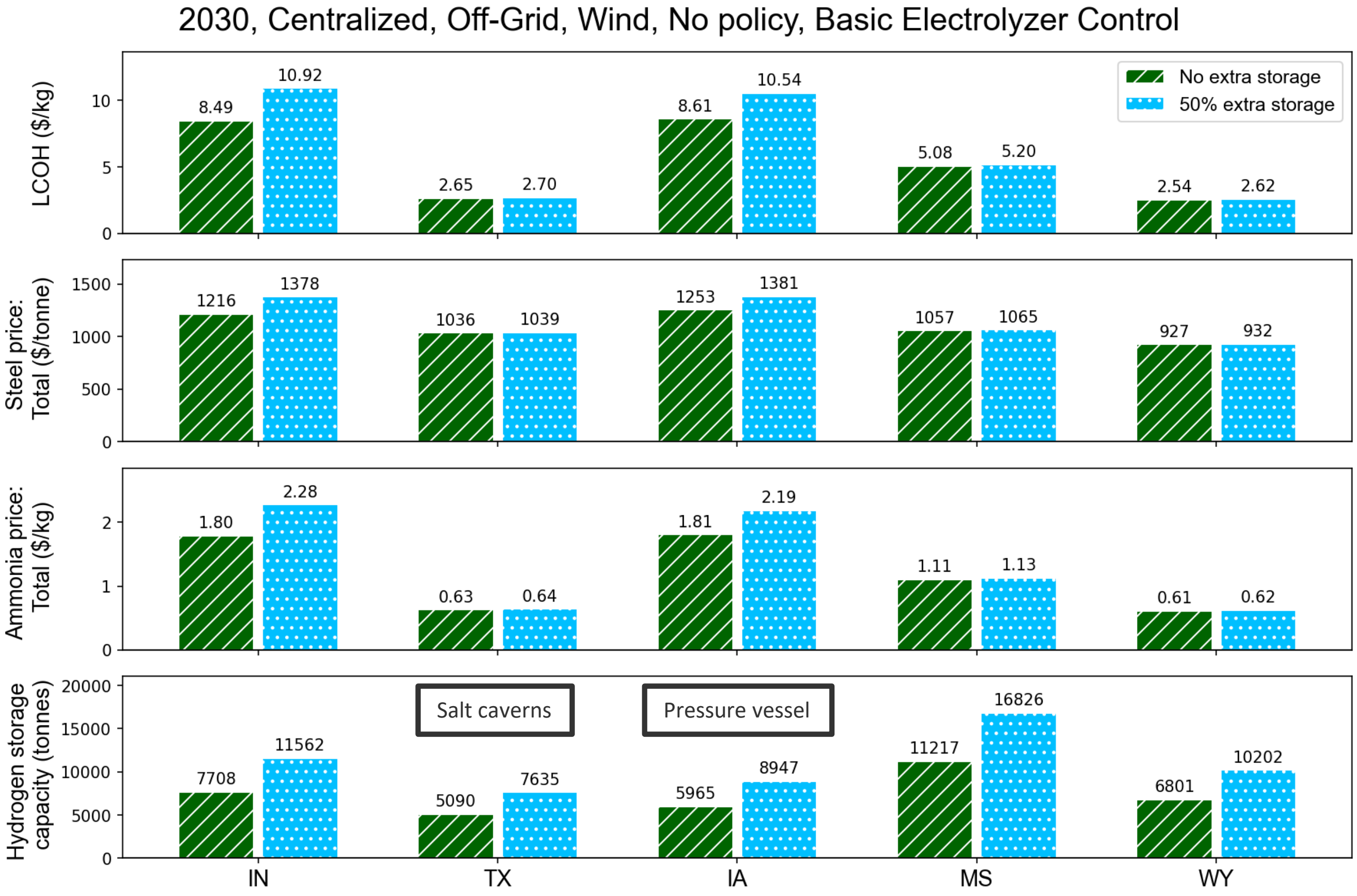
LCOS and LCOA cost competitive with SMR with and without policy



Wind-only (centralized): Locations with geologic storage and excellent wind resource perform best



Sensitivity to Storage Capacity
Viable for Salt Caverns and Prohibitive for PVS



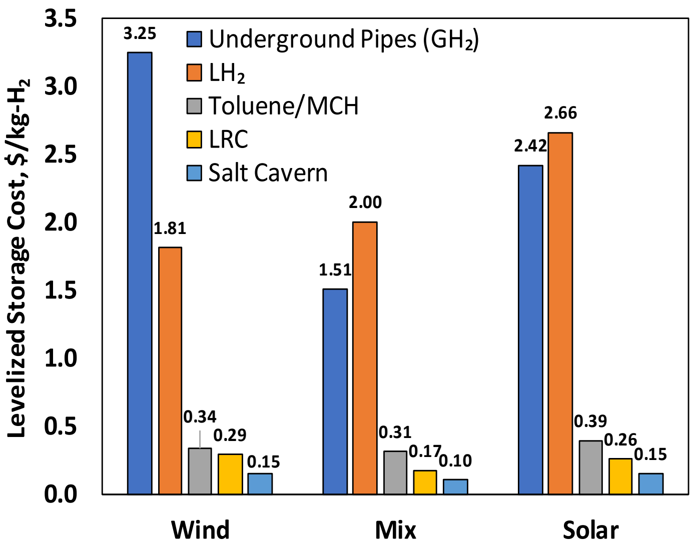
Key Insight #4: Low-cost hydrogen storage is critical

Additional Takeaways

- Adding 50% more storage increases LCOH in all cases.
- Most notably in IA and IN where salt caverns are not accessible.
- Type of storage has a significant impact.

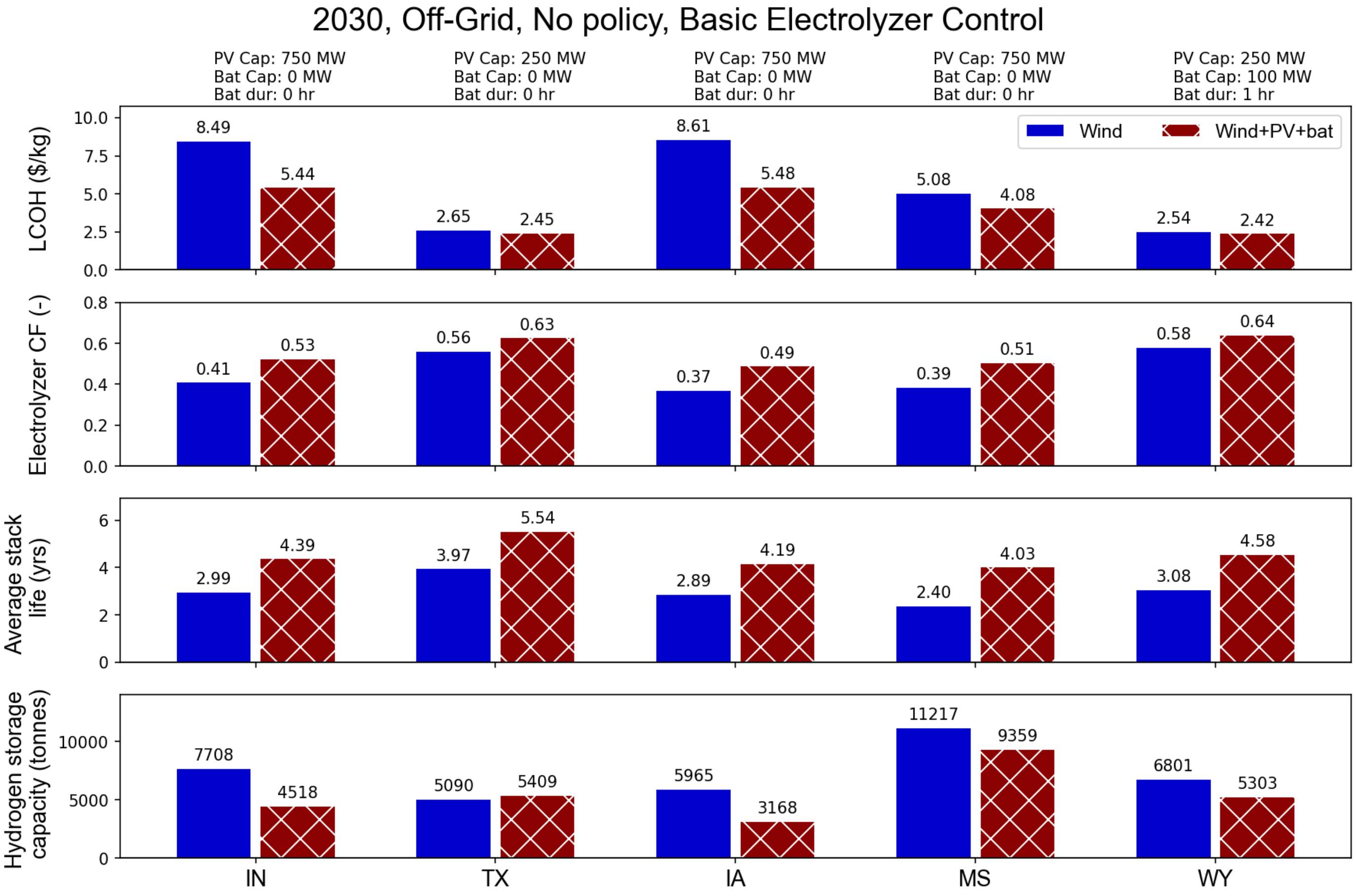
Opportunity space for material storage

Courtesy of LBNL
Hanna Breunig



- Storage cannot cost more than 4x salt caverns to compete with SMR + CCS or 5.3x for SMR
- This also applies to salt caverns deviating from base assumed cost value, which is uncertain.
- Policy credit is key
- Off-grid tends to look better than grid connected
- Closely coupling renewables and electrolyzers offers savings but there are other factors that impact costs more (like storage)

Adding Solar to Wind Can Decrease LCOH Significantly

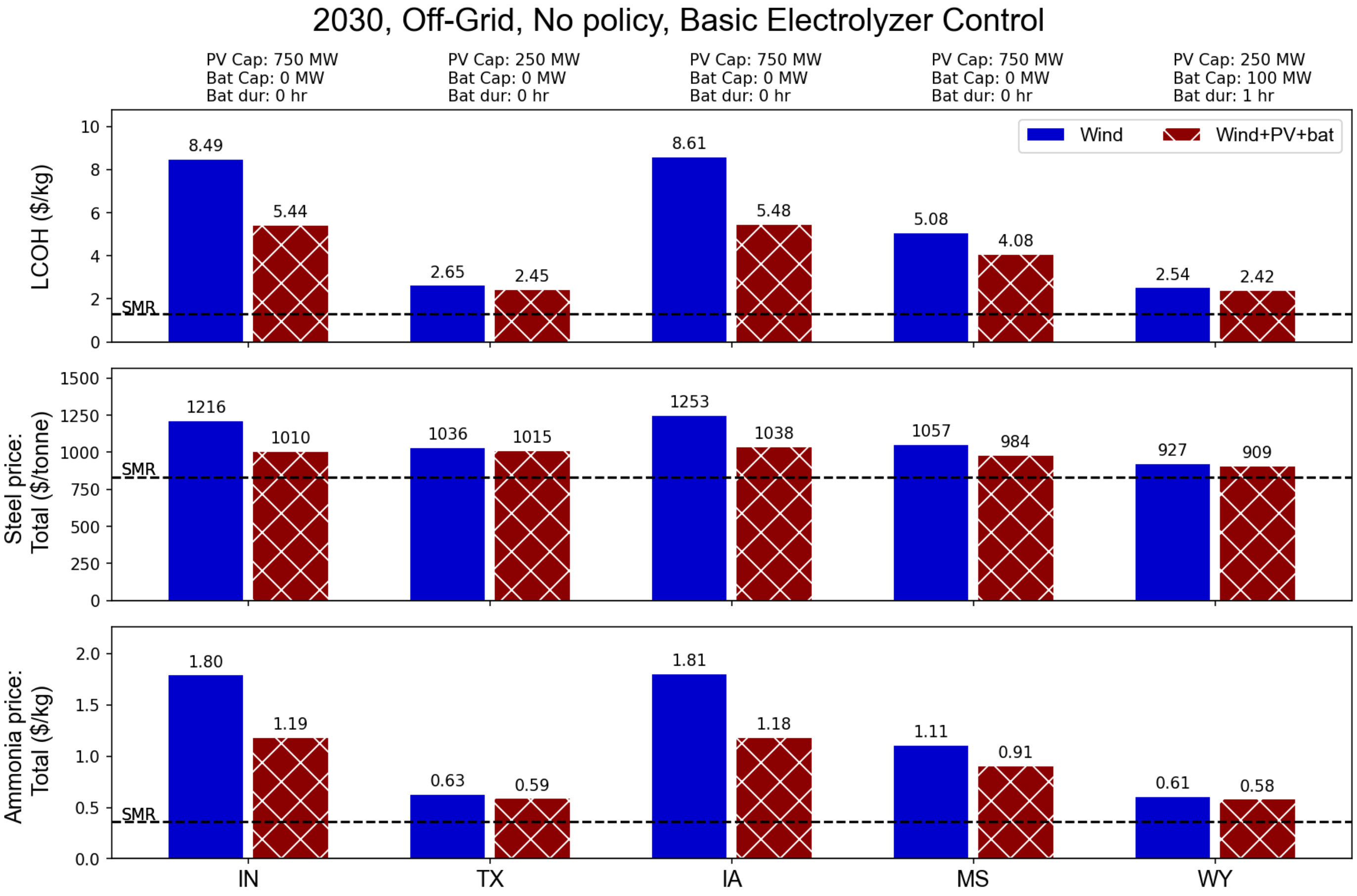


Key Insight #5: Hybrids have significant impact on LCOH

Additional Takeaways

1. Reduce LCOH by 35%
2. Improve CF of PEM by up to 30%
3. Significantly improve lifetime of PEM
4. Reduce hydrogen storage duration by half in some cases.

Steel and Ammonia with Wind-Solar Hybrids, No Policy

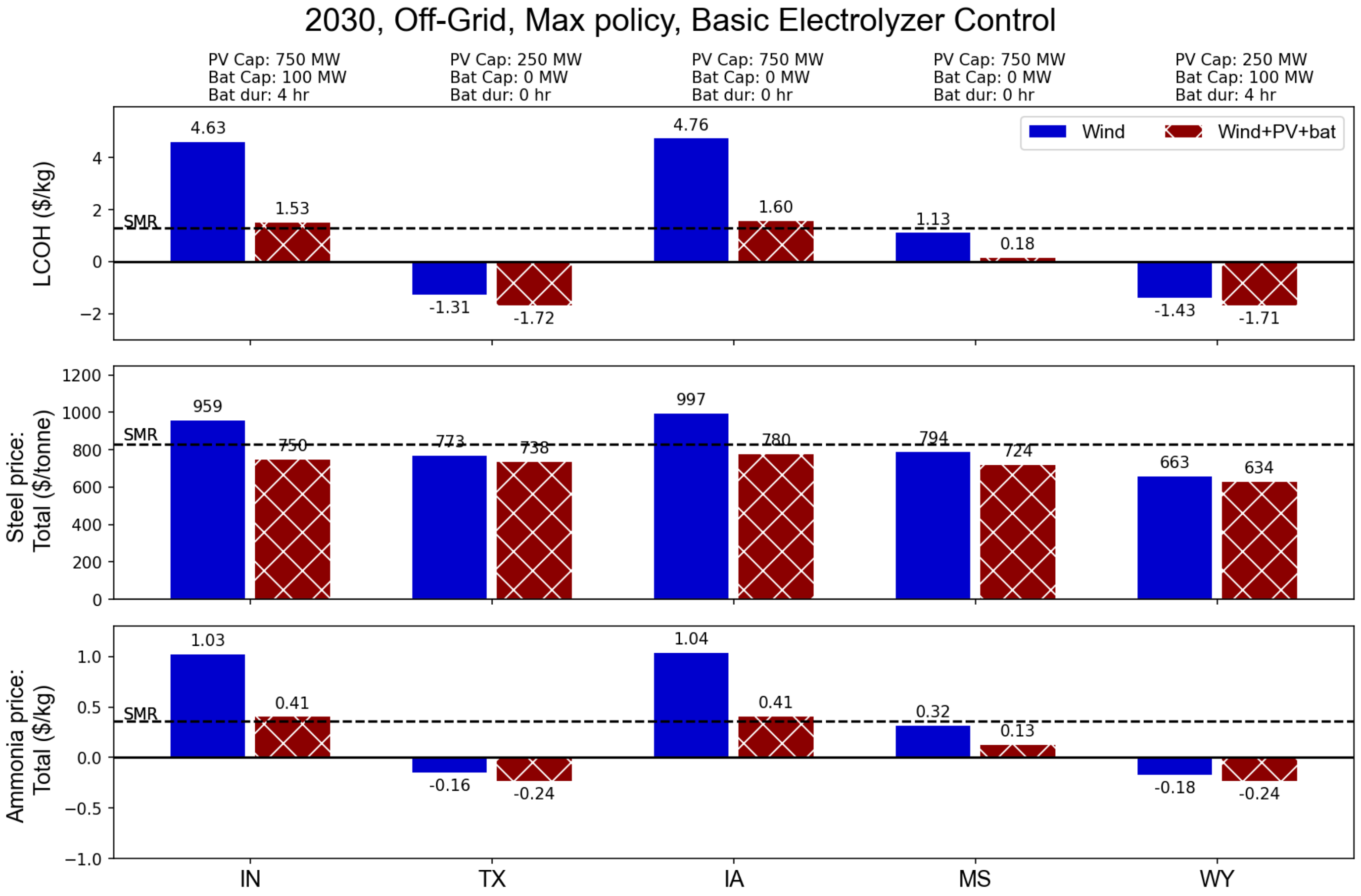


Key Insight #5: Hybrids have significant impact on LCOH

Additional Takeaways

1. LCOH is reduced by up to 35%
2. LCOS is reduced by up to 17%
3. LCOA is reduced by up to 35% (mostly driven by LCOH)

Steel and Ammonia with Wind-Solar Hybrids, Maximum Policy



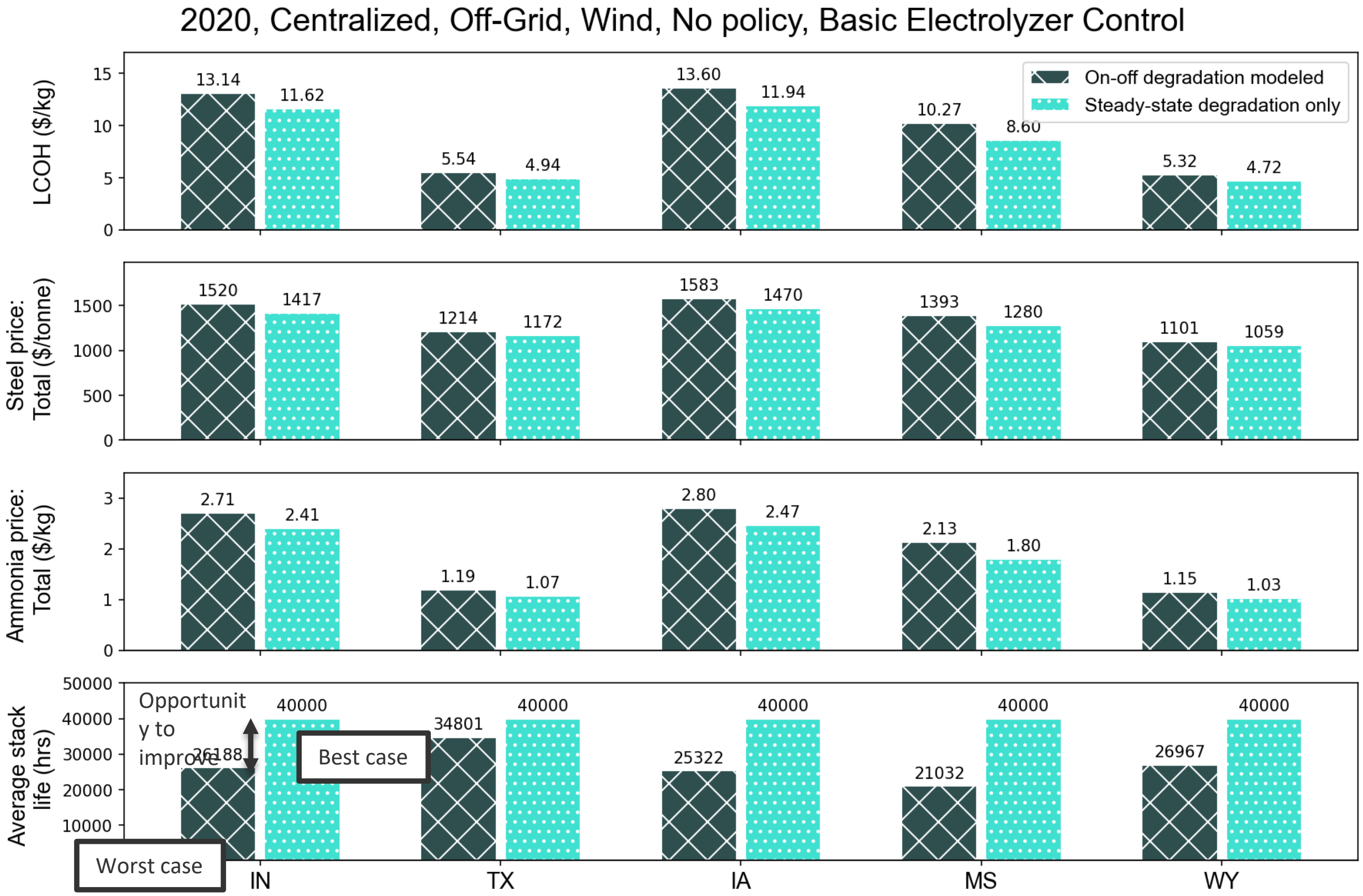
Key Insight #7: With max policy, all locations compete with SMR

Additional Takeaways

1. Adding max policy makes **hydrogen cost competitive in all locations** by 2030

2. Steel and ammonia are competitive in all locations

Does Degradation Impact LCOH?

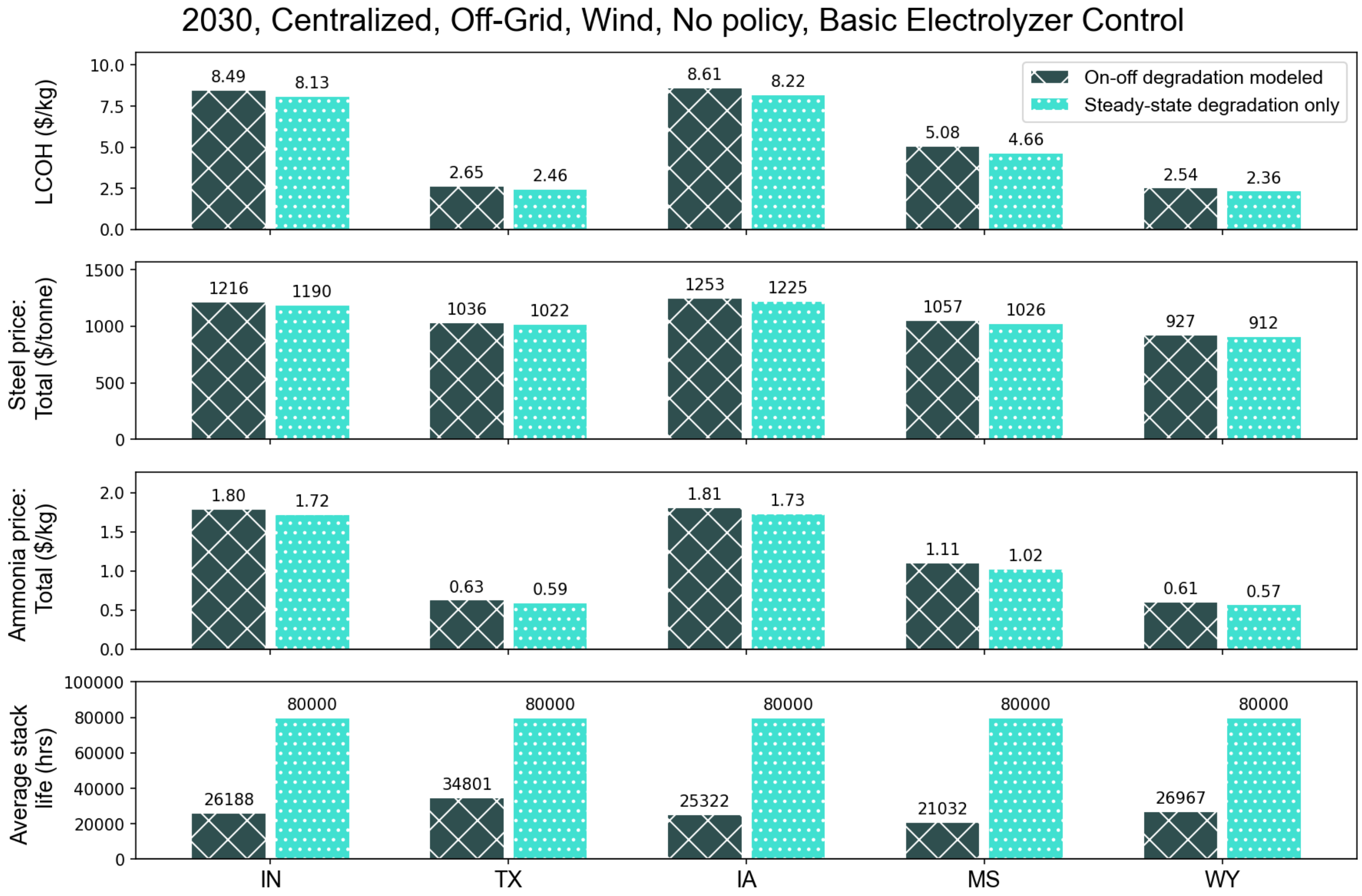


Key Insight #6: Impact of degradation is smaller than expected

Additional Takeaways:

- H2A assumption for stack replacements cost is 15% of capex.
- Improvements to lifetime do not significantly impact LCOH (~12% reduction possible).

Does Degradation Impact LCOH?



Key Insight #6: Impact of degradation is smaller than expected

Additional Takeaways:

- Degradation *minimally* impacts LCOH when using super aggressive electrolyzer costs ($200/kW).
- H2A assumption for stack replacements cost is 15% of capex.

Technology Transfer Activities

- Software record submitted
- Energy I-Corps being pursued
- Future fundings: IEDO, OCED, Industry partners being pursued
- Marketing strategies:
  - We hope to leverage and learn effective strategies through Energy I-Corps.

Special Recognitions and Awards

- N/A

Publications and Presentations

- Draft manuscript to Joule in preparation on Phase 1 results
- Webinars on offshore wind and energy storage and renewable hydrogen