NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Design of wind-based hybrids for grid integration

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August 31, 2022

Goal: Decarbonization

100% clean electricity by 2035

100% clean energy across all sectors 2050

We need 5.6X as much RE generation to meet the 2035 100% goal

Main Risks/Challenges: Highly uncertain if large transmission capacity addition is possible

Our Working Premise: We can meet the 100% clean electricity goal by 2035 with minimal new transmission, minimize the strategic risk.

*Note: transmission in this presentation refers to interstate and inter-regional transmission, rather than transmission capacity needed for new plants to interconnect to local intra-state and intra-regional grids.

Goal: Decarbonization

100% clean electricity by 2035

100% clean energy across all sectors 2050

We need 5.6X as much RE generation to meet the 2035 100% goal

Main Risks/Challenges: To avoid stranded assets and maximize the use of existing interconnection points, co-located wind-based hybrid systems will play a significant role.

Our Working Premise: We can meet the 100% clean energy sector goal by 2050 with focus on RE fuels.

As we prepare for a future of 100% renewable energy…

Hybrid plants will have to play a crucial role in providing services across a **range of timescales (sub-seconds to day-ahead)**.

How do we design hybrid plants with such capabilities?

"Design for Operation"

__Objective:__ Develop **modeling** and **optimization** techniques to design, operate, and analyze hybrid power plants for grid services across a range of timescales from sub-second to day-ahead services.

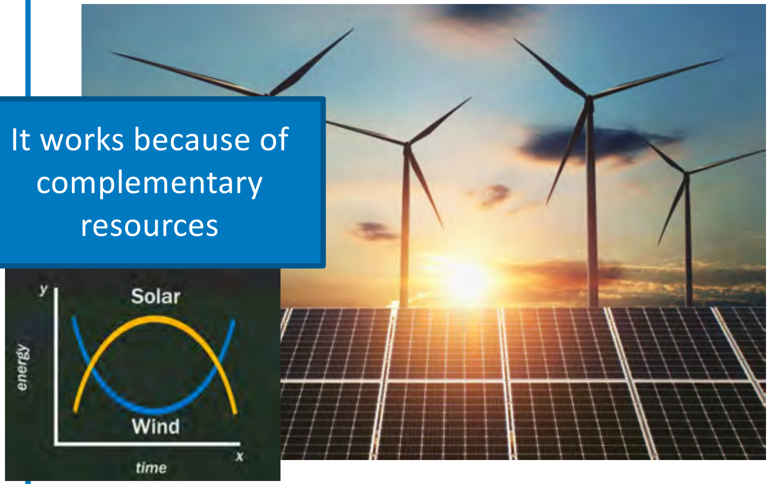
Innovation: Understand and exploit the dynamic interactions of technologies across timescales to design disruptive hybrid energy systems.

We can do this with hybrid systems

Combinations of *mature* technologies can provide services needed to reach goal

Adding solar to existing onshore wind

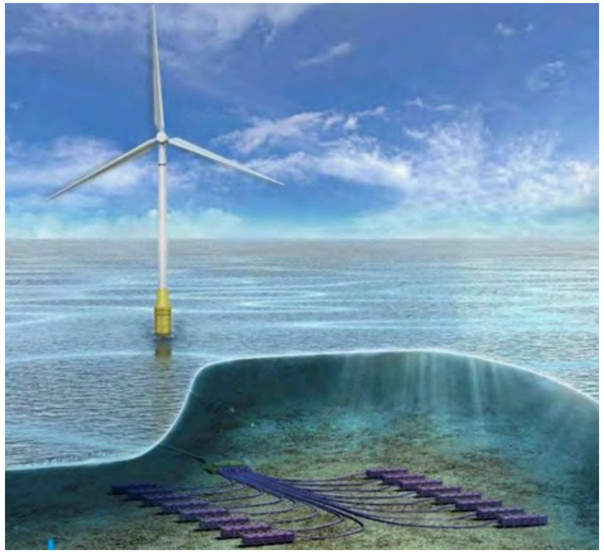
(Maximize current interconnects)



It works because of complementary resources

Easy win – add 30+ GW of solar to wind in next few years

Offshore Wind + Storage



Enables long term storage and grid-independent utility scale energy systems.

Wind-solar-storage

(Greenfield)

Optimal design for a highly customized system to achieve different services.

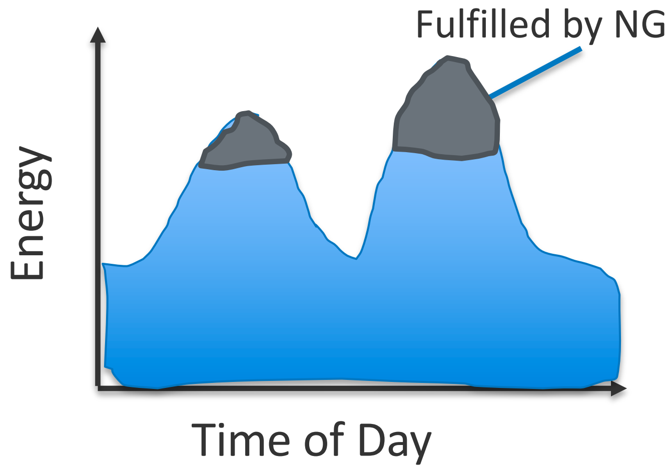
Hybrids Are Highly Customizable

Each will require different designs and operation

Baseload Power

Hybrids can replace coal and natural gas to provide local baseload.

Time Dependent Power



Guaranteed power at the most vulnerable parts of the day

Grid Services

Frequency response
Active generation control
Ramping up/down
Bulk energy

Additional Benefits of Hybrids

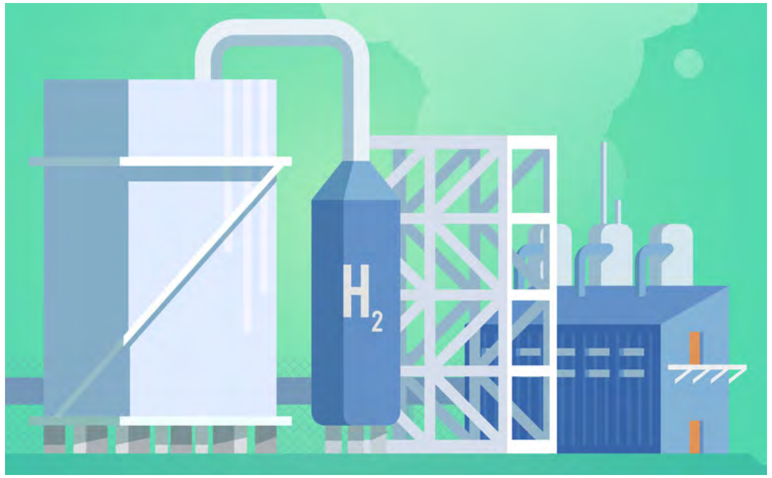
Firm power does not mean ONLY electricity; avoid stranded assets

Firm Power - Electricity

Hybrids can provide certainty of energy generation.

H2 (dual-purpose)

(Ammonia, etc.)



Long-term storage, decarbonizing transportation, drive demand

Other Value Streams

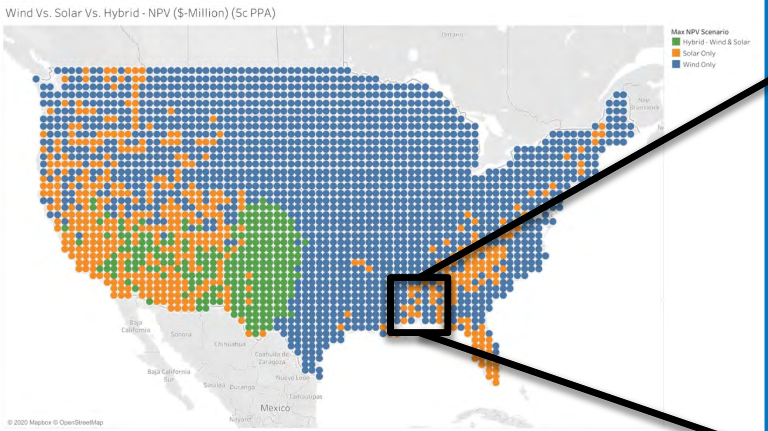
(Carbon capture, desalination)

If grid connected, use excess energy to sell to the grid.

The cheaper we can make electricity means the faster these markets are unlocked

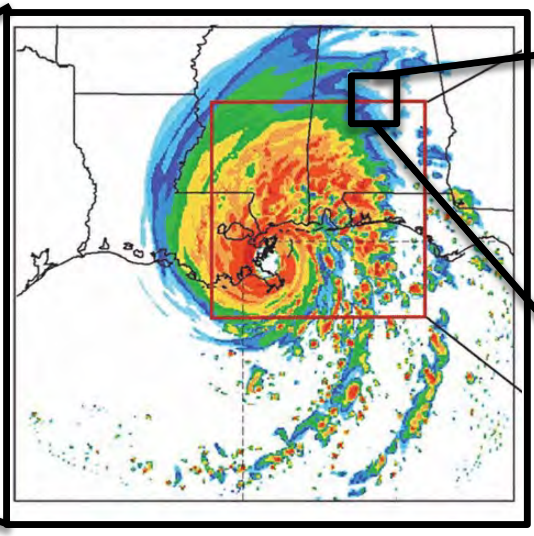
Facilitate Large-Scale Deployment of Hybrids

Techno-Economic Analysis



Investigation of resource mix and deployment. Balance between battery storage and alternative fuels.

System and Plant level design and control



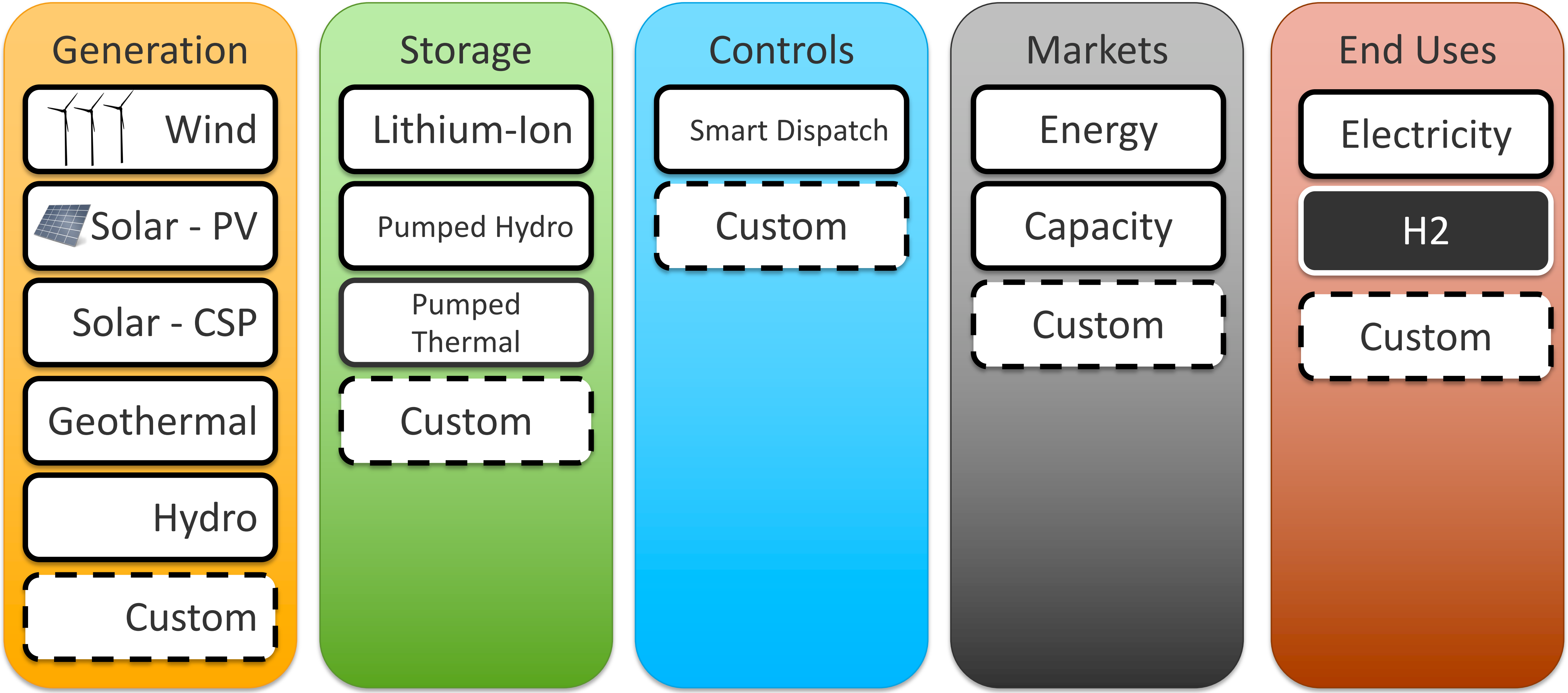
Optimally design and operate plants to achieve different objectives

Hardware and Grid Strength

Support a grid that is 100% inverter-based. Need for inertia, blackstart capabilities.

HOPP –Hybrid Optimization and Performance Platform

- Software developed under NREL – **HOPP** – Hybrid Optimization and Performance Platform
- Optimize co-located, utility-scale hybrid plants down to the component level for different markets



HOPP Integration with Other Tools for End-to-End Analysis

Location info and wind/solar resources | Detailed system design | Location-based cost of H2

System Sizing Design

REopt: optimize energy systems; optimal mix of technologies

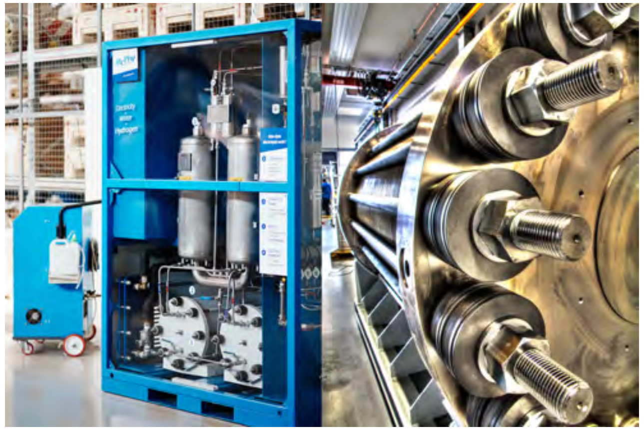
REopt
Renewable Energy Integration and Optimization

Technology Innovation

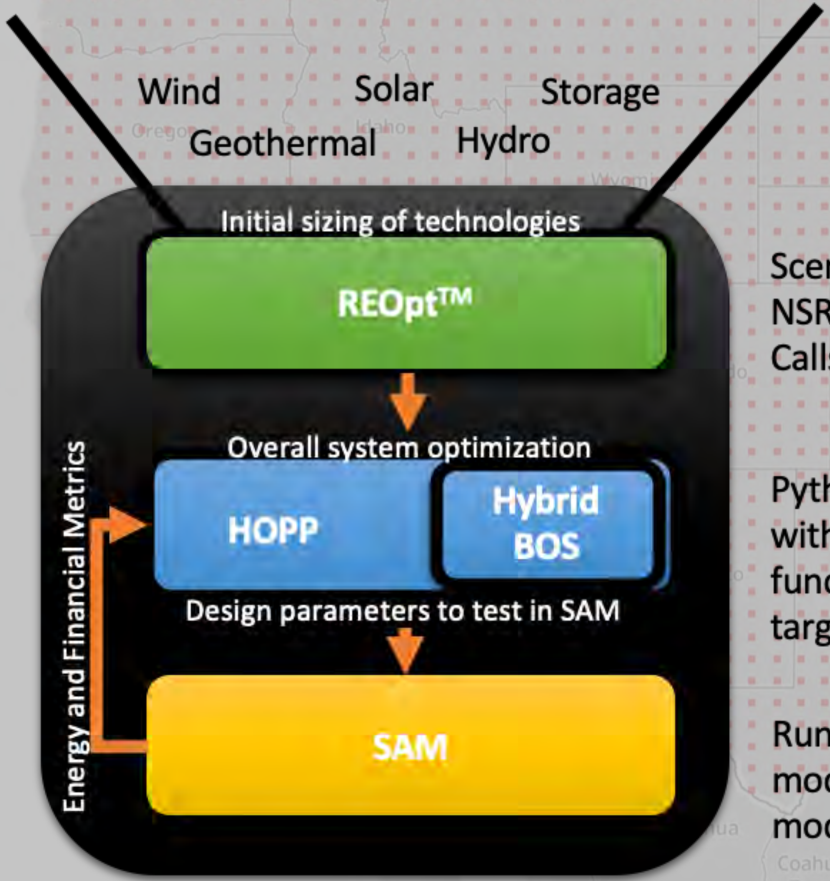
HOPP: Integrated design of hybrid plants at the component level (ex: wind turbine, solar panel, battery, PEM design, performance, and cost)

Hydrogen

H2A: Hydrogen analysis production analysis.



HOPP – Hybrid Optimization and Performance Platform



Repeat until **convergence** on a feasible and economically viable solution

Scenario setup: interface with NSRDB, WindToolKit, URDB, Calls the REOpt API

Python-based optimization with customize objective function depending on the target markets

Run SAM performance models and financial models

Wind Design Variables

1. # of turbines
2. (x,y) locations – layout
3. Hub height
4. Rotor diameter

Solar Design Variables

1. # of panels in a row
2. # of rows
3. Tilt angle
4. Spacing between rows
5. *Future:* controls

Storage Design Variables

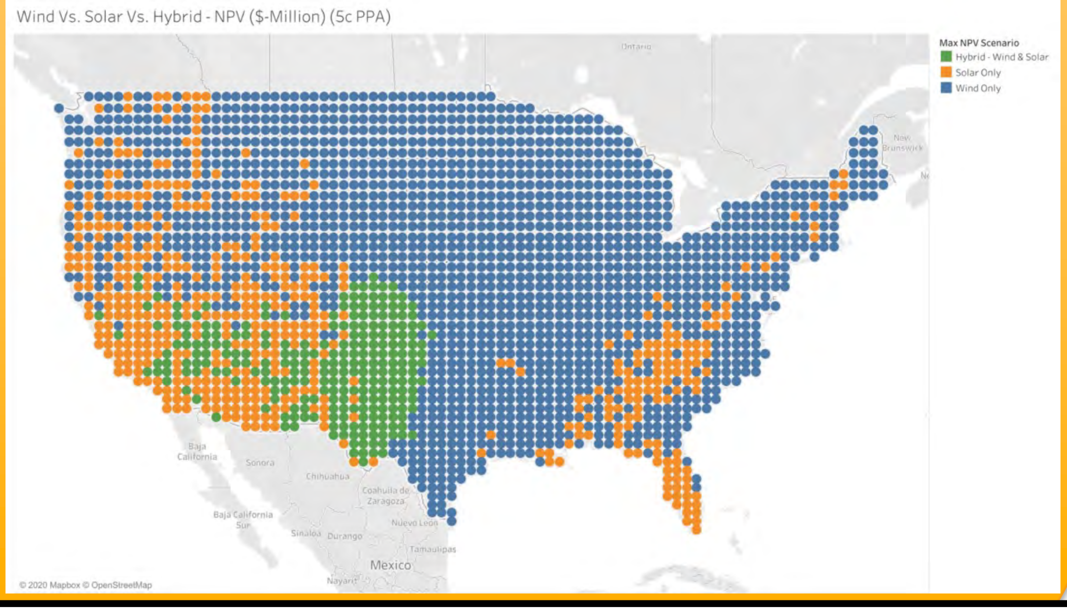
1. Charge/discharge rate
2. Operational time scale

HOPP Capabilities

Analysis

Where to build co-located hybrid plants?

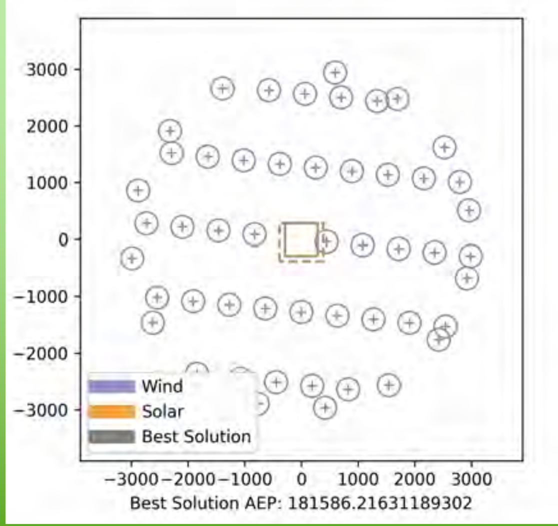
- Resources are complementary
- Overbuild (Ex: 200MW plant at 100MW interconnect)
- Include storage



Strong solar during day and strong wind at night

Optimization

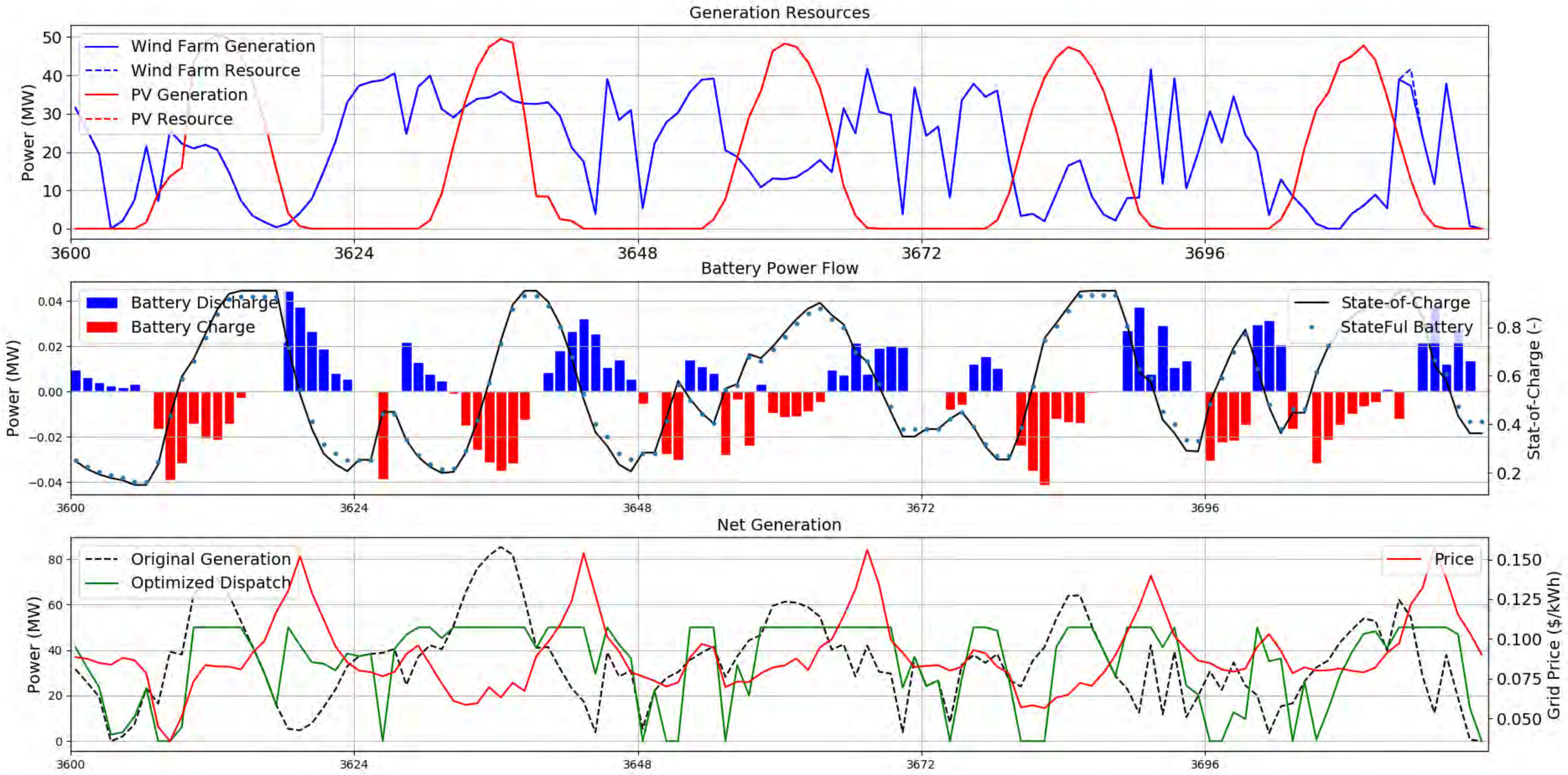
Optimize hybrid plants down to the *component* levels



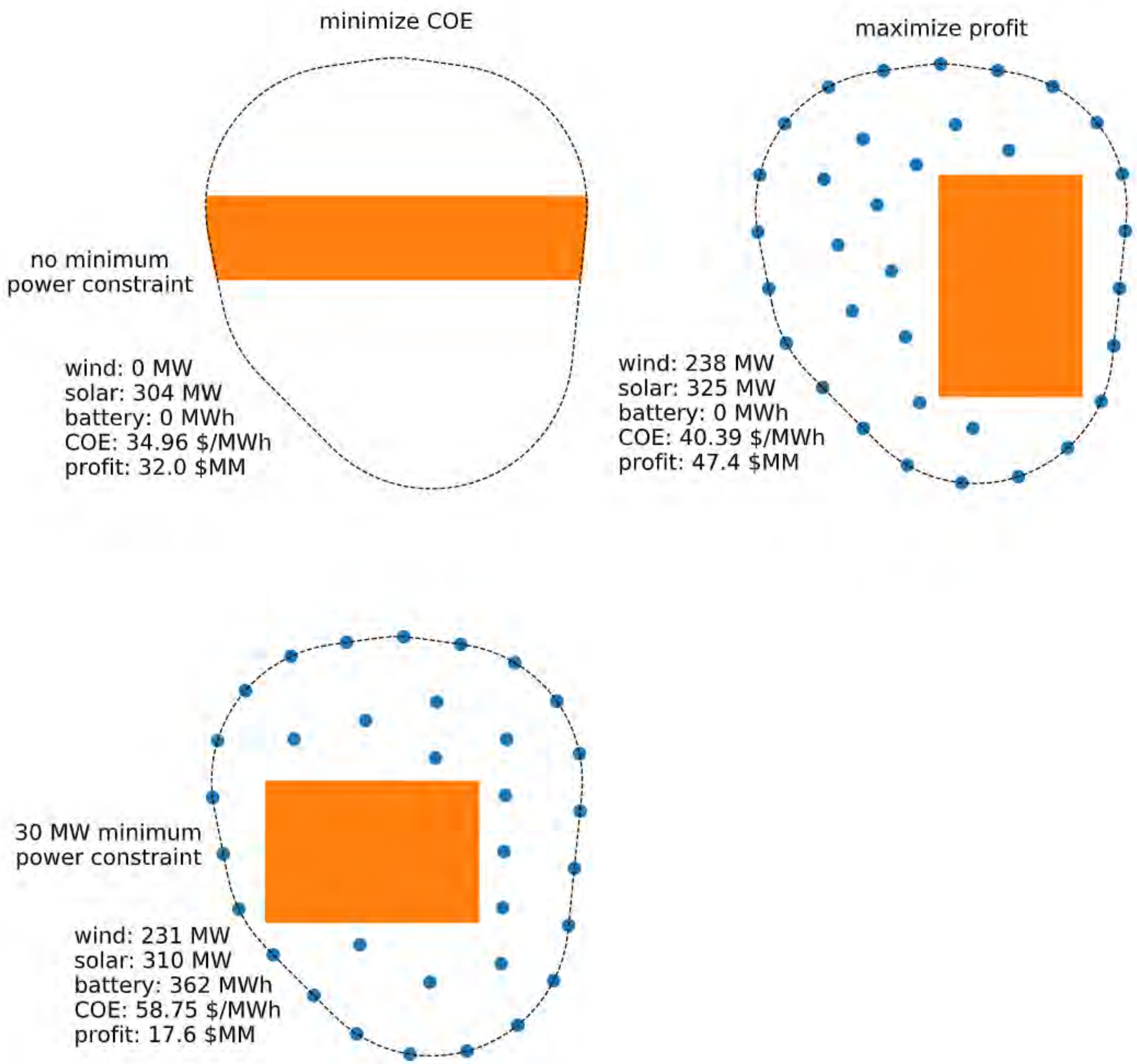
Control/Dispatch Algorithms

- **Wind-solar-storage** dispatch algorithms developed in HOPP
- Operation of plants down to the **1-minute timescale**
- Improve performance of hybrid power plants by > 5%

Dispatch Optimization Results – With Forecasting

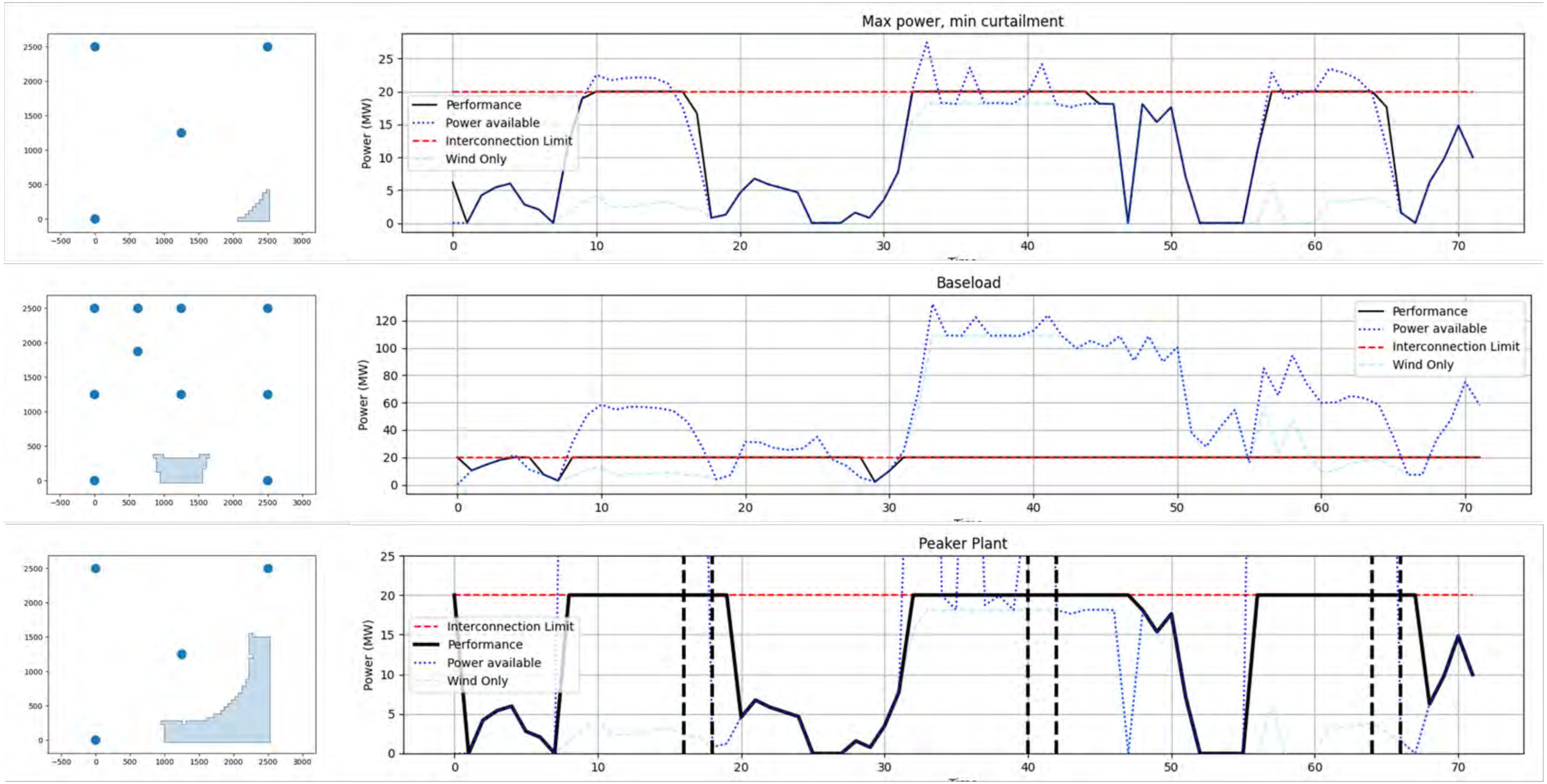


Different Objective Functions



- Highly dependent on resource available
- Highly dependent on objective function
- Optimization approach can handle multiple timescales

Replace Coal and Natural Gas Plants



Hybrid Systems Enable Cost-effective Hydrogen

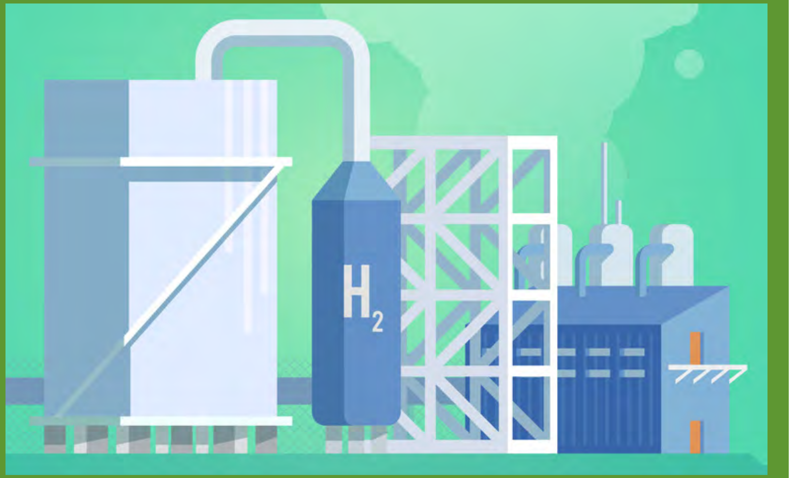
Firm power does not mean ONLY electricity

Firm Power - Electricity

Hybrids can replace coal and natural gas to provide local baseload.

H2 (dual-purpose)

(Ammonia, etc.)



Long-term storage, decarbonizing transportation, drive demand

Other Value Streams

(Carbon capture, desalination)

If grid connected, use excess energy to sell to the grid.

The cheaper we can make electricity means the faster these markets are unlocked

Major Components: Wind-H2 Systems

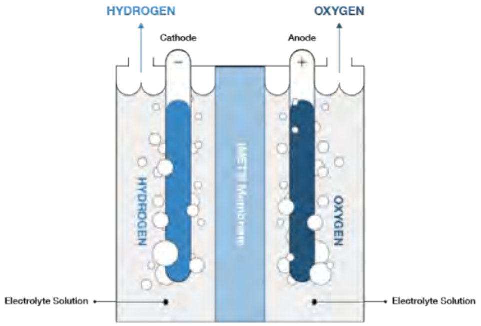
On vs. Off-grid systems

Demonstrate the cost-tradeoffs between on/off grid with ultra-cheap energy.

Impact: can cost-effectively build in remote locations without transmission

Electrolyzer

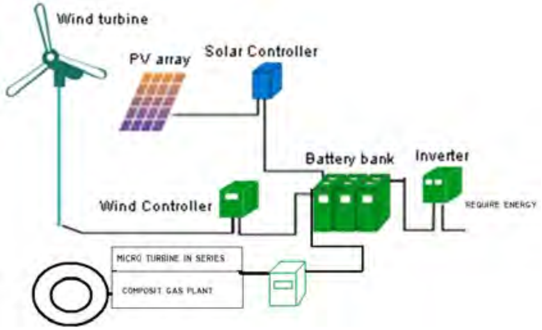
Game changer technology that works with variable power that can minimize storage needs.



Impact: achieve \$1/kg H2 faster than constant power

Optimal Design

Optimal design can inform the user how to design their power plant for different objectives.

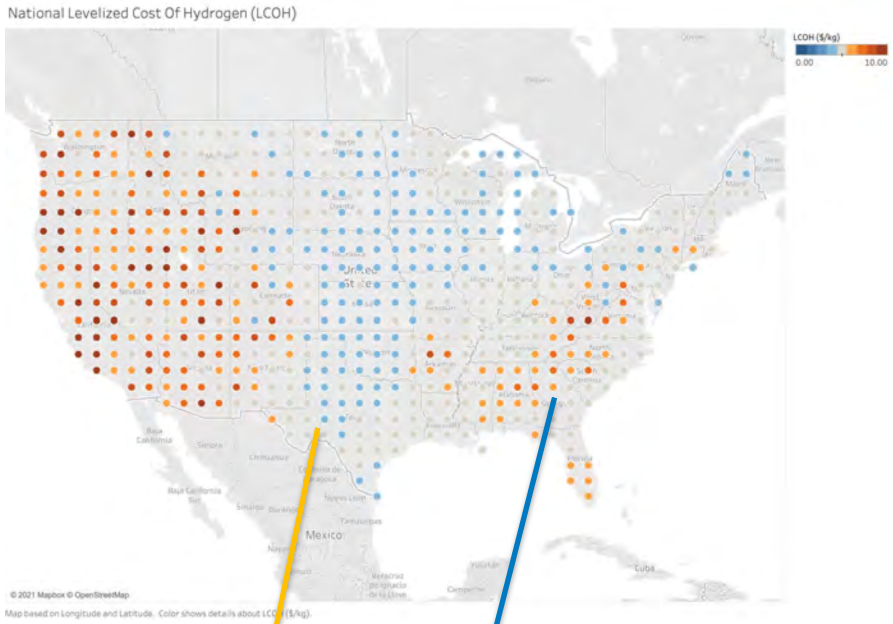


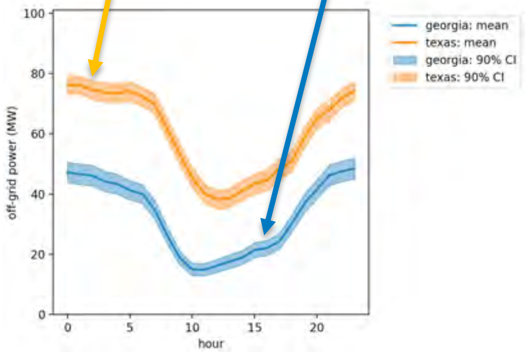
Impact: different designs are required for different objectives/markets/locations.

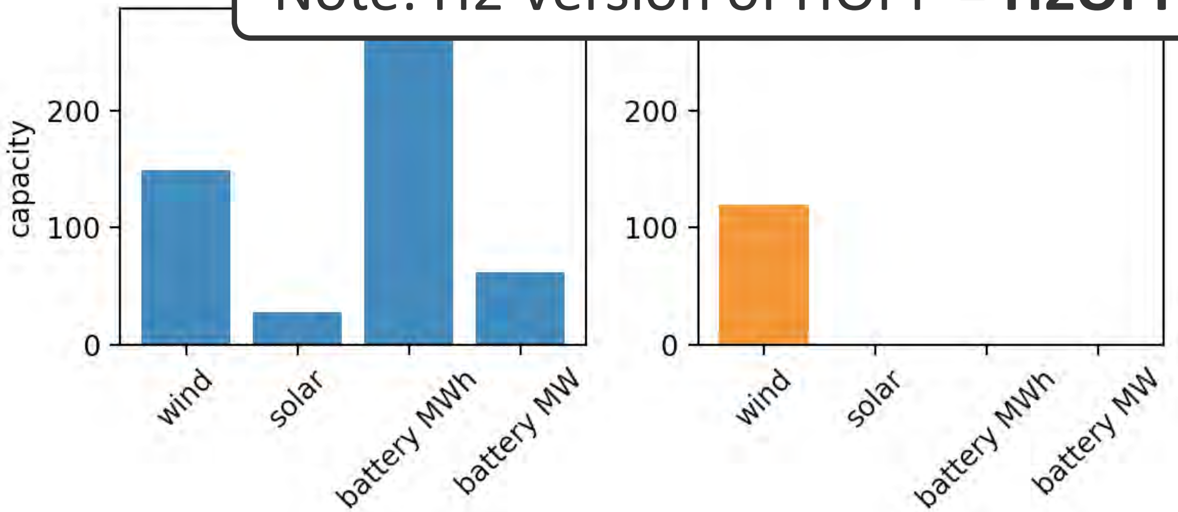
Analyze any combination of technology, cost, policy configuration in near-real-time, at very fine spatial resolution.

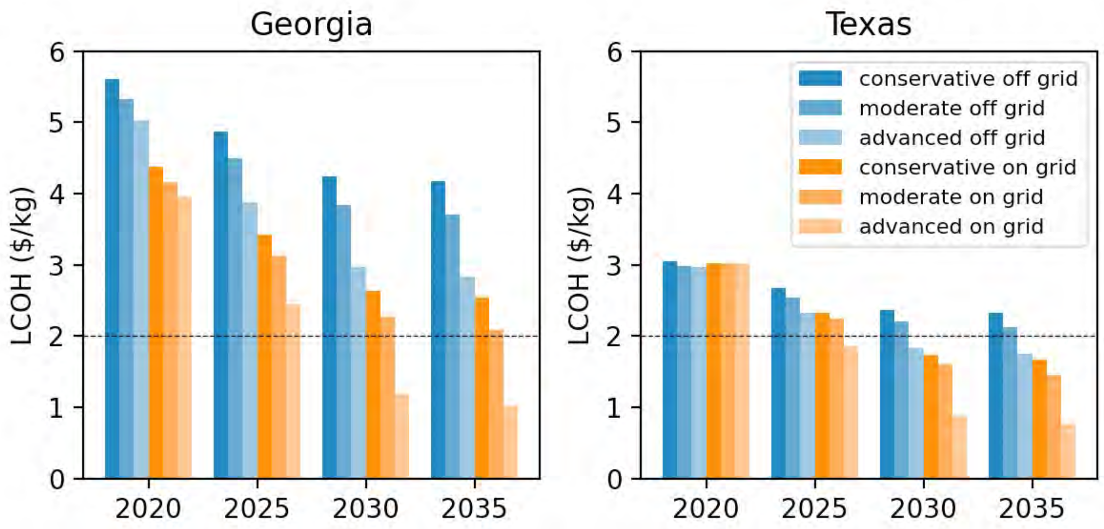
Example 1: Optimal On-grid vs. Off-grid System

Note: H2 Version of HOPP = **H2OPP**





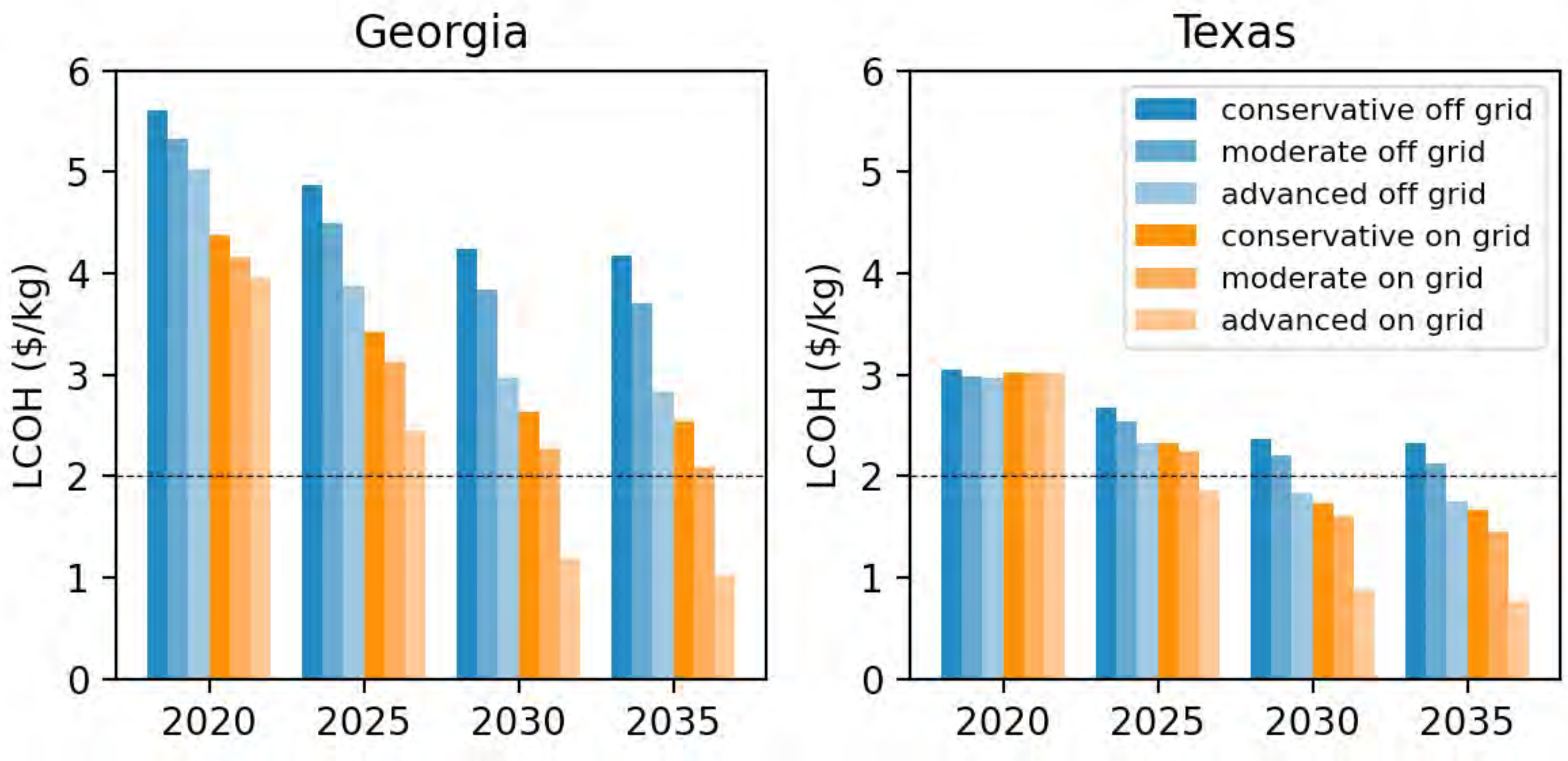




Each result is using the optimal plant + electrolyzer size for that location (resource) and cost scenario

Example 1: On-grid vs. Off-grid System

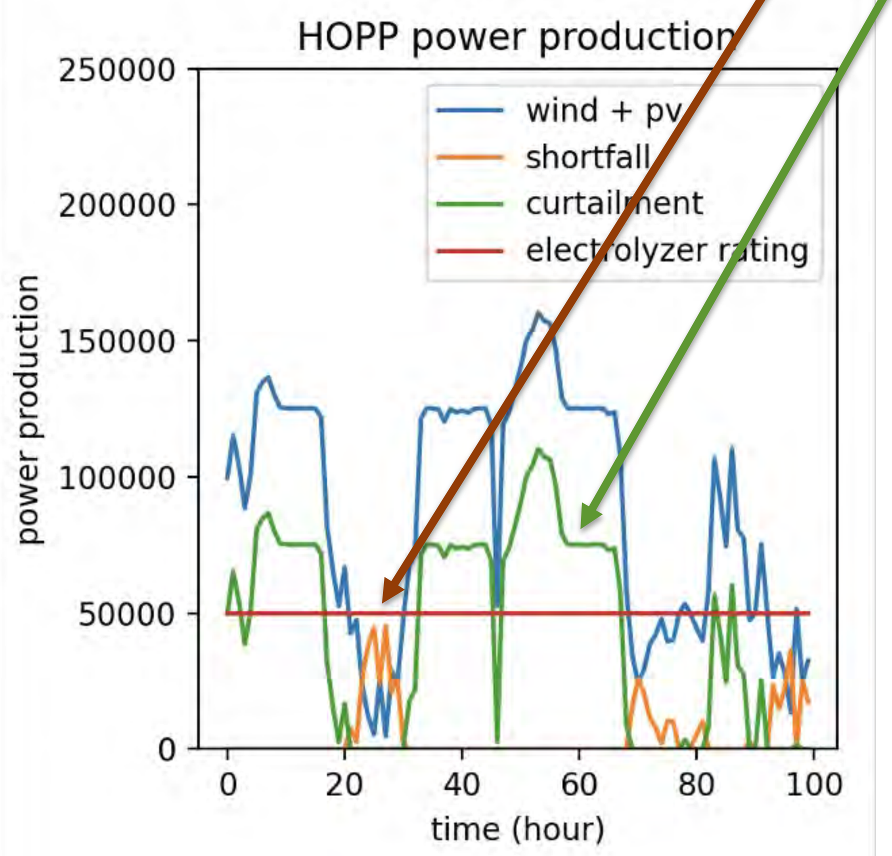
H2OPP can look at future technology innovations expected and their impacts across regions

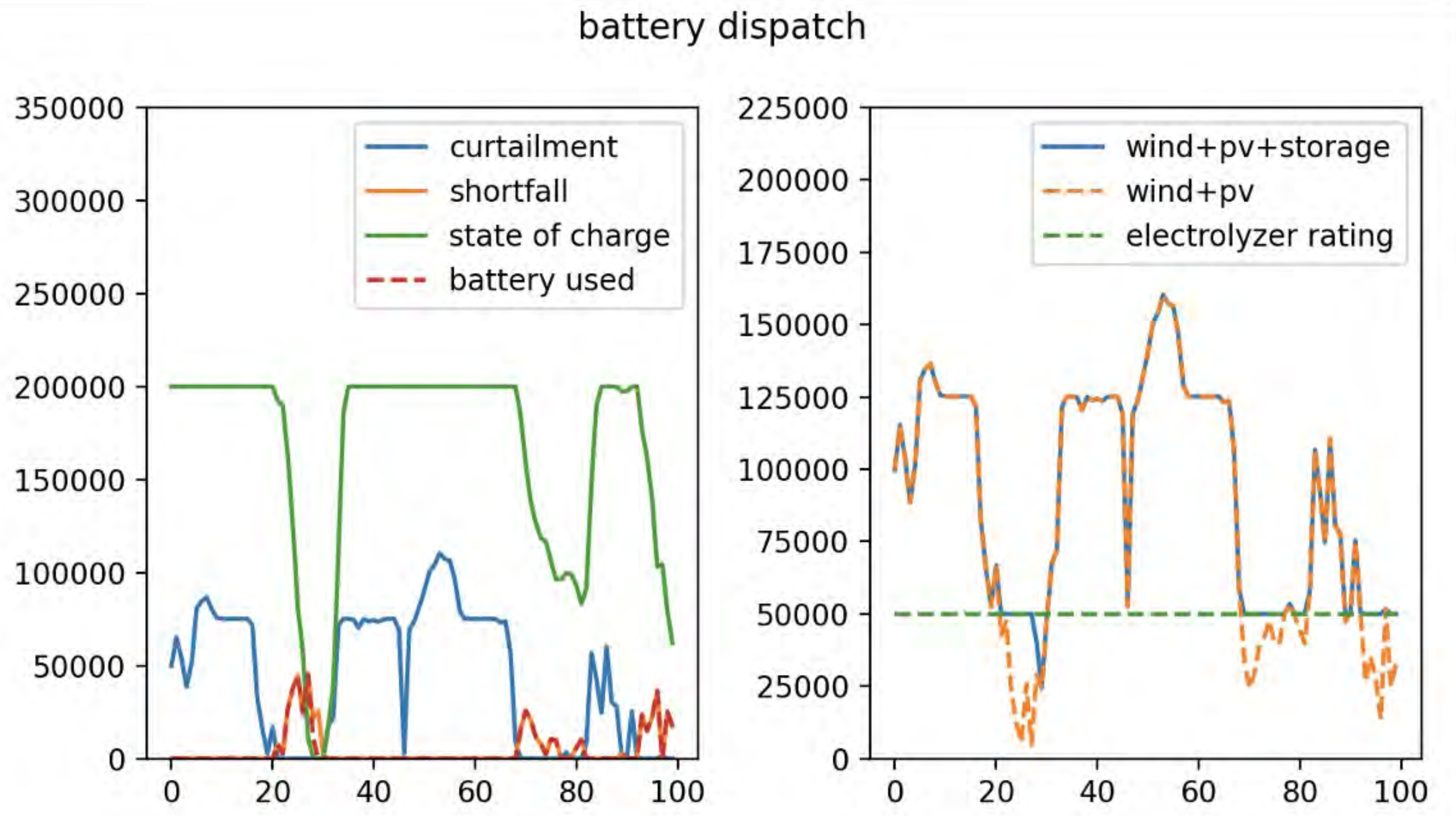


Each result is using the optimal plant + electrolyzer size for that location (resource) and cost scenario

Example 2: Electrolyzer Use vs. LCOH

- Toward optimal wind/solar/storage/PEM for locations, i.e. ratio of wind to PEM sizing
- *Example:* Wind Sizing at 150MW, **Electrolyzer sizing at 50 MW**
- *Result:* Large amounts of wind **curtailed** – excess energy stored in battery, the rest is curtailed
- **LCOH: $6.81/kg H2** - electrolyzer too small

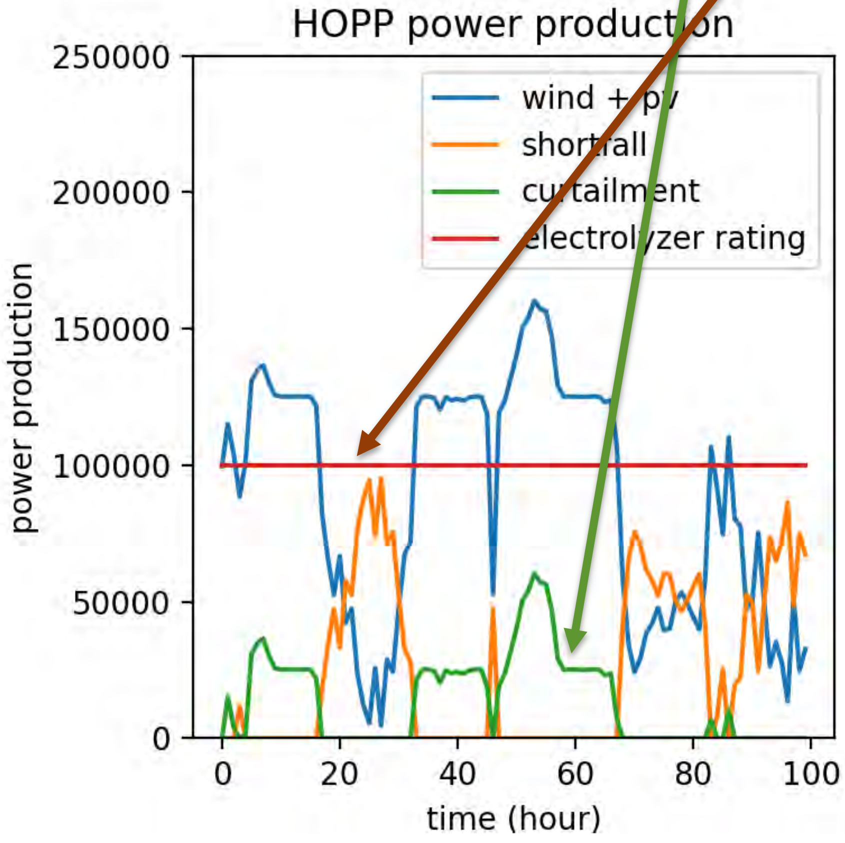


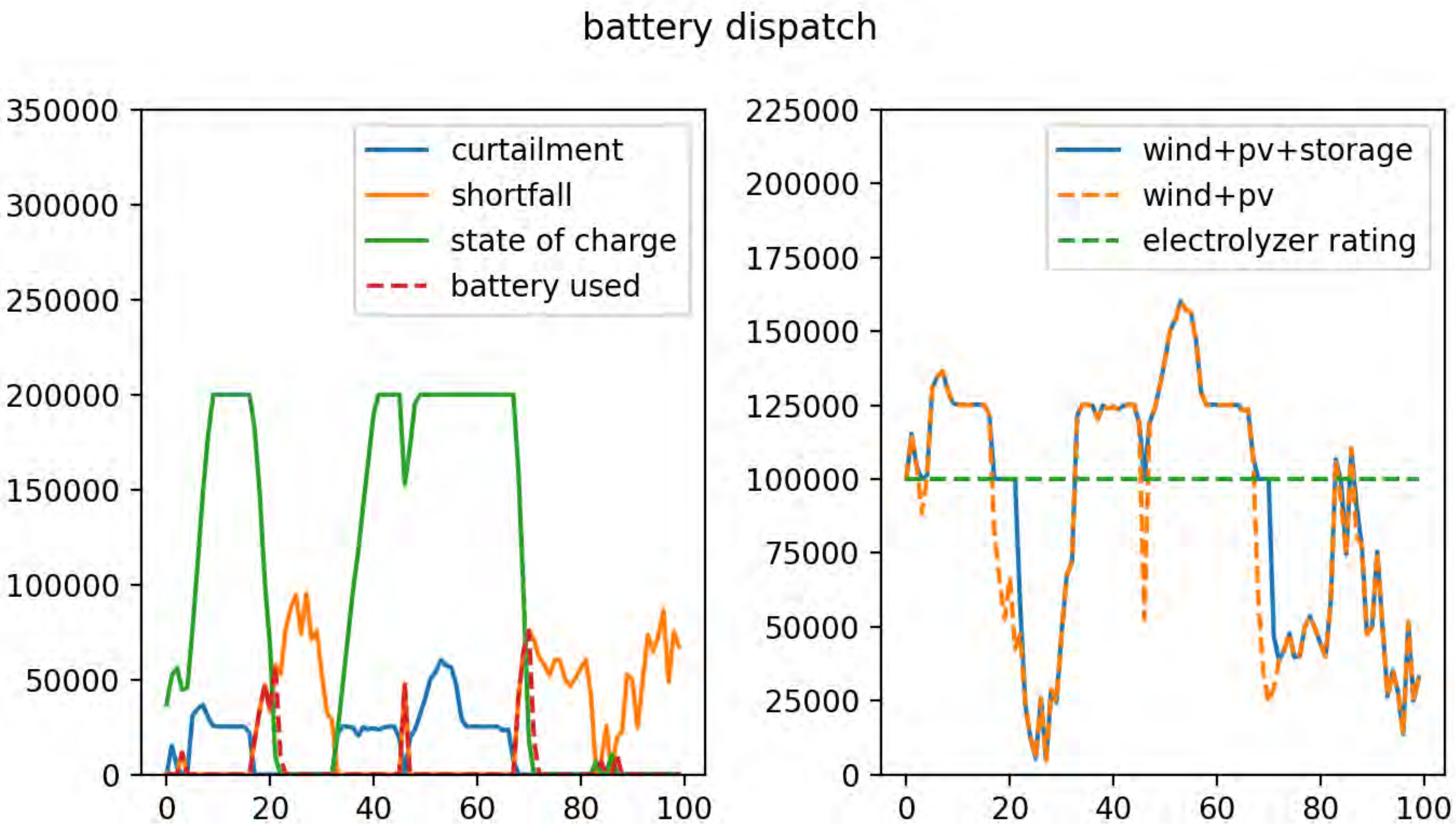


Battery is almost always at max capacity

Example 2: Electrolyzer Use vs. LCOH

- Toward optimal wind/solar/storage/PEM for locations, i.e. ratio of wind to PEM sizing
- *Example:* Wind Sizing at 150MW, **Electrolyzer sizing at 100 MW**
- *Result:* Some wind **curtailed** – excess energy stored in battery, the rest is curtailed
- **LCOH: $4.21/kg H2** - electrolyzer size is more appropriately sized for the system

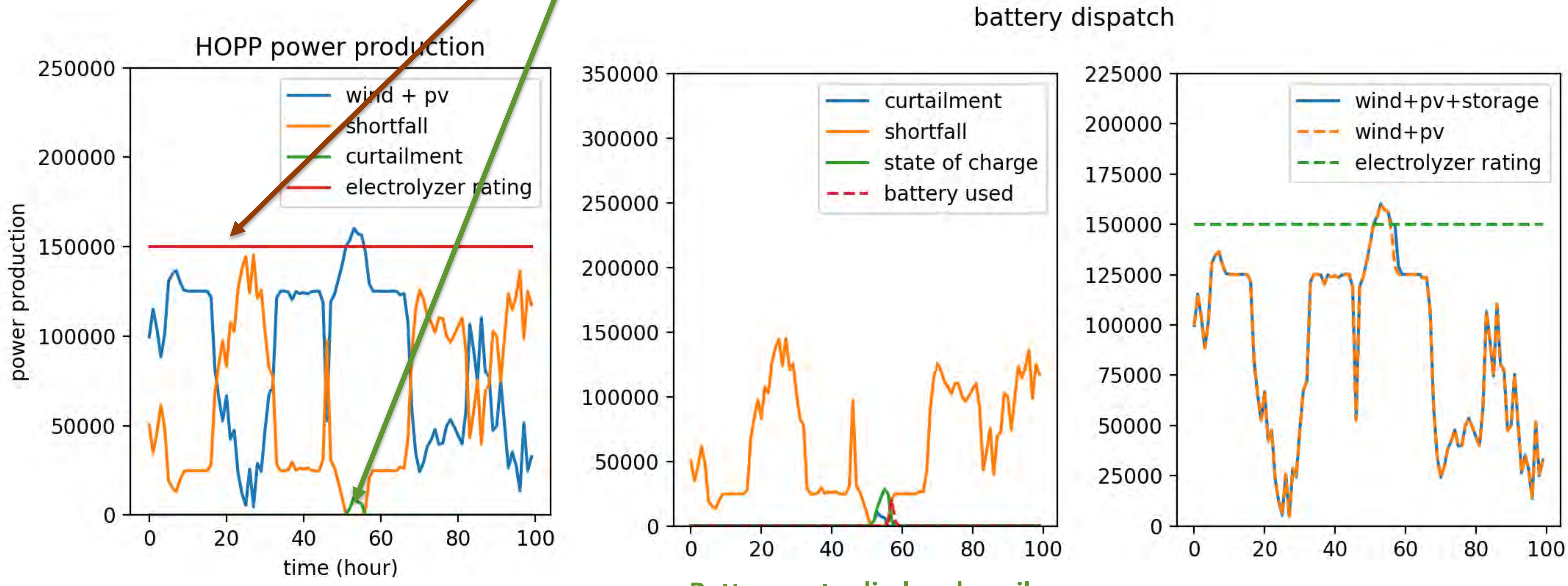




Battery is not always at max capacity

Example 2: Electrolyzer Use vs. LCOH

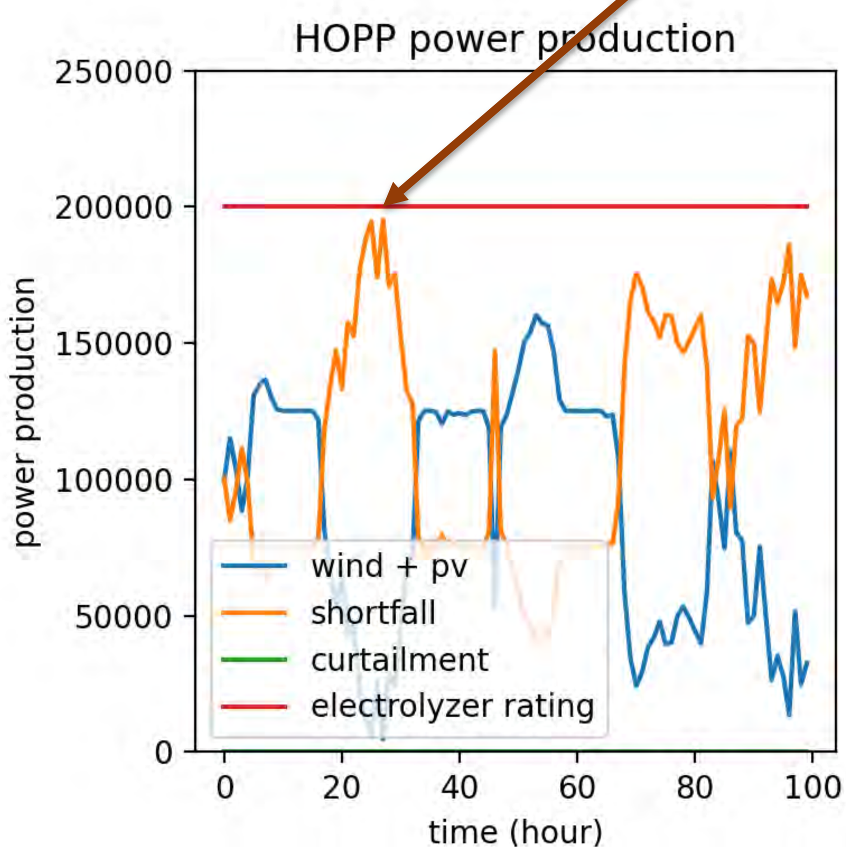
- Toward optimal wind/solar/storage/PEM for locations, i.e. ratio of wind to PEM sizing
- *Example:* Wind Sizing at 150MW, **Electrolyzer sizing at 150 MW**
- *Result:* Small amount of wind **curtailed** – excess energy stored in battery, the rest is curtailed
- **LCOH: $3.84/kg H2** - optimal electrolyzer size

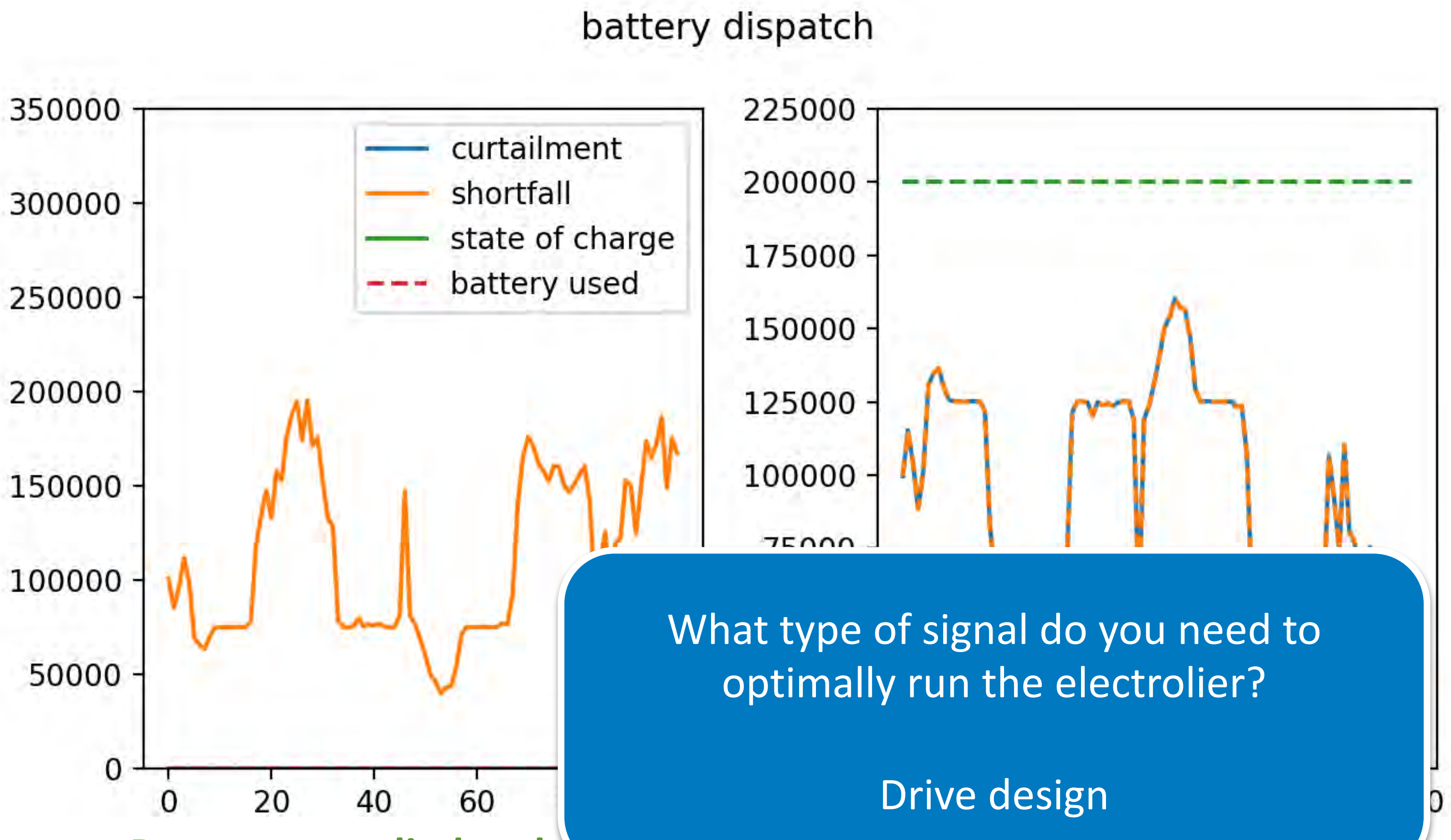


Battery not relied on heavily

Example 2: Electrolyzer Use vs. LCOH

- Toward optimal wind/solar/storage/PEM for locations, i.e. ratio of wind to PEM sizing
- *Example:* Wind Sizing at 150MW, **Electrolyzer sizing at 200 MW**
- *Result:* No wind **curtailed**
- **LCOH: $3.87/kg H2** - electrolyzer size too big, price starts to creep back up.





Battery not relied on he

What type of signal do you need to optimally run the electrolier?

Drive design

Ongoing work – Offshore Systems

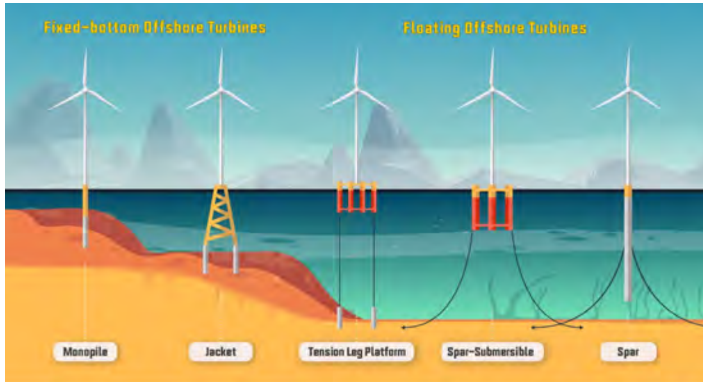
Integrate Offshore Wind Models

Integrate:

- FLORIS for aerodynamics of offshore wind systems (fixed/floating)
- Connect **financial and technical models** to H2OPP
- Opportunity for **shared power electronics**
- **Turbine design** with integrated electrolyzer (Vattenfall, Siemens, etc.)

Fixed vs. Floating systems

Integrate models of fixed vs. floating platforms for wind turbines and electrolyzers to examine optimal wind and electrolzyer configuration.



Pipelines vs. HVDC

Integrate design and analysis of building pipelines, transmission lines, and other transportation and storage solutions for offshore

Summary and Future Work

The objective function drives the design of the hybrid power plant

Hybrid power plants can maximize the use of existing grid infrastructure and provide necessary grid services

Future Work

- Fully-coupled wind-based hybrid systems
  - Shared resources
  - Shared power electronics
  - Shared controls
  - Shared balance of system
  - Objective: firm power

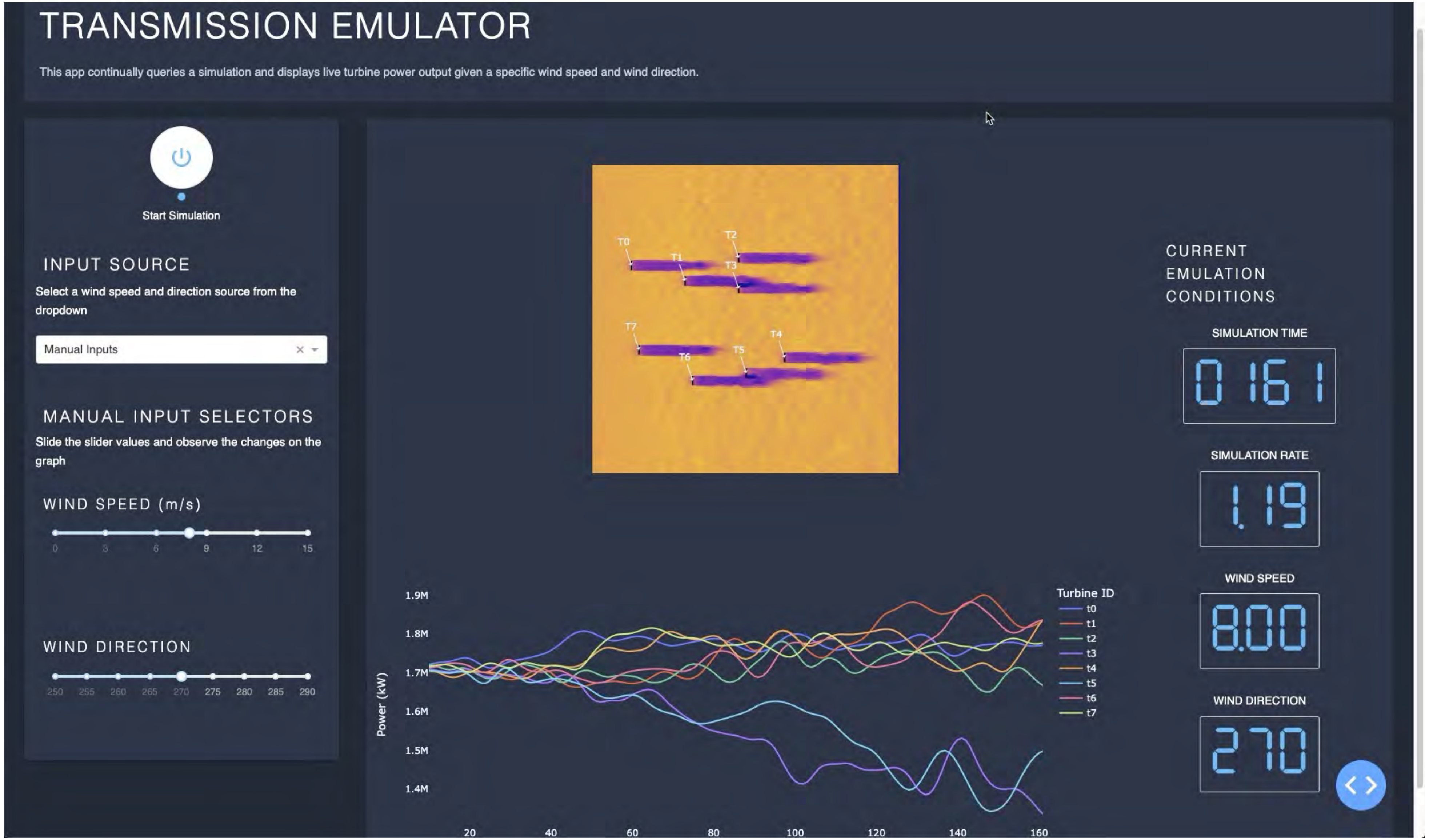
- GW-scale wind-H2 hybrid plants
  - Steel
  - Ammonia

Thank you.

Extra Slides

What are we working on now

Validation Platform: Coupling With Hardware At ARIES



Turning our ARIES assets into GW-scale systems through emulation

Hybrid Energy -> H_2 -> Green Steel/Ammonia

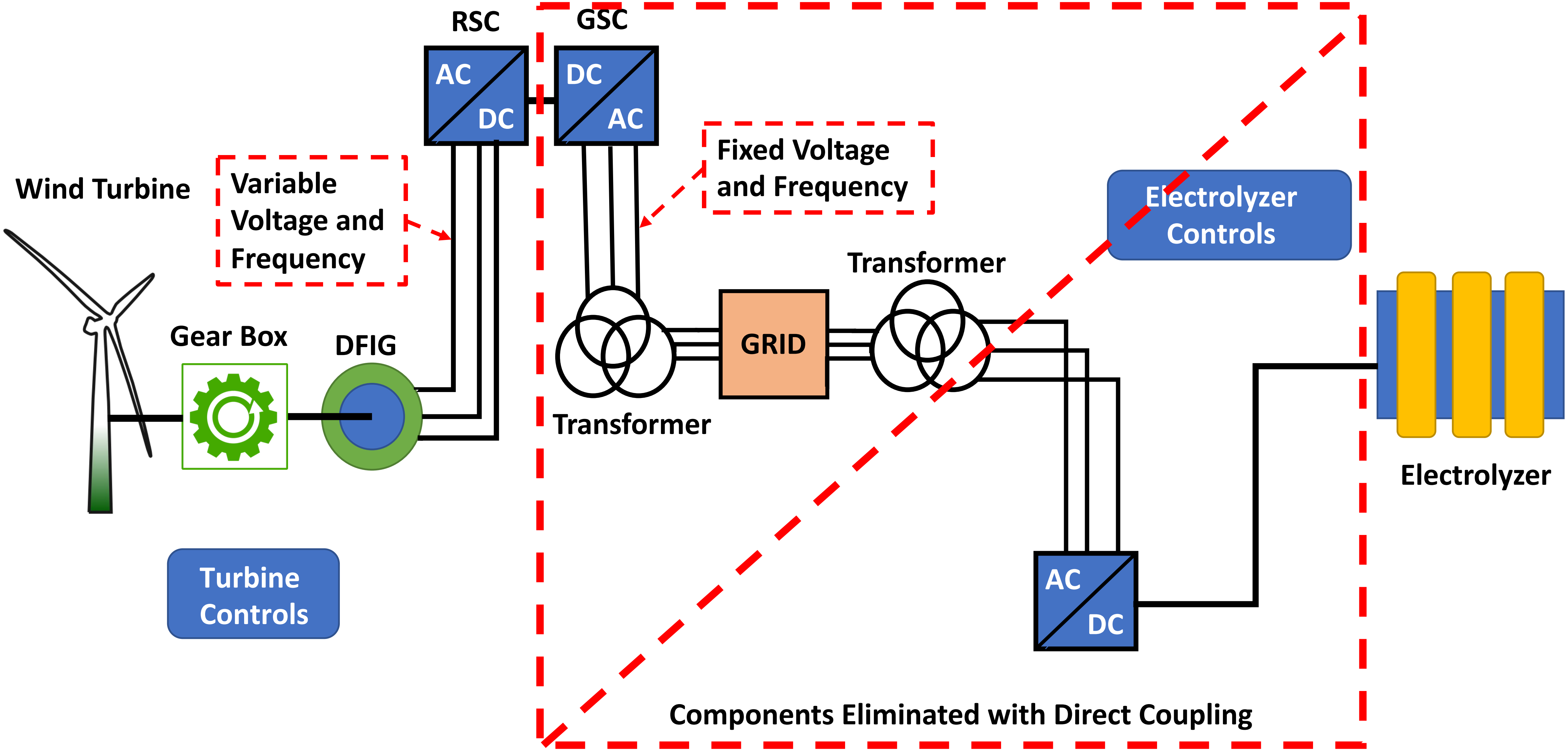
Vision: GW-scale on/**off-grid, purpose-built** systems composed of wind/PV/storage tightly coupled electrolyzers (DC/DC), optimized for LCOH, co-located with or near steel/ammonia production.

Novelty and Advantages:

- **Optimized LCOH** for the specific end use,
- Holistic approach, increased efficiency, & reduced capital costs,
- Independence from natural gas price volatility, grid connection permits and new large-scale transmission build outs.

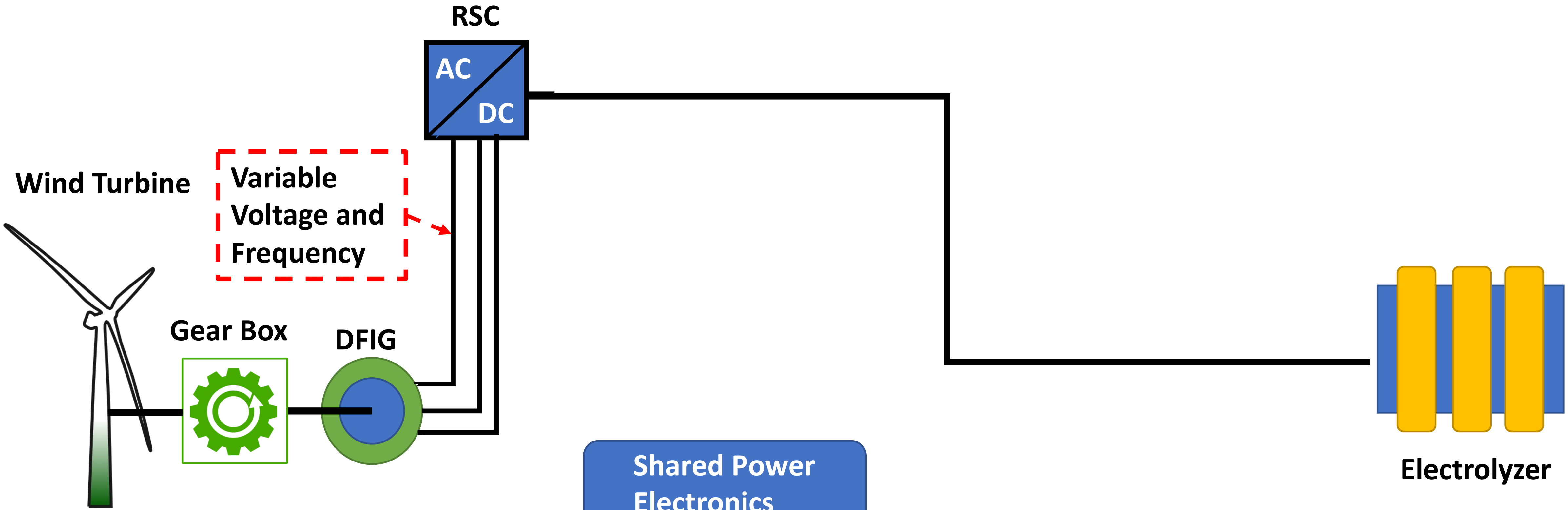
Show economic feasibility of 1GW HES => H2 => green steel/ammonia

How is it done today?



Typical Grid Connected System

Why is Direct Coupling Important?



Shared Power Electronics

Shared Controls

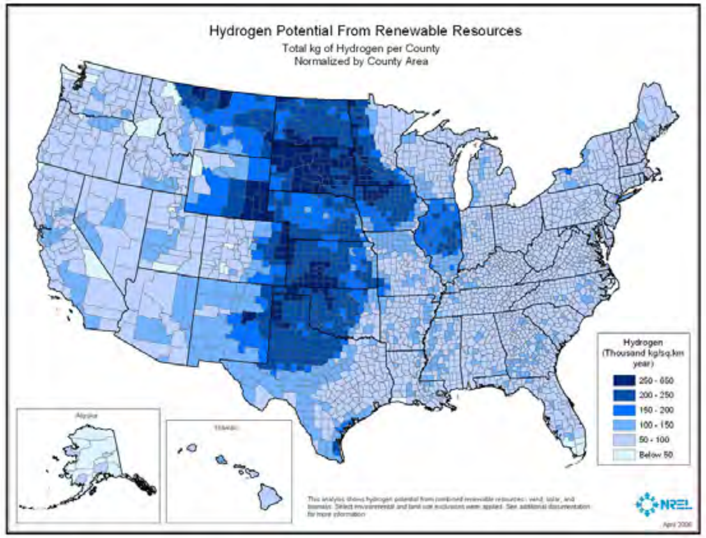
Additional Direct Coupled $ savings comes from elimination of capacity queues and elimination of energy losses

Direct Coupled System

Project Overview

Phase 1: Assessment/Analysis/Design ($2M, 6-9mo)

End-to-end integrated analysis for renewables-H2-steel/ammonia

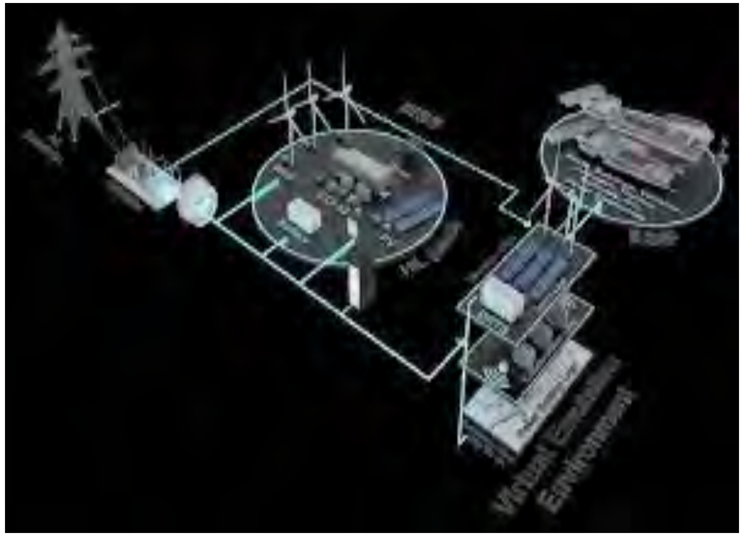


Goal: (Go/no-go)
Determine a path to cost-effective GW-scale wind-H2 production for different end uses including steel/ammonia

Phase 2: System Design and Control. Demonstration Project (1-2 years, could be accelerated)

Goal: Detailed system design and control from power electronics to storage technologies to delivery of the product to end user. 10MW Green Steel Demo at ARIES

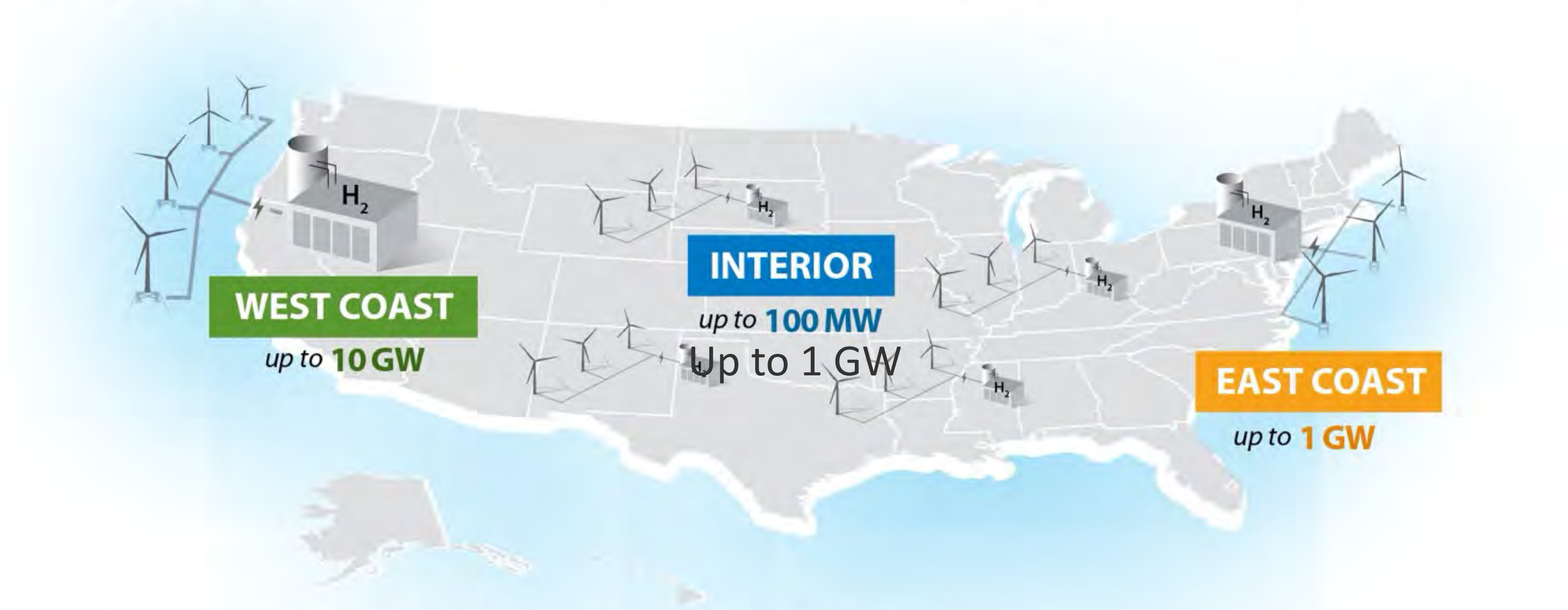
Phase 3: Demonstration, scaling to GW scale. National Roadmap (1-2 years, could be accelerated)



Goal: 10MW hardware demonstration and GW-scale emulation of the end-to-end system at ARIES including renewables-H2-steel

Where are we headed: Path to GW-scale Deployment of Wind-H2

Geographic diversity in U.S. needs a modular, scalable, end-to-end solution



Building complexity by addressing optimal system designs across the U.S.

INTERIOR

- 10 MW–100MW
- Land-based turbines
- Land constraints/setback
- Use existing infrastructure/retrofit
- Could be used at community level

EAST COAST

- 1 GW lease areas
- Fixed bottom turbines
- New infrastructure—HVDC, pipelines, shipping

WEST COAST

- 10 GW
- Floating turbines
- Shipping, fisheries
- New infrastructure—transmission, pipelines, shipping

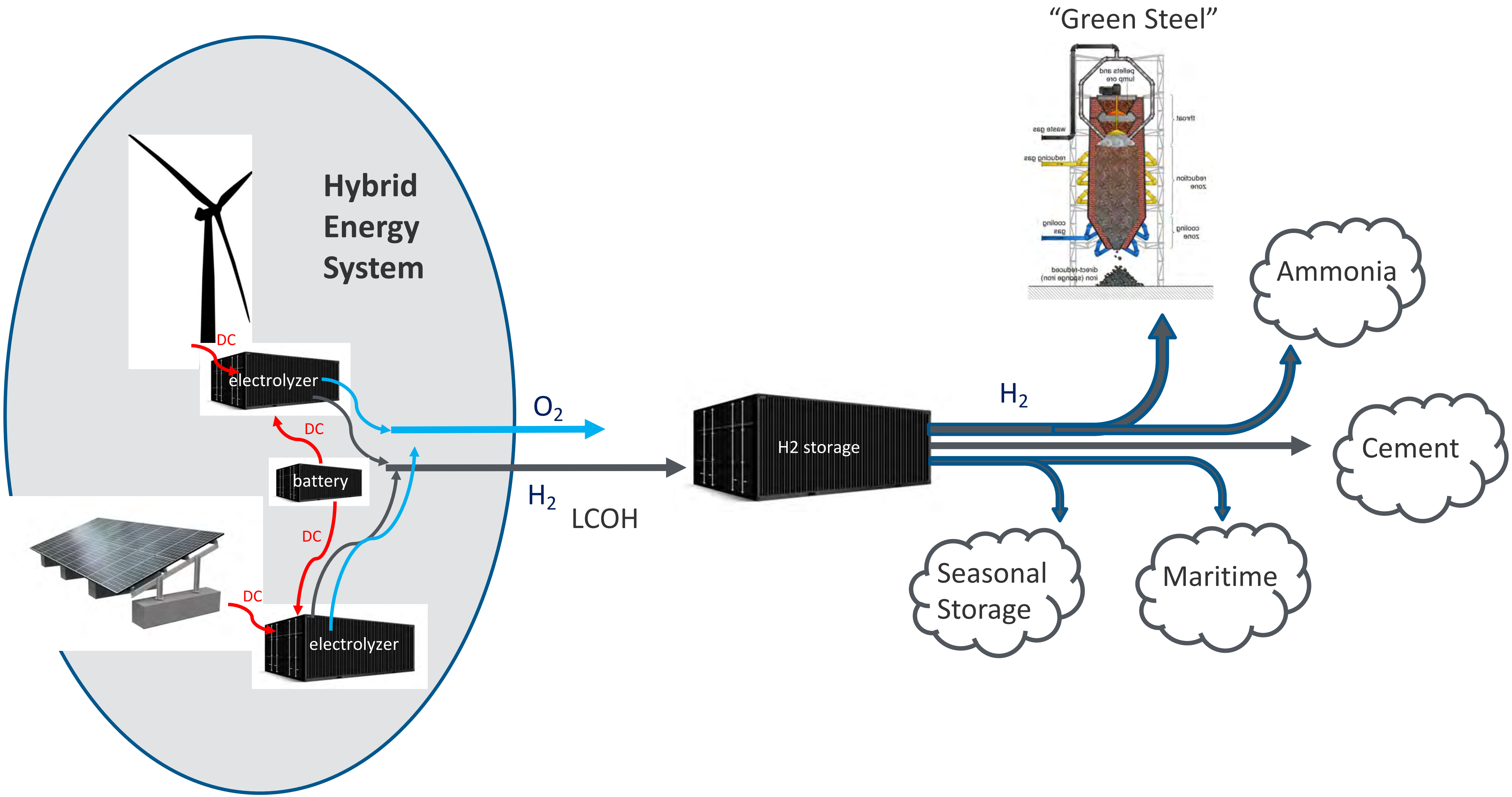
Barriers / Challenges

The technologies exist (wind, PV, electrolyzers, storage, H2 DRI …)

Open Questions arise in integrating these technologies into systems:

- Optimal design and controls of tightly coupled components in an integrated system.
- LCA for carbon neutrality needs to be confirmed.
- The economic viability of integrated system has not yet been demonstrated.
- Life expectancy and durability of dynamic electrolyzer operation is not well understood.
- Wind & solar largely developed for electricity generation rather than H2 production.
- Scale up of hybrid energy systems: ~10MW to 100 MW to GW scale
- Scale up of 100% H2 DRI is not yet modeled and well understood.
- Green ammonia production at scale …
- Water – availability and DI treatment process

ARIES Demonstration Grand Vision



HES => H_2 => Green Steel / Ammonia

Exciting *new* $2M project jointly funded by HFTO/WETO
NREL (lead) + ANL, LBNL, ORNL, & SNL

Phase 1: 6-month TEA sprint on first of a kind off grid, purpose-built "*hybrid energy system to H_2 to industry end use system*" focused on decarbonizing two hard to abate industries (steel & ammonia)

Directly Supports NREL Strategy

- Integrates CO IEP and E2M at ARIES.
- Planning for ~10MW ARIES demonstration.
- Anchor NREL's industry decarbonization efforts.

Grand Challenge: Decarbonize Iron/Ammonia Production

Steelmaking responsible for approx. 7-9% of the global CO_2 emissions.

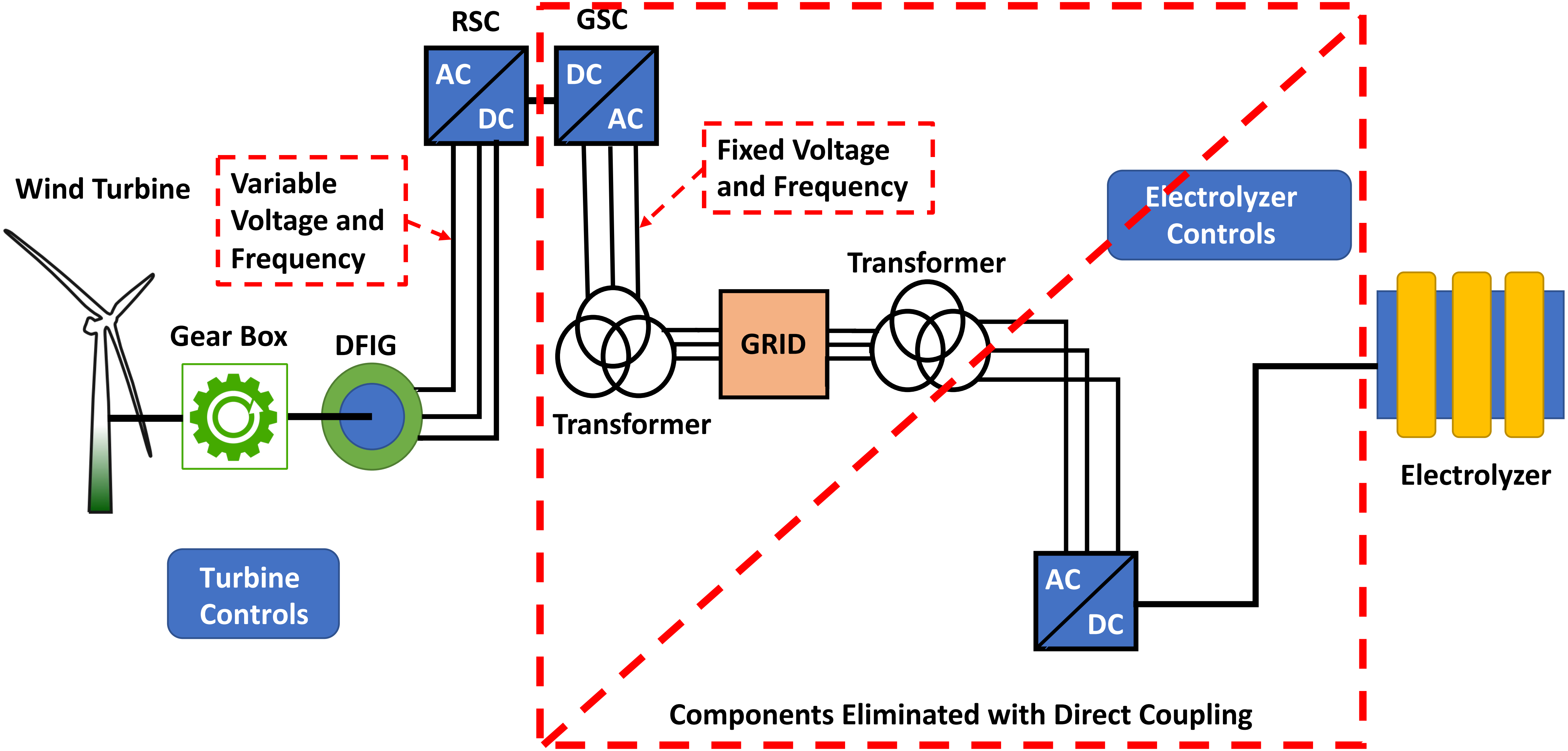
Incremental change won't achieve 2050 goal.

Achieving 2050 goal will require:

- **RD&D at an extraordinary URGENCY and SCALE to accelerate steel/ammonia industry clean energy transition.**
- **Coordinated effort starting in 2022 to demonstrate market success by 2030.**

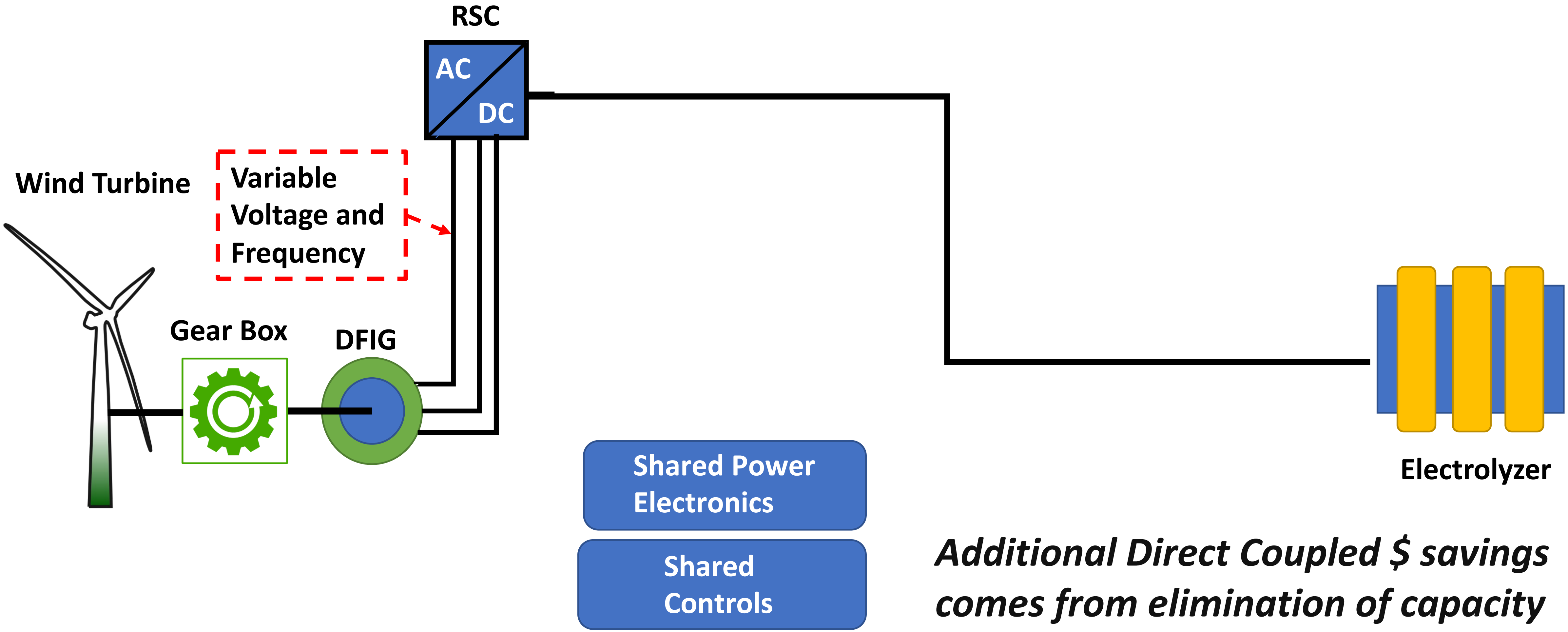
NREL is uniquely positioned to lead integrated TEA, design, controls, ARIES demonstration, accelerate path to green steel/ammonia.

How is it done today?



Typical Grid Connected System

Why is Direct Coupling Important?



Additional Direct Coupled $ savings comes from elimination of capacity queues and elimination of energy losses

Direct Coupled System

“Green Steel” ~10 MW ARIES Demonstration Vision

1

Water Treatment
- Produce DI water
- Understand power/water needed and brines produced

2

Tightly coupled wind turbine and electrolyzer
- DC-DC connection
- Minimal power electronics, shared components
- Optimized for lowest cost H2 production

3

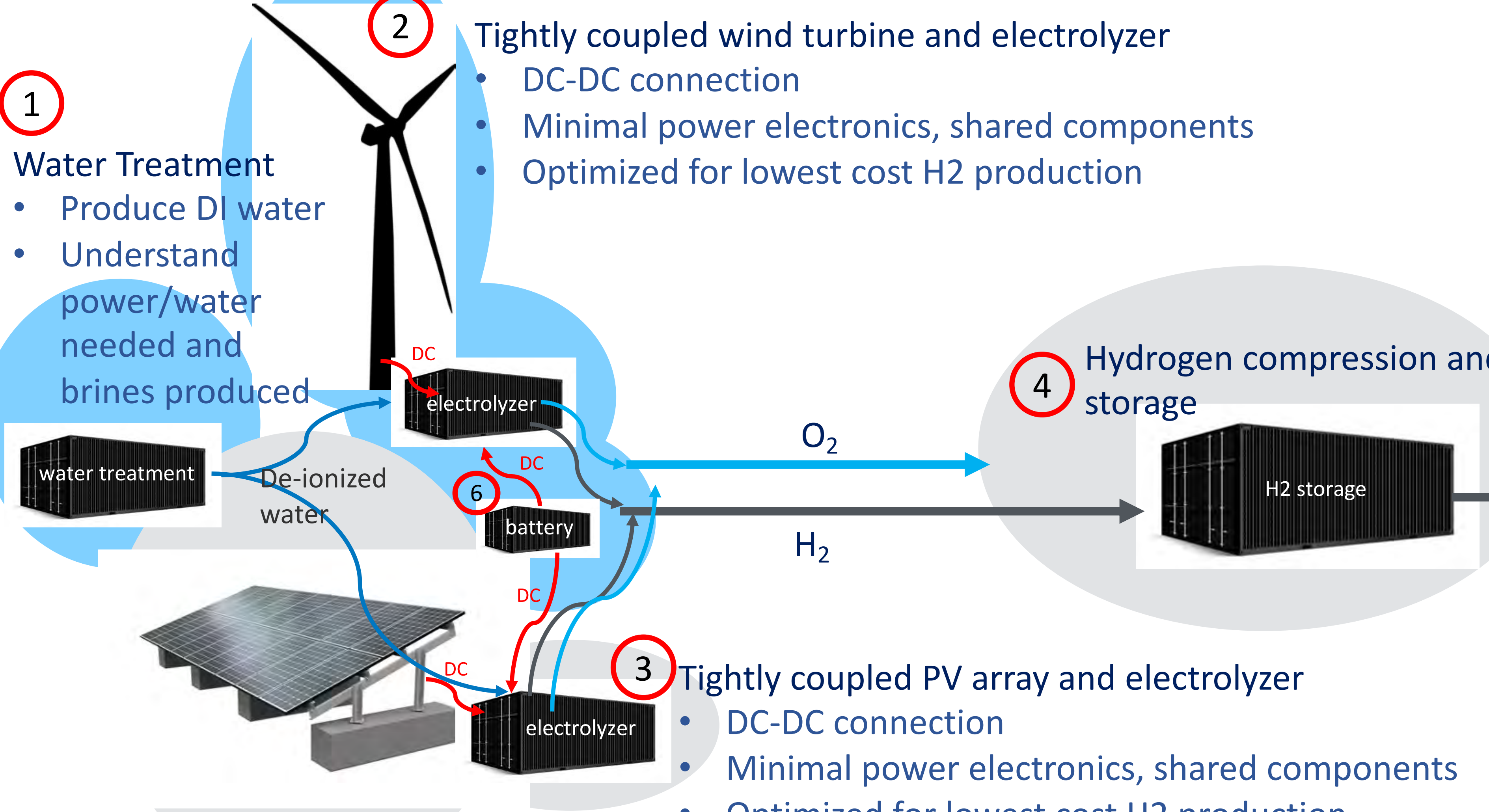
Tightly coupled PV array and electrolyzer
- DC-DC connection
- Minimal power electronics, shared components
- Optimized for lowest cost H2 production

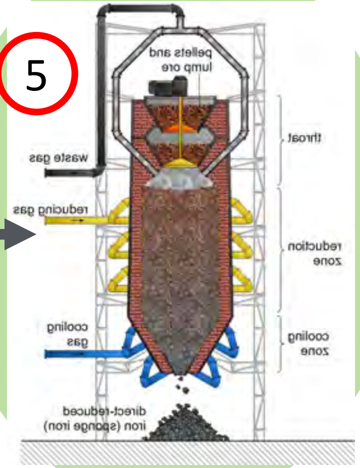
4

Hydrogen compression and storage

5

Furnace for the direct reduced iron process
- H2 is used as the reducing gas
- Takes pellets and lump ore & produces sponge iron





existing
In development
Future need

Barriers / Challenges

The technologies exist (wind, PV, electrolyzers, storage, H2 DRI …)

Open Questions arise in integrating these technologies into systems:

- Optimal design and controls of tightly coupled components in an integrated system.
- LCA for carbon neutrality needs to be confirmed.
- The economic viability of integrated system has not yet been demonstrated.
- Life expectancy and durability of dynamic electrolyzer operation is not well understood.
- Wind & solar largely developed for electricity generation rather than H2 production.
- Scale up of hybrid energy systems: ~10MW to 100 MW to GW scale
- Scale up of 100% H2 DRI is not yet modeled and well understood.
- Green ammonia production at scale …
- Water – availability and DI treatment process

IMPACT: Green Steel/Ammonia Urgency

Market forecasts indicate that major investments in steelmaking capacity are coming.

Avoid locking in high emission levels, and avoid creating stranded assets.

Initiate the sector's transition right away and prevent new blast furnaces from being added – and existing ones from being re-lined*.

Identify and resolve technology innovations needed for purpose-built cost-effective **1GW hybrid energy hydrogen industrial facility** in the U.S. by 2030 or earlier.

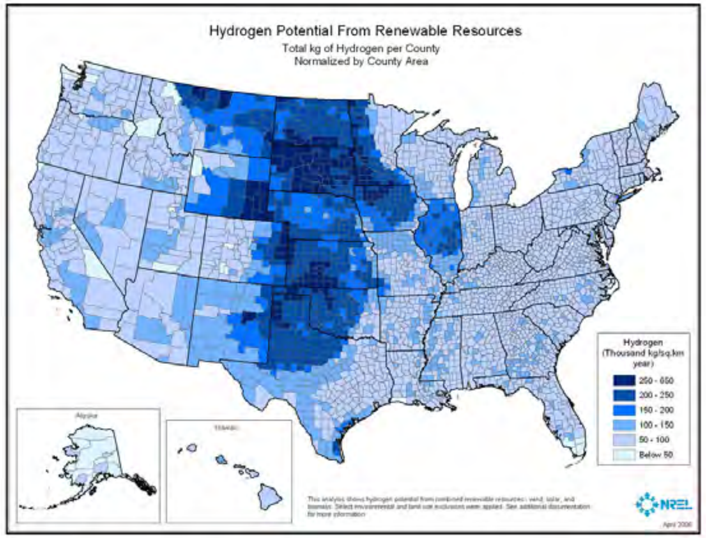
- This would be a first of a kind purpose-built "*hybrid energy system to hydrogen to industry end user system*" focused on decarbonizing two hard to abate industries.
- Supports NREL Strategy, integrates CO IEP and E2M at ARIES.
- ARIES ~10-MW demo significant 1st step on path to 100 MW and 1 GW scale systems.
- Supports/accelerates progress toward DOE Hydrogen Shot 1:1:1 goal.
- ***Bridge the knowledge gap between 'single-topic' R&D and integrated energy systems for green steel/ammonia.***

* https://cdn.sei.org/wp-content/uploads/2021/11/cop26-steel-messages-20211103.pdf

Project Overview

Phase 1: Assessment/Analysis/Design ($2M, 6-9mo)

End-to-end integrated analysis for renewables-H2-steel/ammonia

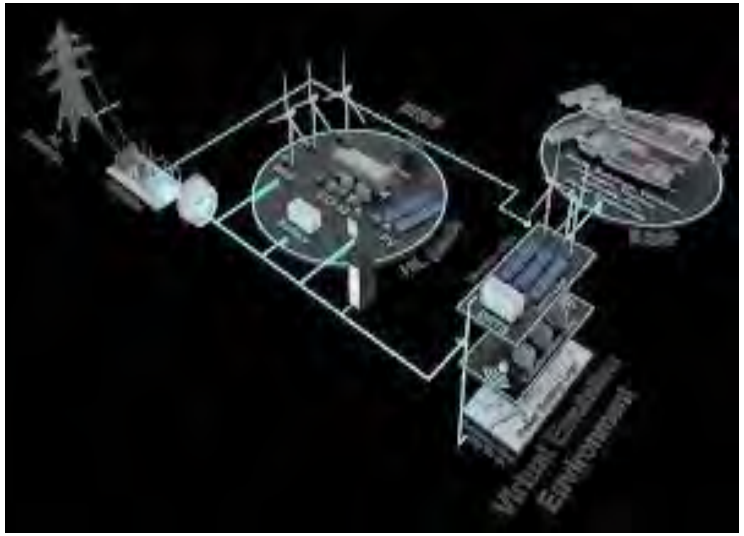


Goal: (Go/no-go)
Determine a path to cost-effective GW-scale wind-H2 production for different end uses including steel/ammonia

Phase 2: System Design and Control. Demonstration Project (1-2 years, could be accelerated)

Goal: Detailed system design and control from power electronics to storage technologies to delivery of the product to end user. 10MW Green Steel Demo at ARIES

Phase 3: Demonstration, scaling to GW scale. National Roadmap (1-2 years, could be accelerated)

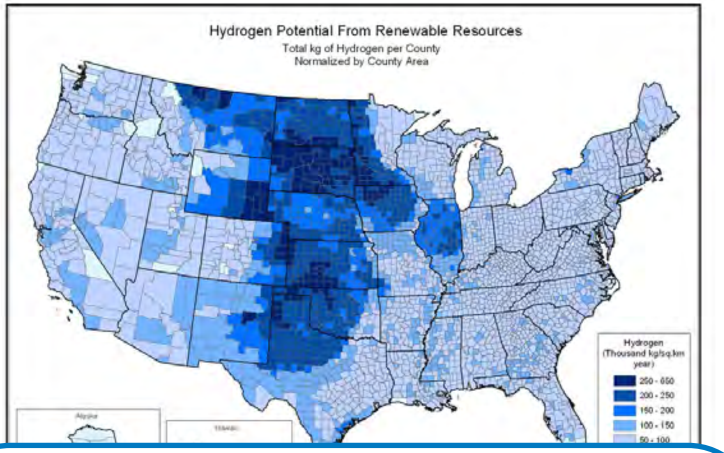


Goal: 10MW hardware demonstration and GW-scale emulation of the end-to-end system at ARIES including renewables-H2-steel

Project Overview

Phase 1: Assessment/Analysis/Design ($2M, 6-9mo)

End-to-end integrated analysis for renewables-H2-steel/ammonia



Outputs:

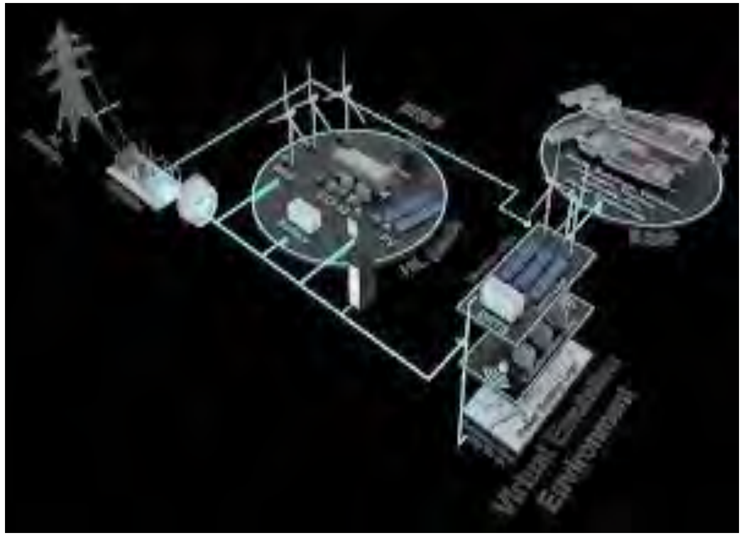
- **Database** of existing tools, data, and demonstrations worldwide
- **TEA** of wind-H2-steel/ammonia for nation-wide economic viability
- **Plan for demonstration** at ARIES

Phase 2: System Design and Control, Demonstration Project (1-2 years, could be accelerated)

Outputs:

- **Open-source tools** for system, design, and control across the full system (pieces exist)
- Preliminary **reference designs** for green steel/ammonia

Phase 3: Demonstration, scaling to GW scale. National Roadmap (1-2 years, could be accelerated)



Outputs:

- Fully **validated** reference designs using ARIES
- National roadmap and location specific reference designs.

5 Labs, $2M FY22, 6 month sprint

	FUNDING	Overall Project Leadership and Coordination	TEA and LCA	Sensing, Safety, Codes, & Standards	Power Electronics and Grid Integration	10MW Demonstration Project Define, Fesibility, and Scoping	Outreach, Academic and Industry Consortium
NREL	$1,200K	X	X	X	X	x	x
ANL	$250K		X				
LBNL	$250K		X				
ORNL	$150K				X		
SNL	$150K			X			

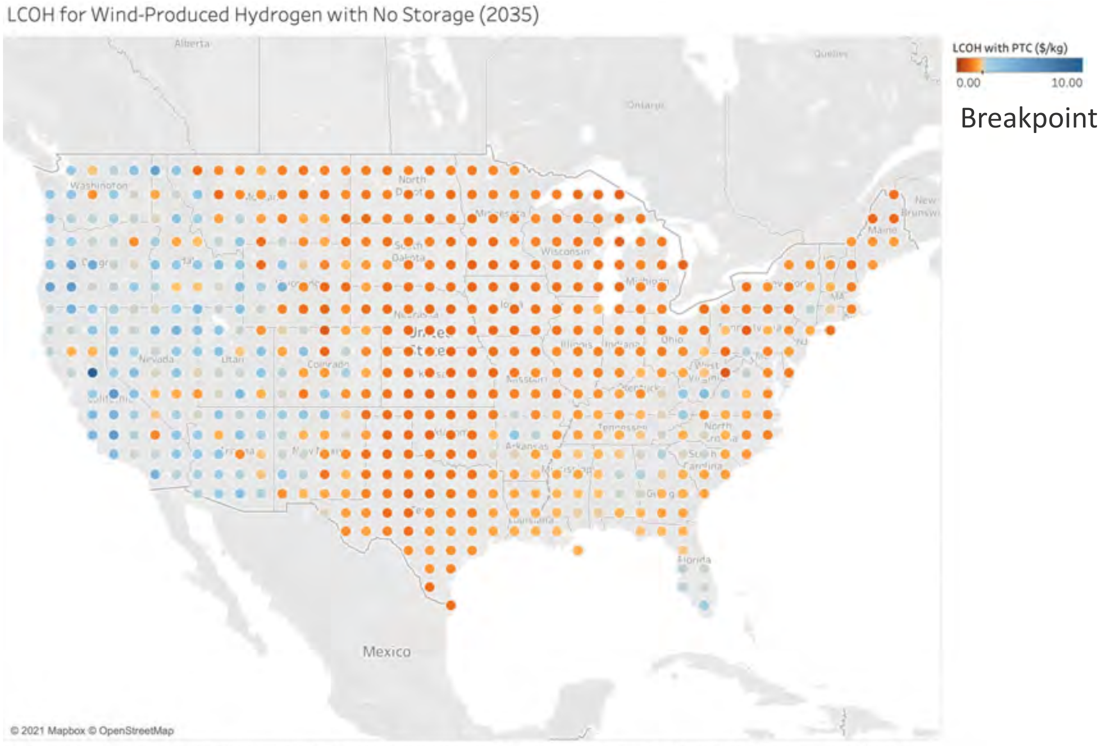
Co-funded
AMO, SETO

Green steel/ammonia Opportunity

Value Proposition:

- *Accelerated progress to industry decarbonization.*
- *Realize efficiency gains and capitol cost reductions through direct coupled HES H2 production and industry end use.*
- *National roadmap LCOH and validated location-specific reference design blueprints.*

- 2035
- **With PTC**
- ATB
- Wind Only
- $656/kw installed
- No storage
- Off-Grid



Breakpoint is at $2/kg

Map based on Longitude and Latitude. Color shows details about LCOH with PTC ($/kg). The data is filtered on Storage Size (MWh) and Year. The Storage Size (MWh) filter ranges from 0 to 0. The Year filter ranges from 2035 to 2035.

NREL |

ARIES Demonstration Grand Vision