2024 NATF-EPRI-NERC Planning and Modeling Virtual Seminar

November 20th, 2024

Transmission Planning & Grid Transformation

Welcome

Anish Gaikwad – EPRI

NATF North American Transmission Forum

NERC NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

EPRI

Day 2 – November 20, 2024 (1:00 pm – 5:00 pm ET)

Item	Leader	Times
10. Opening Remarks		1:00 – 1:10
Session 3 – Planning with Power Electronics		
11. Planning with HVDC a. Grain Belt Express b. Planning Criteria and Applications	Matt Holtz - Invenergy Mike Spector – Grid United	1:10 – 1:50 1:50 – 2:30
Break (5 mins, 2:30 – 2:35)		
Session 4 – Inverter-Based Resource Modeling		
12. EMT Model Quality	John Schmall - ERCOT	2:35 – 3:15
13. Dynamic Modeling recommendations	Jack Gibfried - NERC	3:15 – 3:45
Break (5 mins, 3:45 – 3:50)		
Session 5 – Large Loads		
14. Large Digital Loads Challenges and Learnings	Le Xie - Harvard University	3:50 – 4:20
15. WECC Large Load Risk Assessment WG	Kyle Thomas – Elevate Energy Katie Rogers – WECC	4:20 – 5:00
16. Closing Remarks		5:00
Adjourn (17:00)		

Session 3
Planning with Power Electronics

Grain Belt Express Project

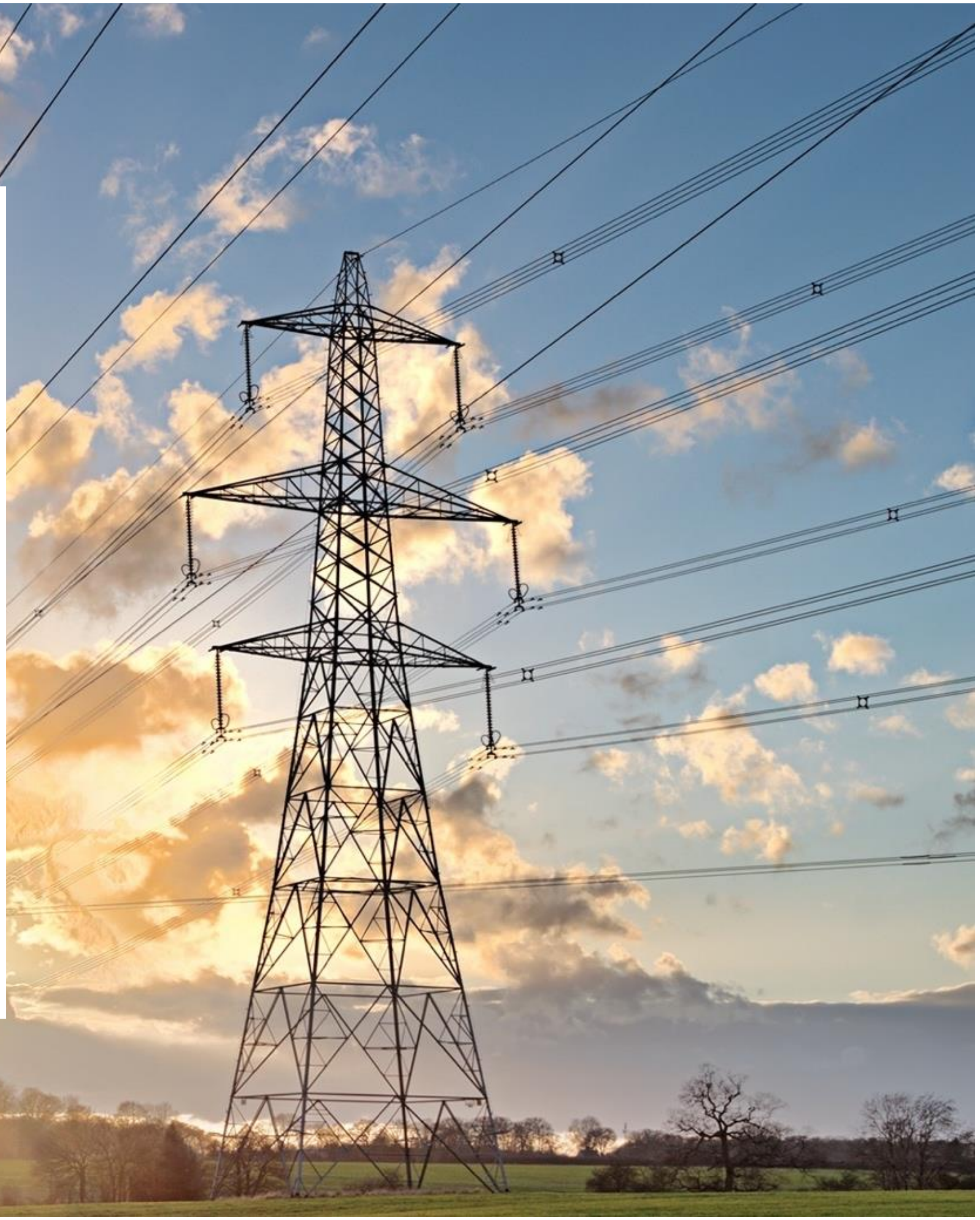
Matt Holtz - Invenergy

Grain Belt Express
An INVENERGY TRANSMISSION *Project*

Grain Belt Express Project

Matt Holtz
VP Transmission Operations, Invenergy

November 20, 2024



Invenergy Transmission

Invenergy Transmission LLC

World's Leading Privately Held Clean Energy Company

Wind
118 projects
19,274 megawatts

Solar
53 projects
6,989 megawatts

Storage
21 projects
1,817 megawatt hours
556 megawatts

Offshore Wind
2 projects
4,000+ megawatts in development

Transmission
4 projects
4,100+ miles of transmission & collection lines developed

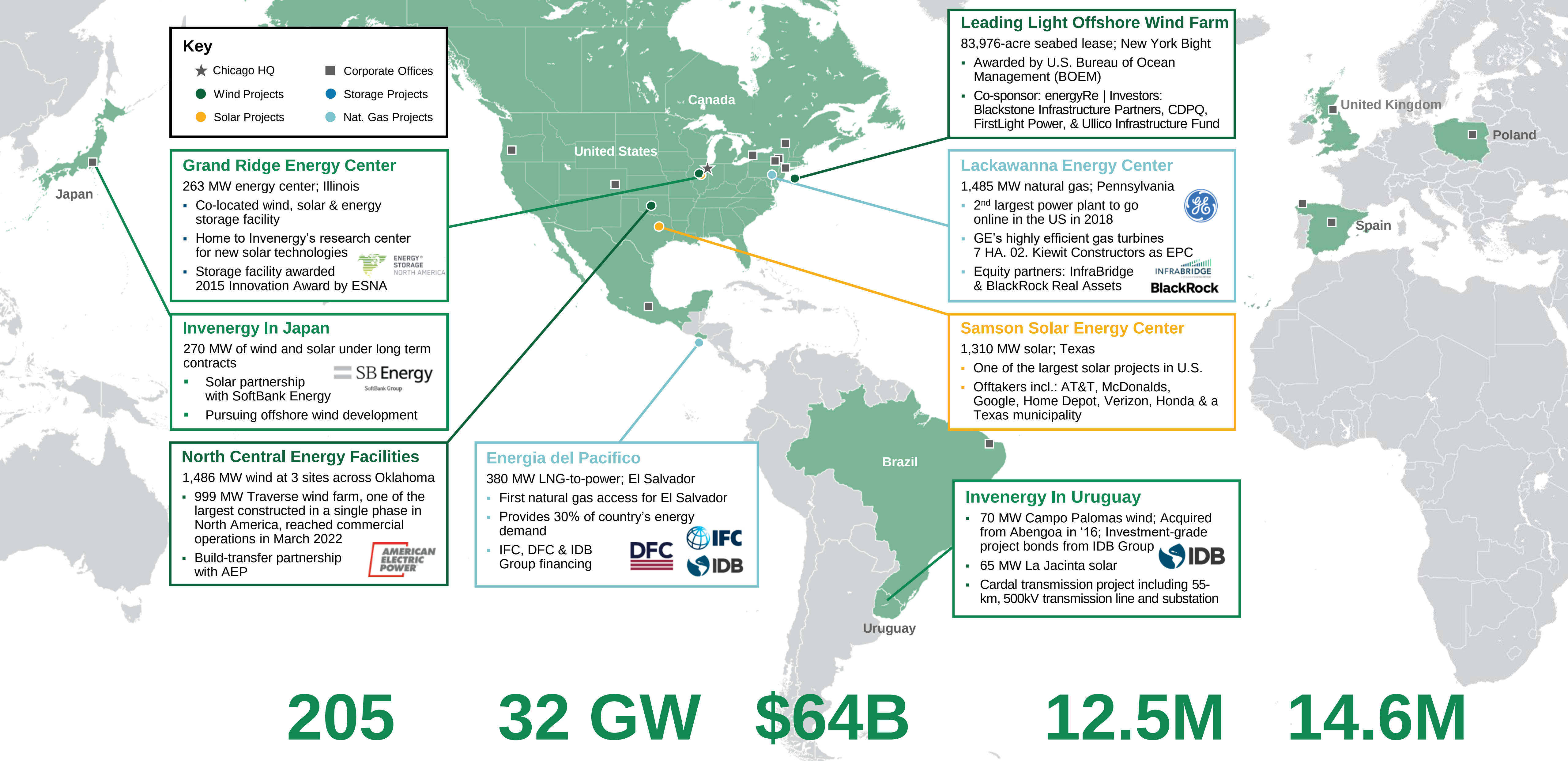
Clean Hydrogen
1 pilot project in construction
40 metric tons will be produced annually

Clean Water
9 water treatment facilities used at our project sites
18 million gallons per day of raw water capacity

Natural Gas
13 projects
6,071 megawatts

Invenergy Services

We use our 20 years of operations and maintenance experience to help you make the most of your energy center. Whether it's day one or years later, we use our owner's mindset to manage our energy centers and on behalf of our customers.



Key

- ★ Chicago HQ
- ■ Corporate Offices
- ● Wind Projects
- ● Storage Projects
- ● Solar Projects
- ● Nat. Gas Projects

Grand Ridge Energy Center

263 MW energy center; Illinois

- Co-located wind, solar & energy storage facility
- Home to Invenergy's research center for new solar technologies
- Storage facility awarded 2015 Innovation Award by ESNA

Invenergy In Japan

270 MW of wind and solar under long term contracts

- Solar partnership with SoftBank Energy
- Pursuing offshore wind development

North Central Energy Facilities

1,486 MW wind at 3 sites across Oklahoma

- 999 MW Traverse wind farm, one of the largest constructed in a single phase in North America, reached commercial operations in March 2022
- Build-transfer partnership with AEP

Energia del Pacifico

380 MW LNG-to-power; El Salvador

- First natural gas access for El Salvador
- Provides 30% of country's energy demand
- IFC, DFC & IDB Group financing

Leading Light Offshore Wind Farm

83,976-acre seabed lease; New York Bight

- Awarded by U.S. Bureau of Ocean Management (BOEM)
- Co-sponsor: energyRe | Investors: Blackstone Infrastructure Partners, CDPQ, FirstLight Power, & Ullico Infrastructure Fund

Lackawanna Energy Center

1,485 MW natural gas; Pennsylvania

- 2nd largest power plant to go online in the US in 2018
- GE's highly efficient gas turbines 7 HA. 02. Kiewit Constructors as EPC
- Equity partners: InfraBridge & BlackRock Real Assets

Samson Solar Energy Center

1,310 MW solar; Texas

- One of the largest solar projects in U.S.
- Offtakers incl.: AT&T, McDonalds, Google, Home Depot, Verizon, Honda & a Texas municipality

Invenergy In Uruguay

- 70 MW Campo Palomas wind; Acquired from Abengoa in '16; Investment-grade project bonds from IDB Group
- 65 MW La Jacinta solar
- Cardal transmission project including 55-km, 500kV transmission line and substation

205	32 GW	$64B	12.5M	14.6M
Projects Developed	Capacity Developed	Completed Transactions	Homes Powered	Cars off the Road Equivalent

Invenergy

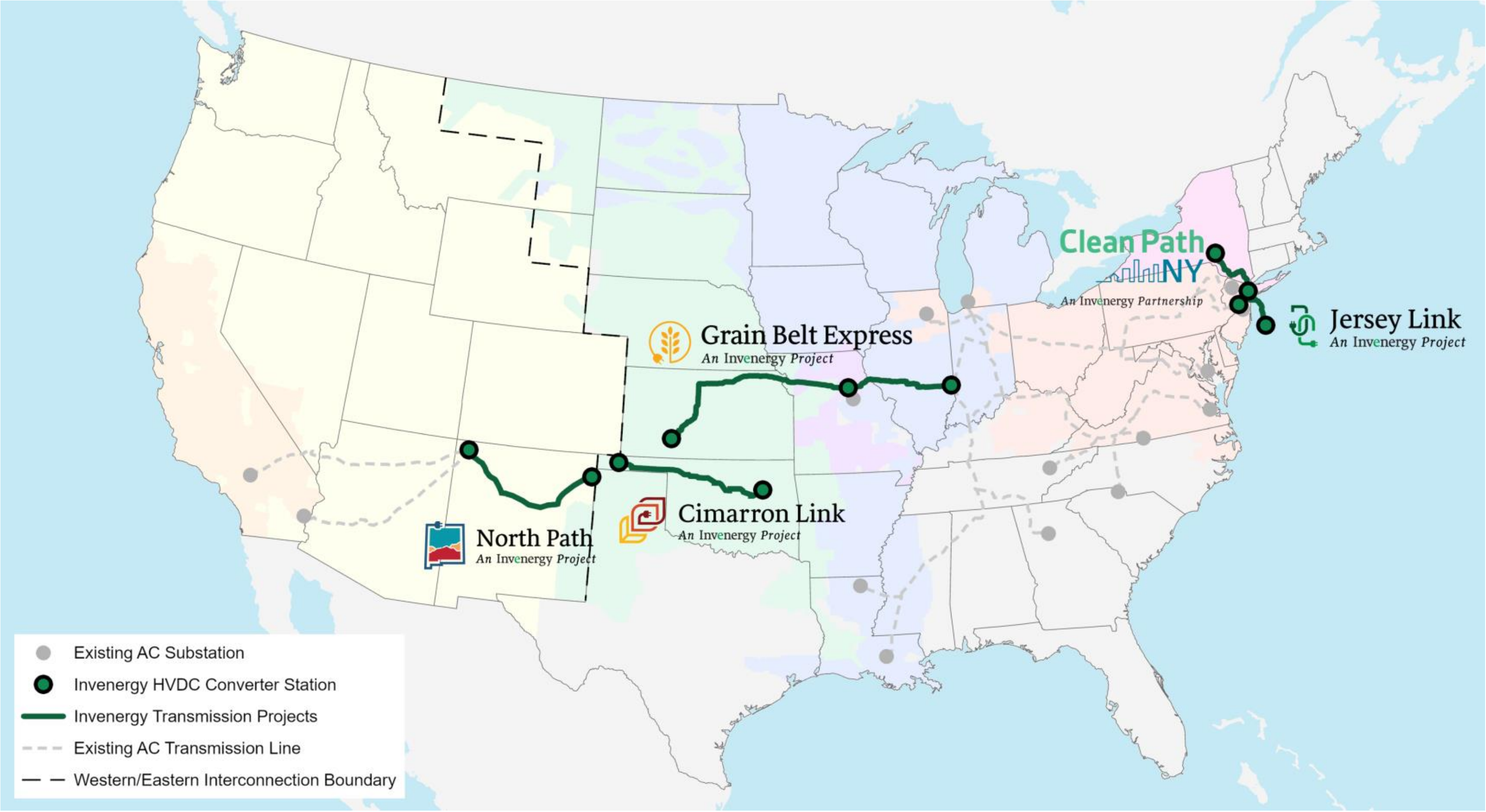
Invenergy Transmission Portfolio Overview

$40 billion
in combined investment in new electric transmission and enabled generation

1,765 linear miles
of new transmission right of way, using 13,100+ miles of conductor lines (12,800 overhead; 370 buried)

12 gigawatts
of transmission capacity enabling equivalent or more new-build wind and solar generation

9 converter stations
to convert power between AC and DC for 4 new-build HVDC lines



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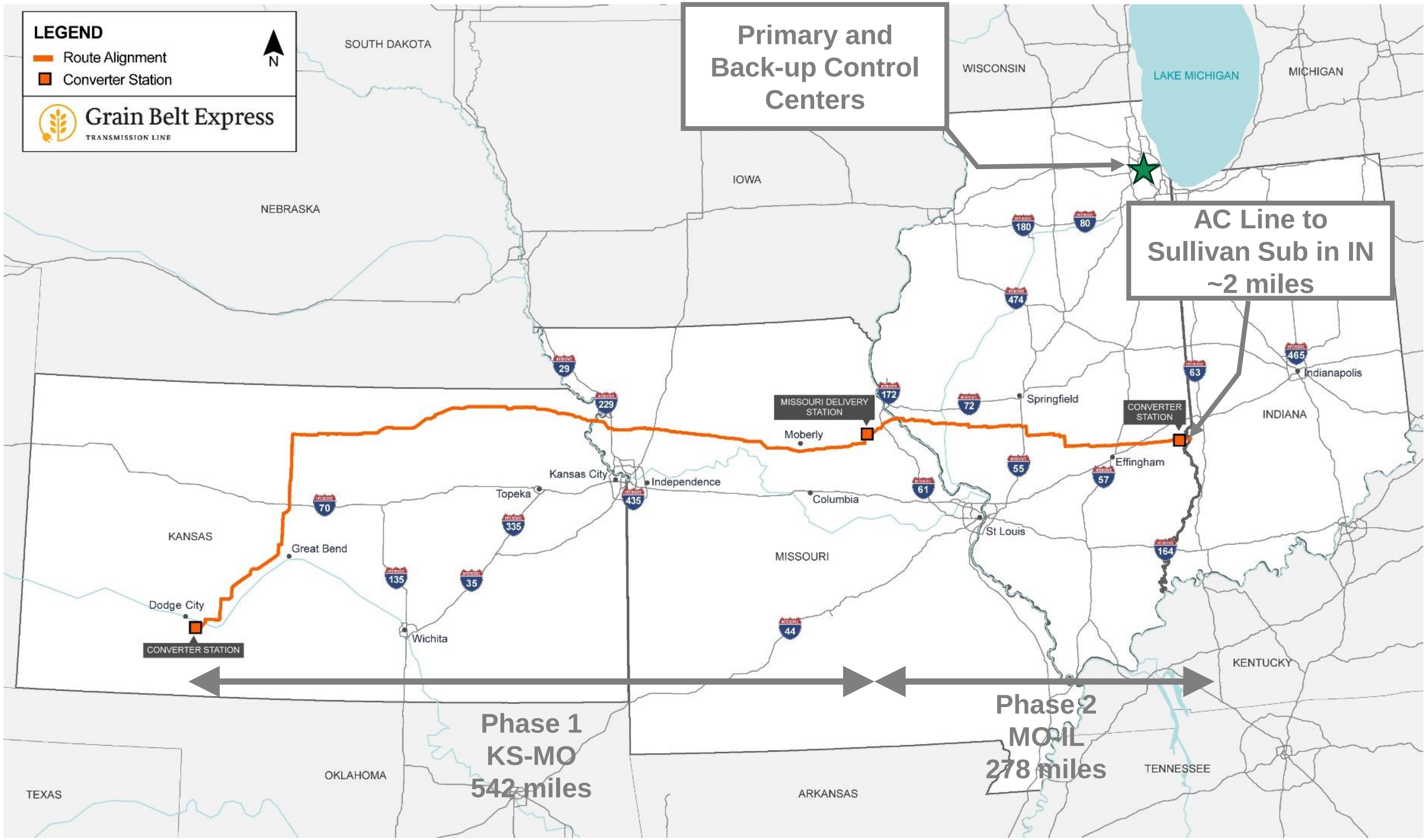
Grain Belt Express
TRANSMISSION LINE



Invenergy

Project Profile

Grain Belt Express
An Invenergy Project

GrainBeltExpress.com

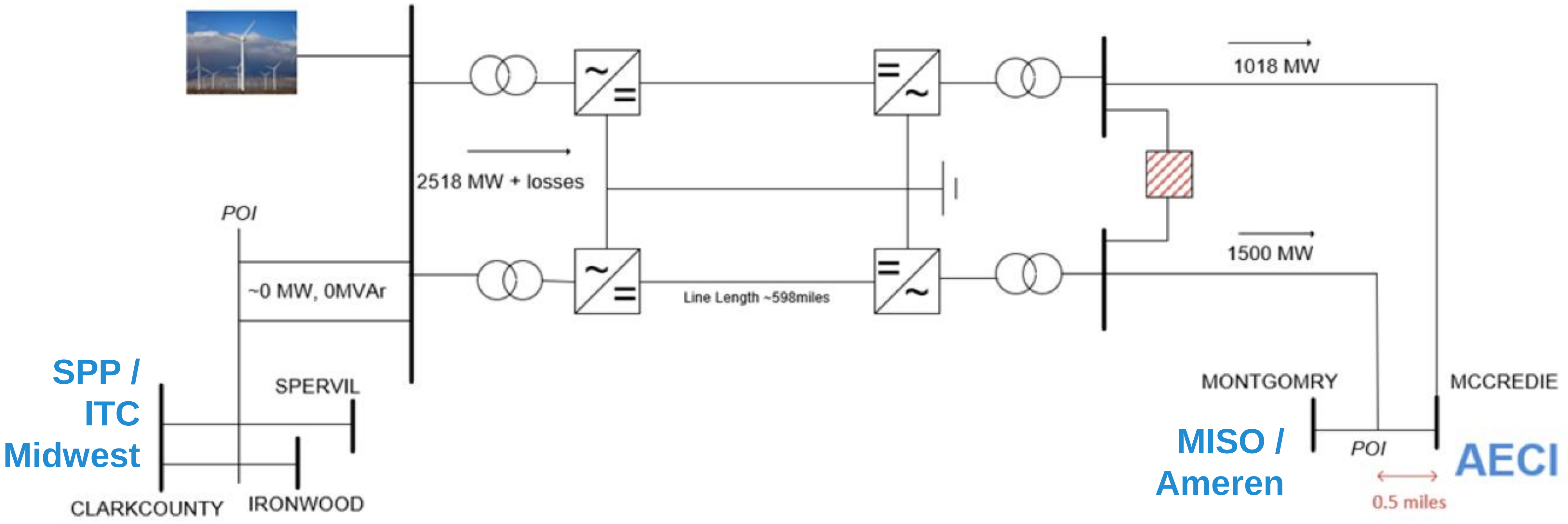
PROJECT SPECIFIC: PHASE 1

- Approximately 542 miles
- ± 600kV High Voltage Direct Current (HVDC)
- Size 5000 MW
- Bi-pole
- Bi-directional
- Phase 1 → 2,500 MW
- COD Phase 1 → 2029
- Kansas - Interconnected with SPP/ITC Great Plains
- Missouri – Interconnected with AECI and MISO/Ameren in Missouri

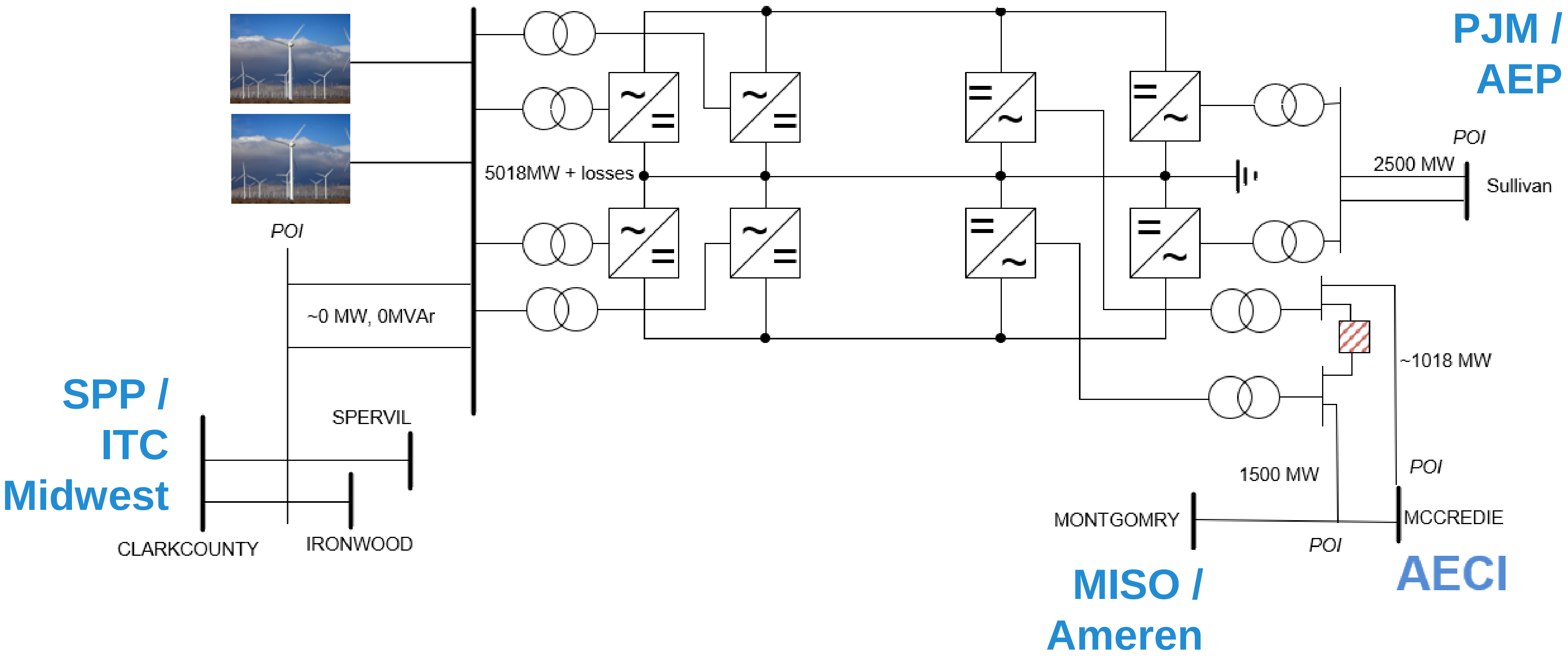
PROJECT SPECIFIC: PHASE 2

- Approximately 278 miles
- Phase 2 size → 2,500 MW
- COD Phase 2 → 2030
- Indiana - Interconnected with PJM/AEP

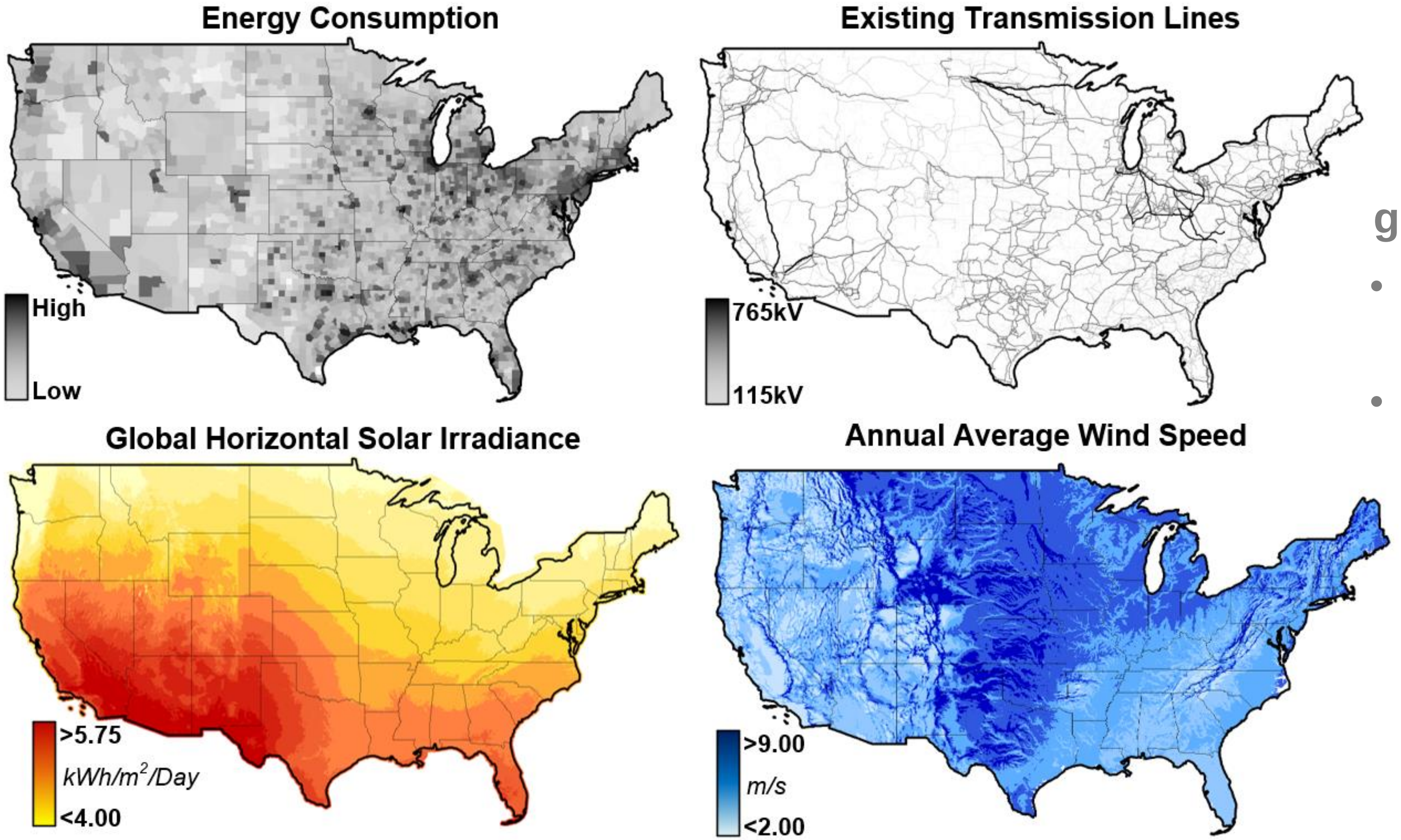
Grain Belt Express – Phase 1



Grain Belt Express – Phase 2



U.S. Electric System and Renewable Resource



Origins as a regional network of thermal generation and nearby load

- Limited transmission across broader regions
- Bottleneck limiting access to best renewable resource

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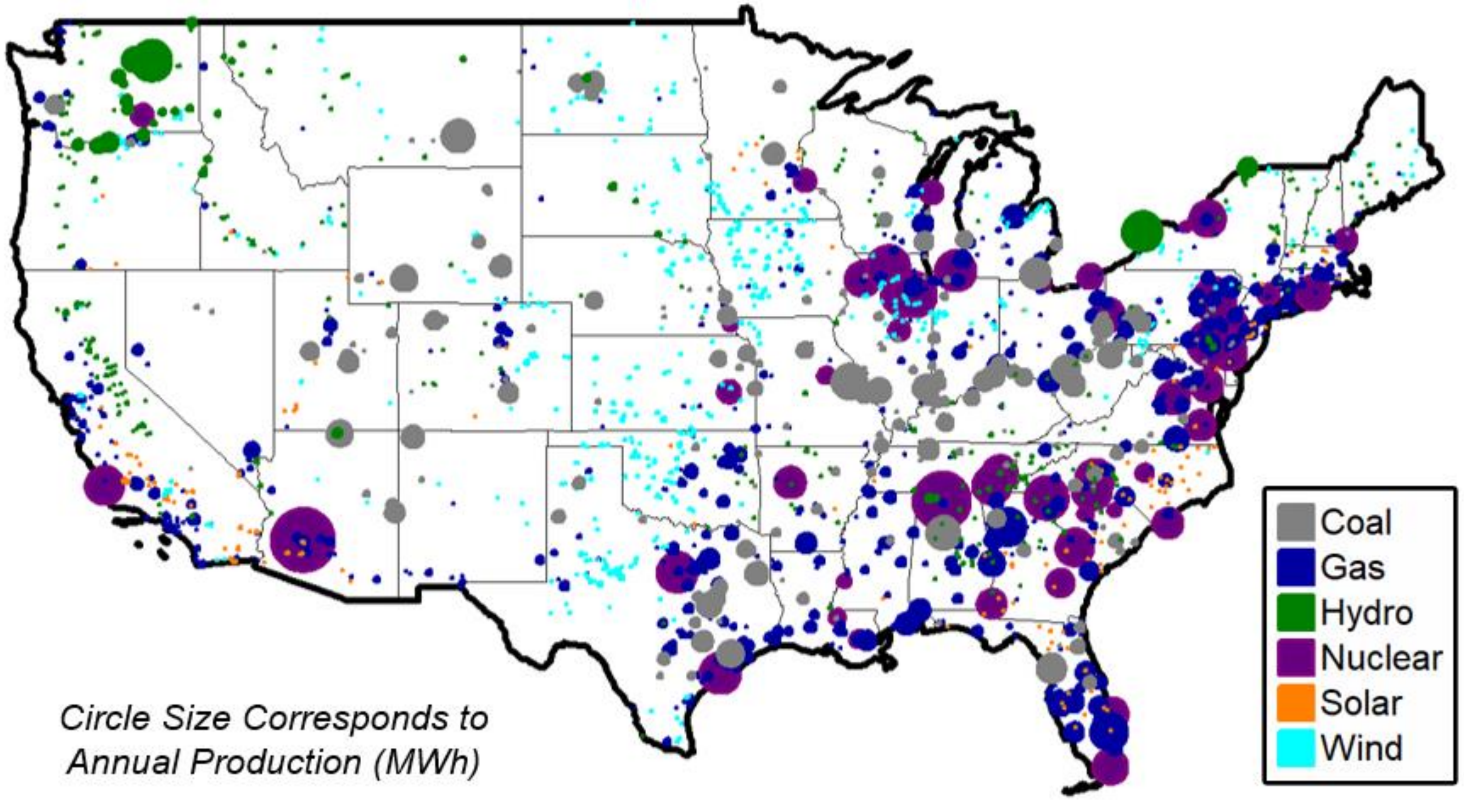
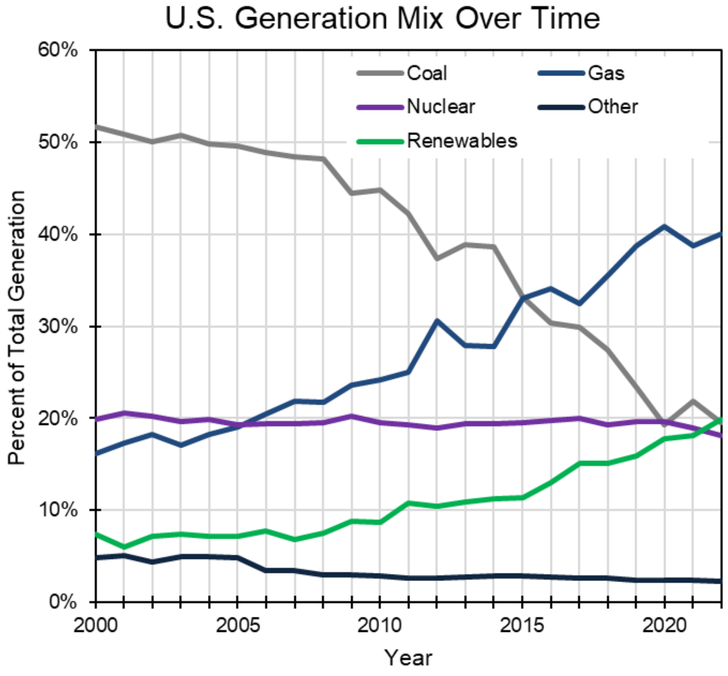
U.S. Electric System Energy Transition

- Aging coal replaced by natural gas, wind, and solar
- Wind and solar concentrated in areas with highest resource efficiency





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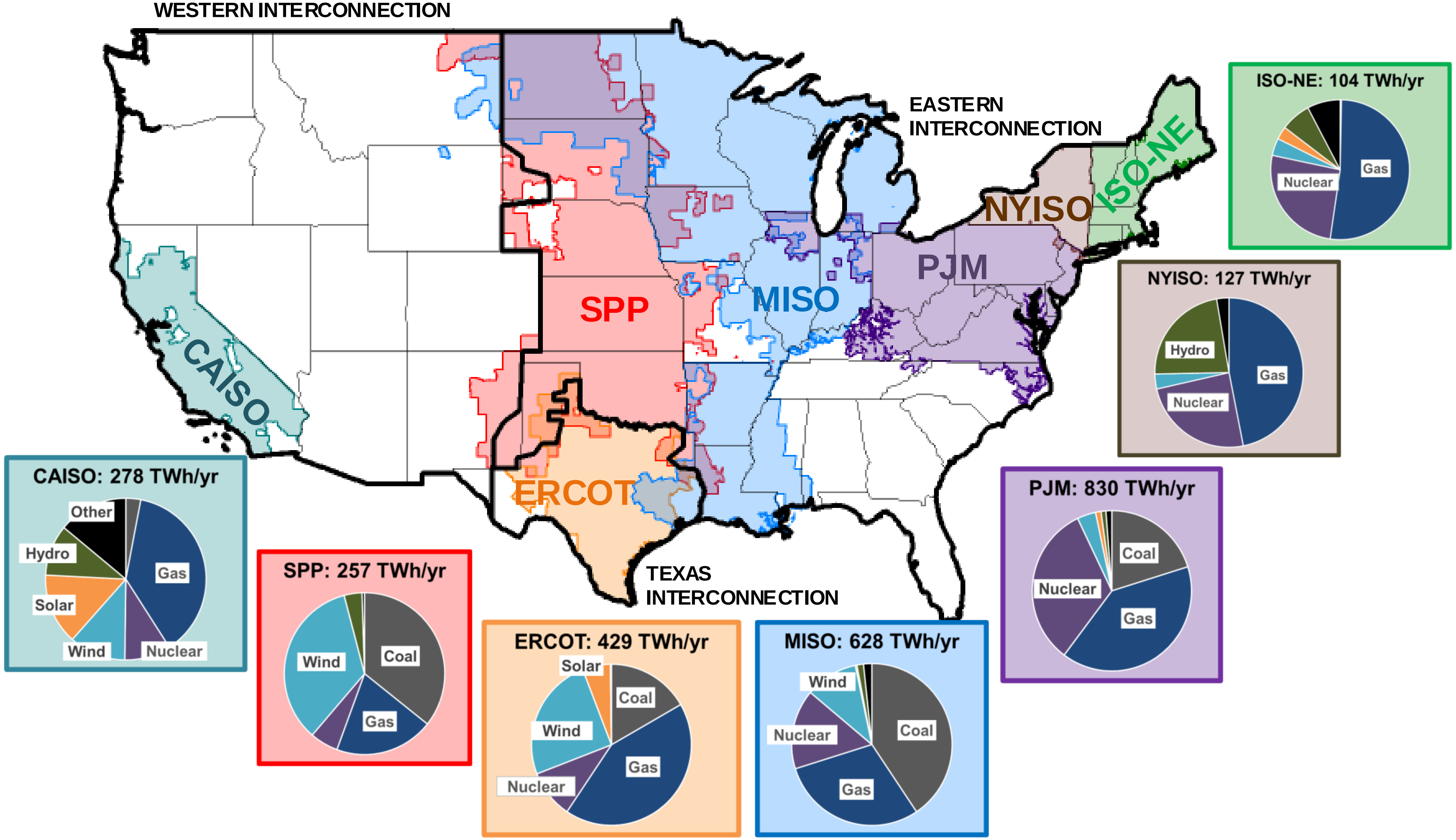
The U.S. Power System – Generation Mix



Greatest Renewable Penetration:

ERCOT

CAISO

SPP

MISO

All areas with access to high resource efficiency

Invenergy

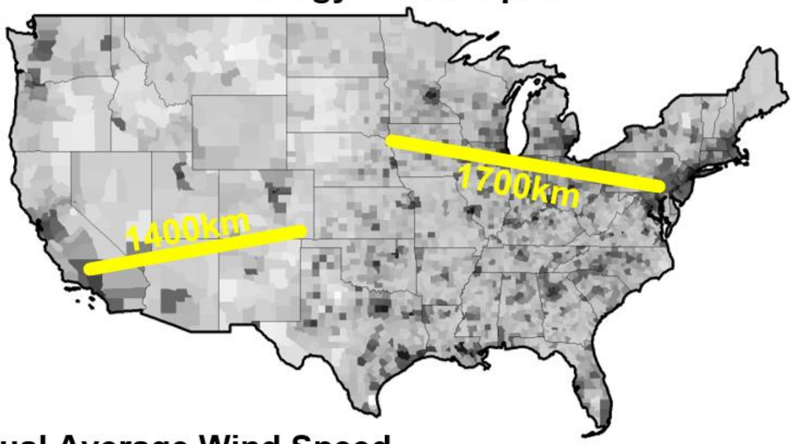
The Need for HVDC – Access to Renewable Resource

Merchant transmission developers providing transmission between RTOs

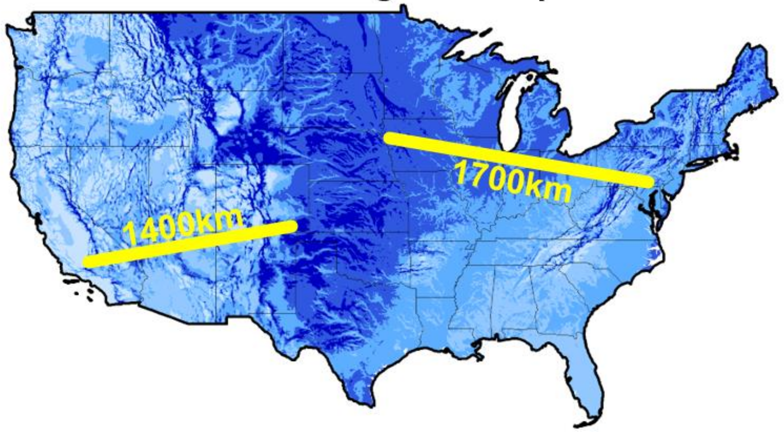
Preferred solution: VSC-HVDC

- Greater electrical efficiency
- Smaller rights of way
- Improved system stability and control
- Less conductor cross section
- Avoids AC compensation
- Connections between weak AC systems
- Connections between asynchronous interconnections

Energy Consumption



Annual Average Wind Speed



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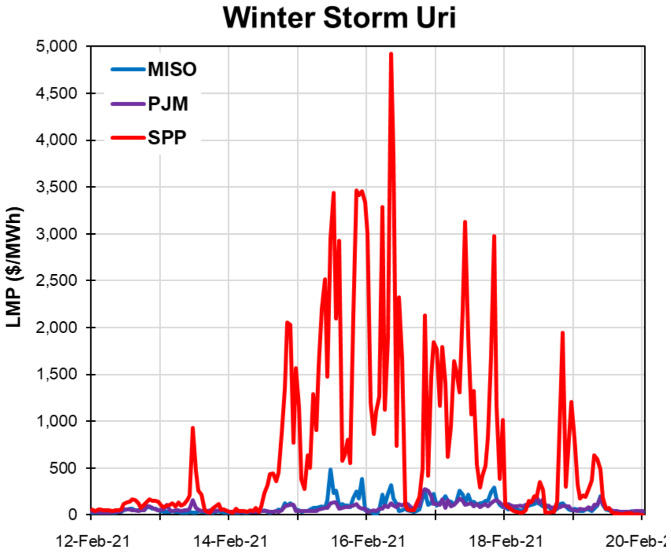
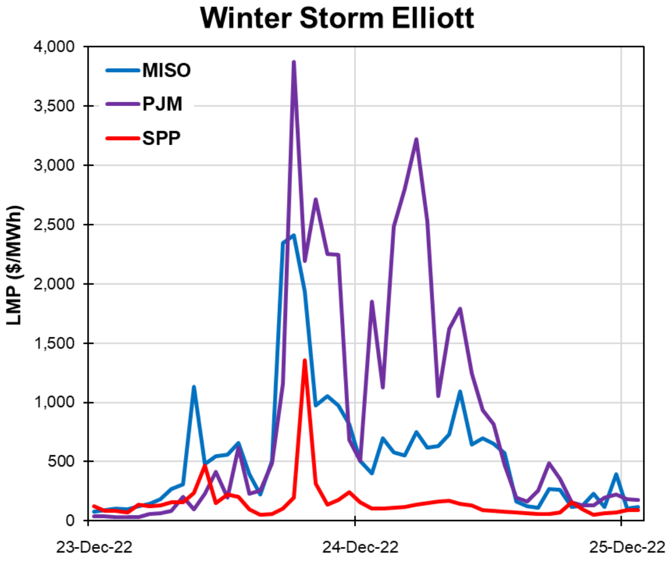
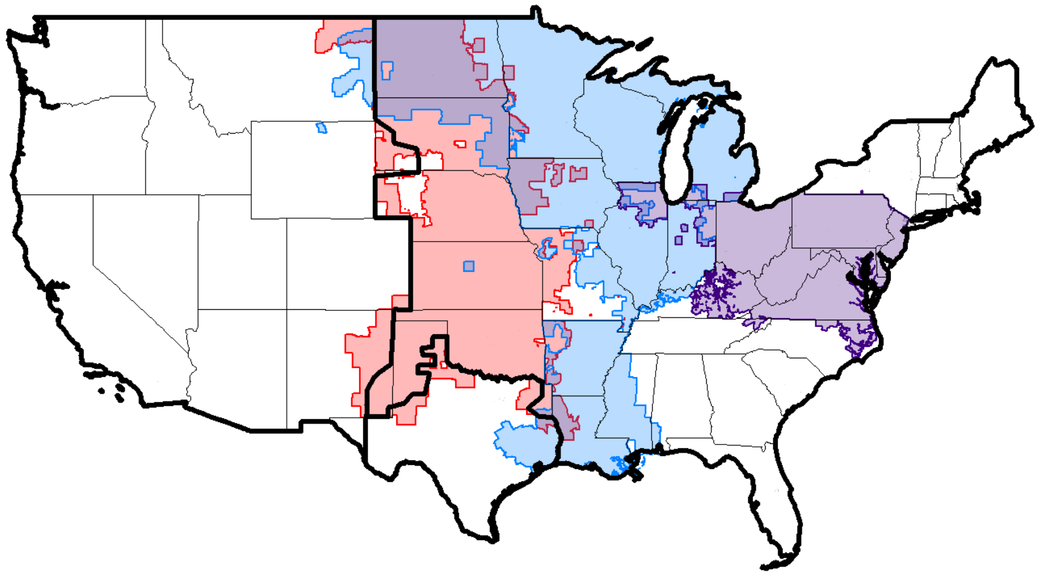
Value of Interregional Transfer Capability

- Regional storms drive significant locational marginal price (LMP) discrepancies
- +1GW interregional capacity would have saved $1B (Uri) and $100M (Elliott)







Invenergy

Grain Belt Interconnection Status

- SPP / ITC Great Plains: executed interconnection agreement for with a POI at ITC's Saddle 345kV substation. In the process of performing more detailed studies with SPP through their Transmission Working Group (TWG)
  - Steady State
  - Short Circuit
  - Dynamic
  - Electro Magnetic Transient - SSTI and SSR studies
- AECI: executed interconnection agreement for 1,018 MW with a POI at the McCredie 345kV substation
- MISO / Ameren: Interconnection agreement for 1,500 MW with a POI at the future Burns 345kV substation
- PJM / AEP: 2,500 MW to be studied in the PJM transitional cluster. Interconnection agreement execution expected in the 2025/2026 timeframe, with a POI at the Sullivan 345kV substation

Grain Belt Challenges

- Magnitude of transfers
    - Contingencies associated to the project could drive Remedial Action Schemes and/or other solutions (e.g., chopper)
    - System upgrades to support project
- Interregional operation
    - Spanning three different RTOs with different interconnection, planning, and operations (incl. markets)
        - New or modified interconnection planning processes and Interconnection Agreements
    - Open Access Transmission Tariff integration
    - Multiple state jurisdictions
- Vendor constraints
    - Worldwide demand for HVDC with limited vendors (GE, Siemens Energy, Hitachi)

Invenergy

Innovators building a sustainable world.

English

Innovadores construyendo un mundo sustentable.

Spanish

持続可能な世界作りを目指す革新者.

Japanese

Innowatorzy budujący zrównoważony świat.

Polish

Des innovateurs construisant un monde durable.

French

Inovadores na construção de um mundo sustentável.

Portuguese

Invenergy Transmission

Join us.

Appendix

World's Leading Privately Held Clean Energy Company

Wind
118 projects
19,274 megawatts

Solar
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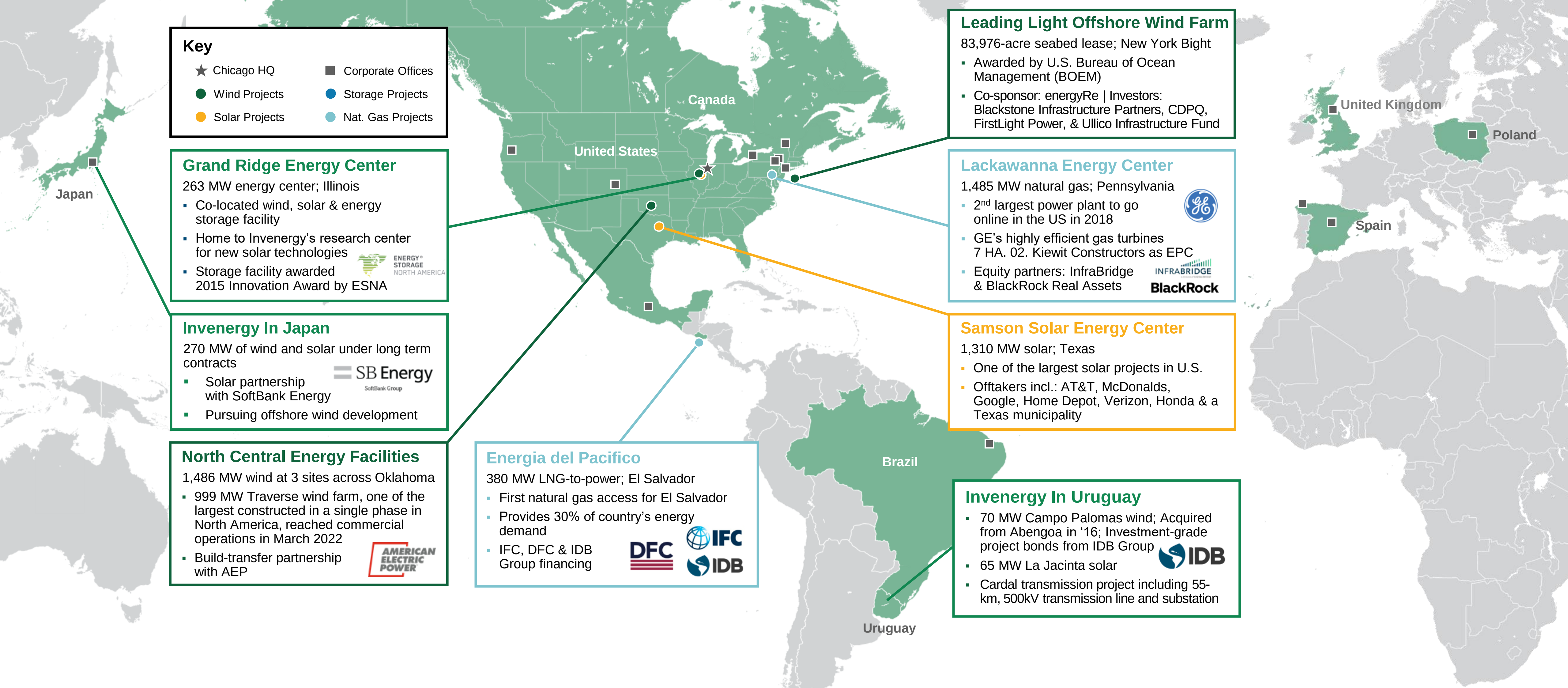

Grand Ridge Energy Center

263 MW energy center; Illinois

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205 Projects Developed

32 GW Capacity Developed

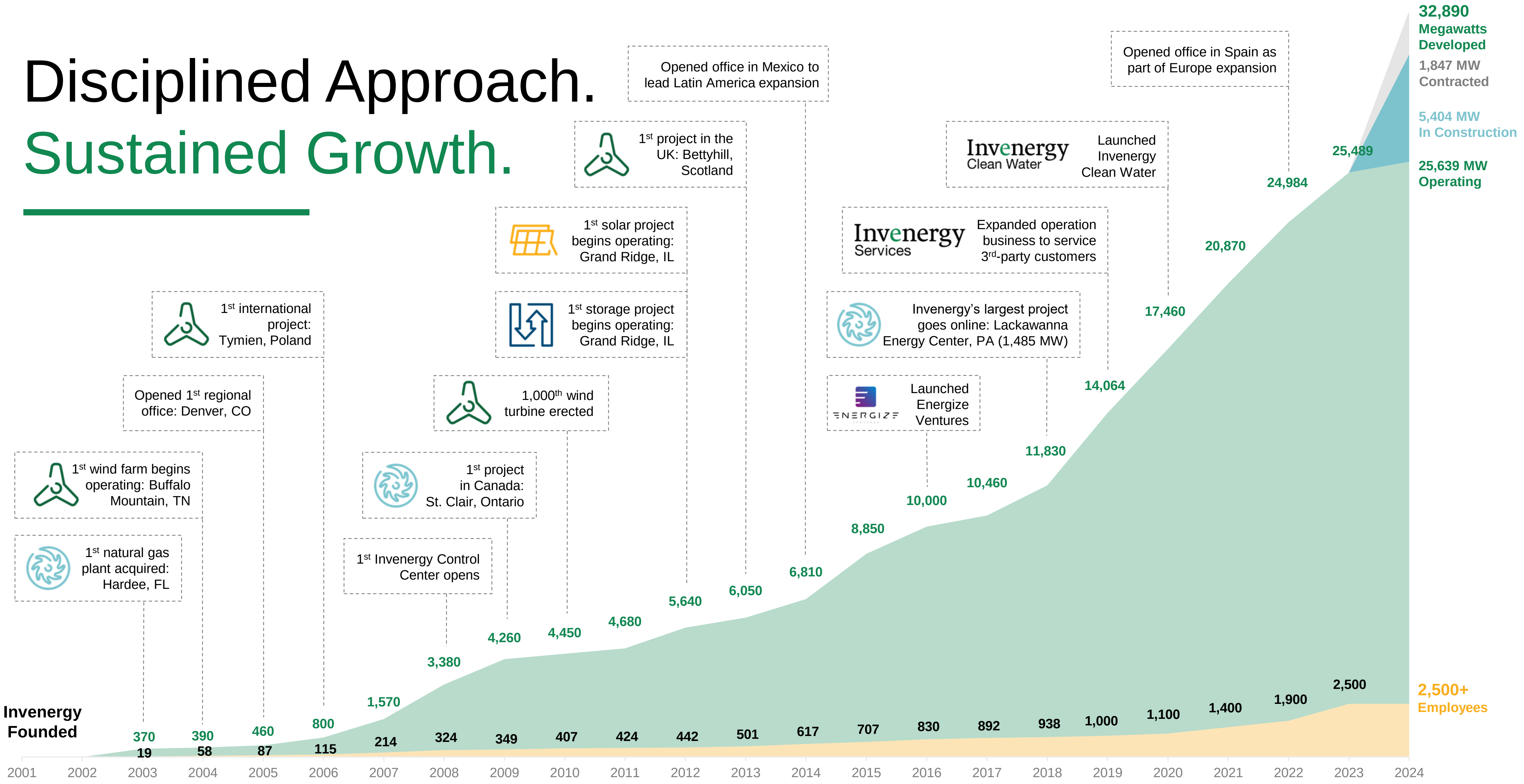
$64B Completed Transactions

12.5M Homes Powered

14.6M Cars off the Road Equivalent

Invenergy

Disciplined Approach.
Sustained Growth.



As of November 14, 2024. Megawatt totals include Invenergy-developed wind, solar, and natural gas power generation and battery storage facilities.

Full-Lifecycle Capabilities and Service

The know-how and experience to get the job done.

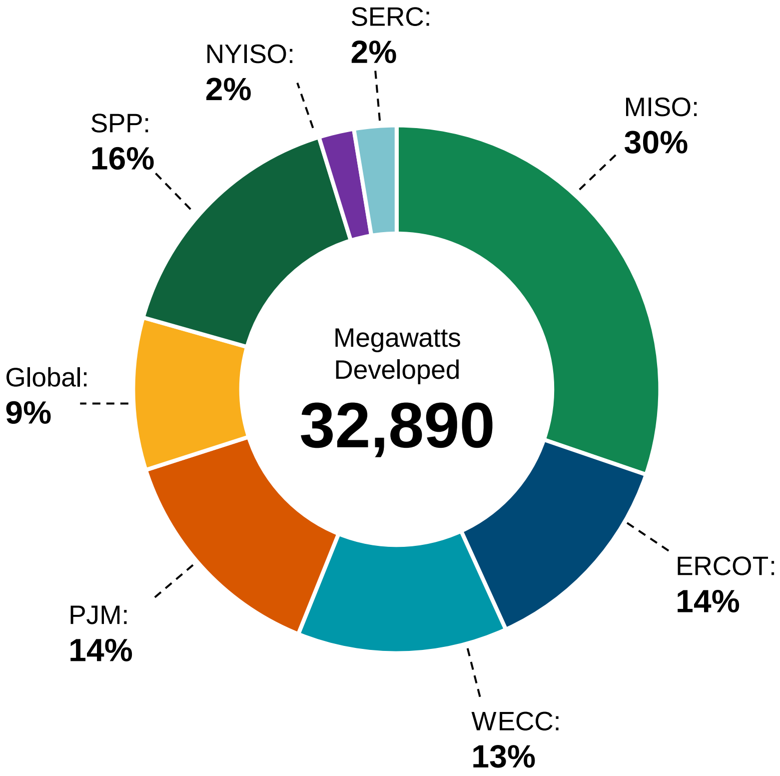
Invenergy has the end-to-end expertise from development to operations to bring clean energy projects where they're needed.

DEVELOPMENT	DESIGN & BUILD	FINANCE	OPERATIONS	ENVIRONMENTAL
• Community and landowner engagement • Engineering studies • Project siting • Interconnection	• Layout and design • Engineering, procurement and construction services • Project management	• Project financing • Mergers and acquisitions • Power purchase agreements (PPAs, VPPAs, Retail and utility sleeved PPA) • Joint development agreements	• Operations and maintenance • Field services • Asset management • Balance of plant • Energy management • Engineering and analysis	• Natural resource management • Vegetation management • Federal land management and permitting • Tribal engagement • Federal and state policy strategy and engagement

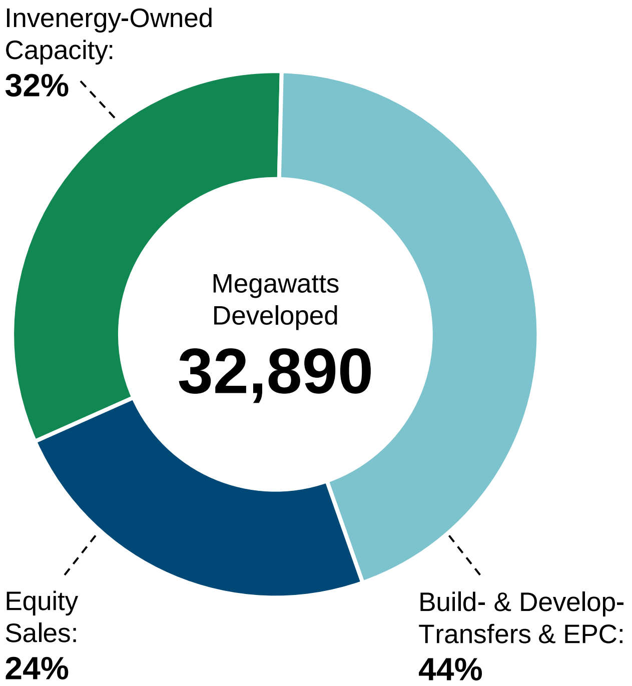
Invenergy

Expertise & Flexibility
Across Markets & Project Structures

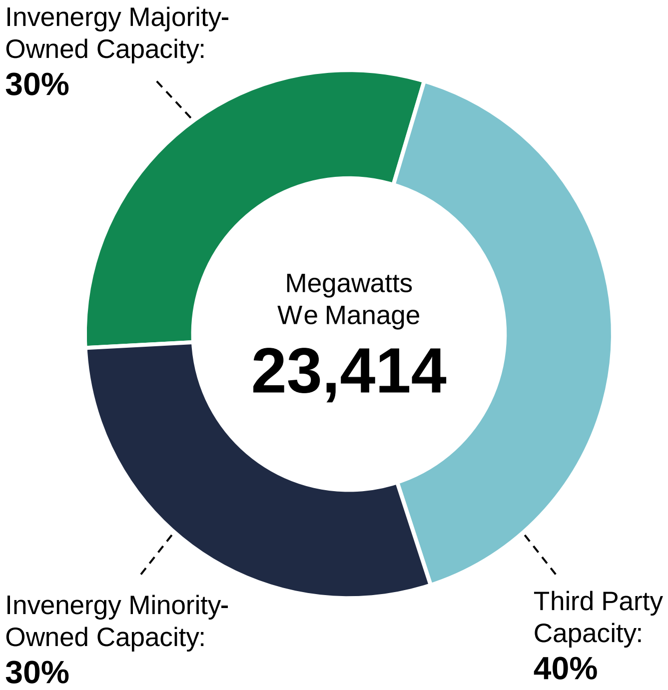
MARKETS



PROJECT OWNERSHIP



OPERATIONS



Invenergy

Breakdowns by megawatt totals

Success Built on Strong Relationships

UTILITY & CO-OP

Berkshire Hathaway Energy

- 4 GW+ of wind, solar and storage developed for BHE companies including PacifiCorp, MidAmerican & NV Energy
- Partner in building industry-leading renewables platform

American Electric Power (Boundless Energy)

- 2,700 MW+ of wind and solar projects completed
- Partner in achieving net-zero CO_2 by 2045

COMMERCIAL & INDUSTRIAL

Meta

- 590 MW+ helping power Meta's 100% renewable energy matching goals

verizon

- 890 MW+ across multiple technologies and markets
- Project sizes and CODs to support Verizon's renewable energy goals

PUBLIC POWER

New York State of Opportunity | NYSERDA

- 900 MW+ across 6 projects with NYSERDA
- Supporting New York's ambitious 70% by 2030 Renewable Energy Target

Success Built on Strong Relationships

FINANCIAL

CDPQ

- Invested in discrete portfolio of wind farms in 2013
- Equity investor in Invenergy's renewables business as part of low-carbon investment strategy

Blackstone

- Entered into one of the largest renewable investments in North American history in 2021
- Equity investment provides capital to accelerate renewables development activities

INFRABRIDGE (a division of DIGITALBRIDGE)

- Entered into equity partnership in 2018
- Investor in portfolio of natural gas facilities in operation and development in North America

OEM

GE

- Partnership dates to Invenergy's 2001 founding
- Strategic partner for wind and natural gas equipment
- 1,400 MW+ financed through tax equity

ENGINEERING & CONSTRUCTION

Kiewit

- Construction partner: 1,400 MW+ Lackawanna Energy Center in PA; 600 MW+ Los Ramones Energy Center in Mexico; Samson and Delilah solar projects in TX
- Engineer of Record: 600 MW Nelson Energy Center in IL

Our Invenergy Impact

$573M
Total 2023 local economic investment in project-generated wages & benefits, land costs & lease payments, and state & local taxes

Net Zero
Invenergy has committed to achieve net-zero greenhouse gas emissions by 2050.

$4.1M
Given to different cause-based organizations in 2023, focusing on veterans, education, emergency services & environmental stewardship

67M
Tons of CO_2 emissions avoided by Invenergy annually

8% veterans
Percent of Invenergy's U.S.-based workforce who are military veterans or reservists

14.6M
Gasoline powered cars off the road
CO_2 equivalent

"Invenergy came in like a lot of big folks do and we didn't know what to expect of them. But it's all been a plus. It's refreshing, to tell you the truth, what they've done for us. And we look forward to the future."

Mike Elkins,
Former County Judge and Director, Irion County, Texas Volunteer Fire Department

Invenergy

Deep Transmission & Distribution Experience

Bringing power to where it's needed most.

Benefits of transmission

- Deliver billions of dollars in customer cost savings
- Power economies for entire states and regions through job creation and payments to local governments and landowners
- Enhance America's grid reliability and energy independence
- Unlock new renewables to support climate and clean energy goals

Invenergy's proven track record

4,100
miles of transmission and collection lines developed

12,000+
landowner relationships across Invenergy generation and transmission projects

$40B
in new interconnection, wind and solar investments enabled by Invenergy transmission projects

Invenergy Transmission Portfolio Overview

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1,765 linear miles
of new transmission right of way, using 13,100+ miles of conductor lines (12,800 overhead; 370 buried)

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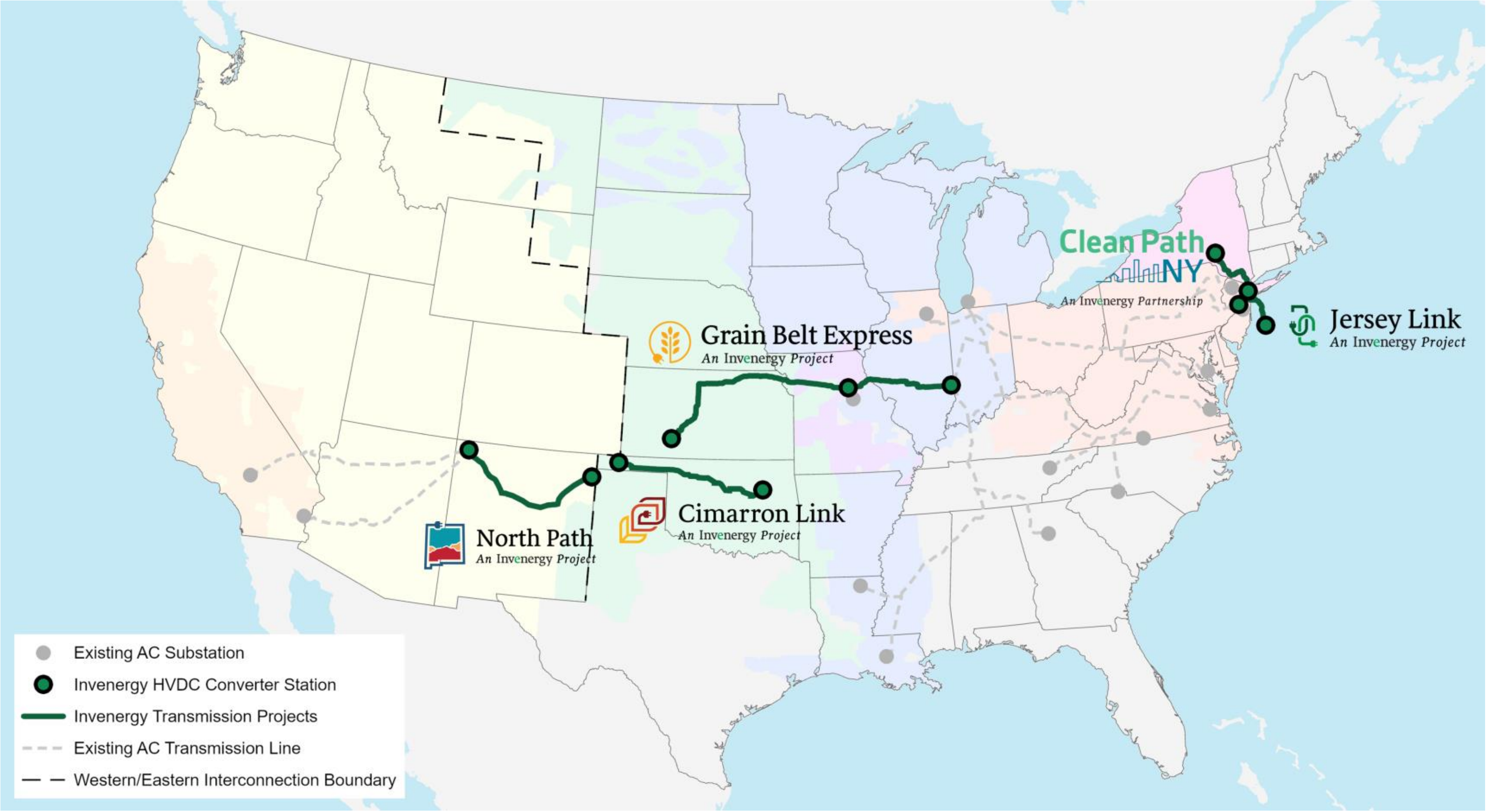


Invenergy

Invenergy's transmission projects represent 35% of proposed new U.S. HVDC transfer capacity

Megawatt-Miles

Line Capacity x Line Miles

Measures how much energy can be carried over distance

150-200 million

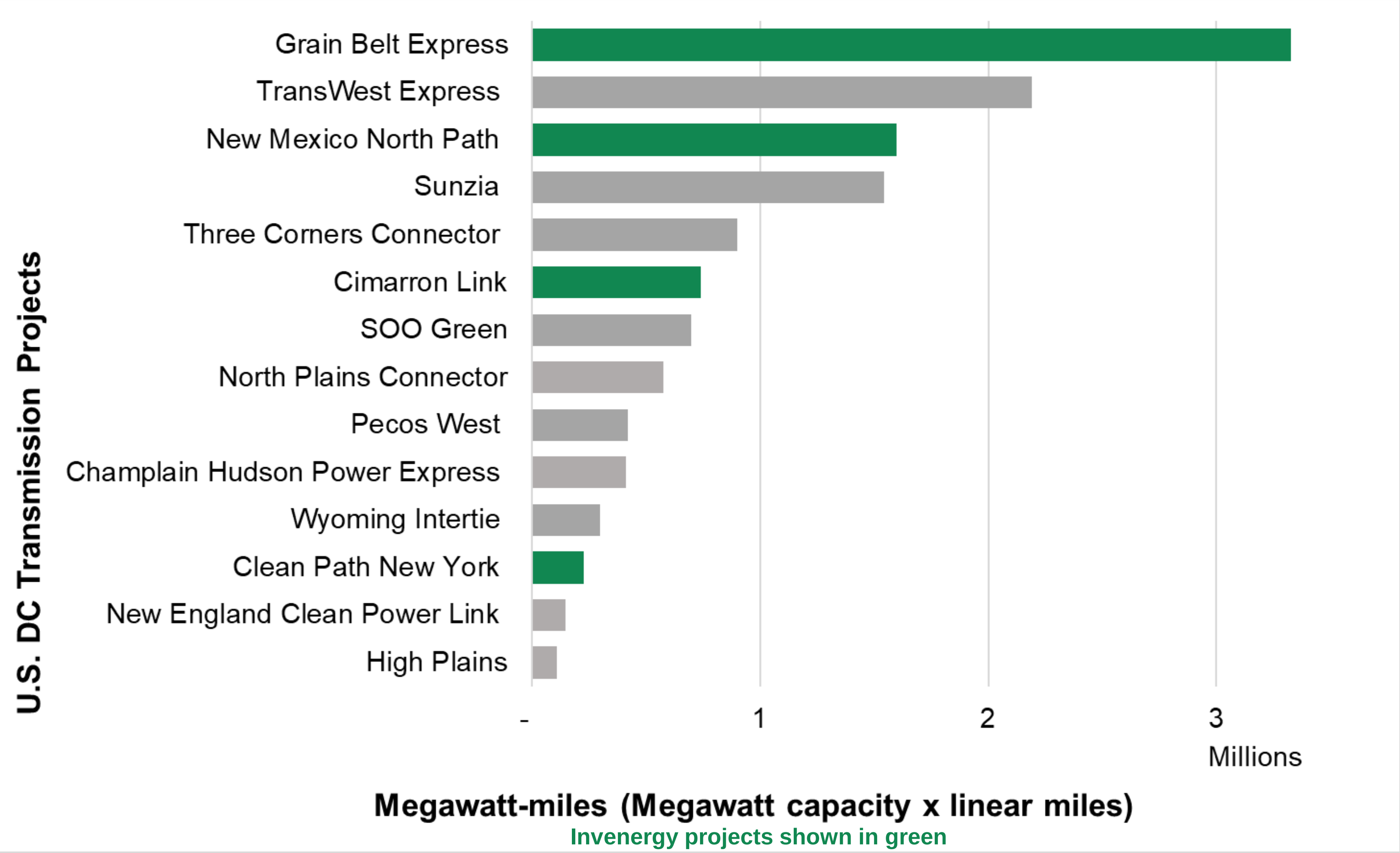
Megawatt-miles of current U.S. transmission system

16.5 million

Megawatt-miles of new proposed HVDC lines in U.S.

5.9 million

Megawatt-miles of proposed Invenergy transmission projects



Invenergy

Achieving Responsible Development in the Transmission Environment

MINIMIZE ENVIRONMENTAL RISK

Collect and assess information on ocean resources to design, build, and operate projects in a way that avoids and minimizes risks to species of concern, sensitive habitats, and areas of cultural significance.

STAKEHOLDER & TRIBAL ENGAGEMENT

Engage with regulatory agencies, Tribes, and affected communities at every stage of development to exchange information on environmental risks and identify appropriate strategies to manage those risks.

INDUSTRY COLLABORATION

Engage in partnerships that enhance knowledge of responsible transmission development, advance innovative solutions, and promote smart policy for responsible development.

Project Profile

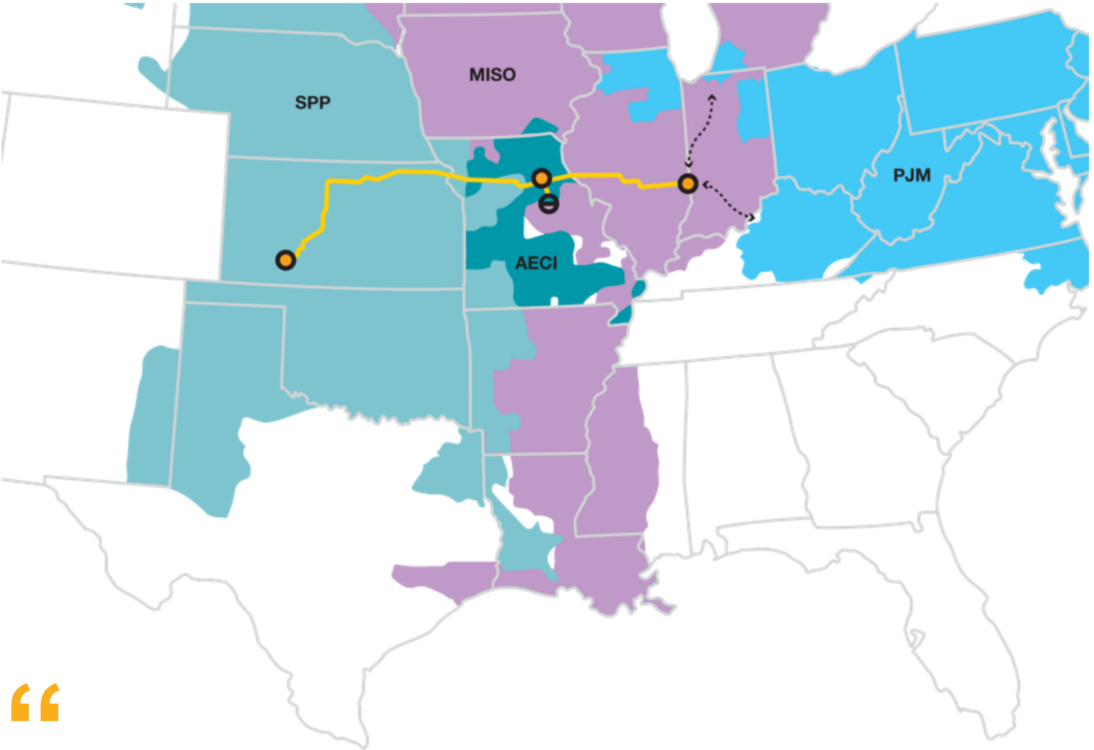
Grain Belt Express
An Invenergy Project

GrainBeltExpress.com

Grain Belt Express is a $7 billion electric transmission infrastructure project connecting four states—Kansas, Missouri, Illinois, and Indiana—across 800 miles. An Invenergy Transmission project, Grain Belt Express will carry more affordable, reliable power to millions of homes and businesses across the Midwest and other regions, delivering 100% domestic, clean electricity while powering economic opportunity and energy security.

AN ENERGY SOLUTION FOR AMERICA'S HEARTLAND

- **$20B Total Investment:** $7B transmission; $13B for new renewables enabled
- **5,000 Megawatts:** Highest capacity U.S. transmission project
- **800 Miles:** Second-longest U.S. transmission line
- **436M Tons CO2 Reduced:** Most for any U.S. power infrastructure project
- **22,300 Jobs:** Direct construction jobs for transmission line and enabled renewables
- **$11B Energy Cost Savings:** For route-state consumers in KS, MO and IL



"[Grain Belt Express] will also be capable of moving electricity both directions, which could have helped mitigate the electricity crisis that hit the United States earlier this year. 'Lines like Grain Belt Express could have been the savior.' ***Kansas City Star*, April 12, 2021**

Invenergy

Project Profile

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An Invenergy Project

GrainBeltExpress.com

COMMERCIAL & DEVELOPMENT

Major Supplier Agreements

- Executed HVDC technology Preferred Supplier Agreement with Siemens Energy
- Executed transmission conductor Preferred Supplier Agreement with Prysmian

Offtake Agreements In Place and In-Progress

- Transmission Service Agreement in place with group of 39 Missouri municipal utilities
- Anchor customer agreement currently in negotiation

Land Control Substantially Advanced

- Approximately 90% land control complete for Phase 1 HVDC route

Interconnection Positions Advancing

- Interconnection positions filed with SPP, MISO, AECI and PJM

Project Phasing to Deliver Benefits Sooner

- Grain Belt Express has proposed constructing the project in two phases, with Phase 1 (530 miles) running between the Kansas and Missouri points of interconnection, and Phase 2 (240 miles) running from the Missouri converter station to the Indiana point of interconnection. Phase 1 would begin construction as soon as the end of 2024 and proceed approximately 18 months ahead of Phase 2

> **"This transmission line is one of the largest economic development projects in the entire state and will help power our towns, while saving every family and business in our communities a total of more than $12.8 million.**
>
> **Missouri Public Utilities Alliance**

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REGULATORY

FERC Negotiated Rate Authority Approved

- The Federal Energy Regulatory Commission (FERC) has authorized Grain Belt Express to sell transmission capacity to potential customers of the project, including utilities and other load-serving entities or clean energy generators, and to negotiate agreements for 100% of the project's capacity.

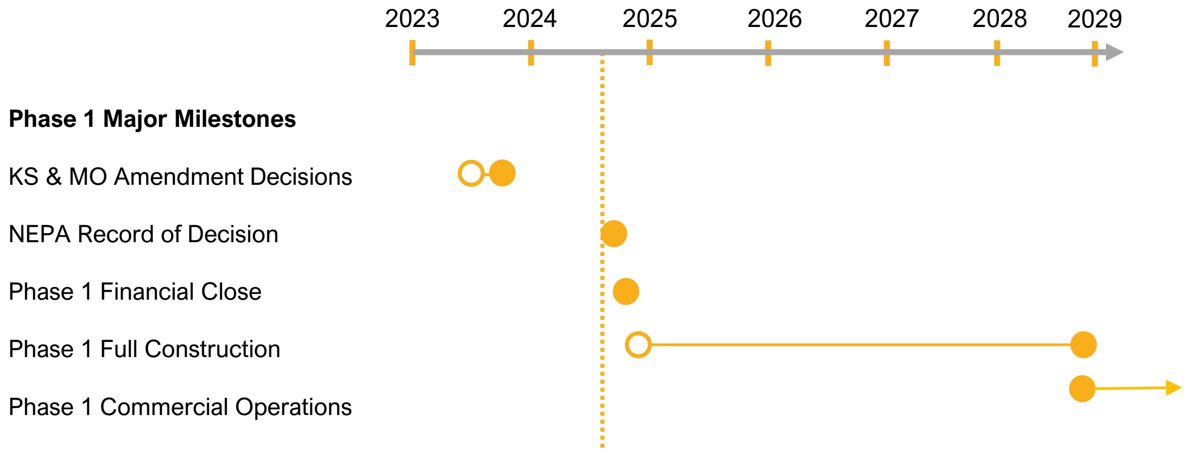
U.S. DOE Loan Program Office Environmental Review Underway

- Grain Belt Express has applied for a loan guarantee from the U.S. Department of Energy (DOE) Loan Programs Office (LPO) and is currently going through the associated National Environmental Policy Act (NEPA) review, with a Record of Decision expected in Q3 2024.

Initial State Siting Approvals in All Route States Secured

- As of Q1 2023, initial state siting approvals have been secured in all four project route states (Kansas, Missouri, Illinois, Indiana); a state siting certificate amendment is currently pending in Missouri, with a decision expected by Q4 2023.

PROJECT TIMELINE



"

There's no question, manufacturers and the communities they support across our region will see significant benefits thanks to this essential investment. Mark Denzler, President & CEO, Illinois Manufacturers' Association

Invenergy

Project Profile

North Path
An Invenergy Project

NewMexicoNorthPath.com

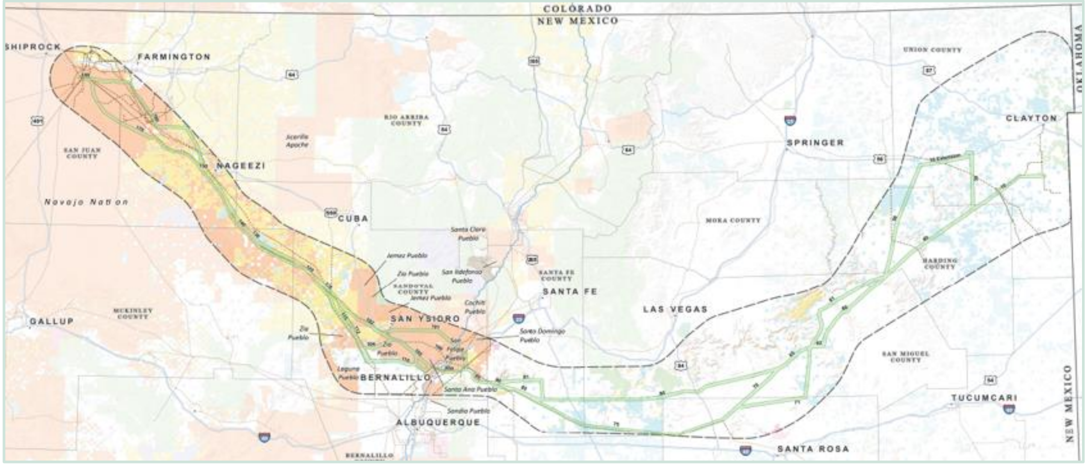
Invenergy Transmission

New Mexico Renewable Energy Transmission Authority RETA

North Path is being developed under a public-private partnership agreement between Invenergy Transmission and the New Mexico Renewable Energy Transmission Authority (RETA). It is a high-voltage direct-current (HVDC) transmission line that will deliver up to 4,000 megawatts of clean energy from northeastern New Mexico to the Four Corners region, helping power New Mexico and other western states.

SEIZING RENEWABLE ENERGY OPPORTUNITY

- **$5 billion:** Investment in in-state renewable generation unlocked by North Path
- **$10s of millions:** Annual payments to Tribal, State & Local governments
- **2 million homes:** Powered by renewable energy
- **3,500 jobs**: Created during 2-year construction period; $500M in worker earnings
- **50% by 2030:** Enables NM's Energy Transition Act renewable energy goals



"New Mexico has some of the best wind and solar energy potential in the United States, and the New Mexico North Path transmission line represents a critically needed pathway for moving low-cost clean energy to consumers across the state and region who are demanding it.

Bob Busch, Chairman, New Mexico Renewable Energy Transmission Authority (RETA)

Invenergy

Project Profile

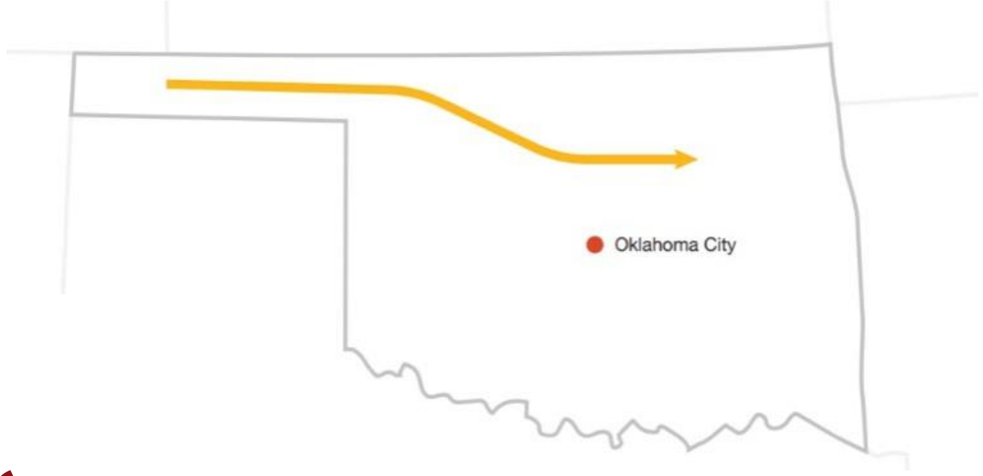
Cimarron Link
An Invenergy Project

CimarronLink.com

Cimarron Link is an electric transmission project that will unlock access to one of the lowest cost, steadiest-producing natural energy resources available anywhere in America - the inexhaustible wind energy of the Oklahoma Panhandle. Like pipelines that transport natural gas, transmission lines carry electricity from where it is generated to where it is needed. Cimarron Link will support energy price competitiveness and stability, bolster reliability, and strengthen long-term energy security by reducing our reliance on foreign energy.

OKLAHOMA POWER FOR OKLAHOMA FAMILIES

- **$5 billion:** Combined transmission and generation investment enabled
- **2,000 megawatts:** Generated in the Panhandle, carried to the East
- **$100+ million:** In new local tax revenues and landowner payments
- **~390 miles:** Transmission link connecting the Panhandle to Northeastern OK
- **1,000+ jobs**: Constructing transmission and generation; $500 mil. worker earnings



“

We are a huge oil and gas state, but what people don't realize is we are also a huge wind state, and we are a net-exporter, we produce more energy than we consume and therefore it's led to a reliable, affordable energy grid that's really the envy of the country and the envy of the world right here in Oklahoma.

Oklahoma Governor Kevin Stitt, Feb 10, 2023

Invenergy

HVDC Criteria & Applications

Mike Spector – Grid United

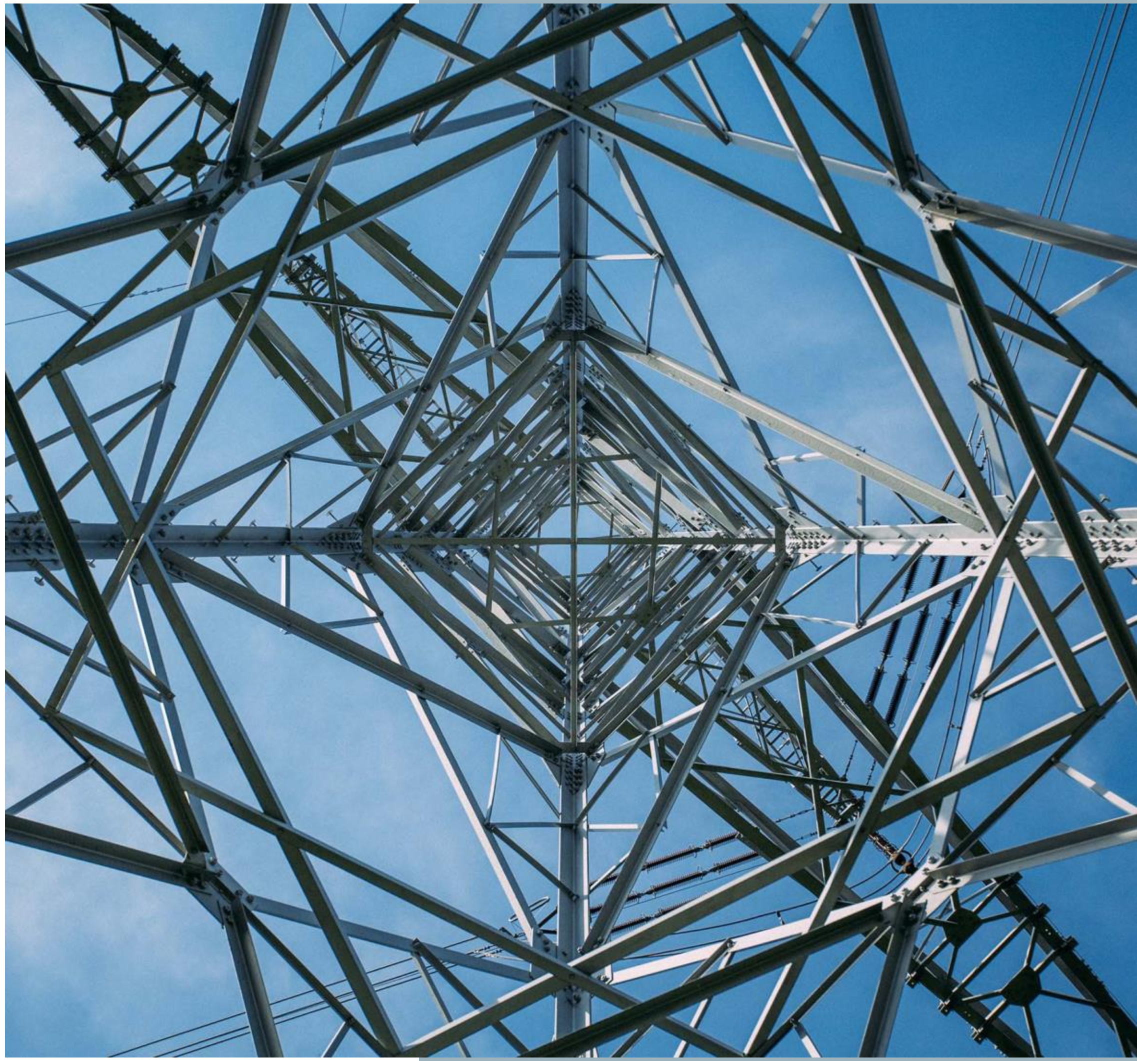
Sid Parmar – Grid United

GRID UNITED

HVDC Criteria & Applications

2024 NATF-EPRI-NERC Annual Transmission Planning and Modeling Virtual Seminar

November 20, 2024



Agenda

GRID UNITED

- Overview of Grid United
- Need for Interregional transmission
- Benefits & Applications of HVDC VSC
- The New Planning Paradigm
- HVDC Criteria
  - Example: Southwest Power Pool (SPP) HVDC Planning Manual

Grid United's Mission

To develop North America's next-generation energy infrastructure to power our future

Our projects:

- Connect key areas of the electric grid
- Create a more resilient and efficient electric system
- Utilize North America's abundant and geographically dispersed natural resources
- Benefit all consumers

Grid United's Strengths

GRID UNITED

Flexible Business Model

- Grid United recognizes that utilities are the natural owners and operators of transmission infrastructure.
- We welcome utility ownership and want to be a preferred utility partner that can facilitate a development or build transfer and—if necessary—ownership and operations.

Risk Capital

- Centaurus Capital, the investment vehicle of John Arnold, brings experience from billions previously invested in traditional and renewable energy projects.
- Centaurus provides patient capital backing Grid United, enabling innovative development strategies.
- We spend millions in at-risk capital to develop challenging projects.

Technical Experience

- Our team has >250 years of collective experience developing high-voltage and linear infrastructure projects.
- Our experience includes:
  - Managing HVDC interconnection processes
  - Project management and development
  - Engineering, procurement, and construction
  - Financing

Singular Focus

- We focus on developing high-value, unconventional HVDC transmission projects in North America.
- By prioritizing stakeholders first, we foster positive relationships with landowners and communities, building organic support for our projects.
- With an unconventional routing and acquisition strategy, Grid United is developing transmission projects faster than the traditional utility/RTO planning process.

About Grid United

Grid United is an independent transmission company aiming to develop next-generation energy infrastructure to create a more resilient and efficient electric system to the benefit of all consumers.

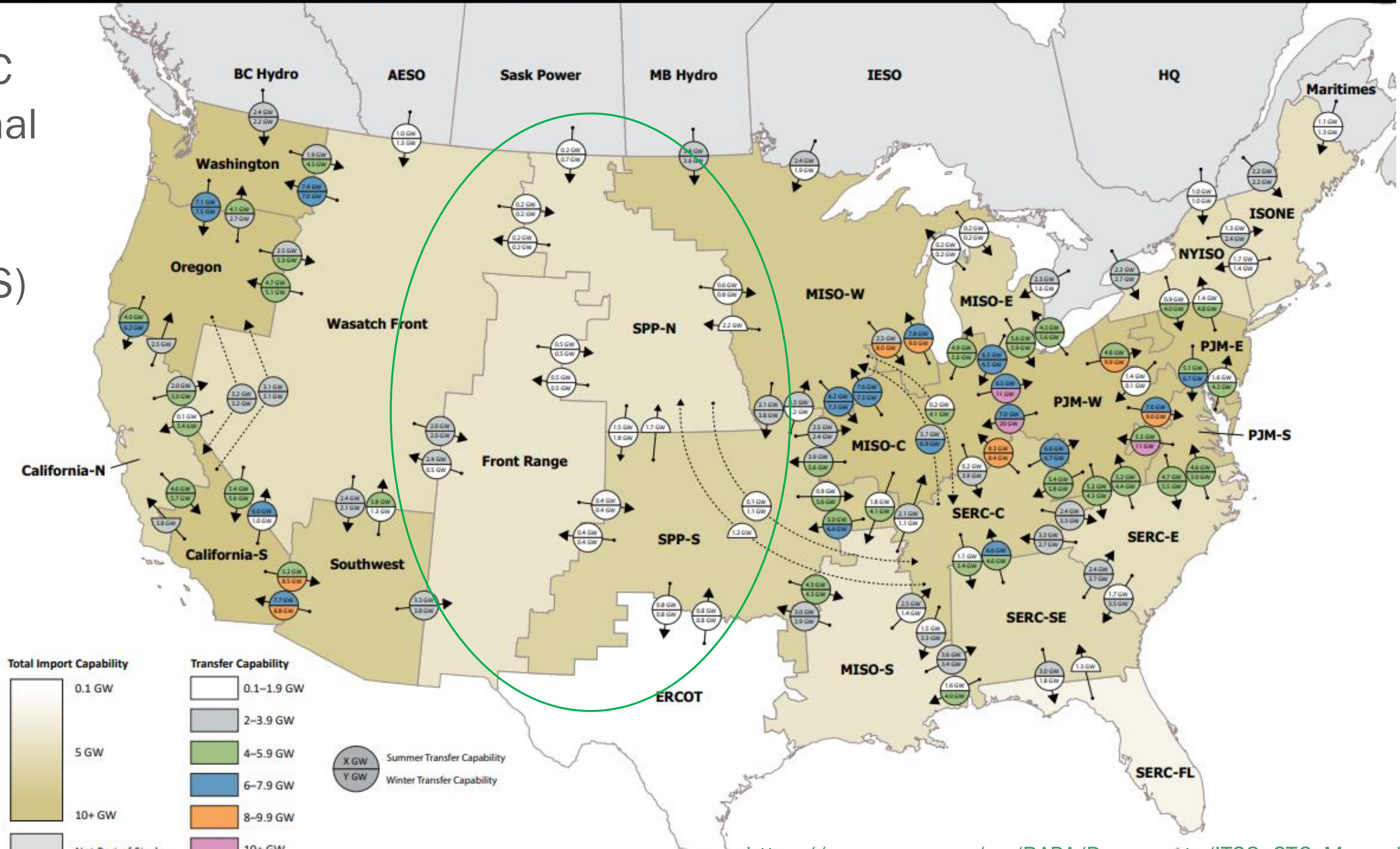
We seek out projects that few other developers are equipped to take on and are determined to develop projects that have a historic impact on America's power grid.

Limited existing transfer capacity

GRID UNITED

From NERC Interregional Transfer Capability Study (ITCS)

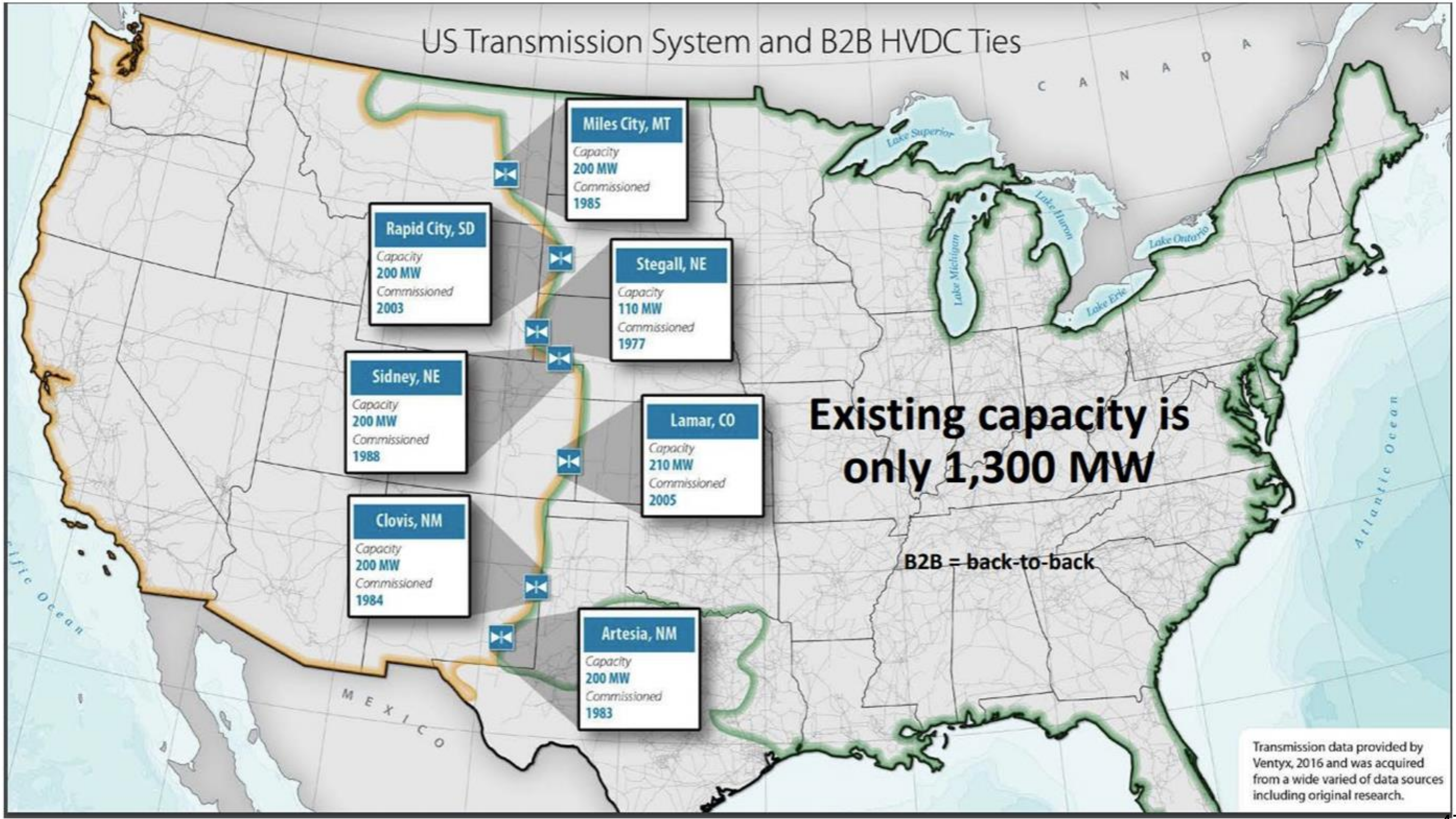
ITCS Calculated 2024/2025 Transfer Capabilities



https://www.nerc.com/pa/RAPA/Documents/ITCS_CTC_Map.pdf

Limited existing transfer capacity

States along the "seam" face constrained import / export capabilities during extreme events.



Why HVDC?

GRID UNITED

HVDC is required to connect asynchronous grids and is the preferred technology for moving large amounts of power across long distances—with higher efficiency and smaller footprint than equivalent power AC.

- Lower cost, due to higher efficiency than AC
- Fast, precise bi-directional power flow control
- Increases grid reliability and resiliency
    - “Black start” capability can jumpstart a grid after a blackout
    - Provides many ancillary services for reliability
    - Dynamic voltage response to grid disturbances in milliseconds

Interregional transmission provides broad, meaningful benefits

GRID UNITED

Transmission development yields a wide array of high-impact benefits—extending far beyond reduced energy costs for consumers—as identified in a report by the Brattle Group and Grid Strategies.

Reliability & Resiliency

- Reduced Loss of Load Probability
- Access to Geographically & Technologically Diverse Resources
- Improved Grid Operations Utilizing HVDC Capabilities

Reliability & Resiliency / Economics

- Reduced Reserve Margin
- Reduced Impact of Load & Renewables Forecast Error
- Reduced Cost and Impact of Extreme Weather
- Bidirectional Transfer of Power

Economics

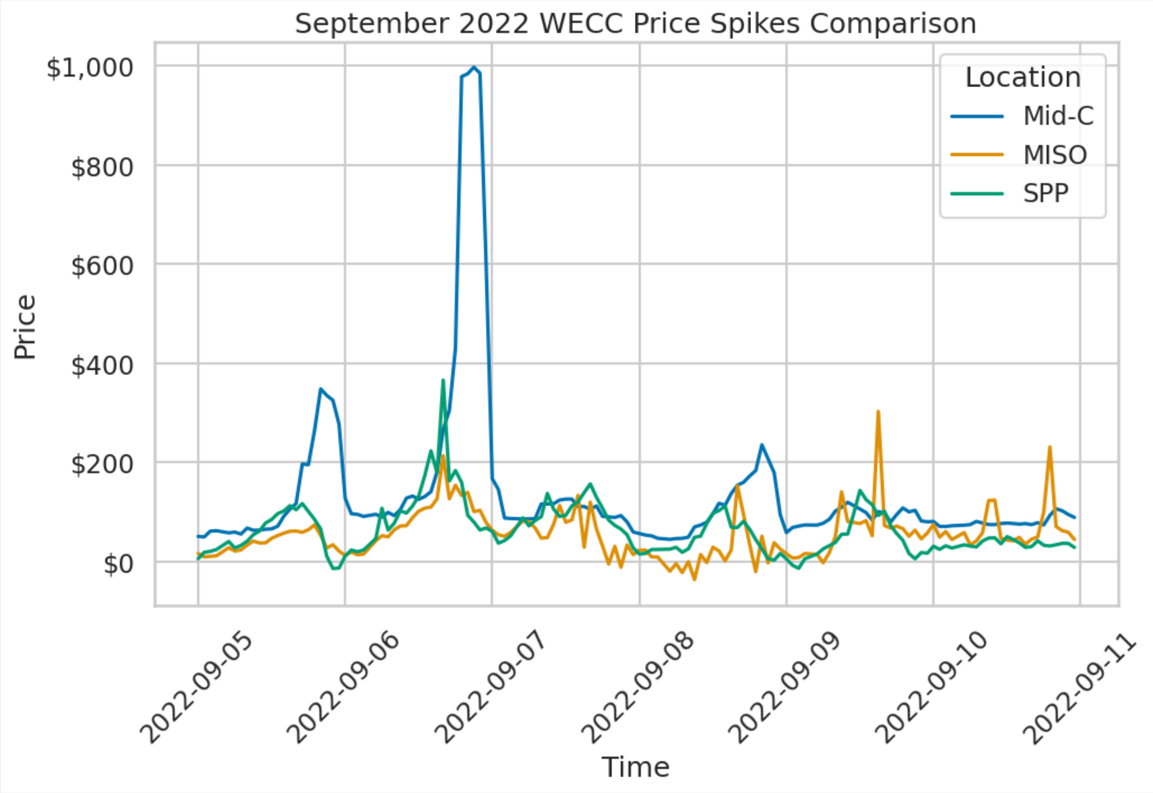
- Reduced Ancillary Services Costs
- Mitigated Impact of Complying with Future Policy, Market Changes
- Insurance-like Value for Low Probability Events

Grid United's portfolio is built around maximizing as many of these attributes as possible to enhance our grid today, & prepare it for future scenarios, such as climate change, natural gas price volatility, & legislative mandates.

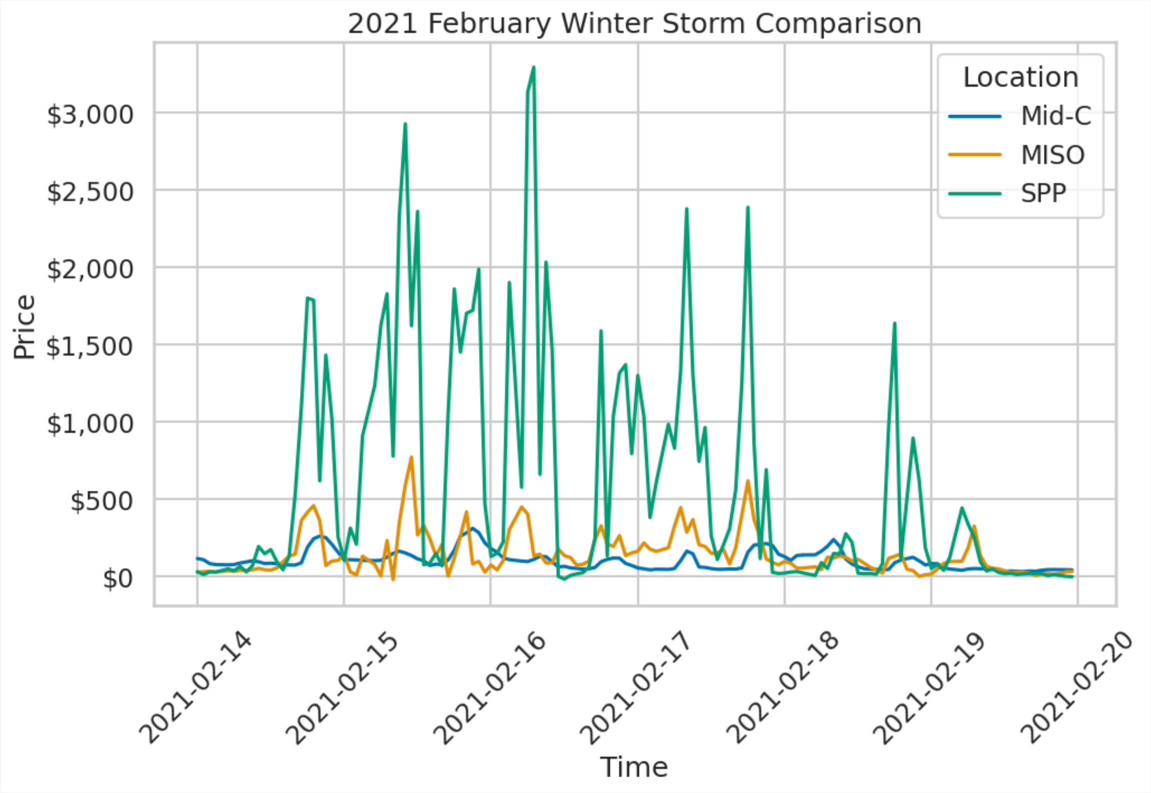
Source: The Brattle Group & Grid Strategies / Pfeifenberger, J., Gramlich, R., et al. "Transmission Planning for the 21st Century: Proven Practices that Increase Value and Reduce Costs." (2021).

Interregional Transmission and Extreme Weather Resiliency

While extreme weather can occur over a large area, severe impacts are typically regional, leading to distinct price volatility in SPP, MISO, and WECC.

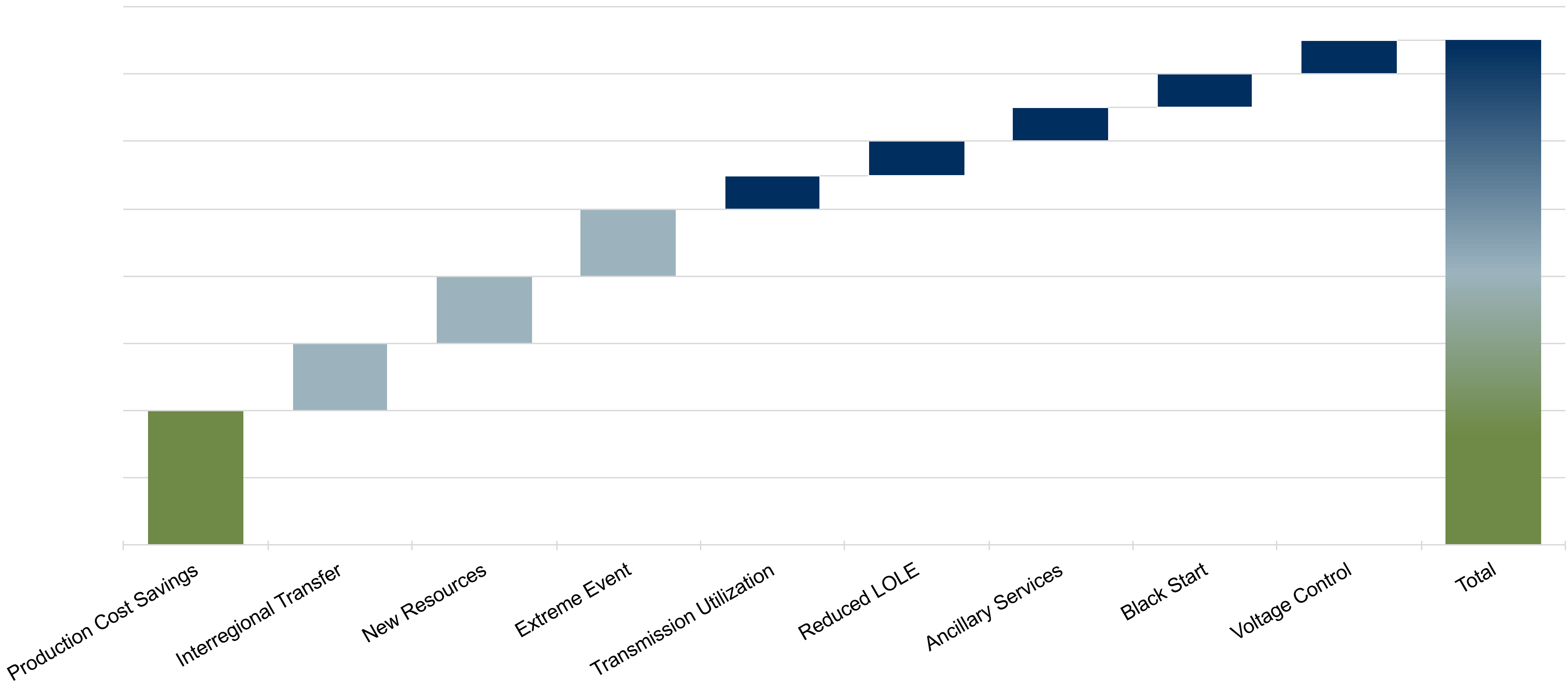


While West prices spiked during the September 2022 heat wave, SPP and MISO prices were unaffected.



When MISO and SPP prices spiked due to high gas prices and demand during Winter Storm Uri, the West was largely unaffected.

The value stack for interregional HVDC includes a wide range of attributes with equally disparate ways to quantify them



Market Efficiencies

Reliability & Resiliency

Additional Benefits

HVDC Applications

GRID UNITED

These examples show that significant experience exists with advanced AC grid support capabilities:

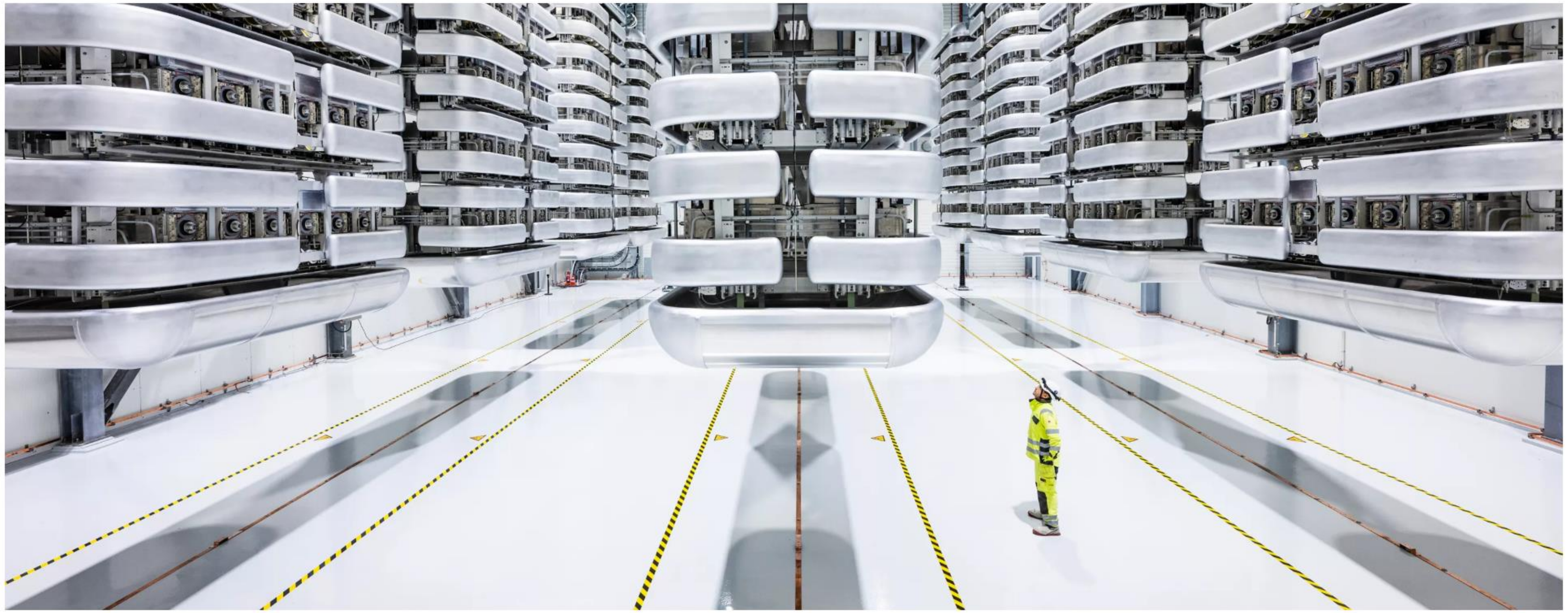
NEMO link Belgium - UK	• Frequency support and emergency energy
NordLink Norway - Germany	• Auto-reclosure for overhead line fault clearing and automatic bi- to monopole change
Maritime Link Canada	• HVDC runback schemes for prevention of overloading of AC lines
Fenno-Skan Sweden - Finland	• Mitigate AC stability constraints and improve system transfer capability
FIL France – Italy	• "AC line emulation" and AC grid loss and congestion reduction
INELFE France - Spain	• Power Oscillation Damping
Skagerrak 4 Norway - Denmark	• Black-start and system-restoration services
ULTRAnet Germany	• Converting existing AC overhead line circuits to HVDC

The Operational and Market Benefits of HVDC to System Operators PRESENTED BY Johannes P. Pfeifenberger (Brattle) Cornelis A. Plet (DNV) PRESENTED AT ACORE Webinar SEPTEMBER 19, 2023

Capacity Reservation Agreement – Hitachi

Press Release | Zurich, Switzerland | 20-03-2024 | 4 min read

Hitachi Energy to accelerate introduction of HVDC technology with Grid United for transmission projects to strengthen US power grid



In March 2024, Hitachi Energy and Grid United announced a collaboration to deliver high-voltage direct current (HVDC) technology for Grid United transmission projects that will interconnect the eastern and western regional power grids in the US. Under an innovative approach known as a capacity reservation agreement, Hitachi Energy will provide HVDC technology to support the development of multiple Grid United HVDC interconnections.

Shortfalls in Current Planning & Market Operations

GRID UNITED

- Lack of multi-value planning processes to capture full range of interregional benefits
- Does not account for the high costs and risks of an inadequate and inflexible transmission infrastructure (i.e., Insurance Value)
- Lack of robust interregional planning & cost allocation that benefits ≥ 2 regions
- Current markets do not optimize for maximizing existing interties

Collaboration:

Energy Systems Integration Group (ESIG) Integrating Transmission Siloes Task Force

Changing Planning Paradigm

GRID UNITED

- Moving away from bulk dispatchable generation in few locations to geographically diverse, weather-dependent, smaller-sized resources further away from load centers.
- Load growth is back!

Current paradigm:

- Traditional RTO Transmission Planning Methodology mainly focuses on transmission network constraints for delivering intra-RTO resources
- Current HVDC VSC interconnection studies evaluate potential negative impacts and not aligned with VSC technology’s abilities.
- Lack of HVDC planning standards:
  - **Collaboration:** Southwest Power Pool (SPP) HVDC Planning Manual

SPP HVDC Collaboration

GRID UNITED

EPRI

HVDC Recommendations for Southwest Power Pool

Recommendations for planning criteria, grid code performance, models and simulations tools

1-117373

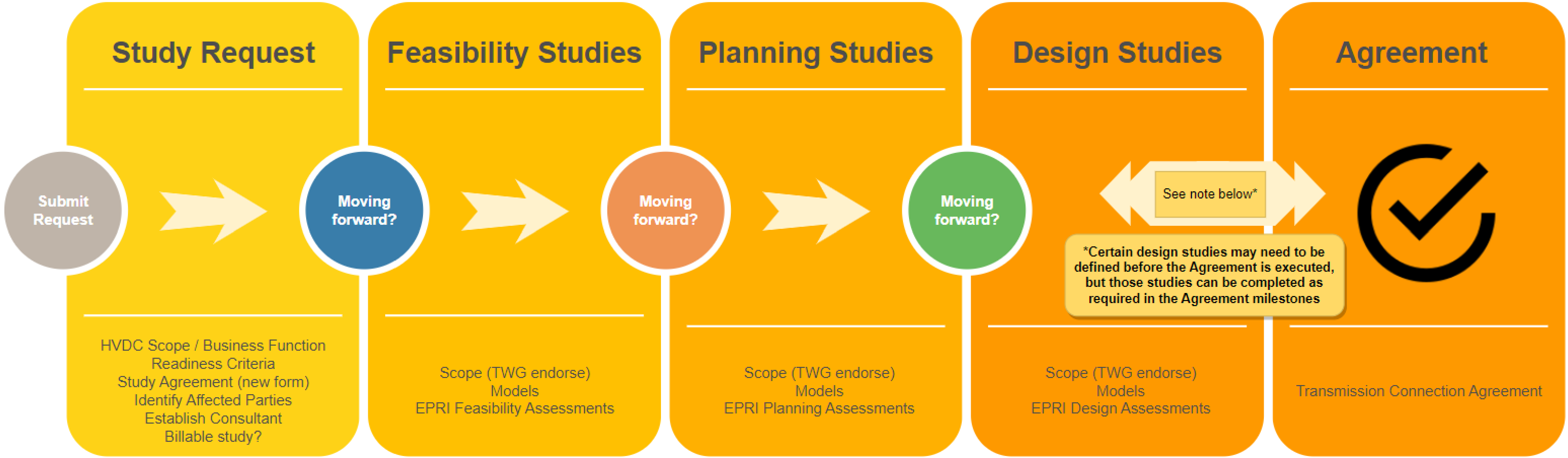
SPP Southwest Power Pool

SPP HIGH VOLTAGE DIRECT CURRENT (HVDC) PLANNING MANUAL

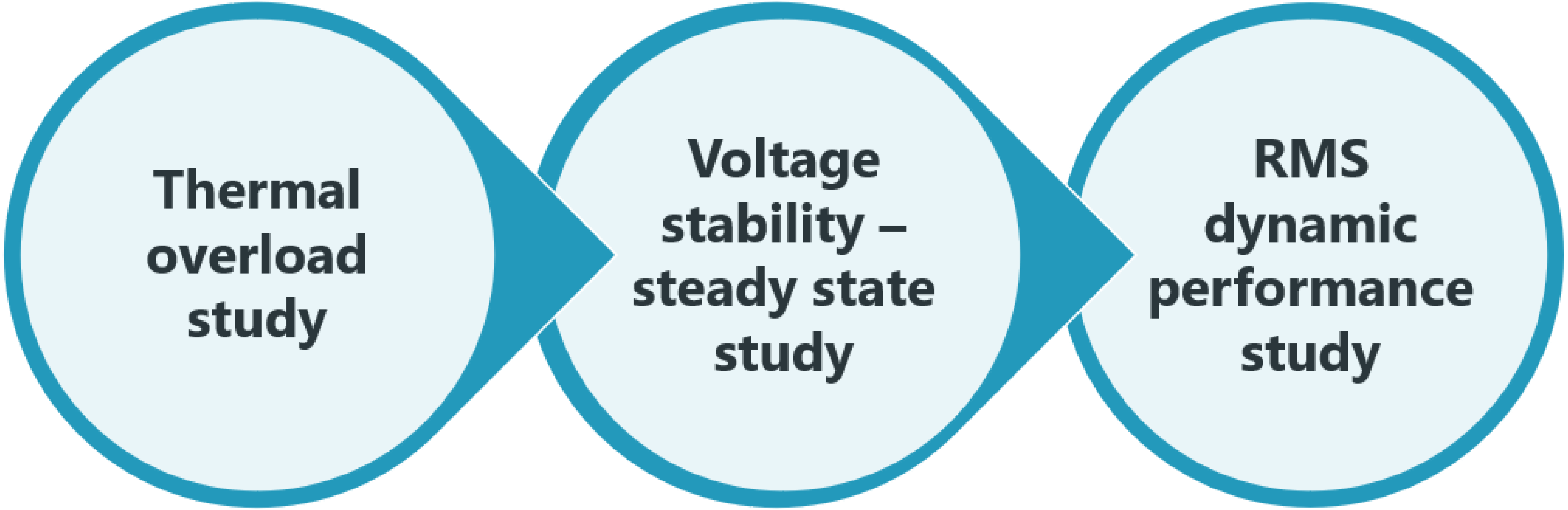
- Over 200 comments on EPRI recommendations
- On-site workshop in November 2023 with stakeholders
- Four rounds of comments; last round with OEMs

- Four rounds of comments including OEMs
- Review of comments & Manual updates at TWG meetings
- Revision Request #650 (RR650) SPP HVDC Planning Criteria & Manual

SPP HVDC Process



- Are there any fatal flaws / major system issues after adding the transmission line?
- Preliminary analysis – no actionable items
- Steady State / Load Flow analysis
- Full contingency analysis
- Full dynamic suite of studies



GRID UNITED

- Cases – 2032 (10-year) Steady state Summer Peak & Light Load cases used
- Summer Peak import and Light Load export cases studied (most probable use of DC ties)
- NERC TPL-001-5 standard
  - P0 (N-0) system intact
  - P1 (N-0) single contingency analysis
  - P6 (N-1-1) two overlapping single contingencies (loss of one element followed by System adjustments)
- Identify worst thermal and voltage constraints

SPP Planning Studies

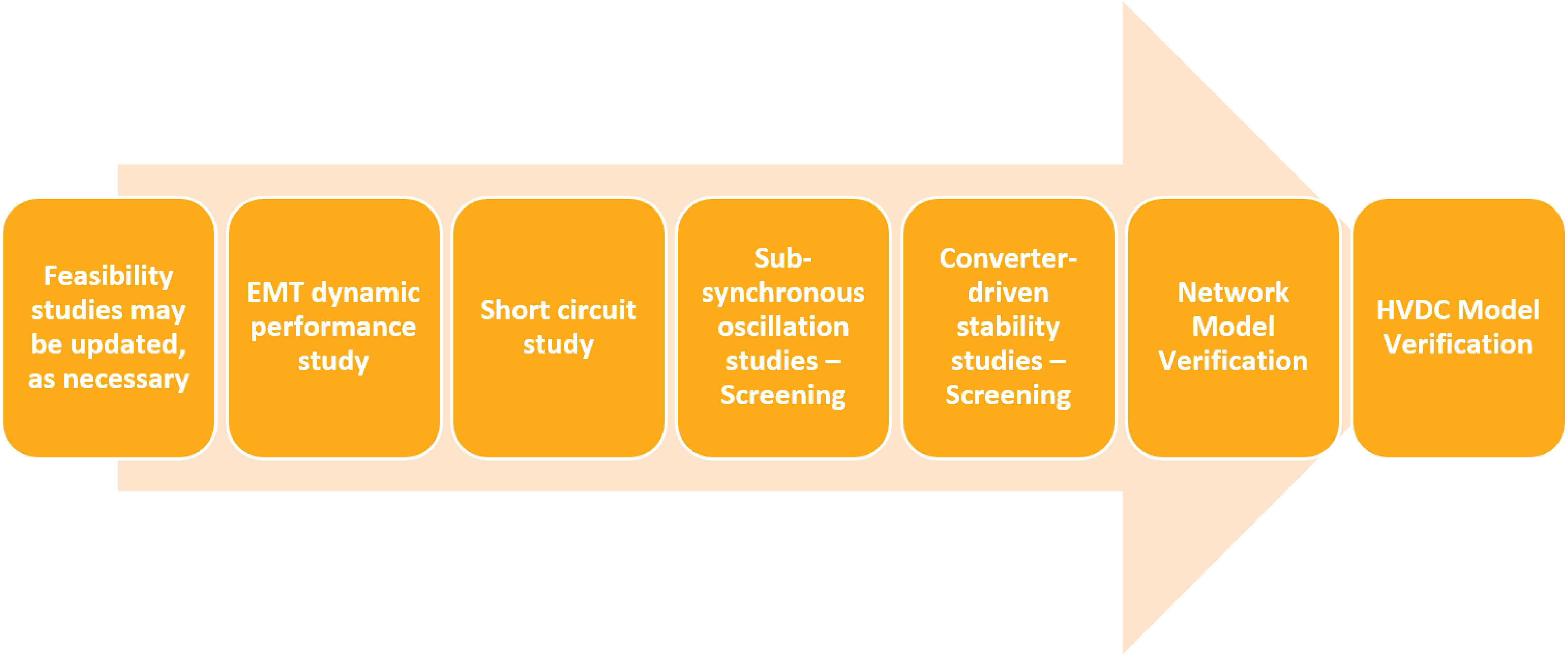
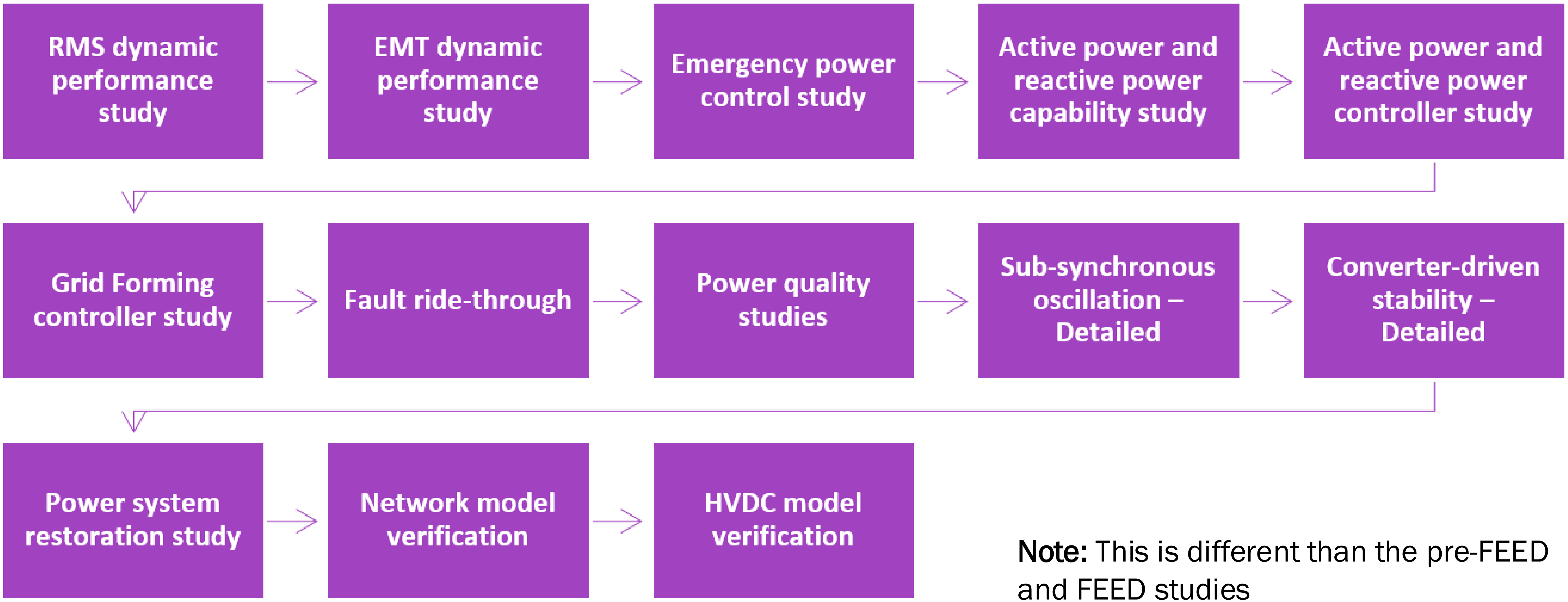


Figure 7.1: Planning studies stage.

SPP Design Studies

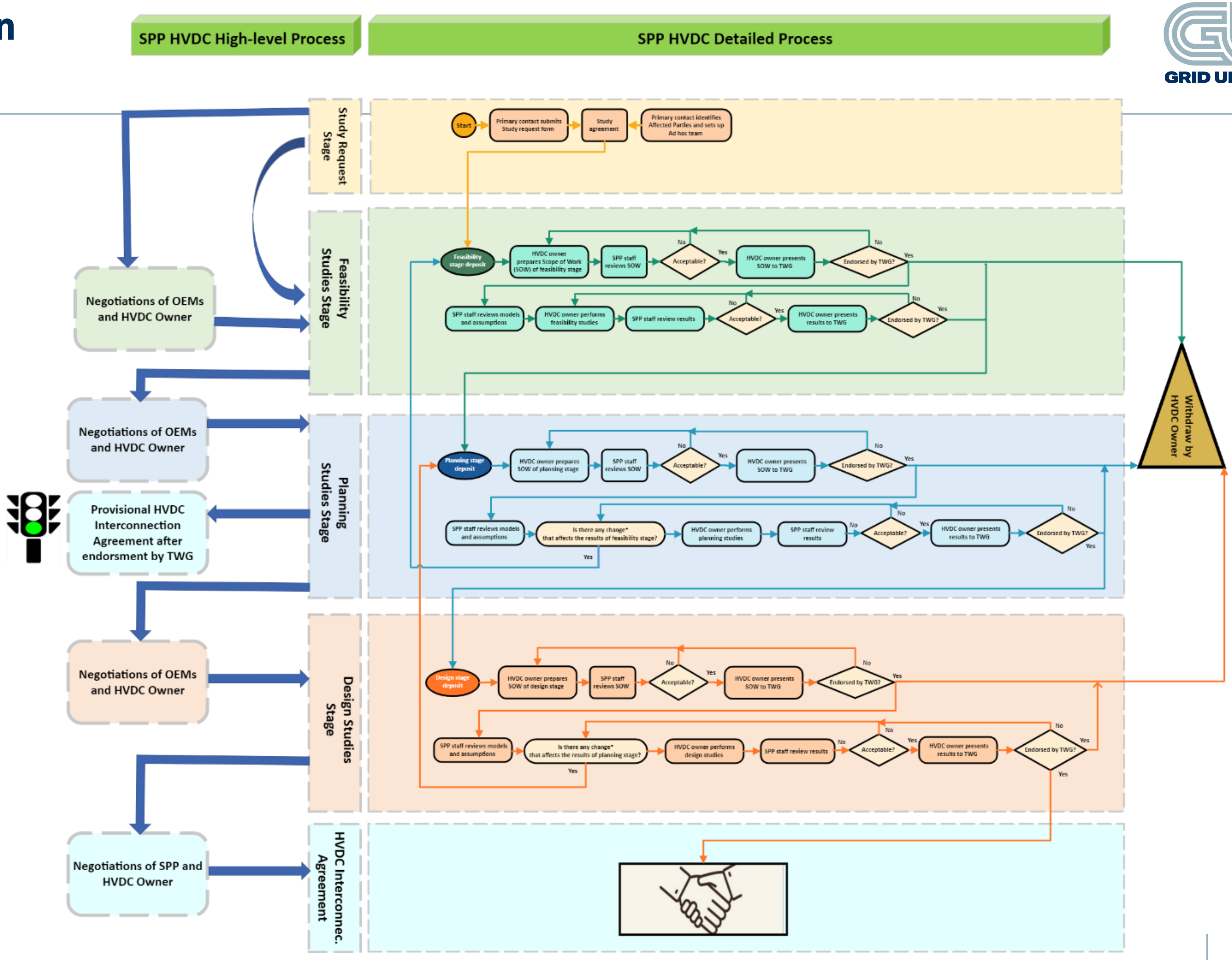
GRID UNITED



Note: This is different than the pre-FEED and FEED studies

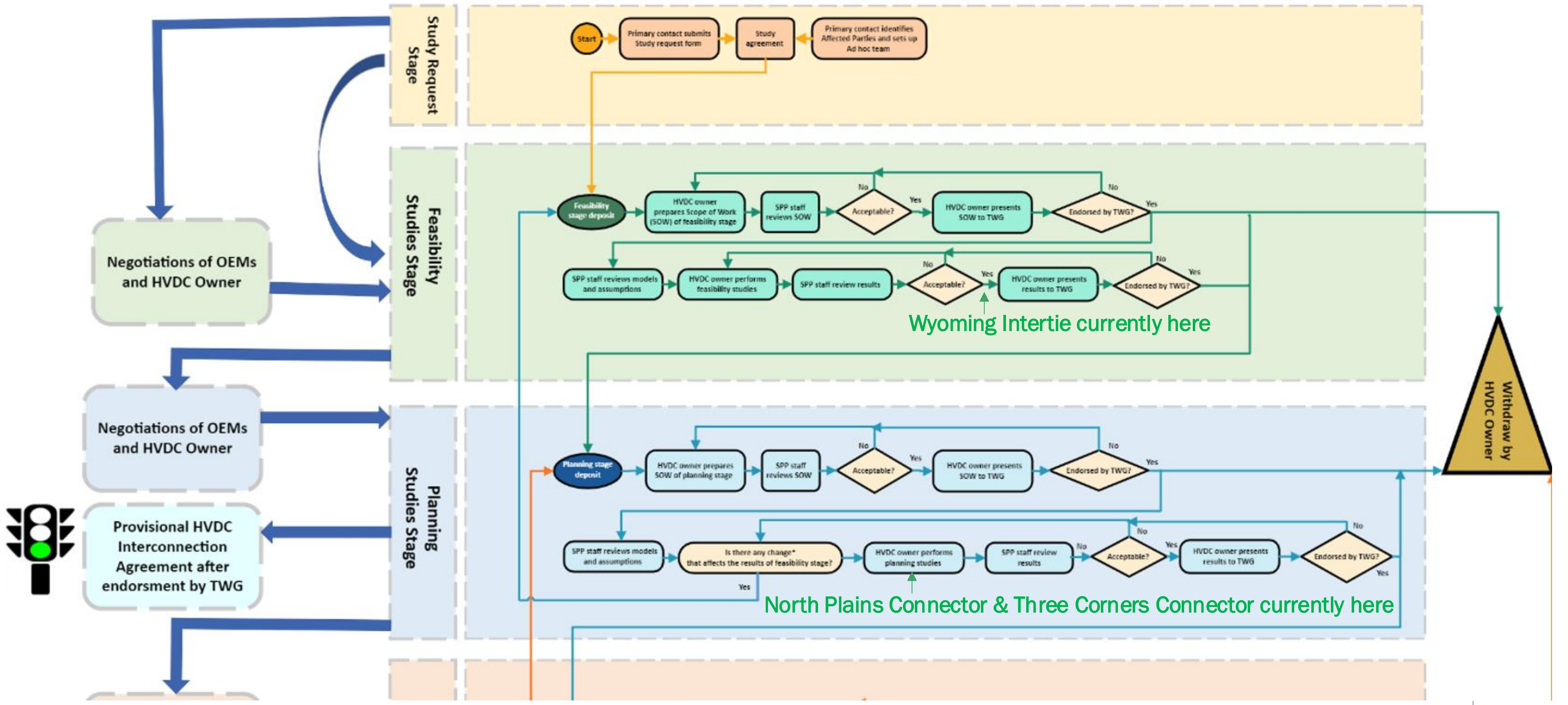
Figure 8.1: Design Studies Stage

SPP HVDC Interconnection Process

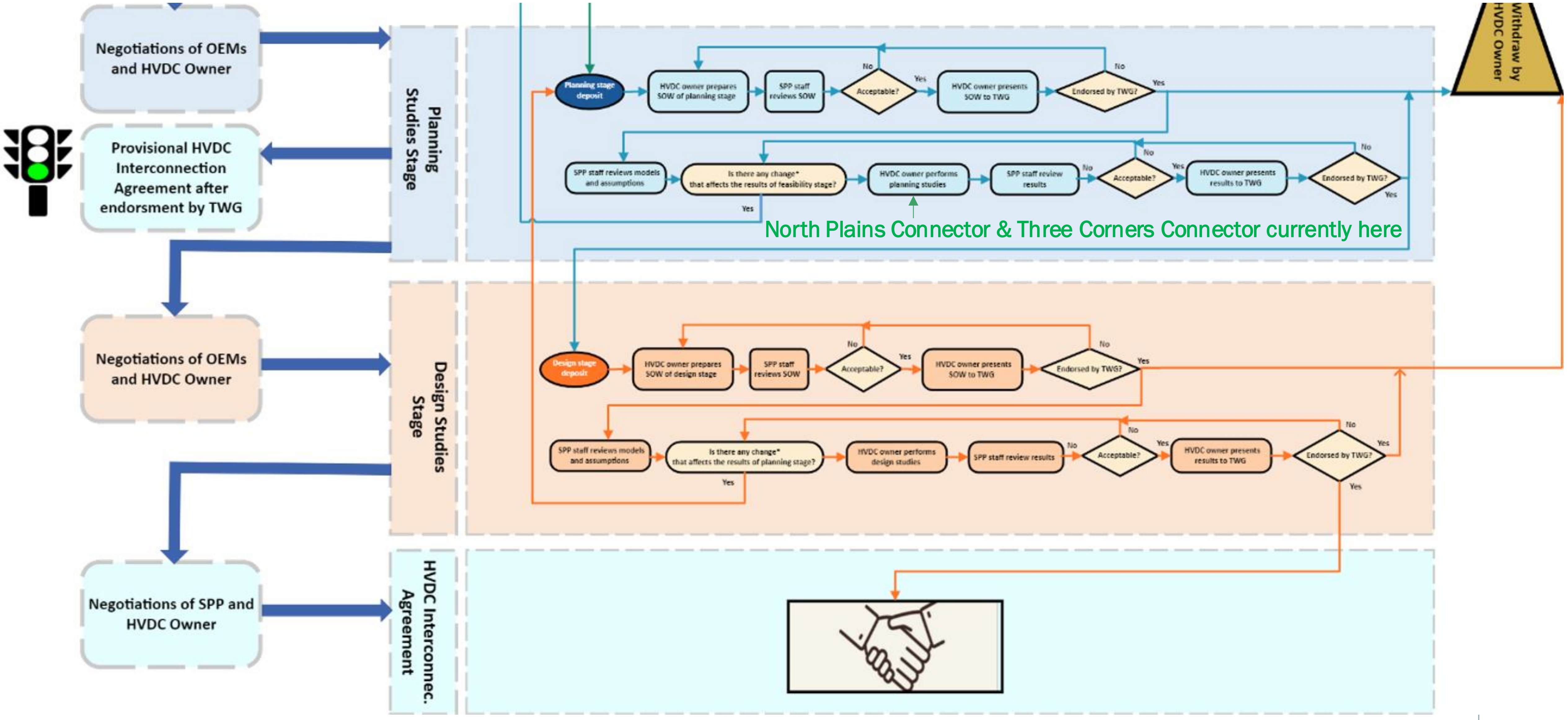


SPP HVDC High-level Process

SPP HVDC Detailed Process



SPP HVDC Interconnection Process



Revision Request #650 (RR650) SPP HVDC Planning Criteria & Manual

GRID UNITED

- **HVDC Manual includes:**
  - HVDC Configurations
  - Contingencies & Faults
  - HVDC Planning Process
  - Project-specific studies
  - Network Model requirements
  - HVDC Model Requirements
  - Performance Criteria

- **RR650 includes:**
- Tariff revisions:
  - Part I, Section 1 Definitions
  - Attachment O, Addendum 5
  - Attachment O, Section IV
- Planning Criteria revisions to Sections 5.5, 7.2.11, 8, 14
- Interconnection Request Form
- Study Agreement
- Interconnection Agreement

GRID UNITED

www.gridunited.com

http://www.linkedin.com/company/grid-united

info@gridunited.com

BREAK - 5 Minutes

Session 4
Inverter-Based Resource Modeling

EMT Model Quality

John Schmall - ERCOT

EMT Model Quality at ERCOT

John Schmall
ERCOT Grid Planning

NERC-NATF-EPRI Annual Transmission Planning and Modeling Workshop
November 19-20, 2024

ERCOT Facts*

85,508 MW

Record peak demand (August 10, 2023)

103,609+ MW

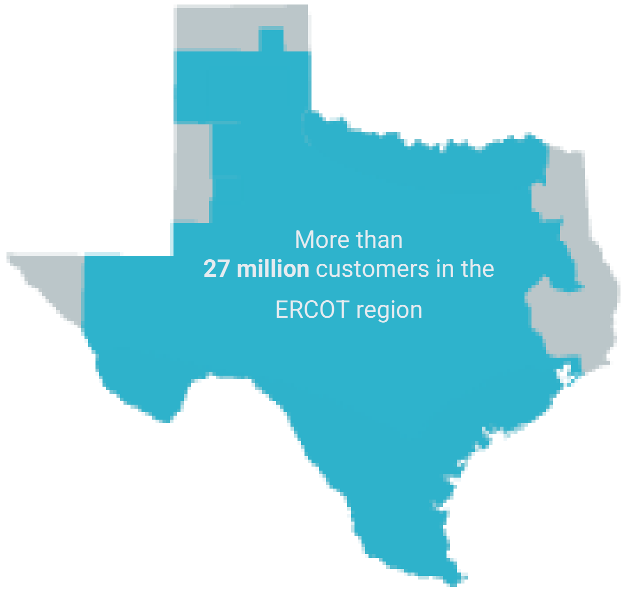
of expected capacity for summer 2024 peak demand

54,100+

miles of high-voltage transmission

$3.3 billion

transmission projects endorsed in 2022



39,450 MW

of installed wind capacity as of June 2024, the most of any state in the nation

25,333 MW

of utility-scale installed solar capacity as of June 2024

27,881 MW

wind generation record (June 17, 2024)

21,667 MW

solar generation record (September 8, 2024)

69.15%

wind penetration record (April 10, 2022)

42.98%

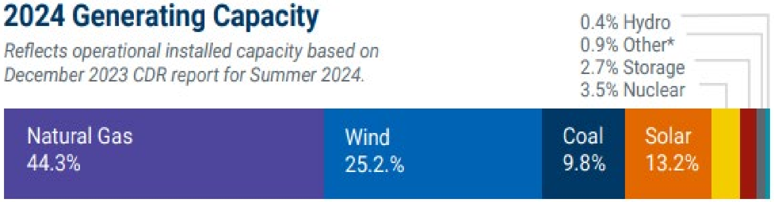
solar penetration record (March 28, 2024)

7,702 MW

of installed battery storage as of January 2024

2024 Generating Capacity

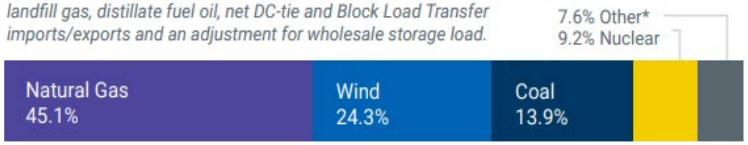
Reflects operational installed capacity based on December 2023 CDR report for Summer 2024.



The sum of the percentages may not equal 100% due to rounding.
**Other includes biomass and DC Tie capacity.*

2023 Energy Use

**Other includes solar, hydro, petroleum coke (pet coke), biomass, landfill gas, distillate fuel oil, net DC-tie and Block Load Transfer imports/exports and an adjustment for wholesale storage load.*



*** As of October 2024**

Evolution of ERCOT EMT Model Requirements

- ~2009 – Subsynchronous Resonance (SSR) / Subsynchronous Control Interaction (SSCI) event in ERCOT
- ~2013-2017 – SSR/SSCI evaluation requirements
- ~2016, 2018, 2020 – Panhandle Studies
  - Large-scale application of EMT analysis beyond the SSR/SSCI realm
- ~2016 – EMT models required to be submitted
  - All new Invertor-Based Resources (IBRs) interconnections
  - EMT model guidelines/checklist
- ~2021 – Implemented more thorough review processes
  - Planning Guide Revision Request (PGRR) 085
  - Validation
  - Benchmarking (PSCAD versus PSS/e)

PGRR-075

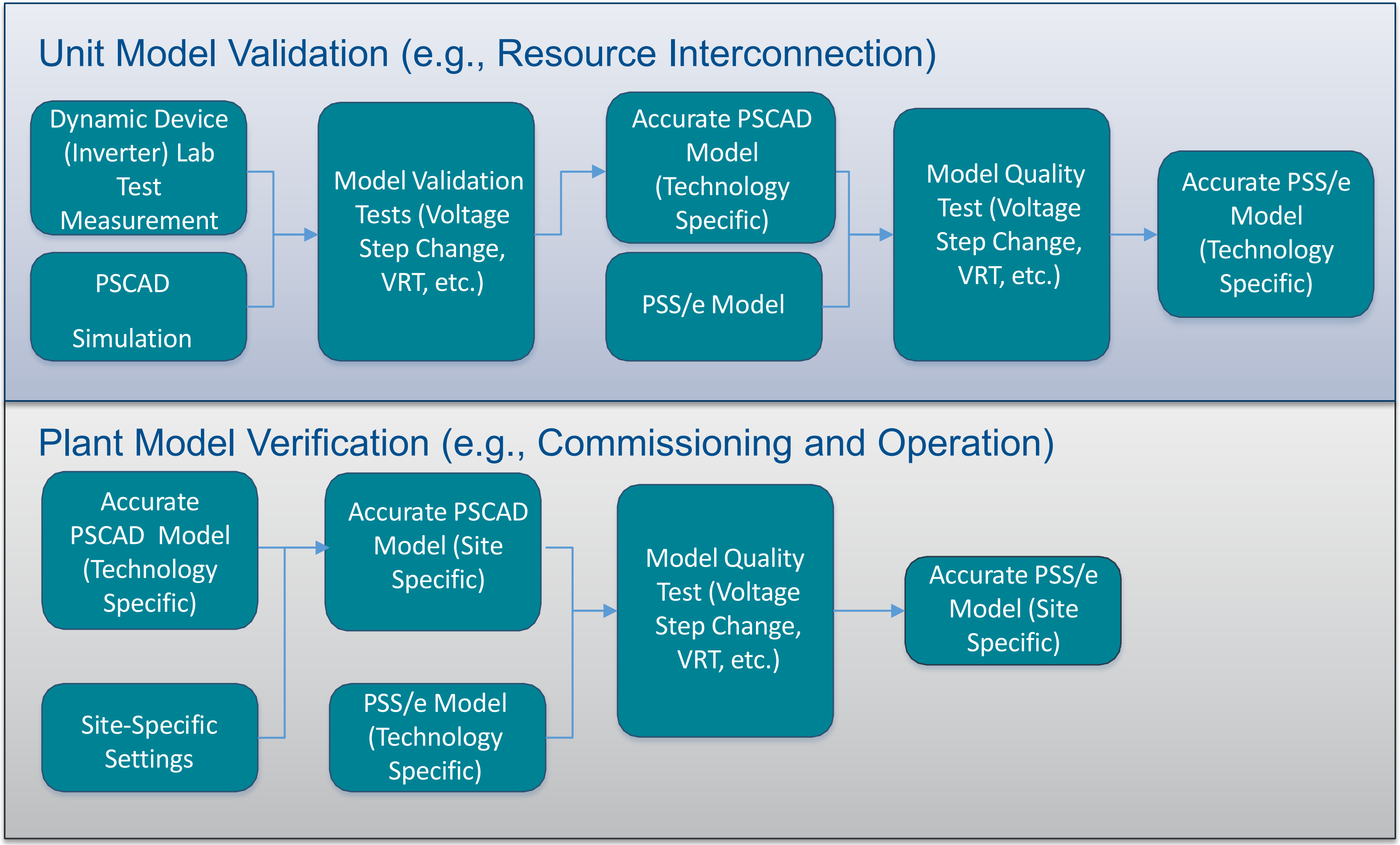
- Effective May 1, 2020
- Introduced model quality test (MQT) requirements for PSS/E dynamic model
- Performed/submitted by resource owner
- Demonstrate basic reasonable model performance
  - Flat Start Test (no disturbance test)
  - Voltage Step Change Test
  - Frequency Step Change Test
  - Voltage Ride Through Test (HVRT & LVRT)
  - Short Circuit Ratio Test
- Performance guidance published in Dynamics Working Group (DWG) Procedure Manual

These were not exclusive EMT model requirements but established a model quality baseline as ERCOT emphasizes model consistency between PSS/e and PSCAD.

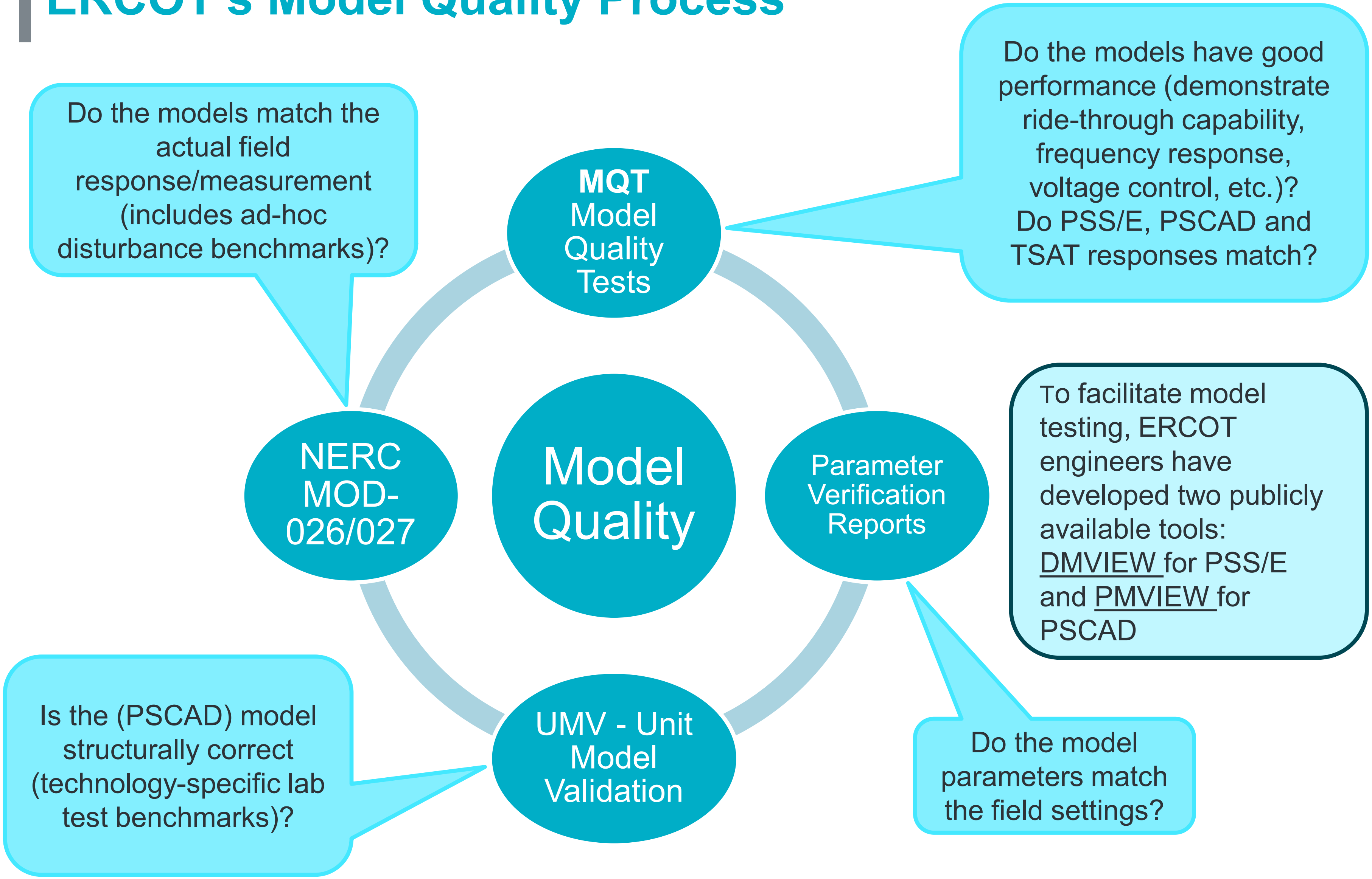
PGRR-085

- Effective March 1, 2021
- Introduced MQT requirements for PSCAD model
  - Same reasonability tests as PSS/e MQT plus added phase angle jump test
  - Performance consistency across software platforms (PSS/e, PSCAD)
- Introduced unit model validation (UMV) requirements (for PSCAD model)
  - Intended to be a lab test model validation
  - Technology specific rather than site specific
- Introduced parameter verification requirements
  - Document that site specific tunable field settings to match model parameters
- Performed/submitted by resource owner
  - Required milestone in interconnection process

Model Validation and Verification Concept



ERCOT's Model Quality Process



Maintaining High Quality Models: PGRR-109

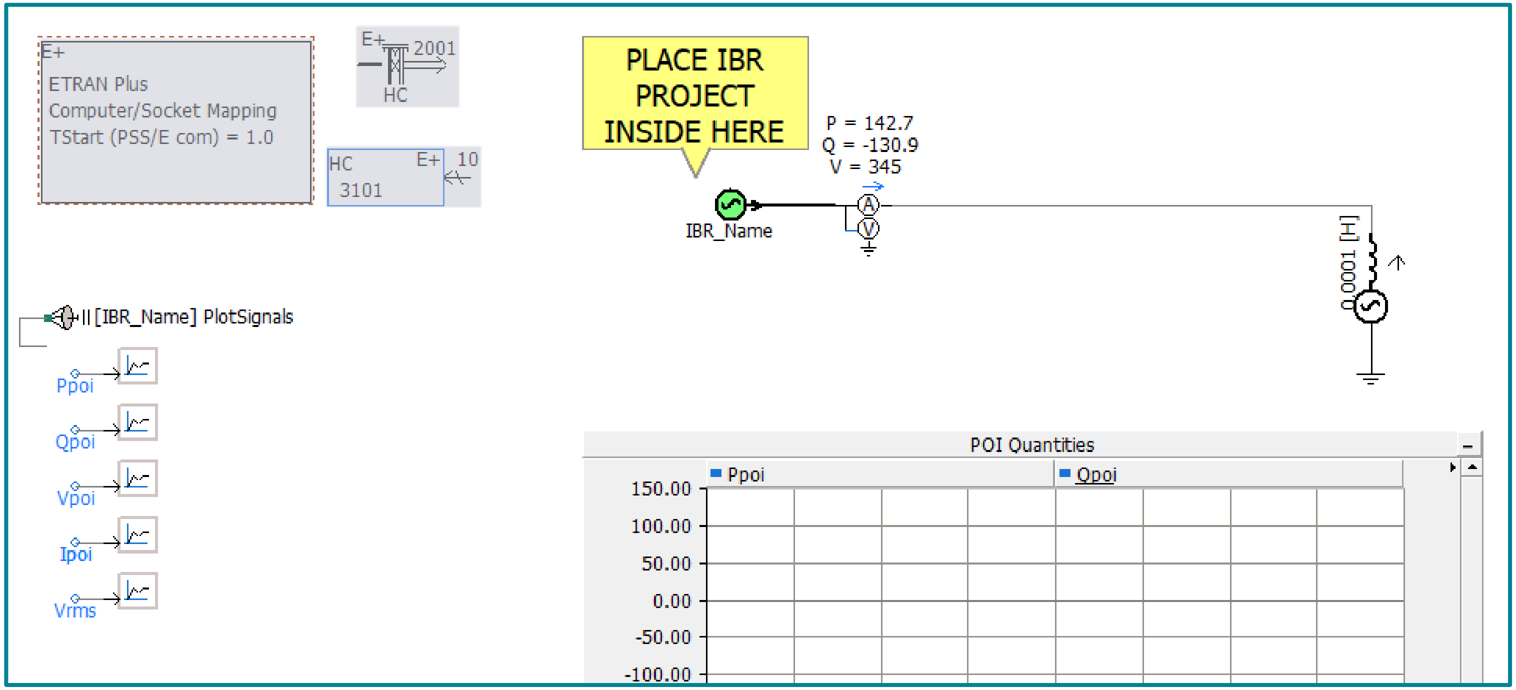
- Effective May 1, 2024
- Introduced model review process prior to implementation of any IBR modifications that impact dynamic response
  - Compares MQT performance before and after the proposed modification (both PSS/e and PSCAD)
  - Observation of significant differences or degradation in performance may trigger more detailed studies
  - Identifies any adverse impacts prior to implementation of modifications in the field
  - Confirms appropriate model performance
- Introduced a similar process to review and compare “as-built” models with the models used for interconnection studies prior to final commissioning

EMT Model Process Challenges

- Timing and availability of EMT Model
  - Resistance/barriers to providing EMT model early in the interconnection process
- Proprietary models (issues largely resolved: Black Box)
- EMT model does not equal a good/accurate model
  - Testing and review is needed
  - Model functionality and usability (troubleshooting)
  - Need for EMT model “template”
  - Beneficial to use single plot axes for performance comparisons across software platforms
  - Cannot test everything: Need to strike an appropriate balance

ERCOT's PSCAD Model Template

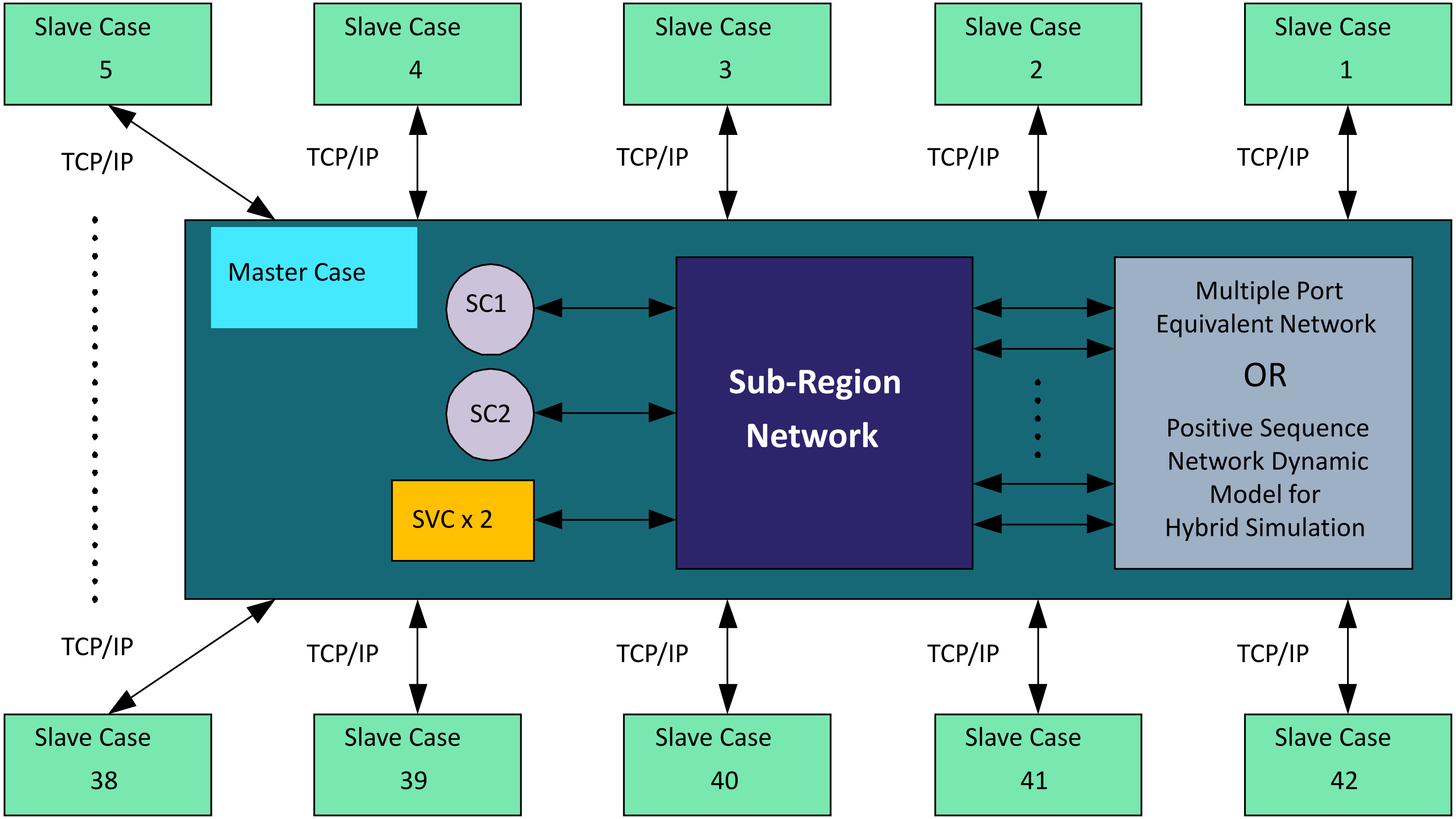
- Resource owners submit PSCAD models in this template format
- Template doubles as an E-TRAN substitution library
- Resource models organized into a single block - facilitates incorporation into a larger study case



EMT Study Challenges

- When is an EMT system study needed?
  - ERCOT does not routinely require an EMT system study during interconnection process unless needed to assess a potential SSR Vulnerability
  - Industry does not agree on a brightline criterion for when large-scale system EMT studies are needed - based on engineering judgment
  - Incorporation of legacy units in the study area
  - Impact on interconnection timelines for new generation
  - More complex models > unexpected study challenges > more uncertainty in study timelines
- Stability is primarily assessed with positive sequence tools in ERCOT
  - EMT studies are conducted when deemed necessary to benchmark positive sequence study results

Parallel Configuration of a EMT Study



References

- Model Quality Guide, posted on the Resource Entity page at ercot.com
  - Includes ERCOT PSCAD model guidelines/checklist
  - Links to external PSCAD tools: PMVIEW
- Dynamic Model Templates, posted on the Resource Entity page at ercot.com
  - Includes PSCAD model template (and help video)
- Planning Guide Revision Request PGRR-075 (approved & effective)
- Planning Guide Revision Request PGRR-085 (approved & effective)
- Planning Guide Revision Request PGRR-109 (approved & effective)
- Planning Guide section 5.5 (in particular, paragraph (2) and (3))
- Planning Guide section 6.2 (in particular, paragraph (5))
- DWG Procedure Manual section 3.1

ERCOT model requirements are intended to complement NERC MOD-026/027 model verification requirements.

Questions

?

Dynamic Modeling Recommendations

Jack Gibfried - NERC

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

NERC Dynamic Modeling Recommendations

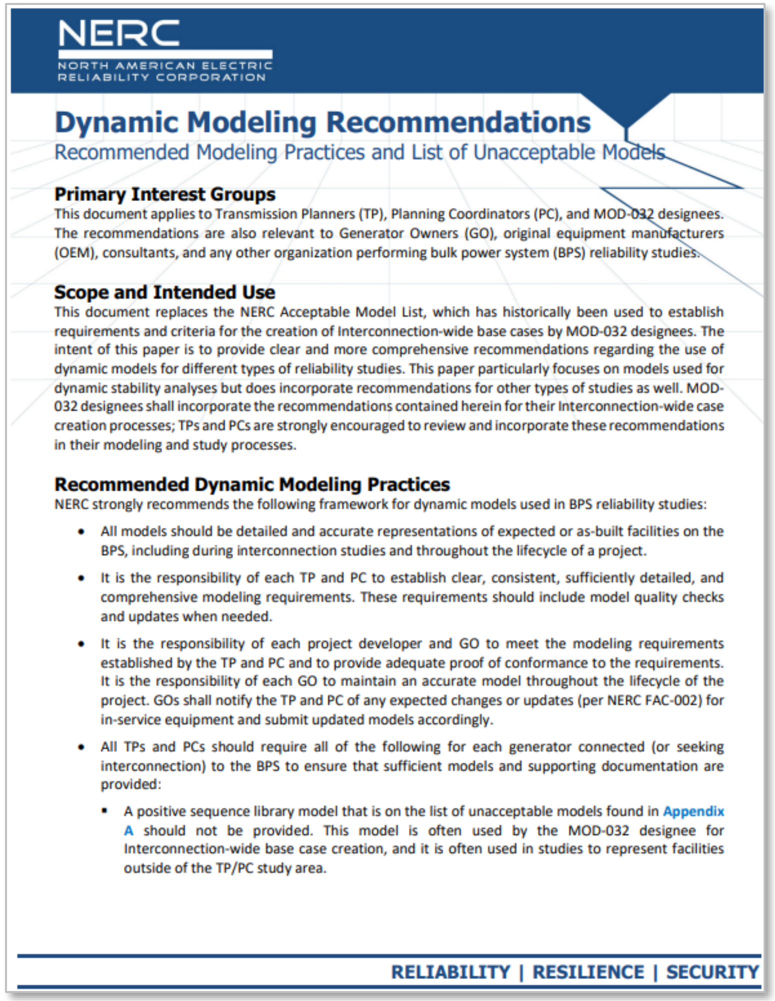
Recommended Modeling Practices and List of Unacceptable Models

Jack Gibfried
Engineer - Power Systems Modeling and Analysis, NERC
2024 EPRI-NATF-NERC Planning and Modeling Virtual Seminar
November 20, 2024

RELIABILITY | RESILIENCE | SECURITY




Overview



NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Dynamic Modeling Recommendations

Recommended Modeling Practices and List of Unacceptable Models

Primary Interest Groups

This document applies to Transmission Planners (TP), Planning Coordinators (PC), and MOD-032 designees. The recommendations are also relevant to Generator Owners (GO), original equipment manufacturers (OEM), consultants, and any other organization performing bulk power system (BPS) reliability studies.

Scope and Intended Use

This document replaces the NERC Acceptable Model List, which has historically been used to establish requirements and criteria for the creation of Interconnection-wide base cases by MOD-032 designees. The intent of this paper is to provide clear and more comprehensive recommendations regarding the use of dynamic models for different types of reliability studies. This paper particularly focuses on models used for dynamic stability analyses but does incorporate recommendations for other types of studies as well. MOD-032 designees shall incorporate the recommendations contained herein for their Interconnection-wide case creation processes; TPs and PCs are strongly encouraged to review and incorporate these recommendations in their modeling and study processes.

Recommended Dynamic Modeling Practices

NERC strongly recommends the following framework for dynamic models used in BPS reliability studies:

- All models should be detailed and accurate representations of expected or as-built facilities on the BPS, including during interconnection studies and throughout the lifecycle of a project.
- It is the responsibility of each TP and PC to establish clear, consistent, sufficiently detailed, and comprehensive modeling requirements. These requirements should include model quality checks and updates when needed.
- It is the responsibility of each project developer and GO to meet the modeling requirements established by the TP and PC and to provide adequate proof of conformance to the requirements. It is the responsibility of each GO to maintain an accurate model throughout the lifecycle of the project. GOs shall notify the TP and PC of any expected changes or updates (per NERC FAC-002) for in-service equipment and submit updated models accordingly.
- All TPs and PCs should require all of the following for each generator connected (or seeking interconnection) to the BPS to ensure that sufficient models and supporting documentation are provided:
  - A positive sequence library model that is on the list of unacceptable models found in Appendix A should not be provided. This model is often used by the MOD-032 designee for Interconnection-wide base case creation, and it is often used in studies to represent facilities outside of the TP/PC study area.

RELIABILITY | RESILIENCE | SECURITY

[Dynamic Modeling Recommendations (nerc.com)](#)

"The intent of this paper is to provide clear and more comprehensive recommendations regarding the use of dynamic models for different types of reliability studies."

Modeling Deficiencies

Can the models recreate the cause of reduction?

Table 3.1: Solar PV Tripping and Modeling Capabilities and Practices		
Cause of Reduction	**Can Be Accurately Modeled in Positive Sequence Simulations?**	**Can Be Accurately Modeled in EMT Simulations?**
Inverter Instantaneous AC Overcurrent	No	Yes
Passive Anti-Islanding (Phase Jump)	Yes[a]	Yes
Inverter Instantaneous AC Overvoltage	No	Yes
Inverter DC Bus Voltage Unbalance	No	Yes
Feeder Underfrequency	No[b]	No[c]
Incorrect Ride-Through Configuration	Yes	Yes
Plant Controller Interactions	Yes[d]	Yes[e]
Momentary Cessation	Yes	Yes
Inverter Overfrequency	No[b]	Yes
PLL Loss of Synchronism	No	Yes
Feeder AC Overvoltage	Yes[f]	Yes
Inverter Underfrequency	No[b]	Yes

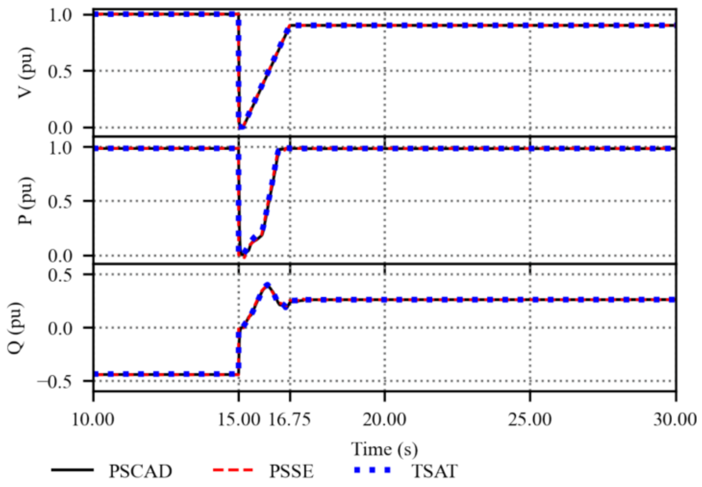
2022 Odessa Disturbance Report (nerc.com)

Do the models recreate the cause of reduction?

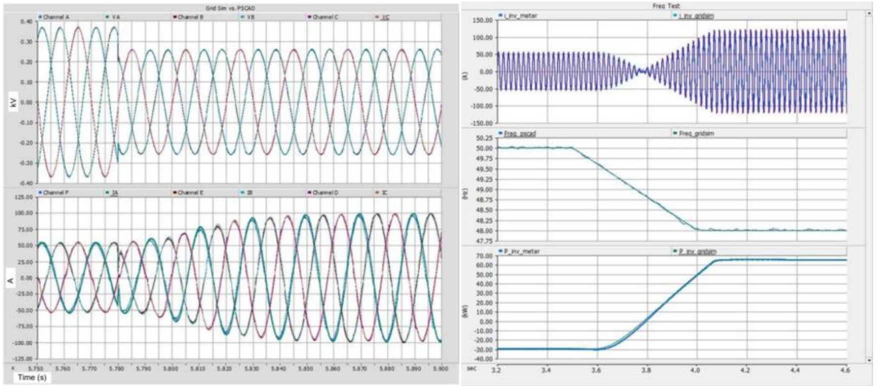
Recommended Dynamic Modeling Practices

Model Quality and Benchmarking

- All models should be:
  - Detailed and accurate representations of expected or as-built facilities
- Positive sequence library models, positive sequence user-defined models (UDMs), and electromagnetic transient (EMT) models should be:
  - Verified by the equipment manufacturer to be accurately parameterized to represent site-specific (or to-be installed) controls, settings, and protections
  - Validated against actual product performance and benchmarked against each other



Source: Vestas



Source: https://arena.gov.au/assets/2022/03/hornsdale-power-reserve-virtual-machine-mode-testing-summary-report.pdf

Dynamic Model Types

Electromagnetic Transient

- Very detailed
- Often include some/all of the equipment's code and logic

Positive Sequence User-Defined

- Less detailed than EMT
- May include some/all of the equipment's code and logic

Positive Sequence Standard Library

- High level model structure with standardized control blocks
- Typically, parameters of standard library models and those of the UDM or actual product don't have one to one correlation or mapping.

NERC Dynamic Model Recommended Use

Electromagnetic Transient

Should be used for any study where **detailed representations of plant controls and protections** are required

Needed to accurately identify possible reliability risks when integrating inverter-based resources.

Typically feasible only for **localized** or **small regional studies** due to computational demand and today's computing capability

NERC Dynamic Model Recommended Use

Positive Sequence User-Defined

When an EMT model is not needed, should be used for detailed reliability studies as these models are more likely to identify reliability risks (compared to standard library models)

Should be used in the **interconnection process** and **local reliability studies** (**unless an EMT model is needed**)

Can be more feasibly utilized in large-scale studies (compared to EMT models); can include manufacturer-specific protections and controls not available in the Standard Library

NERC Dynamic Model Recommended Use

Industry Approved Positive Sequence Standard Library

Can be sufficient for interconnection-wide model representations.

Should usually not be used in the interconnection process or for local reliability studies.

Typically don’t include detailed logic or manufacturer-specific controls but are easy to parameterize, curve fit, and run

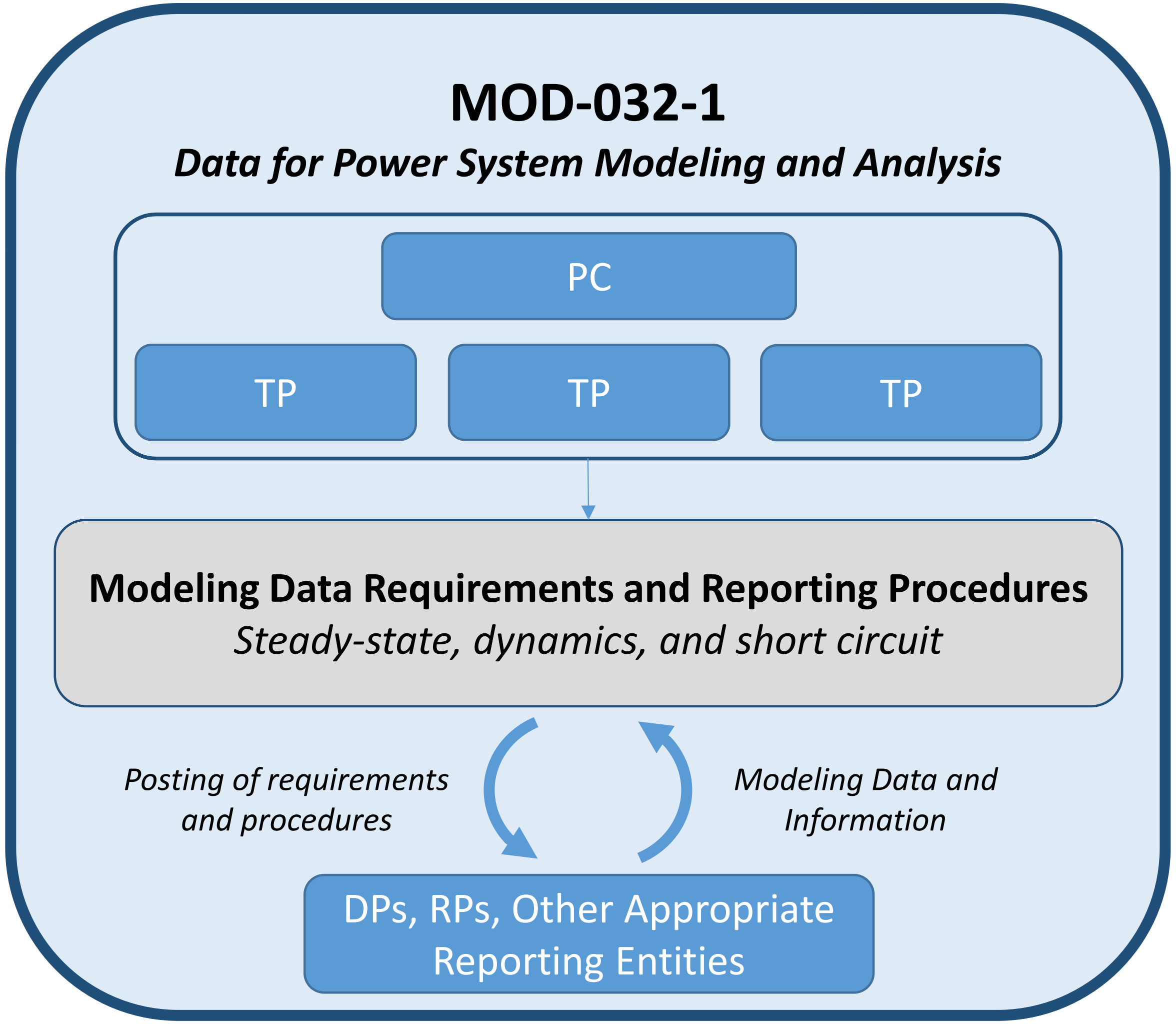
Geomagnetic Disturbance (GMD) Modeling

GMD Models

- NERC TPL-007 establishes requirements during geomagnetic disturbance (GMD) events.
  - R2 requires TP to maintain models for GMD Vulnerability Assessments, yet MOD-032 is the pathway to obtain information
  - TPs and PCs should leverage MOD-032 Attachment 1 for collecting GMD data and should require supporting information to conduct GMD Vulnerability Assessments
- TPs and PCs should require information that includes (but is not limited to):
  - Winding and Phase configuration
  - Terminal Voltages
  - DC model equivalent
  - Thermal and electrical limits of transformer windings
  - Earth conductivity (known or supplemental) for grounded transformers
  - Substation grounding

Models for MOD-032

Models for MOD-032



Same process can be used for EMT and GMD models!

Models for MOD-032

The MOD-032 designees have an agreement with the ERO to:

- Establish model requirements for the Interconnection-wide base cases
  - Includes recommended or acceptable models
  - Accounting for and incorporate the NERC Unacceptable Model List
- Determine (work with TP/PC) whether UDMs will be deemed acceptable in the Interconnection-wide base cases

Models for MOD-032

- GOs will be responsible for the changes of TP/PC/MOD-032 designee modeling requirements
- MOD-032 designees should have a change management process in place for model updates to reflect as-built facilities for these changes
- All applicable entities should adhere to local TP/PC modeling requirements and MOD-032 designee requirements

MOD-032-1 — Data for Power System Modeling and Analysis

A. Introduction

1. **Title: Data for Power System Modeling and Analysis**
2. **Number: MOD-032-1**
3. **Purpose:** To establish consistent modeling data requirements and reporting procedures for development of planning horizon cases necessary to support analysis of the reliability of the interconnected transmission system.

NERC Unacceptable Model List

NERC Unacceptable Model List

- Unacceptable due to proven modeling errors, numerical issues, or those phased out of use for other reasons.

Update Process:

- NERC engages with industry experts to identify model issues

Table A.1: Unacceptable Model List	
Known Unacceptable Model Name	**Model Description**
Renewable Energy Models	
WT3G1,WT3G2, wt3g	Generic Type 3 WTG Generator/Converter Model - Doubly-fed induction generator
WT4G1,WT4G2, wt4g	Generic Type 4 WTG Generator/Converter Model - Variable speed generator with full converter
WT3E1, wt3e	Generic Type 3 WTG Electrical Control Model

Questions and Answers

Feel free to contact the NERC Advanced System Analytics and Modeling department with any questions or to discuss any dynamic modeling concerns:
AdvancedSystemAnalyticsModeling@nerc.net

BREAK - 5 Minutes

Open Distribution

Session 5
Large Loads

Open Distribution

Blockchain and Energy: Flexible Computing Loads

Le Xie - Harvard

Harvard John A. Paulson School of Engineering and Applied Sciences

Blockchain and Energy: A Case Study of Flexible Computing Loads in Texas

Le Xie, Fellow of IEEE
Gordon McKay Professor of Electrical Engineering
Harvard John A. Paulson School of Engineering and Applied Sciences
e-mail: xie@seas.harvard.edu
11/20/2024

The Scale of the Issue

Global trends in digital and energy indicators, 2015-2022

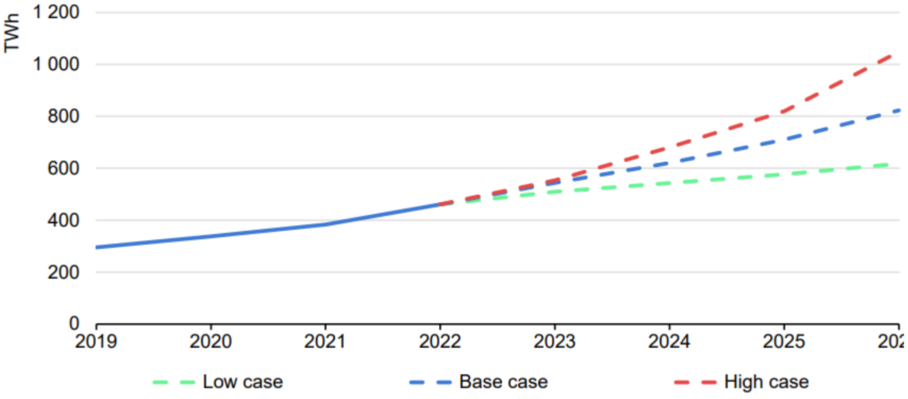
	2015	2022	Change
Internet users	3 billion	5.3 billion	+78%
Internet traffic	0.6 ZB	4.4 ZB	+600%
Data centre workloads	180 million	800 million	+340%
Data centre energy use (excluding crypto)	200 TWh	240-340 TWh	+20-70%
Crypto mining energy use	4 TWh	100-150 TWh	+2300-3500%
Data transmission network energy use	220 TWh	260-360 TWh	+18-64%

The State of Illinois uses about 143TWh of Electricity in 2020

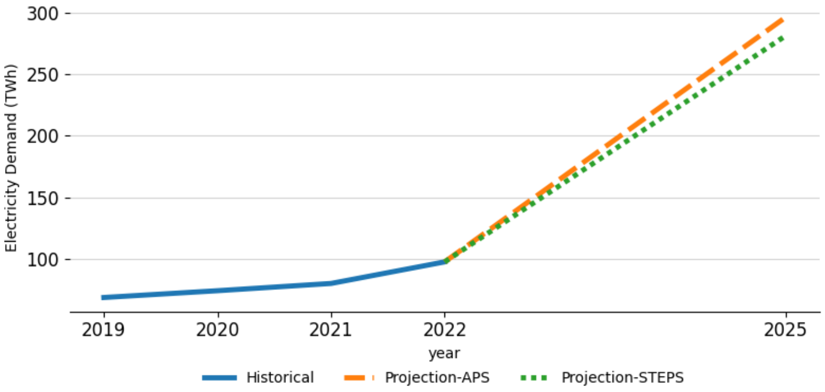
Source: https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks

Datacenters vs Electric Vehicle Electricity Demand

Global Datacenter, AI, cryptocurrency demand[1]



Global EV Electricity demand[2]



STEPS - Stated policies Scenario

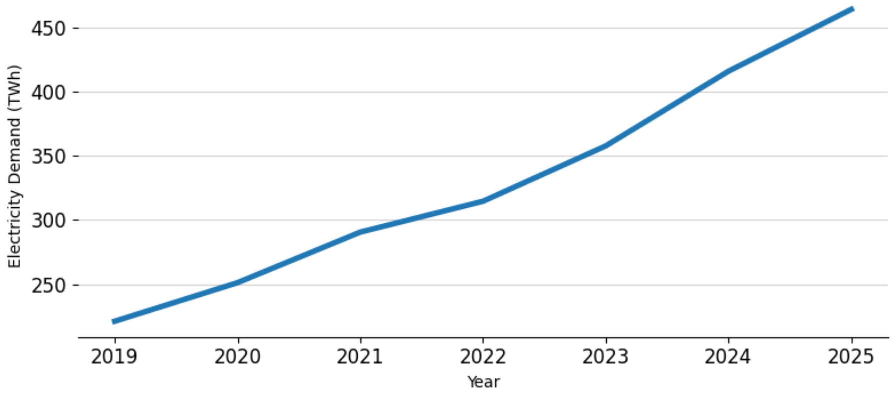
APS - Announced Pledges Scenario

[1]IEA (2024), Electricity 2024, IEA, Paris https://www.iea.org/reports/electricity-2024, Licence: CC BY 4.0

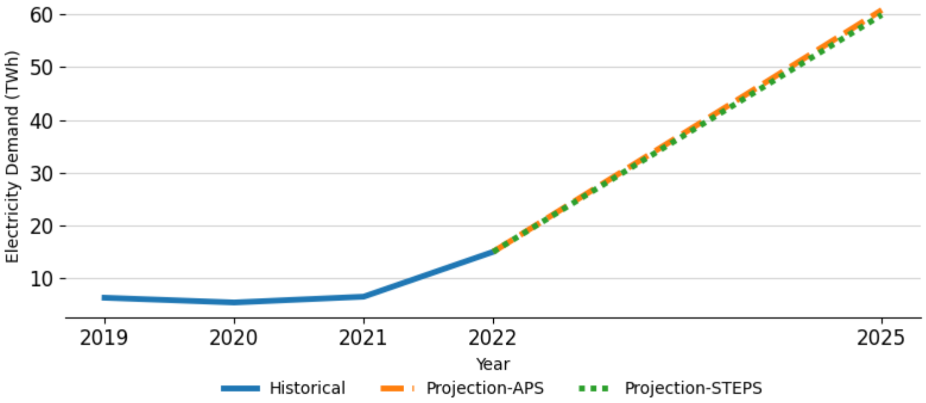
[2] IEA (2023), Global EV Outlook 2023, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2023, Licence: CC BY 4.0

Datacenters vs Electric Vehicle Demand in the U.S.

Datacenter, AI, cryptocurrency demand in the U.S.[1]



Electric Vehicle Electricity demand in the U.S. [2]



STEPS - Stated Policies Scenario
APS - Announced Pledges Scenario

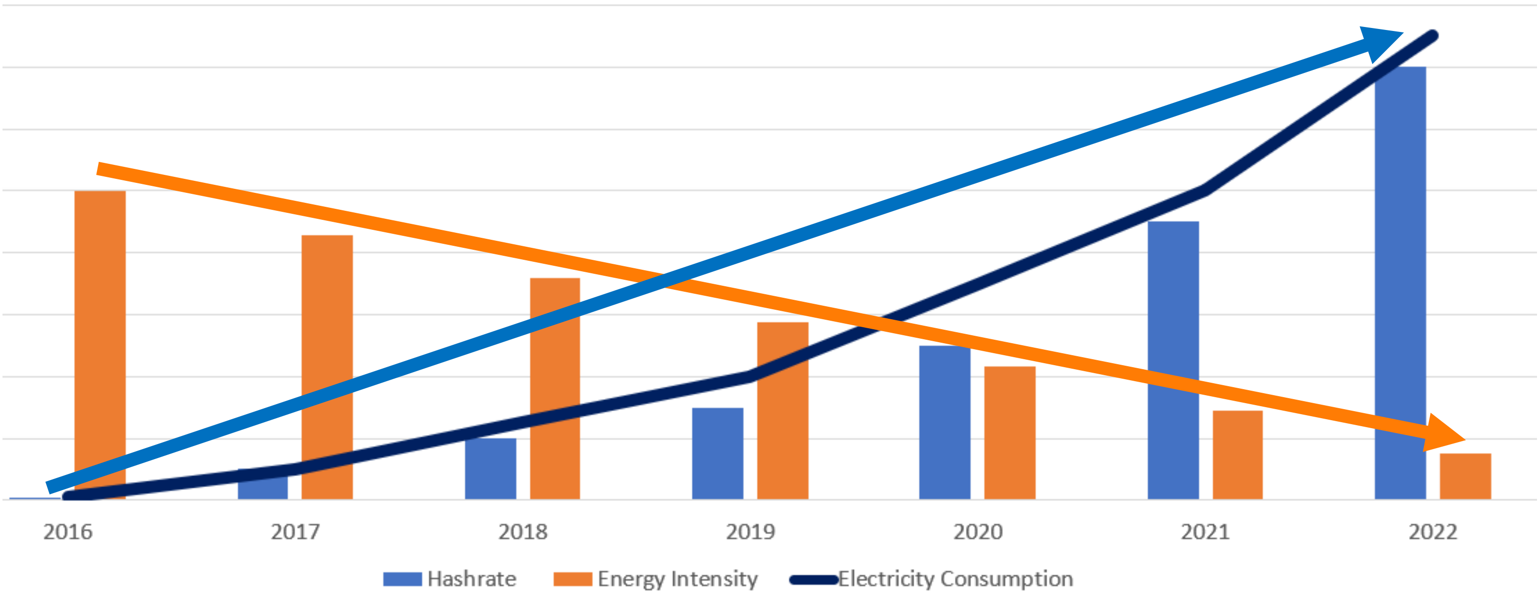
[1] Cambridge Blockchain Network Sustainability Index: CBECI (ccaf.io)
[2] IEA (2023), Global EV Outlook 2023, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2023, Licence: CC BY 4.0

Mining Energy Intensity and Hashrate

The estimated deployed rig energy intensity (the energy needed for one unit of processing power kWh/TH(terahash)) decreased by around 85%

Network Hashrate increased by over 14000%

As a result, a total of 2000% rise in the estimated network electricity usage



Source: Climate and Energy Implications of Crypto-Assets. The White House, 2022.

Blockchain and Its Implication in Energy/Environment

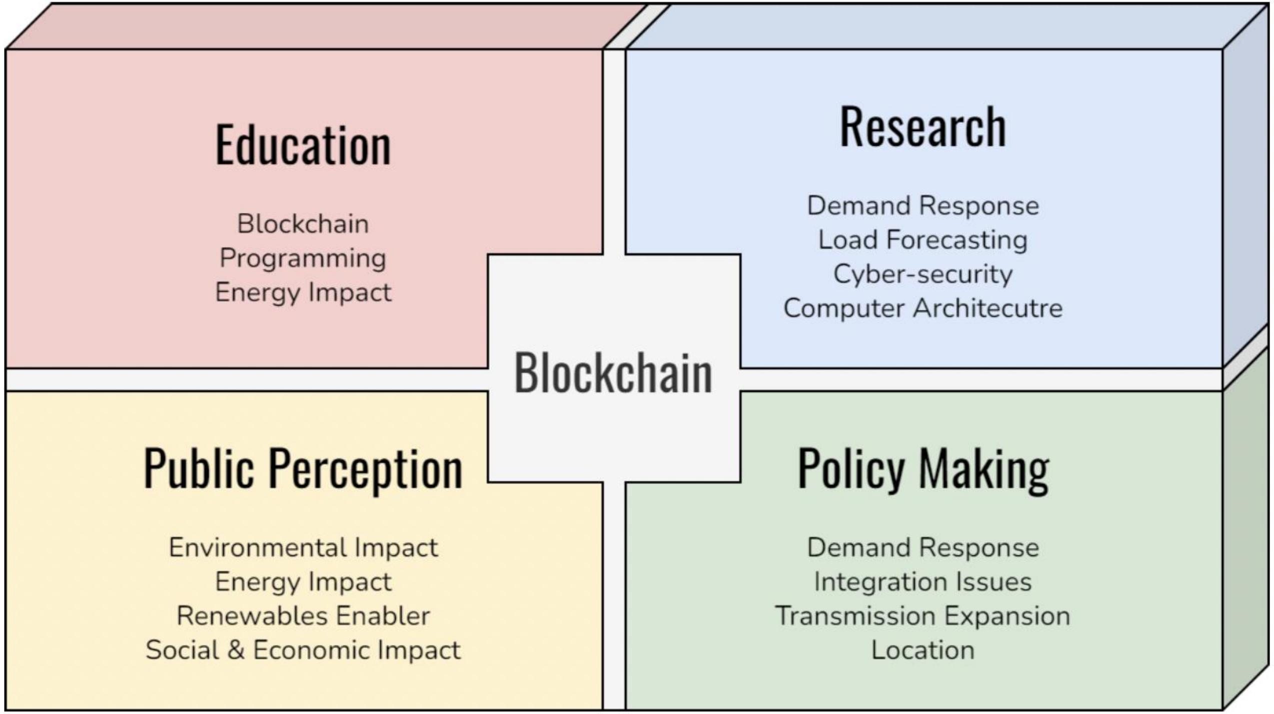


Figure 1 Proposed Areas of Activities

Le Xie, Ali Menati, Prasad Enjeti, and Korok Ray, "Scalable and Sustainable Energy for Crypto Mining," White Paper, Nov 2022

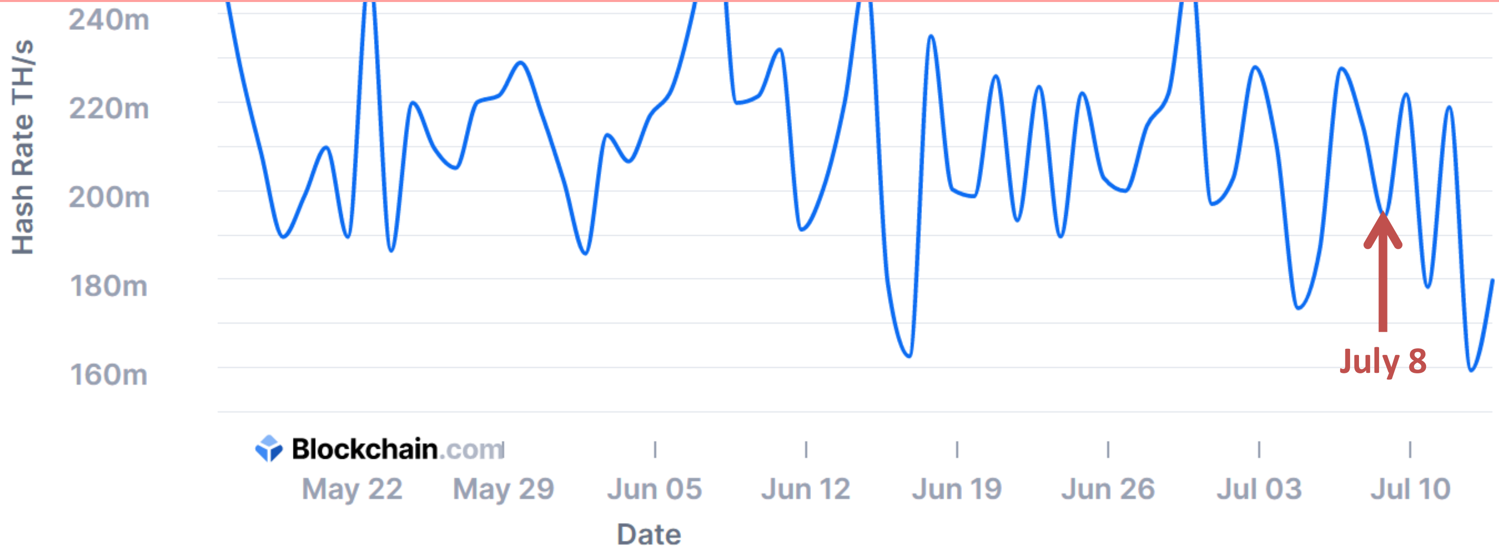
The Blockchain & Energy Research Consortium

tx.ag/berc, Low Voltage Ride Through Workshop, Sep 13, 2023

Total Hash Rate (TH/s)

The estimated number of terahashes per second the bitcoin network is performing in the last 24 hours.

Jul 13, 2022 3:01:43 PM	Reserves are below 3,000 MW. Emergency Response Service 10 minute and 30 minute, including Weather Sensitive have been deployed.



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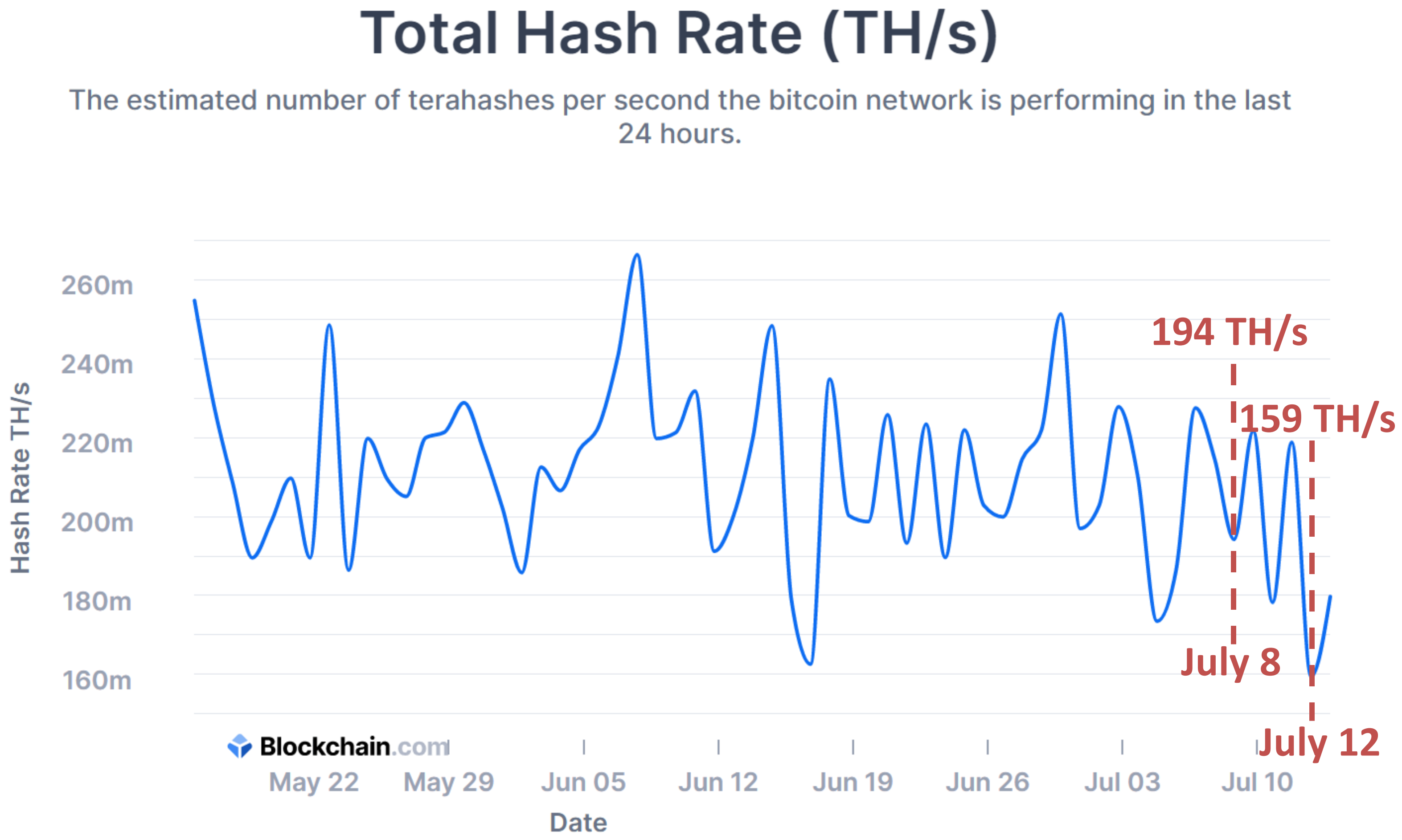

Total Hash Rate (TH/s)
The estimated number of terahashes per second the bitcoin network is performing in the last 24 hours.
260m
240m
220m
200m
180m
160m
Hash Rate TH/s
194 TH/s
159 TH/s
July 8
July 12
Blockchain.com
May 22
May 29
Jun 05
Jun 12
Jun 19
Jun 26
Jul 03
Jul 10
Date

Need of Demand Flexibility for the Grid Resiliency

How Much Demand Flexibility Could Have Spared Texas from the 2021 Outage?

Dongqi Wu[1], Xiangtian Zheng[1], Ali Menati[1], Lane Smith[2], Bainan Xia[3], Yixing Xu[3], Chanan Singh[1], and Le Xie[1,4,*]

[1]Department of Electrical and Computer Engineering, Texas A&M University, College Station, Texas, USA
[2]Department of Electrical and Computer Engineering, University of Washington, Seattle, Washington, USA
[3]Breakthrough Energy Sciences, Seattle, Washington, USA
[4]Texas A&M Energy Institute, College Station, Texas, USA
[*]Corresponding author: le.xie@tamu.edu

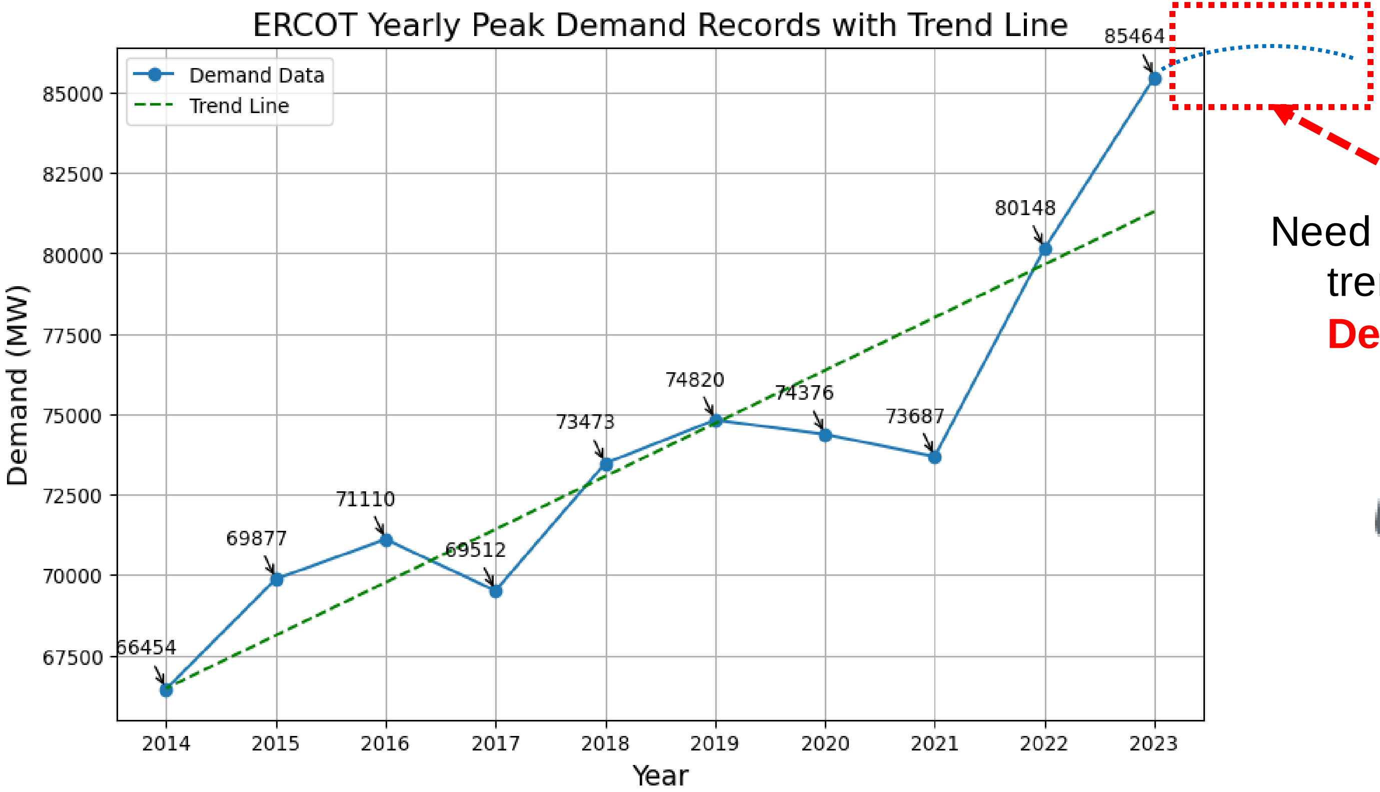
ABSTRACT

The February 2021 Texas winter power outage has led to hundreds of deaths and billions of dollars in economic losses, largely due to the generation failure and record-breaking electric demand. In this paper, we study the scaling-up of demand flexibility as a means to avoid load shedding during such an extreme weather event. The three mechanisms considered are interruptible load, residential load rationing, and incentive-based demand response. By simulating on a synthetic but realistic large-scale Texas grid model along with demand flexibility modeling and electricity outage data, we identify portfolios of mixing mechanisms that exactly avoid outages, which a single mechanism may fail due to decaying marginal effects. We reveal a complementary relationship between interruptible load and residential load rationing and find nonlinear impacts of incentive-based demand response on the efficacy of other mechanisms.

Source of Images:
https://www.nytimes.com/live/2021/02/17/us/winter-storm-weather-live
https://www.newsweek.com/pictures-videos-texas-snow-winter-storm-1569284
https://www.npr.org/sections/live-updates-winter-storms-2021/2021/02/18/969130855/white-house-adviser-says-texas-outages-show-how-u-s-is-unprepared-for-climate-ch
https://www.npr.org/2021/02/16/968357225/texas-governor-calls-for-investigation-into-group-that-manages-state-power-grid

Wu, Zheng, Menati, Smith, Xia, Xu, Singh, and Xie, Advances in Applied Energy, 2022

Peak Demand Growth in TX



Need to break the upward trend **by improving** **Demand Flexibility**

Potential for Scalable Demand Flexibility

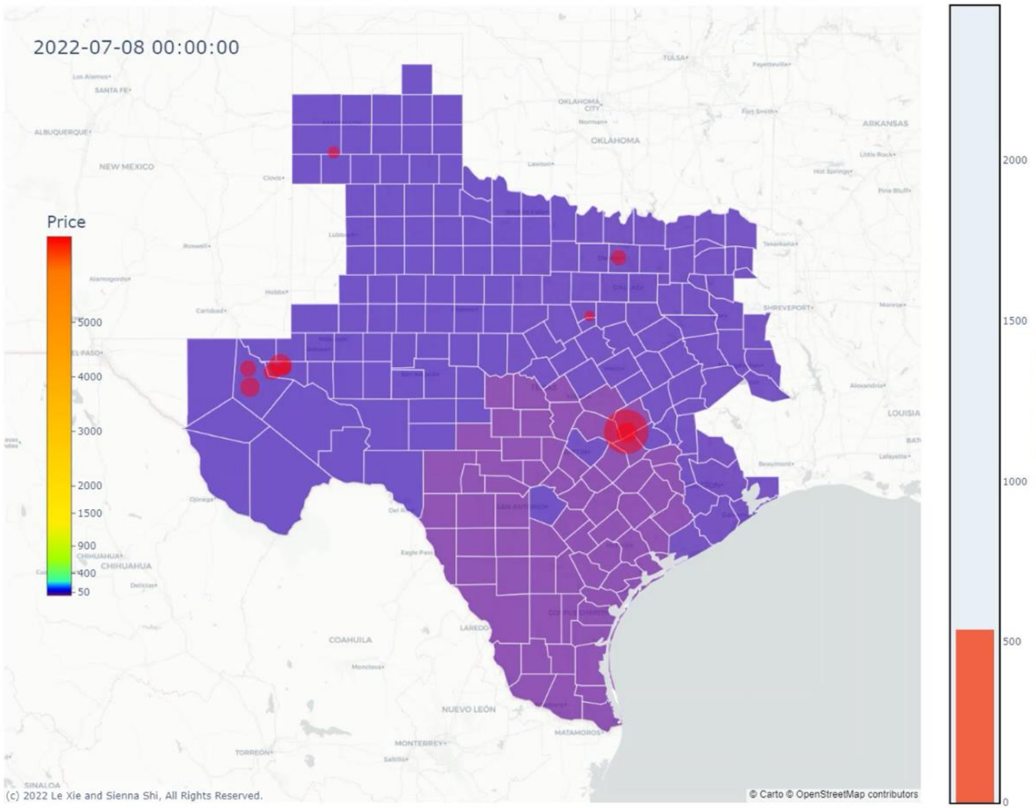
Table 1 Correlation between total mining load, system-wide average LMP, and system-wide net load.

Correlation between	Whole period[1]	Summer peak[2]
Total mining load and system-wide average LMP	-0.042	-0.517
Total mining load and system-wide net load	0.0667	-0.757
Non-mining load and system-wide average LMP	0.009	0.378
Non-mining load and system-wide net load	0.922	0.971

[1] The whole period refers to the period from January 1st, 2021 to October 19th, 2022.
[2] The summer peak time refers to the period from July 7th, 2022 to July 21st, 2022.

A. Menati, X. Zheng, K. Lee, R. Shi, P. Du, C. Singh, and L. Xie "High Resolution Modeling and Analysis of Cryptocurrency Mining's Impact on Power Grids: Carbon Footprint, Reliability, and Electricity Price," Advances in Applied Energy, 2023
A. Menati, K. Lee, and L. Xie, "Modeling and Analysis of Utilizing Cryptocurrency Mining for Demand Flexibility in Electric Energy Systems: A Synthetic Texas Grid Case Study." IEEE Transactions on Energy Markets, Policy and Regulation, 2023.

Electricity Price and Demand of Cryptomining



An Example of a Large Mining Company

Metric	August 2023	July 2023	August 2022	*Comparison (%)* Month/Month	Year/Year
Bitcoin Produced	333	410	374	-19%	-11%
Average Bitcoin Produced per Day	10.8	13.2	12.1	-19%	-11%
Bitcoin Held[1]	7,309	7,275	6,720	0%	9%
Bitcoin Sold	300	400	350	-25%	-14%
Bitcoin Sales - Net Proceeds	$8.6 million	$12.1 million	$7.7 million	-29%	12%
Average Net Price per Bitcoin Sold	$28,617	$30,293	$21,926	-6%	31%
Deployed Hash Rate[1]	10.7 EH/s[2]	10.7 EH/s[2]	4.8 EH/s	0%	123%
Deployed Miners[1]	95,904[2]	95,904[2]	46,658	0%	106%
Power Credits[3,5]	$24.2 million[6]	$6.0 million[6]	$3.0 million	303%	709%
Demand Response Credits[4,5]	$7.4 million[6]	$1.8 million[6]	$0.2 million	316%	2,933%

3. Power curtailment credits received from the Company's ability, under its long-term power contracts, to sell power back to the ERCOT grid at market-driven spot prices.
4. Credits received from participation in ERCOT demand response programs.
5. The Company discloses this figure in its monthly updates if it exceeds $1 million for the current month.

https://www.sec.gov/Archives/edgar/data/1167419/000155837023015517/riot-20230906xex99d1.htm

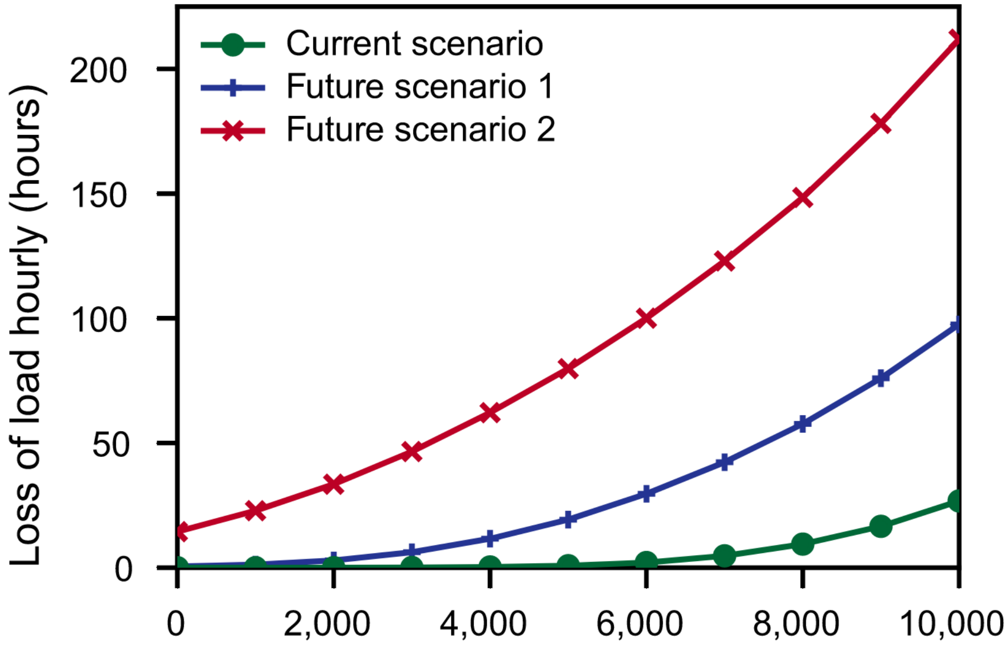
High Resolution Spatial-temporal Analysis of Cryptocurrency Mining on Synthetic Texas Grid: Carbon Footprint, Reliability, and Price

Ali Menati, Xiangtian Zheng, Kiyeob Lee, Sienna Shi, Chanan Singh, Le Xie

Advances in Applied Energy, April 2023

System Reliability

Inflexible Cryptocurrency Mining Demand



Capacity of Cryptocurrency Mining Load (MW)

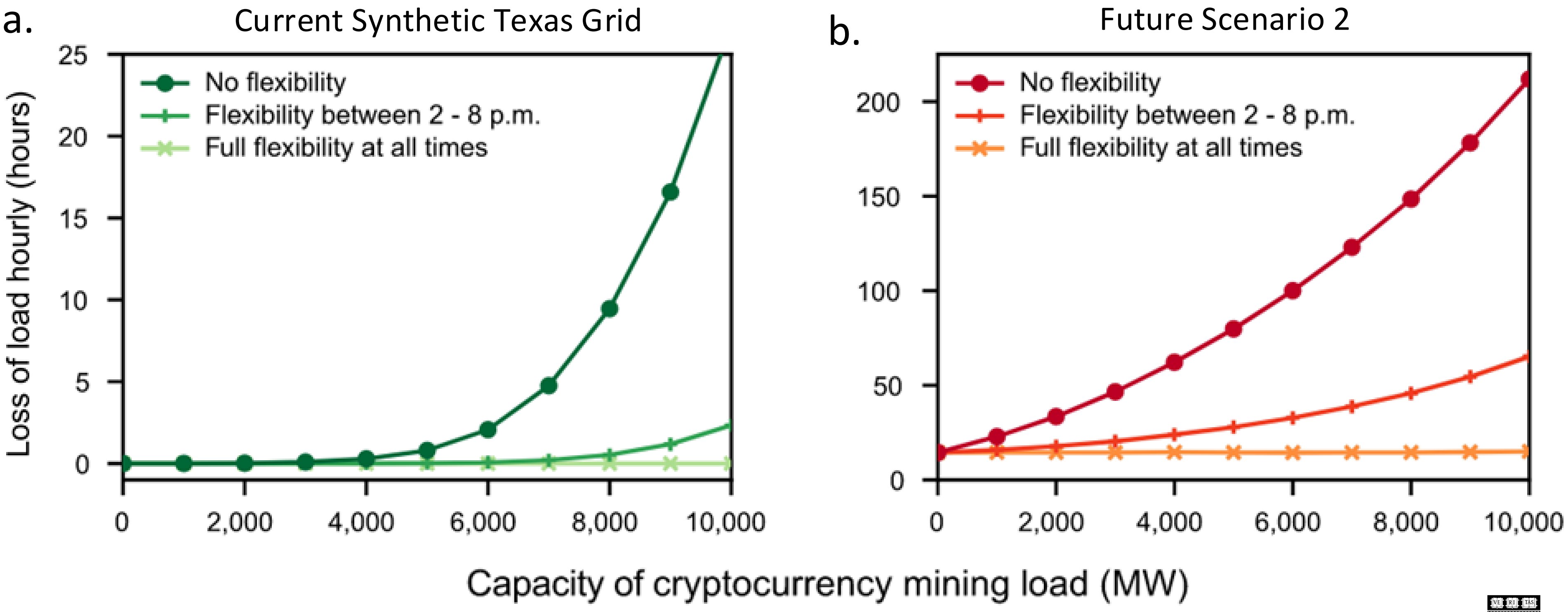
Future Scenario 1: 10% additional firm load, 50% more renewable generation

Future Scenario 2: 20% additional firm load, 100% more renewable generation

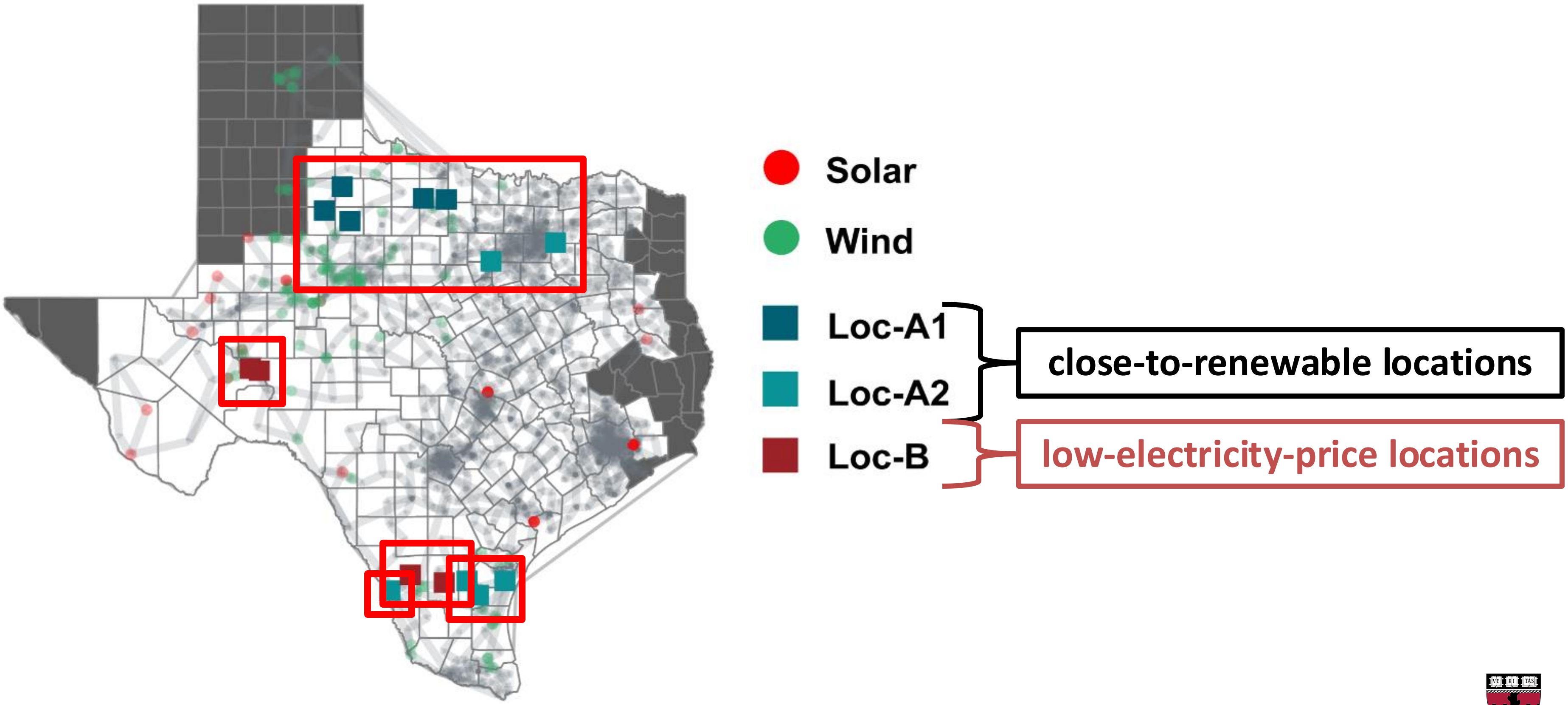
In a **renewable-rich** future grid, reliability incidents will become more frequent due to the intermittent nature of renewable energy generation

If the additional mining demands are ***inflexible*** and without careful location planning, its impact to system reliability is significant

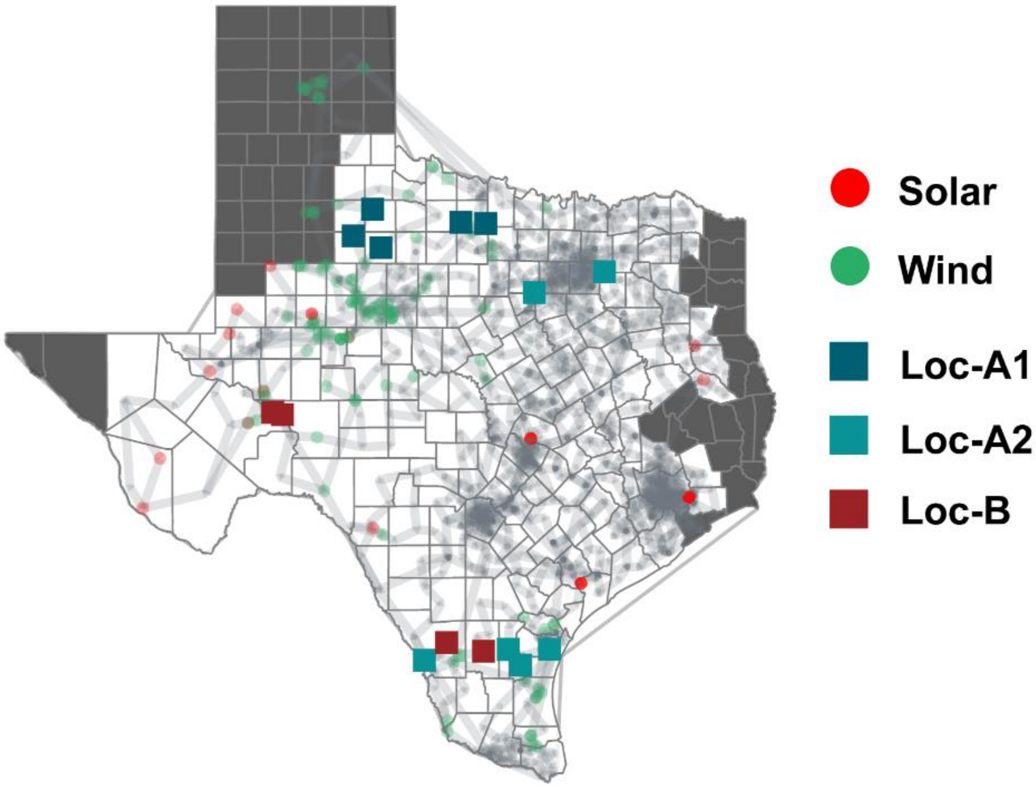
System Reliability



Carbon Footprint



Carbon Footprint



We studied the location of cryptocurrency mining loads as a critical factor impacting carbon emissions.

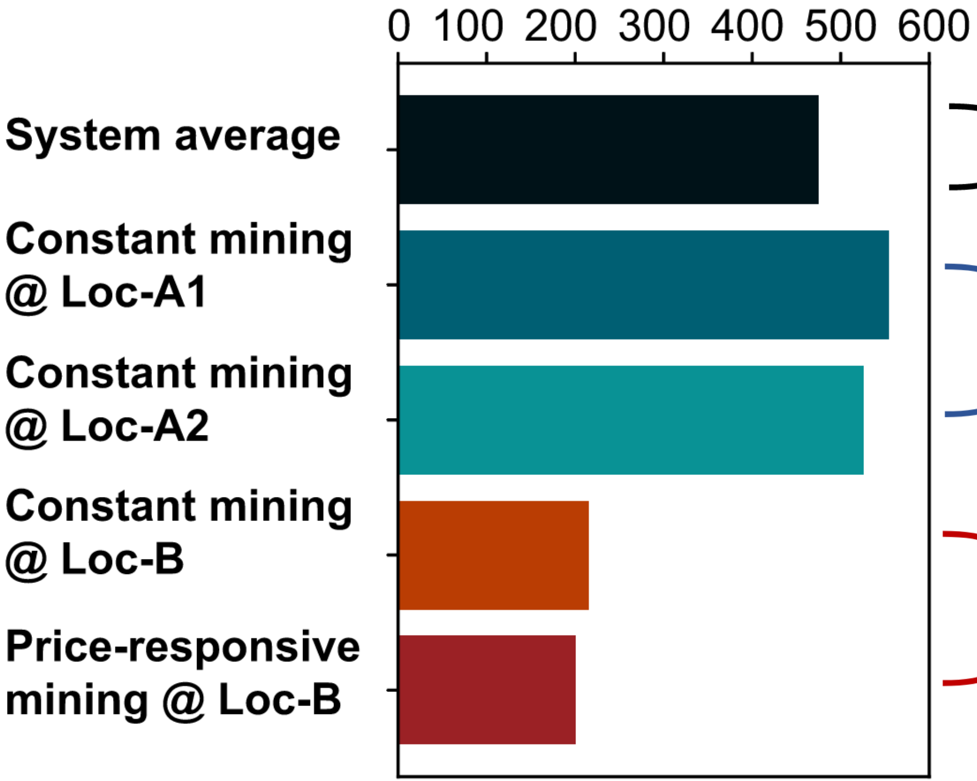
We show that the carbon footprint of mining loads exhibits locational disparity

Low-electricity-price locations can control carbon emission below 50% of the system-wide average, while close-to-renewable locations do not necessarily lead to low carbon emission.

Carbon Footprint

Carbon Emission (kgCO2e/MWh)

Location Matters

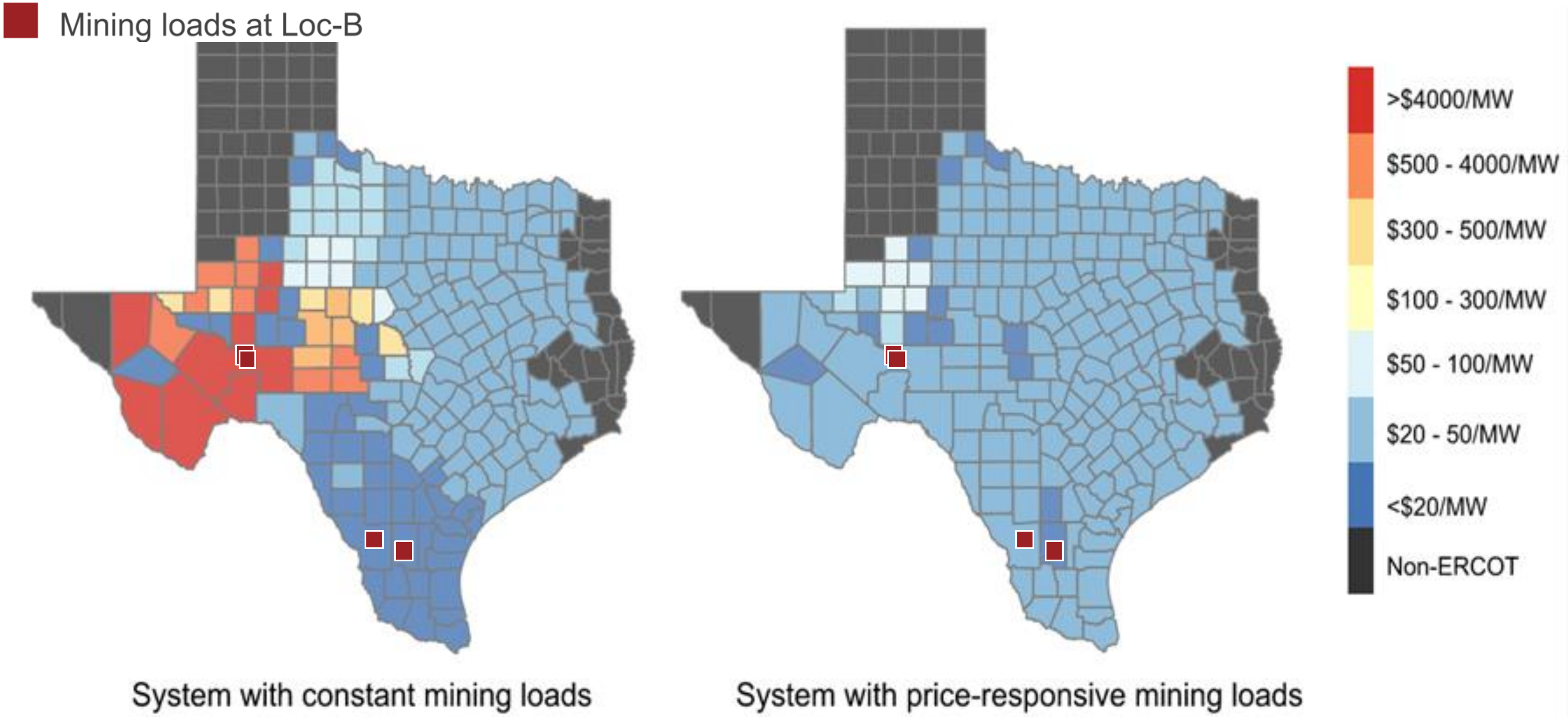


Grid-agnostic estimation by existing studies are not accurate.

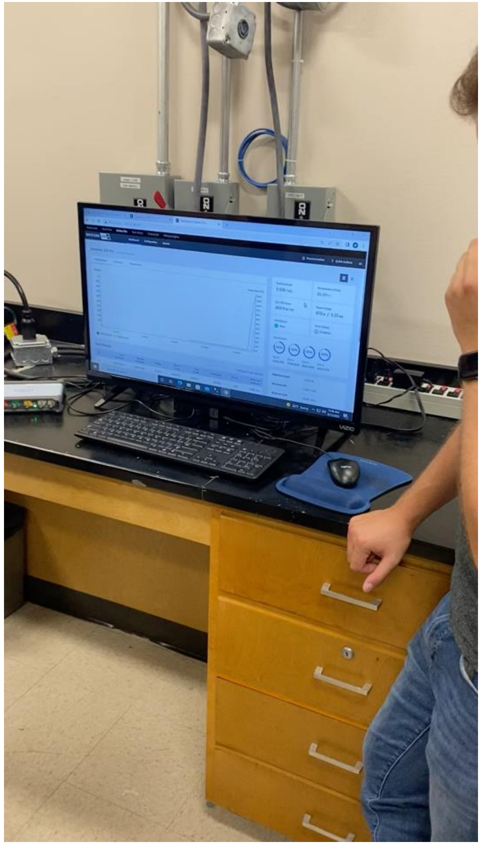
Close-to-renewable sites are not necessarily low-carbon.

Low-electricity-price sites control carbon footprint below 50% of the system average.

Market Price



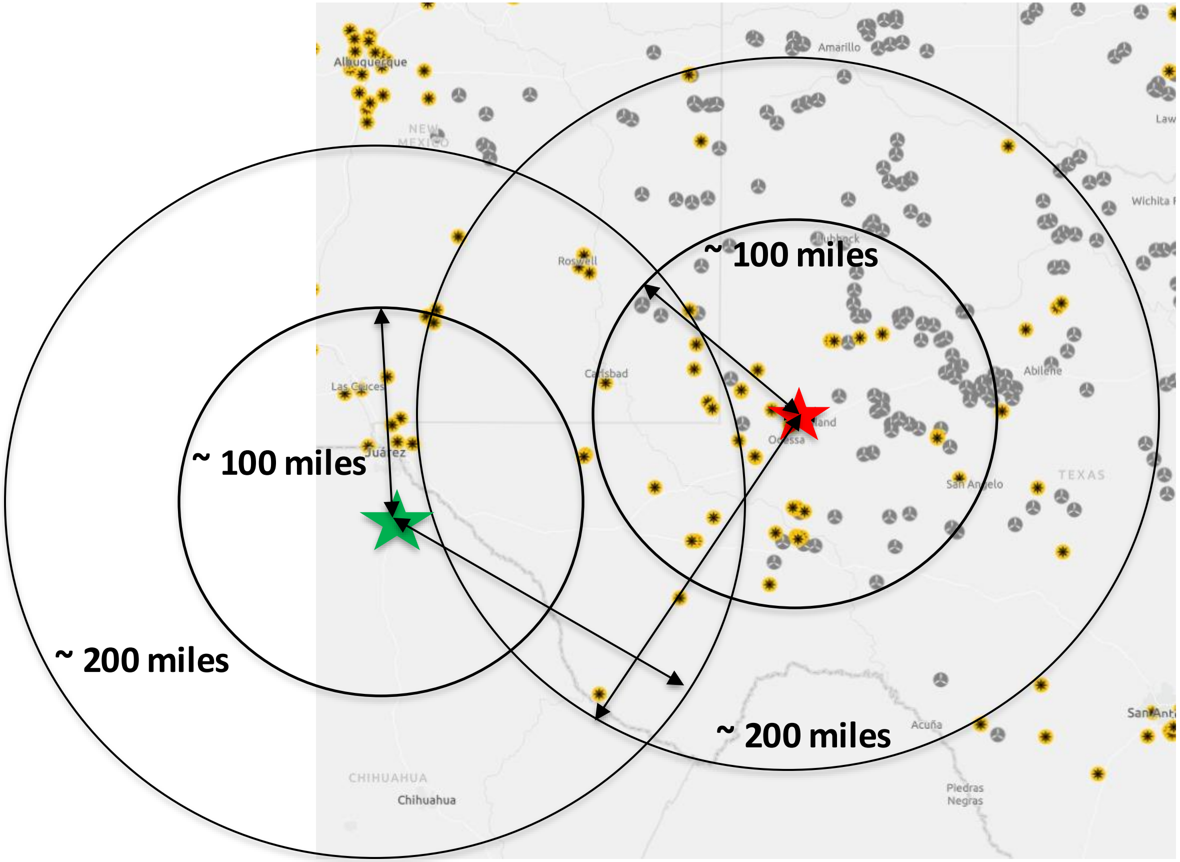
First Bitcoin Mining Unit Installed on Campus for Experiential Learning, Student Entrepreneurship, and Research



Sep 12, 2022
Wisenbaker 118
S-19 Pro Machine
(donated by Texas Blockchain Council)

Recent Examples of Disturbances in TX

solar farms
wind farms



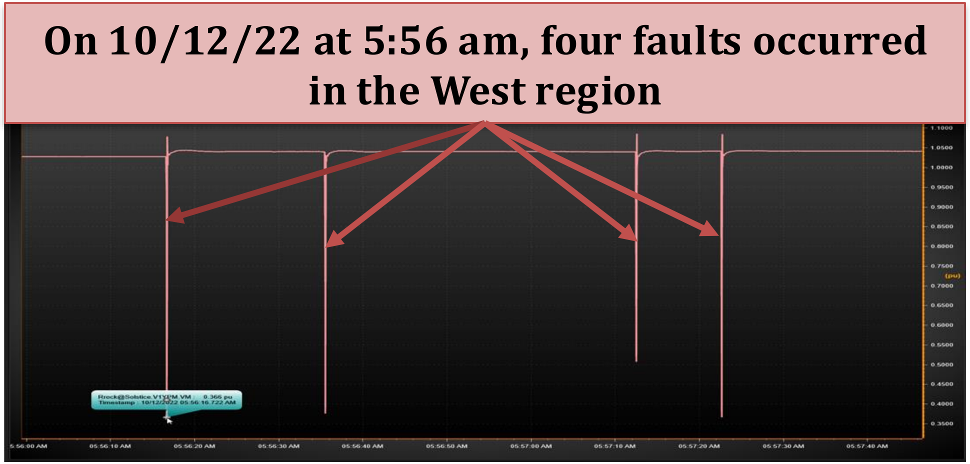
fault at West Texas

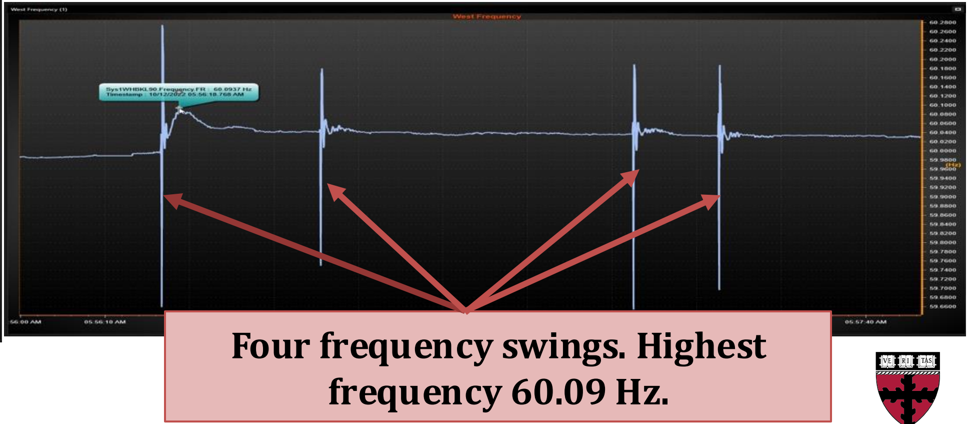
fault at Odessa

https://atlas.eia.gov/apps/895faaf79d744f2ab3b72f8bd5778e68/explore

Example 1: West Texas | 10/12/2022 | 5:56AM

- There was a load voltage ride-through event
- Several loads totaling >400 MWs tripped, including Mining Loads
- Frequency spiked to 60.09 Hz





Example 2 : Near Odessa | 12/7/2022 | 3:50AM

Largest load loss event to-date:

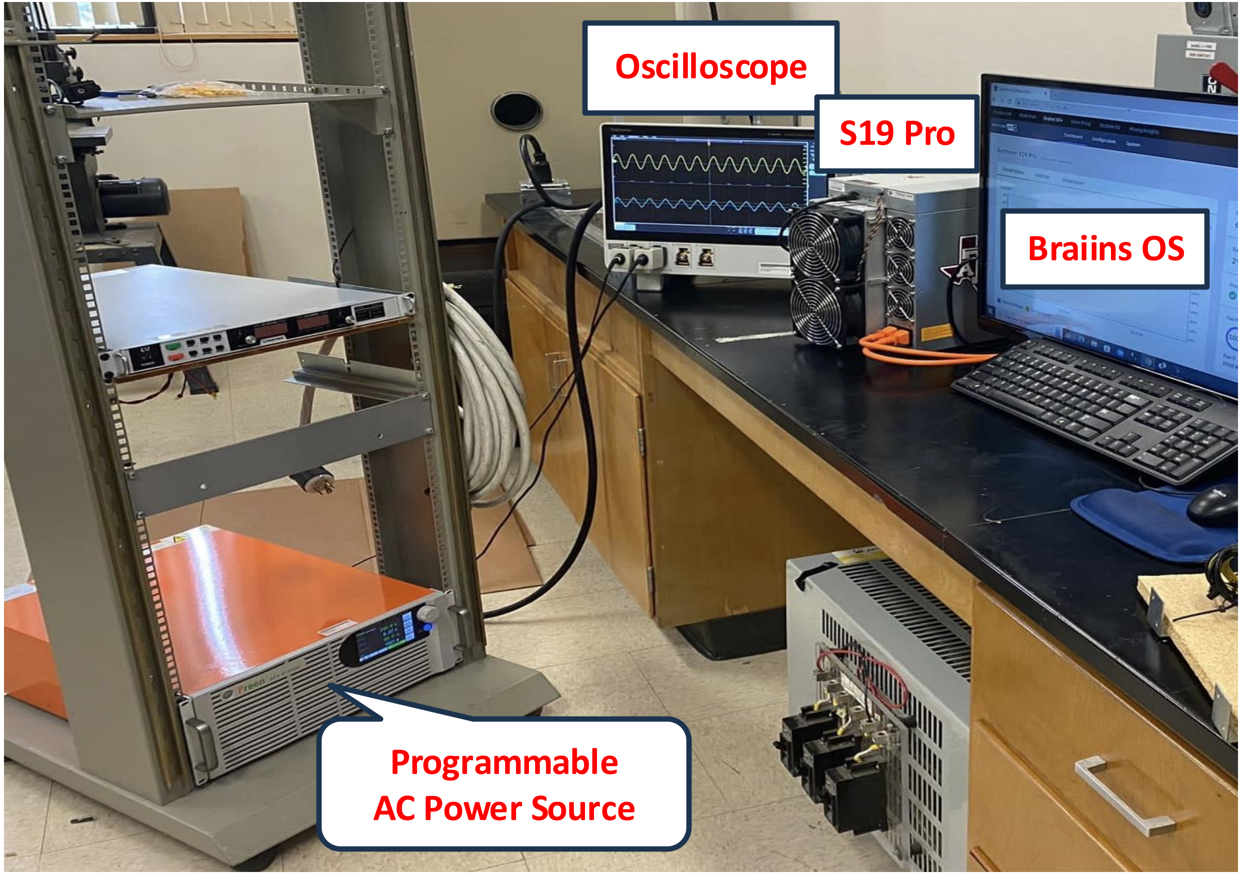
- Multiple faults on 138 kV lines including 3 phase fault due to breaker failure
- Reduction in load of **~1,600 MW**
- Load reduction included mix of large mining loads, oil/gas load, and other industrial loads
- Two thermal generators tripped during the event, totaling 112 MW
- System frequency spiked to 60.235 Hz

Key Takeaway : There is a need for improved interconnection process for large loads and improved simulation models of new load types.

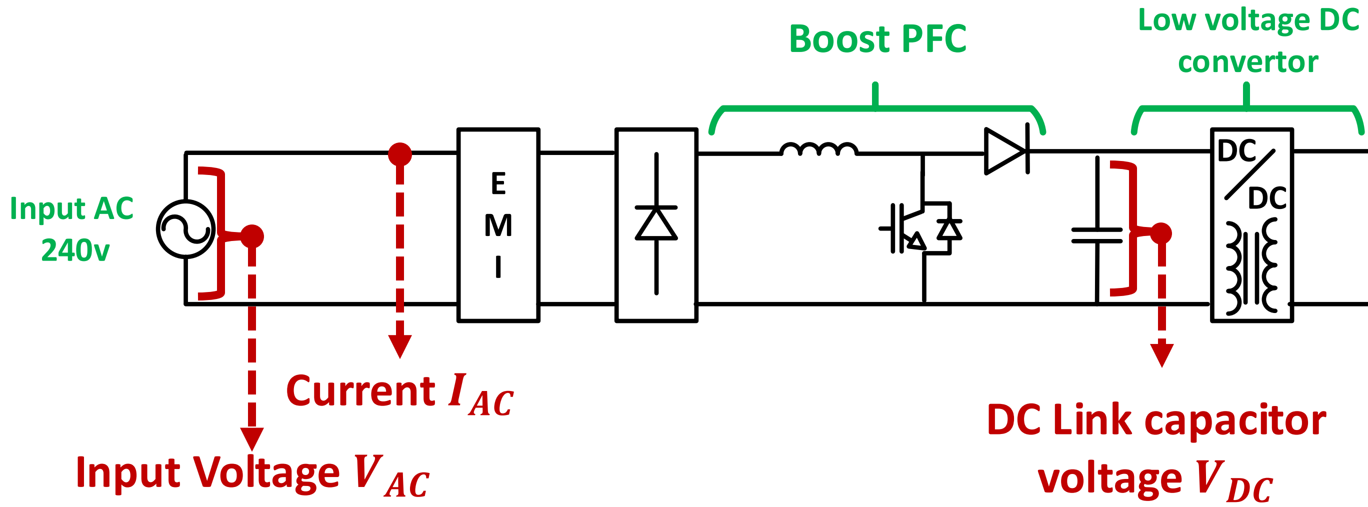
[1] ERCOT Public Presentation : LFLTF: Large Load Voltage Ride-Through Requirements, Jeff Billo, Operations Planning, May 31, 2023
[2] ERCOT Public Presentation : Item 7.2.1: Inverter-Based Resource and Large Load Ride Through Events: Background and Mitigation, Dan Woodfin, System Operations, Reliability and Markets Committee Meeting, June 19, 2023

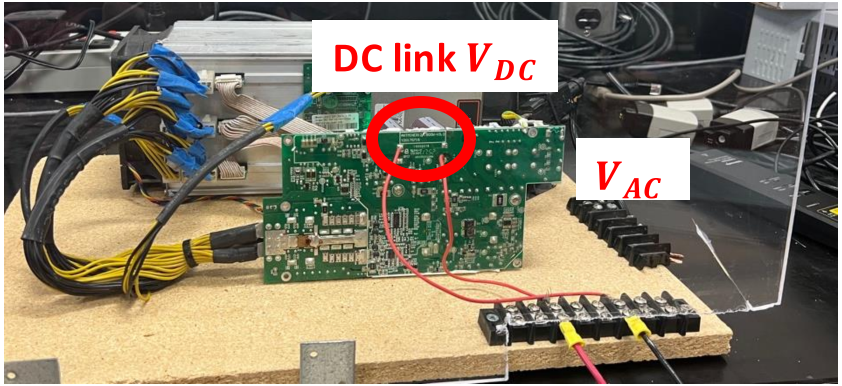
BERC Lab –Low Voltage Ride Through Test Setup

- Programmable AC power source
- Voltage output 0-310 VAC
- Frequency output 40-500Hz
- Step and ramp functions for voltage and frequency variation tests



Internal Circuit Topology of a Typical S19 Pro Miner

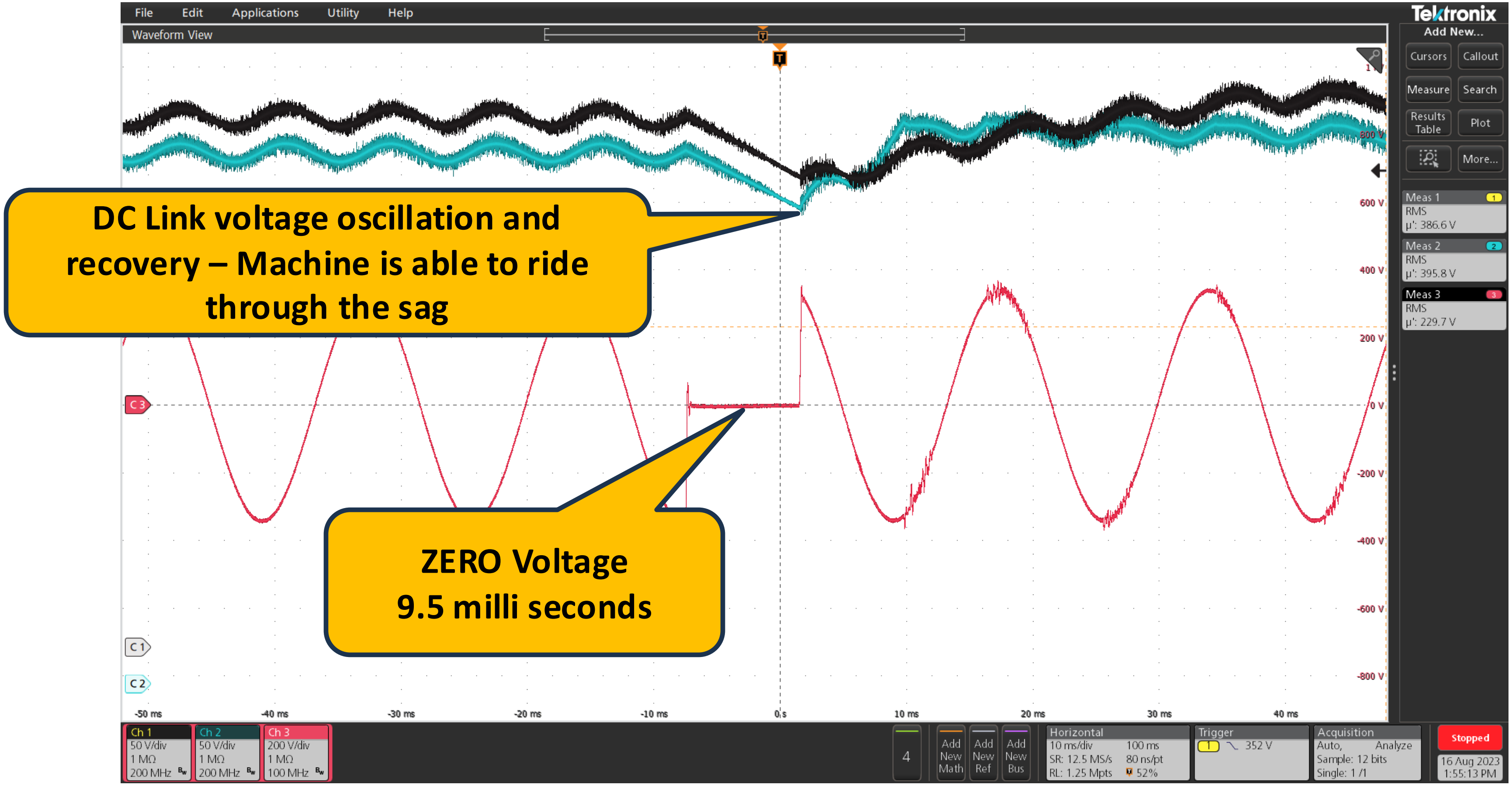




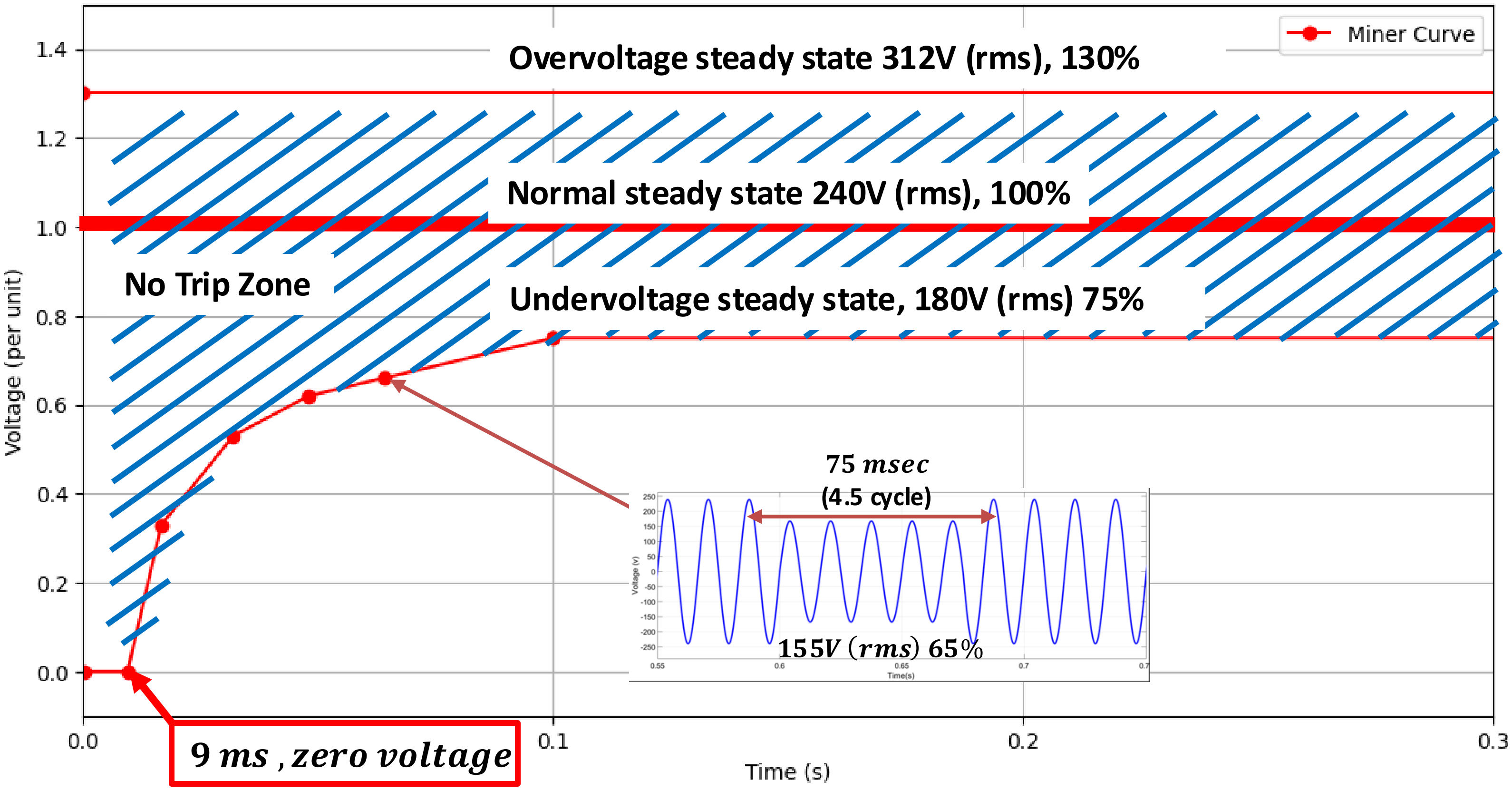
Power Range	Hashrate Range
2.4 - 6.5 kW	10 – 276 TH/S

Samanta et al. "Electromagnetic Transient Model of Cryptocurrency Mining Loads for Low-Voltage Ride Through Assessment in Transmission Grids." IEEE PES GM 2024

9.5 milli seconds Zero Voltage DC Link voltage

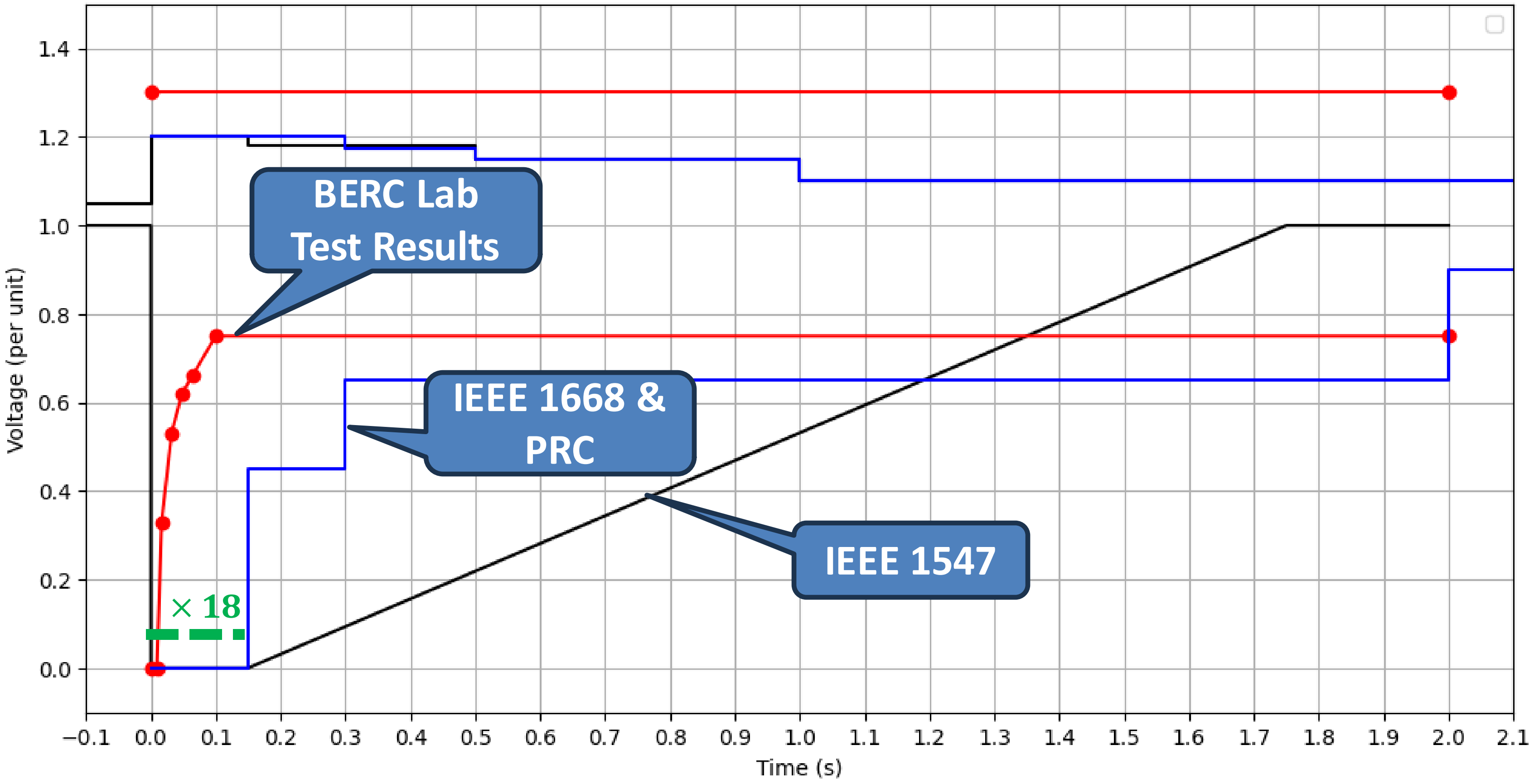


BERC Lab Voltage Ride-through Test Results – S19 Pro



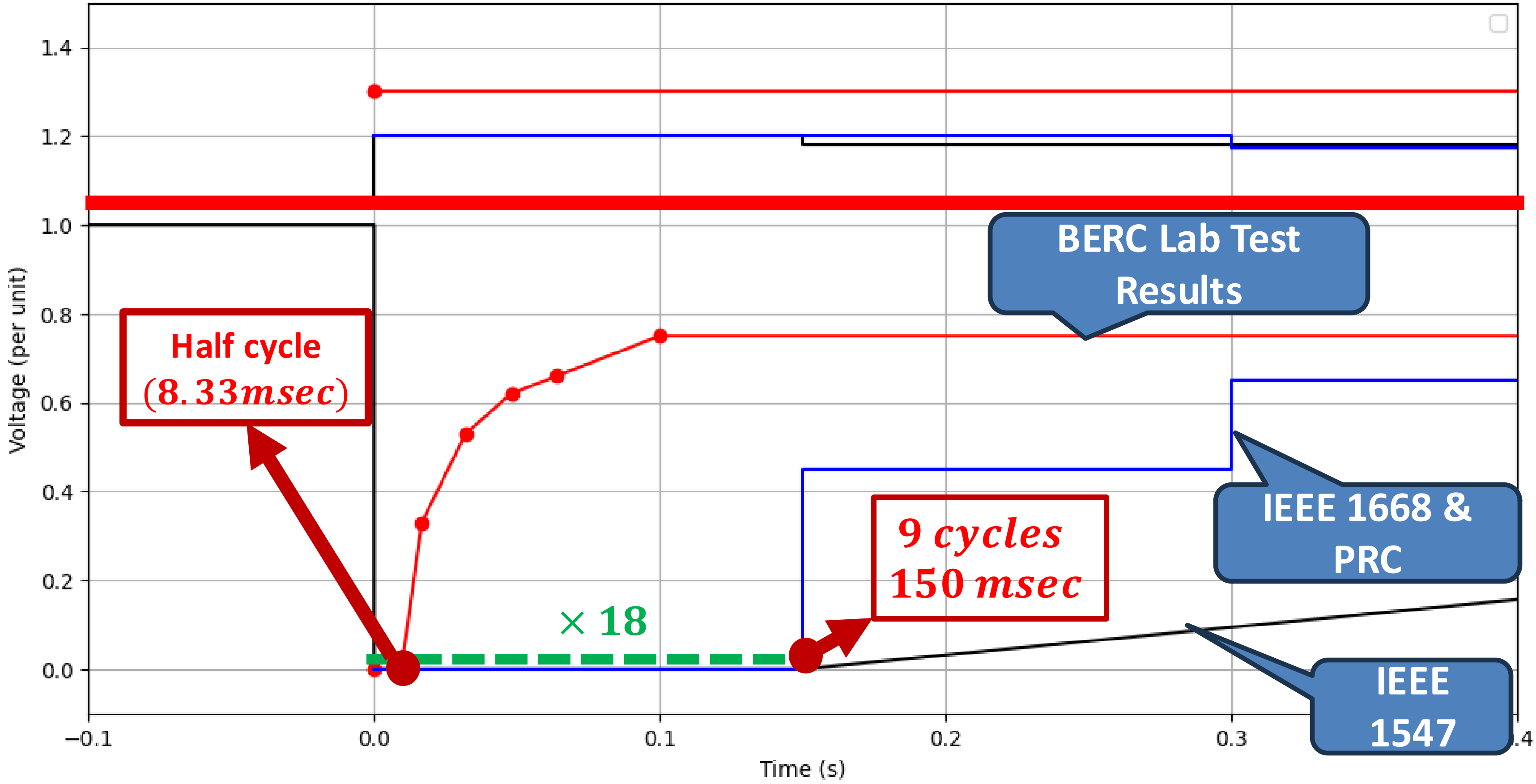
Samanta et al. "Electromagnetic Transient Model of Cryptocurrency Mining Loads for Low-Voltage Ride Through Assessment in Transmission Grids." IEEE PES GM 2024

Bitcoin miner (S19 Pro) curve vs other curves



Samanta et al. "Electromagnetic Transient Model of Cryptocurrency Mining Loads for Low-Voltage Ride Through Assessment in Transmission Grids." IEEE PES GM 2024

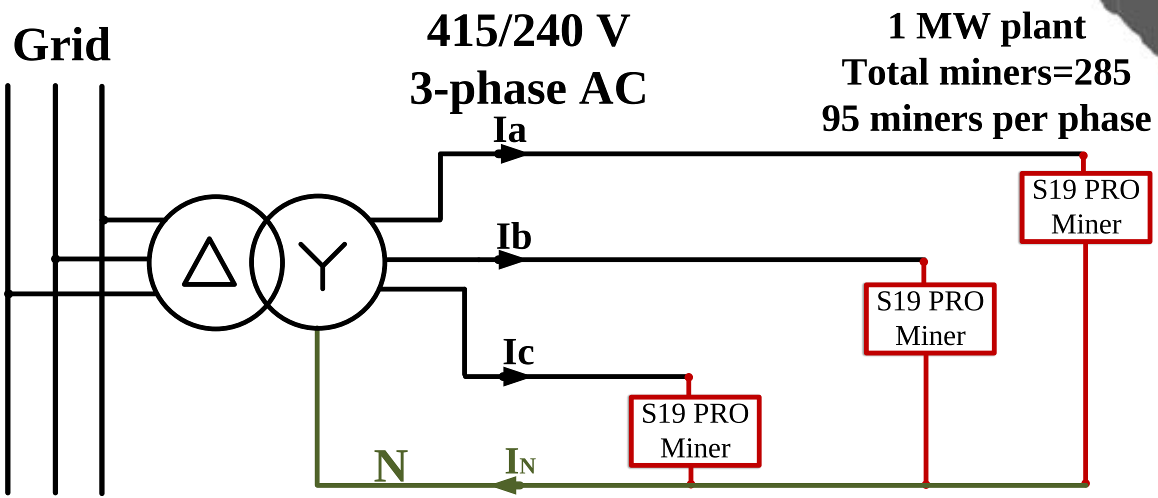
Bitcoin miner curve vs other curves

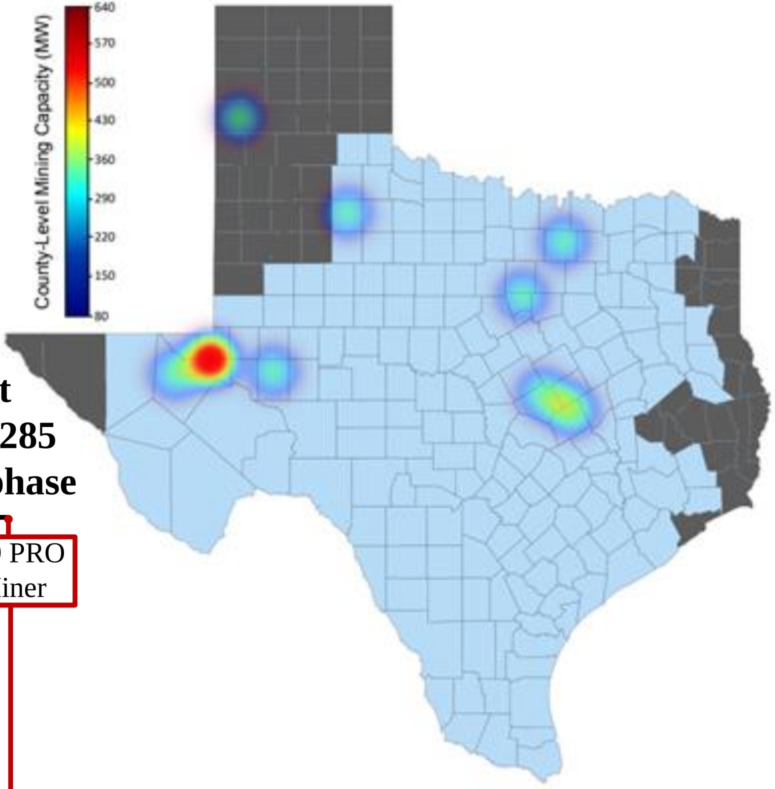


Samanta et al. "Electromagnetic Transient Model of Cryptocurrency Mining Loads for Low-Voltage Ride Through Assessment in Transmission Grids." IEEE PES GM 2024

Helping ERCOT on Large scale Bitcoin Mining Facilities

- Power consumption 3.5 kW per miner
- 100MW mining facility ~28,500 miners
- Ramifications of VRT issues in large-scale facilities on the grid



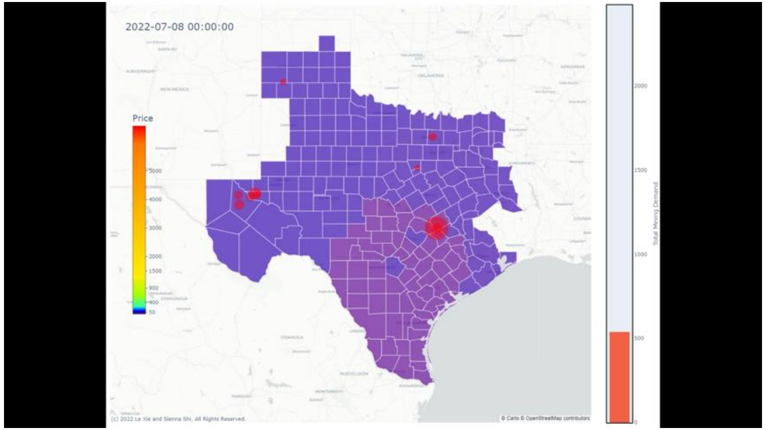


Samanta et al. "Electromagnetic Transient Model of Cryptocurrency Mining Loads for Low-Voltage Ride Through Assessment in Transmission Grids." IEEE PES GM 2024

Summary

- Blockchain and cryptocurrency is still at its infancy
- Increasing amount of energy will be needed for such applications
- How to make it a “win-win” for the energy sector and the computing industry remains a major challenge and opportunity

Texas A&M and ERCOT Tour Riot's Rockdale Facility

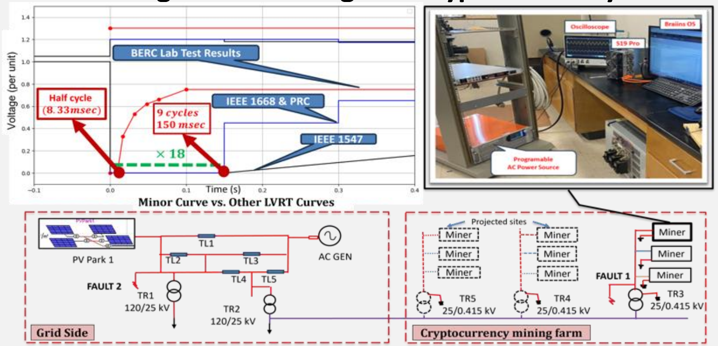


Transients (Control)

Economics (Optimization)

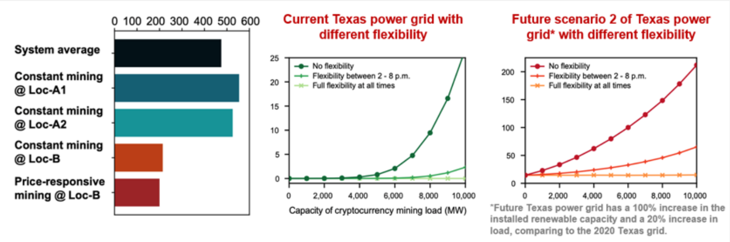
10^{-7} second | 10^{-3} second | 1 second | 1 min | 1 hour | 1 day | 1 week | 1 year

Low-voltage Ride Through of Cryptocurrency Miners



The Blockchain & Energy Research Consortium, TAMU, https://tx.ag/berc

Crypto mining's impact on carbon footprint and reliability



Menati and Xie, et al. *IEEE Tran. On Energy Markets, Policy and Regulation*, 2023 Menati and Xie, et al. *Advances in Applied Energy*, 2023

Contact: xie@seas.harvard.edu

WECC Large Load Risk Assessment & Industry Advisory Group

Katie Rogers – WECC

Kyle Thomas – Elevate Energy Consulting

Open Distribution

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WECC

WECC Large Load Risk Assessment & Industry Advisory Group

Katie Rogers – WECC – Manager, Reliability Assessments
Kyle Thomas – Elevate Energy Consulting – VP of Engineering/Compliance Services

November 20, 2024

WECC Large Load Risk Assessment

- Develop a better understanding of large loads and their potential impacts on BPS reliability
  - Increase WECC regional knowledge and understanding of large loads and their developments, & their potential risks and impacts to the western interconnection
- Gather feedback and concerns from WECC members on this topic, which can help shape the direction/strategy to address identified gaps and challenges
- Obtain information through literature review regarding industry activities, best practices, risks/challenges, actual system events, and more
- Create closer collaboration and information sharing within the WECC region on large loads
- Develop a technical report on the risk assessment of large loads in the Western Interconnection

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WECC Large Load Industry Advisory Group

- Informal industry group that has met monthly over 2024
- Setup to collaborate and share information on:
  - Highlight the large load categories and growth in the WECC region
  - Discuss issues/concerns with large loads
  - Identify new and best practices for large load interconnections
- Help shape direction and strategy for the assessment and for WECC as a whole

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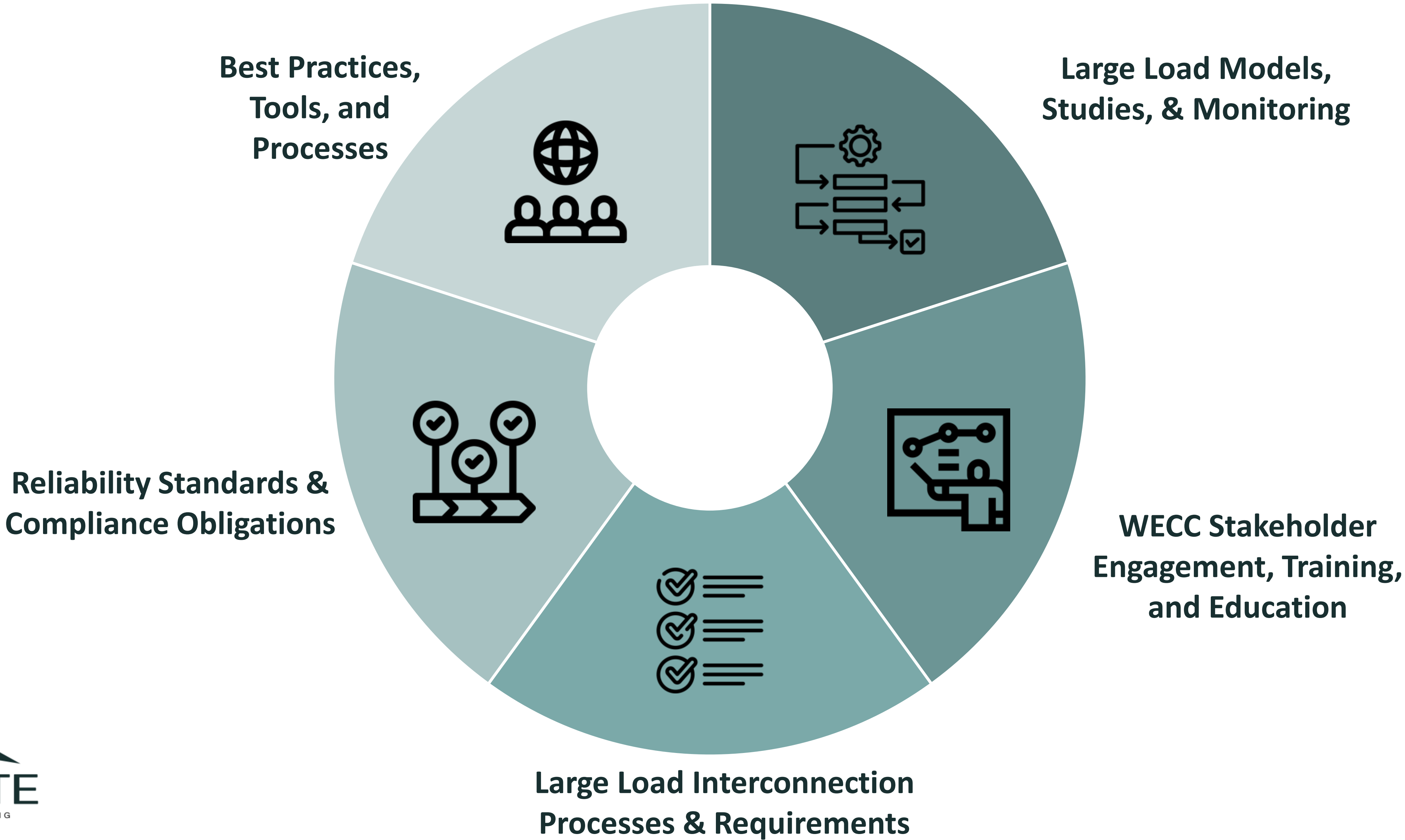
WECC Large Load Risk Assessment Topic Areas



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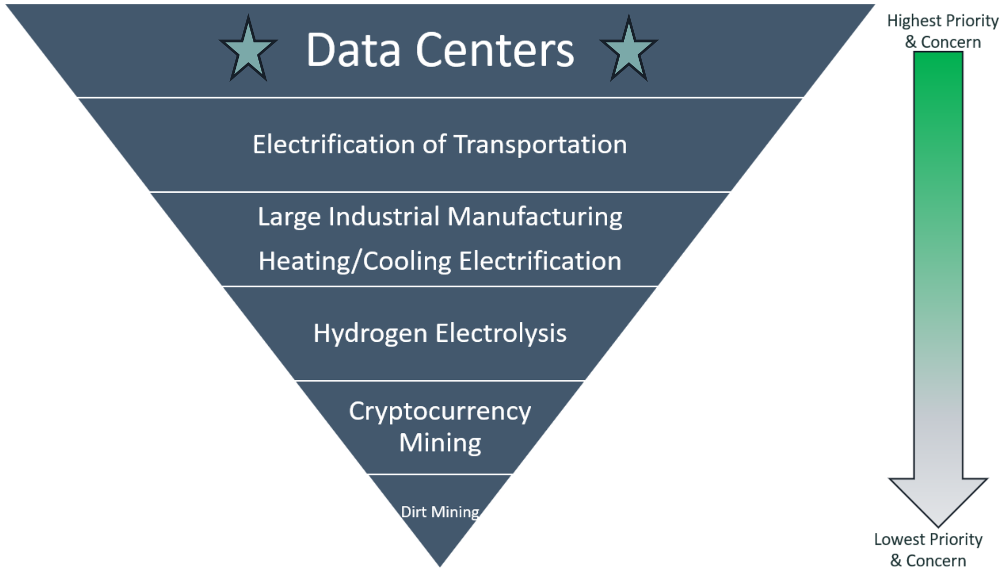
Collected Data from WECC IAG

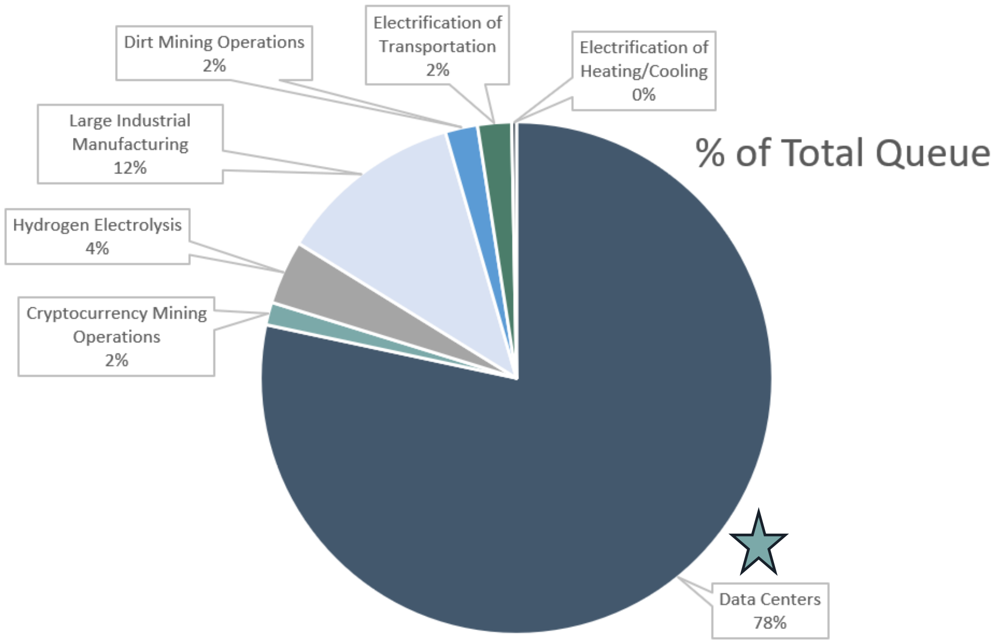
Prioritization/Concern Ranking of Large Load Categories



Other LL categories that were not included in initial survey:

- Agricultural facilities
- Electric arc furnaces/smelters

		Total Peak Load
	10 WECC Utilities	43,927
Load Type	Current Estimate of Interconnection Requests (MW)	% of Total Peak Load
Data Centers	34,893	79
Large Industrial Manufacturing	5,211	12
Hydrogen Electrolysis	1,800	4
Dirt Mining Operations	908	2
Electrification of Transportation	955	2
Cryptocurrency Mining Operations	638	1
Electrification of Heating/Cooling	132	0
Total Queue MW	44,537	



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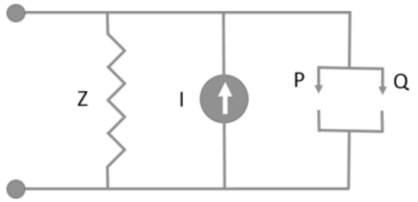
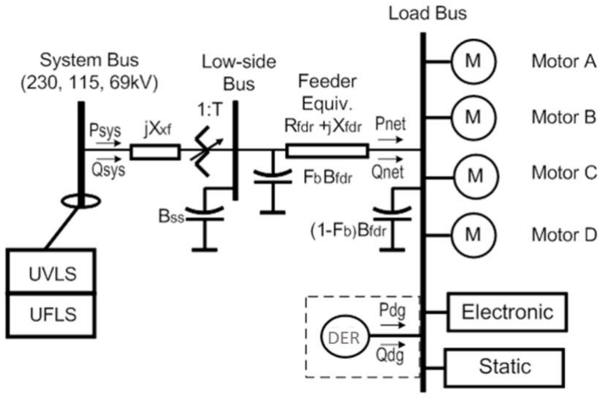
WECC Large Load Technical Challenges & Risks

- Interconnection processes & queues for LL
  - Involves both Transmission & Distribution interconnection processes
- Interconnection requirements and standards for LL
- LL construction times compared to Transmission & Distribution construction times
  - Permitting, ROW, lead time of critical grid equipment, etc.
  - Grid outage management a growing challenge in some areas with heavy LL penetration
- Transmission Planning for LL interconnections: Models & Studies
  - Steady state, Transient Stability, EMT, and Short circuit studies need to be considered
  - Lack of accurate dynamic model representations of LL
  - Lack of contingency definitions and analysis of LL scenarios
    - What if hundreds or thousands of MW of LL suddenly trip offline, and then come back online?
    - An unexpected loss of large amounts of load could have significant reliability impacts to the BPS
  - Transmission & Distribution expansions, upgrades, new builds
  - Cost allocation considerations
- New operating characteristics and risks
  - Fast Load Ramping ("power jitter," potential for subsynchronous oscillations, power electronics control interactions, and resonances with known system modes)
  - System voltage and frequency impacts
  - Voltage & Frequency Ride-through of LL for grid disturbances, such as faults
  - Power quality – potential for flicker, voltage and frequency swings, forced oscillations

Interconnection requirements for entire lifecycle of LL
(from Interconnection Process to Operations)



Static Load Models



Dynamic Composite Load Model [Source: NERC]

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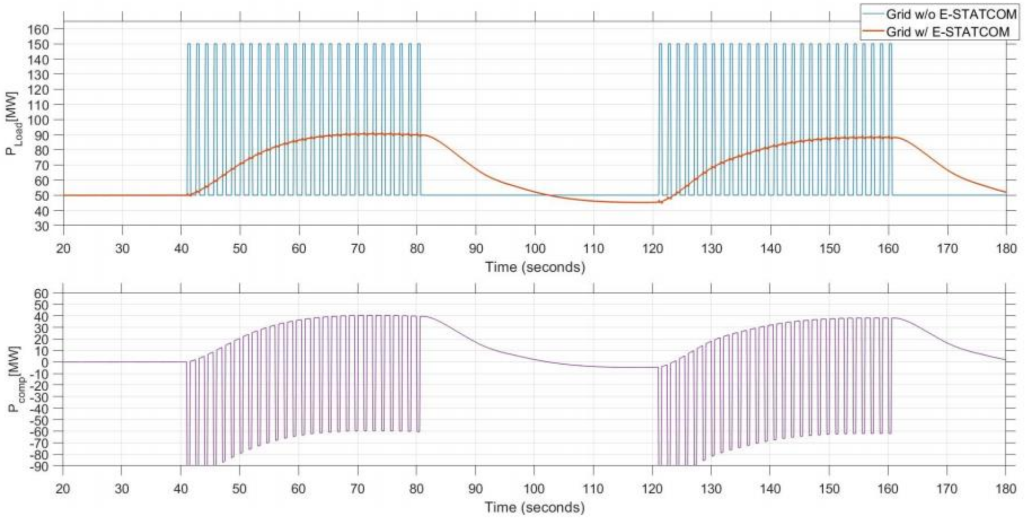
WECC Large Load Technical Challenges & Risks

- Data and Model sharing between LL and Grid Operators
- Firm vs. Flexible transmission service requirements
- Load factor (% uptime)
- Production cost modeling and resource planning
- Generation resource adequacy
- Demand response impacts
- Large load forecasting (Long-term and short-term)
- Coordination with grid operators on outages, maintenance, grid events, LL events, and more
- Backup generation resources BTM
- Impacts to Automatic UFLS
- Market impacts and considerations
- Restoration following blackouts (prioritization of LL, blackstart restoration, and more)



Study of Sub-second LL Ramping and mitigation by an E-STATCOM [Source: Siemens Energy]

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Large Load Interconnection Requirements – Global Perspective

- EU established a Network Code on Demand Connections back in 2016[1,2]

Official Journal of the European Union

COMMISSION REGULATION (EU) 2016/1388

of 17 August 2016

establishing a Network Code on Demand Connection

System security cannot be ensured independently from the technical capabilities of all users. Historically, generation facilities have formed the backbone of providing technical capabilities. However, in this regard, demand facilities are expected to play a more pivotal role in the future. Regular coordination at the level of the transmission and distribution networks and adequate performance of the equipment connected to the transmission and distribution networks with sufficient robustness to cope with disturbances and to help to prevent any major disruption or to facilitate restoration of the system after a collapse are fundamental pre-requisites.

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1. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R1388
2. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.223.01.0010.01.ENG#d1e307-10-1

Large Load Interconnection Requirements – Global Perspective

- Interconnection Requirements in the EU Network Code on Demand Connections:
    - Includes definitions of large loads and considers transmission-connected loads vs. distribution-connected loads
    - Information/Model/Monitoring Data requirements and sharing of data between grid operator & load owner
    - Loads must specify voltage & frequency ranges, ride-through for voltage and frequency disturbances, etc.
    - Demand response requirements
    - Automatic disconnection settings shall be agreed upon between the grid operator & load owner
    - Short circuit requirements
    - Reactive power requirements
    - Protection requirements
    - Control requirements (isolated operation; damping of oscillations; automatic reclosing; automatic switching to backup generation and restoration to normal grid connection)
    - Power quality requirements
    - Model sharing requirements from the load owners
    - Limited operational notifications

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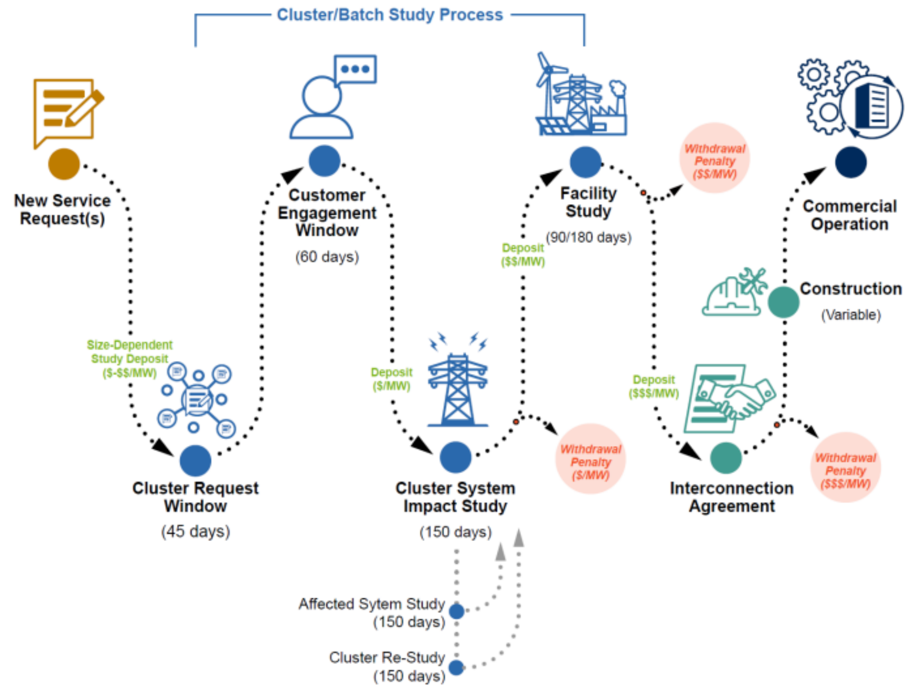
1. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R1388
2. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.223.01.0010.01.ENG#d1e307-10-1

Large Load Interconnection Improvements Are Needed

- Feedback received that the load interconnection processes and queues need improvements
  - Load interconnection processes vary widely as it isn't always driven by the Transmission Interconnection process
  - Rather, often is driven by Distribution Load Interconnection processes due to voltage level of interconnections
  - Queue submittal processes can be as simple as an email to the Load Interconnection teams
  - How to ensure valid real projects move through the interconnection process?
    - Site control requirements, submittal fees for various milestones, etc.
- Can we apply what we've learned and improved upon in the Transmission Generation Interconnection process?
  - Can that be applied to load interconnections at state-level distribution interconnection processes & transmission load interconnection processes?



FERC Order 2023 Generation Interconnection Process

Source: LBNL

https://emp.lbl.gov/sites/default/files/2024-04/Queued%20Up%202024%20Edition_R2.pdf

Next Steps

- Final report targeted for publication in Q1 2025
- Collaborate with NERC Large Load Task Force and other industry large load working groups
- WECC Stakeholder outreach and education
- Continue further discussions with large load industry to learn and collaborate on the challenges and opportunities together
- Work towards mitigating the risk assessment findings and implementing recommendations

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Wrap Up

Latrice Harkness - NERC