PUBLIC

ercot

Lone Star Infrastructure Protection Act (LSIPA)

Senate Committee on Business & Commerce
April 1, 2026

Chad V. Seely
ERCOT Senior Vice President, Regulatory Policy, General Counsel, & Chief Compliance Officer

Key Takeaways:

- SB 2116 (2021) enacted the LSIPA; SB 2013 (2023) and SB 2368 (2025) amended the LSIPA.
- ERCOT has successfully implemented the LSIPA in accordance with legislative requirements and has established ongoing processes to strengthen the program internally and in collaboration with the Public Utility Commission of Texas (PUCT).
- ERCOT consistently evaluates Market Participants' LSIPA compliance and, so far, has found all but one Market Participant to be compliant. The non-compliant Market Participant was terminated.
- ERCOT has identified enhancements it intends to implement to further improve internal processes and LSIPA compliance evaluations.

PUBLIC

LSIPA Enactment and ERCOT’s Response

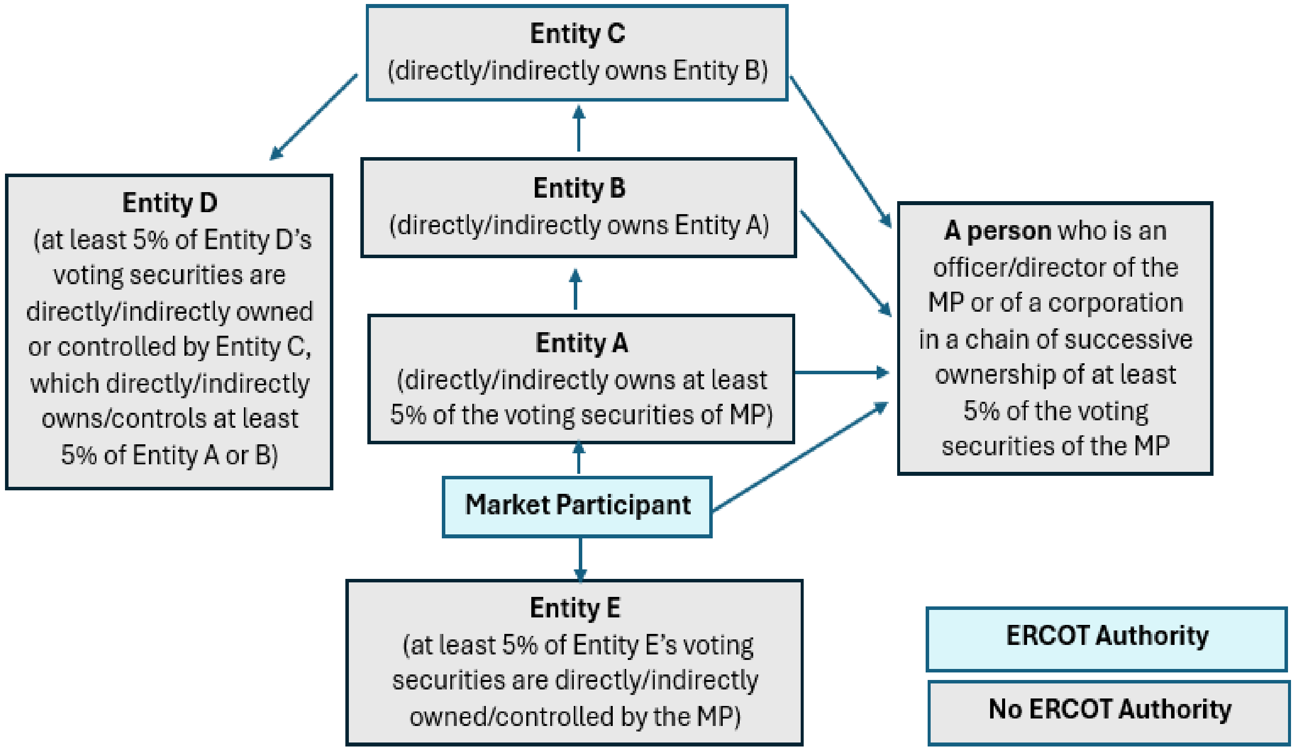
<u>SB 2116 (eff. June 2021):</u> LSIPA Enacted

Prohibits agreements with a known LSIPA Designated Company if that company would be granted direct/remote access to or control of Texas’ electric grid.

A company is an LSIPA Designated Company if it meets any of the LSIPA prohibited citizenship, ownership, or headquarters criteria regarding <u>China, Iran, North Korea, Russia, or any country deemed a threat to Texas critical infrastructure by the Governor</u>.

- **December 2021**: ERCOT confirmed existing Interconnecting Entities’ LSIPA compliance.
- **April 2022:** ERCOT adopted the LSIPA Attestation for Interconnecting Entities.
- **June 2022:** ERCOT adopted the LSIPA Attestation for Market Participants and confirmed existing Market Participants’ LSIPA compliance.
- ERCOT updated its procurement/contracting policies for vendors and standard form agreements to require information and/or confirmations regarding LSIPA criteria.

Example Scope of Market Participant (MP) Affiliate Relationship(s)



ercot

PUBLIC

LSIPA-Related Requirements and Authority Added to the Public Utility Regulatory Act (PURA) and ERCOT's Response

SB 2013 (eff. June 2023): Added Critical Electric Grid Equipment (CEGE) & Critical Electric Grid Services (CEGS) requirements

Existing Market Participants and applicants must: attest to LSIPA compliance; report CEGE/CEGS purchased from LSIPA Designated Companies; and confirm such purchases will not result in unauthorized access/control of CEGE.

- **May 2024:** ERCOT adopted the CEGE/CEGS Attestation for Market Participants that requires:
  - Market Participants to report/attest to purchases of CEGE/CEGS from an LSIPA Designated Company within 180 days of the purchase date; and
  - Applicants to report/attest to purchases of CEGE/CEGS from an LSIPA Designated Company made within the preceding five years.
- **May 2024:** ERCOT required all existing Market Participants to report and attest to CEGE/CEGS purchased from an LSIPA Designated Company since June 8, 2018.
- ERCOT updated its employment policies to identify positions that are "critical to the security of the electric grid."

SB 2368 (eff. Sept. 2025): Granted investigatory/enforcement authority

ERCOT, the Office of Attorney General (OAG), and the Public Utility Commission of Texas (PUCT) were granted various authority to investigate and/or enforce LSIPA compliance.

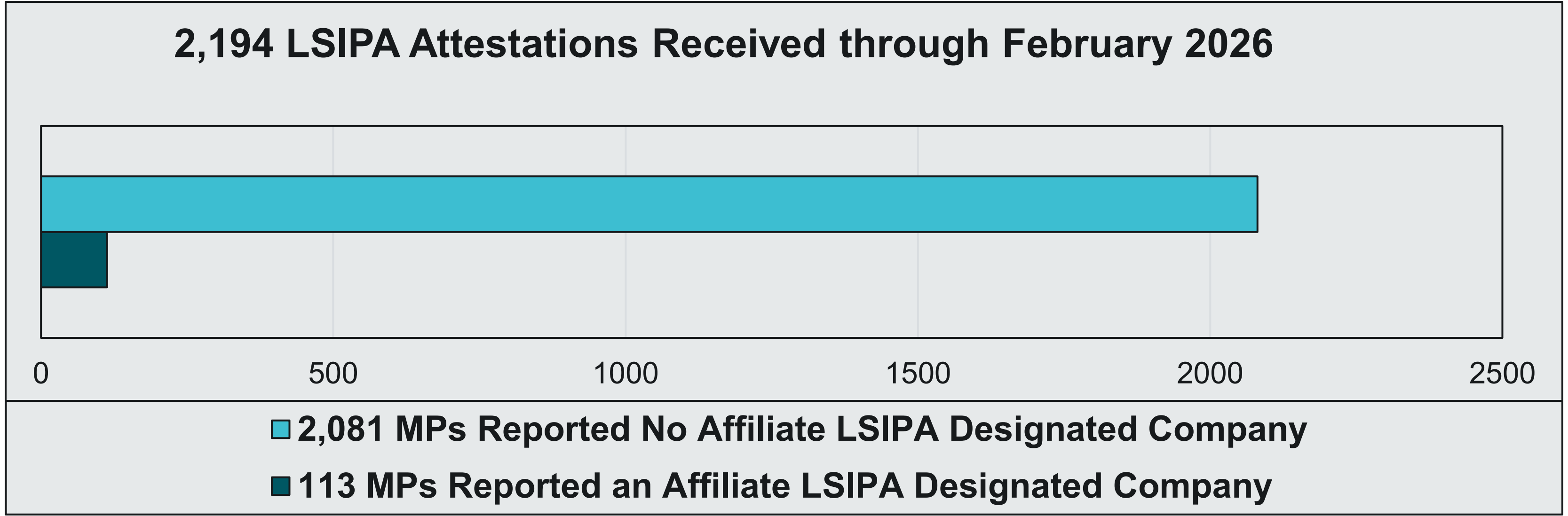
- **February 2026:** ERCOT implemented a more robust process for LSIPA compliance evaluations.
- **March 2026:** ERCOT is developing a more robust Request for Information process for CEGE/CEGS compliance evaluations.
- **March 2026:** ERCOT is developing and will initiate a Nodal Protocol Revision Request that will provide CEGE/CEGS guidelines for Market Participants.

ercot PUBLIC

Breakdown of LSIPA Attestation Data Received

The 1,527 existing Market Participants (MPs) (sans REC Account Holders) on June 1, 2023, were required to submit an Attestation by July 11, 2023	
Timely submissions	807
Late submissions	687
Nonresponsive MPs were terminated	33

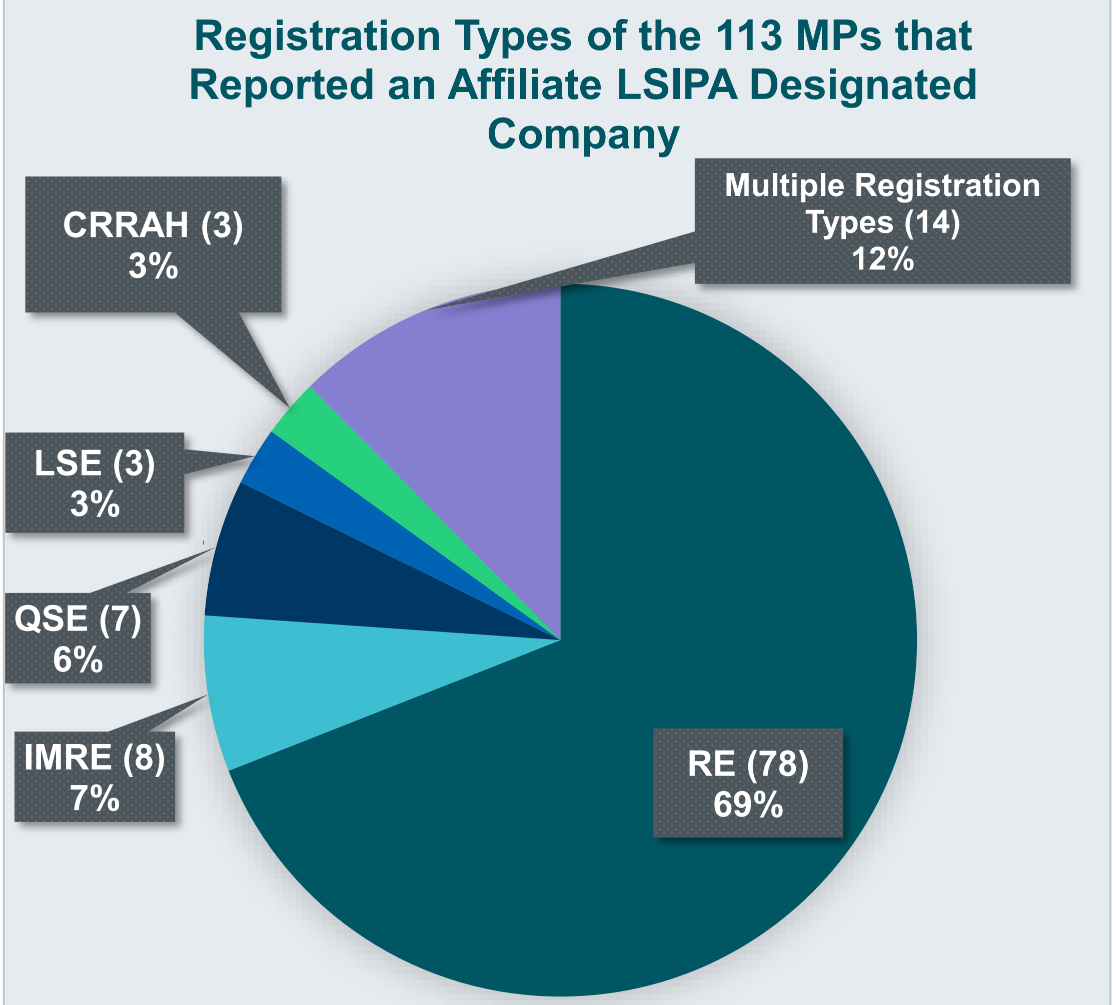
Terminated Nonresponsive MPs	
Resource Entity (RE)	21
Independent Market Information System Registered Entity (IMRE)	10
Qualified Scheduling Entity (QSE)	1
Congestion Revenue Right Account Holder (CRRAH)	1

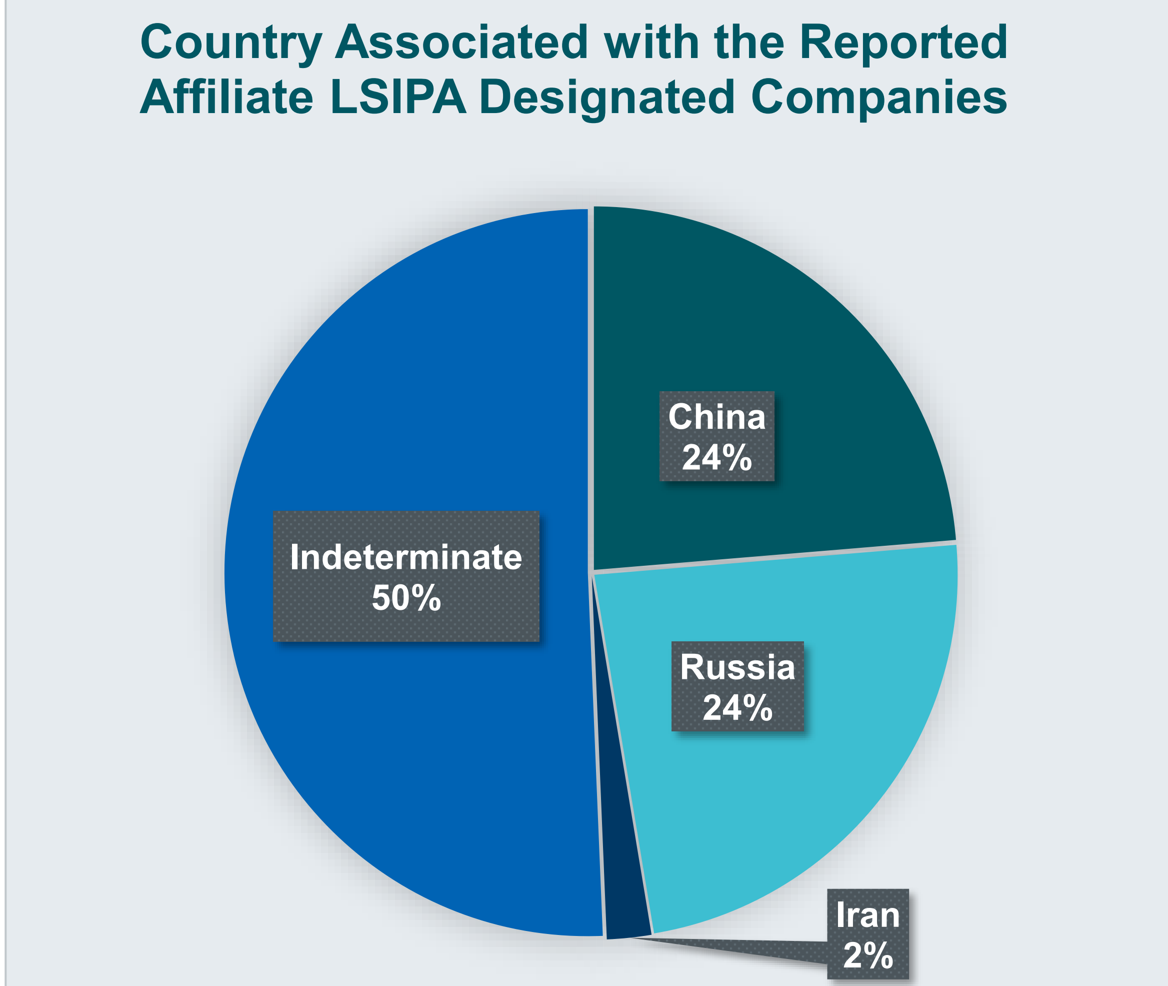


All but 1 of the 113 MPs that reported an Affiliate LSIPA Designated Company attested that their Affiliate WILL NOT have direct/remote access to or control of ERCOT's Wide Area Network, Market Information System, or any data from such ERCOT systems. ERCOT terminated the 1 MP that attested otherwise.

Breakdown of 113 Market Participants (MPs) that Reported an Affiliate LSIPA Designated Company through February 2026

PUBLIC





Key Takeaway: All existing Market Participants with a reported Affiliate LSIPA Designated Company attested their Affiliate **WILL NOT** have direct/remote access to or control of ERCOT's Wide Area Network, Market Information System, or any data from such ERCOT systems.

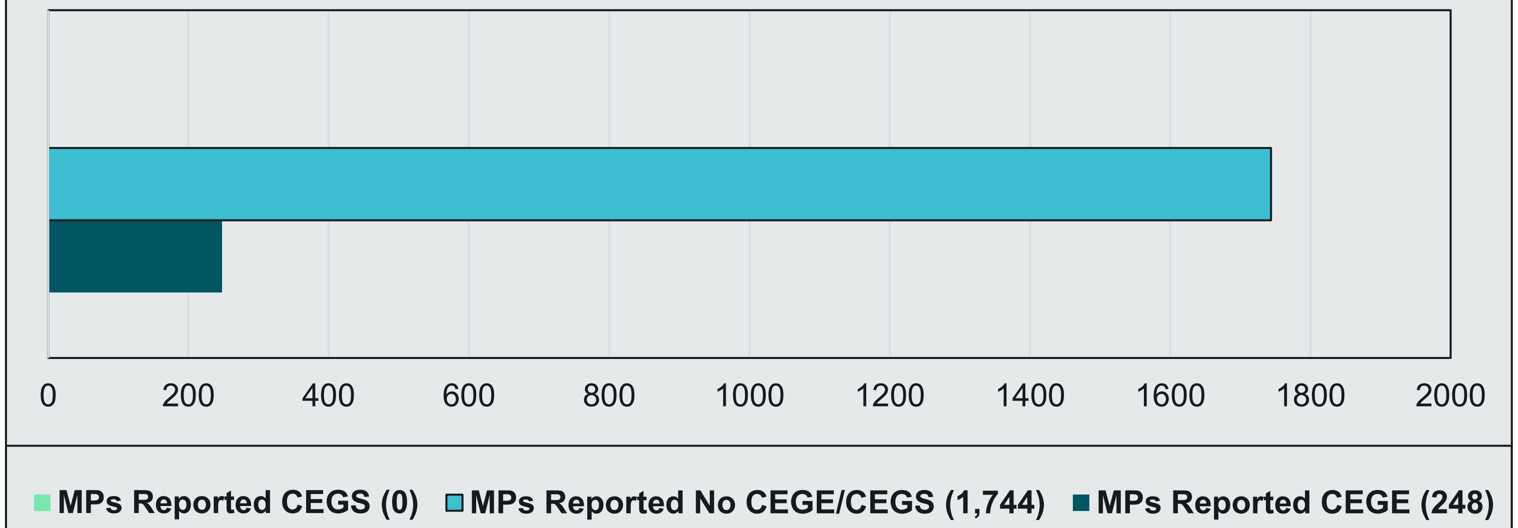
CEGE/CEGS Attestation Data Received

The 1,704 existing MPs (sans REC Account Holders) on May 1, 2024, were required to submit CEGE/CEGS Attestations by October 28, 2024	
Timely submissions	625
Late submissions	953
Nonresponsive	126

Status of 126 Nonresponsive MPs

- 44 IMREs were terminated
- 73 MPs either self-terminated or were terminated by ERCOT for another breach/default reason
- ERCOT/PUCT are coordinating on the remaining 9 nonresponsive MPs

1,992 CEGE/CEGS Attestations Received Through February 2026



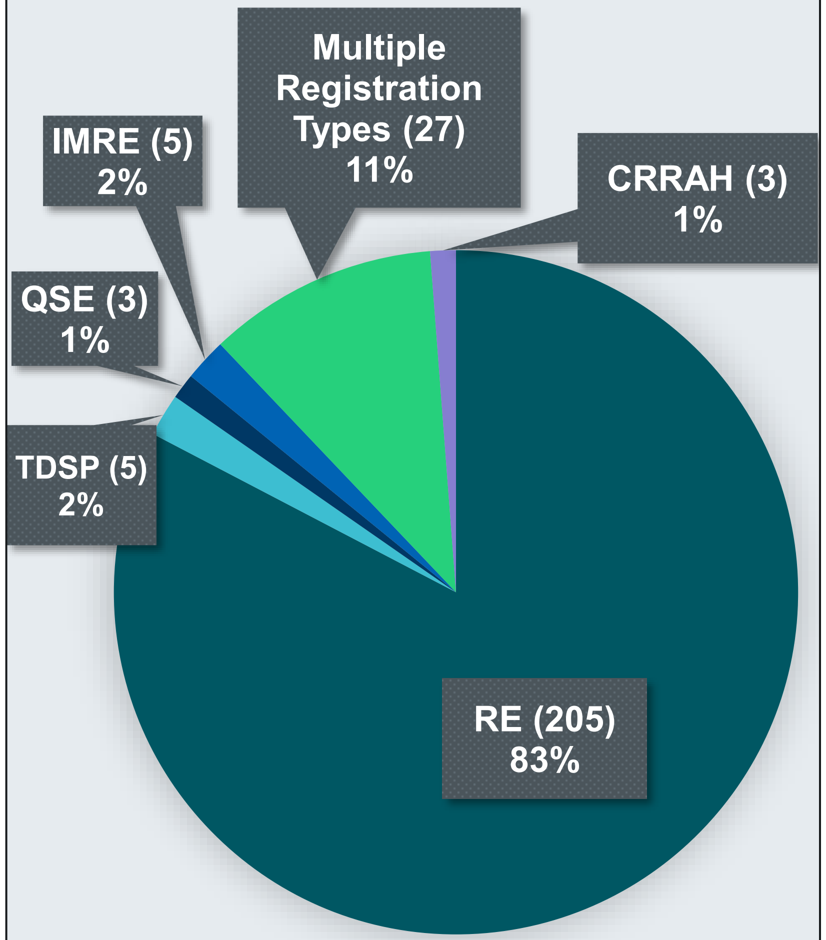
All 248 MPs that reported CEGE purchased from an LSIPA Designated Company **attested that the purchase WILL NOT result in the LSIPA Designated Company's unauthorized access/control of the CEGE.**

PURA § 39.360(d) explicitly allows for the LSIPA Designated Company seller to have authorized access/control of the CEGE for product warranty and support purposes.

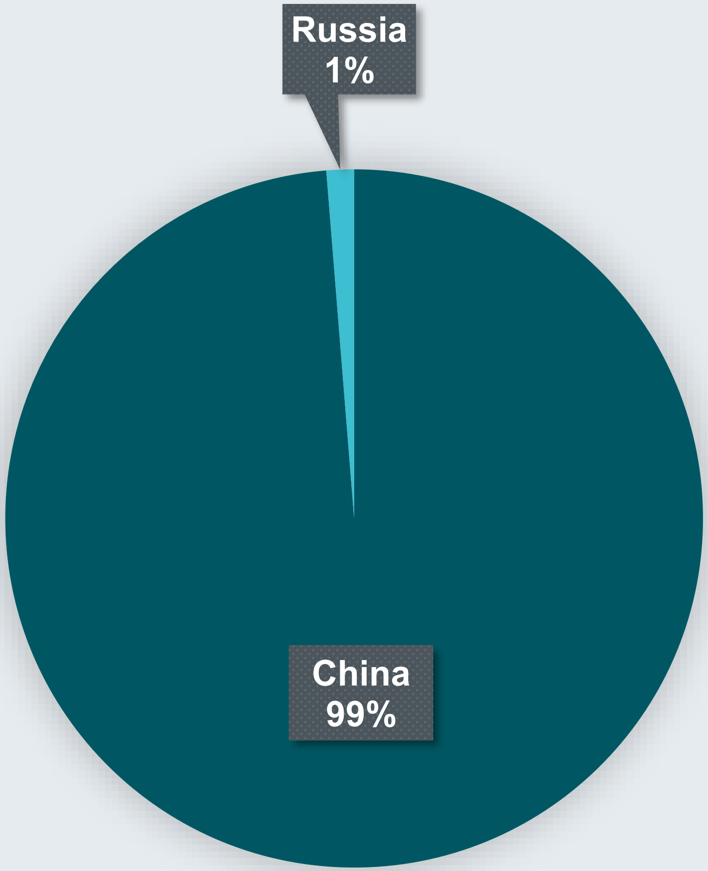
PUBLIC

Breakdown of 248 Market Participants (MPs) that Reported CEGE through February 2026

Registration Types of the 248 MPs that Reported CEGE



Country Associated with Reported CEGE



Most reported CEGE Type:

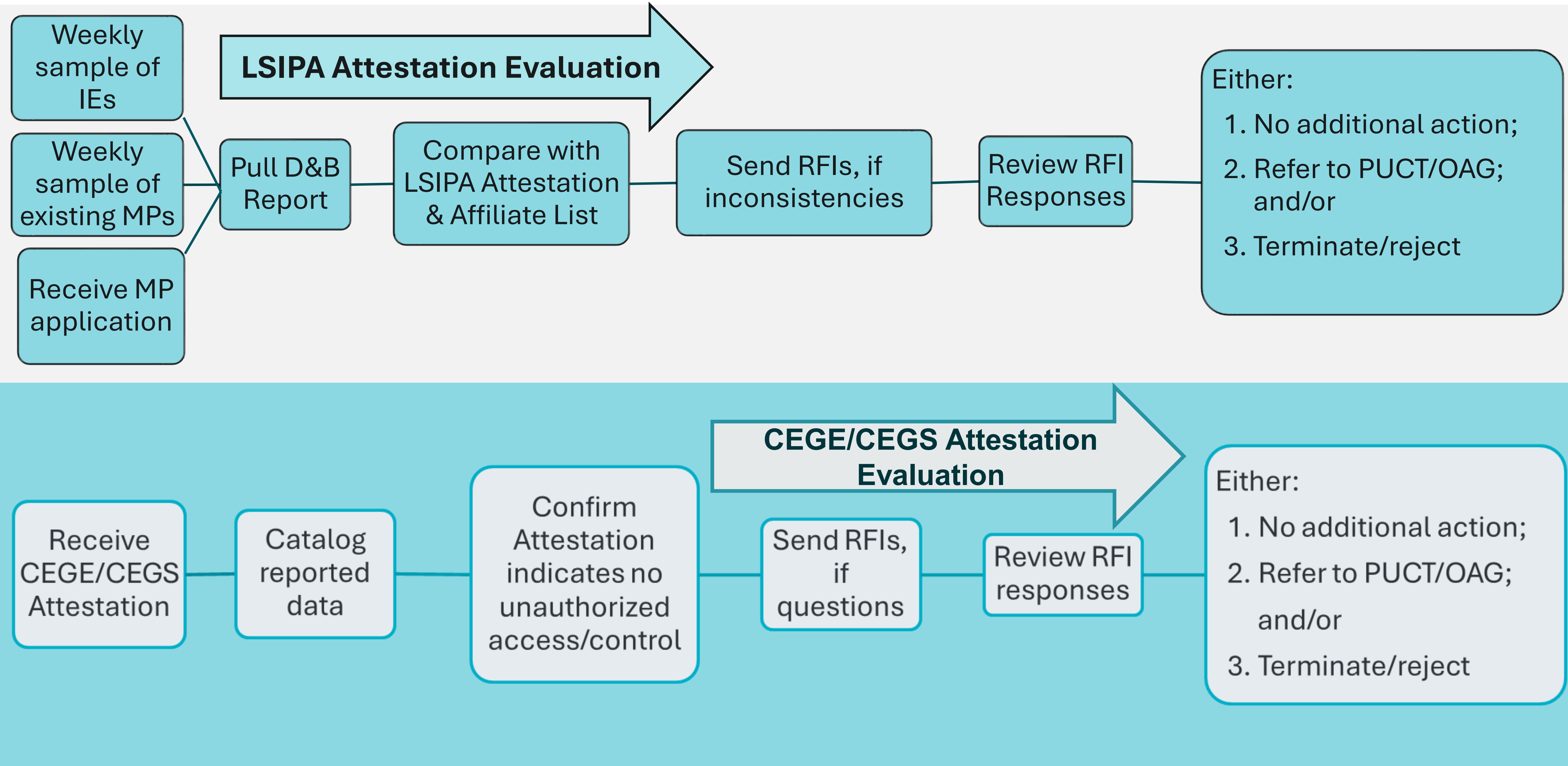
- Batteries/BESS equipment
- Inverters/inverter controllers
- Transformers
- Battery management systems
- Power conversion systems
- Computers
- Switches/circuit breakers
- Solar panels and components

Most reported mitigation measures to prevent unauthorized access/control:

- Firewalls
- Multi-factor authentication
- Identity and access management controls
- Remote access controls

PUBLIC

ERCOT's LSIPA & CEGE/CEGS Compliance Evaluation Processes



ercot

PUBLIC

Enhancements to ERCOT's Processes

- **Update ERCOT's compliance evaluations:**
  - Require Market Participants and Interconnecting Entities to identify the name and associated country for each reported Affiliate that is an LSIPA Designated Company.
  - Implement a more robust Request for Information process for CEGE/CEGS compliance evaluations.

- **Enhance Market Participants' understanding of Protocols regarding CEGE/CEGS:**
  - Develop clear categories of CEGE/CEGS, host a workshop to discuss the categories and any lessons learned, and initiate a Nodal Protocol Revision Request to include CEGE/CEGS guidelines in Protocols.
  - Revise CEGE/CEGS Attestation to require additional information (e.g., quantity of CEGE purchased, scope of authorized access, and description of mitigation measures that have been/will be implemented for such authorized access).

- **Collaborate with OAG regarding the LSIPA compliance investigation process under PURA § 39.360(j) (not yet codified, *see* SB 2368).**

- **ERCOT is currently evaluating whether third-party applications can provide ERCOT with more in-depth visibility and/or real-time updates regarding Market Participant and Interconnecting Entity ownership changes or ERCOT vendor supply chains.**

PUBLIC

Potential Legislative Considerations

- Consider prohibiting Market Participants from purchasing CEGE/CEGS from foreign threat companies identified on the Department of Defense's *Section 1260H List* and Texas' *Prohibited Technologies List.*

- Consider requiring security measures be implemented to mitigate risk for an LSIPA Designated Company's authorized access to CEGE/CEGS for product warranty or support purposes.

- Consider requiring Market Participants to attest that the purchase of **CEGS (grid services)** from an LSIPA Designated Company will not result in unauthorized access under PURA § 39.360(d). Statute addresses only Market Participants' attestation for unauthorized access of **CEGE (grid equipment).**

ercot

PUBLIC

Terminology Reference Table

Acronym	Term
CEGE	Critical Electric Grid Equipment
CEGS	Critical Electric Grid Services
CRRAH	Congestion Revenue Rate Account Holder
D&B	Dun & Bradstreet
IE	Interconnecting Entity
IMRE	Independent Market Infrastructure System Registered Entity
LSE	Load Serving Entity
LSIPA	Lone Star Infrastructure Protection Act
MP	Market Participant
PURA	Public Utility Regulatory Act, Tex. Util. Code §§ 11.001-66.016
QSE	Qualified Scheduling Entity
RE	Resource Entity
RFI	Request for Information
SB	Senate Bill
TDSP	Transmission/Distribution Service Provider

Definitions of the capitalized terms used throughout the slides are provided in ERCOT Protocols Section 2, Definitions.

Testimony of Dr. Emma M. Stewart

Chief Power Grid Scientist, Idaho National Laboratory

Before the Texas Senate Committee on Business & Commerce
Hearing on Securing Critical Infrastructure and Supply Chain Integrity
April 1, 2026

Chairman Schwertner, Members of the Committee,

Thank you for the opportunity to testify today on securing the supply chain of the Texas electric grid and the broader critical infrastructure upon which the state depends. The electric grid is undergoing rapid transformation. Growth in demand, particularly from artificial intelligence supporting data centers and industrial electrification, is driving unprecedented deployment of new infrastructure, and strain on existing resources. In parallel, capacity and growth of the grid is becoming increasingly dependent on a complex supply chain of digital infrastructure including inverter-based resources, battery energy storage systems (BESS), transformers, and interconnected systems.

These technologies that underpin reliability are globally sourced, digitally enabled, and embedded within evolving business ecosystems. As a result, supply chain is no longer simply a procurement issue it is an **organizational, operational, and strategic risk**. This risk is a challenge to manage within the 3000 US electric entities, with a mix of business models, capabilities, and resources.

Idaho National Laboratory sits at the intersection of energy security, cybersecurity, and national resilience through deployment of nuclear technology, and national security. Our mission in energy security is to enable asset owners and operators to understand and mitigate the most consequential risks to the systems that underpin our economy and national defense. Energy delivery is the foundation of economic prosperity, national security, and societal stability, and its reliability must be assured.

Today, the Texas grid is the epitome of this opportunity, experiencing rapid growth and structural transformation. Load growth driven by artificial intelligence, crypto miners, industrial electrification, and economic expansion is accelerating the deployment of inverter-based resources, including battery energy storage systems (BESS), which possess unique capabilities to manage modern load, but also have high dependence on Foreign Entity of Concern Supply Chains, in particular PRC based manufacture. This convergence introduces a new category of risk one that is not purely operational, but systemic, strategic, and adversarial. These risks are real, with the threat to our national infrastructure growing daily, but they are also manageable with the right combination of engineering, procurement, policy, and prioritization.

The United States faces a credible, urgent and evolving threat from People's Republic of China (PRC)-linked actors, who have demonstrated both the capability and intent to target U.S. critical infrastructure through cyber operations and supply chain pathways. As has been observed in campaigns such as Volt

Typhoon [1] and Salt Typhoon[2], these activities include pre-positioning within operational networks, persistence through legitimate access channels, and the potential to influence or disrupt critical functions over extended periods. These actions are not limited to traditional cyber intrusion; they extend to the supply chain for the control systems, communications infrastructure, and power electronics that underpin modern grid operations. The concern is not solely the presence of foreign-manufactured components, but the potential for those components, combined with complex business relationships and limited visibility, to enable long-term access, data collection, or operational influence. This risk must be addressed in a manner that is both technically grounded and operationally realistic, ensuring that the grid remains secure without constraining the growth and innovation required to meet Texas's increasing energy demands.

Organizational Risk and the Business Ecosystem

Evolving business relationships in infrastructure component lifecycles create dependencies that could be leveraged by foreign adversaries to inflict damage. Analysts across the Energy Sector need to consider these business relationships as a key risk element that informs supply chain risk management and cybersecurity.

Supply chain relationships are only one component of a broader business ecosystem that supports critical infrastructure. These relationships span research and development, early-stage investment, land acquisition, manufacturing, ownership, operations, and maintenance. While they are necessary for infrastructure to function, they can also introduce channels for persistence, access, and influence. This is not theoretical. As has been observed in cyber operations, legitimate access, such as that required to support warranty actions, and software updates can be leveraged in unintended ways [3]. The same principle applies in the organizational domain.

These business relationships evolve over time. Transactions such as mergers and acquisitions, divestments, and changes in ownership can introduce what are effectively "frankenstein networks," where systems, access controls, and operational practices are stitched together across entities with differing standards and incentives. At their most concerning, these relationships can function as "dual-use" mechanisms supporting economic growth in peacetime while enabling persistence and influence during periods of competition, and potentially disruption in times of conflict. Managing these relationships is also a momentous task, simply banning or restricting entities becomes a full time role, where technical controls may fall by the wayside.

From Equipment to System Behavior: The Role of Communications

Modern grid infrastructure is no longer composed of passive equipment. It is built upon power electronics, firmware, software, and communications systems that enable real-time control and

---

[1] Emma M. Stewart, *Testimony before the U.S. House Select Committee on the Chinese Communist Party*, "End the Typhoons: How to Deter Beijing's Cyber Actions and Enhance America's Lackluster Cyber Defenses," March 5, 2025

[2] DHS CISA, n.d. "Strengthening America's Resilience Against the PRC Cyber Threats". Department of Homeland Security, Cybersecurity and Infrastructure Security Agency, Jan 15 2025, https://www.cisa.gov/news-events/news/strengthening-americas-resilience-against-prc-cyber-threats

[3] ODNI NCSC, *Venture Capital and Supply Chain Vulnerabilities*, 2021, https://www.odni.gov/files/NCSC/documents/supplychain/Final%20VC.pdf

coordination. While the battery cell material, has garnered much focus for economic risk implications [4], the domestic manufacture of control components related to the operation of BESS and the associated technical and cyber risk has lagged [5].

Inverter-based resources rely on a wide range of communication interfaces, including industrial protocols such as Modbus and IEC 61850, as well as Ethernet, Wi-Fi, Bluetooth, Zigbee, and cellular connectivity [6]. These communications are essential often also for managing vulnerabilities and security patches. They enable monitoring, dispatch, safety functions such as rapid shutdown, and maintenance. However, they also create a control plane through which systems can be influenced if not secured. Recent assessments of inverter technologies, provided through federal efforts such as CyTRICS [7], and Cyber Informed Engineering [8] provide important context [9]. While concerns have been raised about undocumented wireless communications, analysis of multiple devices found limited definitive evidence of intentionally malicious functionality. Findings did include that the "knowledge" of what is in these devices is limited or complicated by ownership and operational models with utilities and operators deferring risk to 3rd party vendors. The processes of EPC's, and integrators, are not understood by asset owners, and transparency is needed to improve security and management of the communications system. Simply disconnecting communications can violate contracts, limit safety controls, and reduce the security [10].

Discrepancies exist between documented and observed communication capabilities. Undocumented or unnecessary communications expand the attack surface and complicate risk management. Lack of documentation, is a mixed responsibility. If documentation is not required in the contract to be representative of all these functions, it is unlikely to be provided. This leads to a fundamental principle that the risk and threat is not solely where equipment is manufactured it is whether its capabilities are understood, constrained, and controlled. Both foreign-sourced and domestic equipment can pose risks if misconfigured, poorly documented, or improperly managed.

---

[4] H. Krejsa, CMIST n.d. "SUN SHIELD: How Clean Tech and Americas Energy Expansion can Stop Chinese Cyber Threats", Carnegie Mellon Institute for Strategy and Technology, Jan 2025, https://www.cmu.edu/cmist/tech-and-policy/sun-shield/krejsa-jan2025.html

[5] USDOE. n.d. "Battery Energy Storage Systems" U.S. Department of Energy Office of Cybersecurity, Energy Security, and Emergency Response . Jan 2025 . https://www.energy.gov/ceser/articles/new-ceserreport-offers-supply-chain-mitigation-strategies-battery-storage-systems

[6] Culler, Megan Jordan, et al. "Securing Solar for the Grid (S2G) Cybersecurity for Solar Systems Workshop at RE+: Fall 2024 IAB Meeting." , Oct. 2024, https://www.osti.gov/biblio/2473249

[7] U.S. Department of Energy, Office of Cybersecurity, Energy Security, and Emergency Response (CESER). *"Cyber Testing for Resilient Industrial Control Systems (CyTRICS™)."* Idaho National Laboratory and DOE National Laboratories Program. https://www.energy.gov/ceser/cybersecurity-testing-resilient-industrial-control-systems

[8] INL. n.d. "Cyber-Informed Engineering." Idaho National Laboratory, Idaho Falls, ID. Accessed April 4, 2024. https://inl.gov/national-security/cie/

[9] Assessment of inverters

[10] Stewart, Emma Mary, et al. "Securing Digital Energy Infrastructure: Procurement, Contracting, and Supply Chain Risk Management Guidance." , Oct. 2024. https://doi.org/10.2172/2473239

III. Battery Energy Storage Systems in Texas: Scale, Ownership, and Exposure

In a study of TX utilizing the INL TOPGEAR tooling [11] [12], and Office of Electricity Technical Assistance for Digital Assurance [13], as of 2025, Texas had over 70 owners and operators of BESS, representing over 18 GW of installed capacity. This scale is growing rapidly and plays a critical role in supporting grid reliability, particularly during peak demand events.

However, this ecosystem is characterized by:

- Diverse ownership structures
- Evolving operator relationships
- Complex vendor and service agreements

In addition, it is common for developers and OEMs to retain operational or remote management roles after transferring ownership. These arrangements create persistent dependencies that extend beyond initial deployment. These dynamics reinforce a key point, that control over infrastructure is not defined solely at commissioning, it evolves over time, but that timeframe of evolution is fast enough that risk can compound as companies and infrastructure changes hands.

Manufacturing, Domestic Investment, and Strategic Dependence

Texas has made significant progress in attracting domestic manufacturing, including battery production and system integration. These investments are critical to economic growth and national capability. However, domestic manufacturing does not inherently eliminate supply chain risk. The DOE CESER Battery Energy Storage Supply Chain [14] analysis highlights that global supply chains for BESS remain highly concentrated, particularly in power electronics, control systems, and firmware. As noted previously, over 70% of manufacturing capacity for key components resides outside the United States, and over 90% of systems contain at least one critical foreign-sourced component. There are over 100 suppliers of inverters, and at a minimum 1700 models across solar and storage infrastructure. Even the limited number of systems assembled domestically often rely on imported hardware and software—the very elements that define system behavior and risk. Examples within Texas, including battery manufacturing facilities and partnerships between U.S. and foreign firms, illustrate this complexity. These arrangements can support economic development while simultaneously embedding long-term dependencies.

Solutions: Technical, Procurement, and Policy Pathways for Lifecycle of Grid Resources

A central finding across this work is that not all infrastructure carries equal risk. A military or life critical site dependent on their generator for backup or microgrid, has a different risk than a set of economically dispatched small generators. Therefore, risk management, and application of engineering solutions,

---

[11] https://inlsoftware.inl.gov/product/topgear

[12] Weaver, G., et al. (2024, October). *Organizational influence on supply chain for digital energy infrastructure: Business models, and policy landscape*. In *Proceedings of the 2024 IEEE 6th International Conference on Trust, Privacy and Security in Intelligent Systems and Applications (TPS-ISA)*

[13] DOE. n.d., "GRIP Technical Assistance for Securing Digital Energy", Department of Energy: Office of Electricity., Feb 2025 https://csdet.inl.gov/technical-assistance-and-training/

[14] https://csdet.inl.gov/tools/bess/

defined in Cyber Informed Engineering efforts [15], such as FEOC component replacement must be prioritized based on criticality. Existing tools, including interconnection studies and system impact analyses, already identify assets that are most important to grid stability. These insights should be used to guide where enhanced security controls are applied, inspection and validation efforts are focused and where replacement or mitigation strategies are prioritized.

This approach enables targeted, efficient action rather than broad, unfocused intervention. The challenges outlined here are not without solutions. In fact, a comprehensive portfolio of technical and policy actions already exists and can be implemented today.

1. Engineering Solutions: Secure by Design[16]

Cyber-Informed Engineering (CIE)[17] provides a framework for designing systems that remain safe and functional even under compromise. This includes:

- Reducing unnecessary communications pathways
- Enforcing clear control boundaries
- Designing systems to limit the impact of compromised components

This represents a shift from attempting to secure every component to ensuring system-level resilience.

2. Communications Control and Verification[18]

Based on inverter and BESS analysis, key actions include:

- Verifying "as-built" communication capabilities and disabling nonessential protocols
- Eliminating or tightly controlling remote access pathways
- Ensuring communications and data remain within trusted networks and jurisdictions
- Requiring full transparency from vendors regarding communication interfaces

These actions directly address one of the most significant and immediate risk vectors.

3. Procurement as a Security Lever[19]

It is critical for those procuring components to have a full understanding of the capabilities of the products received, and contracts which enable remediation and that understanding. Contract power should be reduced for FEOC companies to enable strategic resilience.

This includes requiring:

- Software and hardware bills of materials (SBOMs and HBOMs)

---

[15] Wright, VirginiaL, et al. "Cyber-informed Engineering Microgrid Analysis Tool." , Aug. 2024. https://doi.org/10.11578/dc.20240925.11
[16] https://www.cisa.gov/securebydesign
[17] https://inl.gov/national-security/cie/
[18] https://csdet.inl.gov/technical-assistance-and-training/
[19] Securing Digital Energy Infrastructure: Procurement, Contracting, and Supply Chain Risk Management Guidance Securing Digital Energy Infrastructure: Procurement, Contracting, and Supply Chain Risk Management Guidance

- Disclosure of all communication pathways
- Contractual rights for inspection and validation of hardware, firmware and communications
- Removal of clauses that restrict security evaluation

Embedding these requirements at the procurement stage deters threats from being introduced into the system, and if a malicious risk is present, it can be detected and remediated.

4. Testing and Validation

Programs such as USDOE CESER CyTRICS [20] enable independent evaluation of hardware and firmware to identify vulnerabilities and validate system behavior. These capabilities support a transition from assumed trust to verified trust and should be applied particularly to high-consequence assets.

5. Strategic Mitigation and Replacement

The BESSIE study outlines a pragmatic approach to mitigation:

- Replace or repatriate control components at high-consequence sites
- Apply network segmentation and monitoring at lower-risk locations
- Deploy threat hunting and detection capabilities across installed systems

This approach avoids the need for broad "rip and replace" strategies while still addressing the most critical risks.

6. Policy and Coordination

At the policy level, Texas can build on existing frameworks such as the Lone Star Infrastructure Protection Act and recent initiatives from the Texas Command Cyber Center.

Key actions include:

- Aligning economic incentives with security requirements
- Incorporating lifecycle and ownership considerations into oversight
- Enabling continuous assessment of the business ecosystem
- Leveraging national laboratory capabilities to support industry and smaller utilities

Importantly, coordination across federal, state, and private entities is essential to ensure consistent and effective deployment of these solutions.

A Balanced and Realistic Path Forward

It is important to emphasize that the presence of foreign-manufactured components does not, in itself, define risk. The reality is that both domestic and foreign-sourced systems require secure configuration, controlled communications, transparent supply chains, ongoing monitoring and validation. The focus must therefore be on control, visibility, and resilience, rather than origin alone. Prioritization of actions that can be taken for the existing fleet, and future – are necessary to ensure strategic advantage and

[20] https://cytrics.inl.gov/

deterrence.   At the same time, strategic investment in domestic manufacturing particularly for power electronics and control systems remains essential to long-term security.

Conclusion

The Texas electric grid is a cornerstone of economic growth, innovation, and national security. As it evolves, supply chain integrity will play an increasingly central role in determining not only how infrastructure is built, but how it performs under stress. The risks associated with battery energy storage systems, inverters, and global supply chains are real. But they are also addressable through a combination of:

- Consequence-driven prioritization
- Cyber-informed engineering
- Strong procurement practices
- Independent validation
- Coordinated policy and deployment

Texas can effectively manage these risks while continuing to lead in energy innovation and economic development. The question is no longer simply whether we can build the infrastructure needed to meet demand. The question is whether that infrastructure is understood, controlled, and resilient when it matters most.

Appendix

The following is a sample of the recommendations from the DOE CESER-sponsored report

https://www.energy.gov/ceser/articles/new-ceser-report-offers-supply-chain-mitigation-strategies-battery-storage-systems

Short Term Technical Recommendations for the current BESS install base include the following:

- Strategic replacement of control components in high-consequence locations
- Hunt and threat identification in selected installed units, utilizing both commercial OT Monitoring and Forensics and open source tooling
- Communications isolation and security, data triage, and network segmentation

For the in-design or near-term solutions, recommendations are as follows:

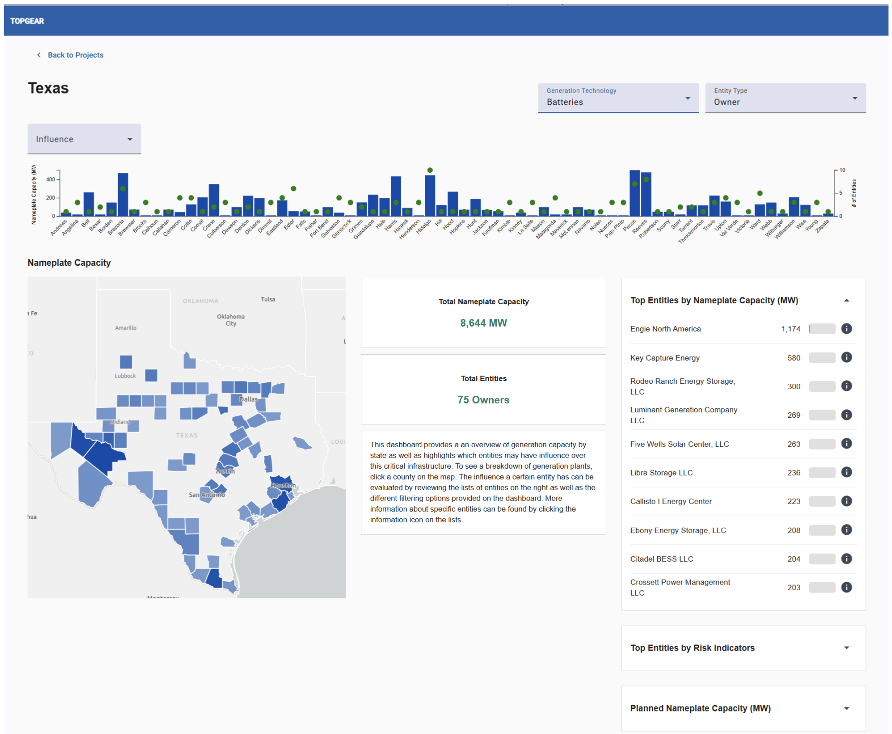
- Inspection of contract and procurement negotiation to allow inspection of systems and security controls.
- Removing harmful clauses which give Chinese companies control and protection from closer inspection
- Adoption of cyber-informed engineering (CIE) design and development
- Software replacement and repatriation of hardware, enabling secure-by-design software packages to replace insecure foreign developed types

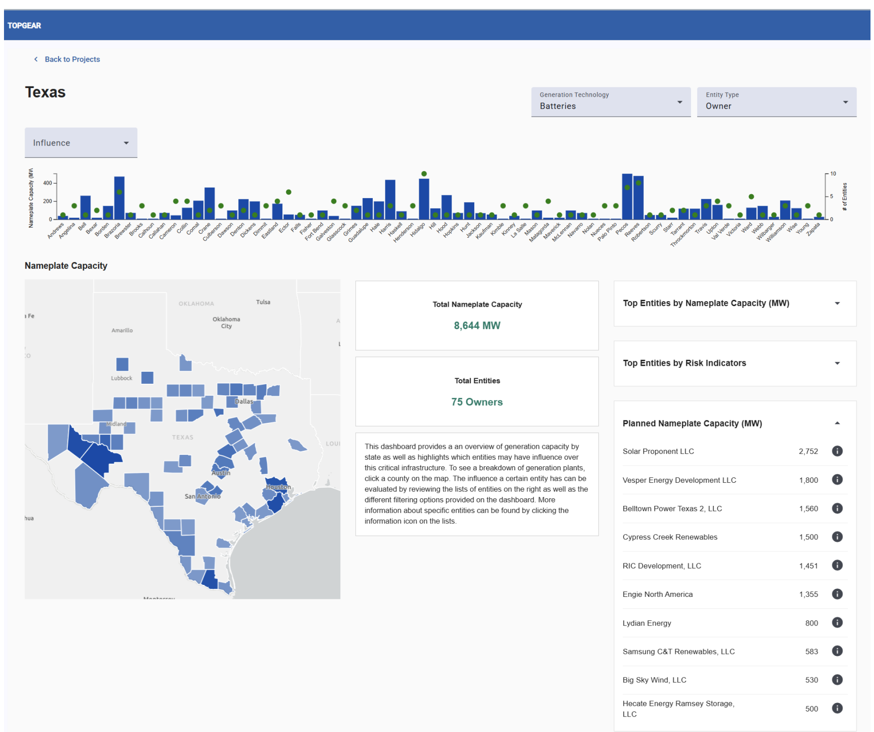
Long-term policy solution recommendations include:

- Equipment inspection and vulnerability analysis as best practice for all equipment irrespective of sourcing
- U.S. manufacture incentives for power electronics and control technology, developing secure designs and dominating the U.S. market with our own innovative designs
- Training and workforce development, enabling new defenders and engineers to build a more secure future.

An INL team, funded through both USDOE CESER and the Office of Electricity (OE), is already providing technical assistance activities to asset owners, hunting for adversary activity, guiding cyber-informed project design, and developing security controls, to remediate known issues in these supply chains. Working with U.S. integrators and businesses, they provide secure designs through CIE, hunt activities and threat reporting, and perform strategic site network monitoring. This program is ongoing and is extended to all digital controls such that asset owners and operators can rapidly, with continued resourcing, remediate and continue secure operation of these fleets. We cannot fix every problem, but in this case, we can remove the low hanging issues and make the nation's energy security more difficult to compromise or entities not as attractive of a target. This solution set has recently been extended to states and local entities to increase the protection provided to the U.S. grid

Excerpts and outcomes from Top GEAR Analysis in TX.





Opening Remarks

R. Britt Freund, PhD
Full Professor of Practice, Assistant Dean
McCombs School of Business
The University of Texas at Austin

Good morning. I am R. Britt Freund, a Professor and Assistant Dean in the McCombs School of Business at the University of Texas at Austin. I have been asked to speak to this committee on potential supply chain risks to the State of Texas, and it is my honor to do so.

I would like to give a very brief bio to address why I might be able to provide some practical insight into risk and supply chain challenges facing the state, especially to those of you who might hold some reservations about the 'usefulness' of a professor's testimony. However, I will delegate most of my 7 minutes to my research associates, Mr. Sumedh Gosavi and Ms. Rabita Saleh, who have done most of the work.

I will steal a term from my friend and colleague, Professor Eric Bickel, who runs the Operations Research group at The University of Texas at Austin. As he likes to say, we are not traditional 'academics' but, rather, 'pracademics' who like to solve real business problems. I am a Full Professor of 'Practice' which means that I focus on the 'practice' of supply chains and risk management. I spend probably 60% of my time working directly with firms on their challenges. I trust that my 'practicality' will come through in this hearing.

For only a short time, less than three months, my research team and I have been looking at the specific question of supply chain risks to critical infrastructure in the State of Texas. We have accomplished quite a lot in that time, but much work remains to be done. We started by asking questions of three important constituents in the electricity 'value chain' – electricity producers (LCRA), grid operators (ERCOT), and firms with commercial interest in electricity generation and usage (ExxonMobil). From this framing, we have focused on two critical elements of the electricity 'value chain' – high voltage transformers and inverters – that we feel are at risk. I will now ask my research associates to summarize their findings…

Mr. Sumedh Gosavi, will you please address the committee…

Thank you, Sumedh.

Ms. Rabita Saleh, will you please address the committee…

Thank you, Rabita.

I am more than willing to address any questions that you might have. I will call upon Sumedh and Rabita to join in the conversation, as appropriate…

APRIL 2026

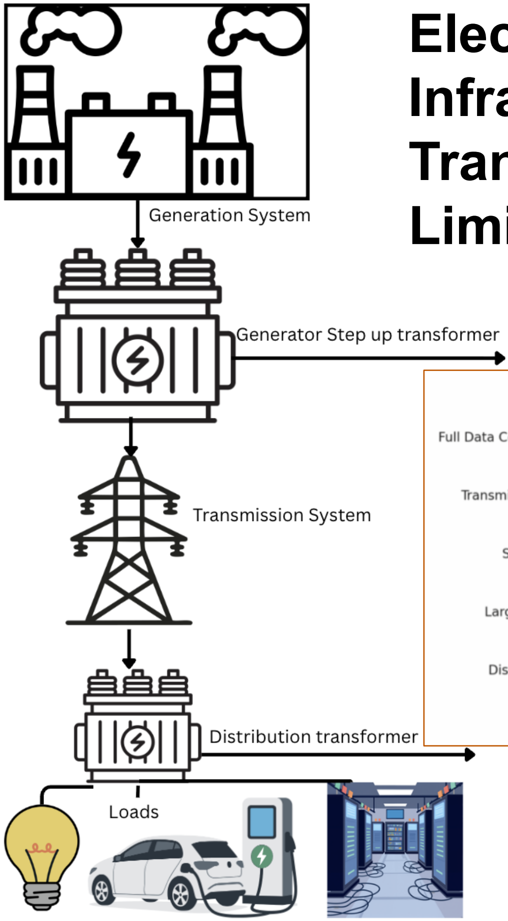
TEXAS
The University of Texas at Austin

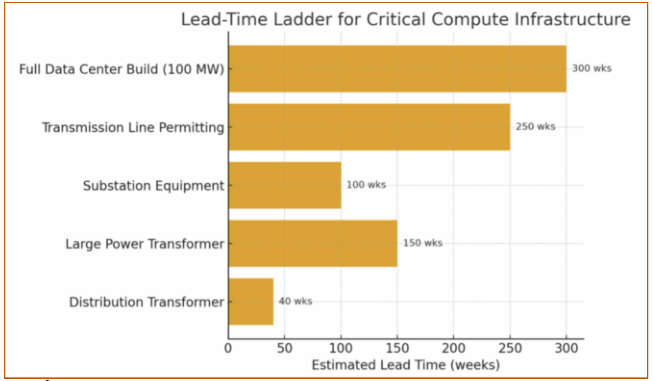
SUPPLY CHAIN RISKS TO TEXAS' ELECTRICAL INFRASTRUCTURE: A FOCUS ON POWER TRANSFORMERS

PRESENTED BY: SUMEDH SUNIL GOSAVI
Research Associate, McCombs School of Business, The University of Texas at Austin.

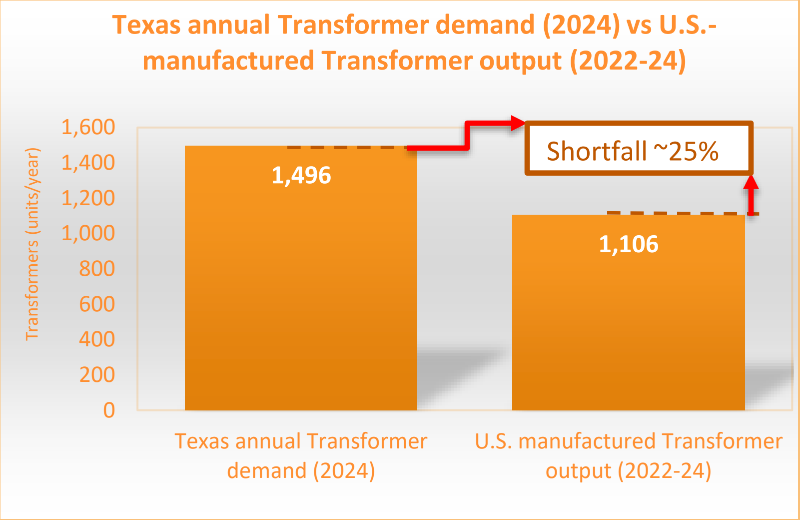
ADVISED BY: DR. R BRITT FREUND
Full Professor of Practice, Assistant Dean, McCombs School of Business, The University of Texas at Austin.

Electric Grid Infrastructure and Transformer Supply Limitations





Source: (guillermo, n.d.)



Source: (Gosavi, 2026)

- Transformers are the bridge between Generation (source) and Load (end-use) in electric grid.
- Transformers are critical T&D assets but have extremely long lead times (>100 weeks).
- Evidence of a supply–demand shortfall ≈ 25% (2024 Texas demand vs. 2022–24 U.S. manufactured output) → structural supply-chain issue, not a one-off delay.

Transformer Supply chain constraints

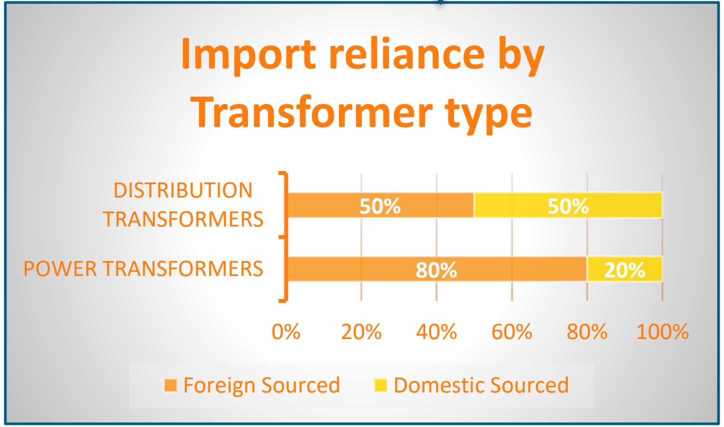
Concentrated U.S. capacity & thin supplier tiers
Few OEMs and first-tier suppliers; sparse Tier-2~Tier-4 ecosystems → single-point failures & long queues.

Geographic concentration outside Texas
Major LPT facilities cluster in the Midwest/East → long-haul logistics and greater exposure to regional shocks for Texas projects.

Long & inflexible lead times
Engineered-to-order; DOE commonly cites ~36 months for LPTs, with cases up to ~60 months → low scheduling flexibility.

Dependence on foreign materials & upstream inputs
Electrical steel (GOES), copper, large forgings, specialty components remain internationally concentrated, some in higher-risk jurisdictions.

Workforce and project delivery challenges
Shortages in winding, welding, testing, transport, installation, commissioning can delay energization even after equipment arrives.



Source: (Power Transformers and Distribution Transformers Will Face Supply Deficits of 30% and 10% in 2025, According to Wood Mackenzie, 2025)

Key Implications

Limited near-term import substitution

Texas's speed advantage at risk
Transformer scarcity introduces delays that money/contracts can't compress—a structural drag on data centers, storage, EV charging, and industrial growth.

Power provisioning ≠ generation alone
Equipment availability sets the schedule. LPT lead times >36 months; new factory capacity takes ~1–5 years to build, equip, and ramp.

Overuse of aging transformers
Delayed LPT supply drives "run-to-fail": aging transformers stay online past design life, degrade faster, and inflate failure and replacement costs.

Conclusion: Resilience of Transformer Supply = Resilience of Texas Growth

- This study finds that transformer availability is becoming a decisive factor in Texas' economic competitiveness, not just its utility operations.
- Transformers have, become a bottleneck for any application that runs on electric power.
- Constraints span the full chain. Current analysis points to a shortfall in supply of LPTs, a tight upstream supply chain, limited U.S. manufacturing, limited Tier 2,3,4 supplier base and workforce challenges.
- Without sufficient access to new LPTs for both maintenance and growth projections, Texas will not be able to meet its electricity requirements.

References

- *Power transformers and distribution transformers will face supply deficits of 30% and 10% in 2025, according to Wood Mackenzie*. (2025, August 14). News Release. https://www.woodmac.com/press-releases/power-transformers-and-distribution-transformers-will-face-supply-deficits-of-30-and-10-in-2025/
- Gosavi, S. S. (2026, March 26). *Power Transformers capacity Hypothesis Test.xlsx*. https://utexas-my.sharepoint.com/:x:/r/personal/sg57572_eid_utexas_edu/_layouts/15/Doc.aspx?sourcedoc=%7B192E8066-D0F3-497A-9195-84761AFD8717%7D&file=Power%20Transformers%20capacity%20Hypothesis%20Test.xlsx&action=default&mobileredirect=true&DefaultItemOpen=1
- guillermo. (n.d.). *Data Centers at Risk: The Fragile Core of American Power - Foreign Policy Research Institute*. Retrieved March 28, 2026, from https://www.fpri.org/article/2025/11/data-centers-at-risk-the-fragile-core-of-american-power/
- *Large Power Transformer Resilience*. (n.d.). Retrieved March 25, 2026, from https://www.energy.gov/sites/default/files/2024-10/EXEC-2022-001242%20-%20Large%20Power%20Transformer%20Resilience%20Report%207-10-24.pdf
- Patel, S. C. (2026, January 2). Transformers in 2026: Shortage, Scramble, or Self-Inflicted Crisis? *POWER Magazine*. https://www.powermag.com/transformers-in-2026-shortage-scramble-or-self-inflicted-crisis/

Appendix-Approach: Bottom-up demand estimation + OEM capacity modeling using publicly available data.

Demand estimation

1. Conversion to Required MVA
Start with **Net Electricity Generation (MWh)** and apply Power Factors (0.95, 0.97, 0.99) to derive **Required MVA.**

2. Effective Unit Rating
Calculate **"Rated MVA"** by applying a 10% N-1 Contingency Margin to representative transformer ratings (765kV, 345kV, 138kV).

3. Unitization
Calculate using the following relationship: **Total Units Needed = Required MVA / Rated MVA per Transformer.**

Structural Gap Analysis
Cross-referencing the "Resulting Units Needed" against the "Estimated OEM Output" to confirm the capacity deficit.

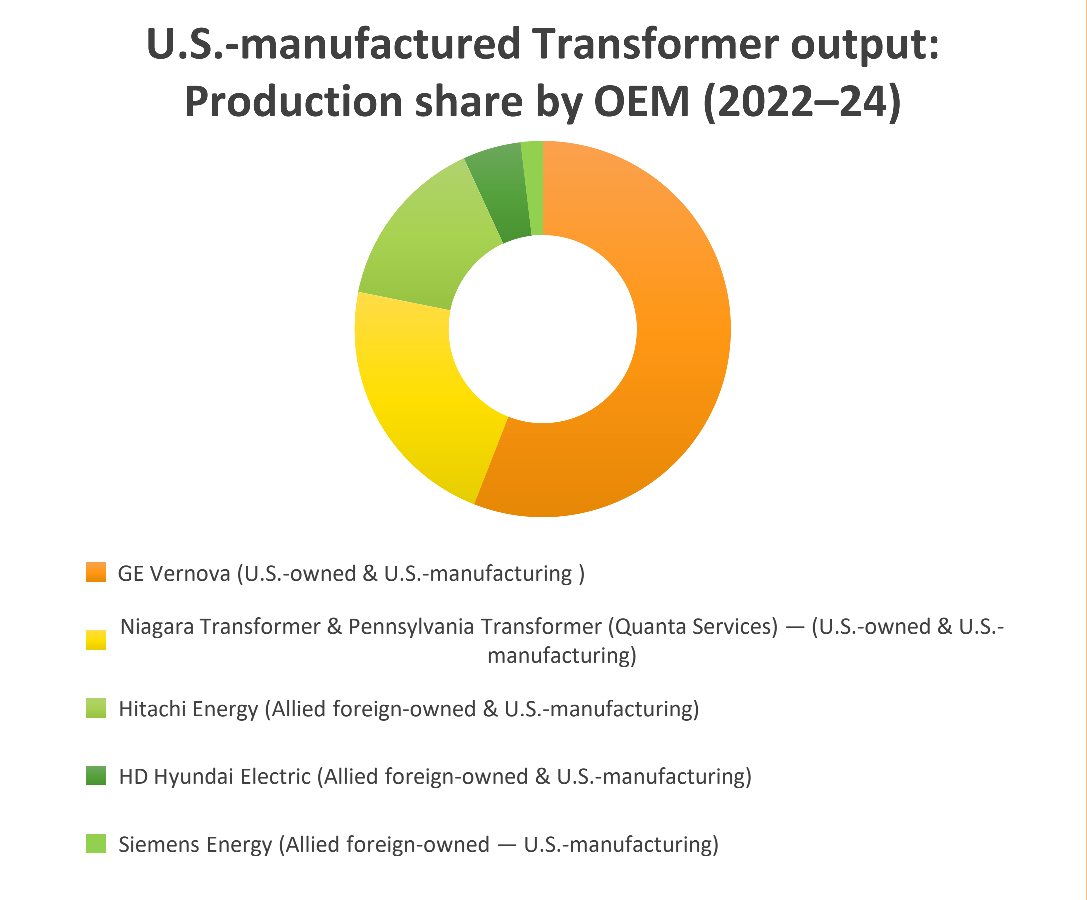
1. Revenue Sourcing
Derive U.S. transformer output using total OEM revenue from 10-K filings and consolidated annual statements.

2. Market Segment Allocation
Isolate Power Transformer share (65%) vs. Distribution (35%) and apply Texas-specific revenue allocation.

3. Estimated Unit Output
Divide the allocated Power Transformer revenue by Average Selling Price (ASP) mid-points for each major OEM.

OEM capacity modeling

Appendix-Large Power Transformer OEMs



TEXAS
The University of Texas at Austin

Supply Chain Risks to Texas' Electrical Infrastructure: A Focus on Power Transformers

Report by: Sumedh Sunil Gosavi,
Research Associate, McCombs School of Business, The University of Texas at Austin.

Advised by: Dr. R Britt Freund,
Full Professor of Practice, Assistant Dean,
McCombs School of Business, The University of Texas at Austin.

Executive Summary

An electric grid is of utmost importance for the welfare of Texans and the economic growth of Texas. Disruptions in the electric grid can have serious consequences for the lives, livelihoods, and economy of the citizens. Therefore, it is important to have resilient supply chains built around critical components that can provide a layer of redundancy to better withstand shocks to the system. Transformers, especially Large Power Transformers (LPTs), are one such component. Without sufficient access to new LPTs for both maintenance and growth projections, Texas will not be able to meet its electricity requirements. The goal of this paper is to first, analyze LPT supply chains by answering the question of whether there is enough domestic LPT supply to satisfy the surging demand due to increased AI and Cloud compute data center applications, rapid growth in electric vehicle (EV) adoption, increased deployment of renewable energy resources, ongoing grid modernization initiatives, and growth in electrification across industrial, commercial, and residential sectors. Secondly, to highlight risks in LPT supply chains. Our initial studies indicate that these supply chains could become bottlenecks for the projected power generation growth in Texas through 2030, especially considering the possibility of relying on 'potentially hostile' foreign governments. There is not enough capacity currently to meet this increased electricity demand. Further analysis revealed risks such as limited domestic manufacturing capacity, long/complicated manufacturing processes, and hence long lead times, dependence on foreign-sourced raw materials, and a lack of an experienced workforce. Given the critical role a transformer plays in enabling the user to harness electric power, the implications of any delay in transformer supply chains are serious, which could cause project delays and incur heavy losses. Transformers have therefore, become a bottleneck for any application that runs on electric power.

In this paper, I begin by establishing context for this project in the introduction. Then, in the Texas electricity demand outlook section, I estimate the number of LPTs required by Texas to meet the state's demand by analyzing data from open-source and authoritative sources. Similarly, in the following section, I provide the supply outlook by examining five leading power transformer OEMs with manufacturing operations in the United States: Hitachi Energy, Siemens Energy, GE Vernova, Quanta Services, and HD Hyundai Electric, and estimating their annual production. Based on supply-demand analysis, I highlight risks and constraints in the LPT supply chain and cover the implications of these risks in the subsequent section.

It is not enough to study the well-known Tier 1 suppliers such as Hitachi, Siemens, and others that we have focused on to date. Furthermore, simply standing up new Tier 1 suppliers will not necessarily solve the supply chain problem. Ultimately, a robust supply chain requires line of sight throughout the critical materials procurement including Tier 2, Tier 3, Tier 4 etc. supplier network analysis and mapping, and this is where we face even more constraints. Future studies will dive deeper into the supply chain to identify these challenges.

Acknowledgement

I am deeply grateful to everyone who supported this work and placed their confidence in me. I especially would like to thank my family and friends for their encouragement, Dr. R Britt Freund-my professor and mentor for his guidance and unwavering support, Clements Center for National Security for helping to make this research possible by funding my position, and Shelby Vestal-Senate Business Committee for the opportunity and assistance that helped bring this project to fruition.

Use of AI: Microsoft Copilot (enterprise version approved by The University of Texas at Austin) was used to assist in editing, organizing, and refining the structure of this manuscript. This tool was used solely to enhance the clarity and flow of the author's original writing. The author reviewed and edited all output and remain fully responsible for the accuracy and integrity of the final content.

Introduction

The State of Texas has placed increased focus upon supply chain risks to critical infrastructure, as exemplified by SB 2312 also known as the "Texas Geopolitical Conflict Stress Test Act". Our research team has been looking into supply chain risks and vulnerabilities to the State arising from dependencies on, potentially hostile, foreign governments.

The Governor directed Senate committee on Business and Commerce to set up closed-door hearings to evaluate the integrity of the supply chain for the Texas electric grid and other critical infrastructure, identify any vulnerabilities or potential risks posed by hostile foreign entities of concern including, but not limited to, China, Russia, and Iran and make recommendations for improvements and an ongoing evaluation process to remain vigilant in maintaining a reliable and secure Texas electric grid. Senator Charles Schwertner, Chair of the Senate Committee on Business and Commerce, is leading this study and hearing.

Electricity has become a commodity of strategic importance in Texas because according to the US Energy Information Agency (EIA), the state already operates the largest electricity system, by total energy consumption in the country, more than twice the output of the next-largest state, Florida while remaining largely dependent on its own grid resources to meet in-state demand [43]. That demand base is now expanding rapidly. The state-level analyses drawing on ERCOT planning materials indicate that peak demand could exceed 150 GW by 2030 [1]. A significant share of this incremental load is being driven by large commercial computing facilities, including AI and cloud data centers as well as cryptocurrency mining operations, which the EIA identifies as an increasingly important source of power demand in Texas [10]. At the same time, broader electrification trends are intensifying pressure on the grid [9]. Texas ranks third nationally in electric vehicle ownership and had approximately 3,700 public EV charging locations as of July 2025, adding further demand across transmission, substation, and distribution infrastructure [46]. In this context, electricity is not merely a utility input but a foundational enabler of Texas' 2030 growth trajectory [1] [9]. Reliability of Texas' electric system increasingly depends not only on generation capacity, but also on the availability of the equipment required to move power across the grid, i.e. transmission and distribution systems [1] [24] [49]. Transformers are a crucial component of this system. They link generation sources with the demand centers in an electric grid, allowing power to reach to the end user either in 120/240V level for a residential user or 120/208V and 277/480V, 3-phase for a commercial user or some other required voltage level all the way from kV, MV generation levels. Their importance is independent of the source of generation i.e. whether electricity is produced from natural gas, wind, solar, nuclear, or storage, transformer capacity is required at each stage of transmission and delivery.

Recent industry evidence suggests that transformer manufacturing has become a binding constraint across the United States [3] [41] [49]. Lead times for Large Power Transformers (LPTs) have remained above 100 weeks, with estimates reaching as high as 144 weeks in 2025, potentially impacting project timelines [6] [7] [32]. Moreover, constraints in raw material supply chains, policy and geopolitical dependencies further accentuates this supply chain vulnerability [24] [35] [49].

Given the legislative mandate under SB2312, Senate Business committee's charge regarding supply chain risks in electric grid and recent analysis on manufacturing of Transformers, it is prudent to evaluate if the domestic manufacturing capacity available to Texas is sufficient to meet current and emerging power demand.

Texas electricity demand outlook

Texas already represents the largest electricity market in the United States by both net generation and retail electricity sales. In 2024, the state generated approximately 566.5 million MWh of electricity and recorded 505.4 million MWh in retail sales, both ranking first nationally [39].

Demand growth has accelerated since 2021. The U.S. EIA reported that, in the first nine months of 2025, electricity demand within ERCOT reached a record high, increasing 5% over the same period in 2024 and rising 23% above the same months in 2021 [44]. More broadly, the EIA's July 2025 Short-Term Energy Outlook projected that electricity demand in ERCOT would grow at an average rate of 11% in 2025 and 2026, making Texas one of the fastest-growing electricity-demand regions in the country [42]. By 2030, the scale of projected growth becomes even more significant, reaching approximately 152 GW by 2030, following a substantial upward revision in forecasted load [1] [51].

In an August 2025 analysis, consulting firm Wood Mackenzie warned that the U.S. transformer market remains structurally out of balance, and that demand continues to outpace any realistic near-term increase in manufacturing capacity [6] [35]. The firm noted that power-transformer demand has risen 116% since 2019, and distribution-transformer demand is up 41%, driven by faster-than-expected load growth such as the emergence of AI/Cloud Data Centers and Cryptocurrency mining applications which are highly energy intensive, increase in Electric Vehicle adoption and the need for charging infrastructure, an expanding clean-energy pipeline, increasing the demand for step-up transformers as well as grid interconnection equipment, and a wave of end-of-life replacements [8] [27] [35] [40]. DOE and NREL estimate that the United States has approximately 60–80 million distribution transformers in service and that roughly 55% of those units are more than 33 years old and approaching end of life [8].

The state of Texas is no exception to this transformers trend. Bloomberg NEP reports multiple Texan utilities like Oncor Electric, ETT Texas, CenterPoint Energy and AEP Texas spent over

$8.8 billion annually in capital expenditure on average over 2022-23, ramping up spending in building infrastructure assets. AEP Texas is upgrading 16% of current transmission circuit miles. Oncor announced a $24.2 billion five-year capex plan and leads on planned transformer installations [29].

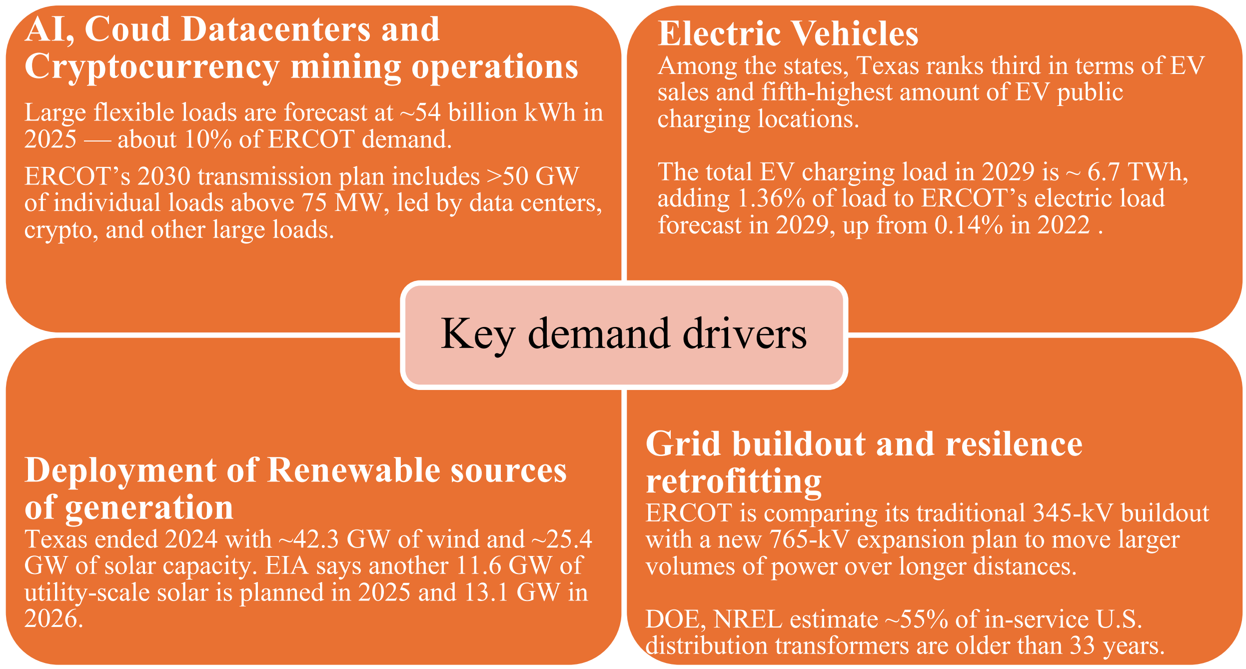


Exhibit-A: Key demand drivers

This demand outlook indicates that investments and upgrades are necessary across the entire generation, transmission, and distribution systems to meet rising electricity demand and ensure reliable service, regardless of the generation source. Transformers, especially LPTs, are crucial components of a transmission and distribution system and thus, require special attention not only because of their critical function and but also due to reports of longer lead times compared to other components, limited manufacturing capacity, and labor and material shortages.

Using data from open and authoritative sources such as U.S. Energy Information Administration's (EIA) "Sales of electricity to end use consumers in the residential, commercial, industrial, and transportation sectors-2024", the Electric Reliability Council of Texas (ERCOT), the Public Utility Commission of Texas (PUCT), and other relevant industry reports, current power demand (MWh) to power such large loads was estimated and subsequently required Transformer MVA ratings was obtained in the range of 388K-405K MVA. To obtain an estimate of number of transformers needed of a particular class, Transformer Sizing relationship was used wherein obtained required MVA ratings were divided by Transformer nameplate ratings. Aggregating numbers of transformers across various classes in LPT category, number of LPTs required was calculated to be in the range of 1450-1550. (Refer Appendix-A for detailed demand estimation methodology) [15].

Transformer supply outlook

Transformer supply conditions can be viewed through two distinct lenses. Given the strength of demand, the transformer market is, from an OEM business standpoint, highly favorable. From a consumer's standpoint, however, available supply is limited, production to specification is time-intensive, and whatever capacity is available comes at a premium. According to Wood Mackenzie's report on Transformer supply chain challenges, since 2019, unit costs have risen by 45% for generation step-up transformers, 77% for power transformers and 78–95% for distribution transformers depending on specification, though higher-voltage units have seen larger US dollar-based cost escalations due to heftier baseline costs [40].

The near-term U.S. supply outlook is further complicated by conditions in the broader transformer fleet. LPT production depends on constrained inputs such as grain-oriented electrical steel (GOES), copper, skilled labor, and specialized transportation [40]. China happens to be a leader when it comes to steel production and among the top producers of copper in the world [25] [34] [50] [53]. Given the supply chain challenges, utilities therefore, are increasingly turning to the import market to meet project timelines. Today, imports account for an estimated 80% of US power transformer supply and 50% of distribution transformer supply [35] [40].

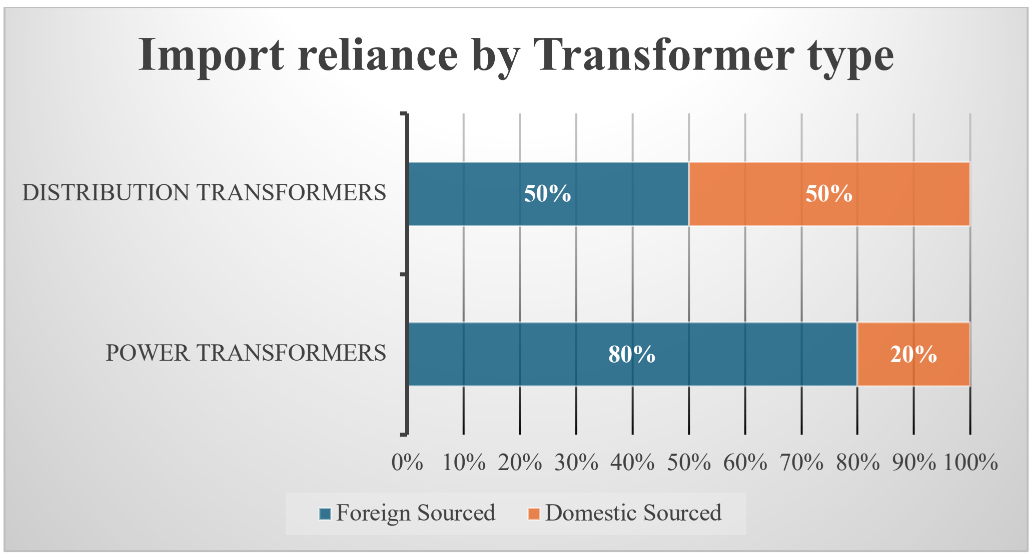


Exhibit-B: Import reliance by Transformer type

As far as domestic manufacturing goes, since 2023, manufacturers have committed nearly $2 billion to new or expanded transformer capacity in the US, spanning everything from pole-mount units to 765-kV transmission-class equipment. Hitachi Energy leads the surge with more than $1 billion in continental investments, including a $457 million facility in South Boston, Virginia, which is set to become the nation's largest large power transformer plant by 2028 and a $106 million expansion in Alamo, Tennessee, focused on critical components [20]. Siemens Energy is building its first U.S. large power transformer plant in Charlotte, North Carolina, a $150 million project expected to begin production in early 2027 [26] [37]. Mid-sized and specialized manufacturers are scaling aggressively as well. Prolec GE (now part of GE Vernova) is investing more than $300 million across new and expanded sites, including a medium-power facility in Goldsboro, North Carolina [14]. MGM Transformer Co. announced a 430,000-square-foot facility in Waco, Texas, focusing on custom liquid-filled transformer production to meet soaring demand from data centers, renewable energy, EV charging infrastructure, and utilities [30]. HD Hyundai Electric is enlarging its Alabama footprint, aiming to increase U.S. production by 30% by 2026 [21].

For the purposes of estimating domestic transformer supply, this study examined five leading power transformer OEMs with manufacturing operations in the United States: Hitachi Energy, Siemens Energy, GE Vernova, Quanta Services, and HD Hyundai Electric. Annual production estimates for these firms were developed from publicly available information, including annual reports, consolidated financial statements, SEC filings, company guidance, industry projections, and market research reports in the period from 2022 to 2024. It was estimated that the combined US LPT production capacity of these OEMs is in the range of 950-1250 annually (Refer Appendix-B for detailed production estimation methodology) [15].

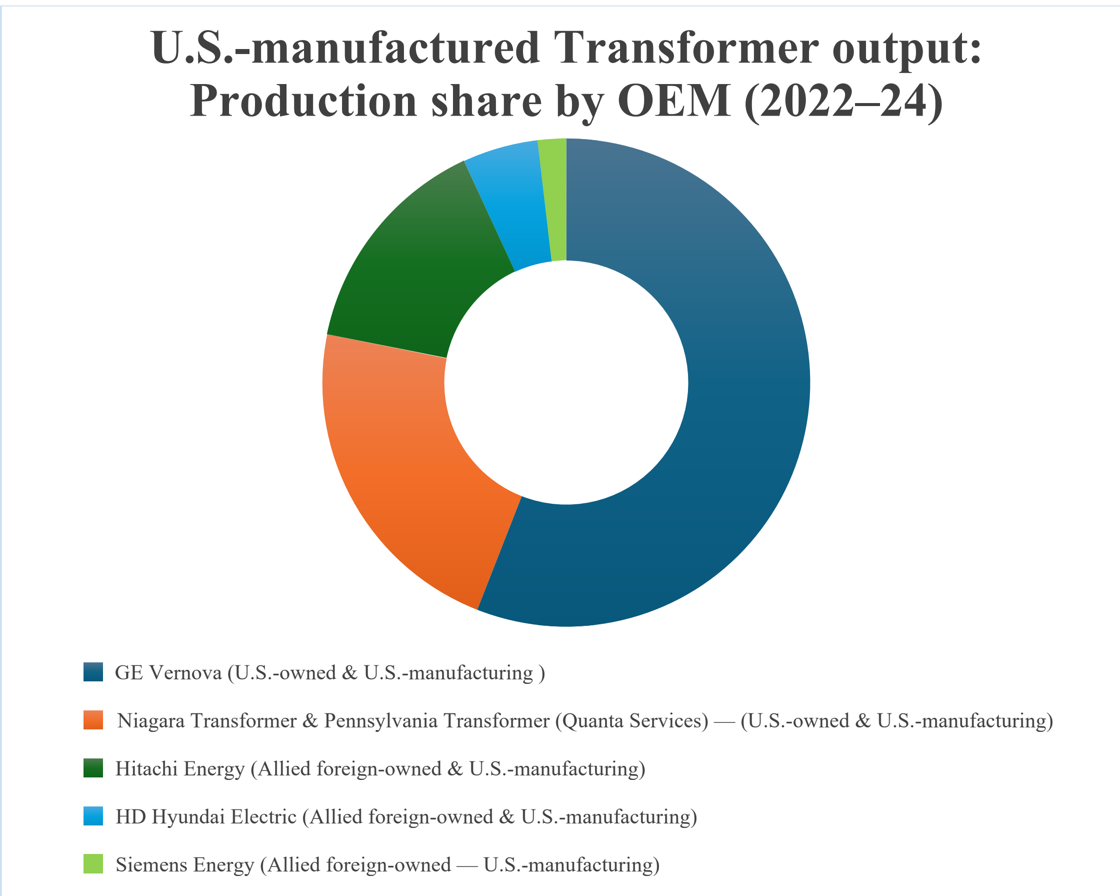


Exhibit-C: U.S.-manufactured Transformer output: Production share by OEM (2022–24)

Supply Chain Risks and Constraints

A comparison of the demand and supply estimates developed in this study indicates a clear supply–demand mismatch in the transformer market. Under the base-case assumptions used for both demand and supply, the analysis suggests an estimated shortfall of approximately 25%.

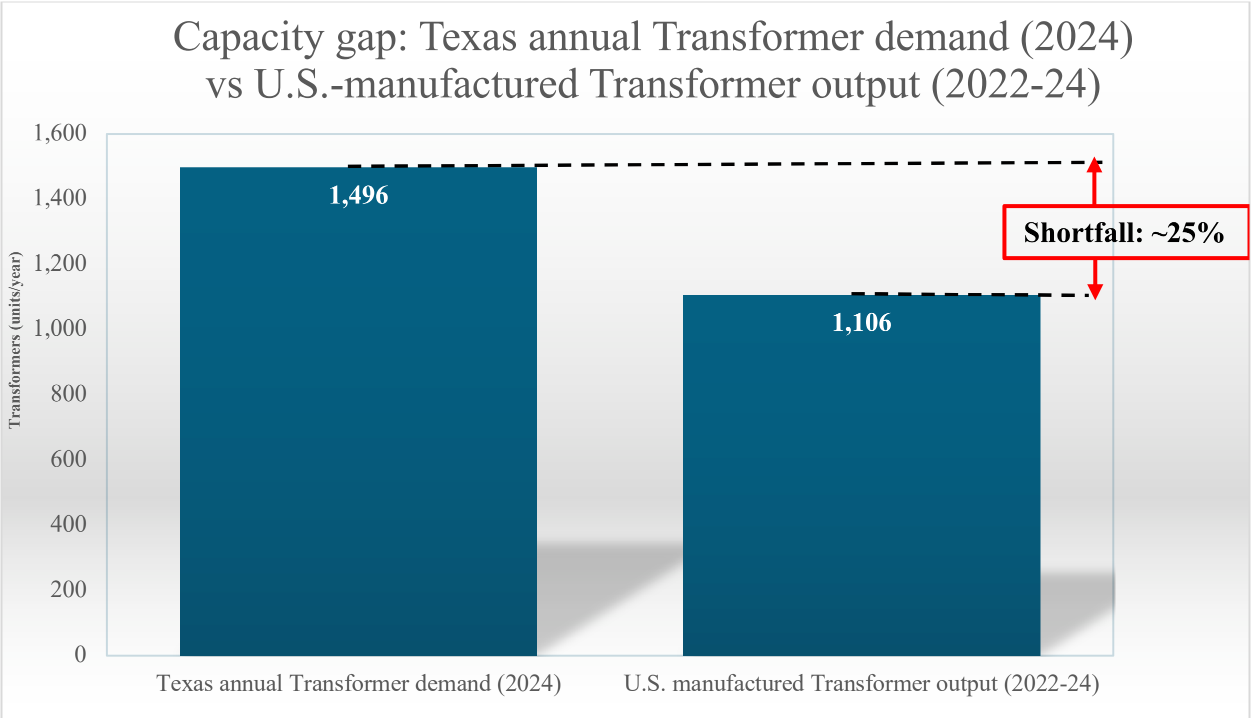


Exhibit-D: Capacity gap: Texas annual Transformer demand (2024) vs U.S.-manufactured Transformer output (2022-24)

This means that transformer availability and not generation capacity alone could become a binding constraint on Texas' grid expansion through 2030. The risk is amplified by long manufacturing cycles, dependence on imported materials, the concentration of supply among a small number of OEMs, and the pace at which new large loads are emerging in Texas. Federal agencies and industry stakeholders continue to describe transformer availability as a resilience and reliability concern for the U.S. grid more broadly.

Based on the analysis, following supply-chain risks and constraints stand out.

Limited U.S. manufacturing capacity, supplier diversity and geographic concentration

Transformer manufacturing in the U.S. is concentrated among a small set of OEMs and first-tier suppliers, creating vulnerability to single-point failures and extended queues. Standing up additional U.S. plant capacity alone will not eliminate this risk. Today's focus on Tier-1 inputs is underpinned by thin Tier-2 through Tier-4 ecosystems, many of which remain concentrated outside the United States and, in some cases, in higher-risk jurisdictions. Geographic concentration compounds the issue. For Texas in particular, the siting of existing and planned large-power-transformer facilities is clustered in the Midwest and the eastern half of the country (e.g., Virginia, Pennsylvania, Missouri, North Carolina, Wisconsin, Alabama), leaving Texas with comparatively limited in-state manufacturing presence. The result is a structurally fragile supply base in which regional shocks, logistics bottlenecks, or upstream material constraints can disproportionately delay high impact, high value Texas projects.

Long and inflexible lead times

Power transformers are highly customized, capital-intensive assets that move through prolonged engineering, fabrication, testing, logistics, and commissioning cycles, making them inherently slow to procure [6][24][49]. The U.S. Department of Energy notes that 36-month lead times are commonly quoted for large power transformers, with some replacements stretching to as much as 60 months [24]. Such long lead times reduce procurement flexibility and make it difficult for utilities, transmission developers, and large-load customers to respond quickly to changing system needs, and many are pushed toward import substitution when domestic slots are unavailable, introducing additional schedule and logistics risk even when equipment is ultimately sourced.

Dependence on foreign materials and upstream inputs

Transformer manufacturing depends on a set of specialized upstream materials and components including Electrical steel, Copper and other critical inputs that remain internationally concentrated, even in “hostile” foreign nations [24] [34]. DOE’s supply-chain assessments explicitly identify dependence on foreign equipment and materials as an ongoing vulnerability in the U.S. transformer market. This dependence creates a structural exposure to geopolitical disruption and broader supply instability [3] [24] [31] [49].

Workforce and project delivery constraints

Transformer supply risk is not limited to manufacturing capacity alone. It is also shaped by shortages in the skilled workforce required to design, manufacture, transport, install, test, and commission transformer-related infrastructure [6] [24] [49]. Even where equipment can be procured, shortages in skilled labor and project delivery capacity may still delay installation, energization, and commissioning [24] [41] [49].

Implications

Viewed through the lens of supply-chain resilience, the outlook of tight transformer supply combined with continued dependence on externally sourced and geopolitically exposed inputs is a material concern for Texas. This is because transformer availability has implications not only for grid expansion, but also for the timing and viability of data center projects, battery energy storage deployments, EV charging buildout, and broader industrial growth across the state. Key implications from this study are-

Power provisioning depends on industrial supply chains, not generation alone	• Texas’ ability to provision power is no longer determined only by how much electricity it can generate, but increasingly by whether critical enabling equipment can be sourced, manufactured, and deployed in time.

Supply-chain resilience becomes a strategic planning issue, not just a procurement issue	• The combination of extended lead times limited domestic manufacturing flexibility, geographic concentration of production, and dependence on externally sourced inputs means that transformer availability must be incorporated into infrastructure planning from the outset. • As a result, the timing of power-sector projects increasingly depends not only on whether they are needed or financed, but on whether the enabling equipment can be secured early enough to keep those projects on schedule.
Transformer scarcity introduces fragility into a speed-based growth system	• Texas has built much of its economic momentum around speed i.e. speed of project execution, industrial expansion, and increasingly speed of energization for large electricity users. • A transformer bottleneck undermines that advantage because it introduces a category of delay that cannot easily be compressed by financing, contracting, or market incentives alone.

Conclusion

This study finds that transformer availability is becoming a decisive factor in Texas' economic competitiveness, not just its utility operations. Current analysis points to a shortfall in supply of LPTs. Supply-chain resilience depends on end-to-end visibility and diversification across the upstream supplier tiers, especially Tier-2 through Tier-4 suppliers of critical materials and components where concentration and country-of-risk are greatest. The state's emerging demand profile is increasingly tied to sectors that require timely, high-confidence access to power, yet the supply chain for one of the most critical enabling assets remains tight and exposed to external dependencies. The resulting implication is that supply-chain resilience in case of LPT is not merely a matter of reliability or procurement efficiency but is a part of the state's capacity to convert infrastructure demand into sustained economic growth.

Appendix

Appendix-A) Demand estimation methodology

Texas electricity demand was estimated using publicly available data from authoritative sources, including the U.S. EIA, ERCOT, PUCT, and other relevant industry reports. These sources were used to establish the scale of electricity generation, electricity sales, and broader demand trends relevant to the Texas power system.

To translate electricity demand into transformer requirements, this study used a transformer sizing / transformer capacity calculation approach, under which the number of large power transformers required is estimated as:

$$Number\ of\ Transformers = \frac{Total\ Required\ MVA\ Load}{Rated\ MVA\ per\ Transformer}$$

The first step in this process was to estimate the required apparent power, expressed in MVA, from electricity sales and load data. This conversion was based on the standard power factor relationship:

$$Power\ Factor\ (PF) = \frac{Real\ Power\ (MW)}{Apparent\ Power\ (MVA)}$$

Power factor on both the U.S. and Texas grids is generally maintained within a range of 0.95 to 0.99 (lagging). Because ERCOT Nodal Protocols Section 3.15 and ERCOT Nodal Operating Guide Section 2.7 reference a 0.97 power factor standard in the context of distribution-side obligations, this study adopts PF = 0.97 as the base-case assumption, while also recognizing a broader range of 0.95–0.99 for sensitivity analysis. Using this relationship, annual electricity sales were converted into an estimate of the required transformer MVA per hour, assuming 100% capacity factor for simplification.

The second step was to estimate the rated MVA capacity of transformers that would serve this demand. For this purpose, power transformers were grouped by voltage class and represented using typical nameplate MVA ratings commonly used in utility-scale applications.

Extra High Voltage (EHV) Transformers	High Voltage (HV) Transformers	Other Voltage levels
These transformers support bulk power transmission over long distances and are used in major transmission corridors and backbone substations.	These transformers connect the bulk transmission system to regional load centers and sub-regional networks.	These are generally used in legacy systems, municipal utilities, and smaller load pockets.
765 kV: 1000–1800 MVA 500 kV: 500–1200 MVA 345 kV: 200–750 MVA	230 kV: 100–300 MVA 161 kV: 50–150 MVA 138 kV: 50–200 MVA	115 kV: 25–100 MVA

To reflect operating reliability requirements, a 10% N-1 contingency margin was then applied to transformer nameplate ratings. This adjustment was used to approximate the effective available rating of each transformer under contingency-aware planning assumptions:

$$Rated\ Transformer\ MVA = nameplate\ MVA\ rating * 0.9$$

Finally, the required MVA load and the rated transformer MVA derived from the steps above were applied to the transformer sizing formula to estimate the number of transformers required to serve projected Texas electricity demand.

This approach is intended to provide a directional and transparent estimate of transformer demand based on publicly available electricity data and representative engineering assumptions. The resulting figures should therefore be interpreted as planning-level estimates, suitable for comparing broad demand requirements against estimated transformer supply capability.

Appendix-B) Transformer Supply Modelling

Because transformer production volumes are proprietary and are not publicly disclosed by manufacturers, this study developed OEM-level production estimates using a structured proxy-based approach. The analysis focused on five major power transformer OEMs with manufacturing operations in the United States Hitachi Energy, Siemens Energy, GE Vernova, Quanta Services, and HD Hyundai Electric and reviewed a broad set of publicly available sources for the period 2022 through 2024, including consolidated annual financial statements, 10-K filings, segment-level revenue disclosures, geographic revenue breakdowns, investor materials, press releases, product and service portfolios, and relevant market research.

To estimate production, the analysis first approximated the share of each OEM's revenue attributable to transformer-related business activities within the relevant reporting segment. Because most firms do not separately disclose transformer revenue, transformer revenue shares were inferred from segment composition, product offerings, business positioning, and market focus. The share of transformer revenue within the relevant segment was assumed as follows:

- GE Vernova: 35%-45% (base case: 40%)
- Hitachi Energy: 25%-30% (base case: 27.5%)
- Siemens Energy: 20%-25% (base case: 22.5%)
- Quanta Electric: 10%-15% (base case: 12.5%)
- HD Hyundai Electric USA: 70%-80% (base case: 74.5%)

A further revenue split was then applied to distinguish between power transformers and distribution transformers, with transformer revenue allocated 65% to power transformers and 35% to distribution transformers.

For OEMs with global reporting structures, U.S. revenue as a share of total revenue was used as a proxy to approximate the portion of production attributable to the U.S. market. This approach was particularly relevant for OEMs such as GE Vernova, Hitachi Energy, Siemens Energy and HD Hyundai Electric, where domestic manufacturing activity is embedded within broader global operations.

Since OEM list prices are not publicly available and transformer pricing varies significantly by voltage class, size, and project specification, the study used average selling price (ASP) mid-points to estimate unit output. The following ASP assumptions were applied for power transformers:

- GE Vernova: $3.6 million
- Hitachi Energy: $5.2 million
- Siemens Energy: $3.6 million
- Quanta: $5.2 million
- HD Hyundai Electric USA: $4.5 million

These values are intended as directional pricing assumptions rather than exact transactional prices. Once estimated power transformer reve**nue** was obtained, annual production volume was calculated using the following expression:

$$Number\ of\ Power\ Transformers\ produced = \frac{Power\ Transformer\ revenue}{Average\ Selling\ Price}$$

This method does not claim to reproduce exact OEM production totals. Rather, it provides a reasonable, transparent, and replicable estimate of likely annual output based on the best publicly available evidence. The resulting figures should therefore be interpreted as directional production estimates, suitable for comparing broad supply capability against projected transformer demand.

References

[1]. *2024 Regional Transmission Plan (RTP) 345-kV Plan and Texas 765-kV Strategic Transmission Expansion Plan Comparison, January 2025 | ERCOT*. (n.d.). Retrieved March 25, 2026, from https://www.ercot.com/files/docs/2025/01/27/2024-regional-transmission-plan-rtp-345-kv-plan-and-texas-765-kv-strategic-transmission-expans.pdf

[2]. *2025 ERCOT Electricity Market Outlook 2nd Edition*. (n.d.). Retrieved March 25, 2026, from https://www.energyonline.com/reports/2025_ERCOT_Outlook_v2.pdf

[3]. *Addressing the Critical Shortage of Power Transformers to Ensure Reliability of the U.S. Grid*. (n.d.). Retrieved March 25, 2026, from https://www.cisa.gov/sites/default/files/2024-09/NIAC_Addressing%20the%20Critical%20Shortage%20of%20Power%20Transformers%20to%20Ensure%20Reliability%20of%20the%20U.S.%20Grid_Report_06112024_508c_pdf_0.pdf

[4]. Brown, J., Henderson, W., & Ruelas, S. (2025, March 5). *Meeting Texas' Growing Energy Demands – Texas Legislative Study Group*. Texas LSG. Policy Reports. https://texaslsg.org/2025/03/05/meeting-texas-growing-energy-demands/

[5]. Chin, M. (2026, March 13). *Who is really footing the AI energy bill? Inside the debate about data center electricity costs*. CNBC. https://www.cnbc.com/2026/03/13/ai-data-centers-electricity-prices-backlash-ratepayer-protection.html

[6]. Chopra, S., & Boucher, B. (2024, April 2). *Supply shortages and an inflexible market give rise to high power transformer lead times | Wood Mackenzie*. Wood Mackenzie. Opinion. https://www.woodmac.com/news/opinion/supply-shortages-and-an-inflexible-market-give-rise-to-high-power-transformer-lead-times/

[7]. Cuthrell, S. (n.d.). *Transformer Supply Chain Woes Persist as Energy Demand Grows—Tech Insights*. EE Power. Tech Insights. Retrieved March 25, 2026, from https://eepower.com/tech-insights/transformer-supply-chain-woes-persist-as-energy-demand-grows/#

[8]. *Distribution Transformer Demand: Understanding Demand Segmentation, Drivers, and Management Through 2050 | NREL*. (n.d.). Retrieved March 25, 2026, from https://docs.nrel.gov/docs/fy25osti/92076.pdf

[9]. Donald, J., & Grubbs, S. (2024, September). *The future of Texas power*. Texas Comptroller of Public Accounts. Industry: Special Edition on Energy. https://omptroller.texas.gov/economy/fiscal-notes/industry/2024/energy-demand/

[10]. Enerknol. (2024, October 7). *TX's Electricity Demand Growth by Data Centers and Crypto Mining*. Enerknol. https://enerknol.com/texas-sees-significant-electricity-demand-growth-fueled-by-data-centers-and-cryptocurrency-mining-eia/

[11]. *ERCOT EV ALLOCATION STUDY - METHODOLOGY FOR DETERMINING EV LOAD IMPACT AT THE SUBSTATION LEVEL*. (n.d.). Retrieved March 25, 2026, from https://www.ercot.com/files/docs/2023/08/28/ERCOT-EV-Adoption-Final-Report.pdf

[12]. ERCOT. (n.d.). *Load Forecast*. Grid Information. Retrieved March 25, 2026, from https://www.ercot.com/gridinfo/load/forecast

[13]. Federal Reserve Bank of Dallas. (2024, March 13). *Energy Indicators, March 13, 2024*. Federal Reserve Bank of Dallas. https://www.dallasfed.org/research/energy/indicators/2024/en2404

[14]. GE Vernova. (2026, February 2). *GE Vernova completes Prolec GE acquisition, accelerating Electrification segment growth trajectory | GE Vernova News*. GE Vernova.

https://www.gevernova.com/news/press-releases/ge-vernova-completes-prolec-ge-acquisition

[15]. Gosavi, S. S. (2026, March 26). *Power Transformers capacity Hypothesis Test.xlsx*. https://utexas-my.sharepoint.com/:x:/r/personal/sg57572_eid_utexas_edu/_layouts/15/Doc.aspx?sourcedoc=%7B192E8066-D0F3-497A-9195-84761AFD8717%7D&file=Power%20Transformers%20capacity%20Hypothesis%20Test.xlsx&action=default&mobileredirect=true&DefaultItemOpen=1

[16]. Golding, G. (2025, January 14). *Solar, battery capacity saved the Texas grid last summer; an uncertain future awaits*. Federal Reserve Bank of Dallas. Federal Reserve Bank of Dallas. https://www.dallasfed.org/research/economics/2025/0114

[17]. Guo, K. (2025, January 24). Data centers are booming in Texas. What does that mean for the grid? *The Texas Tribune*. https://www.texastribune.org/2025/01/24/texas-data-center-boom-grid/

[18]. Hitachi. (2025, April 8). *Hitachi Energy boosts Pennsylvania investments to more than $70 million*. Hitachi Energy. https://www.hitachienergy.com/us/en/news-and-events/press-releases/2025/04/hitachi-energy-boosts-pennsylvania-investments-to-more-than-70-million

[19]. Hitachi. (2025, April 25). *Hitachi Energy expands U.S. footprint with $22.5 million investment to increase transformer production in Virginia*. Hitachi Energy. https://www.hitachienergy.com/news-and-events/press-releases/2025/04/hitachi-energy-expands-us-footprint-with-22-5-million-investment-to-increase-transformer-production-in-virginia

[20]. Hitachi. (2025, September 4). *Hitachi announces historic $1 billion USD manufacturing investment to power America's energy future through production of critical grid infrastructure*. Hitachi Energy. https://www.hitachienergy.com/news-and-events/press-releases/2025/09/hitachi-announces-historic-1-billion-usd-manufacturing-investment-to-power-america-s-energy-future-through-production-of-critical-grid-infrastructure

[21]. Hyundai. (2026, March 8). *HD Hyundai Electric Expands U.S. Production Subsidiary, Solidifies Leadership in North American Extra High Voltage Power Transformer Market*. HD Hyundai. http://www.hd.com/en/newsroom/media-hub/press/view?&

[22]. *Item 5: CEO Board Update*. (n.d.). Retrieved March 25, 2026, from https://www.ercot.com/files/docs/2024/04/22/5%20CEO%20Update.pdf

[23]. *Item 8.1: Long-Term Load Forecast Update (2025-2031) and Methodology Changes*. (n.d.). Retrieved March 25, 2026, from https://www.ercot.com/files/docs/2025/04/07/8.1-Long-Term-Load-Forecast-Update-2025-2031-and-Methodology-Changes.pdf

[24]. *Large Power Transformer Resilience*. (n.d.). Retrieved March 25, 2026, from https://www.energy.gov/sites/default/files/2024-10/EXEC-2022-001242%20-%20Large%20Power%20Transformer%20Resilience%20Report%207-10-24.pdf

[25]. Liu, Z. (2024, August 15). *Securing copper supply: No China, no energy transition*. Wood Mackenzie. https://www.woodmac.com/horizons/securing-copper-supply-china-energy-transition/

[26]. Mahoney, A. (2024, February 13). *Siemens Energy expands in North Carolina—Axios Charlotte*. Axios. Axios Charlotte. https://www.axios.com/local/charlotte/2024/02/13/siemens-expands-north-carolina

[27]. *Major Drivers of Long-Term Distribution Transformer Demand*. (n.d.). Retrieved March 25, 2026, from https://docs.nrel.gov/docs/fy24osti/87653.pdf

[28]. Meehan, T. (2024, December 12). *What Is Driving the Demand for Distribution Transformers? | NLR*. NREL. NREL. https://www.nlr.gov/news/detail/program/2024/what-is-driving-the-demand-for-distribution-transformers

[29]. mkaczmarski. (2024, July 15). Texas Power Grid Grapples With Rising System Needs. *BloombergNEF*. https://about.bnef.com/insights/commodities/texas-power-grid-grapples-with-rising-system-needs/

[30]. MGM Transformers and VanTran Strengthen U.S. Energy Supply Chain with Texas Expansion. (2025, April 24). *MGM Transformers*. https://mgmtransformers.com/vantran-and-mgm-transformers-strengthen-u-s-energy-supply-chain-with-texas-expansion/

[31]. Nguyen, R., Severson, M., Zhang, B., Vaagensmith, B., Rahman, M. M., Toba, A.-L., Price, P., Davis, R., & Williams, S. (2022). *Electric Grid Supply Chain Review: Large Power Transformers and High Voltage Direct Current Systems* (DOE/OP-0004). USDOE Office of Policy (OP), Washington, DC (United States). https://doi.org/10.2172/1871501

[32]. Patel, S. C. (2024, June 26). The Transformer Crisis: An Industry on the Brink. *POWER Magazine*. https://www.powermag.com/the-transformer-crisis-an-industry-on-the-brink/

[33]. Patel, S. C. (2026, January 2). Transformers in 2026: Shortage, Scramble, or Self-Inflicted Crisis? *POWER Magazine*. https://www.powermag.com/transformers-in-2026-shortage-scramble-or-self-inflicted-crisis/

[34]. Patel, S. C. (2023, May 25). U.S. Power Sector Trade Groups Flag Critical Electrical Steel Crunch. *POWER Magazine*. https://live-powermag.pantheonsite.io/u-s-power-sector-trade-groups-flag-critical-electrical-steel-crunch/

[35]. *Power transformers and distribution transformers will face supply deficits of 30% and 10% in 2025, according to Wood Mackenzie*. (2025, August 14). News Release. https://www.woodmac.com/press-releases/power-transformers-and-distribution-transformers-will-face-supply-deficits-of-30-and-10-in-2025/

[36]. Prolec GE Invests an Additional $140 Million in the U.S. to Support North American Electric Grid Goals. (n.d.). *Prolec Energy*. Retrieved March 26, 2026, from https://www.prolec.energy/news/prolec-ge-invests-an-additional-140-million-in-the-u-s-to-support-north-american-electric-grid-goals/

[37]. Siemens Energy. (2024, February 14). *Siemens Energy addresses the shortage of US power transformers and invests in new factory*. Siemens Energy. https://www.siemens-energy.com/global/en/home/press-releases/siemens_energy_addresses_shortage_US_powertransformers_invests_new_factory.html

[38]. Simmons, T. J. P., Daniel. (2026, March 19). Have Data Centers Driven Up Electricity Prices? *IER*. https://www.instituteforenergyresearch.org/the-grid/have-data-centers-driven-up-electricity-prices-the-state-level-data-dont-support-the-narrative/

[39]. *State Electricity Profile 2024*. (2025, November 10). Texas. https://www.eia.gov/electricity/state/Texas/index.php

[40]. Thomas, D., Boucher, B., & Mendeck-Laske, M. (2025, August 13). *Transformer troubles: Manufacturing and policy constraints hit US transformer supply*. Wood Mackenzie. https://www.woodmac.com/news/opinion/transformer-troubles-manufacturing-and-policy-constraints-hit-us-transformer-supply/

[41]. Trabish, H. K. (2025, February 12). *Transformer supply bottleneck threatens power system stability as load grows | Utility Dive*. Utility Dive. Deep Dive. https://www.utilitydive.com/news/electric-transformer-shortage-nrel-niac/738947/

[42]. U.S. Energy Information Administration. (2025, July 31). *We expect rapid electricity demand growth in Texas and the mid-Atlantic*. Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=65844

[43]. U.S. Energy Information Administration. (2025, October 1). *Texas used twice as much energy as California and three times as much as Florida in 2023—U.S. Energy Information Administration (EIA)*. In-Brief Analysis. https://www.eia.gov/todayinenergy/detail.php?id=66224

[44]. U.S. Energy Information Administration. (2025, October 24). *ERCOT increasingly meets rising demand with solar, wind, and batteries—U.S. Energy Information Administration (EIA)*. Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=66464

[45]. U.S. Energy Information Administration. (n.d.). *Texas End-use energy consumption 2023, estimates*. Texas End-Use Energy Consumption 2023, Estimates. Retrieved March 25, 2026, from https://www.eia.gov/states/TX/overview

[46]. U.S. Energy Information Administration. (n.d.). *Analysis*. Texas. Retrieved March 25, 2026, from https://www.eia.gov/states/TX/analysis

[47]. U.S. Energy Information Administration. (n.d.). *Texas Electricity data*. Texas. Retrieved March 25, 2026, from https://www.eia.gov/states/tx/data/dashboard/electricity

[48]. U.S. Energy Information Administration. (n.d.). *Texas End-use energy consumption 2023, estimates*. Texas. Retrieved March 25, 2026, from https://www.eia.gov/states/TX/overview

[49]. U. S. Government Accountability Office. (2023, August 2). *Electricity Grid: DOE Could Better Support Industry Efforts to Ensure Adequate Transformer Reserves | U.S. GAO*. Reports and Testimonies. https://www.gao.gov/products/gao-23-106180

[50]. Vendetti, B. (2022, December 12). *Which countries produce the most copper?* World Economic Forum. World Economic Forum. https://www.weforum.org/stories/2022/12/which-countries-produce-the-most-copper/

[51]. Walton, R. (2024, April 24). *ERCOT launches new planning efforts as 2030 load growth projections soar 40 GW in a year | Utility Dive*. Utility Drive. Dive Brief. https://www.utilitydive.com/news/ercot-transmission-planning-2030-load-growth-projections/714104/

[52]. Watson, M. (2025, January 27). *Texas grid operator sees increased costs, benefits from 765-kV transmission*. S&P Global Energy. https://www.spglobal.com/energy/en/news-research/latest-news/electric-power/012725-texas-grid-operator-sees-increased-costs-benefits-from-765-kv-transmission

[53]. World Steel in Figures 2025. (2025). *Worldsteel.Org*. https://worldsteel.org/data/world-steel-in-figures/world-steel-in-figures-2025/

Jurisdictional Exposure in Grid-Scale Solar Inverter Supply Chains

April 2026

Report by: Rabita Saleh
Graduate Student
Engineering Management, TxEEE
Cockrell School of Engineering
The University of Texas at Austin

Advised by: Dr. R. Britt Freund
Full Professor of Practice
Assistant Dean
McCombs School of Business
The University of Texas at Austin

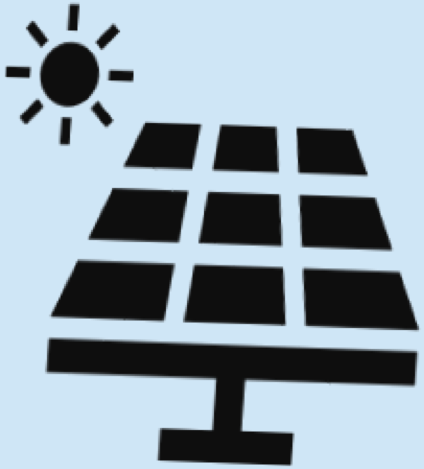
TEXAS
The University of Texas at Austin

Core Research Question

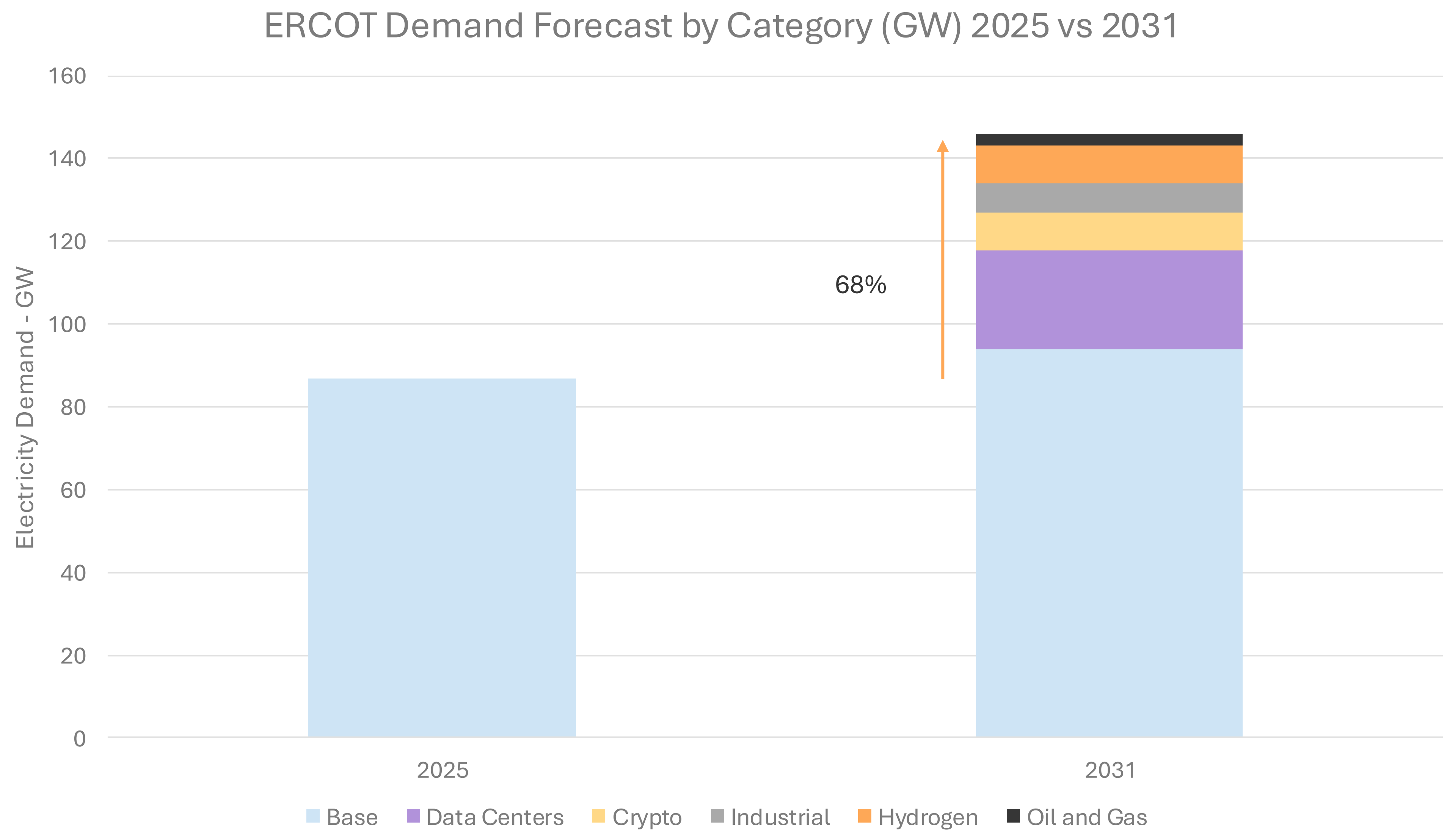
To what extent are grid-scale solar inverters deployed within ERCOT

exposed to foreign jurisdictional influence through:

- Manufacturer incorporation
- Manufacturing footprint
- Firmware development and update control?



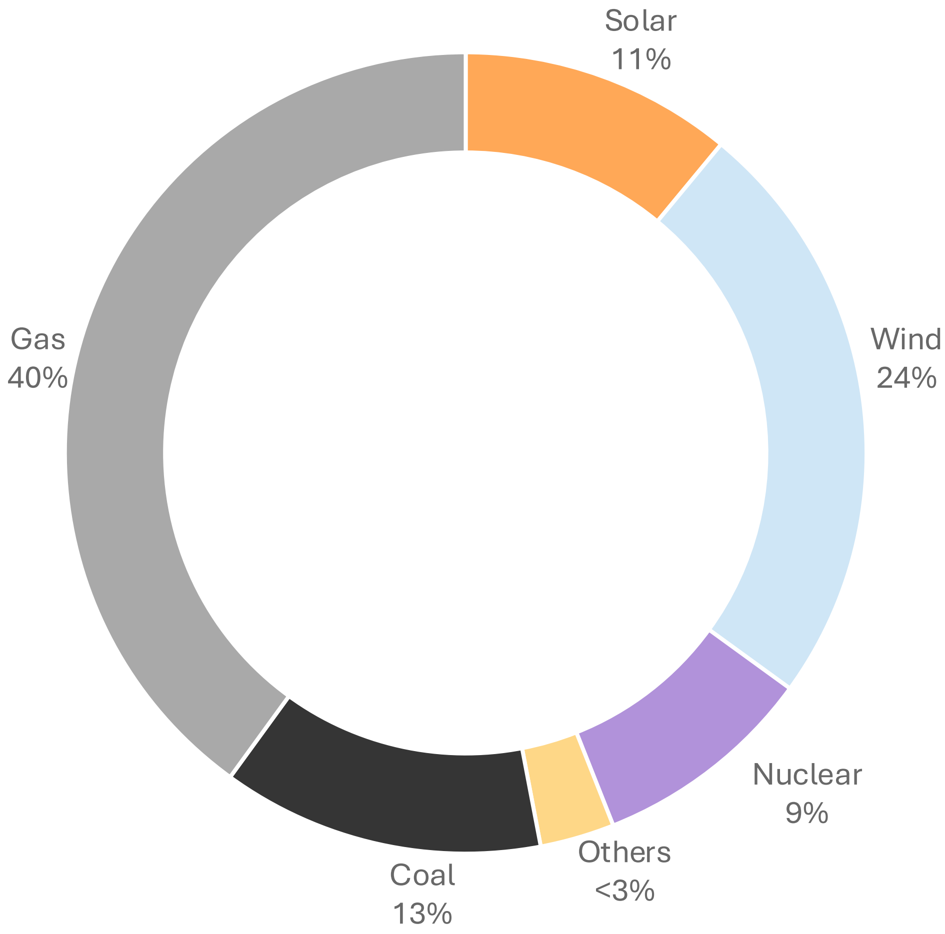
The Growing Demand for Electricity



Source: ERCOT 2025b

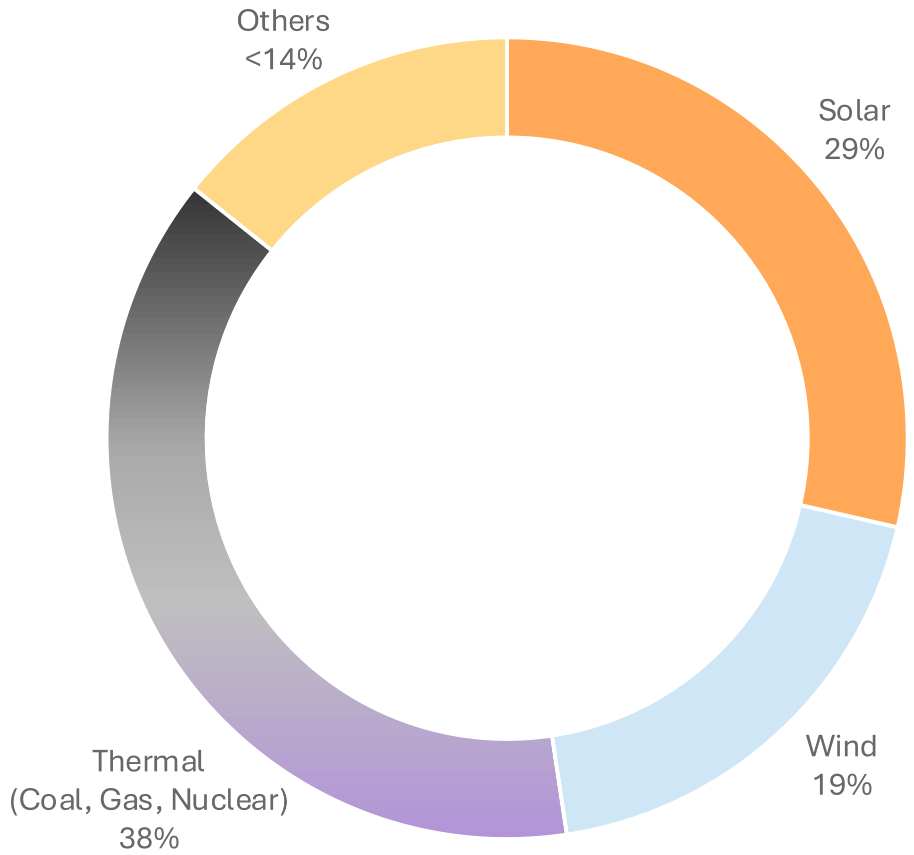
ERCOT Projections for Inverter Based Resource Expansion

ERCOT POWER GENERATION MIX 2026



Source: ERCOT Interval Generation by Fuel Report Feb 2026

ERCOT PROJECTED GENERATION MIX 2029



Source: ERCOT 2024 State of the Grid Report (Simplified from figure on p6)

Inverter Based Resources

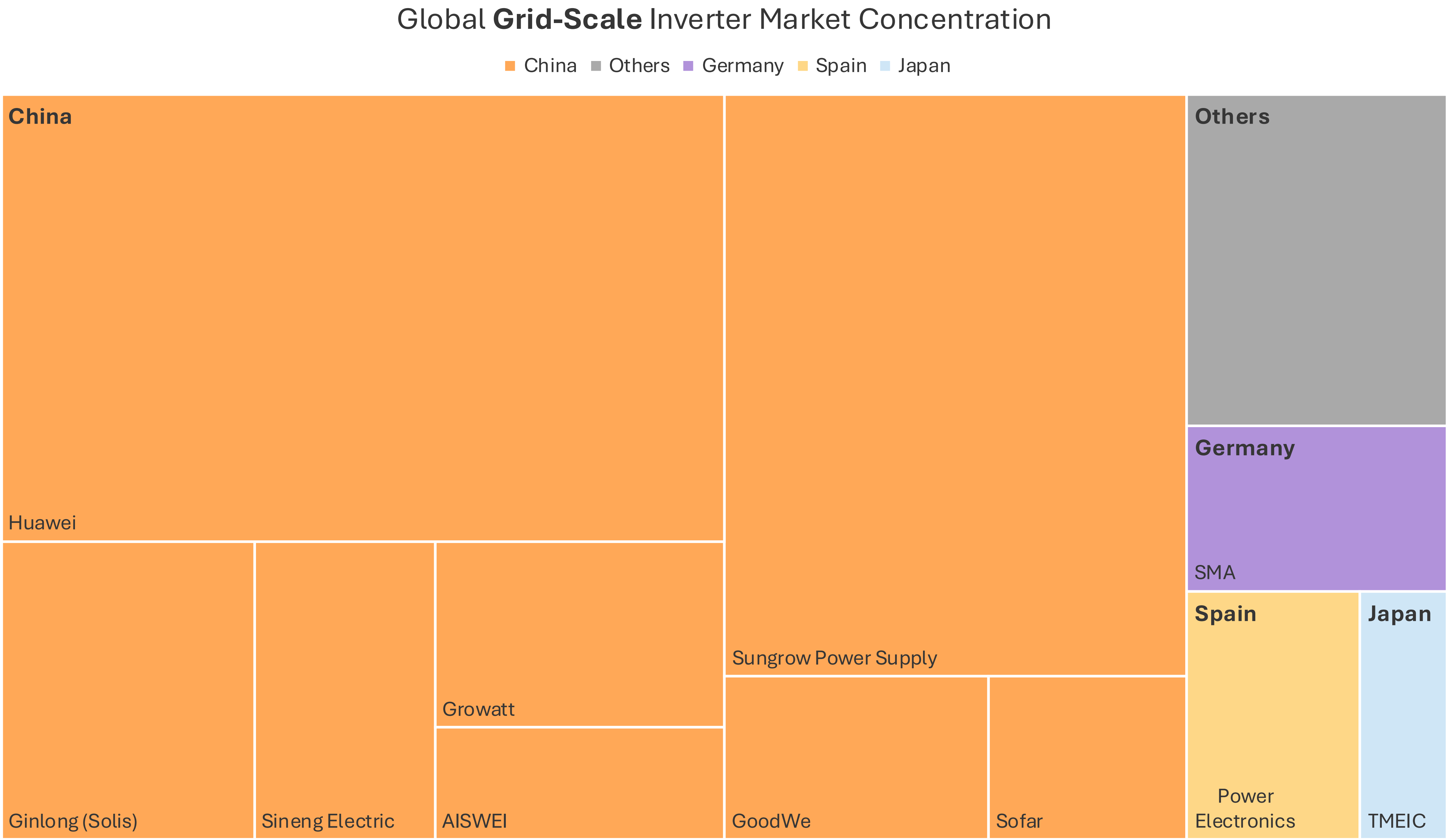
Inverter Based Resources, such as solar and wind, are, as their name suggests, dependent on inverters that primarily convert DC generation into grid-compatible AC power. Inverters also act as the digital control interface between solar plants and the transmission network.

Key considerations regarding their nature:

- They are **digitally active** and are used to conduct real-time control of the solar array
- They require continued **remote manufacturer access** for support using **firmware updates**

Analytical Questions

- Can ERCOT's planned renewable expansion be supported solely through **supply chains located within allied or domestic jurisdictions**?
- What share of ERCOT's installed inverter infrastructure originates from firms operating under potentially unfriendly **foreign jurisdictional authority**?
- What portion of the current supply chain may be **exposed to disruption or control risks** under geopolitical stress scenarios?



Source: Wood Mackenzie's Global Solar Inverter Manufacturer Rankings 2024 and H1 2025

Hypothesis Framework

Null Hypothesis (H_0)
Owing to primary supply chains, especially Tier 2 and below, all converging to a few select vendors, grid-scale inverter installations in ERCOT are predominantly exposed to foreign jurisdictional control across manufacturer incorporation, manufacturing footprint, and firmware management dimensions.

Alternative Hypothesis (H_1)
Grid-scale inverter installations in ERCOT are not predominantly exposed to foreign jurisdictional control across manufacturer incorporation, manufacturing footprint, and firmware management dimensions.

The Two Possible Errors:

"False Alarm" Error:
Overestimating supply chain vulnerability and recommending unnecessary mitigation investments.

"No Alarm Error" (Prioritized):
Underestimating supply chain exposure and failing to identify meaningful infrastructure risk.

Case Study: Selected ERCOT Projects & Data Requirements

INR	Project Name	Interconnecting Entity	County	Capacity (MW)
28INR0486	Spectra Solar	SE DC Devco	Scurry	1200
31INR0018	Permian I Solar	S&S Renewables, LLC	Pecos	1125.69
29INR0003	Aurelius Solar	IP Roman, LLC	Deaf Smith	1124.24
25INR0207	Shadow Ranch Solar	LectricWind LLC	Upton	807.61
24INR0095	Dovetail Solar 2	Hecate Energy Dovetail Solar 2 LLC	Jack	666.1
22INR0337	Skylab Solar	EDF Renewables Development, Inc.	Wharton	609.74
29INR0160	Cazadores Solar	OCI Energy LLC	Duval	301.62
19INR0075	Horseshoe Bend Solar	Clenera	Brown	301.1
27INR0355	Gardner Draw Solar	RWE Clean Energy Development, LLC	Glasscock	300
21INR0380	Charolais Solar	RWE Solar Development, LLC	Matagorda	261.63
22INR0244	Razorbill Solar	RWE Solar Development, LLC	Matagorda	240
21INR0349	Pearl Crescent Solar	RWE Solar Development, LLC	Colorado	208.35
21INR0413	Big Star Solar	RWE Solar Development, LLC	Bastrop	203.1
25INR0512	Monument Hill Solar	RWE Solar Development, LLC	Fayette	200

Granular project-level data, including vendor data for Tier 1 and above, is required to conduct:

- Supply Chain Mapping
- Procurement Analysis
- Firmware Dependency Evaluation
- Stress test under geopolitical disruptions

Case Study Objective:

Produce a scalable method of analyzing supply chain exposure for the **600**+ grid-scale solar generation projects in ERCOT's GIS under geopolitical disruption scenarios.

References

1. Abdelhady, M., Iakovou, E., Pistikopoulos, E. N., & Robertson, R. (2025, November). Meeting rising U.S. electricity demand from AI and data centers: An integrated technical and policy perspective. Texas A&M Energy Institute. https://oaktrust.library.tamu.edu/server/api/core/bitstreams/9e3a2987-b802-4d25-8083-21d7aafdcbec/content

2. Electric Reliability Council of Texas. (2025, May 16). Report on the capacity, demand and reserves (CDR) in the ERCOT region, 2026–2030 (Revised). https://www.ercot.com/files/docs/2025/05/16/CapacityDemandandReservesReport_May2025_Revised.pdf

3. Wood Mackenzie. (2025, July 10). Global PV inverter shipments grew by 10% in 2024 to 589 GWac. https://www.woodmac.com/press-releases/global-pv-inverter-shipments-grew-by-10-in-2024-to-589-gwac/

4. Keiding, N., & Budtz-Jørgensen, E. (2004). The Precautionary Principle and statistical approaches to uncertainty. *International journal of occupational medicine and environmental health*, *17*(1), 147–151.

TEXAS
The University of Texas at Austin

Jurisdictional Exposure in Grid-Scale Solar Inverter Supply Chains within ERCOT

Report by: Rabita Saleh
Graduate Student, Engineering Management, TxEEE
Cockrell School of Engineering, The University of Texas at Austin

Advised by: Dr. R. Britt Freund
Full Professor of Practice, Assistant Dean
McCombs School of Business, The University of Texas at Austin

April 2026

Abstract

The rapid expansion of solar generation within ERCOT has brought to light growing dependencies on globally concentrated supply chains, particularly in the case of inverter-based resources. While existing regulatory frameworks address ownership and physical control of infrastructure, they provide limited visibility into how procurement-driven supply chain decisions may influence operational dependencies over time. The analysis also underscores that jurisdictional exposure extends beyond Tier 1 suppliers to upstream tiers of the inverter supply chain, where a limited number of Tier 2–4 vendors result in supply convergence and concentrated dependencies.

This report examines how these dynamics may contribute to foreign jurisdictional exposure within ERCOT's solar fleet. An analytical framework is proposed to examine a selected set of utility-scale solar projects across three dimensions: manufacturer incorporation and corporate jurisdiction, manufacturing and component production geography, and firmware development, update pathways, and remote management capabilities.

By framing these risks within existing regulatory and market structures, the report aims to support more informed assessment of system-level exposure and highlight areas where additional visibility and technical evaluation may be required.

Table of Contents

1. Introduction

In 2015 solar PV accounted for approximately 0.3% of ERCOT's power generation mix (ERCOT, 2015). As of 2026, that share has reached nearly 11% (ERCOT, 2026). By ERCOT's projections, in 2029, solar generation will account for approximately 29% of the total power generation mix, overtaking wind, and reaching nearly 75% (ERCOT, 2024) of the energy generated through thermal (coal, gas, nuclear, and so on).

This rapid growth of solar generation is rooted in sustained load growth across Texas, driven by population expansion, electrification of end uses such as transportation, and large industrial loads including data centers, semiconductor manufacturing, and crypto mining operations. To support this growing electricity demand, ERCOT has projected over 235 GW of installed generation capacity by 2029. Over 50% of this will be generated through Inverter Based Resources (IBRs) (ERCOT, 2024).

Inverter based resources (IBRs) are the cornerstone of renewable power generation including wind and solar. These power generation methods differ from traditional generation in that they produce DC electricity, which must be converted to AC before it can be transmitted along the grid. Inverters perform this DC-to-AC conversion while also regulating voltage and frequency, synchronizing output with grid conditions, and enabling grid operators to monitor and control generation behavior in real time.

The projected reliance on renewable energy, particularly solar, in ERCOT's generation mix, merits increased scrutiny of the security and reliability of the supply chains that feed these projects. Growth in demand, combined with still relatively low production capacity in the US, leads to increased reliance on globally manufactured inverter hardware and software.

The importance of supply chain governance for grid infrastructure lies in the online nature of inverters. They are digitally controlled systems that directly influence grid stability and operational behavior. Their hardware origin, embedded firmware, and update pathways can introduce dependencies on external jurisdictions, creating potential cybersecurity risks. As inverter-based resources scale, these risks are no longer isolated at the unit level but can propagate system-wide, affecting reliability, resilience, and operator visibility. Ensuring transparency and accountability across the inverter supply chain is therefore critical to maintaining the security of the grid.

In 2025 the State of Texas passed the Lone Star Infrastructure Protection Act, to protect the critical infrastructure of Texas, including the power grid, from exposure to foreign ownership and control. In light of that, other means of foreign jurisdictional exposure, beyond primary on-paper ownership, are merited examination. This project aims to analyze the extent to which grid-scale solar inverters deployed in ERCOT territory are exposed to foreign jurisdictional influence across three dimensions: manufacturer incorporation, manufacturing footprint, and firmware development or update control location.

We have adopted a hypothesis-testing framework designed for engineering management decision-making under conditions of incomplete or uncertain data. Rather than relying solely on statistical inference, the analysis will apply structured reasoning to evaluate available evidence regarding supply chain exposure and operational dependencies.

Primary Research Question

To what extent are grid-scale solar inverters deployed in ERCOT territory exposed to foreign jurisdictional influence through manufacturer incorporation, manufacturing footprint, and firmware development or update control location?

Null Hypothesis (H_0)

Owing to primary supply chains, especially Tier 2 and below, all converging to a few select vendors, grid-scale inverter installations in ERCOT are predominantly exposed to foreign jurisdictional control across manufacturer incorporation, manufacturing footprint, and firmware management dimensions.

Alternative Hypothesis (H_1)

Grid-scale inverter installations in ERCOT are not predominantly exposed to foreign jurisdictional control across manufacturer incorporation, manufacturing footprint, and firmware management dimensions.

This report is structured to provide a systematic analysis of jurisdictional exposure in ERCOT's inverter-based solar infrastructure, progressing from strategic context and analytical framework to proposed empirical evaluation and actionable recommendations. The following section elaborates on the strategic context, including the role of IBRs in renewable generation, ERCOT's expansion trajectory, global market concentration for grid-scale inverters, and the geopolitical factors involved in risk assessment for these particular supply chains. Subsequent sections present the methodology and analytical framework, followed by a description of the case study dataset and the rationale behind its selection. Finally, the report concludes with a discussion of anticipated implications, as well as limitations and next steps as the analysis proceeds upon availability of data.

2. Strategic Context

2.1 ERCOT's Power Generation Mix and Projections

The Electric Reliability Council of Texas (ERCOT) is the electricity grid and market operator for the majority of the state of Texas. It manages the power flow to about 27 million Texas customers, representing approximately 90% of the state electricity demand. As the region's independent system operator (ISO), ERCOT schedules power on an electric grid that connects more than 55,000+ miles of transmission lines and 1,460+ generation units. (ERCOT). It has 104,850+ MW of total generating capacity and a peak load of 85,508 MW as of March 2026 (ERCOT, 2026). There are more than 1900 active market participants that generate, move, buy, sell, or use wholesale electricity in the ERCOT market.

Texas's free market approach to electricity production and loose regulation of development encourages big electricity projects. In this market environment, the decision of building new generation is still largely dominated by the prospect of future demand.

The Growing Demand of Electricity

In the first nine months of 2025, electricity demand in ERCOT reached a record high compared with the same period in previous years. Over those same months, ERCOT had the fastest electricity demand growth among U.S. electricity grids between 2024 and 2025. (EIA, 2025) Several factors are responsible for this rising electricity demand.

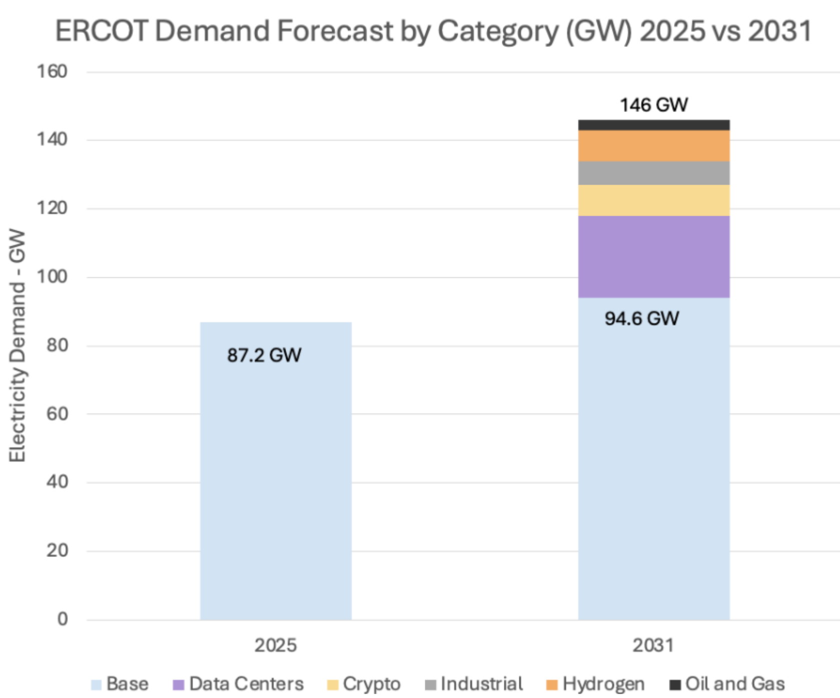


Figure 1. ERCOT demand forecast by category (GW) 2025 vs 2031
Source: Abdelhady et al., 2025; ERCOT, 2025b

Reflecting national trends, Figure 1 breaks ERCOT demand projections into the six main categories. By 2031, peak demand is expected to surge by a whopping 68%, to 146 GW from 87 GW in 2025. 24 GW of this growth can be attributed to the development of new data centers, cryptocurrency mining accounts for another 8.5 GW, industrial demand contributes 7.5 GW, and hydrogen and oil & gas operations make up the remainder (Abdelhady et al., 2025).

The Emergence of Solar Generation

West Texas has long been well positioned for large-scale solar expansion, given its strong solar irradiance and extensive open land suitable for utility-scale projects. Technological innovations have also led to the cost of developing solar farms in Texas to decrease by 40% in the five years between 2014 and 2019, according to the Solar Energy Industries Association (SEIA). Compared to gas and coal fired plants, solar farms are inexpensive to operate once built, since the fuel is essentially free of cost. Moreover, Federal tax credits, such as the Investment Tax Credit (ITC) and Production Tax Credit (PTC), have further reduced the cost of developing solar farms. Meanwhile, the acceptance of solar electricity by both the public and corporations as a clean alternative to fossil fuels has resulted in increased demand. (Du, 2023)

Compared to the same period in 2024, utility-scale solar generated 50% more of electricity in the first nine months of 2025, and nearly four times more than the same period in 2021. Wind and solar generation combined generated 36% of ERCOT's electricity demand from January to September 2025. (EIA, 2025) It should be noted that the types of energy sources used for electricity generation can vary through the day, sometimes hourly, especially during the summer. Solar production peaks around midday, and its growing presence in ERCOT has reduced reliance on natural gas during those hours. (EIA, 2025)

As illustrated in Figure 3, ERCOT plans to meet growing electricity demand primarily through large-scale renewable expansion. Solar generation alone is projected to exceed 70 GW of installed capacity, surpassing wind and approaching roughly three-quarters of the projected thermal capacity. In total, solar and wind could account for more than 110 GW of capacity by 2029, underscoring the increasing reliance on inverter-based resources.

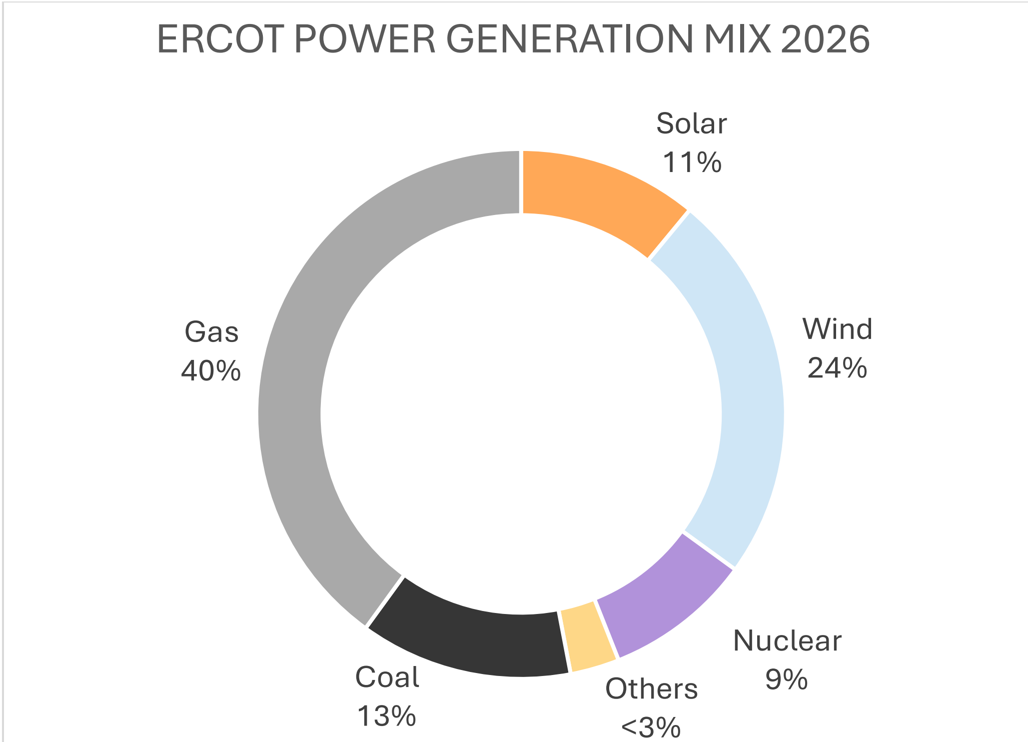


Figure 2: ERCOT Power Generation Mix 2026
Source: Interval Generation by Fuel Report, February 2026

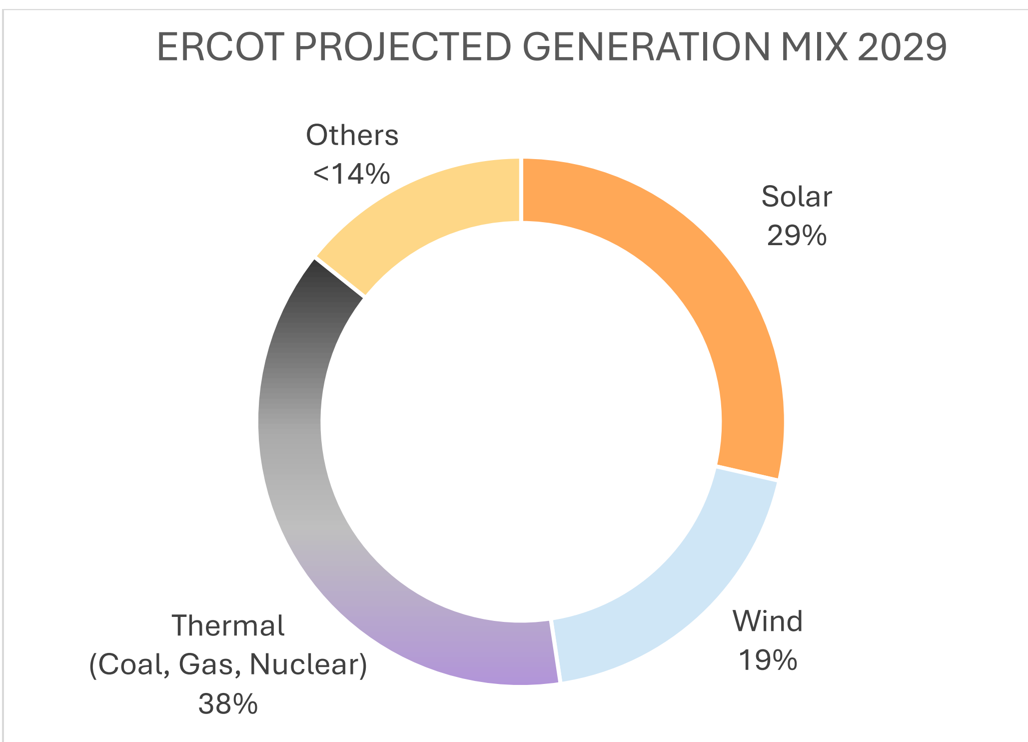


Figure 3: ERCOT Project Generation Mix 2029
Source: ERCOT 2024 (see Appendix A for Detailed Capacity Expansion Plans)

2.2 Inverter Based Resources

Inverter-Based Resources (IBRs), including solar, wind, and battery systems, rely on inverters primarily to convert direct current (DC) into grid-compatible alternating current (AC) (IEA PVPS, 2025). However, modern inverters extend far beyond this basic function. They are digitally controlled systems that actively regulate power output, interface with the grid, and influence overall system stability (Mallwitz & Engel, 2010).

At the core of this functionality is proprietary firmware, developed and maintained exclusively by the manufacturer. This firmware governs inverter behavior, manages system interactions, and is updated remotely to address performance, cybersecurity, and regulatory requirements. As a result, manufacturers retain significant control over how these assets operate in the field.

As inverters become increasingly networked, they introduce potential cybersecurity risks (see Appendix B for details). While a single compromised device poses limited concern, coordinated manipulation of large numbers of inverters could result in cascading generation loss, voltage and frequency instability, and broader system disruptions (Musleh et al., 2024). Taken together, these characteristics position inverters as both critical enablers of grid functionality and potential points of vulnerability.

2.3 Development and Procurement Structure in Utility-Scale Solar

To determine the factors that dictate the supply chain for utility-scale solar inverters, we must first understand the multi-tiered structure for the development and interconnection process for ERCOT's solar PV projects. Extracting a simplistic view from *Understanding and Negotiating EPC Contracts Volume I* by Howard Steinberg, and updating it with current industry practices, the onboarding process for a solar PV plant is illustrated in Figure 4 (see Appendix C for details).

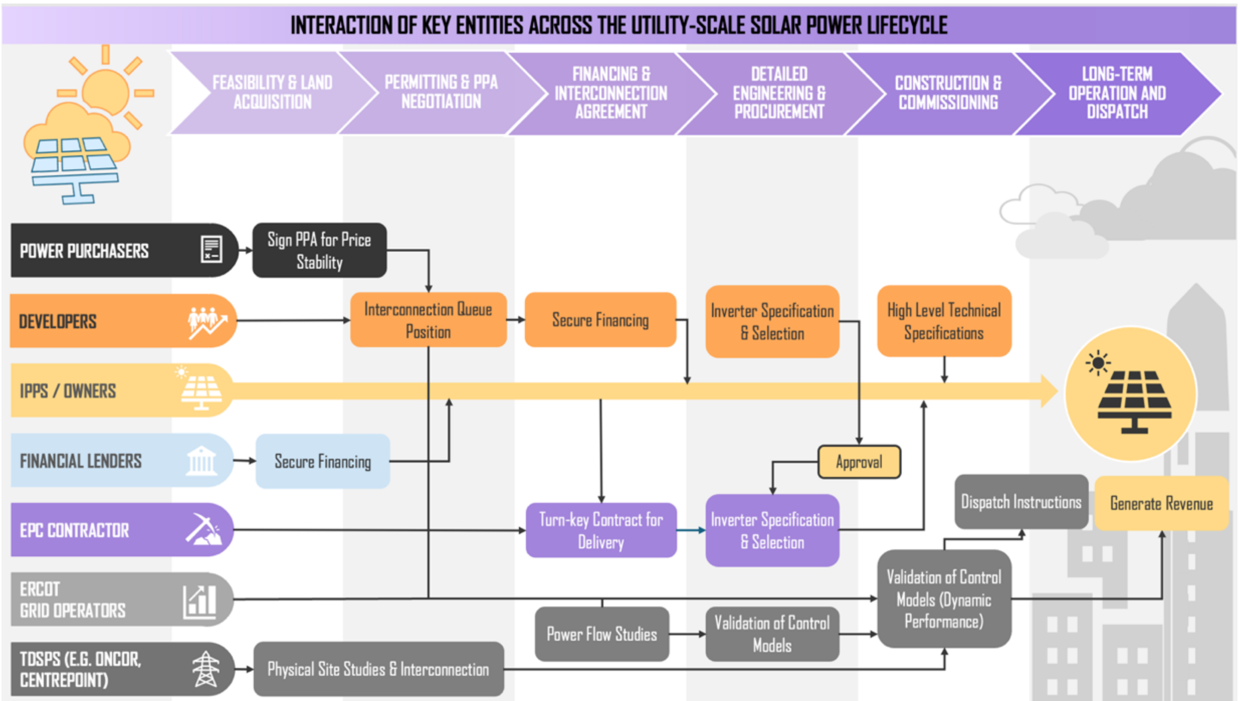


Figure 4: Interaction of Key Entities across the Utility-Scale Solar Power Lifecycle

Procurement-Driven Supply Chain Exposure

Supply chain decisions in utility-scale solar projects are decentralized across multiple actors. It is important to note that while ERCOT and TDSPs play a decisive role in whether a project qualifies for grid connection, they focus on evaluating the functional aspects of the infrastructure. They are not involved in procurement decisions. That responsibility lies with the EPCs and the Developers.

EPC contractors and IPPs typically select vendors through a multi-criteria evaluation process (IFC, 2022) that prioritizes cost competitiveness, bankability, and delivery reliability, with "bankable" vendors often favored due to their track record in securing project financing. Procurement decisions are also influenced by the EPC's schedule constraints and supply availability. This selection process naturally narrows down the potential vendor list to those who can meet the financial and execution requirements at competitive costs, converging toward a limited set of globally scaled manufacturers. Such concentration can increase systemic exposure, as issues affecting a widely deployed technology may permeate multiple projects (IEA, 2022).

This division of responsibility is central to understanding how inverter supply chains are shaped in practice: procurement decisions are made upstream by EPCs and IPPs optimizing for project-level economics (Mehos et al., 2020), whereas downstream entities must integrate and operate these assets within a grid environment where reliability and security take precedence.

Market-Driven Constraints on Procurement Leverage and Transparency

In the process of requesting data for this report representatives from ERCOT and Lower Colorado River Authority (LCRA) were contacted. Following those meetings, several key constraints became apparent, primarily driven by intense market competition lowering long-term project leverage and a multi-tiered procurement model that potentially limits supply chain visibility.

Extrapolating from the previous section, the free-market nature of the current utility-scale solar industry makes it highly tilted in favor of Tier-1 component vendors. Multiple entities, ranging from traditional utilities like LCRA to deep-pocketed buyers like Google and Amazon, are competing for a limited pool of suppliers (BloombergNEF, 2026), leaving the IPPs and EPC contractors deficient in bargaining leverage. Consequently, demanding deep-tier supply chain visibility (Tiers 2 through 4) becomes fraught. Vendors, facing a surplus of demand, may prioritize contracts with simpler compliance requirements, fostering a culture of diminished transparency along the supply chain (Barlow et al., 2024).

This challenge of informational opacity is further complicated by the "Reasonable Inquiry" standard outlined in ERCOT Nodal Protocol Section 16.1.4. A Resource Entity registered under ERCOT is defined as an entity with ownership or control of a generation resource, a load resource, and/or a Non-Modeled Generator (ERCOT). Under the terms detailed in Section 16.1.4, a Resource Entity is generally not required to investigate the deep-tier origins of equipment if they obtain a contractual representation from their immediate vendor (ERCOT) signaling compliance with the Lone Star Infrastructure Protection Act (discussed in Section 2.5). Combined with the IPP's low market leverage, this reliance on vendor-provided attestations may discourage deeper supply chain audits, potentially leaving the origins of Tier 2 and Tier 3 critical sub-components unexamined, provided that reasonable obscurity of information can be claimed.

It is important to note that as of early 2026, ERCOT has begun issuing Notices of Material Breach (ERCOT, 2026) when "clearly evident" public data contradicts these vendor letters, signaling that the exceptions detailed under Section 16.1.4 may no longer act as umbrella protection against state-level enforcement.

2.4 Current Global Market Concentration for Grid-Scale Inverters

The global solar inverter market is highly concentrated and dominated by a handful of manufacturers, forming a tightly consolidated supply base. Manufacturers of Chinese origins account for roughly 75-80% of global market share in 2025 (IEA PVPS, 2025), as illustrated in Figure 5.

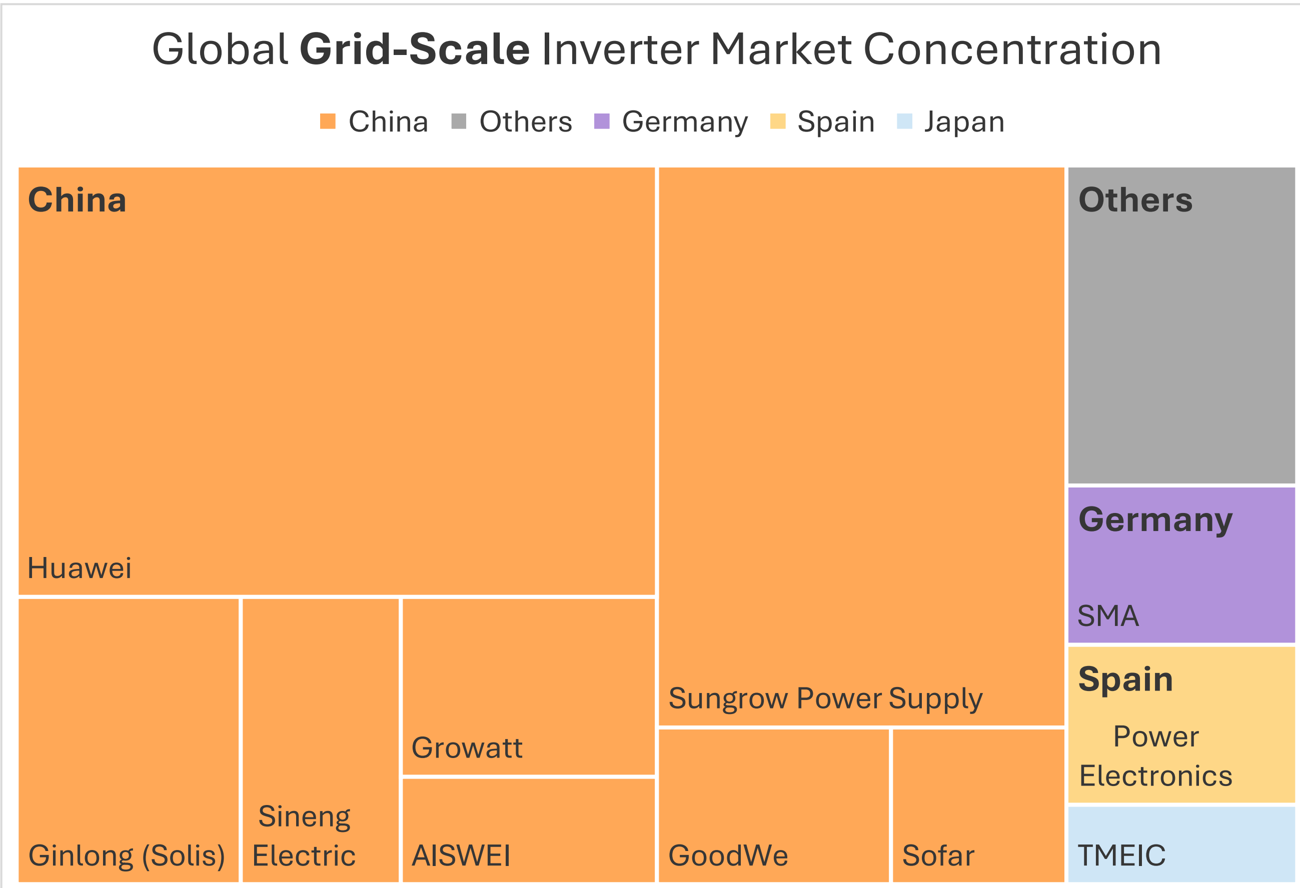


Figure 5: Global Grid-Scale Inverter Market Concentration, 2025
Source: Wood Mackenzie's Global Solar Inverter Manufacturer Rankings 2024 and H1 2025

Firms such as Huawei and Sungrow have maintained the top two global positions for multiple consecutive years, together accounting for over 50% of global inverter shipments in 2024 alone (Wood Mackenzie, 2025). Beyond the top two, additional Chinese manufacturers, including Ginlong (Solis), GoodWe, and Growatt, populate much of the remaining top-tier supplier list, reinforcing a market structure where a single national ecosystem underpins the majority of global supply. The result is a procurement landscape in which EPCs, even outside China, are structurally dependent on Chinese-origin inverter technology.

Through-Shoring and the Illusion of Supply Diversification

"Through-shoring" is defined here as the structuring of manufacturing, supply chain, or corporate operations across jurisdictions in a manner that obscures the apparent origin or ownership profile of a product without changing underlying dependencies or control. This can be implemented through a range of strategies, including relocation of final-stage assembly to third countries to reclassify product origin for trade purposes.

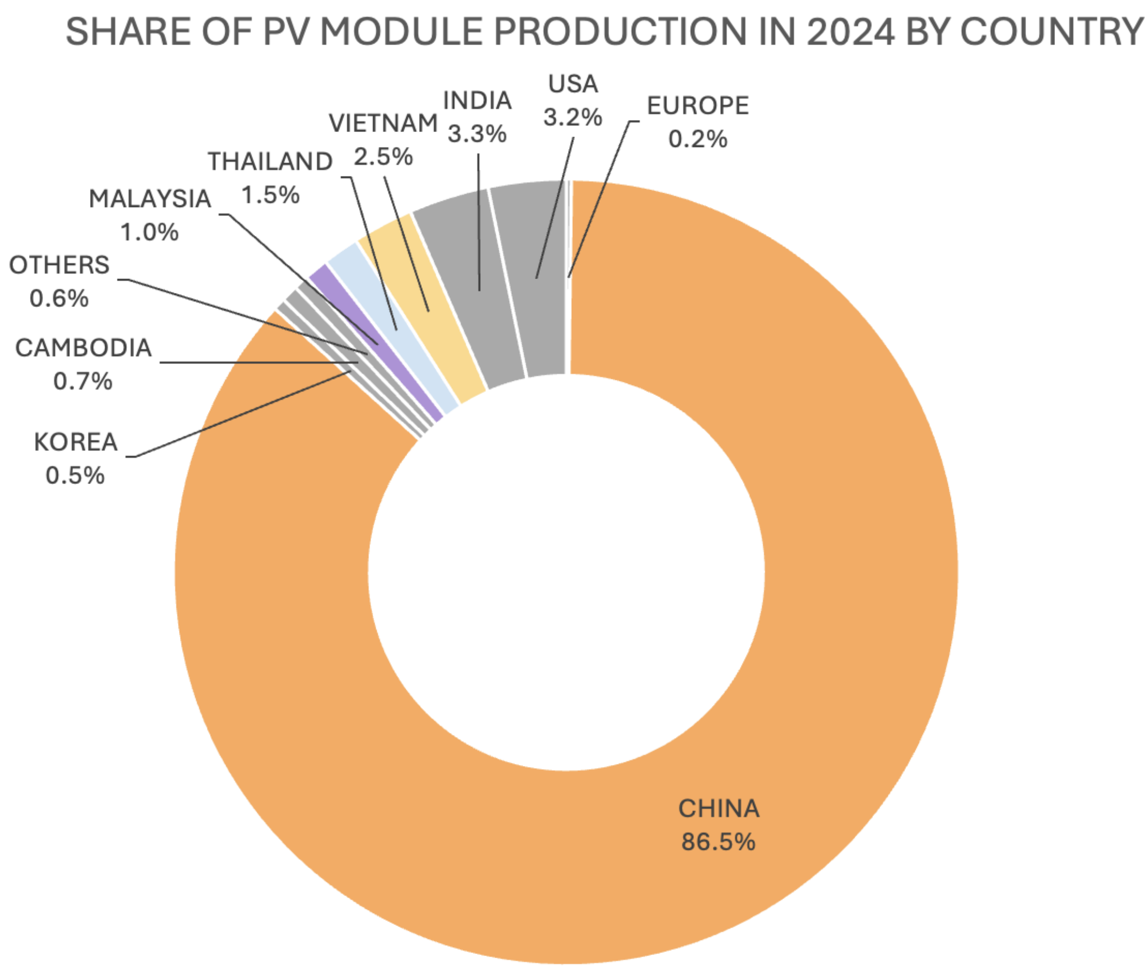


Figure 6. Share of PV Module Production in 2024 by Country, Source: IEA PVPS, RTS Corporation

As illustrated in Figure 6, the 2024 production distribution of PV modules (used here as representative of broader solar supply chain dynamics) shows about 5% combined shares accounted to Malaysia, Thailand, and Vietnam. (IEA PVPS, 2025) While this may suggest geographic diversification, these markets have largely expanded due to investments from Chinese manufacturers establishing overseas assembly operations.

These facilities have historically served the U.S. market, enabling firms to export products that are formally classified as originating outside China, while still relying on Chinese components, design, and parent company control structures.

In 2024, U.S. authorities determined that imports from several Southeast Asian countries were effectively circumventing existing trade measures on Chinese solar products. This led to the imposition of new anti-dumping and counteracting duties targeting these pathways, constraining the viability of this particular through-shoring tactic. (IEA PVPS, 2025)

While manufacturing may shift geographically, firm-level control, component sourcing, and technological dependencies can remain concentrated within the same set of Chinese manufacturers. Apparent diversification in manufacturing location does not necessarily translate into reduced jurisdictional exposure. Given that inverter manufacturers operate within the same supply ecosystem, similar patterns of through-shoring are plausible.

State Influence in China's Solar PV industry magnifies Jurisdictional Risk

China's dominance in the solar PV industry is the result of sustained state-led industrial policy, long-term financing, and strategic designation of renewables as a national priority. At the same time, embedded channels of state influence within private manufacturers, reinforced by legal obligations to support national intelligence and data access mandates, blur the boundary between commercial operations and state interests (see Appendix D for detailed discussion).

In the context of inverter-based resources, the nature of grid-scale inverters as digitally active and remotely accessible assets entails that these statutes take on added significance. The obligation of Chinese manufacturers to comply with domestic mandates introduces a potential misalignment with the operational security requirements of the host grid. As a result, supply chain concentration in this sector begins to intersect with questions of infrastructure sovereignty and systemic risk (USCC, 2024; OECD, 2026), motivating the range of preemptive measures adopted by the United States to safeguard critical infrastructure.

2.5 The Lone Star Infrastructure Protection Act and the Firmware Question

At both the federal and state levels, policymakers have begun to recognize the risks associated with foreign involvement in critical energy infrastructure. Federal measures such as the Secure and Trusted Communications Networks Act of 2019, reviews by the Committee on Foreign Investment in the United States, and reliability standards developed by the Federal Energy Regulatory Commission and the North American Electric Reliability Corporation reflect a broader shift toward restricting foreign participation in sensitive sectors. This analysis focuses on how these concerns are addressed at the state level in Texas, particularly through the Lone Star Infrastructure Protection Act (LSIPA), and its implementation within ERCOT market protocols.

The Lone Star Infrastructure Protection Act (LSIPA), enacted in 2021, was introduced in response to growing concerns over foreign ownership and influence in critical infrastructure. It restricts entities associated with designated foreign adversary countries from owning, controlling, or accessing assets in sectors such as energy, water, and telecommunications. In practice, it places due diligence and compliance obligations on infrastructure owners and operators, aiming to limit external jurisdictional influence.

Within ERCOT, LSIPA considerations are embedded directly into market participation requirements. Section 16.1.4 of the ERCOT Protocols requires Market Participants to disclose procurement of Critical Electric Grid Equipment (CEGE) sourced from designated companies or countries. More importantly, participants must attest that such procurement "will not result in access to or control of CEGE" by designated foreign entities.

The Question of Firmware Updates

While the LSIPA attempts to restrict foreign jurisdictional access or control over critical infrastructure, there are still protocols in place, detailed in ERCOT Protocols Section 16.1.4 (c) and (d), that allow exceptions for access provided "for product warranty and support purposes."

This allowance reflects the technical constraints of modern solar infrastructure. The functionality of inverter systems depends on vendor-managed software ecosystems that include firmware updates, remote diagnostics, and performance optimization services. These services are typically delivered through on-going vendor access under the umbrella of warranty and support agreements. As a result, while the framework places clear restrictions on ownership and procurement, it still permits limited forms of vendor interaction after deployment.

In inverter-based system, this creates a distinction between formal control, which is regulated, and operational dependencies that may persist through software and support arrangements. This does not imply non-compliance, but it does indicate that certain forms of post-deployment influence fall outside the primary focus of existing safeguards. In a supply chain with concentrated global manufacturing, these residual pathways become relevant when assessing overall system exposure.

Summarizing the Strategic Context

Taken together, the growing demand for electricity in Texas, ERCOT's projections of solar capacity expansion to meet this demand, and the supply chain concerns detailed in the procurement and maintenance of inverter based resources, create a compelling argument for further examination of jurisdictional vulnerabilities in what is shaping up to be a large piece of the energy equation for the State of Texas.

The following section outlines the methodology and analytical framework that is planned to be used to examine a selected set of ERCOT solar projects, with a focus on supply chain mapping, procurement pathways, and firmware-level dependencies. With access to project-level data, this approach is intended to support scenario-based stress testing under conditions of geopolitical disruption, enabling a more grounded assessment of system-level exposure.

3. Methodology and Analytical Framework

The analytical approach will focus on a case study of fourteen solar generation projects from the ERCOT GIS Report (February 2026). These projects were selected based on two criteria:

- Project capacity and significance within ERCOT's solar expansion pipeline
- Prior industry reporting linking certain developers or contractors with specific suppliers

The analysis will examine supply chain exposure across three primary dimensions:

1. Manufacturer incorporation and corporate jurisdiction
2. Manufacturing and component production geography
3. Firmware development, update pathways, and remote management capabilities

Data sources will include ERCOT interconnection reports, industry publications, corporate disclosures, regulatory filings, and direct communication with relevant organizations.

Where complete quantitative data is unavailable, the analysis will rely on qualitative evidence, supply chain mapping, and scenario-based reasoning. While a hypothesis testing framework using the Precautionary Principle to prioritize No Alarm errors has been utilized as the scaffolding on which to build our case (see Appendix E for details), the goal of this study is not to produce a binary statistical conclusion. Instead, the analysis aims to evaluate whether current procurement and infrastructure management practices could produce operational exposure under geopolitical stress conditions.

Granular project-level data on the selected projects will enable supply chain mapping, procurement analysis, firmware dependency evaluations, and stress tests under geopolitical disruptions to be conducted. The ultimate objective for the study is to produce a scalable method of analyzing supply chain exposure for the 600+ grid-scale solar generation projects in ERCOT's GIS under geopolitical disruption scenarios.

3.2 Case Study Dataset: Selecting ERCOT Solar Projects

INR	Project Name	Interconnecting Entity	County	Capacity (MW)
28INR0486	Spectra Solar	SE DC Devco	Scurry	1200
31INR0018	Permian I Solar	S&S Renewables, LLC	Pecos	1125.69
29INR0003	Aurelius Solar	IP Roman, LLC	Deaf Smith	1124.24
25INR0207	Shadow Ranch Solar	LectricWind LLC	Upton	807.61
24INR0095	Dovetail Solar 2	Hecate Energy Dovetail Solar 2 LLC	Jack	666.1
22INR0337	Skylab Solar	EDF Renewables Development, Inc.	Wharton	609.74
29INR0160	Cazadores Solar	OCI Energy LLC	Duval	301.62
19INR0075	Horseshoe Bend Solar	Clenera	Brown	301.1
27INR0355	Gardner Draw Solar	RWE Clean Energy Development, LLC	Glasscock	300
21INR0380	Charolais Solar	RWE Solar Development, LLC	Matagorda	261.63
22INR0244	Razorbill Solar	RWE Solar Development, LLC	Matagorda	240
21INR0349	Pearl Crescent Solar	RWE Solar Development, LLC	Colorado	208.35
21INR0413	Big Star Solar	RWE Solar Development, LLC	Bastrop	203.1
25INR0512	Monument Hill Solar	RWE Solar Development, LLC	Fayette	200

Table 1. Selected ERCOT Solar Projects for Case Study

The project selection was guided by capacity-based prioritization and prior procurement patterns in inverter sourcing, particularly involving internationally dominant suppliers. The four largest projects in the dataset were selected based on installed capacity, as utility-scale assets exceeding 800 MW represent a disproportionate share of generation and therefore introduce greater potential system-level risk if associated with vulnerable supply chains.

The remaining projects were selected based on documented or inferred relationships between the developers and inverter suppliers, particularly in cases where prior industry reporting (specifically for Clenera, RWE Development, EDF Renewables Development) and vendor disclosures indicate the use of equipment from major global manufacturers such as Sungrow. While project-level inverter attribution is not consistently disclosed in public datasets, established procurement patterns provide a reasonable basis for assessing supply chain exposure.

A subset of projects developed by RWE Development was intentionally included to examine intra-developer consistency in supplier selection. Given prior evidence of RWE’s use of specific vendors in utility-scale deployments, this grouping enables analysis of whether inverter sourcing strategies remain consistent across projects or vary by location, timeline, or other factors.

3.3 Limitations

The depth of our analysis is challenged by a number of limiting constraints, primarily related to data availability and the structure of publicly accessible information on utility-scale solar projects within ERCOT.

First, project-level data on inverter suppliers, firmware architecture, and remote access configurations is not consistently disclosed in public sources. As a result, portions of the supply chain assessment may have to rely on indirect indicators such as developer procurement patterns, prior industry reporting, and vendor disclosures. While these sources provide a reasonable basis for inference, they do not allow for definitive attribution at the individual project level.

Second, the evaluation of firmware-related dependencies is constrained by the limited transparency surrounding software architectures, update mechanisms, and vendor access protocols. These elements are typically proprietary and are not included in standard regulatory or interconnection filings. As a result, the analysis focuses on identifying potential pathways for operational influence rather than verifying their implementation in specific systems.

Third, the use of qualitative assessment and scenario-based reasoning, particularly in the context of geopolitical stress testing, reflects the absence of comprehensive datasets. The objective of this approach is to evaluate plausible exposure under defined conditions, rather than to produce statistical conclusions.

Finally, the scope of the case study is limited to a selected subset of ERCOT solar projects and focuses specifically on inverter-based resources. As such, the findings are not intended to represent the entirety of ERCOT's generation fleet or broader infrastructure landscape, but rather to provide a structured examination of potential exposure within a high-growth segment of the system.

4. Conclusion

4.1 Summary of Key Concepts

- ERCOT's rapid shift toward inverter-based solar generation is structurally increasing exposure to globally concentrated supply chains, making inverter dependencies a system-level, not project-level, concern.
- Jurisdictional exposure is not limited to ownership or physical control but can also emerge through these three dimensions: manufacturer origin, manufacturing geography, and firmware control.
- Procurement structures place critical supply chain decisions in the hands of EPCs and developers, where cost and bankability can take precedence over grid reliability.
- Global inverter supply is highly concentrated, with a small number of manufacturers, predominantly from a single national ecosystem, underpinning a majority of deployments, reinforcing systemic dependency.
- Firmware and software dependencies represent a persistent and under-addressed vector of influence, as vendor-managed updates, remote access, and proprietary control systems extend exposure beyond initial procurement.
- Existing regulatory frameworks, including LSIPA, primarily address ownership and procurement compliance, but are less explicit in governing ongoing operational dependencies introduced through software and support arrangements.
- Market dynamics limit supply chain transparency, as high demand and low buyer leverage discourage deep-tier visibility, while reliance on vendor attestations may obscure critical subcomponent origins.
- Systemic risk arises from scale and uniformity, where vulnerabilities in widely deployed inverter technologies could propagate across multiple projects.
- Targeted project-level analysis and stress testing are an essential next-steps to translate supply chain dependencies into actionable assessments of system-level risk under geopolitical disruption scenarios.
- Access to granular, project-level data is essential to validate and operationalize this analysis.

This analysis set out to address three core questions: the extent of foreign jurisdictional exposure within ERCOT's installed inverter base, the feasibility of supporting planned renewable expansion through domestic or allied supply chains, and the degree to which existing procurement structures may introduce disruption or control risks under geopolitical stress.

The analysis to date indicates that while precise quantification remains constrained by limited project-level transparency, the risk itself is not speculative. Foreign jurisdictional exposure may enter and persist within ERCOT's inverter-based resources in ways that are not fully addressed by existing regulatory frameworks. This exposure originates in initial procurement decisions and is reinforced over time through firmware updates, and vendor-managed operational relationships.

Recent federal and state-level efforts indicate growing institutional awareness of these risks. While measures such as the Lone Star Infrastructure Protection Act establish clear restrictions on ownership and direct control, they are less explicit in addressing operational dependencies that may persist through firmware, software updates, and vendor-managed systems.

The analytical framework outlined in this report is intended to examine these dynamics at the project level through supply chain mapping, procurement analysis, and evaluation of firmware-related dependencies. A targeted case study would enable deeper insight into these risks, support the development of a stress-testing model scalable across ERCOT's GIS, and help evaluate whether current measures are sufficient to address concerns regarding foreign influence over critical solar grid infrastructure. With access to project-level data, this approach can support a more rigorous assessment of how these factors translate into system-level exposure under conditions of geopolitical disruption.

4.2 Recommendations

1. Develop Regional Capability for Independent Firmware Evaluation

Technical expertise required to assess inverter firmware and update mechanisms is currently concentrated within a limited number of national laboratories. Expanding this capability at the state or regional level would support more timely and independent evaluation of software-driven system behavior. This should include the ability to review vendor-supplied firmware and updates for inverter-based resources, particularly those originating from high-risk jurisdictions, to ensure that malicious or unauthorized functionality is not embedded within otherwise legitimate code. Introducing this capability would reduce reliance on vendor attestations and automated testing alone and establish a more robust validation layer for critical grid infrastructure.

2. Strengthen Domestic and Allied Manufacturing Capacity for Inverters

Support the development of industrial capacity to manufacture solar PV inverters within the United States and allied jurisdictions. While full vertical integration may not be immediately feasible, targeted investment in key stages of inverter production can reduce dependence on concentrated foreign supply chains and improve long-term supply resilience.

3. Mandate Tiered Supply Chain Transparency for Digitally Active Components

Require comprehensive supply chain disclosure for components with embedded digital functionality, such as inverters and control systems. While upstream materials (e.g., polysilicon, wafers) may be addressed through attestations, components that are digitally active and remotely accessible, introducing operational or cyber risk, should be subject to stricter traceability requirements, including verified origin and supplier relationships beyond self-reported vendor disclosures.

4. Clarify the Scope of "Warranty and Support" Access

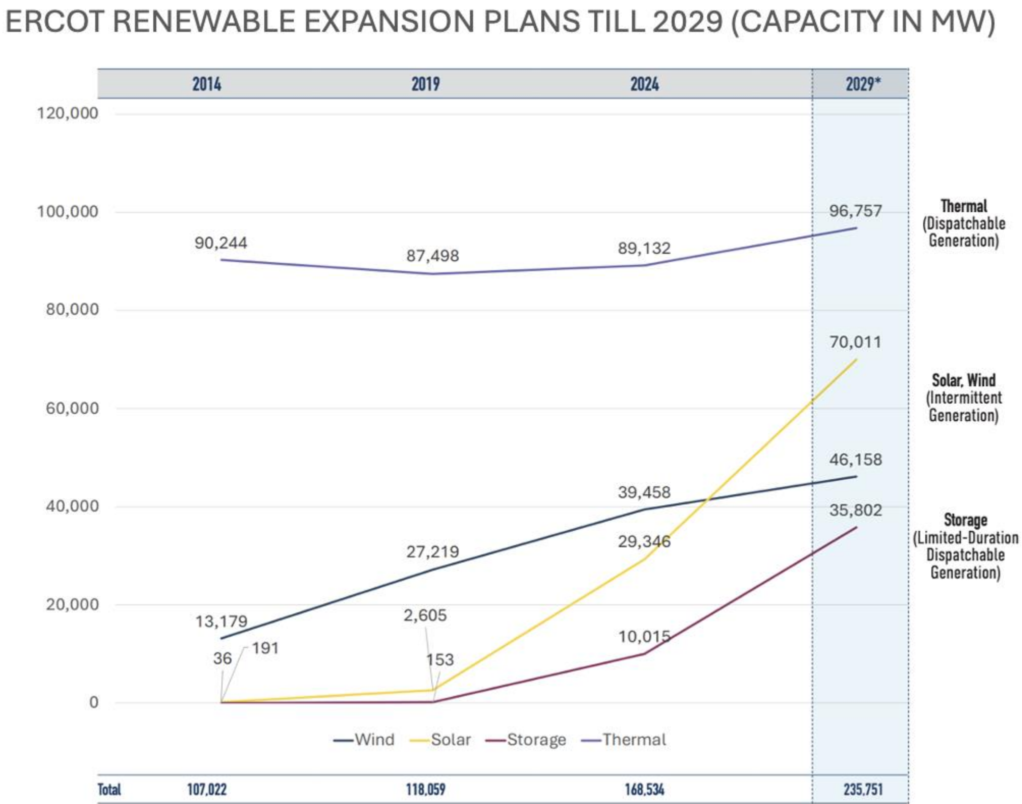
Regulatory allowances for vendor access under warranty and support agreements would benefit from clearer definition, particularly with respect to remote connectivity, update authority, and operational control boundaries. As currently structured, these arrangements may permit ongoing vendor interaction with critical systems in ways that are not fully visible or consistently governed. Establishing clearer limits and oversight mechanisms for such access can help reduce the risk of unintended external influence over inverter-based resources during operations.

Disclosure on Use of AI Tools

This report made limited use of AI-assisted tools, namely ChatGPT based on GPT-5.3 and Gemini 3 for language refinement and editing. All analysis, interpretations, and conclusions are solely those of the author.

5. Appendix

Appendix A: ERCOT's Projected Capacity Expansion Till 2029



Source: ERCOT 2024 State of the Grid Report

Appendix B: Technical Functionality and Cyber Risk Vectors of IBRs

Inverter-Based Resources (IBRs) are renewable energy technologies (solar, wind, battery) that use inverters to convert direct current (DC) power to grid-compatible alternating current (AC) for the electrical grid (IEA PVPS, 2025). Beyond this core function, modern solar inverters perform a wide range of additional tasks, including real-time control of the solar array, measurement of electrical parameters on both the DC and AC sides, system monitoring and protection, and communication with grid operators and users. As a result, inverters are not passive devices but digitally controlled systems that actively shape grid behavior and stability. (Mallwitz & Engel, 2010)

At the center of this functionality is the inverter's firmware, the embedded software that provides low-level control over the inverter's hardware. In solar and energy storage systems, firmware governs power flow from solar panels, optimizes the charging and discharging of high-performance LiFePO4 batteries, and ensures seamless communication between all system components. (Anern, 2025) Because this firmware is proprietary, it is developed and maintained exclusively by the manufacturer, who remain the sole entity with access to and understanding of the underlying code. Firmware updates, crafted by the manufacturers, are essential for improving system performance through enhanced control algorithms, addressing cybersecurity vulnerabilities through patches, and ensuring compliance with evolving grid codes and regulatory requirements.

However, where there is connectivity, there is vulnerability. As inverters become increasingly networked, they also introduce the threat of cyber-attacks. While the compromise of a single inverter is unlikely to significantly affect grid operations, coordinated attacks on large numbers of inverters can have systemic consequences. These may include cascading generation losses, voltage and frequency instability, load shedding, or even widespread blackouts. (Musleh et al., 2024)

Several attack vectors illustrate these risks. Examples include malicious firmware reconfiguration, where attackers exploit insecure update mechanisms or supply chain weaknesses to alter inverter behavior. This can occur at multiple stages of the supply chain, including manufacturing, transportation, installation, maintenance, or through the deployment of compromised updates, allowing adversaries to override grid commands or mask true operating conditions. A related but more targeted approach involves manipulating protection settings, such as fault ride-through parameters, enabling attackers to trigger simultaneous disconnection of large numbers of inverters during routine grid disturbances. Additionally, inverters increasingly function as distributed grid sensors, providing critical data on voltage, current, and system conditions. Attacks that spoof or intercept this data can distort grid visibility and lead to flawed operational decisions, particularly during periods of system stress or emergency response. (Musleh et al., 2024)

Taken together, these characteristics position solar inverters as both essential enablers of modern grid functionality and potential points of systemic risk, particularly when supply chain dependencies, firmware control, and network connectivity intersect.

Appendix C: Development of Solar Power Plants

The development typically begins with the “Power Purchasers”- Google, Amazon, Walmart, are prominent examples- who seek long-term price stability, through a Power Purchase Agreement, for the electricity for their datacenters, industrial facilities, or other large-scale operations. While Developers often initiate the interconnection process independently to establish project viability, the formal contract, drawn between a “Power Purchaser” and a “Developer”, acts as the primary catalyst for full-scale realization. The Developer is the entity responsible for end-to-end project realization, from securing financing, and acquiring land, to arranging permits, and coordinating with all involved regulatory bodies. Once a project reaches a viable stage, it is often transitioned to an “Independent Power Producer (IPP)” or owner-operator, frequently the same entity as the Developer in vertically integrated firms, who manages the project’s long-term commercial life.

The Developers or IPPs leverage the Power Purchase Agreement as evidence to support the potential profitability of the plant in order to secure the primary financing from “Lenders”, which may include private financial institutions as well as public mechanisms.

Developers and IPPs also define the high-level technical specifications for the plant and outsource the execution of the project delivery to “Engineering, Procurement, and Construction” contractors or “EPCs”, who assume the responsibility for detailed engineering, equipment procurement, and plant construction. It is the EPCs who lead general procurement decisions, acting as the “turn-key” delivery agents for the plant. However, the IPP can maintain final approval over key components, like inverters, to ensure long-term fleet compatibility. In industries such as solar power, in which the government is interested in limiting foreign influence, prohibitions may exist on the procurement of equipment from certain jurisdictions. In such cases the Developer or IPP may request the EPC contractor and its subcontractors to provide certificates of origin and supply chain disclosures for all the equipment and services procured. (Steinberg, 2017).

Once construction is complete, the plant must be interconnected with the grid before it can operate commercially. The interconnection process introduces two additional critical actors: the grid operator i.e. ERCOT and the transmission and distribution utilities.

ERCOT manages interconnection at the system level and is responsible for evaluating whether the new plant can be reliably integrated through studies of power flow, fault conditions, and dynamic performance, and by validating control models for compliance with required operating characteristics (ERCOT, 2021).

Transmission and Distribution Service Providers (TDSPs), such as Oncor Electric Delivery and CenterPoint Energy, handle the physical interconnection, verifying that the plant safely integrates with existing grid infrastructure through commissioning rigorous tests such as protection systems, breaker operations, and telemetry validation. (ERCOT, 2026). Once interconnection is complete, ERCOT can dispatch the plant’s electricity to the grid as needed.

Appendix D: Chinese State Influence in Solar PV Industry Magnifies Risk

The dominance of Chinese manufacturers in the solar photovoltaic industry is not solely a function of private sector competitiveness, but rather the result of sustained and far-sighted state support through industrial policy, subsidies, and financing mechanisms over multiple decades. Through their 12th and 13th Five-Year Plans and the "Made in China 2025" initiative, China designated renewable energy as a "Strategic Emerging Industry" (Lewis, 2023). This designation was followed by massive capital injections into the sector and ultimately enabled Chinese firms to achieve their current unrivaled scale in the solar PV industry (Hart, 2020).

At the same time, the structure of China’s solar industry reflects a system in which channels of both indirect and direct state influence are embedded within their private firms. Manufacturers such as Huawei and Sungrow are reported to maintain deep links to the state, with several executives holding concurrent positions within the CCP or regional People's Congresses (Strider Technologies, 2025). Such interweaving of responsibilities acts to blur the boundaries between private commerce and national mandate. This dynamic is further reinforced by requirements under Chinese law, which mandate the establishment of internal CCP cells within private enterprises, granting the state a formalized "soft power" mechanism to exert influence over corporate governance (Goldenziel, 2023).

Beyond these indirect channels, under the 2017 National Intelligence Law (Article 7), all Chinese organizations are legally required to "support, assist, and cooperate with national intelligence efforts," constituting a direct mechanism of state intervention. The 2021 Data Security Law and 2023 Counter-Espionage Law further mandate firms to provide the state with access to data and systems upon request.

Appendix E: The Precautionary Principle for Choosing H_0 and H_1

Consistent with engineering management decision frameworks, the project will evaluate the potential consequences of Type I and Type II decision errors:

- Type I Error ("False Alarm"): Overestimating supply chain vulnerability and recommending unnecessary mitigation investments.
- Type II Error ("No Alarm"): Underestimating supply chain exposure and failing to identify meaningful infrastructure risk.

Our hypotheses have been formulated in accordance with the "Precautionary Principle" which reverses the burden of proof, prioritizing the prevention of potential harm in situations where scientific evidence may be uncertain (Keiding & Budtz-Jørgensen, 2004). Conventionally, the null hypothesis is framed as "no effect" or "safe". It is the alternate hypothesis that supposes hazards. The evidence of harm then has to be substantial enough to reject the "safe" null hypothesis. However, applying the precautionary principle shifts this structure. The conventional null hypothesis (H_0: no effect/safe) is replaced with a "precautionary" null hypothesis (H_0: hazardous), the rejection of which requires considerable evidence that supports the "safe" alternate hypothesis.

This approach is intentional and is often observed in domains where there is a greater priority placed upon avoiding a Type II Error compared to a Type I, such as in the environmental and public health sectors. In this context, of the two possible types of errors, we have explicitly assumed that the State of Texas has greater concerns regarding the No Alarm error of underestimating our level of exposure, than the False Alarm error of overestimating vulnerability.

Given the critical nature of infrastructure security, this approach is warranted. A No Alarm error in this setting constitutes failing to identify and therefore mitigate infrastructure risk under geopolitical disruptions, potentially leading to severe system-level consequences.

6. References

1. Abdelhady, M., Iakovou, E., Pistikopoulos, E. N., & Robertson, R. (2025, November). Meeting rising U.S. electricity demand from AI and data centers: An integrated technical and policy perspective. Texas A&M Energy Institute. https://oaktrust.library.tamu.edu/server/api/core/bitstreams/9e3a2987-b802-4d25-8083-21d7aafdcbec/content
2. Barlow, I., Stewart, E. M., & Culler, M. J. (2024, December). Analysis of supply chain challenges in the U.S. solar industry: Focus on Build America, Buy America Act and inverter supply issues. Idaho National Laboratory. https://inldigitallibrary.inl.gov/sites/STI/STI/Sort_147618.pdf
3. BloombergNEF. (2026, February 19). Corporate clean energy buying fell in 2025 after nearly a decade of growth. https://about.bnef.com/insights/clean-energy/corporate-clean-energy-buying-fell-in-2025-after-nearly-a-decade-of-growth/
4. Du, P. (2023). Renewable integration at ERCOT. In Renewable energy integration for bulk power systems. Springer. https://doi.org/10.1007/978-3-031-28639-1_1
5. Electric Reliability Council of Texas. (n.d.). Company profile. https://www.ercot.com/about/profile
6. Electric Reliability Council of Texas. (2021, December 17). ERCOT planning guide. www.ercot.com/files/docs/2021/12/15/December_17_2021_Planning_Guide.pdf
7. Electric Reliability Council of Texas. (2025, December 12). Confirm Market Participants' affiliates and Lone Star Infrastructure Protection Act (LSIPA) attestation by January 30, 2026, for LSIPA compliance purposes (M-B121225-01). https://www.ercot.com/services/comm/mkt_notices/M-B121225-01
8. Electric Reliability Council of Texas. (2026, February 1). ERCOT planning guide. https://www.ercot.com/files/docs/2026/01/29/February-1-2026-Planning-Guide.pdf
9. Electric Reliability Council of Texas. (2026, March). ERCOT fact sheet. https://www.ercot.com/files/docs/2022/02/08/ERCOT_Fact_Sheet.pdf
10. Electric Reliability Council of Texas. (n.d.). Nodal protocols. https://www.ercot.com/mktrules/nprotocols/current
11. Electric Reliability Council of Texas. (n.d.). Resource entities. https://www.ercot.com/services/rq/re
12. Goldenziel, J. I. (2023, February 27). Chinese Communist Party demands employees at Western firm show their support. Forbes. https://www.forbes.com/sites/jillgoldenziel/2023/02/27/chinese-communist-party-demands-employees-at-western-firm-show-their-support/
13. Hart, D. M. (2020, October 5). The impact of China’s production surge on innovation in the global solar photovoltaics industry. Information Technology and Innovation Foundation. https://www2.itif.org/2020-china-solar-industry.pdf

14. International Energy Agency. (2022). Special report on solar PV global supply chains. OECD Publishing. https://iea.blob.core.windows.net/assets/d2ee601d-6b1a-4cd2-a0e8-db02dc64332c/SpecialReportonSolarPVGlobalSupplyChains.pdf

15. International Energy Agency Photovoltaic Power Systems Programme. (2025). Trends in photovoltaic applications 2025. https://iea-pvps.org/wp-content/uploads/2025/10/IEA-PVPS_Trends_2025-.pdf

16. International Finance Corporation. (2022). Utility-scale solar photovoltaic power plants: A project developer's guide. World Bank Group. https://ppp.worldbank.org/sites/default/files/2022-03/IFC_Solar_Report_Web__08_05.pdf

17. Keiding, N., & Budtz-Jørgensen, E. (2004). The Precautionary Principle and statistical approaches to uncertainty. International journal of occupational medicine and environmental health, 17(1), 147–151.

18. Lewis, J. I. (2023). Cooperating for the climate: Learning from international partnerships in China's clean energy sector. MIT Press.

19. Mallwitz, R., & Engel, B. (2010). Solar power inverters. In 2010 6th International Conference on Integrated Power Electronics Systems (pp. 1–7). IEEE. https://ieeexplore.ieee.org/document/5730644

20. Mehos, M., Price, H., Cable, R., Kearney, D., Kelly, B., Kolb, G., & Morse, F. (2020, June). Concentrating solar power best practices study. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy20osti/75763.pdf

21. Musleh, A. S., et al. (2024). Experimental cybersecurity evaluation of distributed solar inverters: Vulnerabilities and impacts on the Australian grid. IEEE Transactions on Smart Grid, 15(5), 5139–5150. https://doi.org/10.1109/TSG.2024.3393439

22. OECD. (2026). Subsidies and the solar panel industry: Too close to the sun (OECD Policy Briefs No. 47). OECD Publishing. https://doi.org/10.1787/68481900-en

23. Steinberg, H. M. (2017). Understanding and negotiating EPC contracts (Vol. 1): The project sponsor's perspective. Routledge.

24. Strider Technologies. (2025, November). In broad daylight: U.S. grid exposed to risk from PRC-manufactured inverter equipment. https://content.striderintel.com/wp-content/uploads/2025/11/Strider-Report-In-Broad-Daylight-2025.pdf

25. U.S. Energy Information Administration. (2025, October 24). Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=66464

26. U.S.–China Economic and Security Review Commission. (2024). 2024 annual report to Congress. https://www.uscc.gov/annual-report/2024-annual-report-congress

27. Wood Mackenzie. (2025, July 10). Global PV inverter shipments grew by 10% in 2024 to 589 GWac. https://www.woodmac.com/press-releases/global-pv-inverter-shipments-grew-by-10-in-2024-to-589-gwac/

28. Wu, B. (2025, September 3). Firmware updates & remote monitoring. Anern. https://www.anernstore.com/blogs/diy-solar