Applied Journal of Economics, Law and Governance https://doi.org/10.57017/ajelg.v1.i2(2).03

Strategic Grid Modernization for Enhanced Energy Security and Industrial Competitiveness: A Multi-Pillar Framework for the United States

Noah PARSONS
Civic Innovation, American Forge Institute, United States
https://orcid.org/0009-0000-7224-6040

Abstract

The United States electrical grid confronts unprecedented challenges from surging demand, cybersecurity threats, and climate-related disruptions. This paper presents a comprehensive strategic framework for grid modernization organized around three interdependent pillars: technological innovation and deployment, regulatory reform and workforce development, and strategic public-private partnerships. Through detailed analysis of legal barriers, including federal-state jurisdictional conflicts under the Federal Power Act, transmission siting authority limitations, and cybersecurity regulatory gaps, we identify specific legislative and regulatory instruments required for implementation.

The framework proposes establishing a Federal Grid Modernization Authority with hybrid public-private governance structures, incorporating risk-sharing mechanisms and performance-based incentives. Economic analysis demonstrates that proactive modernization investments of $300-400 billion over ten years compare favorably with an estimated $1 trillion in expected costs of continued underinvestment over the same period, giving an illustrative benefit-cost ratio of 4.4:1. Drawing on comparative international analysis and synthesizing current policy gaps, our phased implementation strategy projects that achieving 80% renewable integration, 99.97% grid reliability, and elimination of foreign dependency for critical components is feasible within a ten-year horizon given appropriate policy support and investment frameworks.

Keywords: grid modernization, energy security, renewable, cybersecurity, industrial competitiveness.

JEL Classification: L94; Q42; Q48; K23; H54; O33.

Introduction

The United States electrical grid, constructed primarily during the mid-20th century to support centralized fossil fuel generation, now confronts a convergence of systemic pressures (NERC, 2024). American electricity demand is experiencing its most robust growth in decades, with projections indicating growth of about 25% by 2030 relative to 2023 driven by data center proliferation, artificial intelligence processing requirements, and growth in manufacturing (US EIA, 2025a; ICF International, 2025). Concurrently, the retirement of baseload generation capacity creates supply-demand mismatches that threaten grid stability and industrial competitiveness. Sustained power interruptions cost US electricity customers an estimated $44 billion annually (LaCommare et al., 2018), representing a substantial drag on economic productivity. This expansion occurs against a backdrop of escalating cybersecurity threats and climate-related disruptions. Cyberattacks targeting utility infrastructure have prompted Federal Energy Regulatory Commission (FERC) to propose enhanced Critical Infrastructure Protection

standards requiring entities to identify supply chain risks and implement internal network security monitoring (FERC, 2024a).

Hurricane Maria and Hurricane Fiona caused island-wide power outages in Puerto Rico, resulting in combined economic losses of approximately $118 billion (NOAA NCEI, n.d.), while the Texas winter storm in 2021 left more than 4.5 million people in Texas without power (FERC et al., 2021), causing 246 deaths (Texas Department of State Health Services, 2021) and economic losses estimated at $80-130 billion (Donald, 2021). These events demonstrate how infrastructure vulnerabilities compound into humanitarian and economic crises.

While existing literature addresses individual components of grid modernization, smart grid technologies, transmission expansion, or cybersecurity frameworks (Goudarzi et al., 2022; Brown & Botterud, 2021), few studies synthesize these elements into an integrated strategic framework that addresses technological, regulatory, institutional, and workforce dimensions simultaneously. In the European Union alone, the European Commission (2023) estimates that €584 billion of grid investment is needed by 2030, yet implementation mechanisms remain underspecified.

This paper fills critical gaps by providing: (1) detailed analysis of legal and regulatory barriers impeding grid modernization, including specific federal-state jurisdictional conflicts and remedial legislative instruments; (2) comprehensive institutional design for a Federal Grid Modernization Authority with explicit governance structures and risk allocation frameworks; (3) rigorous cost-benefit analysis comparing proactive modernization investments against catastrophic failure scenarios; and (4) phased implementation with measurable outcomes suitable for policy evaluation.

This policy analysis synthesizes data from multiple authoritative sources including the US Energy Information Administration, Department of Energy, Federal Energy Regulatory Commission, North American Electric Reliability Corporation, and International Energy Agency. We employ comparative analysis of grid modernization approaches in China, the European Union, and the United States, examining investment levels, technological strategies, and policy frameworks. Legal analysis draws on Federal Power Act jurisprudence, FERC orders, and recent transmission siting legislation. Our recommendations derive from systematic evaluation of current policy gaps, technological capabilities, international best practices, and institutional design principles for public-private infrastructure development. This policy analysis employs a multi-method approach integrating quantitative analysis, comparative case studies, legal analysis, and institutional design principles. Our methodology addresses the complex, multi-dimensional nature of grid modernization through systematic evaluation of technological capabilities, policy instruments, economic costs and benefits, and implementation feasibility.

1. Literature Review

The academic and policy literature on grid modernization has evolved significantly over the past decade, driven by technological advances, climate imperatives, and security concerns. Early work focused primarily on smart grid technologies and their potential for demand response and distributed generation integration (Goudarzi et al., 2022). More recent scholarship examines the intersection of renewable energy deployment, transmission constraints, and market design, with Brown & Botterud (2021) demonstrating the substantial value of inter-regional coordination in decarbonizing the electricity system.

The transmission planning literature has increasingly emphasized the need for proactive, long-term approaches that anticipate rather than merely respond to generation changes. Pfeifenberger et al. (2021) provide comprehensive guidance on cost-benefit analysis for interregional transmission projects, highlighting methodological challenges in capturing option value and resilience benefits. The National Academies (2021) synthesized technical and policy challenges facing the US electric power sector, calling for coordinated federal action to address jurisdictional barriers and investment gaps.

Energy storage research has matured substantially, with Sepulveda et al. (2021) characterizing the design space for long-duration storage in decarbonized systems and identifying technology pathways beyond lithium-ion batteries. The Department of Energy's commercial liftoff reports (US DOE, 2023) assess market barriers and policy interventions required to achieve cost competitiveness for emerging storage technologies.

Cybersecurity literature increasingly treats grid infrastructure as a critical vulnerability requiring comprehensive frameworks beyond traditional information technology approaches. CTIIC (2024) documents escalating attacks on US infrastructure, and US DOE (2022) sets out the expanding attack surface created by digitalization and distributed energy resources.

Comparative international studies provide valuable insights into alternative governance models and policy instruments. China's ultra-high voltage transmission deployment demonstrates technical feasibility of long-distance power transfer (Liu, 2015), while the European Union's coordinated planning through ENTSO-E offers a model for multi-jurisdictional cooperation (IEA, 2024). The UK's competitive tendering for offshore transmission (Offshore Transmission Owner regime) illustrates effective public-private partnership structures for infrastructure development.

Recent modeling exercises project pathways to deep decarbonization of the US electricity system. Larson et al. (2021) and Williams et al. (2021) demonstrate technical feasibility of net-zero emissions by mid-century but emphasize transmission expansion as a critical enabling factor. Jenkins et al. (2022) assess the climate and energy impacts of recent federal legislation, identifying remaining policy gaps for achieving ambitious climate targets.

Despite this rich literature, significant gaps remain. Few studies integrate technological, regulatory, institutional, and workforce dimensions into a coherent implementation framework. Cost-benefit analyses often focus narrowly on energy system costs while neglecting catastrophic failure risks and broader economic impacts. Institutional design proposals tend toward either purely market-based solutions that ignore coordination failures or highly centralized models incompatible with US federalism. This paper addresses these gaps by synthesizing insights across disciplines while proposing concrete legislative, regulatory, and institutional mechanisms for implementation.

2. Data Collection and Sources

We synthesize data from authoritative government, international, industry, and research sources to ensure reliability and policy relevance:

- Government sources: US EIA, DOE, FERC, NERC, NOAA, CDC, relevant state agencies, CTIIC, and CISA, covering electricity demand, grid reliability, cybersecurity, regulatory frameworks, and disaster impacts.
- International sources: IEA, European Commission, Ofgem, and Enerdata, providing insights into energy markets, grid investments, and international regulatory practices.

- Industry and research sources: The Brattle Group, Grid Strategies, Lawrence Berkeley National Laboratory, ICF International, Lloyd's, Cambridge Centre for Risk Studies, Climate Central, Clean Air Task Force, DIHK, and Princeton University, supporting analyses of transmission economics, infrastructure resilience, industrial competitiveness, and decarbonization pathways.

Data collection focused on six domains: (1) electricity demand projections and drivers, (2) infrastructure performance metrics and investment levels, (3) cybersecurity incidents and regulatory frameworks, (4) international grid modernization approaches, (5) technology costs and performance, and (6) legal and regulatory barriers. We prioritized sources published from 2021-2025 to capture current conditions while incorporating seminal earlier work where appropriate.

Analytical Frameworks

We develop a comprehensive economic assessment comparing modernization investment costs against multiple benefit categories: avoided catastrophic failures (estimated using historical event costs and probability assessments), avoided chronic costs (annual outages, congestion), and direct economic benefits (job creation, industrial competitiveness, technology exports). The analysis employs a 10-year time horizon with 7% discount rate the real rate prescribed by the 1992 OMB Circular A-94 for evaluating federal programs, which OMB reinstated in 2025 (Office of Management and Budget, 2025). Sensitivity analysis tests robustness under alternative assumptions about catastrophic event probabilities.

We examine grid modernization approaches in three jurisdictions: China (centralized state-led model), European Union (coordinated multi-national model), and United Kingdom (competitive market-based model for offshore transmission). Case selection provides maximum variation in institutional structures and policy instruments while ensuring relevance to US context. For each case, we analyze governance structures, investment levels and sources, technology strategies, regulatory frameworks, and performance outcomes. Synthesis identifies transferable lessons while accounting for institutional differences.

We systematically evaluate legal barriers through examination of: Federal Power Act statutory provisions and case law, FERC regulatory proceedings and orders, state public utility commission authorities, transmission siting processes and timelines, cybersecurity regulatory frameworks (NERC CIP standards), and interstate coordination mechanisms. Analysis identifies specific statutory conflicts, regulatory gaps, and procedural barriers requiring legislative or regulatory remediation. We propose specific legal instruments (statutory amendments, regulatory rulemakings) with attention to constitutional constraints and federalism principles.

Drawing on public administration and infrastructure governance literature, we develop design principles for the proposed Federal Grid Modernization Authority: governance structures balancing stakeholder representation with technical expertise, authority allocations respecting federal-state jurisdictional boundaries, financial mechanisms enabling public-private partnerships, risk allocation frameworks appropriate to project characteristics, and performance accountability mechanisms. Design proposals incorporate lessons from analogous institutions (Tennessee Valley Authority, US Army Corps of Engineers, state infrastructure banks) while adapting to grid modernization's unique requirements.

Phased Implementation Framework Development

We develop a detailed implementation timeline organizing actions across three phases over ten years. The framework specifies: legislative actions (bills required, timing, cost estimates), regulatory agency actions (FERC rulemakings, DOE initiatives, DHS/CISA programs), institutional development milestones (FGMA establishment and operationalization), infrastructure deployment targets (transmission miles, storage capacity, smart grid penetration), and performance metrics (reliability improvements, economic outcomes, security achievements). Phase sequencing reflects legislative and regulatory prerequisites for later phases, technological learning curves and supply chain development requirements, workforce development timelines, and political economy considerations regarding demonstration of early benefits.

Limitations and Mitigation Strategies

Our methodology confronts several inherent limitations. Cost estimates derive from analogous projects and industry benchmarks rather than detailed engineering studies for specific facilities; we address this through conservative assumptions and sensitivity analysis examining cost variations of ±30%. Catastrophic failure probability estimates involve substantial uncertainty; we employ historical event frequencies and expert assessments while acknowledging the difficulty of predicting rare events. International comparisons may not fully capture institutional and market structure differences affecting technology transfer; we explicitly discuss these differences and conditions for successful adaptation. Political feasibility assessment remains qualitative; future research should employ stakeholder analysis and political economy modeling. Technology uncertainty regarding breakthrough innovations could alter optimal pathways; our framework emphasizes flexibility and periodic reassessment rather than rigid technology mandates.

Despite these limitations, our multi-method approach provides robust foundations for policy development. Integration of quantitative economic analysis, qualitative institutional assessment, and detailed legal analysis offers comprehensive understanding of grid modernization challenges and implementation pathways. Reliance on authoritative government and peer-reviewed sources ensures data quality and policy credibility. Comparative international analysis broadens the evidence base beyond US experience. The framework's specificity regarding legislative language, regulatory actions, and institutional structures facilitates translation from analysis to implementation.

3. Strategic Challenges

Demand Growth and Industrial Competitiveness

US electricity consumption, roughly flat for nearly two decades, has risen since 2020: the US Energy Information Administration expects average growth of 1.7% a year between 2020 and 2026 (US EIA, 2025a), and ICF International (2025) projects demand 25% above 2023 levels by 2030 and 78% above by 2050. This acceleration reflects structural economic shifts: data center electricity demand alone is projected to double or triple by 2028 (US DOE, 2024a), while commercial sector consumption grows at 2.6% annually (US EIA, 2025a).

Table 1: Projected US Electricity Demand Growth

Period	Projected growth	Measured as	Source
2020-2026	1.7%	Average per year, all sectors	US EIA (2025a)
2020-2026	2.6%	Average per year, commercial sector	US EIA (2025a)
2023-2030	25%	Increase on 2023 demand	ICF International (2025)
2023-2050	78%	Increase on 2023 demand	ICF International (2025)

Sources: US EIA (2025a), ICF International (2025)

For American manufacturers, reliable and affordable electricity constitutes a strategic input determining competitive advantage. Grid congestion alone cost consumers an estimated $20.8 billion in 2022 (Shreve et al., 2024), while grid instability and price volatility directly undermine domestic manufacturing investment, a pattern visible in Germany, where 37% of industrial firms, and 45% of those with high electricity costs, report considering restricting production at home or relocating it abroad because of energy costs (DIHK, 2024).

Cybersecurity Threat Landscape

The grid represents perhaps the most attractive target for nation-state adversaries and sophisticated criminal organizations. Check Point Research documented 1,162 cyberattacks on US utilities in 2024, a 70% increase on the previous year (Kansas Legislative Research Department, 2024). The 2021 Colonial Pipeline ransomware attack demonstrated both infrastructure vulnerability and cascading economic impacts, including fuel shortages along the East Coast (Easterly & Fanning, 2023).

FERC recently proposed directing the North American Electric Reliability Corporation to require entities to identify current supply chain risks to grid-related cybersecurity systems at specified intervals, assess and validate vendor information accuracy, and document and respond to system risks (FERC, 2024a). On June 26, 2025, FERC approved Reliability Standard CIP-015-1 (Order No. 907) requiring internal network security monitoring inside entities' electronic security perimeters, with plans to extend these protections outside the perimeter to electronic access control systems and physical access control systems (FERC, 2025). Renewable energy integration introduces additional attack surfaces. Each distributed solar installation, wind farm, and battery storage system represents a potential entry point for malicious actors (US DOE, 2022). The digitization necessary for grid modernization paradoxically expands vulnerability even as it enhances operational capability.

Climate Resilience Imperatives and Economic Costs

The average annual number of weather-related power outages in the United States rose by roughly 78% in 2011-2021 compared with 2000-2010 (Climate Central, 2022). The 2020 extreme weather events cost the US a combined $95 billion (NOAA, 2021), while the Pacific Northwest heatwave resulted in 3,504 heat-related emergency department visits in May and June 2021, most of them between 25 and 30 June (Schramm et al., 2021). The February 2021 Texas winter storm caused estimated economic losses of $80-130 billion (Donald, 2021).

These disruptions not only threaten immediate public safety but erode confidence in American infrastructure among domestic and international investors. Climate-related challenges will intensify as weather patterns become more volatile. Building resilience into grid infrastructure represents not merely an environmental policy choice but a national security imperative protecting American communities and economic stability.

4. Legal and Regulatory Barriers: Detailed Analysis

4.1 Federal-State Jurisdictional Conflicts Under the Federal Power Act

The Federal Power Act (FPA) of 1935 establishes a dual regulatory framework creating fundamental barriers to grid modernization. Under FPA Section 201(b)(1) (16 U.S.C. § 824(b)(1)), states exercise authority over generation facilities and local distribution, while FERC regulates interstate wholesale electricity sales and transmission. This division, arising from the Supreme Court's Public Utilities Commission v. Attleboro Steam & Electric Co. (273 US 83, 1927) decision, creates the "Attleboro gap", areas of regulatory vacuum enabling project delays.

FERC possesses authority over rates and terms of transmission lines but critically lacks authority to direct transmission facility siting, a gap that paralyzes interstate projects. The Energy Policy Act of 2005 attempted remediation through limited backstop siting authority in National Interest Electric Transmission Corridors (NIETCs), but the Fourth Circuit's Piedmont Environmental Council v. FERC (558 F.3d 304, 2009) decision held that this backstop authority does not apply where a state has denied a permit. The Infrastructure Investment and Jobs Act of 2021 amended Section 216 to reverse that holding, and FERC implemented the change in Order No. 1977 (FERC, 2024c), but the authority still applies only within corridors DOE has designated, and DOE's designation process that began in 2023 ended without designating any (US DOE, n.d.). Construction remains slow: just 322 miles of 345 kV and higher transmission were completed in 2024, the third slowest year in 15 years, against an estimated need of about 5,000 miles a year derived from DOE's National Transmission Planning Study (Shreve et al., 2025; US DOE, 2024b).

Interstate coordination failures compound these barriers. FERC Order No. 1920 (May 2024) mandates 20-year transmission planning, yet implementation depends on voluntary RTO cooperation. With RTO boundaries crossing state lines and some states divided among multiple RTOs, jurisdictional complexity creates coordination deadlock absent compulsory mechanisms (FERC, 2024b).

4.2 Cybersecurity Regulatory Gaps

NERC Critical Infrastructure Protection (CIP) standards, currently in their fifth iteration, establish requirements for access control, physical security, and incident response for bulk electric systems operating at 100 kV or higher. However, critical gaps persist generation facilities under 20 MW face only partial coverage, reactive rather than proactive standards predominate, and supply chain vulnerabilities remain largely unaddressed despite FERC's September 2024 proposed enhancements (FERC, 2024a). The enforcement regime lacks adequate resources, with NERC relying on Regional Entities of varying capability, while penalties prove insufficient deterrents given catastrophic consequences of successful attacks estimated at $243 billion to more than $1 trillion for a single modeled attack on the northeastern grid (Lloyd’s & University of Cambridge Centre for Risk Studies, 2015).

Federal environmental reviews alone took an average of 4.3 years for transmission projects reviewed in 2010-2020, more than twice the two-year schedule DOE now sets under its CITAP program, before state siting and construction begin (Manitius et al., 2024). Delays arise from: multiple agency jurisdiction (Bureau of Land Management, Forest Service, Department of Defense each conducting independent reviews), NEPA Environmental Impact Statement requirements consuming multiple years, and state-level opposition through certificate of need requirements and local zoning. DOE's Coordinated Interagency

Transmission Authorizations and Permits (CITAP) portal offers procedural improvements but cannot overcome fundamental statutory barriers requiring congressional action.

5. Required Legislative and Regulatory Instruments

5.1 Federal Legislative Actions

Congress must enact three coordinated legislative initiatives employing distinct legal instruments with specified economic trade-offs.

Comprehensive Transmission Reform Act

Act of Congress amending Federal Power Act Section 216 and Section 201 (federal jurisdiction definition). Statutory provisions required:

- Amend FPA Section 216(b) to authorize FERC to issue transmission permits in NIETCs where state approval has been denied or pending exceeding 180 days, eliminating state veto while preserving environmental review under NEPA.
- Designate DOE as lead agency under 42 U.S.C. § 4336a with authority to establish 18-month maximum timelines for Environmental Impact Statements and coordinate all federal approvals using "one federal decision" framework similar to FAST-41 (42 U.S.C. § 4370m).
- Enable states to form binding transmission compacts under Article I, Section 10 of US Constitution with congressional consent, providing dispute resolution through compact commission similar to Delaware River Basin Commission model (Pub. L. 87-328).
- Building on the 2021 amendments that already allow FERC to act after a state denial, amend FPA Section 216 to shorten the one-year state review period before FERC may act to 180 days and to require DOE to designate NIETCs on a fixed statutory schedule, while preserving environmental review under NEPA.

Reduced state sovereignty over transmission siting creates political opposition but enables cost reductions. Pfeifenberger et al. (2021) document that proactive, multi-value planning delivers benefits well above costs, with benefit-cost ratios of 2.2-3.4 for MISO's Multi-Value Projects and benefits of about 3.5 times cost for SPP's 2012-2014 upgrades, while congestion cost US consumers an estimated $20.8 billion in 2022 (Shreve et al., 2024). Political costs include state resistance requiring federal preemption; implementation costs approximate $50 million annually for enhanced FERC/DOE coordination.

Grid Modernization Investment Act

Legal Instrument: Congressional appropriations bill under Article I, Section 9 spending authority combined with Internal Revenue Code amendments for tax credits. Funding mechanisms: direct appropriations: $40 billion over 10 years allocated through annual appropriations process; tax incentives: Amend 26 U.S.C. § 48 (Investment Tax Credit) establishing 25% credit for domestic grid component manufacturing, 15% for grid-scale storage deployment, 30% for advanced transmission technologies (HVDC, grid-enhancing technologies), modeled on CHIPS Act 26 U.S.C. § 48D; loan guarantees: Expand 42 U.S.C. § 16513 (DOE Loan Programs Office) authority by $100 billion for transmission and storage projects.

Total federal investment of $117 billion over 10 years under these measures (appropriations $40 billion, tax expenditures $35 billion, and the net cost of bonds and loan guarantees $42 billion) versus the expected costs of continued underinvestment. The

illustrative cost-benefit analysis in Section 9 gives a benefit-cost ratio of 4.4:1 for the full $396 billion program, set against approximately $1 trillion in expected costs of underinvestment over ten years. Political trade-offs include deficit concerns offset by avoided disaster costs; tax credits favor private investment but reduce federal revenue by estimated $35 billion over 10 years.

Domestic Grid Manufacturing Act

Congressional statute establishing domestic content requirements under Commerce Clause authority (Article I, Section 8) and trade remedy provisions under 19 U.S.C. § 1671 (countervailing duties). Core provisions: Federal procurement preferences: Amend 41 U.S.C. § 8301 (Buy American Act) requiring 75% domestic content for grid components in federally funded projects within 5 years, with waiver authority only for national security or unavailability; Manufacturing tax credits: Establish 25% Advanced Manufacturing Production Credit under 26 U.S.C. § 45 times for transformers, inverters, advanced conductors, control systems; Trade enforcement: Authorize countervailing duties under 19 U.S.C. § 1671 on subsidized foreign grid components, with expedited investigation procedures.

We estimate that domestic content requirements would raise initial component costs by 15-25% relative to foreign alternatives, while reducing supply chain vulnerabilities and supporting the 500,000 domestic jobs targeted in Section 8.2, with an estimated $98 billion in associated tax revenue over ten years. Trade enforcement risks WTO disputes but protects critical infrastructure; estimated implementation costs $30 billion over 10 years offset by enhanced economic security, which we value at $50 billion or more (reduced foreign dependency for critical components).

5.2 Regulatory Agency Actions

FERC Rulemakings

Legal instrument. FERC rulemaking authority under 16 U.S.C. § 824e (jurisdiction over transmission rates and services) and 16 U.S.C. § 824o (electricity reliability standards).

Order No. 1920 Implementation: FERC must issue follow-on orders within 12 months establishing compliance filing deadlines, beneficiary-pays cost allocation methodologies with transparent formulas allocating costs proportional to benefits measured through production cost modeling, and cluster study interconnection processes reducing 2,600+ GW queue backlogs by 50% within 3 years (FERC, 2024b).

Enhanced cybersecurity standards. FERC must direct NERC under 16 U.S.C. § 824o(d) to develop modified CIP standards within 12 months mandating: zero-trust network architecture for high/medium-impact BES Cyber Systems, quarterly penetration testing and vulnerability assessments, mandatory incident reporting within 1 hour of detection, and expanded CIP coverage for distributed energy resources above 5 MW aggregate capacity addressing attack surface expansion from renewable integration (CTIIC, 2024).

Economic trade-offs. Compliance costs estimated $50-100 million annually per major utility versus estimated economic losses of $243 billion to more than $1 trillion from a single major attack (Lloyd's & University of Cambridge Centre for Risk Studies, 2015). Rulemaking process requires 12-18 months including notice-and-comment under 5 U.S.C. § 553 (Administrative Procedure Act), creating implementation delays but ensuring stakeholder input and judicial defensibility.

Department of Energy Initiatives

DOE authority under 42 U.S.C. § 7101 et seq. (Department of Energy Organization Act) and 42 U.S.C. § 16513 (loan guarantee authority). Launch $10 billion initiative under 42 U.S.C. § 16352 (technology demonstration programs) supporting long-duration storage (100+ MWh, 10+ hour duration), alternative technologies (compressed air, liquid air, thermal storage), and manufacturing scale-up. Economic trade-off: public R&D investment reduces private sector technology costs 40-60% through learning-by-doing, accelerating commercial deployment 5-7 years versus purely market-driven timelines (US DOE, 2023).

Establish joint DOE-DHS facility under 6 U.S.C. § 659 (CISA cybersecurity authorities) providing real-time threat intelligence, 24/7 incident response, penetration testing services, and best practices development. Operating budget $500 million annually justified because the center's $5 billion ten-year cost is a small fraction of the $243 billion or more estimated for a single major attack (Lloyd's & University of Cambridge Centre for Risk Studies, 2015).

6. Institutional Framework: Federal Grid Modernization Authority

6.1 Governance Structure and Legal Authority

We propose establishing a Federal Grid Modernization Authority (FGMA) through congressional statute as a federally chartered corporation under U.S.C. Title 16 (similar to Tennessee Valley Authority, 16 U.S.C. § 831), combining governmental coordination authority with operational flexibility necessary for complex infrastructure deployment.

Board Composition and Appointment

Governing Board (11 members): 3 Presidential appointees requiring Senate confirmation under Article II, Section 2 (Chair, Vice Chair, Member) serving 6-year staggered terms; 2 FERC Commissioners serving ex officio; 2 State Public Utility Commissioners selected by National Association of Regulatory Utility Commissioners representing diverse geographic regions; 1 DOE Assistant Secretary for Electricity; 1 DHS CISA Director or designee; 1 utility industry representative jointly selected by Edison Electric Institute and American Public Power Association; 1 renewable energy industry representative selected by American Clean Power Association. Staggered terms ensure institutional continuity transcending administration changes while balanced representation addresses federal-state tensions and public-private coordination.

FGMA Powers and Authorities

Planning and coordination powers (16 U.S.C. § XXXX(a)): Develop binding National Grid Modernization Master Plan updated biennially; coordinate regional transmission planning across RTO/ISO boundaries with authority to resolve disputes; identify and designate National Interest Electric Transmission Corridors subject to FERC consistency review; establish mandatory national interoperability and cybersecurity standards.

Financial Powers (16 U.S.C. § XXXX(b)): Administer Grid Modernization Investment Fund receiving congressional appropriations; issue up to $100 billion in federally backed bonds with full faith and credit guarantee, carrying the same credit standing as US Treasury securities; provide loan guarantees covering 80% of debt service for investment-grade projects; operate Grid Component Manufacturing Initiative with grant and technical assistance programs.

Regulatory and Enforcement Powers (16 U.S.C. § XXXX(c)): Approve or deny transmission siting applications in NIETCs with decisions subject to judicial review only in U.S. Court of Appeals for D.C. Circuit under substantial evidence standard; set performance standards for federal funding recipients with authority to withhold payments for non-compliance; enforce cybersecurity requirements for federally supported projects; resolve interstate disputes regarding cost allocation through binding arbitration.

Relationship to Existing Agencies

FGMA complements rather than replaces existing agencies through carefully delineated authority boundaries: FERC retains exclusive jurisdiction over wholesale electricity rates under 16 U.S.C. § 824d, transmission service terms and conditions, and reliability standards development, with FGMA siting decisions subject to FERC consistency review ensuring alignment with federal power policies. State PUCs retain complete authority over retail rates under FPA Section 201(b) (16 U.S.C. § 824(b)), distribution system regulation, and resource adequacy planning, with FGMA exercising backstop siting authority only for interstate transmission projects of national significance after state process exhaustion. DOE continues R&D programs under 42 U.S.C. § 16352 while FGMA coordinates commercial deployment and market adoption. RTOs/ISOs maintain operational control of regional grids with FGMA facilitating interregional coordination and resolving disputes preventing multi-regional projects.

6.2 Public-Private Partnership Structure and Risk Allocation

Project Delivery Models

FGMA employs three PPP models adapted to project characteristics and risk profiles.

Model 1, Availability Payment Concessions (greenfield transmission): Private consortium designs, builds, finances, operates, and maintains transmission infrastructure under 25–35-year concession. FGMA makes availability payments based on performance metrics (99.5%-line availability target, transmission capacity delivery). Private sectors bear construction risk (technology, cost overruns), technology obsolescence risk, and operational performance risk. Public sector bears demand risk (payments independent of utilization) and regulatory/political risk. Financial structure: private equity minimum 20%, senior debt 60-70% with federal loan guarantees, subordinated debt 10-20%. Comparable availability-payment concessions include the I-595 Corridor Roadway Improvements (Florida) and the Port of Miami Tunnel (Federal Highway Administration, n.d.-a).

Model 2, Regulated Asset Base (RAB) (grid-scale storage, smart grid deployment): Private sector finances and constructs assets; utility operates under FGMA oversight; costs recovered through regulated charges with performance incentives (±15% revenue adjustments based on availability and response time metrics). Construction risk shared: private sector bears technology and delivery risk (75%), public sector bears material cost and permitting delay risk (25%). Operational risk: utility bears performance risk with incentive regulation. Modeled on UK's Offshore Transmission Owner regime achieving 99%+ availability with 10-15% cost reductions versus incumbent utility estimates (National Academies, 2021).

Model 3 - Merchant Transmission (specific high-value corridors): Private sector bears full project risk (construction, demand, operation) in exchange for market-based transmission rates under FERC Section 205 authority. FGMA provides regulatory certainty through streamlined permitting, access to eminent domain under 16 U.S.C. § XXXX(d), and transmission rights guarantees. Minimal public subsidy but limited to projects with strong

merchant economics. Example: TransWest Express Transmission (Wyoming-Nevada HVDC line under development).

Risk Allocation Framework

The proposed risk allocation framework distributes construction, operational, and financial risks between public and private partners according to their respective capacities to manage them. During construction, the private sector assumes 85% of technology and design risks, including technical failures and construction defects. Regulatory delays are shared between the Federal Grid Modernization Authority (FGMA) (60%) and private partners (40%), depending on their causes, while the public sector provides financial protection against force majeure events through federal disaster relief mechanisms.

During operation, private partners bear full responsibility for performance and availability, subject to contractual penalties and incentives. Demand and revenue risks are transferred to the public sector through availability payments (Model 1) or regulated cost recovery (Model 2), reducing investment uncertainty. Cybersecurity risks are allocated according to causation, with private operators liable for negligence or regulatory noncompliance and the public sector covering sophisticated nation-state attacks occurring despite full compliance with federal security standards.

Financial risk mitigation relies on federal loan guarantees covering 80% of debt service for investment-grade projects (BBB− or higher), potentially reducing the assumed private cost of capital from 8–10% to 4–5%. Minimum private equity contributions are set at 20% for transmission and 30% for storage projects, complemented by performance bonds equivalent to 10% of project costs and a minimum debt service coverage ratio of 1.3×. Together, these mechanisms aim to strengthen financial viability, incentivize private participation, and ensure an equitable distribution of project risks.

6.3 Performance-Based Incentive Mechanisms

PPP contracts incorporate explicit incentives driving innovation and value delivery.

Payment adjustments ±15% based on line availability (99.5% target); penalties $10,000 per hour for unplanned outages plus lost availability payments; bonuses $5,000 per month for sustained performance exceeding 99.7% over 12-month rolling periods. Mechanism aligns private operator interests with public reliability objectives while maintaining proportionate risk-reward balance.

Annual third-party security audits by FGMA-approved firms; payment reductions 5% for audit failures (remediable deficiencies), 10% for security incidents attributable to negligence; bonuses 3% annual premium for exceeding minimum standards, maintaining zero security incidents, and implementing advanced protection beyond requirements. Incentivizes proactive security investment rather than mere compliance.

Gain-sharing where private sector retains 50% of cost savings below approved project budget, encouraging innovation and efficient delivery; cost overruns borne 100% by private sector for first 10% above budget (strong cost discipline), 50-50 sharing thereafter (limiting catastrophic exposure). Comparable efficiency incentives, under which network companies keep a set share of any spending below their allowance and bear a share of any overspend, are a core element of Great Britain’s RIIO price controls (Ofgem, 2010).

6.4 Financing Mechanisms and Fiscal Sustainability

FGMA Revenue Sources

Congressional appropriations $40 billion over 10 years through annual discretionary spending; bond issuance up to $100 billion in federally backed bonds at yields close to those on US Treasury securities and below typical corporate borrowing rates; transmission surcharge $0.50/MWh on all wholesale electricity transactions generating estimated $2 billion annually with minimal consumer impact ($0.40/month average residential); asset recycling revenue through sale-leaseback arrangements with pension funds, sovereign wealth funds, and insurance companies seeking long-term returns, estimated $15 billion over 10 years.

Selection of appropriate financial instruments requires economic analysis of instrument characteristics, costs, and market conditions (Kosov et al., 2016). Private Activity Bonds with tax-exempt status under 26 U.S.C. § 142 reducing borrowing costs 100-150 basis points; infrastructure investment funds partnering with institutional investors (CalPERS, OMERS, Australian Super) targeting $150 billion private capital mobilization; green bonds issued by states, municipalities, and FGMA targeting ESG-focused investors, estimated $30 billion over 10 years.

Financial Sustainability and Return Targets

Target ratio 1.3-1.5x (revenue-to-debt service) ensuring bond repayment capacity; revenue sources diversified across availability payments, transmission tariffs, federal appropriations, and asset recycling; conservative demand projections using 1.5% annual growth (below the 1.7% average annual growth the US EIA (2025a) forecasts for 2020-2026) provide downside protection. Public sector targets break-even to 3% real return focusing on public benefits (reliability, security, economic development) rather than profit maximization; private sector targets 8-12% nominal return competitive with infrastructure equity benchmarks; combined benefit-cost ratio of approximately 4.4:1 when including avoided catastrophic failure costs, reliability improvements, and economic competitiveness benefits (detailed Section 9).

FGMA designed for long-term financial independence post-initial capitalization phase. Years 1-5: federal appropriations provide 70% of funding; Years 6-10: transition to 40% federal, 60% self-generated (bond proceeds, surcharges, asset recycling); Years 11+: fully self-sustaining through combination of surcharges, asset management revenues, and bond refinancing. Model parallels Tennessee Valley Authority achieving fiscal independence while maintaining public mission.

7. Comparative International Analysis

China emphasizes ultra-high voltage transmission and smart grid technologies while aggressively exporting standards and infrastructure; State Grid alone planned to invest CNY 500 billion (about US$70 billion) in grid construction in 2024 (Enerdata, 2024). The European Commission (2023) estimates that €584 billion of investment in EU electricity grids is needed by 2030, much of it for cross-border interconnection and the modernization of aging distribution networks. The United States, where investment is led by individual utilities and varies by region, risks technological dependence and industrial competitiveness erosion without accelerated modernization.

Table 2: Grid Modernization Approaches by Region

Region	Investment	Strategic Focus
China	About US$70 billion planned by State Grid for 2024	UHV transmission, technology export, state-led deployment
European Union	€584 billion by 2030	Cross-border interconnection, digitalization, market integration
United States	Utility-led	Incremental upgrades, regional variation, private sector-led
Rest of World	Varies	Diverse approaches, often constrained by capital availability

Sources: Enerdata (2024); European Commission (2023)

China's state-owned enterprises enable rapid deployment and coordinated planning but limit innovation and transparency. The EU's ENTSO-E coordination respects national sovereignty while enabling market-based mechanisms but faces slower decision-making and uneven implementation. The proposed U.S. FGMA model balances coordination with competition, maintains political feasibility, and allocates risks appropriately while requiring sustained political commitment and guarding against regulatory capture.

Key lessons include centralized planning with decentralized execution as demonstrated by EU's ENTSO-E model, long-term commitment as shown by China's sustained investment in UHV transmission since 2009 (Liu, 2015), early technology standards setting creating network effects, and effective regulated PPPs for transmission as shown by UK's Offshore Transmission Owner regime.

8. Implementation Framework

8.1 Phased Timeline

Phase 1: Foundation Building (Years 1-2) includes enacting Comprehensive Transmission Reform Act and Grid Modernization Investment Act, establishing FGMA, implementing FERC Order No. 1920 compliance requirements and enhanced cybersecurity standards, developing National Grid Modernization Master Plan, launching Grid Cyber Intelligence Center, and establishing first 3 Regional Grid Innovation Hubs. Funding includes congressional appropriations of $3 billion (Year 1) and $5 billion (Year 2), plus FGMA bond issuance of $10 billion (Year 2).

Phase 2: Accelerated Deployment (Years 3-5) involves deploying smart grid infrastructure in 20 major metropolitan areas, initiating construction on 5 National Interest Electric Transmission Corridors (3,000+ miles total), increasing grid-scale storage capacity by 50% over its level at the start of the program, extending advanced metering to all remaining customers, establishing 4 domestic transformer manufacturing facilities and 6 advanced inverter production lines, and achieving 50% domestic content for grid components in federal projects. Funding includes congressional appropriations of $4 billion annually and FGMA bonds of $15 billion annually, mobilizing $60 billion cumulative private sector investment.

Phase 3: System Integration (Years 6-10) completes National Interest Electric Transmission Corridors (10,000+ total miles), achieves 80% renewable energy integration capacity nationwide, deploys 1,000+ community microgrids, reaches 150 GW grid-scale storage capacity, installs advanced distribution management systems serving 90% of US population, achieves 99.97% grid reliability, eliminates single-point failure cascading blackout risk, achieves 100% domestic sourcing for critical grid components, creates 500,000 high-

skilled jobs, positions US as leading grid technology exporter with $100 billion annual exports by Year 10, and establishes 10 Regional Grid Innovation Hubs. Funding includes congressional appropriations of $4 billion annually, FGMA bonds averaging $9 billion annually (decreasing as projects reach operation), $174 billion cumulative private sector investment, and $15 billion asset recycling revenue.

8.2 Performance Metrics and Monitoring

Reliability and resilience metrics include halving average interruption duration excluding major events, which has routinely been about two hours per customer a year, to less than one hour; reducing average interruption frequency from 1.5 per customer in 2024 to less than 0.8 (US EIA, 2025b); achieving 99.97% grid reliability, increasing renewable integration capacity to 80% without curtailment, and achieving 95% service restoration within 48 hours of major weather events.

Economic competitiveness metrics include maintaining industrial electricity prices below OECD average, reducing congestion costs from $20.8 billion to less than $10 billion annually by Year 5, creating 500,000 cumulative high-skilled jobs with average salary of $75,000+, growing grid technology exports to $100 billion annually by Year 10, and achieving $50 billion annual domestic grid component production by Year 8.

Security and independence metrics include achieving 75% domestic content for transmission projects by Year 5 and 100% for critical components by Year 8, achieving zero successful cyberattacks causing more than 1,000 customer-hours of outage annually, achieving 100% of utilities meeting enhanced CIP standards by Year 4, eliminating Chinese-sourced components from critical infrastructure by Year 7, and achieving 75% reduction in weather-related outage duration and frequency by Year 10.

FGMA maintains a performance dashboard with public website displaying real-time metrics, quarterly reports to Congress and state governors, annual independent audits by Government Accountability Office, and performance-based budget adjustments of ±10% based on achievement of milestone targets.

9. Economic Cost-Benefit Analysis

9.1 Investment Requirements

Total estimated investment over a 10-year horizon includes transmission infrastructure ($150 billion: $60 billion public, $90 billion private), distribution modernization ($70 billion: $25 billion public, $45 billion private), grid-scale storage ($80 billion: $30 billion public, $50 billion private), cybersecurity systems ($25 billion: $15 billion public, $10 billion private), domestic manufacturing capacity ($55 billion: $20 billion public, $35 billion private), workforce development ($12 billion: $8 billion public, $4 billion private), and administration and oversight ($4 billion public). Total investment reaches $396 billion, with $162 billion in public and $234 billion private.

Public investment of $162 billion comprises federal appropriations ($40 billion), tax expenditures ($35 billion), the Domestic Grid Manufacturing Act ($30 billion), the net federal cost of federally backed bonds and loan guarantees ($42 billion of $100 billion issued), and state and local contributions ($15 billion). Private investment is mobilized through PPPs, tax incentives, and regulatory frameworks.

9.2 Expected Costs of Continued Underinvestment

Historical single-event costs demonstrate the magnitude of grid failures: Texas Winter Storm Uri (2021) caused $80-130 billion in losses (Donald, 2021), Hurricane Maria (2017) caused $115.2 billion with power system failures contributing substantially, and Hurricane Fiona (2022) caused a further $2.7 billion and another island-wide outage in Puerto Rico (NOAA NCEI, n.d.).

The following scenarios are illustrative: their probabilities and costs are the author's assumptions, informed by the historical events above and by published estimates such as Lloyd's and University of Cambridge Centre for Risk Studies (2015), not outputs of a published model. Projected catastrophic failure scenarios over 10 years without modernization include Scenario 1 (Major Cyberattack on Eastern Interconnection) with 8-12% probability, affecting 70+ million customers for 2-5 days partial restoration and 10-14 days full restoration, causing $900 billion to $1.4 trillion in total costs including direct economic losses, public health impacts, and infrastructure damage. Scenario 2 (Extreme Climate Event with Multi-State Grid Collapse) has 15-20% probability, affecting 30-50 million customers for 5-10 days, causing $380-650 billion in total costs. Scenario 3 (Cascading Failure from Undersized Grid) has 10-15% probability, affecting 20-40 million customers for 3-7 days, causing $250-500 billion in total costs.

Expected value of catastrophic failures totals $252 billion over 10 years, calculated as: Scenario 1 at 10% probability × $1.15 trillion = $115 billion, Scenario 2 at 17.5% probability × $515 billion = $90 billion, and Scenario 3 at 12.5% probability × $375 billion = $47 billion.

Additional chronic costs over 10 years without modernization include annual sustained-outage costs of $44 billion × 10 years = $440 billion (LaCommare et al., 2018), escalating congestion averaging $25 billion annually = $250 billion, and lost manufacturing competitiveness totaling $50 billion. Total chronic costs reach $740 billion. Combined expected costs without modernization total $992 billion over 10 years.

9.3 Return on Investment Analysis

Primary benefits of modernization include avoided catastrophic failures totaling $182 billion (reducing Scenario 1 probability by 75% saves $86 billion, reducing Scenario 2 by 60% saves $54 billion, reducing Scenario 3 by 90% saves $42 billion), avoided chronic costs totaling $420 billion (halving sustained outages saves $220 billion, reduced congestion saves $150 billion, enhanced manufacturing competitiveness saves $50 billion), and direct economic benefits totaling $1.144 trillion (job creation worth $394 billion, industrial productivity improvements worth $200 billion, grid technology exports worth $450 billion cumulative, and energy cost savings worth $100 billion), consistent with empirical findings on infrastructure-driven development impacts (Di Foggia, 2016; Larson et al., 2021).

Total quantifiable benefits reach $1.746 trillion over 10 years. Assuming benefits and costs are spread evenly over the period and discounting at 7%, the present value of benefits is $1.23 trillion and the present value of total costs ($396 billion, public and private) is $278 billion, giving a net present value of $948 billion and an overall benefit-cost ratio of 4.4:1. Because both streams are spread evenly, the ratio does not depend on the discount rate. Measured against public costs alone (present value $114 billion), the ratio is 10.8:1.

Sensitivity analysis demonstrates robustness: halving the benefits from avoided catastrophic failures yields a ratio of 4.2:1, the base case yields 4.4:1, and increasing them by 50% yields 4.6:1; a 30% cost overrun lowers the base-case ratio to 3.4:1, and excluding the direct economic benefits, the least certain category, lowers it to 1.5:1. Even in pessimistic scenarios with significantly lower catastrophic event probabilities, the framework demonstrates strong positive returns driven by chronic cost reductions and direct economic benefits.

Benefits accrue across stakeholder groups: households receive $221 billion (reduced outage and catastrophic-failure losses $161 billion, lower bills $60 billion); industrial and commercial sectors receive $681 billion (reduced business interruption $241 billion, lower electricity prices and congestion costs $190 billion, productivity and manufacturing competitiveness $250 billion); workers and government receive $394 billion from job creation, including associated tax revenue; and private sector investors achieve 8-12% target returns plus $450 billion in grid technology export revenues.

Cost distribution: public sector $162 billion ($147 billion federal, $15 billion state and local), financed through general revenues $100 billion, transmission surcharges $20 billion, asset recycling $15 billion and bond proceeds $27 billion; private sector $234 billion, of which an estimated $112 billion is recovered from ratepayers through regulated rates (if recovered in proportion to retail sales, about $2.40 a month for the average residential customer and about $0.003/kWh for commercial and industrial customers; US EIA, n.d.).

Equity considerations: propose 25% bill assistance for households below 150% federal poverty level ($12 billion over 10 years); minimum 15% FGMA funding directed to rural projects; priority resilience upgrades in environmental justice communities; workforce development prioritizes displaced fossil fuel workers ensuring just transition.

Conclusion

The modernization of the United States electrical grid has become increasingly important for energy security, economic stability, and industrial competitiveness. Growing electricity demand, aging infrastructure, cybersecurity threats, and the transition toward more diversified energy sources have exposed weaknesses that cannot be addressed through technological improvements alone. This study has argued that meaningful progress requires a coordinated approach bringing together technological innovation, regulatory reform, and public-private investment. The proposed Strategic Grid Modernization Framework seeks to connect these elements within a practical policy agenda, recognizing that infrastructure development depends as much on effective institutions and investment conditions as it does on technological capabilities.

The economic analysis suggests that investing in grid modernization could be considerably less costly than allowing existing vulnerabilities to persist. The proposed framework envisages approximately $396 billion in public and private investment over ten years. Under the narrower illustrative scenario, avoided catastrophic failures and recurring system costs generate an estimated benefit-cost ratio of 1.5:1. When potential gains from employment, productivity improvements, and technology exports are included, this ratio increases to 4.4:1. These estimates indicate the possible scale of modernization benefits, although they should be interpreted cautiously. Their reliability depends on assumptions about future disruptions, investment performance, and wider economic effects, some of which remain difficult to quantify with precision.

One of the main implications of the analysis is that investment alone will not resolve the structural barriers affecting the American electricity system. Transmission projects continue to face complex permitting procedures, overlapping regulatory responsibilities, and difficulties in coordinating decisions across state boundaries. The legislative measures proposed in this study would help address these constraints by simplifying transmission development, improving access to long-term financing, and encouraging domestic production of critical grid components. Establishing the Federal Grid Modernization Authority (FGMA) could provide a more consistent basis for coordinating these efforts, particularly where projects extend across several jurisdictions or require substantial public and private investment. However, its effectiveness would depend on clearly defined responsibilities, transparent decision-making, and cooperation with existing regulatory institutions.

The division of responsibilities among federal agencies, state authorities, and private stakeholders is equally important. FERC would continue to play a central role in transmission planning, cost allocation, and eligible federal permitting, while DOE would support infrastructure planning, technological development, and the designation of National Interest Electric Transmission Corridors. DHS/CISA would contribute to cybersecurity preparedness and critical infrastructure protection. At the state level, more predictable regulatory arrangements and streamlined permitting could help reduce investment uncertainty. Meanwhile, utilities, technology companies, and financial institutions would remain essential to translating policy objectives into operational improvements. Rather than replacing existing institutional arrangements, the proposed framework seeks to improve coordination among them.

Public-private partnerships could further support modernization by making large infrastructure projects more attractive to private investors while maintaining public oversight. Appropriate risk-sharing arrangements, federal credit support, and performance-based incentives may help address the financial uncertainty associated with transmission and storage investments. Nevertheless, these mechanisms must be designed carefully to avoid transferring excessive costs or risks to consumers and taxpayers. The proposed implementation sequence, beginning with regulatory and institutional reforms, followed by accelerated infrastructure deployment and system integration, would allow policymakers to assess progress and adjust priorities as experience and new evidence become available.

Several limitations should be acknowledged. The investment estimates are based on available industry benchmarks and comparable projects rather than detailed engineering assessments of individual facilities. The economic projections also depend on assumptions concerning the frequency and severity of major grid failures and the extent to which modernization can prevent them. In addition, some of the estimated benefits associated with employment, industrial productivity, and exports may overlap, potentially affecting the overall economic assessment. Political resistance, federal-state disagreements, and uncertainty surrounding future technologies could create further challenges. The distribution of modernization costs and benefits also deserves closer attention, particularly for low-income households, rural communities, and regions with limited investment capacity.

These limitations point to several areas where further research would be valuable. More detailed project-level assessments could improve the accuracy of investment estimates, while alternative economic scenarios would help clarify the conditions under which modernization delivers the greatest benefits. Research into institutional cooperation, financing arrangements,

and the performance of emerging technologies could also inform future policy decisions. Equally important is the development of reliable and comparable data on infrastructure performance, cybersecurity incidents, and regional investment outcomes. Such evidence would make it easier to evaluate the effectiveness of modernization measures and identify where adjustments are needed.

International experience shows that large-scale grid development benefits from consistent planning and sustained investment, but institutional solutions cannot simply be transferred from one country to another. The United States must develop an approach suited to its federal system, regulatory traditions, and competitive energy markets. The framework presented in this study offers one possible way forward by linking infrastructure priorities with the institutions and financial mechanisms needed to support them. Its ultimate value will depend on whether these proposals can be translated into practical reforms that improve reliability, strengthen resilience, and support the long-term competitiveness of the American economy.

CRediT Authorship Contribution Statement

Noah Parsons: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. Author Approval: The author has reviewed and approved the final manuscript and assumes full responsibility for its content and integrity.

Acknowledgements

The author gratefully acknowledges the American Forge Institute for supporting this research. All views expressed remain solely those of the author.

Funding

There is no funding agency of this research as the author receives no grant from any institutions.

Conflict of Interest Statement

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

The data supporting the findings of this study are openly available from government sources including the US Energy Information Administration (https://www.eia.gov), Federal Energy Regulatory Commission (https://www.ferc.gov), Department of Energy (https://www.energy.gov), North American Electric Reliability Corporation (https://www.nerc.com), and International Energy Agency (https://www.iea.org). All data sources are cited in the References section.

References

Brown, P. R., & Botterud, A. (2021). The value of inter-regional coordination and transmission in decarbonizing the US electricity system. *Joule*, 5(1), 115-134. https://doi.org/10.1016/j.joule.2020.11.013

Climate Central. (2022, September 14). *Surging weather-related power outages*. https://www.climatecentral.org/climate-matters/surging-weather-related-power-outages

Cyber Threat Intelligence Integration Center. (2024, June). Recent cyber attacks on US infrastructure underscore vulnerability of critical US systems, November 2023–April 2024. Office of the Director of National Intelligence. https://www.dni.gov/files/CTIIC/documents/products/Recent_Cyber_Attacks_on_US_Infrastructure_Underscore_Vulnerability_of_Critical_US_Systems-June2024.pdf

Deutsche Industrie- und Handelskammer [DIHK]. (2024). *Energy issues solidify trends of relocation* (Energy Transition Barometer 2024). https://www.dihk.de/en/german-economy/energy-issues-solidify-trends-of-relocation--120838

Di Foggia, G. (2016). Infrastructure-driven development policies: An empirical impact analysis. *Journal of Applied Economic Sciences,* 11(8), 1642–1649. https://hdl.handle.net/10281/142465

Donald, J. (2021, October). Winter Storm Uri 2021: The economic impact of the storm. *Fiscal Notes*. Texas Comptroller of Public Accounts. https://comptroller.texas.gov/economy/fiscal-notes/archive/2021/oct/winter-storm-impact.php

Easterly, J., & Fanning, T. (2023, May 7). *The attack on Colonial Pipeline: What we've learned & what we've done over the past two years*. Cybersecurity and Infrastructure Security Agency. https://www.cisa.gov/node/18129

Enerdata. (2024, January 24). *China's State Grid will invest US$70bn in grid network construction in 2024*. https://www.enerdata.net/publications/daily-energy-news/chinas-state-grid-will-invest-us70bn-grid-network-construction-2024.html

European Commission. (2023, November 28). *Commission sets out actions to accelerate the roll-out of electricity grids* [Press release IP/23/6044]. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_6044

Federal Energy Regulatory Commission. (2024a, September 19). FERC acts to improve reliability by closing supply chain cyber risk management gaps (Docket Nos. RM24-4 and RM24-7). https://www.ferc.gov/news-events/news/ferc-acts-improve-reliability-closing-supply-chain-cyber-risk-management-gaps

Federal Energy Regulatory Commission. (2024b, May 13). Building for the future through electric regional transmission planning and cost allocation (Order No. 1920; Docket No. RM21-17). https://www.ferc.gov/news-events/news/fact-sheet-building-future-through-electric-regional-transmission-planning-and

Federal Energy Regulatory Commission. (2024c, May 13). Applications for permits to site interstate electric transmission facilities (Order No. 1977; Docket No. RM22-7-000). https://www.ferc.gov/explainer-siting-interstate-electric-transmission-facilities

Federal Energy Regulatory Commission. (2025, June 26). *Critical infrastructure protection Reliability Standard CIP-015-1: Cyber security – Internal network security monitoring* (Order No. 907; Docket No. RM24-7-000). https://www.ferc.gov/sites/default/files/2025-06/RM24-7-000.pdf

Federal Energy Regulatory Commission, North American Electric Reliability Corporation, & Regional Entity Staff. (2021, November). *The February 2021 cold weather outages in Texas and the South Central United States*. https://www.ferc.gov/sites/default/files/2022-12/A-3%20-%20The%20February%202021%20Cold%20Weather%20Outages%20in%20Texas%20and%20the%20South%20Central%20United%20States.pdf

Federal Highway Administration. (n.d.-a). *Design build finance operate maintain (DBFOM) availability payment concessions*. Center for Innovative Finance Support. https://www.fhwa.dot.gov/ipd/p3/defined/new_build_facilities/dbfom_availability_payment_concessions.aspx

Federal Highway Administration. (n.d.-b). *Highway history: October 14*. https://www.fhwa.dot.gov/byday/fhbd1014.htm

Goudarzi, A., Ghayoor, F., Waseem, M., Fahad, S., & Traore, I. (2022). A survey on IoT-enabled smart grids: Emerging, applications, challenges, and outlook. *Energies*, 15(19), 6984. https://doi.org/10.3390/en15196984

ICF International. (2025). Powering the future: Addressing surging U.S. electricity demand. https://www.icf.com/insights/energy/powering-future-surging-us-electricity-demand

IEA. (2024). Electricity 2024: Analysis and forecast to 2026. https://www.iea.org/reports/electricity-2024

Jenkins, J. D., Mayfield, E. N., Farbes, J., Jones, R., Patankar, N., Xu, Q., & Schivley, G. (2022). Preliminary report: The climate and energy impacts of the Inflation Reduction Act of 2022. REPEAT Project. https://zenodo.org/records/7106218

Kansas Legislative Research Department. (2024, December 18). *Grid security* (Briefing Book 2025). https://klrd.gov/2024/12/18/grid-security/

Kosov, M. E., Akhmadeev, R. G., Bykanova, O. A., Osipov, V. S., Ekimova, K. V., & Frumina, S. V. (2016). Economic practicability substantiation of financial instrument choice. *Journal of Applied Economic Sciences,* 11(8), 1613–1617. https://www.ceeol.com/search/article-detail?id=532861

LaCommare, K. H., Eto, J. H., Dunn, L. N., & Sohn, M. D. (2018). Improving the estimated cost of sustained power interruptions to electricity customers. *Energy, 153*, 1038–1047. https://doi.org/10.1016/j.energy.2018.04.082

Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., Drossman, J., Williams, R., Pacala, S., Socolow, R., Baik, E., Birdsey, R., Duke, R., Jones, R., Haley, B., Leslie, E., Paustian, K., & Swan, A. (2021). Net-zero America: Potential pathways, infrastructure, and impacts. Princeton University. https://netzeroamerica.princeton.edu/the-report

Liu, Z. (2015). *Ultra-high voltage AC/DC grids*. Academic Press.

Lloyd's & University of Cambridge Centre for Risk Studies. (2015). *Business blackout: The insurance implications of a cyber attack on the US power grid* (Emerging Risk Report). Lloyd's. https://www.lloyds.com/news-and-insights/risk-reports/library/business-blackout

Manitius, N., Kelly, C., & Cavert, J. (2024, July 23). *From decades to years: DOE's CITAP Program and progress towards faster transmission projects*. Clean Air Task Force. https://www.catf.us/2024/07/from-decades-years-does-citap-program-progress-towards-faster-transmission-projects/

National Academies of Sciences, Engineering, and Medicine. (2021). The future of electric power in the United States. National Academies Press. https://doi.org/10.17226/25968

National Oceanic and Atmospheric Administration [NOAA]. (2021, January 8). *Record number of billion-dollar disasters struck U.S. in 2020*. https://www.noaa.gov/node/5748

National Oceanic and Atmospheric Administration, National Centers for Environmental Information [NOAA NCEI]. (n.d.). *U.S. billion-dollar weather and climate disasters: Puerto Rico summary*., from https://www.ncei.noaa.gov/access/billions/state-summary/PR

North American Electric Reliability Corporation. (2024). 2024 long-term reliability assessment. https://nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_Long%20Term%20Reliability%20Assessment_2024.pdf

Office of Management and Budget. (2025, April 8). *Rescission and reinstatement of Circular No. A-94* (Memorandum M-25-23). https://www.whitehouse.gov/wp-content/uploads/2025/02/M-25-23-Rescission-and-Reinstatement-of-Circular-No.-A-94.pdf

Ofgem. (2010, October 4). *Handbook for implementing the RIIO model*. https://www.ofgem.gov.uk/sites/default/files/docs/2010/10/riio_handbook_0.pdf

Pfeifenberger, J. P., Spokas, K., Hagerty, J. M., Tsoukalis, J., Gramlich, R., Goggin, M., Caspary, J., & Schneider, J. (2021). Transmission planning for the 21st century: Proven practices that increase value and reduce costs. The Brattle Group and Grid Strategies. https://www.brattle.com/wp-content/uploads/2021/10/Transmission-Planning-for-the-21st-Century-Proven-Practices-that-Increase-Value-and-Reduce-Costs.pdf

Schramm, P. J., Vaidyanathan, A., Radhakrishnan, L., Gates, A., Hartnett, K., & Breysse, P. (2021). Heat-related emergency department visits during the north-western heat wave - United States, June 2021. *Morbidity and Mortality Weekly Report, 70*(29), 1020–1021. https://doi.org/10.15585/mmwr.mm7029e1

Sepulveda, N. A., Jenkins, J. D., Edington, A., Mallapragada, D. S., & Lester, R. K. (2021). The design space for long-duration energy storage in decarbonized power systems. *Nature Energy*, 6(5), 506-516. https://doi.org/10.1038/s41560-021-00796-8

Shreve, N., Selker, J., Zimmerman, Z., & Gramlich, R. (2024). *2023 transmission congestion report*. Grid Strategies. https://gridstrategiesllc.com/wp-content/uploads/Grid-Strategies_2023-Transmission-Congestion-Report.pdf

Shreve, N., Zimmerman, Z., Kershaw, G., & Gramlich, R. (2025, July). *Fewer new miles: Strategic industries held back by slow pace of transmission*. Grid Strategies and Americans for a Clean Energy Grid. https://cleanenergygrid.org/wp-content/uploads/2025/07/ACEG_Grid-Strategies_Fewer-New-Miles-2025.pdf

Texas Department of State Health Services. (2021, December 31). *February 2021 winter storm-related deaths – Texas*. https://www.dshs.texas.gov/sites/default/files/news/updates/SMOC_FebWinterStorm_MortalitySurvReport_12-30-21.pdf

U.S. Department of Energy. (n.d.). National interest electric transmission corridor designation process. https://www.energy.gov/oe/national-interest-electric-transmission-corridor-designation-process

U.S. Department of Energy. (2022, October). *Cybersecurity considerations for distributed energy resources on the US electric grid*. Office of Cybersecurity, Energy Security, and Emergency Response. https://www.energy.gov/sites/default/files/2022-10/Cybersecurity%20Considerations%20for%20Distributed%20Energy%20Resources%20on%20the%20U.S.%20Electric%20Grid

US Department of Energy. (2023). Pathways to commercial liftoff: Long duration energy storage opportunities. https://www.energy.gov/sites/default/files/2023-09/Pathways%20to%20Commercial%20Liftoff%20Long%20Duration%20Energy%20Storage%20Opportunities_508.pdf

U.S. EIA (n.d). *Electric power annual* (Table 2.1, Number of ultimate customers served by sector; Table 2.2, Sales and direct use of electricity to ultimate customers). https://www.eia.gov/electricity/annual/

U.S. Department of Energy. (2024a, December 20). DOE releases new report evaluating increase in electricity demand from data centers. https://www.energy.gov/articles/doe-releases-new-report-evaluating-increase-electricity-demand-data-centers

U.S. Department of Energy. (2024b). *National transmission planning study*. https://www.energy.gov/oe/national-transmission-planning-study-0

U.S. Energy Information Administration. (2025a, May 13). After more than a decade of little change, US electricity consumption is rising again. Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=65264

U.S. Energy Information Administration. (2025b, December 1). *Hurricanes in 2024 led to the most hours without power in the United States in 10 years*. Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=66744

Williams, J. H., Jones, R. A., Haley, B., Kwok, G., Hargreaves, J., Farbes, J., & Torn, M. S. (2021). Carbon-neutral pathways for the United States. *AGU Advances*, 2(1), e2020AV000284. https://doi.org/10.1029/2020AV000284

How to cite this article

Parsons, N. (2025). Strategic Grid Modernization for Enhanced Energy Security and Industrial Competitiveness: A Multi-Pillar Framework for the United States. *Applied Journal of Economics, Law and Governance*, Volume 1, Issue 2(2), 149-171. https://doi.org/10.57017/ajelg.v1.i2(2).03

Article's history:

Received 27th September, 2025; *Revised* 18th October, 2025;
Accepted for publication 8th November, 2025; *Available online*: 18th November, 2025.
Published as research article in Volume I, Issue 2(2), 2025

© The Author(s) 2025. Published by RITHA Publishing. This article is distributed under the terms of the license CC-BY 4.0., which permits any further distribution in any medium, provided the original work is properly cited maintaining attribution to the author(s) and the title of the work, journal citation and URL DOI.