21st Century
POWER
PARTNERSHIP
Accelerating the transformation of power systems

STATUS OF POWER SYSTEM TRANSFORMATION

LEADING TOPICS OF 2024

iea

IRENA
International Renewable Energy Agency

ISGAN
INTERNATIONAL SMART GRID ACTION NETWORK

RETA
Regulatory Energy Transition Accelerator

GLOBAL PST CONSORTIUM

ELECTRIC VEHICLES INITIATIVE
AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

SUPERCHARGING BATTERY STORAGE
AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

CLEAN ENERGY SOLUTIONS CENTER
AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

NICE NUCLEAR INNOVATION: Future CLEAN ENERGY
AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

LTES LONG-TERM SCENARIOS FOR THE ENERGY TRANSITION
AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

September 2024

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of all individuals and organizations that supported the development of this report. Special thanks to the experts who provided valuable insights, particularly to authors from the National Renewable Energy Laboratory for their essential contributions. We also appreciate and acknowledge the contributions of the report's advisory panel for their guidance and critical feedback throughout the drafting process. We should like to recognize the editorial and design teams for their dedication in ensuring the report's clarity and accessibility, and to everyone else who contributed both directly and indirectly to its publication.

TABLE OF CONTENTS

Note: The order of the topics does not indicate its priority/importance. Topics highlighted in this report are intended to illustrate some areas of emerging promises or needed work and are not comprehensive of challenges for power system transformation.

HIGH-LEVEL TAKEAWAYS

- Power systems today are achieving **unprecedented levels of clean energy** while maintaining reliable and cost-effective operations.

- **Renewable energy is the lowest-cost option** for new generation capacity in many jurisdictions, with significant cost declines driven by technology innovation and economies of scale.

- **Many cost-effective measures are availabl**e to achieve significant rapid progress. Technology R&D, pilot projects, deployment at scale, scaling of new technologies, workforce development, and supply chain improvements can help mainstream deeper decarbonization measures.

- Emerging international goals bolstered by recent analyses underscoring the **importance of grids and energy storage for clean energy transitions** present an opportunity to accelerate adoption of innovative power systems solutions.

- However, **more progress is needed to bend the curve of global energy sector emissions** and achieve net-zero goals.

BACKGROUND

21st Century
POWER
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Accelerating the transformation of power systems

21CPP: BACKGROUND AND OBJECTIVES

Accelerate the transition to clean, efficient, reliable, and cost-effective power systems.

Evolving Generation Portfolios

Electrification of Transport, Buildings, and Industry

Smart Grid, Energy Efficiency, and Demand Response

Cross-Cutting Issues:
Operations,
Transmission,
Distributed Generation,
Market Design,
Workforce Capacity

Coordinated Power System Planning, Building, and Operating Best Practices

Peer-learning, knowledge-sharing, and technical assistance

Coordinating with related CEM Campaigns and Partners

CLEAN ENERGY MINISTERIAL
Advancing Clean Energy Together

Australia

Brazil
(co-lead)

China

India
(co-lead)

Denmark

Finland

Mexico

South Africa

Spain

United States
(co-lead)

Chile

A DECADE OF THOUGHT LEADERSHIP BY 21CPP AND OTHER PARTNERS

21st Century POWER PARTNERSHIP
Accelerating the transformation of power systems

Ten Principles for Power Sector Transformation in Emerging Economies

Power System Transformation Principles

Foundations of Power System Transformation
1. Power System Transformation Benefits from Strong Leadership and Vision.
2. Policy and Regulatory Certainty and Consistency are Critical Enablers of Power System Transformation, Helping to Secure Financing and Promote Utility Financial Sustainability.
3. Efforts to Enhance Institutional and Workforce Capacity are Central to Power System Transformation.
4. Charting Transformation Pathways Involves the Orchestration of a Diverse Portfolio of Actions.

Accelerating Power System Transformation
5. Strategic Partnership Between the Public and Private Sectors Can Help Jump-start Power System Transformation.
6. Power System Transformation is Enabled by Good Data and Analytics to Evaluate a Wider Set of Pathways and Advanced Information Systems to Operate the Power System Efficiently and Reliably.
7. Auctions are Emerging as a Global Best Practice Mechanism for Generation Procurement; However, They May Take Multiple Cycles to Yield Desired Results.
8. Modern Power Systems Focus on Flexibility as a Key Resource.

Moving Forward Inclusively with Power System Transformation
9. In the Face of New Technologies and Evolving Power System Requirements, New Administrative Efforts are Likely Needed to Ensure Power System Transformation is Fair and Inclusive.
10. Power System Transformation Efforts Can Promote More Socially Equitable Development.

CLEAN ENERGY MINISTERIAL

Electric Vehicle and Power System Integration: Key insights and policy messages from four CEM workstreams

Developed jointly by four CEM workstreams: 21st Century Power Partnership Initiative (21CPP), Electric Vehicles Initiative (EVI), International Smart Grid Action Network initiative (ISGAN) and Power System Flexibility campaign (PSF)

This report was prepared for the 11th Clean Energy Ministerial (CEM11), September 2020.

LESSONS LEARNED FOR RAPID DECARBONIZATION OF POWER SECTORS: KEY MESSAGES FOR ENERGY MINISTERS

Background

This report covers key lessons learned for the rapid decarbonization of power sectors, emphasizing best practices in **planning**, **building**, and **operating** electricity systems.

This report is the result of a collaborative effort among various Clean Energy Ministerial (CEM) workstreams and partner initiatives:
- 21st Century Power Partnership (21CPP)
- Carbon Capture, Utilization and Storage (CCUS)
- Global Power System Transformation Consortium (G-PST), a partner to CEM
- Industrial Deep Decarbonisation Initiative (IDDI)
- International Energy Agency Digital Demand-Driven Electricity Networks Initiative (IEA 3DEN), a partner to CEM
- International Smart Grid Action Network (ISGAN)
- Long Term Scenarios for the Energy Transition (LTES)
- Nuclear Innovation: Clean Energy Future (NICE Future)
- Super-Efficient Equipment and Appliance Deployment (SEAD)

This work is intended to complement other work at the Clean Energy Ministerial and offers options for consideration, not specific policy recommendations.

Overarching Themes

Overarching themes for energy ministers, within the categories of **planning**, **building**, and **operating** are highlighted in Figure 1 from the compilation of detailed lessons learned for rapid power sector decarbonization.

Collaborating Workstreams

Status of Power System Transformation 2019
Power system flexibility

NREL Transforming ENERGY
CLEAN GRID VISION: A U.S. PERSPECTIVE
Executive Summary

Next-Generation Performance-Based Regulation
VOLUME 1
Introduction—Global Lessons for Success

Status of Power System Transformation 2017
System integration and local grids

Status of Power System Transformation 2018
Advanced Power Plant Flexibility

Explore the Thought Leadership reports:

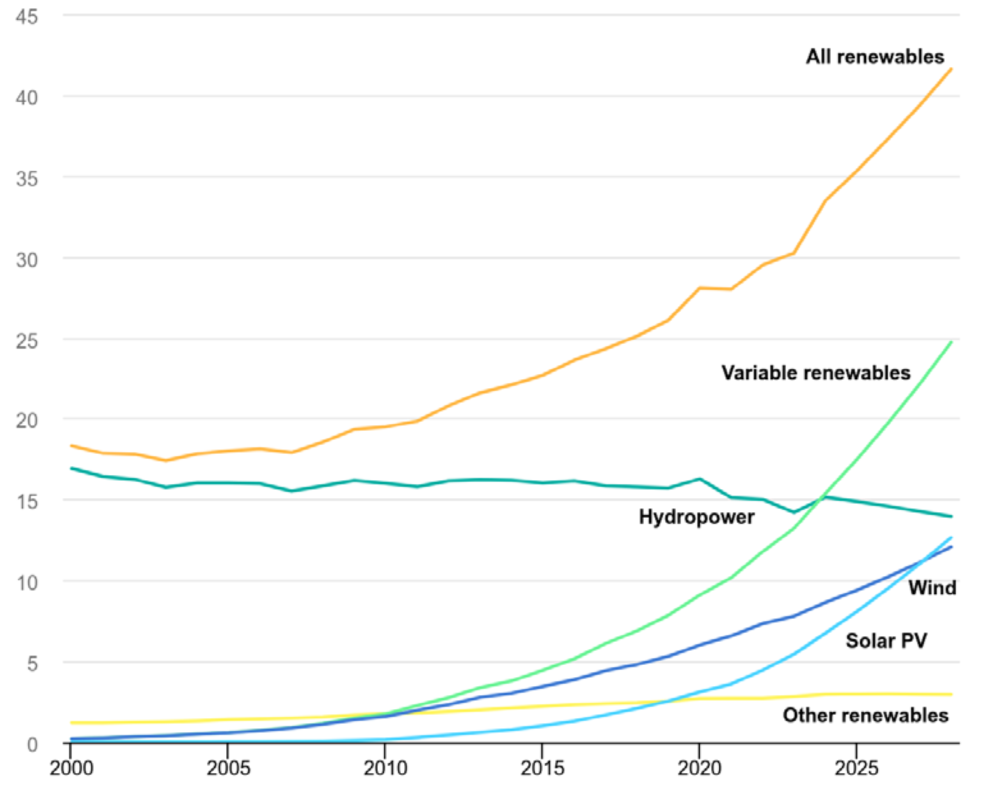
CLEAN ENERGY MINISTERIAL
Advancing Clean Energy Together

Australia	Brazil (co-lead)	China	India (co-lead)	Denmark	Finland	Mexico	South Africa	Spain	United States (co-lead)	Chile

POWER SYSTEM TRANSFORMATION: WHERE ARE WE NOW?

- **Significant progress in clean energy deployment.** “From 2019 to 2023, clean energy growth outpaced growth in fossil fuels by a ratio of two-to-one…without deployment of solar PV, wind, nuclear, electric cars, and heat pumps, the increase in CO_2 emissions globally over the same period would have been more than three times larger.” – IEA
- **More progress is needed to decarbonize the global energy system.** “Global energy-related CO_2 emissions grew by 1.1% in 2023…to reach a new record high of 37.4 billion tons (Gt)…global shortfall in hydropower generation due to droughts drove up emissions by around 170 Mt.” – IEA
- **Technological advancements and economies of scale have led to substantial reductions in the cost of renewable energy technologies**. Since 2010, the costs of solar photovoltaics (PV) and onshore wind have fallen by around 85% and 55%, respectively. Offshore wind has also seen significant reductions, with costs decreasing by nearly 60% over the same period.”- IRENA
- **Power systems are achieving unprecedented levels of clean energy while maintaining reliable and cost-effective operations. “**Wind and solar PV together are expected to generate more than hydropower in 2024, and each surpass nuclear generation in 2025 and 2026, respectfully.” - IEA

Share of renewable electricity generation by technology, 2000-2028



Source: IEA, https://www.iea.org/reports/renewables-2023/executive-summary

POWER SYSTEM TRANSFORMATION: WHERE ARE WE NOW?

- **Global collaboration is needed to solve common challenges of technology innovation and rapid deployment.** Assuming enhanced implementation of existing policies and targets, G20 countries could triple their collective installed RE capacity by 2030. "However, to achieve the global goal, the rate of new installations needs to accelerate in other countries, too…" – IEA

- **Increase in workforce development initiatives that promote women's representation and gender perspectives in power system transformation.** Initiatives such as G-PST's Women in Power System Transformation are enhancing leadership, training, and employment opportunities for women in the power sector.

iStock: 813968046

Enabling Strategies To Facilitate Power Sector Decarbonization

Developing Future-Ready, Resilient, Clean Power Systems Requires Multiple Enabling Strategies

Enabling strategies help ensure power systems and electricity markets are prepared to implement large investments and deployments of clean energy capacity needed for decarbonization.

Advanced Planning

Flexible System Operations

Flexible Load Operations

Flexible Plant Operations

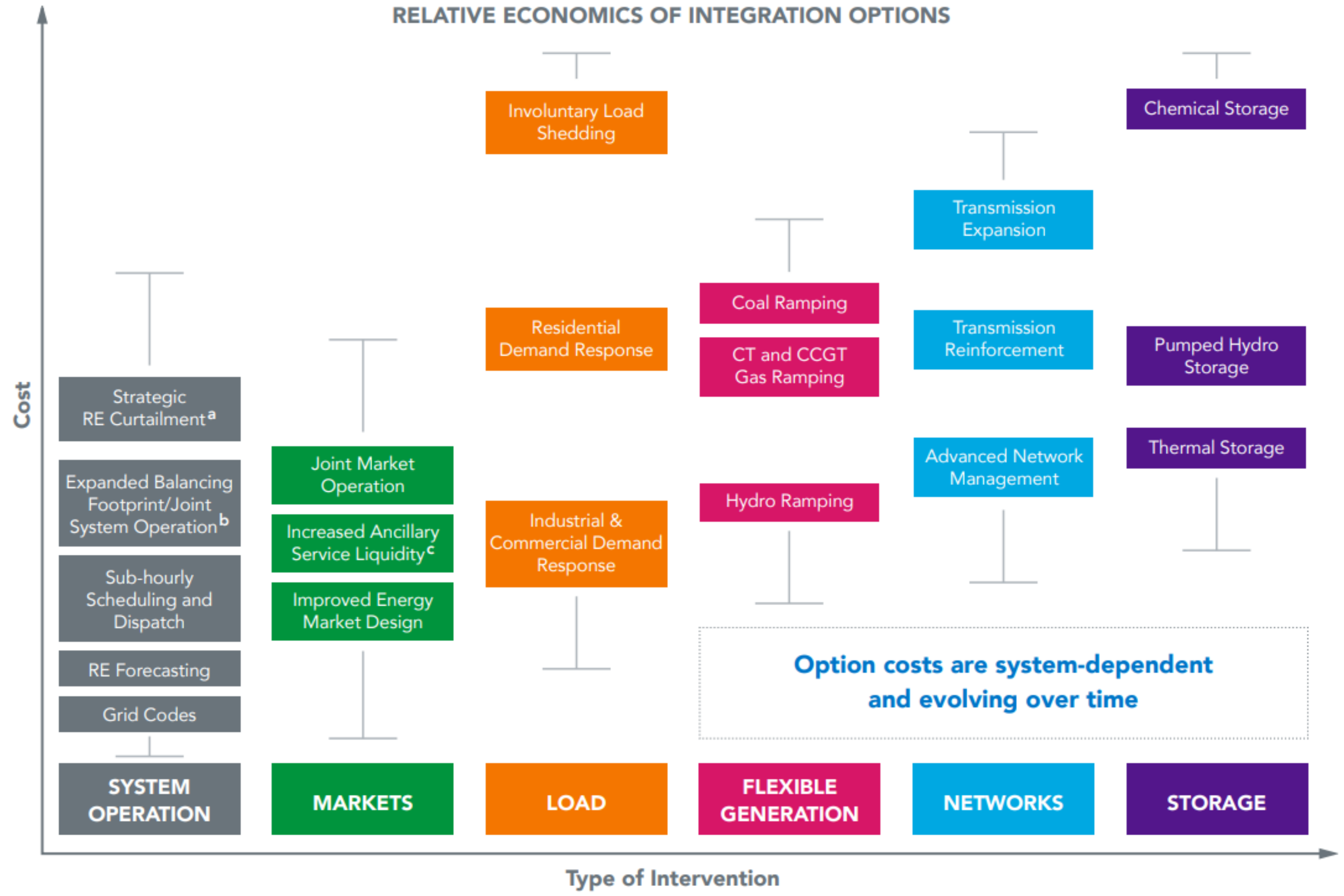
Transmission

Energy Storage

System Stability

Strategies can be implemented simultaneously, with specific interventions tailored to the unique context of each system.

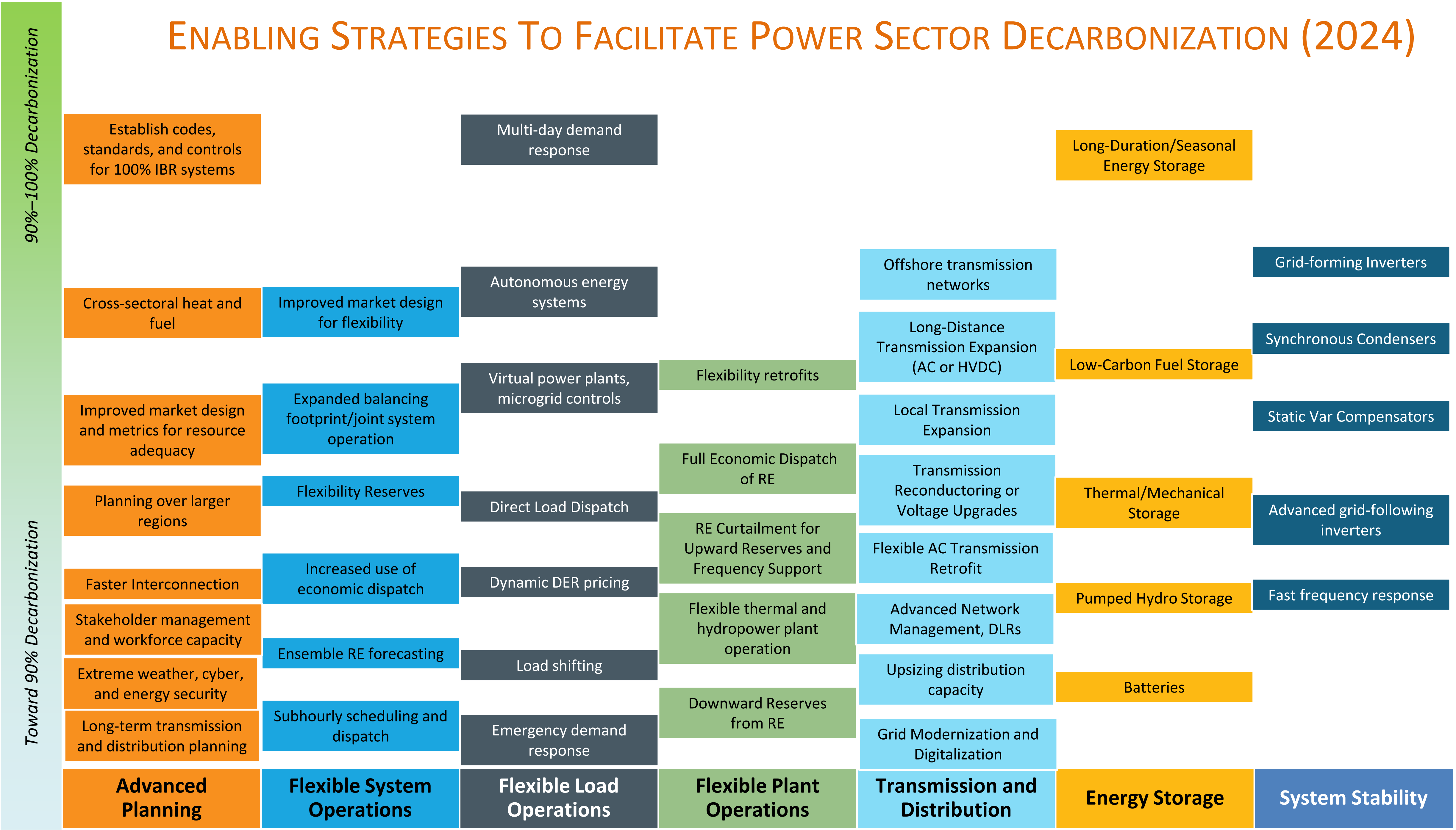
ENABLING STRATEGIES TO FACILITATE POWER SECTOR DECARBONIZATION (2014)



- Back in 2014, approaches were focused on increasing grid flexibility to integrate clean energy.
- A decade later, a greater suite of options is available for 100% power system decarbonization, as seen on the next slide.

Source: Flexibility in Power Systems -2014 -21CPP

ENABLING STRATEGIES TO FACILITATE POWER SECTOR DECARBONIZATION (2024)



90%–100% Decarbonization

Toward 90% Decarbonization

Advanced Planning

- Establish codes, standards, and controls for 100% IBR systems
- Cross-sectoral heat and fuel
- Improved market design and metrics for resource adequacy
- Planning over larger regions
- Faster Interconnection
- Stakeholder management and workforce capacity
- Extreme weather, cyber, and energy security
- Long-term transmission and distribution planning

Flexible System Operations

- Improved market design for flexibility
- Expanded balancing footprint/joint system operation
- Flexibility Reserves
- Increased use of economic dispatch
- Ensemble RE forecasting
- Subhourly scheduling and dispatch

Flexible Load Operations

- Multi-day demand response
- Autonomous energy systems
- Virtual power plants, microgrid controls
- Direct Load Dispatch
- Dynamic DER pricing
- Load shifting
- Emergency demand response

Flexible Plant Operations

- Flexibility retrofits
- Full Economic Dispatch of RE
- RE Curtailment for Upward Reserves and Frequency Support
- Flexible thermal and hydropower plant operation
- Downward Reserves from RE

Transmission and Distribution

- Offshore transmission networks
- Long-Distance Transmission Expansion (AC or HVDC)
- Local Transmission Expansion
- Transmission Reconductoring or Voltage Upgrades
- Flexible AC Transmission Retrofit
- Advanced Network Management, DLRs
- Upsizing distribution capacity
- Grid Modernization and Digitalization

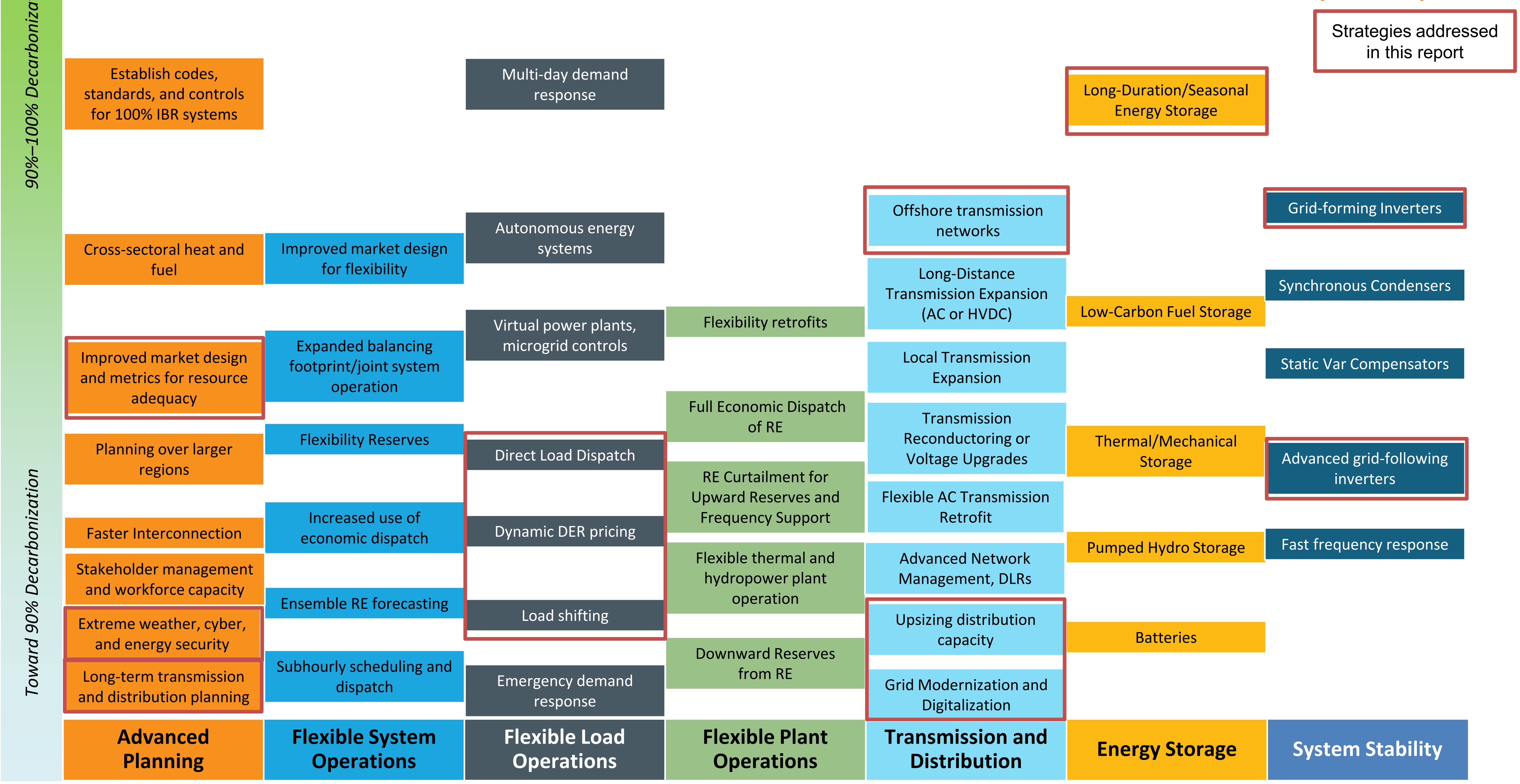
Energy Storage

- Long-Duration/Seasonal Energy Storage
- Low-Carbon Fuel Storage
- Thermal/Mechanical Storage
- Pumped Hydro Storage
- Batteries

System Stability

- Grid-forming Inverters
- Synchronous Condensers
- Static Var Compensators
- Advanced grid-following inverters
- Fast frequency response

ENABLING STRATEGIES TO FACILITATE POWER SECTOR DECARBONIZATION (2024)



Strategies addressed in this report

90%–100% Decarbonization

Toward 90% Decarbonization

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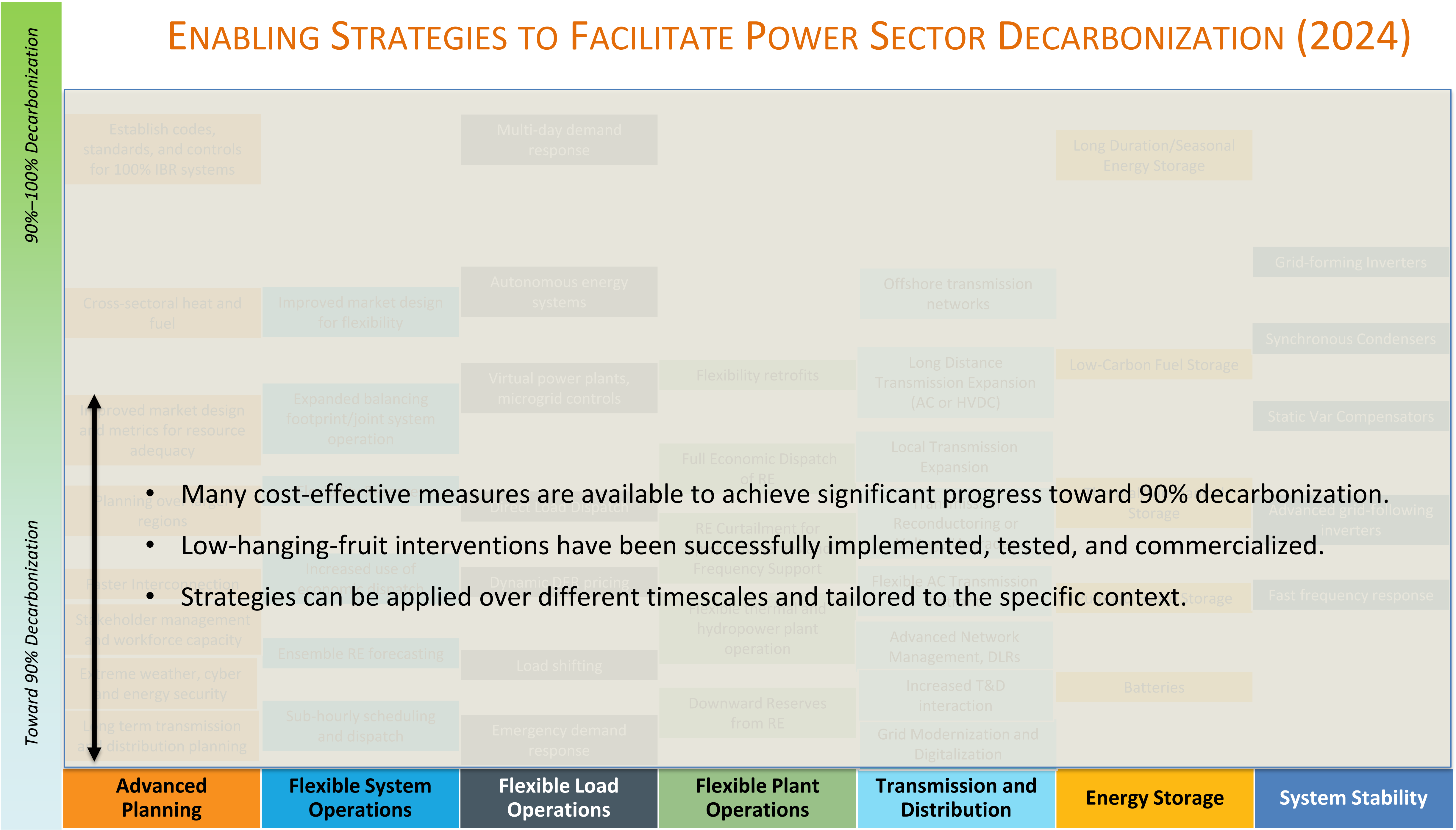
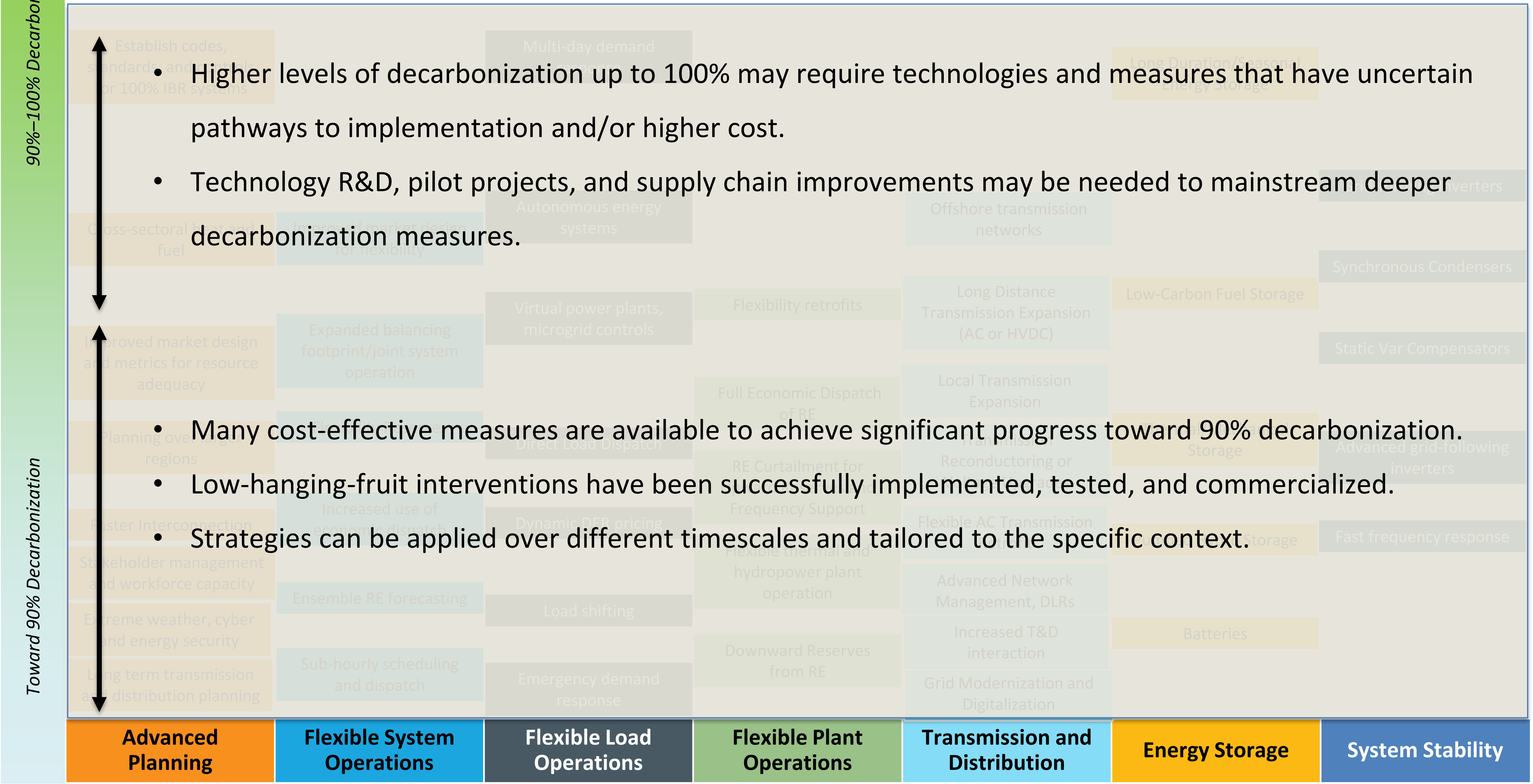


- Many cost-effective measures are available to achieve significant progress toward 90% decarbonization.
- Low-hanging-fruit interventions have been successfully implemented, tested, and commercialized.
- Strategies can be applied over different timescales and tailored to the specific context.

ENABLING STRATEGIES TO FACILITATE POWER SECTOR DECARBONIZATION (2024)



90%–100% Decarbonization

- Higher levels of decarbonization up to 100% may require technologies and measures that have uncertain pathways to implementation and/or higher cost.
- Technology R&D, pilot projects, and supply chain improvements may be needed to mainstream deeper decarbonization measures.

Toward 90% Decarbonization

- Many cost-effective measures are available to achieve significant progress toward 90% decarbonization.
- Low-hanging-fruit interventions have been successfully implemented, tested, and commercialized.
- Strategies can be applied over different timescales and tailored to the specific context.

Advanced Planning | **Flexible System Operations** | **Flexible Load Operations** | **Flexible Plant Operations** | **Transmission and Distribution** | **Energy Storage** | **System Stability**

POLICY AND REGULATORY ACTIONS

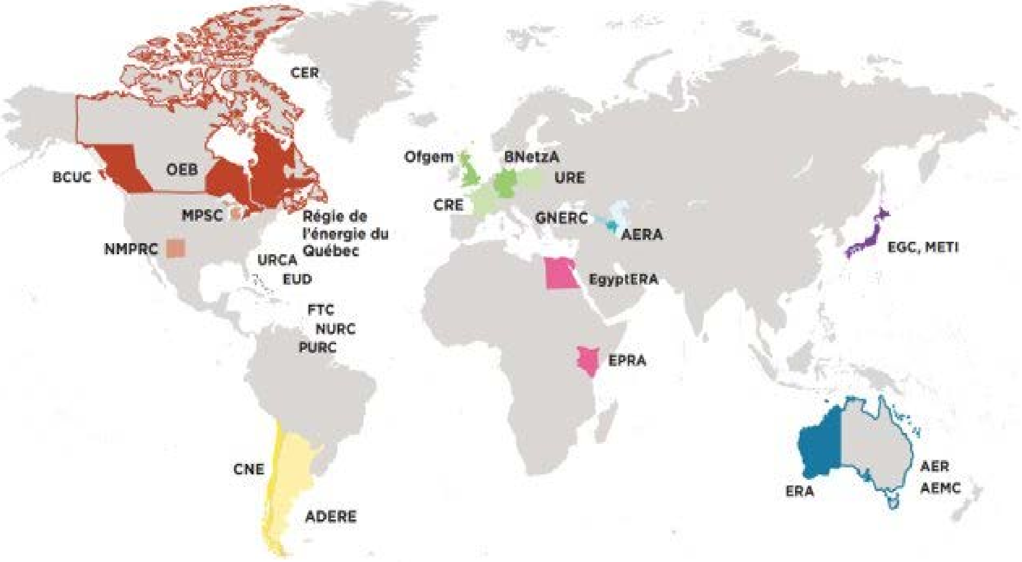
- To ensure timely deployment of grid infrastructure that enables secure energy transition, these are the key actions for policymakers and regulators:
  - Ensure grid infrastructure planning and anticipatory investments are in sync with other sectors’ plans toward decarbonization goals
  - Reform regulation to enable proper collection of investment costs and incentivize release of grid capacity that facilitates fast supply/demand connections
  - Unlock financing with dedicated policy attention and explore innovative approaches, leveraging the private sector
  - Empowering regulators by reviewing mandates, providing coordinated guidance on decarbonization efforts, and ensuring they are well-resourced and included in key policy discussions
  - Leverage digitalization to manage power system transformation efficiently
  - Establish concrete and transparent project pipelines so that equipment providers can build secure supply chain strategies
  - Foster skilled workforce capable of tackling the complex tasks and increasing volume of work
  - Develop robust governance structures that ensure comprehensive stakeholder participation and coordination across different entities involved in scenario development
  - Expand the scope of LTES to better incorporate socio-economic impacts, innovation, and the evolving complexities of the clean energy transition
  - Clearly define the purpose of scenarios—whether for forecasting, back-casting, or consensus-building—and communicate them transparently and effectively to all stakeholders
  - Implement integrated approach that maintains consistent feedback loops across planning time horizons, ensuring that both technical and economic impacts of VRE are accurately represented in all assessments and policies, leading to more resilient and adaptive energy systems
  - Implement participatory processes to ensure that scenarios are inclusive, transparent, and reflective of the diverse needs of the energy transition.

Case Study: Responding to a Broader Regulatory Mandate in Great Britain

This example is highlighted in a report by the Regulatory Assistant Project (RAP) and the Regulatory Energy Transition Accelerator (RETA) As part of the United Kingdom’s 2023 Energy Act, Ofgem, the Energy Regulator of Great Britain, emerged as a key player to support the net-zero mandate through four key additional responsibilities:

- Mandate to consider net zero in regulatory decision-making
- Development of a regulatory framework for heat networks
- Development of a framework for CO_2 transport and storage networks
- Greater oversight over energy market rules.

In this case, the key innovation was recognizing the regulator’s role in enabling decarbonization in areas beyond what is typically considered the remit of energy regulation.



Source: RAP Elevating the Priority of Decarbonization in Energy Regulators' Decision Making (2024)

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LONG-TERM PLANNING OF SMART DISTRIBUTION GRIDS

CONTEXT AND CHALLENGES TO LONG-TERM PLANNING OF DISTRIBUTION GRIDS

Vision: State-of-the-art distribution grids enable electrification of end uses, energy access, affordability, resilience, and enhanced flexibility.

Challenges:

- The full benefits of increased renewable energy source (RES) integration and the acceleration of electrification on the demand-side hinge on modernizing our low- and medium-voltage grids. Deployment of critical decarbonization technologies is currently slowed due to grid congestion and grid connection delays.
- The need for extensive investments in low- and medium-voltage grids is now recognized as far more substantial than previously anticipated and is acutely felt by many actors on the ground. The International Energy Agency (IEA) estimates that, after over a decade of stagnation, smart grid investment will need to nearly double globally by 2030 to over USD 600 billion per year, with emphasis on digitalizing and modernizing thousands of local grids. Without immediate coordinated action, the security, affordability, and quality of service for consumers could be compromised.
- Climate-related costs are expected to be substantial, but are likely underrepresented in current investment estimates due to uncertain predictions and the growing frequency of extreme weather events. Electricity grids may need to be upgraded or redesigned to withstand the impacts of increasingly severe hurricanes, floods, heatwaves, and wildfires, as well as cyberattacks and other human-related events.
- In planning and implementing grid upgrades, grid actors face growing uncertainties. Energy policies play a critical role in de-risking infrastructure investments to attract the necessary capital for grid modernization. Policymakers must therefore craft policies that support and incentivize smart grid upgrades and reduce uncertainties for grid owners, operators, and planners.

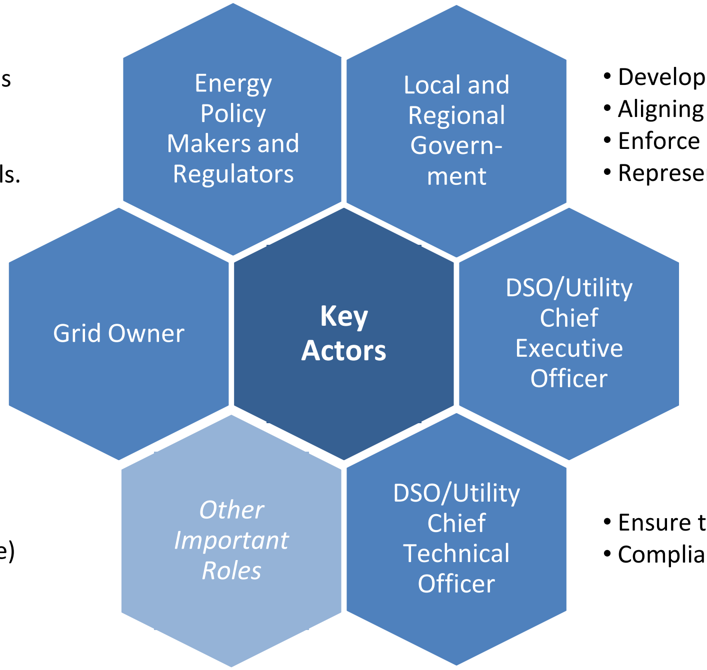
Uncertainties impacting grid modernization

- Effects of climate change on grid resilience
- Changing political and regulatory priorities
- Rapid technological developments (e.g. AI)
- Complex actor interdependencies
- Higher shares of variable generation
- Changing production and consumption patterns
- Flexibility solutions adoption effects
- ...

To ensure cost-efficient grid modernization and address rapid demand growth, grid planning should consider alternatives to grid-only investments, including demand- and production-side flexibility and smart-grid technologies.

KEY ACTORS FOR LONG-TERM PLANNING OF DISTRIBUTION GRIDS

- Different key actor groups play crucial roles in forward-looking long-term planning of Smart Distribution Grids: Mandates and responsibilities vary between jurisdictions, and these roles can overlap (e.g. a local government may be the grid owner).
- The importance for them to involve and partner with other energy sector actors, such as transmission system planners, energy suppliers, aggregators, and both active and passive grid users, grows with the increasing complexity of the evolving energy landscape and the need to be more proactive in long-term planning.



Key Actors

Energy Policy Makers and Regulators

- Formulate and enforce energy policies and regulations
- Oversee and regulate energy markets
- Coordinate national energy strategy
- Ensure alignment to reach broader energy sector goals.

Local and Regional Govern-ment

- Develop and implement local/regional energy policies
- Aligning with broader policy priorities and other planning processes
- Enforce regional regulations
- Represent community interests.

Grid Owner

- Invest in grid assets, focusing on long-term viability
- Align investment with strategic objectives and societal goals
- Assess and manage grid ownership risks.

DSO/Utility Chief Executive Officer

- Set long-term strategy
- Align utility goals with public policy
- Ensure financial sustainability of long-term investments
- Balance economic viability with strategic objectives.

Other Important Roles

- Technology providers
- Transmission system actors
- Grid users and citizens (active or passive)
- Intermediary actors
- Researchers.

DSO/Utility Chief Technical Officer

- Ensure technical integrity and reliability
- Compliance with regulation.

POLICY AND REGULATORY ACTIONS

- By crafting policies that support and incentivize grid modernization, energy policymakers can ensure that the necessary infrastructure is in place to meet our global energy transition goals, safeguarding both economic stability and environmental sustainability

Key messages from ISGAN Policy Brief on Long-Term Planning & Implementation of Smart Distribution Grids:

Message 1:
Confidence to invest in smart distribution grids requires reliable and supportive legal and institutional conditions for a long-term planning horizon.

Message 2:
Planning of medium- and low-voltage grids demands broader coordination across key actors in the energy sector. This would facilitate de-risking the upfront investments for lasting and efficient smart-grid infrastructures.

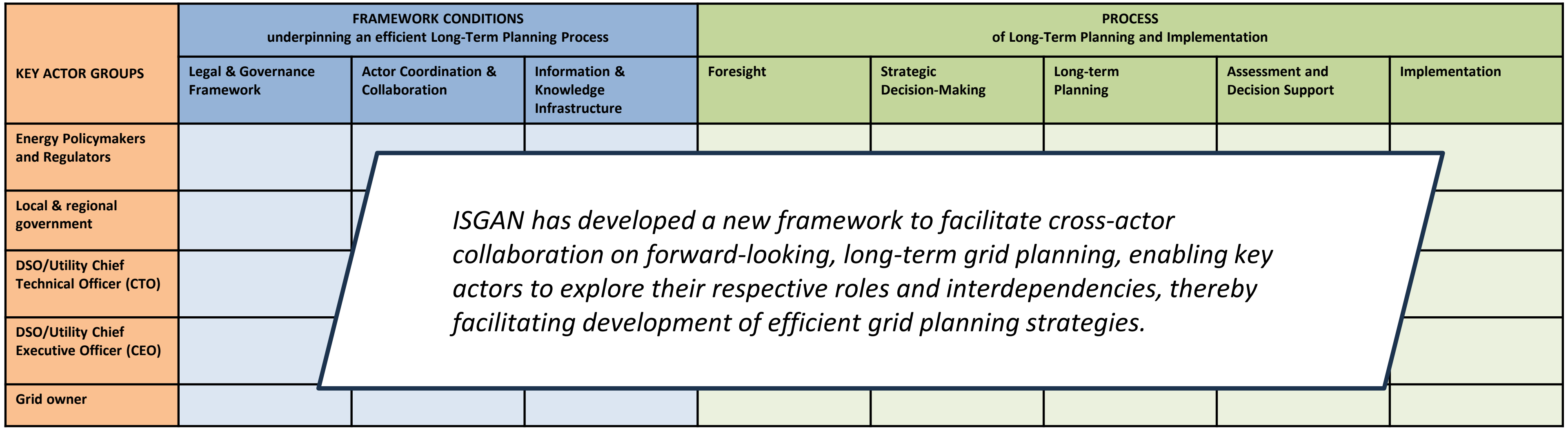
Message 3:
Long-term planning must be adapted to new complex realities, shifting from traditional master plan approaches to forward-looking, agile, and scenario-based approaches.

Message 4:
Policymakers should ensure the availability of sufficient knowledge and data infrastructure to support agile planning and resilient operations. This includes building a knowledge base for planning of smart grids and promoting data sharing.

Case Study

Insights from the ISGAN Lighthouse Project on Long-term Planning & Implementation of Smart Distribution Grids

- Global shared challenges - however, regional nuances and contexts set the specific framework conditions for grid modernization in specific geographies.
- Strong need for increased multilateral dialogue and learning partnerships (e.g., Communities of Practice convening key grid actors within/between countries).



KEY ACTOR GROUPS	FRAMEWORK CONDITIONS underpinning an efficient Long-Term Planning Process			PROCESS of Long-Term Planning and Implementation				
	Legal & Governance Framework	Actor Coordination & Collaboration	Information & Knowledge Infrastructure	Foresight	Strategic Decision-Making	Long-term Planning	Assessment and Decision Support	Implementation
Energy Policymakers and Regulators								
Local & regional government								
DSO/Utility Chief Technical Officer (CTO)								
DSO/Utility Chief Executive Officer (CEO)								
Grid owner								

ISGAN has developed a new framework to facilitate cross-actor collaboration on forward-looking, long-term grid planning, enabling key actors to explore their respective roles and interdependencies, thereby facilitating development of efficient grid planning strategies.

Source: ISGAN Lighthouse Project

REFERENCES AND ADDITIONAL RESOURCES

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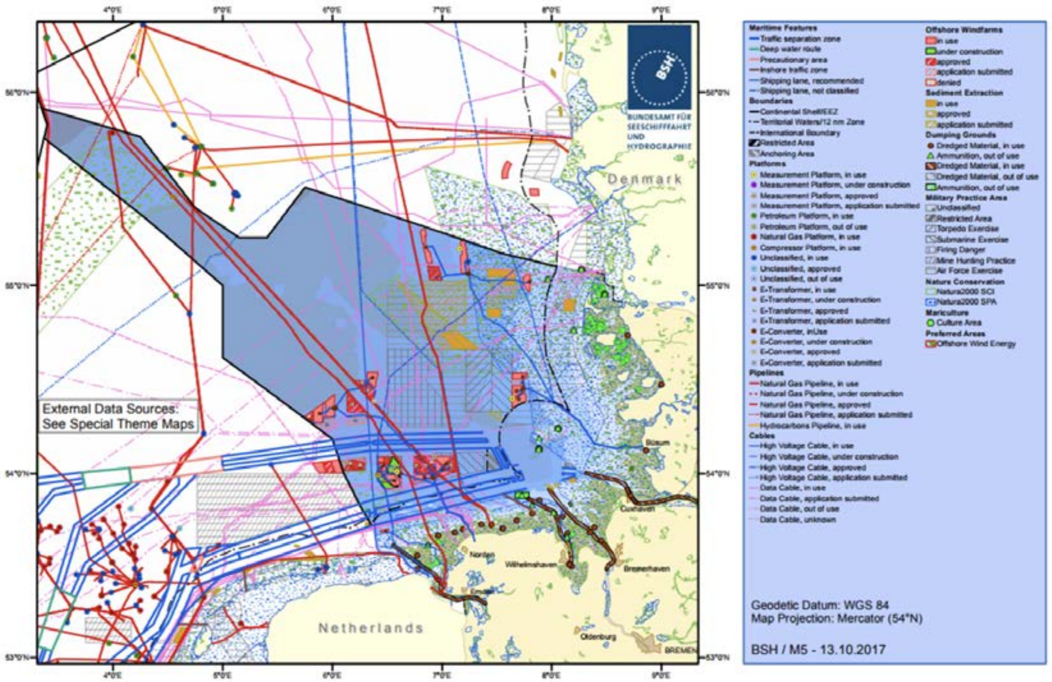
OFFSHORE TRANSMISSION NETWORKS

Challenges to the Deployment of Offshore Grid Transmission Networks

Vision: Develop interconnected, inter-regional offshore transmission networks that enable the large-scale integration of offshore wind and support onshore grid reliability.

Challenges:

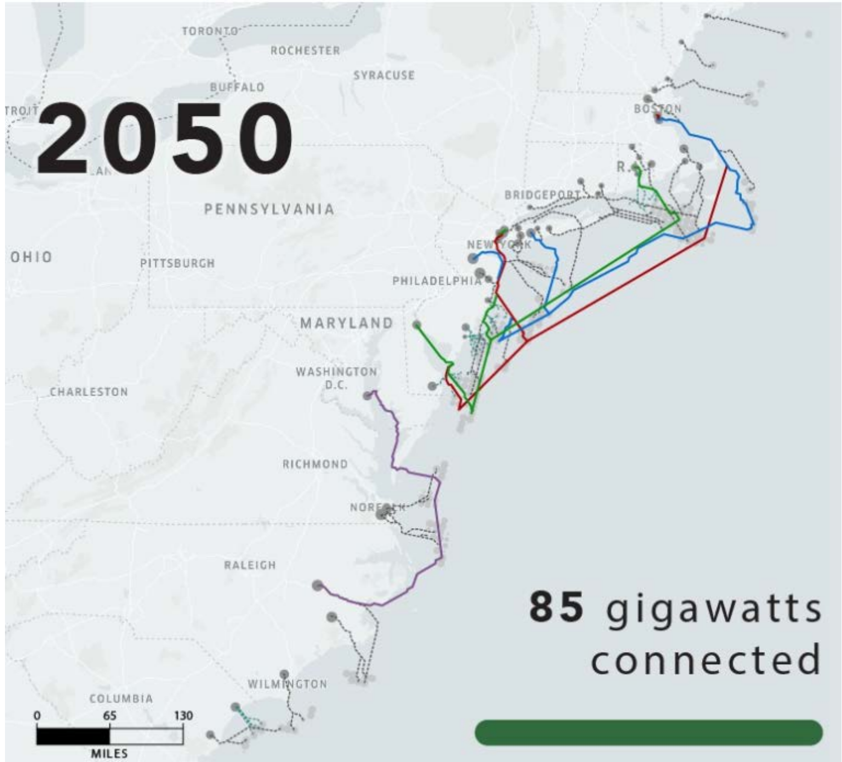
- **Uncertain/variable policies and price signals**: Consistent government funding and policies are needed to reduce investment risks and develop efficient supply chains.
- **Early adoption of key standards**: While offshore networks can be built out in phases, early adoption of standardized HVDC technologies is needed to ensure future interoperability.
- **Interregional coordination and planning**: Coordinate the long-term deployment of transmission infrastructure to maximize reliability and renewable integration acros large geographic areas under environmental constraints.
- **Development of onshore grid infrastructure:** Onshore grids must be reinforced an expanded to support offshore wind integration.
- **Intersectoral coordination and multi-use marine spatial planning:** Coordinate the long-term strategies of resource use, permitting, and siting to maximize synergies between production systems within an offshore space to accommodate spatial limitations.



Source: Multi-Use in European Seas Project, https://maritime-spatial-planning.ec.europa.eu/sites/default/files/annex-3-case-study-1c.pdf

STATE-OF-THE-ART RESEARCH

- Offshore wind offers a near “limitless” potential globally that can be tapped to achieve decarbonization goals (IEA).
- Offshore networks offer benefits over radially connected offshore wind:
    - Reduce curtailment of offshore wind
    - Reduce usage of higher-cost generating units
    - Increase grid reliability by contributing to resource adequacy and managing contingencies.
- Designing transmission routes requires sufficient long-term planning, coordination, and diverse and inclusive stakeholder engagement:
    - To reduce transmission congestion and support interregional transfers
    - To optimize trade-offs between wind resource quality and cable length
    - To ensure future interoperability despite multi-phased buildouts.
- Intersectoral collaboration on long-term planning of spatial and resource use for infrastructure and economic activities.

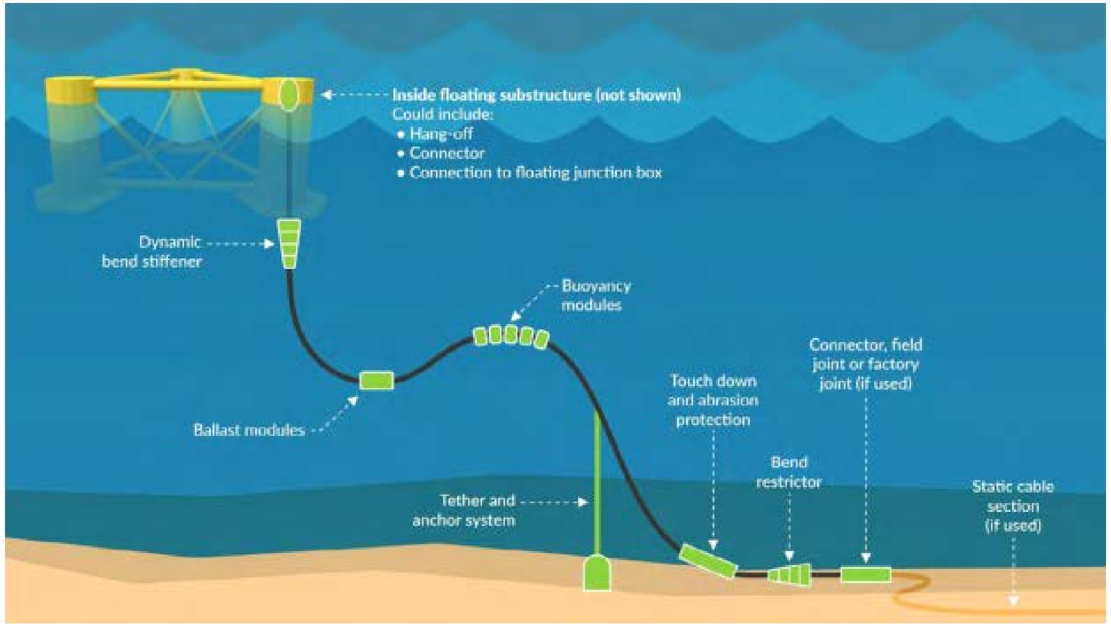


Source: Atlantic Coast Offshore Wind Transmission Planning (https://www.energy.gov/gdo/atlantic-coast-offshore-wind-transmission-planning)

CASE STUDY: OFFSHORE GRID AND FLOATING GENERATION

IRENA's Floating offshore wind outlook highlights the emerging potential of this technology, including several remarks on transmission implications in the context of deep waters:

- Floating substructures are reaching commercial maturity and before 2030 are called to unlock offshore potential in countries with limitations on bottom-fixed foundations due to narrow continental shelf.
- Cables required, especially array cables, are dynamic, meaning that they are designed to follow and withstand the motion of the floating substructure caused by wind, waves, and currents.
- In the short and mid term, radial topologies are preferred to network configuration due to added technical complexity of the floating elements.
- A major gap has been identified regarding standardization of floating substations, which is being addressed by a joint industry project led by DNV.
- Grid-planning onshore must take into consideration updated spatial marine planning involving floating offshore potential.

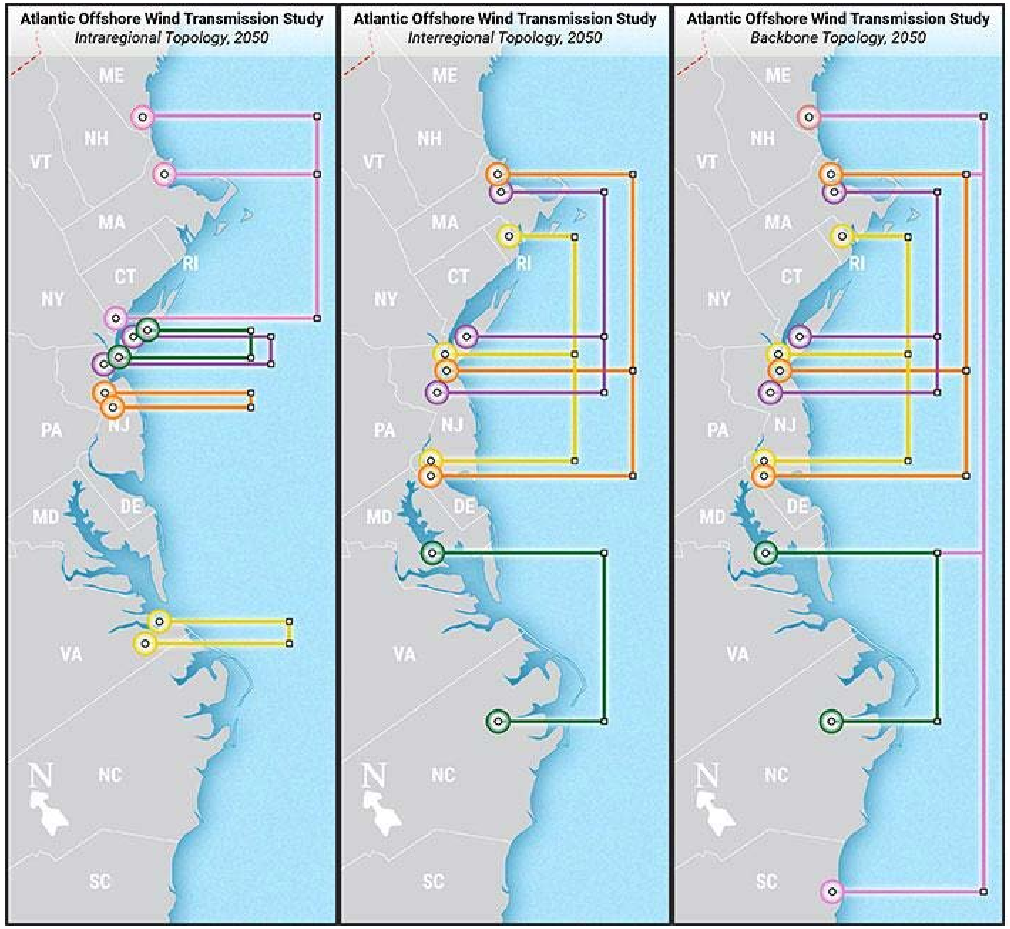


Source: IRENA, https://www.irena.org/Publications/2024/Jul/Floating-offshore-wind-outlook

CASE STUDY: ATLANTIC OFFSHORE WIND TRANSMISSION STUDY

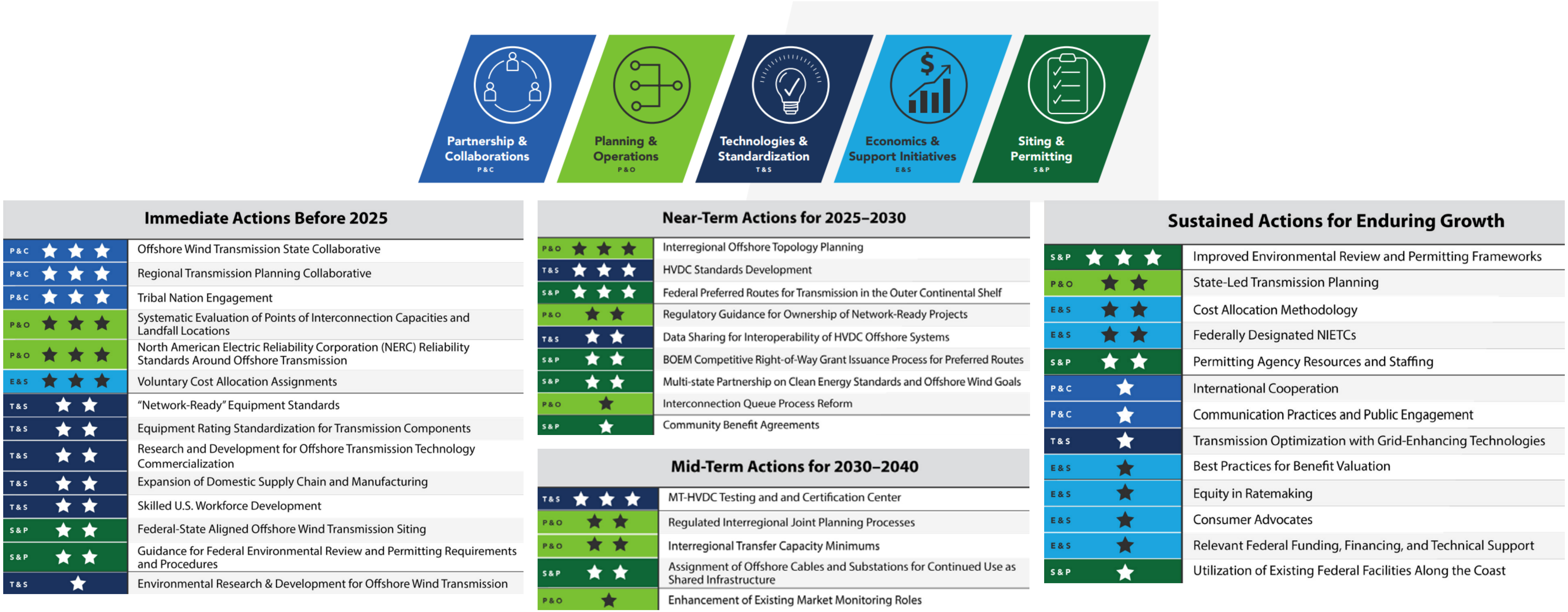
The Atlantic Offshore Wind Transmission Study identifies and compares different transmission strategies for enabling offshore wind energy deployment along the U.S. Atlantic Coast. Key findings include:

- Offshore transmission can be planned while considering ocean co-uses and environmental constraints.
- Benefits of networking offshore transmission come from reduced curtailment, reduced usage of higher-cost generators, and contributions to reliability.
- Offshore transmission networks contribute to grid reliability by enabling resource adequacy and helping manage the unexpected loss of grid components (contingencies).
- Benefits of offshore transmission networking outweigh the costs, often by a ratio of 2 to 1 or more. Offshore networks with interregional interlinks provide the highest value.
- Building offshore transmission in phases can help reduce development risk, but early implementation of high-voltage direct current technology standards is essential for future interoperability.



Source: NREL, https://www.nrel.gov/wind/atlantic-offshore-wind-transmission-study.html

POLICY AND REGULATORY ACTIONS



Immediate Actions Before 2025

P&C	★★★	Offshore Wind Transmission State Collaborative
P&C	★★★	Regional Transmission Planning Collaborative
P&C	★★★	Tribal Nation Engagement
P&O	★★★	Systematic Evaluation of Points of Interconnection Capacities and Landfall Locations
P&O	★★★	North American Electric Reliability Corporation (NERC) Reliability Standards Around Offshore Transmission
E&S	★★★	Voluntary Cost Allocation Assignments
T&S	★★	"Network-Ready" Equipment Standards
T&S	★★	Equipment Rating Standardization for Transmission Components
T&S	★★	Research and Development for Offshore Transmission Technology Commercialization
T&S	★★	Expansion of Domestic Supply Chain and Manufacturing
T&S	★★	Skilled U.S. Workforce Development
S&P	★★	Federal-State Aligned Offshore Wind Transmission Siting
S&P	★★	Guidance for Federal Environmental Review and Permitting Requirements and Procedures
T&S	★	Environmental Research & Development for Offshore Wind Transmission

Near-Term Actions for 2025–2030

P&O	★★★	Interregional Offshore Topology Planning
T&S	★★★	HVDC Standards Development
S&P	★★★	Federal Preferred Routes for Transmission in the Outer Continental Shelf
P&O	★★	Regulatory Guidance for Ownership of Network-Ready Projects
T&S	★★	Data Sharing for Interoperability of HVDC Offshore Systems
S&P	★★	BOEM Competitive Right-of-Way Grant Issuance Process for Preferred Routes
S&P	★★	Multi-state Partnership on Clean Energy Standards and Offshore Wind Goals
P&O	★	Interconnection Queue Process Reform
S&P	★	Community Benefit Agreements

Mid-Term Actions for 2030–2040

T&S	★★★	MT-HVDC Testing and and Certification Center
P&O	★★	Regulated Interregional Joint Planning Processes
P&O	★★	Interregional Transfer Capacity Minimums
S&P	★★	Assignment of Offshore Cables and Substations for Continued Use as Shared Infrastructure
P&O	★	Enhancement of Existing Market Monitoring Roles

Sustained Actions for Enduring Growth

S&P	★★★	Improved Environmental Review and Permitting Frameworks
P&O	★★	State-Led Transmission Planning
E&S	★★	Cost Allocation Methodology
E&S	★★	Federally Designated NIETCs
S&P	★★	Permitting Agency Resources and Staffing
P&C	★	International Cooperation
P&C	★	Communication Practices and Public Engagement
T&S	★	Transmission Optimization with Grid-Enhancing Technologies
E&S	★	Best Practices for Benefit Valuation
E&S	★	Equity in Ratemaking
E&S	★	Consumer Advocates
E&S	★	Relevant Federal Funding, Financing, and Technical Support
S&P	★	Utilization of Existing Federal Facilities Along the Coast

Source: An Action Plan for Offshore Wind Transmission Development in the U.S. Atlantic Region (https://www.energy.gov/gdo/atlantic-offshore-wind-transmission-action-plan)

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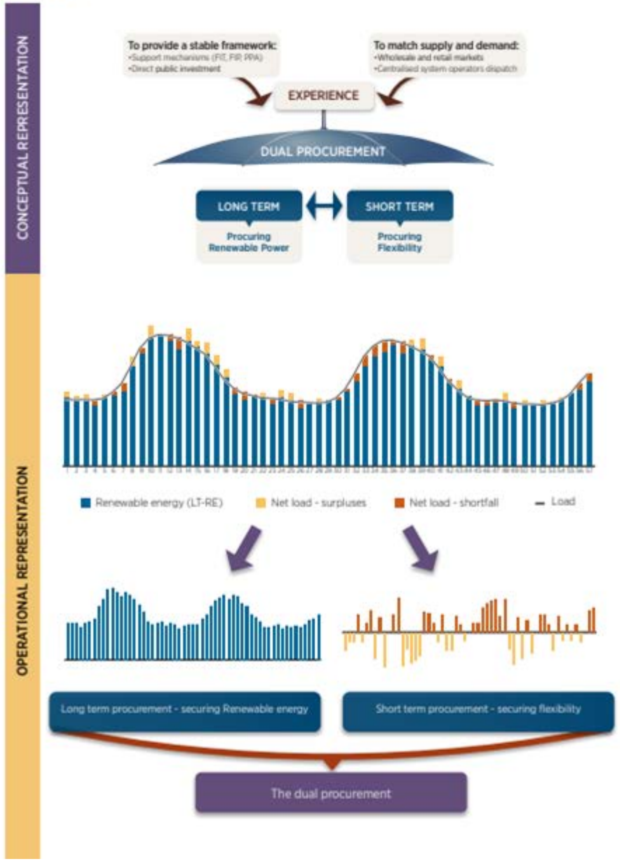
IMPROVED MARKET DESIGN FOR FLEXIBILITY

MODERNIZING POWER SYSTEMS FOR THE TRANSITION

Vision: Create an organizational structure that is well-suited for the renewable energy era. This vision focuses on transitioning from current power system frameworks to a "dual-procurement" mechanism that acknowledges and accommodates the distinct characteristics of renewable energy (primarily variable renewable energy or VRE) and flexibility resources.

The main goal is to design a power system that is sustainable, reliable, and capable of supporting high shares of renewable energy while ensuring system adequacy, reducing inequalities, and enhancing socio-economic resilience.

FIGURE 42. The dual procurement proposal



Source: IRENA RE-organising power systems for the transition report https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jun/IRENA_Organising_Power_Systems_2022.pdf

CHALLENGES TO IMPROVING MARKET DESIGN FOR POWER SYSTEM FLEXIBILITY

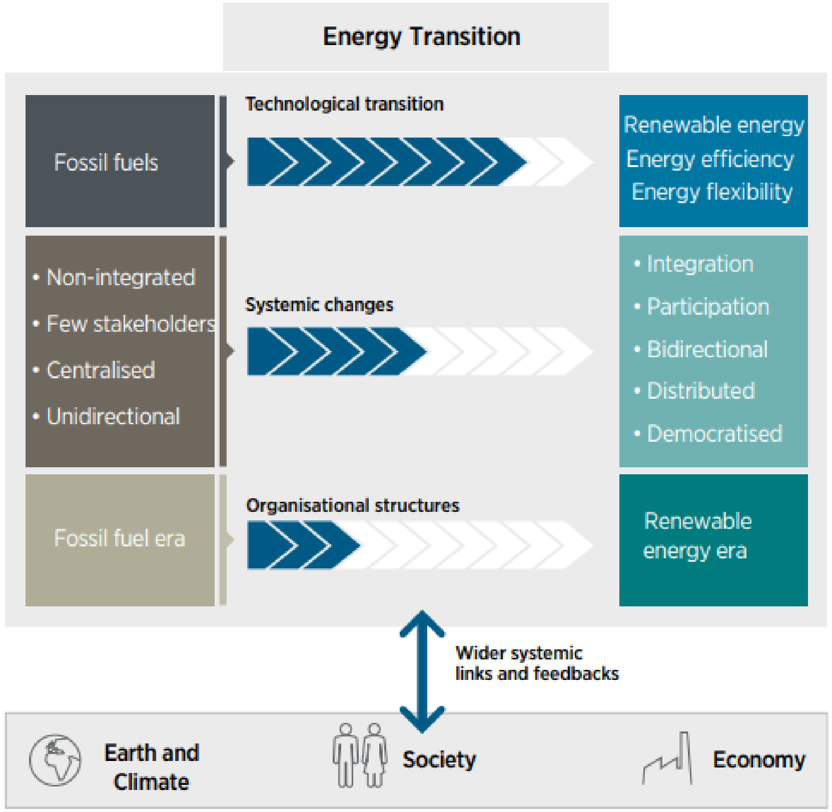
Challenges:

- **Misalignment with Current Structures**: Existing power system structures are often inadequate for the needs of the renewable energy transition. This misalignment can create barriers to the effective integration of renewable energy, leading to inefficiencies and hindering progress.
- **Balancing Short-Term and Long-Term Needs:** The power sector must balance immediate operational needs with long-term investment signals. Short-term fixes without a holistic vision could reinforce structural misalignments, making the energy transition more difficult.
- **Systemic Change and Evolution:** There is a significant lag in the evolution of organizational structures compared to the technological advancements in renewable energy and flexibility. Systemic changes are needed to support the deployment of renewable energy technologies and to ensure that power systems can adapt to the demands of a high-renewable future.
- **Integrating Diverse Stakeholders:** Both regulated and liberalized power systems face the challenge of reformulating their procurement mechanisms to support the transition. This requires balancing regulation, competition, and collaboration while ensuring that all stakeholders are effectively engaged and aligned with the transition goals.
- **Ensuring Financial Viability**: The economic signals provided by the current market structures may not guarantee cost recovery for VRE plants as their penetration increases. There is a need to design procurement mechanisms that provide stable long-term payments for renewable energy and adequately compensate flexibility providers.
- **Addressing Socio-Economic Impacts**: The power sector must address the wider socio-economic impacts of the energy transition, including reducing inequalities, ensuring just transitions, and fostering socio-economic resilience in the face of climate change.

STATE-OF-THE-ART RESEARCH

- Power system structures have evolved differently across regions based on sociopolitical frameworks.
- These structures now need to adapt to the demands of the energy transition.
- The challenges and goals vary across different organizational structures, and the appropriate transition pathway will be case-dependent.
- Existing power system structures, designed for the fossil fuel era, may create barriers during the energy transition.
- Misalignments, such as the "cannibalization effect" and inadequate capacity mechanisms, must be addressed to support a renewable-based power system.
- The transition requires a holistic approach that includes fostering participation, improving governance, and aligning the socio-economic system with climate goals to ensure a just and successful energy transition.

Unequal advance in different layers of the energy transition, with organisational structures lagging



Energy Transition

Fossil fuels

Technological transition

Renewable energy
Energy efficiency
Energy flexibility

- Non-integrated
- Few stakeholders
- Centralised
- Unidirectional

Systemic changes

- Integration
- Participation
- Bidirectional
- Distributed
- Democratised

Fossil fuel era

Organisational structures

Renewable energy era

Wider systemic links and feedbacks

Earth and Climate

Society

Economy

POLICY AND REGULATORY ACTIONS

Long-Term Renewable Energy (LT-RE) Procurement:

- Establish stable, long-term contracts (e.g., Feed-in Tariffs, Power Purchase Agreements) to reduce financial risks for renewable energy projects
- Increase public investment to support large-scale renewable energy development.

Short-Term Flexibility (ST-Flex) Procurement:

- Reform energy markets to better support flexibility resources like storage and demand-side management
- Introduce pricing mechanisms that ensure flexible resources are available when needed, without causing price spikes for consumers.

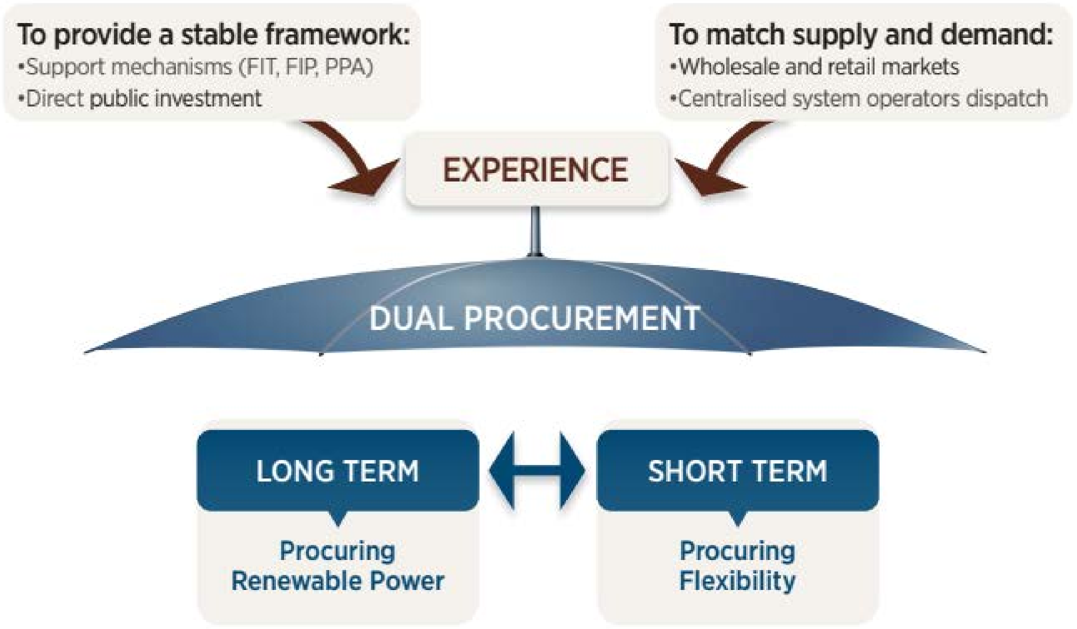
Integrated Policy Framework:

- Develop policies that connect long-term renewable energy procurement with short-term flexibility needs, ensuring the power system remains stable and efficient
- Strengthen governance to improve transparency, accountability, and collaboration among all stakeholders.

Inclusive and Equitable Transition:

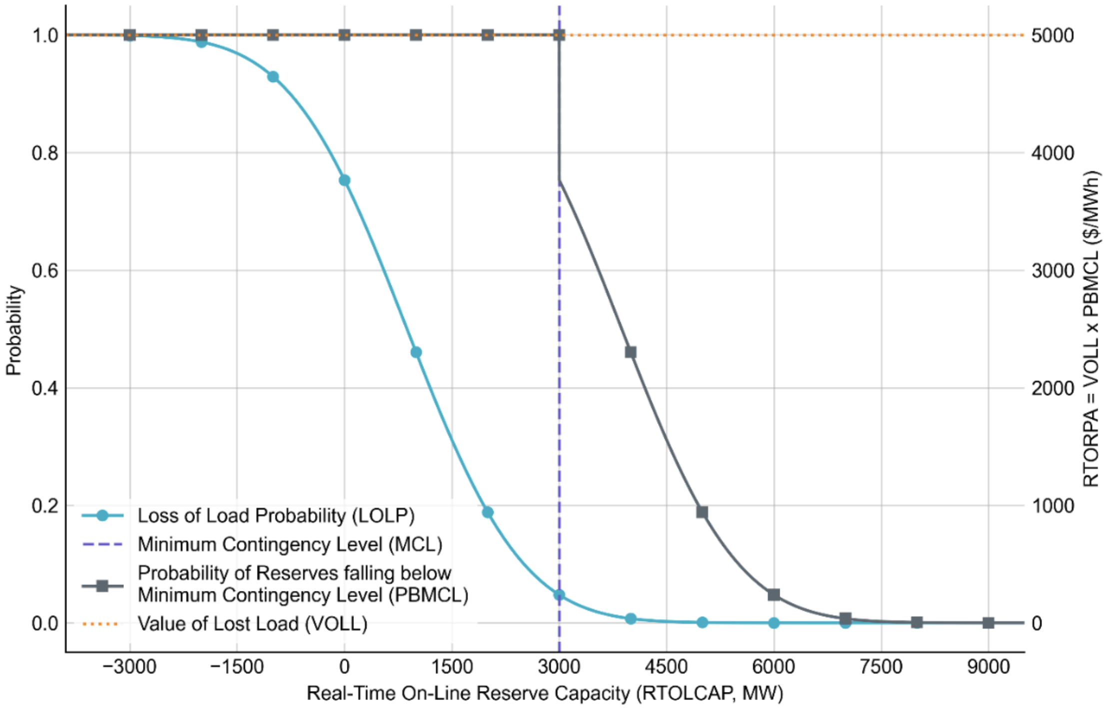
- Ensure that energy policies reduce inequalities and share benefits fairly, making the energy transition inclusive and just for all
- Support diverse stakeholders, including small-scale producers, to actively participate in the energy market.

Figure S-3. The dual procurement concept



CASE STUDY: ERCOT OPERATING RESERVE DEMAND CURVE

- As the amount of operating reserves decreases, ERCOT automatically raises wholesale electricity prices to reflect the increasing value of electricity when outages become more likely.
- This approach rewards flexible, available resources that can increase production during low supply conditions by increasing revenues.
- Incentivizes market response to system-wide reliability needs in real time.
- Parameters have been updated many times since initial introduction in 2014 to increase effectiveness.



Source: ERCOT ORDC Report, https://www.ercot.com/files/docs/2022/10/31/2022%20Biennial%20ERCOT%20Report%20on%20the%20ORDC%20-%20Final_corr.pdf

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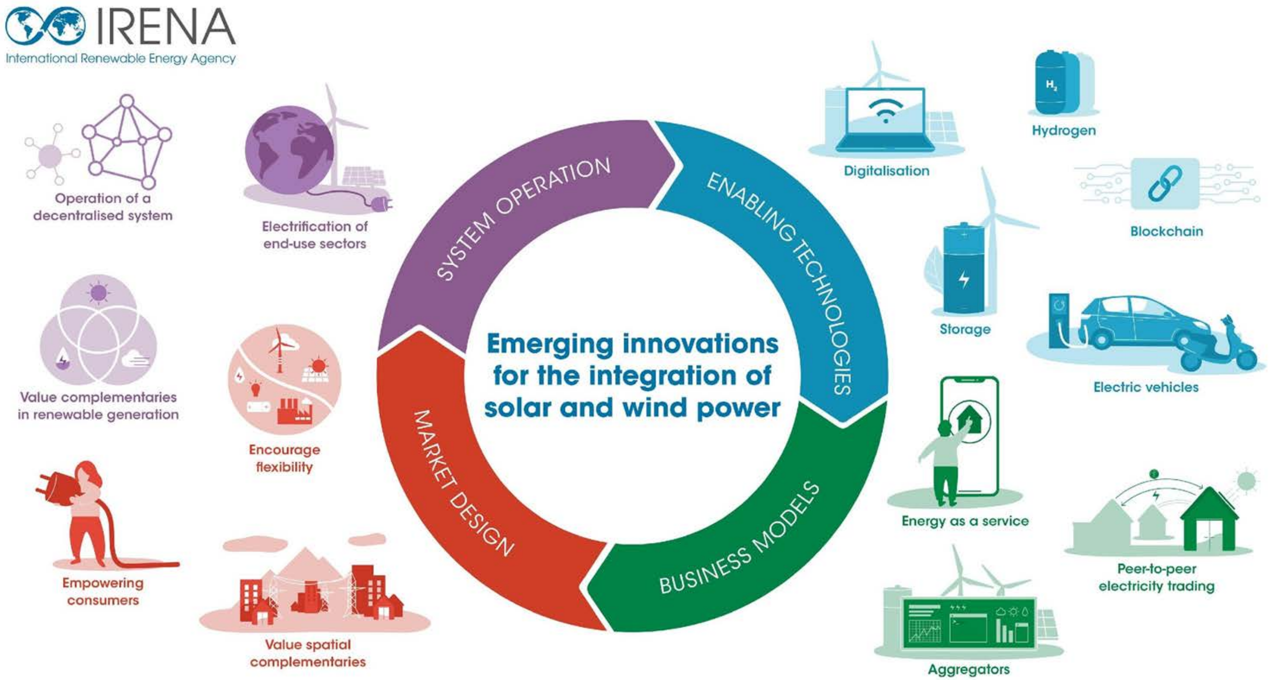
INNOVATION LANDSCAPE FOR SMART ELECTRIFICATION

CONTEXT AND VISION FOR INNOVATION LANDSCAPE FOR SMART ELECTRIFICATION

Vision: Accelerate the global energy transformation toward a carbon-neutral future by innovating both the production and consumption of energy. This transformation emphasizes smart electrification—the coordinated decarbonization of energy supply and demand using renewable electricity. This approach aims to drive economic growth, improve energy security, and reduce climate impacts while meeting sustainability goals.



CHALLENGES TO INNOVATION LANDSCAPE FOR SMART ELECTRIFICATION

Challenges:

- While renewable energy technologies, like wind and solar, have advanced rapidly, the demand side (e.g., transportation, heating) has not evolved at the same pace and still heavily relies on fossil fuels.
- Achieving deep decarbonization will triple global electricity demand by 2050 [IRENA World Energy Transitions 2023], placing immense pressure on power systems and necessitating significant upgrades in infrastructure and efficiency.
- Electrifying energy consumption is complex and requires systemic innovation across technology, market design, system planning, and business models, involving all stakeholders in the energy value chain.
- Implementing smart electrification strategies must account for the diverse technical, economic, social, and cultural contexts across different regions, avoiding a one-size-fits-all approach.

THREE INNOVATION TRENDS

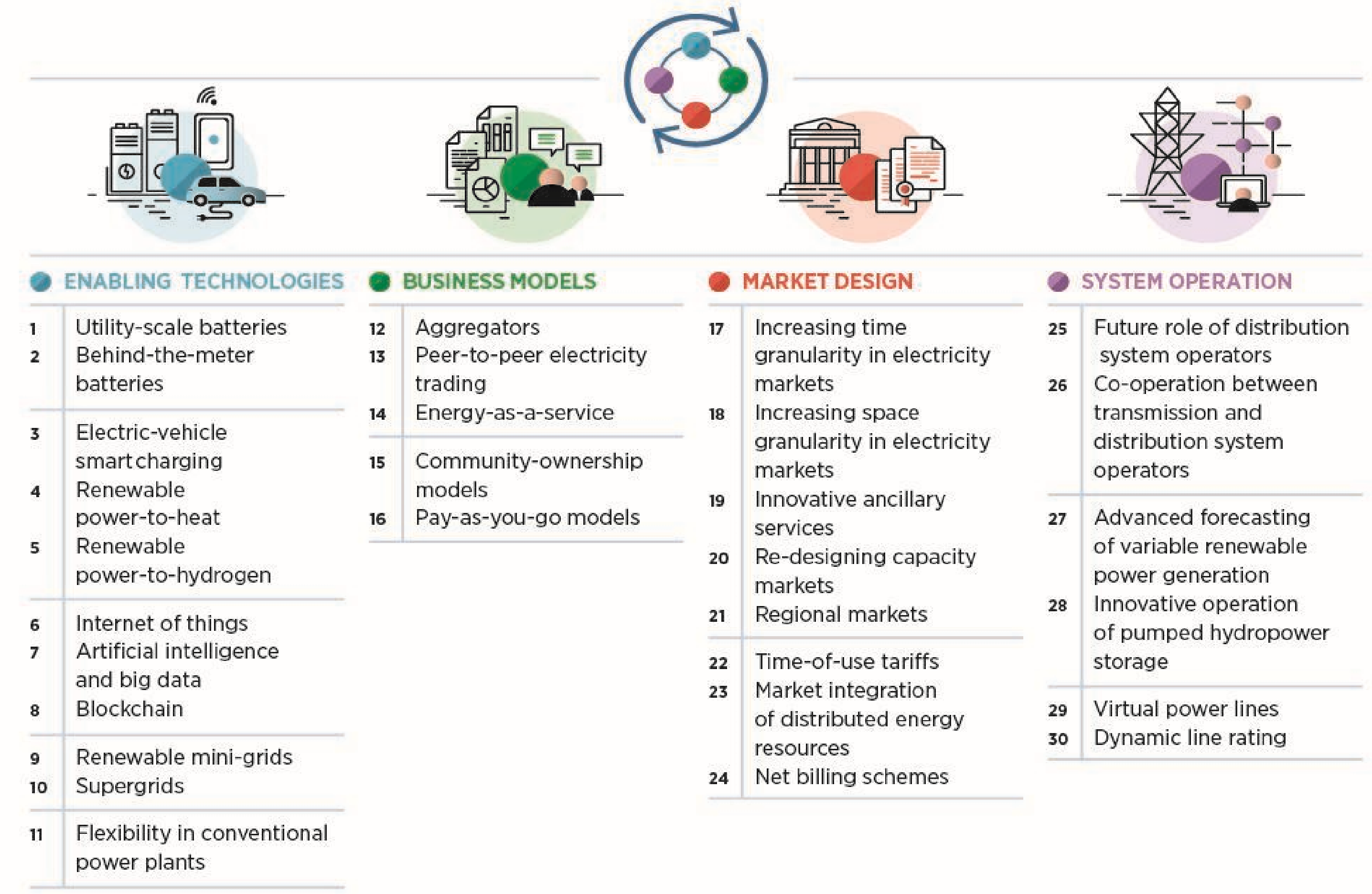
- Electrification of end-use sectors is an emerging solution to **maintain value and avoid curtailment of VRE** and help decarbonize other sectors.

- The increasing deployment of distributed energy resources (DERs) turns the consumer into an active participant, **fostering demand-side management**.

- Digital technologies enable **collecting data, monitoring and control, connecting devices, and faster response.**

Source: IRENA (2019), Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables

Innovation Landscape



ENABLING TECHNOLOGIES

1 Utility-scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

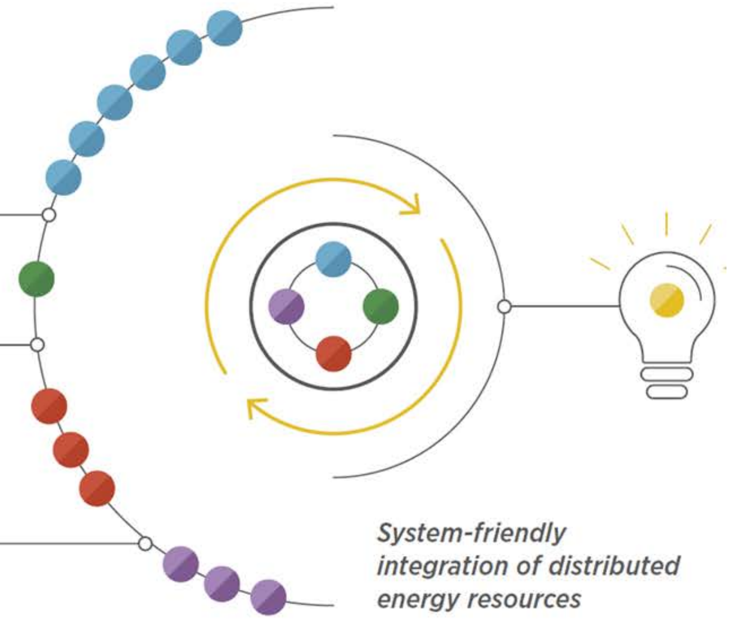
25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

Source: IRENA (2019), Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables

Case Study: Distributed Energy Resources (DERs) Providing Services to the Grid



Enabling technologies

- Behind-the-meter batteries
- EV smart charging
- Renewable power-to-heat
- Internet of things
- Artificial intelligence and big data
- Blockchain

Business models

- Aggregators

Market design

- Time-of-use tariffs
- Innovative ancillary services
- Market integration of distributed energy resources

System operation

- Future role of distribution system operators
- Co-operation between transmission and distribution system operators
- Virtual power lines

System-friendly integration of distributed energy resources

Sweden – Time-of-use tariffs

Sweden – Smart Heat Grids

Sweden – CoordiNet project

Netherlands – EV batteries for grid stability

Denmark – Parker Project

Germany – Aggregator providing grid services to the transmission system operator

Innovations do not emerge in isolation.
Synergies between innovations are needed.

POLICY AND REGULATORY ACTIONS

- Market Structure and Incentives: Governments or utilities offer incentives and subsidies for the adoption of smart electrification of technologies.

- Regulations for Grid Integration: Policies may govern how smart technologies integrate with existing electrical grids. This includes standards for interoperability and communication between smart devices and grid infrastructure.

- Standards and Protocols: There are various standards and protocols to ensure compatibility and performance of smart electrification technologies. For example, protocols for smart meters and home energy management systems are essential for ensuring interoperability.

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- Increasing time granularity in electricity markets
- Increasing space granularity in electricity markets
- Innovative ancillary services
- Re-designing capacity markets
- Regional markets
- Time-of-use tariffs
- Market integration of distributed energy resources
- Net billing schemes.

GRID SERVICES AND DEMAND FLEXIBILITY FROM EV CHARGING

CHALLENGES TO THE POWER SYSTEM WITH INCREASED EV CHARGING INFRASTRUCTURE

Vision: Innovative markets and technological advancements in artificial intelligence and controls enable EVs to provide flexibility and grid-support services as EV charging demand scales up.

Challenges:

- Mismatch of the timeline for building charging infrastructure compared to rapid consumer adoption of EVs
- Lack of incentives and markets for EVs to participate in grid flexibility services
- Tension between consumer preferences for charging times and grid needs, as well as consumer concerns with EV battery degradation
- Limited availability and higher cost of EV models and charging equipment with bidirectional capabilities
- Complexity of distributed communications and control to enable EV managed charging and demand response.

FLEXIBILITY SERVICES PROVIDED BY EVS

SYSTEM FLEXIBILITY		LOCAL FLEXIBILITY	
Wholesale market	**Transmission System Operator**	**Distribution System Operator**	**Behind-the-meter**
• Peak-shaving • Portfolio balancing	• Frequency control • (primary, secondary and tertiary reserve) • Other ancillary services (*e.g.*, voltage management, emergency power during outages)	• Voltage control • Local congestion and capacity management	• Increasing the rate of Renewable Energy self-consumption • Arbitrage between locally produced electricity and electricity from the grid • Back-up power

Source: IRENA

CASE STUDY

In Oslo, Norway, the energy company Tibber aggregated EVs to provide bids with 1-MW steps to the grid operator's (Statnett's) manual Frequency Response and Restoration (mFRR) market.

- The aggregator demonstrated that groups of EVs can successfully adjust charging patterns to participate in grid services markets.

In another example from Norway, the Tiber Røverkollen Housing Cooperative invested in electrical infrastructure with smart energy management to enable up to 230 EVs to charge simultaneously in a common parking garage.

- The demonstration revealed that EV owners keep their EVs plugged in longer when they have access to dedicated charging infrastructure at home, increasing the flexibility potential of the EV fleet.

POLICY AND REGULATORY ACTIONS

- Electricity system regulators can increase the competitiveness of EV demand response by enabling their participation in regional wholesale markets through aggregations. For example, see FERC Order No. 2222. Source: IEEE, https://ieeexplore.ieee.org/document/10287699.
- Charging infrastructure support can include subsidizing new stations, regulatory measures requiring EV readiness in different buildings and parking lots, and clear charging standards that enable managed charging and grid flexibility services.
- Smart charging does not necessarily mean bidirectional charging (V2G).
- Development of charging infrastructure should not mimic the petrol filling stations nor focus only on fast charging.
- Ensure that charging infrastructure is standardized and interoperable.
- Planning for EV charging infrastructure deployment should be inclusive and reflect the local setting.
- Mobility trends need to be considered in electrification strategies.
- Co-locating EV charging points with solar generation to minimize impact on grids.
- State agencies should coordinate and maintain consistency.

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LONG-DURATION ENERGY STORAGE (LDES) THROUGH HYDROGEN

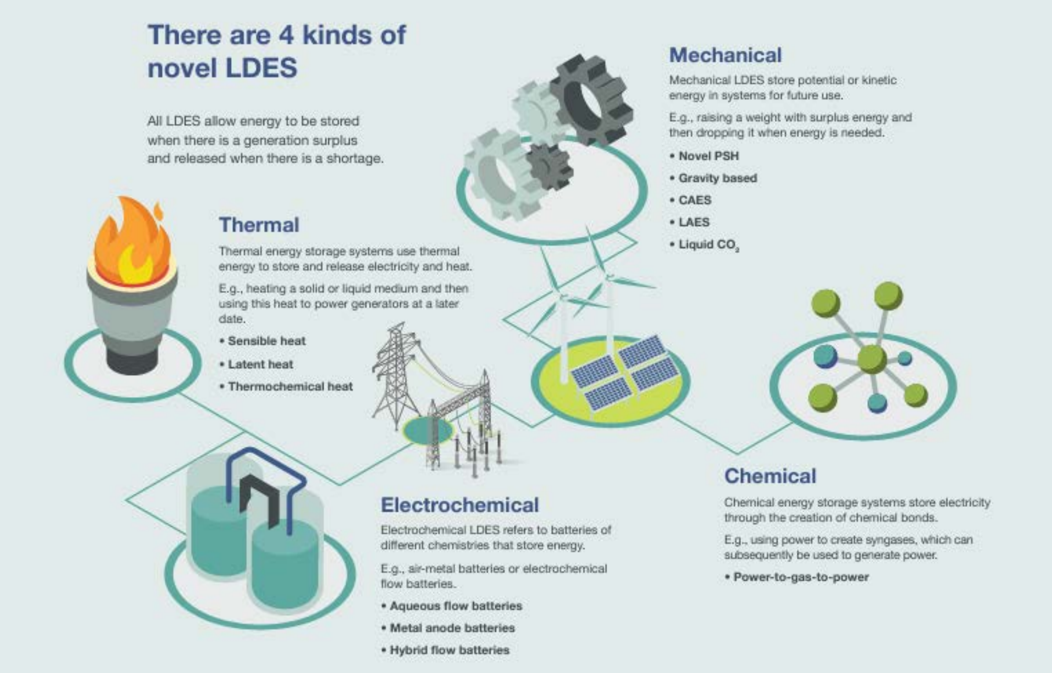
LDES TECHNOLOGIES

Types of LDES:

•**Inter-day LDES** is defined as shifting power by **10–36 hours** and includes almost all mechanical storage technologies and some electrochemical technologies (e.g., flow batteries). These technologies primarily serve a diurnal market need by shifting excess power produced at one point in a day to another point within the same or next day.

•**Multi-day/week LDES** is defined as shifting power by **36–160+** hours and includes many thermal and electrochemical technologies. It fills a market and end-use customer need where there may be an extended shortfall of power (e.g., multiple days of low wind and solar or resiliency applications) several times per year; multi-day/week LDES can also reduce the required curtailment/interconnection over-build to support variable renewables.

•**Seasonal LDES** is defined as moving energy for an extended time period, mostly over **several months** (e.g., summer to winter) and is a need likely to be filled by a fuel-based technology (e.g., hydrogen or natural gas with carbon capture).



There are 4 kinds of novel LDES

All LDES allow energy to be stored when there is a generation surplus and released when there is a shortage.

Mechanical

Mechanical LDES store potential or kinetic energy in systems for future use.

E.g., raising a weight with surplus energy and then dropping it when energy is needed.

- **Novel PSH**
- **Gravity based**
- **CAES**
- **LAES**
- **Liquid CO_2**

Thermal

Thermal energy storage systems use thermal energy to store and release electricity and heat.

E.g., heating a solid or liquid medium and then using this heat to power generators at a later date.

- **Sensible heat**
- **Latent heat**
- **Thermochemical heat**

Electrochemical

Electrochemical LDES refers to batteries of different chemistries that store energy.

E.g., air-metal batteries or electrochemical flow batteries.

- **Aqueous flow batteries**
- **Metal anode batteries**
- **Hybrid flow batteries**

Chemical

Chemical energy storage systems store electricity through the creation of chemical bonds.

E.g., using power to create syngases, which can subsequently be used to generate power.

- **Power-to-gas-to-power**

Credit: LDES Council

CHALLENGES TO THE DEPLOYMENT OF HYDROGEN-BASED LONG-DURATION ENERGY STORAGE

Vision: A scaled-up hydrogen industry large enough for hydrogen to serve as a chemical feedstock, energy carrier, and/or fuel in hard-to-decarbonize industrial sectors and as a mechanism for long-duration grid storage to enable the operation of 100% clean electricity systems.

Challenges

- **Technology development and scale-up to reduce costs:** The production of low-carbon hydrogen is currently expensive compared to other storage technologies and requires coordinated investment and planning to achieve cost efficiencies from economies of scale.
- **Storage and transportation infrastructure development:** Hydrogen has a relatively low energy density by volume and requires costly infrastructure for long-term storage, transportation, and/or conversion into alternative energy carriers (e.g., ammonia).
- **Market uncertainty:** Hydrogen as long-duration storage for the power system depends on the evolution of electricity market prices and pace of power sector decarbonization.
- **Safety concerns:** Hydrogen poses safety risks and requires extensive measures for proper production, storage, and transportation.
- **Regulatory environment:** Hydrogen lacks standardized regulations, codes, and permitting processes.
- **Renewable energy supply and land-use challenges:** Low-carbon hydrogen production requires significant renewable energy capacity, requiring additional land above and beyond what is needed for electricity production.

STATE-OF-THE-ART RESEARCH

Hydrogen R&D is focusing on fundamental questions that will determine the future of the industry, such as:

- Which of the early stage technologies will be most economically viable for long duration grid storage?
- Which mechanisms for hydrogen storage will be the most viable (e.g., high-pressure vessels, salt caverns, next-generation materials)?
- How can electrolyzer operations support the grid with flexible and controllable operations?

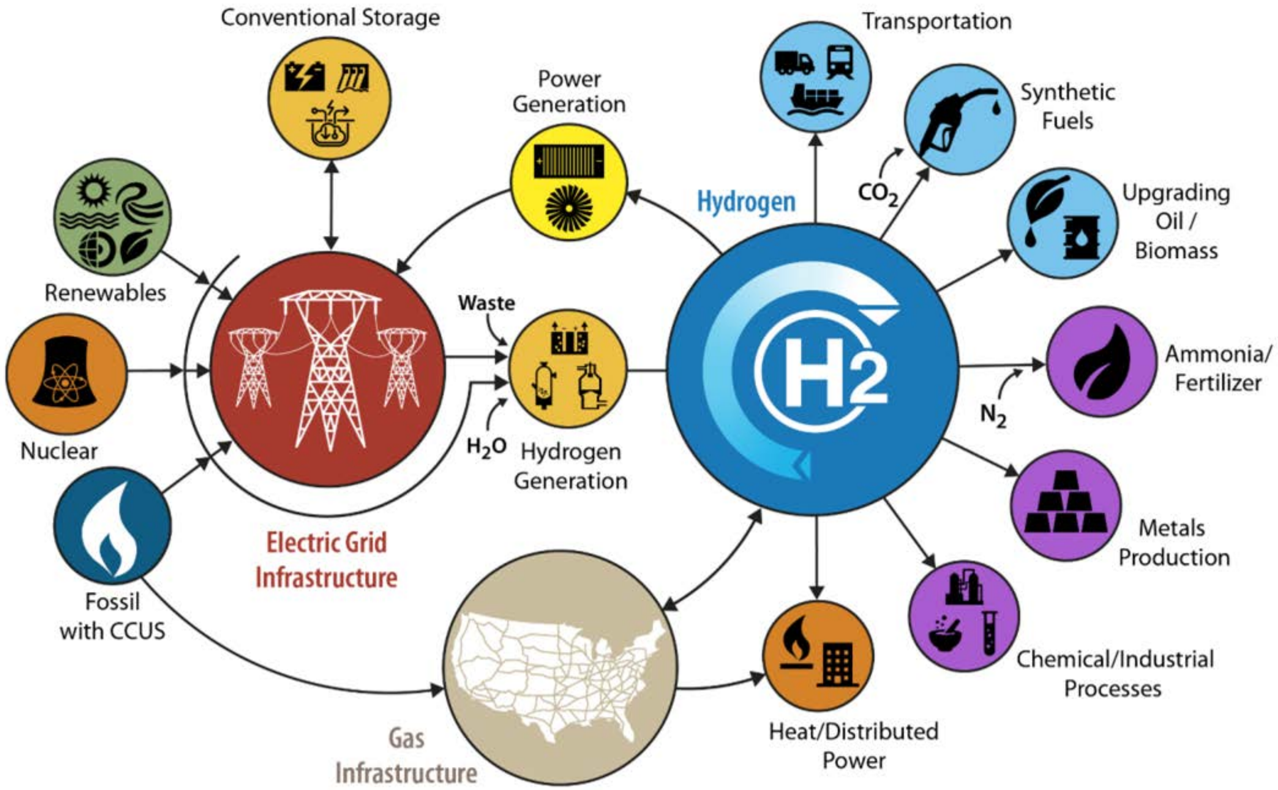
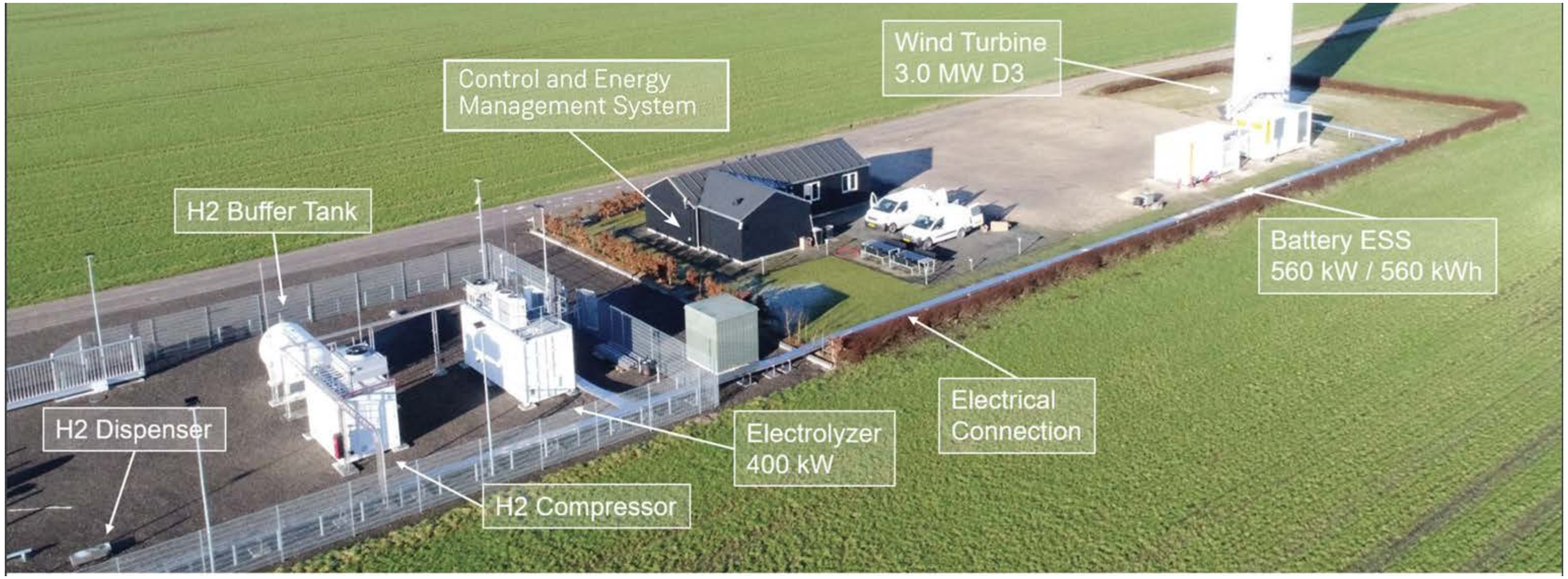


Figure Source: U.S. Department of Energy (DOE) https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/hydrogen-program-plan-2020.pdf?Status=Master

CASE STUDY: BRANDE HYDROGEN PILOT PROJECT

Test bed for hydrogen production in Brande, Denmark.

- Producing green hydrogen directly from a 3-MW wind turbine coupled to a 400-kW electrolyzer.
- Hydrogen is compressed and stored on-site in a specialized tube trailer for transportation to Copenhagen.
- The hydrogen is used in fuel cells to power the city's publicly owned taxis.



Source: Siemens Gamesa, https://www.siemensgamesa.com/-/media/siemensgamesa/downloads/en/products-and-services/hybrid-power-and-storage/green-hydrogen/green-hydrogen-unlocked-the-brande-hydrogen-project-white-paper.pdf

POLICY AND REGULATORY ACTIONS

Identify policy landscape and regulatory frameworks:

- Is there a regulatory framework for production, storage, transportation?
- Are there emissions reduction targets that can drive greater adoption?

Develop incentives and support programs:

- Are there government incentives or subsidies available for hydrogen?
- Are there any other forms of support or incubator programs?
- Is there a carbon market or pricing mechanism available?

Establish regulations and standards:

- Are safety standards developed for hydrogen and its derivatives?
- Are there national and/or international certification schemes in place?
- Are there safety requirements for handling, storing, distribution, and operation of hydrogen and its derivatives?

International collaboration:

- Are international cooperation mechanisms: partnerships, trade agreements, global initiatives (e.g., IPHE) supporting the project(s)?
- Is there established standardization to enable cross-border trade and deployment of clean hydrogen?

Source: NREL, https://www.nrel.gov/docs/fy24osti/87797.pdf

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ADVANCED GRID-FOLLOWING AND GRID-FORMING INVERTERS

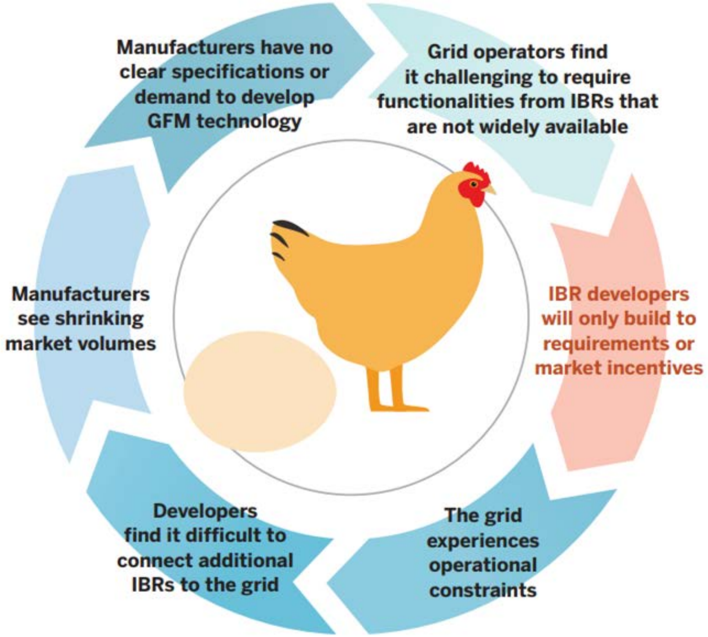
CHALLENGES TO THE USE OF GRID-FOLLOWING AND GRID-FORMING INVERTERS

Vision: Enable the reliable operation of 100% RE grids with scaled-up deployment of advanced grid-scale inverter technology that replaces the reliability services currently provided by synchronous generators

Challenges:

- Need for accurate models to better simulate and understand grid impacts for, as an example, digital twins
- Black-box models and original equipment manufacturer (OEM) differences
- Lack of manufacturing scale to-date
- Protection and fault current limitations
- Need for standardized specifications for performance, behavior, and associated tests and testing
- Uncertainty of GFM performance in a large grid setting with many devices.

The Circular Problem of Requirements and Deployment of Advanced IBR Controls

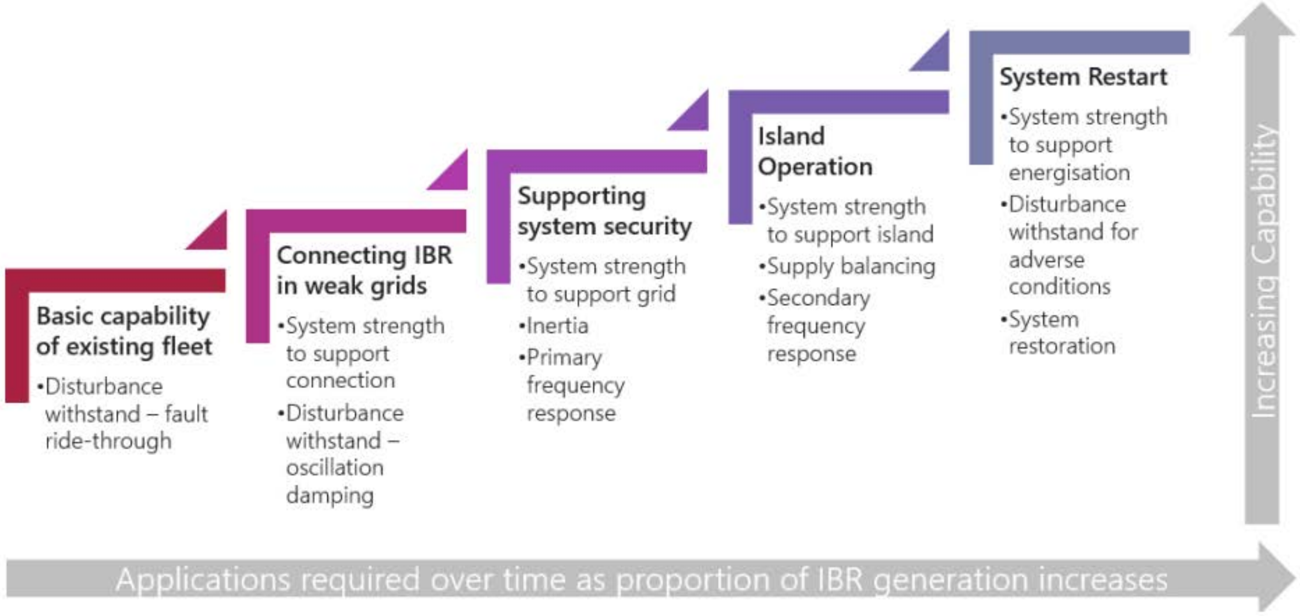


Source: ESIG GFM Deployment Fact Sheet, ESIG https://www.esig.energy/wp-content/uploads/2022/03/ESIG-GFM-deployment-fact-sheet-2022.pdf

STATE-OF-THE-ART RESEARCH

- Inverter technologies are not limited by mechanical physics.
  - Can rapidly increase or decrease output and sustain the response
  - More accurate and faster response compared to synchronous generators (SG).
- More advanced inverters are needed at higher instantaneous penetrations of inverter-based resources (IBRs).
  - Grid-following (GFL): grid-friendly features, ride-through capability
  - Advanced GFL: Weak grid features, control interaction mitigations
  - Grid forming (GFM): inertia emulation, black start, islanded operation, enhanced fault contribution, stabilize nearby GFLs.
- Active areas of ongoing research include:
  - Fault protection for 100% IBR systems
  - Electromagnetic transient (EMT) modeling of complex GFM interactions.

Figure 5 **Capabilities required for advanced grid-scale inverter applications**



Source: Application of Advanced Grid-Scale Inverters in the NEM (AEMO): https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/application-of-advanced-grid-scale-inverters-in-the-nem.pdf

GRID FORMING INVERTER

Comparison Expected Capabilities of GFM

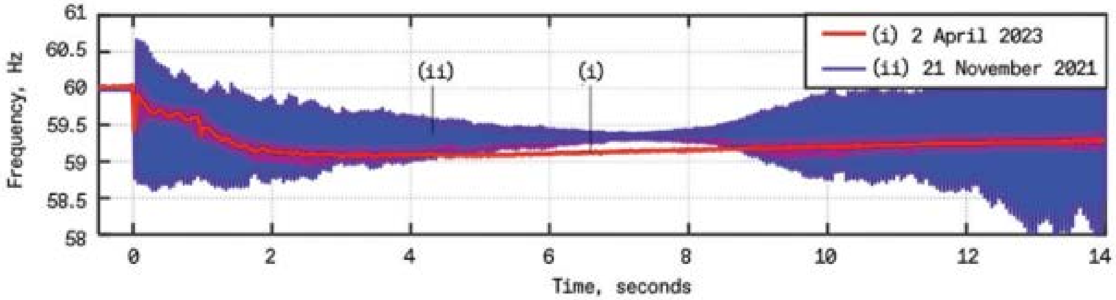
Topic	AEMO	ACER	Fingrid	German TSOs	HECO	NGESO	NERC
Maintain Synchroni.	✓				✓		✓
Provide Frequency Regulation	✓	✓	✓	✓	✓	✓	✓
Provide Voltage Regulation	✓	✓	✓	✓	✓	✓	✓
Provide Damping	✓		✓	✓		✓	✓
Coordinate Protection	✓		✓	✓		✓	✓
Maintain Power Quality	✓		✓	✓			✓
Support Black start	✓			✓	✓		✓
Support stable Island Oper.	✓		✓		✓		✓

Summary of GFM capability & performance requirements driven by system needs.

Source: G-PST

CASE STUDY: KAUAI ELECTRIC

Kauai electric grid now has two GFM inverters that have helped the system better respond to major disturbances (April 2023) compared to when it only had one (November 2021).



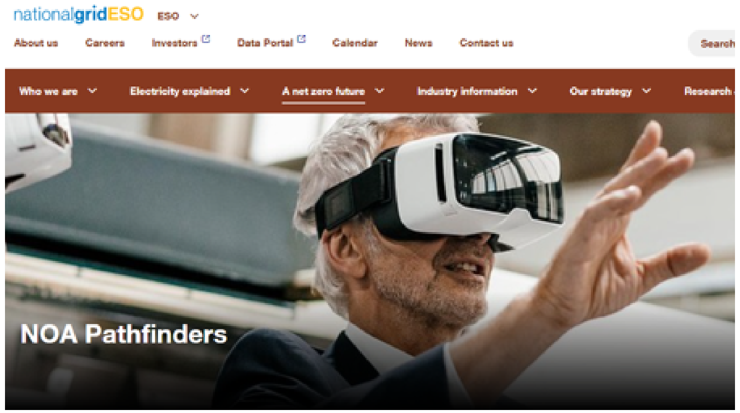
A recording of the frequency responses to two different grid disruptions on Kauai shows the advantages of grid-forming inverters. The red trace shows the relatively contained response with two grid-forming systems in operation. The blue trace shows the more extreme response to an earlier, comparable disruption, at a time when there was only one grid-forming inverter plant online.

Real-world experience shows how Kauai's grid stability improved after deployment of a second GFM inverter.

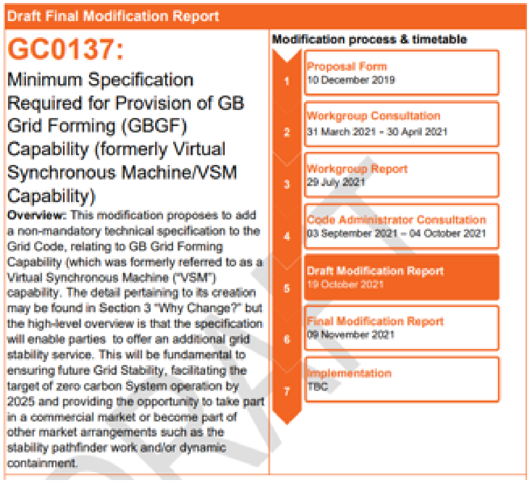
- Without the two GFM PV-battery plants, there would have been a system-wide blackout after a large oil-fired turbine tripped off.

Source: IEEE, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10523014&tag=1

CASE STUDY: GREAT BRITAIN STABILITY PATHFINDER INFORMING NERC IRPS



A tender process for new services needed in high-IBR power system, to gain experience and understanding of new technologies available to provide these services



Draft Final Modification Report

GC0137:

Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability)

Overview: This modification proposes to add a non-mandatory technical specification to the Grid Code, relating to GB Grid Forming Capability (which was formerly referred to as a Virtual Synchronous Machine ("VSM") capability. The detail pertaining to its creation may be found in Section 3 "Why Change?" but the high-level overview is that the specification will enable parties to offer an additional grid stability service. This will be fundamental to ensuring future Grid Stability, facilitating the target of zero carbon System operation by 2025 and providing the opportunity to take part in a commercial market or become part of other market arrangements such as the stability pathfinder work and/or dynamic containment.

Modification process & timetable

1. Proposal Form
10 December 2019
2. Workgroup Consultation
31 March 2021 - 30 April 2021
3. Workgroup Report
29 July 2021
4. Code Administrator Consultation
03 September 2021 – 04 October 2021
5. Draft Modification Report
19 October 2021
6. Final Modification Report
09 November 2021
7. Implementation
TBC

G-PST/ESIG Webinar Series: Operating the System Towards Zero Carbon

August 30 @ 4:00 pm - 5:30 pm EDT

« Webinar: Proactive Planning for Generator Interconnection: A Case Study of SPP and MISO

2022 Fall O&M Users Group Meeting »

About the Webinar: National Grid Electricity System Operator (ESO) plays a very important role of ensuring that Great Britain has the essential energy it needs by making sure supply meets demand every second of every day. The flow of electricity is getting more complex in the GB system with key features of more renewable energy and interconnectors; a growing number of ways to source electricity as well as more participants in "demand side response". National Grid ESO is working hand in hand with the energy industry and continually finding ways to innovate, invest and adapt the electricity system to keep electricity flowing reliably to homes and businesses across Great Britain.

GB Stability Pathfinder and GC0137 informing draft GFM Specifications NERC IRPS is developing

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Grid Forming IBR Specification and Modeling

--Bulk Power System Reliability Considerations

Aug. 2022

RELIABILITY | RESILIENCE | SECURITY

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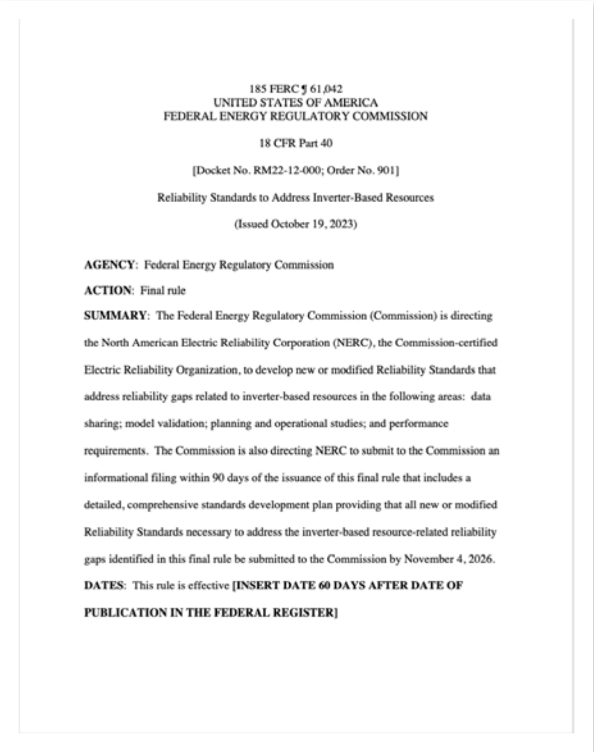
404-446-2560 | www.nerc.com

POLICY AND REGULATORY ACTIONS

- Align economic models and incentives to encourage commercialization of advanced GFL and GFM inverter capabilities
- Enable GFM to participate in essential grid service markets such as products for primary frequency response (PRF) and fast frequency response (FFR)
- Develop interconnection standards and grid codes to provide clear specifications of GFM technology performance
- Address data-sharing, model validation, planning and operational studies, and inverter performance specifications in grid reliability requirements.



185 FERC ¶ 61,042
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

18 CFR Part 40

[Docket No. RM22-12-000; Order No. 901]

Reliability Standards to Address Inverter-Based Resources

(Issued October 19, 2023)

AGENCY: Federal Energy Regulatory Commission

ACTION: Final rule

SUMMARY: The Federal Energy Regulatory Commission (Commission) is directing the North American Electric Reliability Corporation (NERC), the Commission-certified Electric Reliability Organization, to develop new or modified Reliability Standards that address reliability gaps related to inverter-based resources in the following areas: data sharing; model validation; planning and operational studies; and performance requirements. The Commission is also directing NERC to submit to the Commission an informational filing within 90 days of the issuance of this final rule that includes a detailed, comprehensive standards development plan providing that all new or modified Reliability Standards necessary to address the inverter-based resource-related reliability gaps identified in this final rule be submitted to the Commission by November 4, 2026.

DATES: This rule is effective **[INSERT DATE 60 DAYS AFTER DATE OF PUBLICATION IN THE FEDERAL REGISTER]**

Example regulatory proceeding in the U.S. to modify reliability standards and address gaps in regulations for inverter-based resources. Source: FERC, https://www.ferc.gov/media/e-1-rm22-12-000

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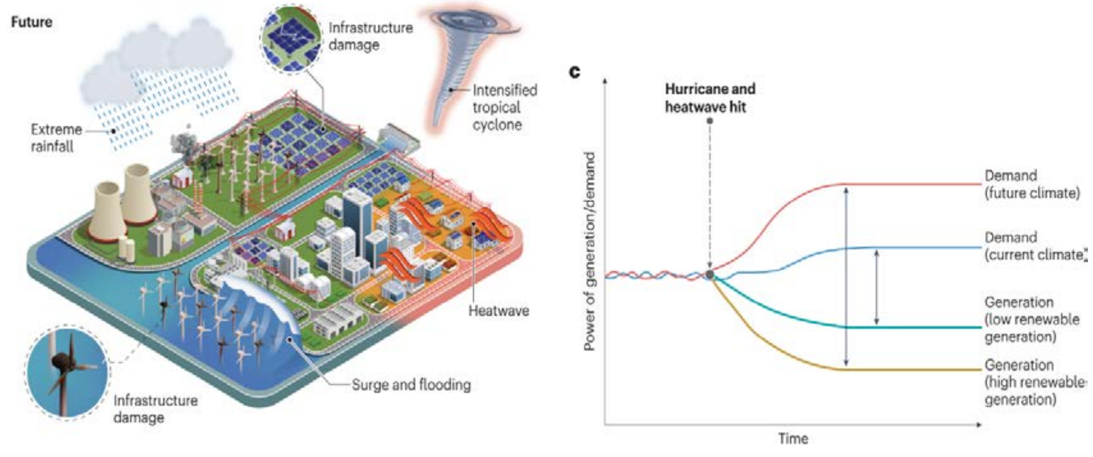
IMPACT OF CHANGING WEATHER ON RELIABILITY

Challenges to Improving Power System Reliability in the Face of Changing Weather Conditions

Vision: Grid planners and operators can identify and plan for interventions needed to maintain reliable grids in the face of changing weather over the next decades.

Challenges:

- Grids were not designed to manage the increasing severity and frequency of large weather events.
- Changing weather in combination with electrification of end uses (e.g., heat pumps, cooking, transportation) increases uncertainty of demand forecasting.
- Challenging to identify the impacts of changing weather on RE resources, both during extreme events and changes to long-term availability due to climate change.
- Lack of standardized risk metrics that are tailored to help utilities identify appropriate mitigation measures.
- Grid-hardening requires significant financial resources that may not be available.



Source: IRENA, Xu et al.

STATE-OF-THE-ART RESEARCH

Detailed power system modeling is coupled with robust weather modeling to identify impacts of changing weather on grid reliability.

- Grid planners concerned about a wider range of weather-related events that can occur at any time, increasing the scope of traditional reliability analysis.
- Studies show that future grids will be increasingly stressed by severe, but not extreme, hot/cold weather conditions occurring concurrently with extended periods of low wind and solar resources could be the new "extreme" weather when it comes to the impact to power system operations.
- Further research needed to capture more recent weather events and capture the influence of climate change on weather patterns.

Source: https://www.nrel.gov/news/program/2024/moderate-is-the-new-extreme-weathers-impact-on-growing-renewable-grid-operations.html

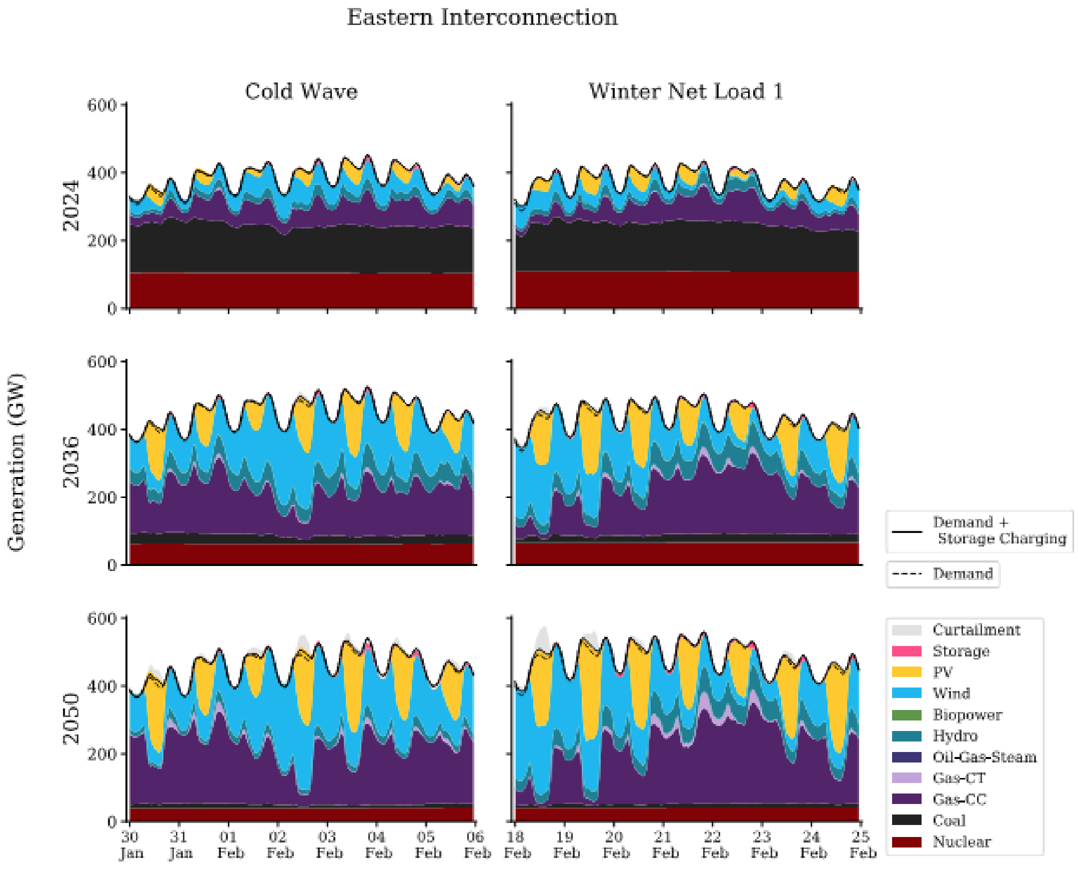


Figure source: NREL, https://www.nrel.gov/docs/fy22osti/78394.pdf

POLICY AND REGULATORY ACTIONS

- **Conduct Comprehensive Climate Risk Assessments:** Establish a strong scientific foundation for climate resilience strategies by performing thorough assessments of climate risks and impacts.
- **Integrate Climate Resilience in Energy Planning:** Embed climate resilience into national energy strategies and regulations to signal the importance of building resilient electricity systems to utilities and investors.
- **Identify and Prioritize Cost-Effective Resilience Measures:** Develop plans and guidelines that help utilities recognize the most cost-effective measures to enhance resilience at the planning stage, considering synergies with other business goals.
- **Create Incentives for Utility Investment in Resilience:** Implement mechanisms, such as performance-based ratemaking, to encourage timely investments by utilities in resilient electricity infrastructure.
- **Implement, Monitor, and Adjust Resilience Measures:** Enhance the climate resilience of electricity systems through physical system hardening, advanced operations, better recovery coordination, and capacity-building, with ongoing evaluation and adjustments based on feedback.
- **Align Investments with Decarbonization and Energy Security Goals:** Policymakers must ensure that investments in the energy sector are aligned with decarbonization objectives while maintaining energy security. This includes updating planning methods to manage seasonal demand variability, incentivizing demand response, and removing regulatory barriers to enhance system reliability and efficiency. Additionally, clear signals and reforms are needed to financially reward essential power plants and storage technologies, reflecting their value in a high-renewable energy system.

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SUMMARY

SUMMARY

Future power systems will provide clean energy at scale through coordinated planning, flexible operations, market evolution, and technology innovation. This report identifies enabling strategies to accelerate power system decarbonization and highlights seven transformation-leading topics in 2024:

- Enabling Strategies to Facilitate Power Sector Decarbonization
- Long-Term Planning of Smart Distribution Grids
- Offshore Transmission Networks
- Improved Market Design for Flexibility
- Innovation Landscape for Smart Electrification
- Grid Services and Demand Flexibility From EV Charging
- Long Duration Energy Storage Through Hydrogen
- Advanced Grid-Following and Grid-Forming Inverters
- Impact of Changing Weather on Reliability.

ORGANIZATIONS/INITIATIVES

- **IRENA:** is an intergovernmental organization mandated to facilitate cooperation, advance knowledge, and promote the adoption and sustainable use of renewable energy.
- **IEA:** is an intergovernmental organization providing analysis, data, policy recommendations and solutions for energy security and clean energy transitions.
- **RETA:** is a global initiative of more than 60 energy regulators from across the globe working together to accelerate decarbonization.
- **G-PST:** is a network of system operators, manufacturers, utilities, standard bodies, and research institutions accelerating solutions to enable grids across the world to run on 100% renewable energy.
- **LTES:** this initiative promotes the improved use of model-based LTES to support and accelerate energy transitions in CEM countries.

ORGANIZATIONS/INITIATIVES

- **ISGAN:** is an international platform for the development and exchange of knowledge and expertise on smarter, cleaner, and more flexible and resilient electricity grids (“Smart Grids”).
- **SBS:** This initiative boosts stationary battery storage development and deployment and reduces technology costs through international cooperation, diversified, sustainable, responsible, secure and transparent supply chains, to promote grid stability and reliability, while supporting global renewable energy integration.
- **NICE Future:** aims to initiate a dialogue on the role that clean and reliable nuclear energy can play in bolstering economic growth, energy security and access, and environmental stewardship.
- **CESC:** This initiative helps governments, advisors, and analysts create policies and programs that advance the deployment of clean energy technologies.
- **EVI:** This initiative is a multi-government policy forum dedicated to accelerating the introduction and adoption of electric vehicles worldwide.

21st Century
POWER
PARTNERSHIP
Accelerating the transformation of power systems

STATUS OF POWER SYSTEM TRANSFORMATION
LEADING TOPICS OF 2024

iea
IRENA International Renewable Energy Agency
ISGAN International Smart Grid Action Network
RETA Regulatory Energy Transition Accelerator
GLOBAL PST CONSORTIUM
ELECTRIC VEHICLES INITIATIVE – AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL
SUPERCHARGING BATTERY STORAGE – AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL
CLEAN ENERGY SOLUTIONS CENTER – AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL
NICE NUCLEAR INNOVATION: Future CLEAN ENERGY – AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL
LTES LONG-TERM SCENARIOS FOR THE ENERGY TRANSITION – AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

September 2024

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21st Century POWER PARTNERSHIP
Accelerating the transformation of power systems

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