Lessons Learned for Rapid Decarbonization of Power Sectors

Collaborative Report from the Clean Energy Ministerial

Delivered for the Global Clean Energy Action Forum (GCEAF/CEM13/MI7)

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Report Background

This report covers key lessons learned for the rapid decarbonization of power sectors, emphasizing best practices in *planning*, *building*, and *operating* electricity systems. Decarbonization covers all greenhouse gases, including carbon dioxide and methane. The intended audience of this report consists of energy ministers and other high-level energy sector decisionmakers.

This report is the result of a collaborative effort among various Clean Energy Ministerial (CEM) Workstreams & partner initiatives:

- 21st Century Power Partnership (21CPP)
- Carbon Capture, Utilization and Storage (CCUS)
- Global Power System Transformation Consortium (G-PST)
- Industrial Deep Decarbonisation Initiative (IDDI)
- International Energy Agency Digital Demand-Driven Electricity Networks Initiative (IEA 3DEN)
- 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)

The contents are not intended to be comprehensive of all power sector topics, and there may be overlap between content in each section due to the nature of this first-of-its-kind collaborative effort to deliver unified messaging on power sector decarbonization to energy ministers. Topics not related to the power sector are not fully covered. For example, green hydrogen for use in industry or transportation is not included but is discussed under the topic of energy storage.

Synthesized key messages for ministers are highlighted at the beginning of the report.
These findings are options, not recommendations, for ministers.

Report Contents

Executive Summary: Overarching accelerants for power sector decarbonization, synthesized from the detailed lessons learned compiled in the report (Sections I-III).

I. Planning

1. Increase collaborative governance practices
2. Plan with new tools and methodologies
3. Ramp up capacity to develop national scenarios
4. Effectively use long-term scenarios
5. Integrate different levels of planning
6. Conduct renewable energy and storage integration studies
7. Coordinate renewable energy and transmission planning
8. Enable integrated clean energy systems
9. Include all technologies appropriate within national context
10. Research social equity impacts

II. Building

1. Set a robust and escalating carbon price
2. Incentivize zero-carbon energy technologies, including clean hydrogen
3. Increase grid investments at an unprecedented rate
4. Rapidly transition to digitalized smart power systems
5. Ensure electricity markets support clean energy
6. Scale renewable energy and storage via auctions
7. Design policy packages to deploy energy efficiency
8. Foster innovation for heat pumps and industrial motors
9. Support advanced nuclear demonstration projects
10. Develop carbon capture incentives and hubs

III. Operating

1. Champion knowledge sharing with peers
2. Promote standards and open-source tools
3. Endorse interoperability to integrate different technologies
4. Assure integration of flexible resources, including grid-edge assets
5. Endorse transmission interconnections
6. Advocate for state-of-the-art metrics, data, models and tools
7. Enable the various grid services of energy storage
8. Assure the use of improved wind and solar forecasting capabilities
9. Accelerate deployment of grid enhancing technologies
10. Support demand response via appropriate regulations and incentives

Annex: Supplemental lessons on leveraging the power sector to enable industrial sector decarbonization.

Executive Summary

Lessons Learned for Rapid Decarbonization of Power Sector

Synthesized key messages for energy ministers

Some of the messages may be more relevant to ministers than others depending on the country context.

OVERARCHING ACCELERANTS

Overarching accelerants for power sector decarbonization, in the stages of **planning, building, and operating**, are highlighted from the compilation of detailed lessons learned.

Planning

Increase Coordination

- Inter- and Intra-governmental
- Cross-sectoral
- Public-Private sector

Develop Capacity

- Government & universities
- Energy systems planning
- Long-term scenarios
- Legislative incentives
- Effective communication

Building

Scale Financing

- Grid modernization
- Demonstrations
- Private capital
- Business models

Set Clear Incentives

- Carbon pricing
- Procurement
- Transparent incentives

Operating

Adopt Robust Standards

- Open-source tools
- Harmonized standards
- Market design

Prioritize Grid Flexibility

- Compensation mechanisms
- Load aggregation
- Transmission & distribution

Overarching Accelerants: Planning

Increase Coordination

- Inter-governmental and intra-governmental: Initiate sharing of data, tools, methodologies, and lessons learned
- Cross-sectoral: Drive integrated planning of generation and transmission, transportation and grid, and industry and grid, including distributed energy resources
- Public-Private sector: Embrace inclusive processes with private sector and NGOs in government-led planning

Develop Capacity

- Champion capacity building in the government and at supporting universities and organizations
- Integrate energy systems planning capabilities across disciplines
- Promote transparent and robust long-term scenarios based on rigorous studies
- Create enabling environment for zero-carbon legislative incentives
- Effectively communicate to the public on the energy transition

Overarching Accelerants: Building

Scale Financing

- Allocate sufficient funding for electricity grid modernization, digitalization, and resilience
- Finance pre-commercial demonstration projects (e.g., advanced nuclear, carbon capture, advanced storage, etc.)
- Leverage private sector capital to finance zero-carbon technology (e.g., green bonds)
- Enable new business models to deploy zero-carbon products and services (e.g., energy service companies, aggregation, etc.)

Set Clear Incentives

- Champion carbon pricing and other zero-carbon incentives
- Develop ambitious procurement mechanisms (e.g., auctions)
- Design incentives that are transparent, accessible, and inclusive

Overarching Accelerants: Operating

Adopt Robust Standards

- Champion use of open-source operational tools to monitor real-time grid performance
- Include harmonized standards for technology interoperability and materials
- Promote operational efficiency through innovative market designs

Prioritize Grid Flexibility

- Develop mechanisms to compensate the flexibility of assets (e.g., grid-edge and utility-scale)
- Commission efforts to enable aggregation of flexible and efficient end-use loads (e.g., demand response)
- Enable flexible transmission and distribution infrastructure (e.g., via digitalization and grid-enhancing technologies)

I. Planning

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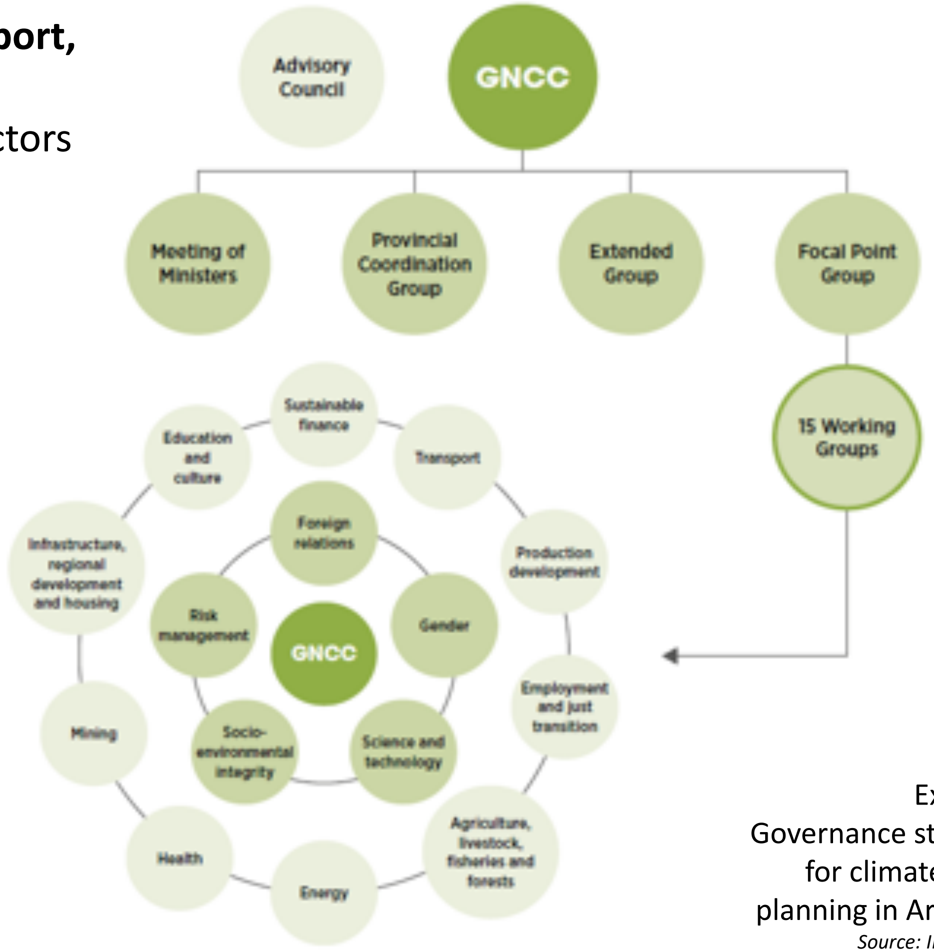
Increase Collaborative Governance Practices

Increased coordination between different institutions (climate, energy, transport, industry, etc.) can help unify visions between institutions for more effective policymaking, creating more consistent signals for investments, ensuring all sectors follow a common vision for decarbonization, and avoiding duplication of work.

<u>Examples of Integrated Departments/Ministries:</u>

Danish Ministry of Climate, Energy and Utilities
French Ministry of Ecological Transition
Italian Ministry of Ecological Transition
German Federal Ministry for Economic Affairs and Climate Action
United States Joint Office of Energy and Transportation

Lessons for Ministerial Action: Increase coordination between energy and climate/transport/finance/industrial institutions (intra- and inter-governmental) through developing or merging dedicated units, establishing a common platform of information, forming working groups, and increasing stakeholder engagement.



Example:
Governance structure for climate action planning in Argentina
Source: IRENA, 2022

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Plan with New Tools and Methodologies

Decarbonization requires **systems thinking and integrated planning** to address the increasing level of complexity of emerging systems and ensure that heterogeneous systems can effectively work together.

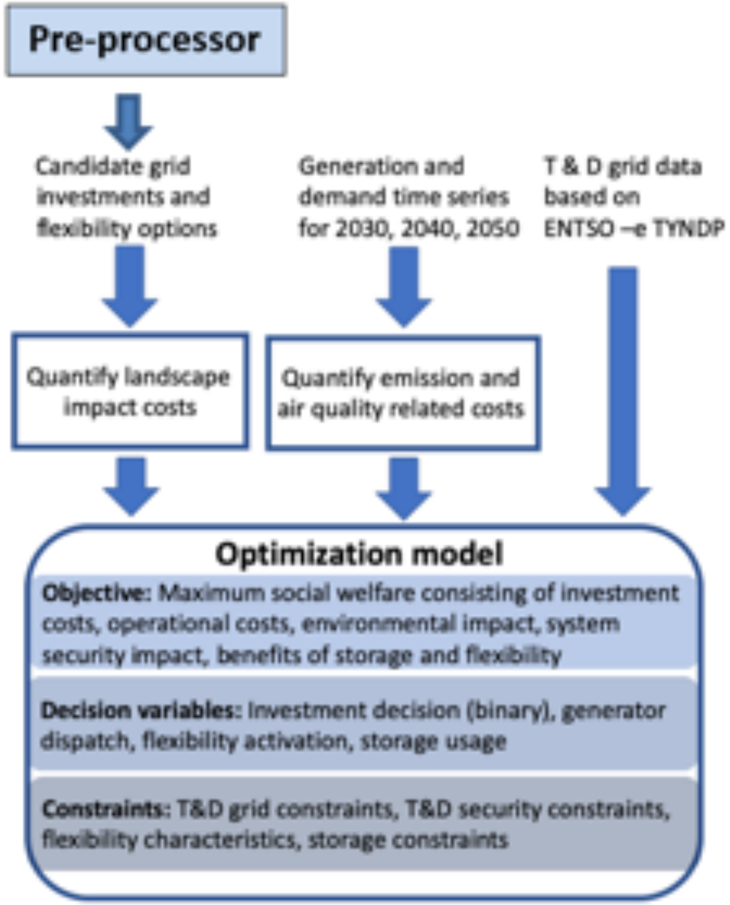
Better understand and adapt tools and methodologies

- More effective utilization of traditional and new data sources to inform planning processes
- New tools and models to cope with increased complexity, energy security, climate impacts, etc.

Create mechanisms and define protocols for data exchange among system actors

- With particular attention devoted to real-time electricity market architectures and the growing array of products that facilitate the participation of storage and demand-side resources in a future grid that will be a hybrid between a centralized and decentralized system.

Lessons for Ministerial Action: Ensure that the power system planning processes make effective use of digital tools and solutions and engage the multiple actors with a stake in the power system, especially system operators at both the transmission and distribution level.



Source: FlexPlan Project

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Ramp Up Capacity to Develop National Scenarios

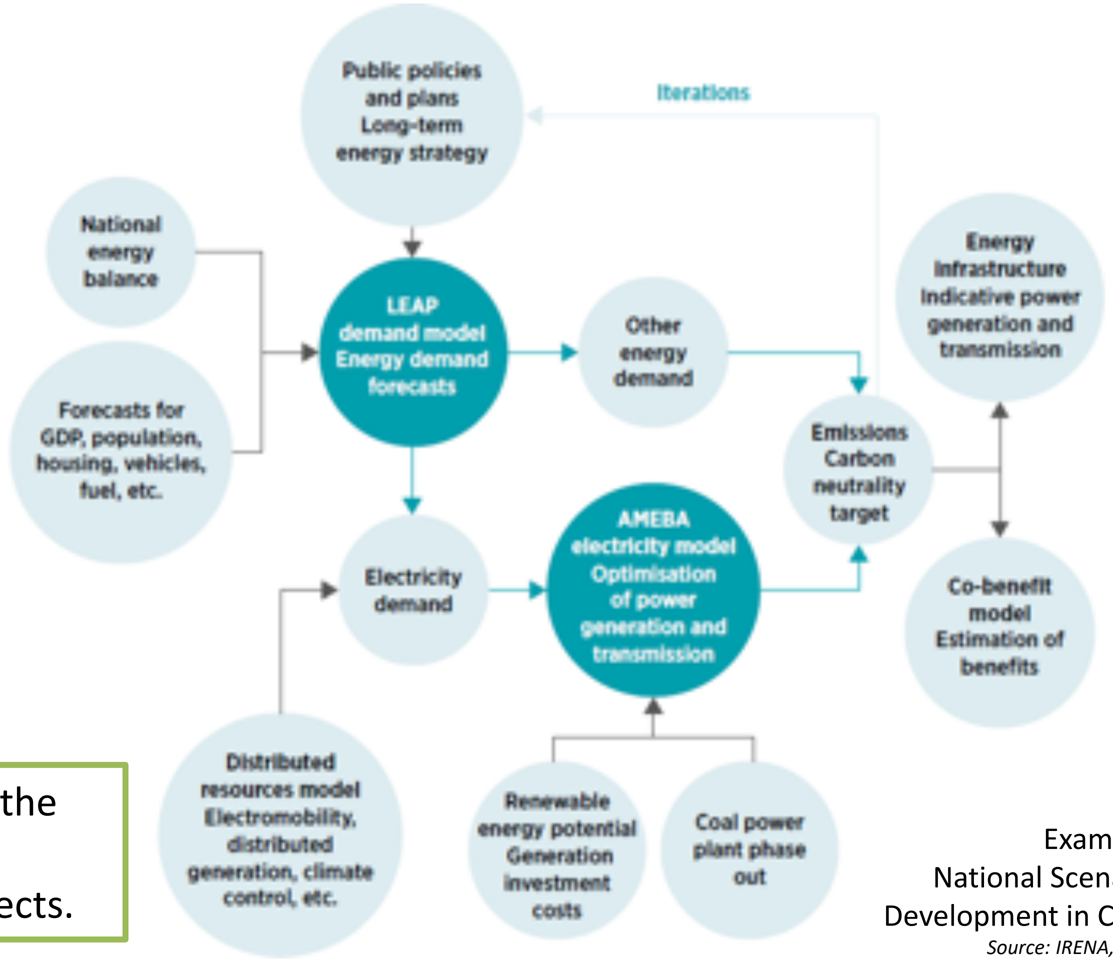
Deep decarbonization requires **expanding the methodology and sectoral scope of scenarios**.

A systematic approach towards developing modeling capacities can allow for more comprehensive scenarios.

These modeling capacities can account for energy security, climate resilience, and other priorities that continue to evolve. National scenarios should also account for the impacts of interconnected global energy systems (e.g., continental power grid in Europe).

Outsourcing scenario development can be useful while building internal capacity, but government ownership of the process can promote robustness, transparency, and reduce costs in the long term.

Lessons for Ministerial Action: Promote diverse modeling capacity across the public and academic sectors, through cooperation with international organizations and academia, and fund modeling and scenario-related projects.



Example:
National Scenario Development in Chile
Source: IRENA, 2022

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Effectively Use Long-Term Scenarios

Long-term energy scenarios (LTES) can be used for various objectives to support national energy planning. Clarifying the purpose of scenario development and establishing a common understanding of the scenario ensures its utility in a robust and forward-looking policymaking process. Transparency and public availability of these long-term scenarios is important.

Lessons for Ministerial Action: Officially integrating the use of long-term scenarios in the policymaking process is key to signal ambition, challenge targets, explore uncertainties, and set short- and mid-term policies that pave the way for deep decarbonization.

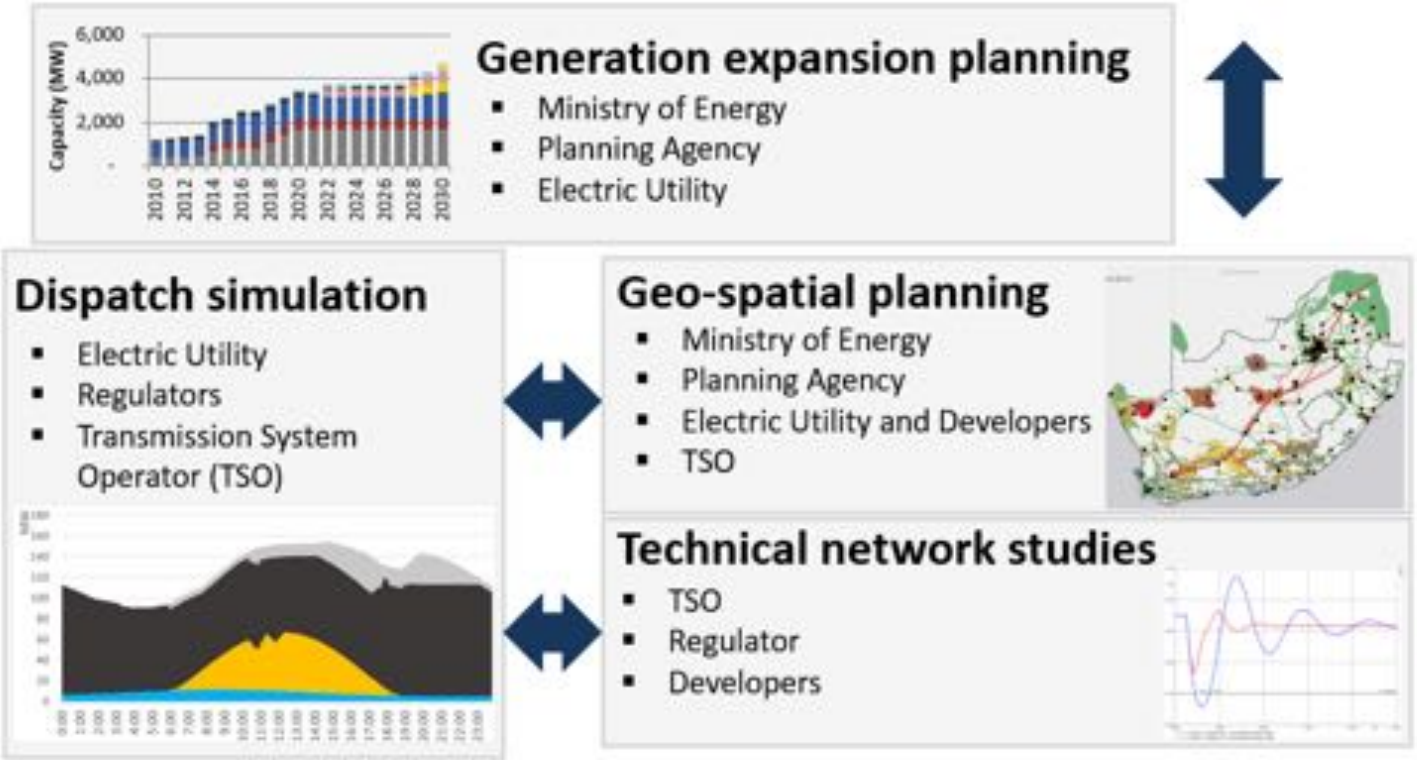
Source: IRENA, 2020

Integrate Different Levels of Planning

Levels of Planning: Different institutions perform different stages and time horizons of power system planning. Further collaboration can improve modeling results and insights.

Lessons for Ministerial Action: Ensuring a high-level of coordination and feedback loops between the different stages of planning, through dedicated units or committees, can ensure robust outcomes for integrated planning of power systems.

Integrated Resource Plan (IRP) Flowchart:



Source: LTES

Conduct Renewable Energy and Storage Integration Studies

Grid Integration Study: Analytical framework for evaluating power systems with high levels of variable renewable energy (e.g., wind and solar PV) and storage (e.g., lithium-ion batteries, green hydrogen, etc.) that can help determine cost and reliability implications of different future grid scenarios.

Lessons for Ministerial Action: Stakeholder engagement is crucial to build confidence in the study across all types of analyses and all components.

Types of Grid Integration Analyses

Capacity Expansion
Optimize generation and transmission planning.

Future Generation & Transmission Scenarios

Production Cost
Cost/benefit analysis of system operations.

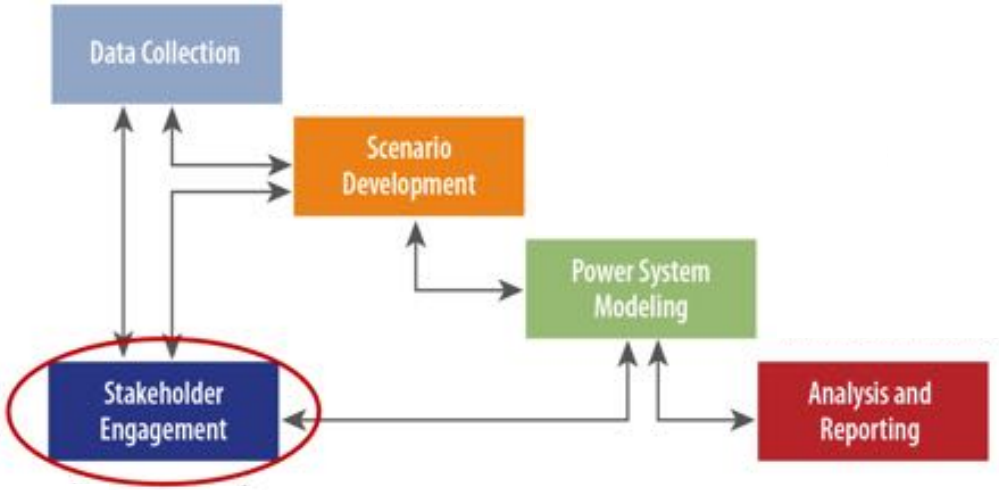
"Interest Periods" of System Stress

Power Flow
Technical feasibility and reliability analysis. Can also focus on reliability under extreme events.

Revise Parameters to Ensure Stability

Revise Parameters to Ensure Reliability & Cost-Effectiveness

Key Components of a Grid Integration Analysis



Source: Katz and Chernyakhovskiy (2020)

Coordinate Renewable Energy and Transmission Planning

Lessons for Ministerial Action: Coordinating generation and transmission planning (e.g., with a REZ transmission planning process) can unlock access to the highest-quality and lowest-cost RE resources.

Traditional transmission planning might miss best renewable resources

Timescale Misalignment

Proactive transmission planning with Renewable Energy Zones (REZ)

- High quality RE resources
- Suitable topography and land-use designations
- Demonstrated interested from developers

Source: Lee et al. (2020)

Enable Integrated Clean Energy Systems

Integrated Energy Systems: Include one or more power generation source, energy storage mechanism, heat transfer system, control system, and heat and/or electricity consumers. Coordination of heat and electricity distribution can maximize clean energy for industry, transportation, and the grid.

Lessons for Ministerial Action: Integrated energy systems can enable decarbonization of multiple key sectors (e.g., industry, transportation) by coordinating energy (heat and electricity) distribution to end-uses.

Many industries can benefit from carbon-free heat

Agriculture: Heat can be used for greenhouses, soil warming, and to help dry or process crops

Water: Heat and electricity can power desalination or wastewater facilities

Bioenergy and bioproducts: Heat can dry and process biomass into more usable forms for biofuels

Carbon capture: Heat and electricity can power chemical reactions that convert carbon dioxide into useful chemicals

Hydrogen: Heat and electricity can be used to make clean hydrogen, which can be used for various purposes

INCLUDE ALL TECHNOLOGIES APPROPRIATE WITHIN NATIONAL CONTEXT

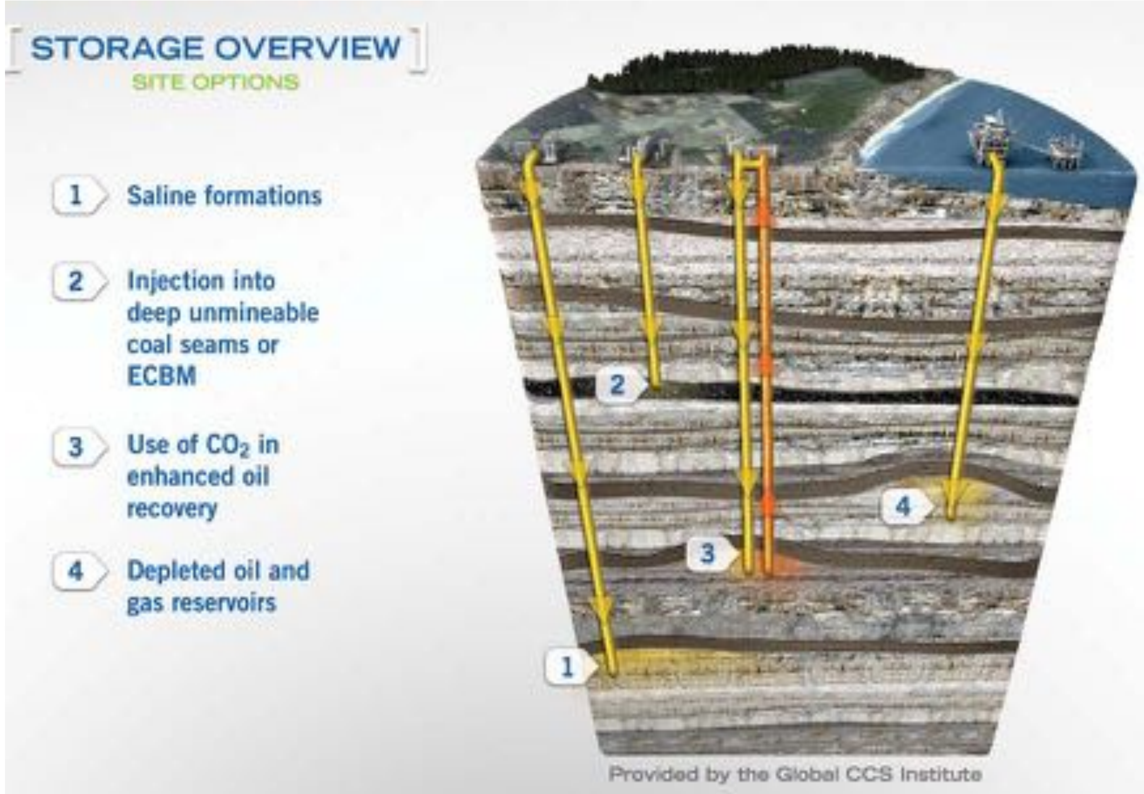
CO_2 Storage: Governments can play a key role in accelerating the creation and regulation of safe storage of CO_2. **This is an example of a technology that may be appropriate for some countries to pursue.**

CO_2 Storage development is long-term and requires appropriate regulation.

- Developing CO_2 storage from scratch can take 10 years
- Large investment upfront is required but helps enable low cost per tonne of storage over the long term
- Governments can take a central role in encouraging the investigation and creation of large-scale CO_2 storage and lowering costs
- Safe storage requires appropriate regulation to ensure permanence

Lessons for Ministerial Action: Implement laws and regulations to ensure safe and permanent storage of CO_2.

Various options for CO_2 storage sites



Source: Global CCS Institute

Research Social Equity Impacts

Research how clean energy technologies (e.g., nuclear, renewables, etc.) can advance **social equity, environmental justice**, and provide **economic benefits** to communities.

Lessons for Ministerial Action: Environmental justice and workforce development research can enable an equitable expansion of decarbonization efforts.

Key activities of the RISE$_3$ campaign (focused on nuclear)

- Recommending how clean technologies can advance **environmental justice and equity**.
- Publishing analyses detailing how **nuclear energy can complement and advance renewables** through coupling and flexible operation.
- Examining how flexible utilization of nuclear energy for electric and nonelectric applications can **lift economies and improve quality of life** for communities, including remote or islanded areas.
- Tracking **community transformations**, including monitoring how potential coal site conversions to nuclear and renewables may yield economic and jobs impacts.

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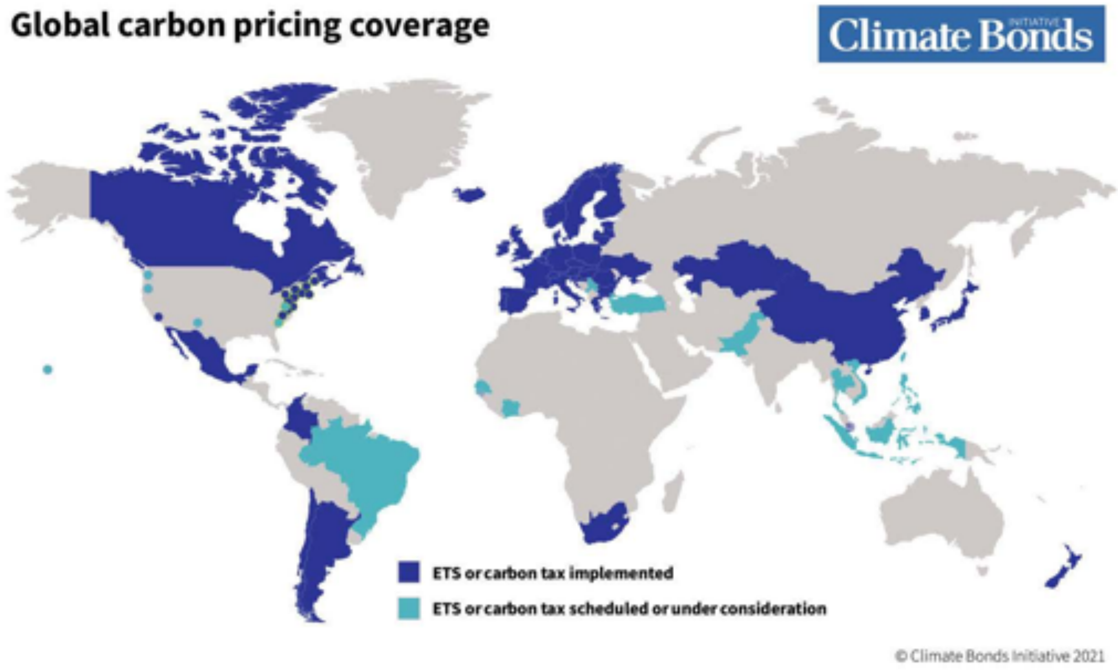
Set a Robust and Escalating Carbon Price

Carbon Pricing: A robust and escalating carbon price (as a cap-and-trade mechanism or direct carbon tax) will be the backbone to drive all clean energy investments. This is a powerful action that governments can take to accelerate grid decarbonization.

Lessons for Ministerial Action: Implement robust carbon pricing as a backbone for all clean energy investment.



Source: Climate Bonds Initiative (2021)

EU Carbon Price: Recent Trends

Source: Rabobank

Incentivize Zero-Carbon Energy Technologies, Including Clean Hydrogen

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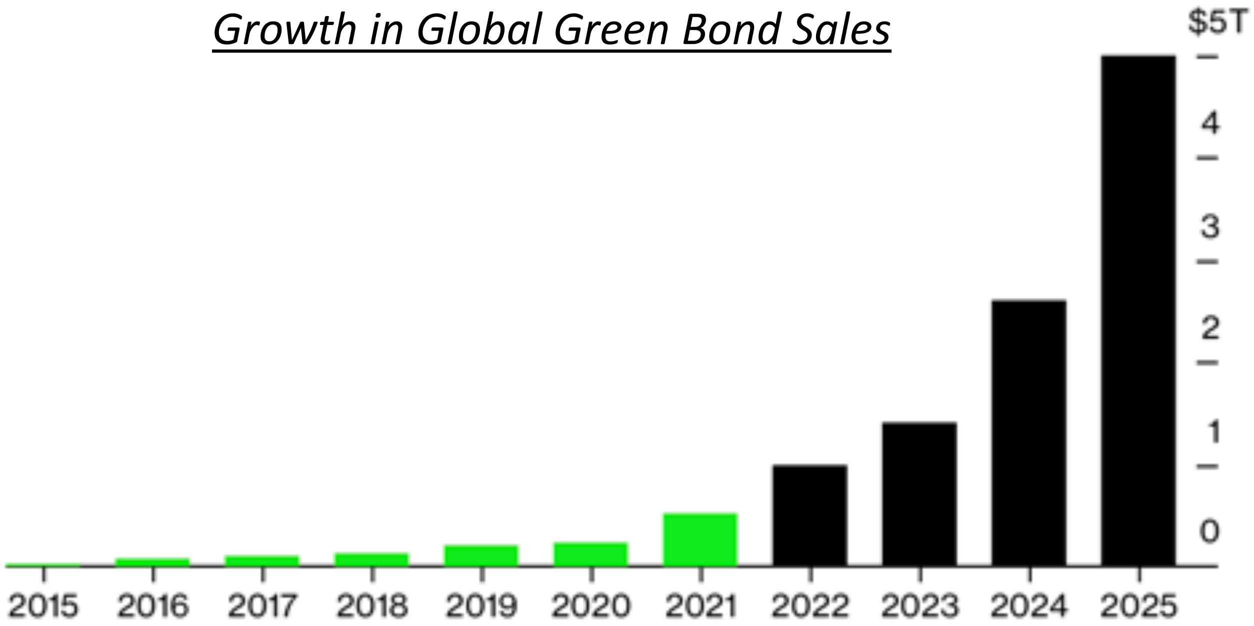
A variety of **administrative and financial incentives** exist to promote the use of zero-carbon energy technologies, including clean hydrogen. Each can be tailored to local conditions.

- Feed-in-tariffs (FITs)
- Clean and renewable energy standards (targets)
- Grants, low-interest loans, and green banks
- Tax credits
- Innovative financial products such as green bonds
- Public information sharing campaigns

Lessons for Ministerial Action: Develop strategies to pass national, regional and local legislation that incentivizes zero-carbon options. Inform the public about their lifecycle energy costs.

Growth in Global Green Bond Sales



Green Bond Sales Expected to Reach $1 Trillion in 2022

Source: Bloomberg 2022 (https://www.bloomberg.com/news/articles/2022-02-01/green-bonds-still-have-a-long-way-to-go-to-dent-climate-crisis)

INCREASE GRID INVESTMENTS AT AN UNPRECEDENTED RATE

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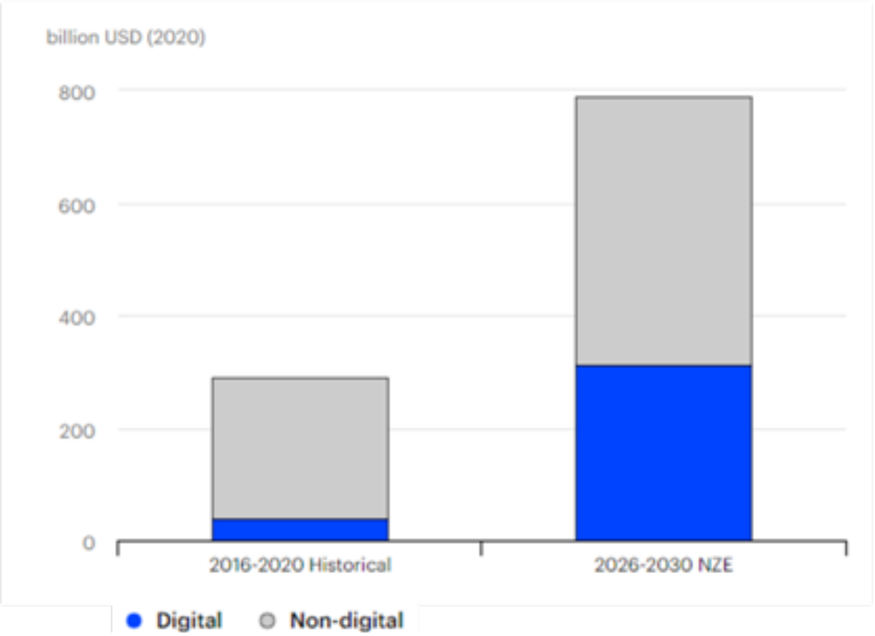
While power systems are at the center of clean energy transitions, **investments are lagging,** particularly in **smart grids solutions** and especially in **emerging economies.**

Paradigm Shift: Minimizing Risk of Grid Over-Investment → Minimizing Risk of Grid Under-Investment

- Globally, capital expenditure in grids needs to increase more than six times faster to be on track for net zero emissions.
- Spending on transmission and distribution networks must occur in parallel with investments in electrification and renewables.
- Policymakers must work to understand who bears the risk in a particular investment program and then work to mitigate that risk.
- Measures are needed to ensure that electricity remains accessible and affordable.

Lessons for Ministerial Action: Create conducive policy and regulatory frameworks to build confidence and drive investments and take steps to de-risk investments to enable greater private sector participation (e.g., coordinated standards development).

Investment spending in electricity networks, 2016-2020 and 2026-2030 in the Net Zero Scenario



Source: IEA

Rapidly Transition to Digitalized Smart Power Systems

Power systems are at the **center of net zero** goals but **face severe challenges** that **digitalized, smart grids solutions** can help address through improved planning and more effective operation and maintenance of assets.

Lessons for Ministerial Action: Develop a roll-out strategy for power system digitalization that is not just limited to grid operators, remove barriers to investments in digitalization, and provide workforce training to support new technology.

Digital opportunities are not being systematically exploited due to various challenges:

- Many utilities struggle to recover costs for a variety of reasons, resulting in underinvestment that negatively impacts electricity reliability and efficiency
- Extreme weather events induced by climate change put power system assets and reliability at further risk
- Power outages, especially longer ones, have far reaching and costly impacts on all critical infrastructure and services
- Reliability issues, outages, and rising electricity costs are driving consumers in many locales to stop paying bills or invest in off-grid systems, further weakening utilities

Source: ASEAN Centre for Energy

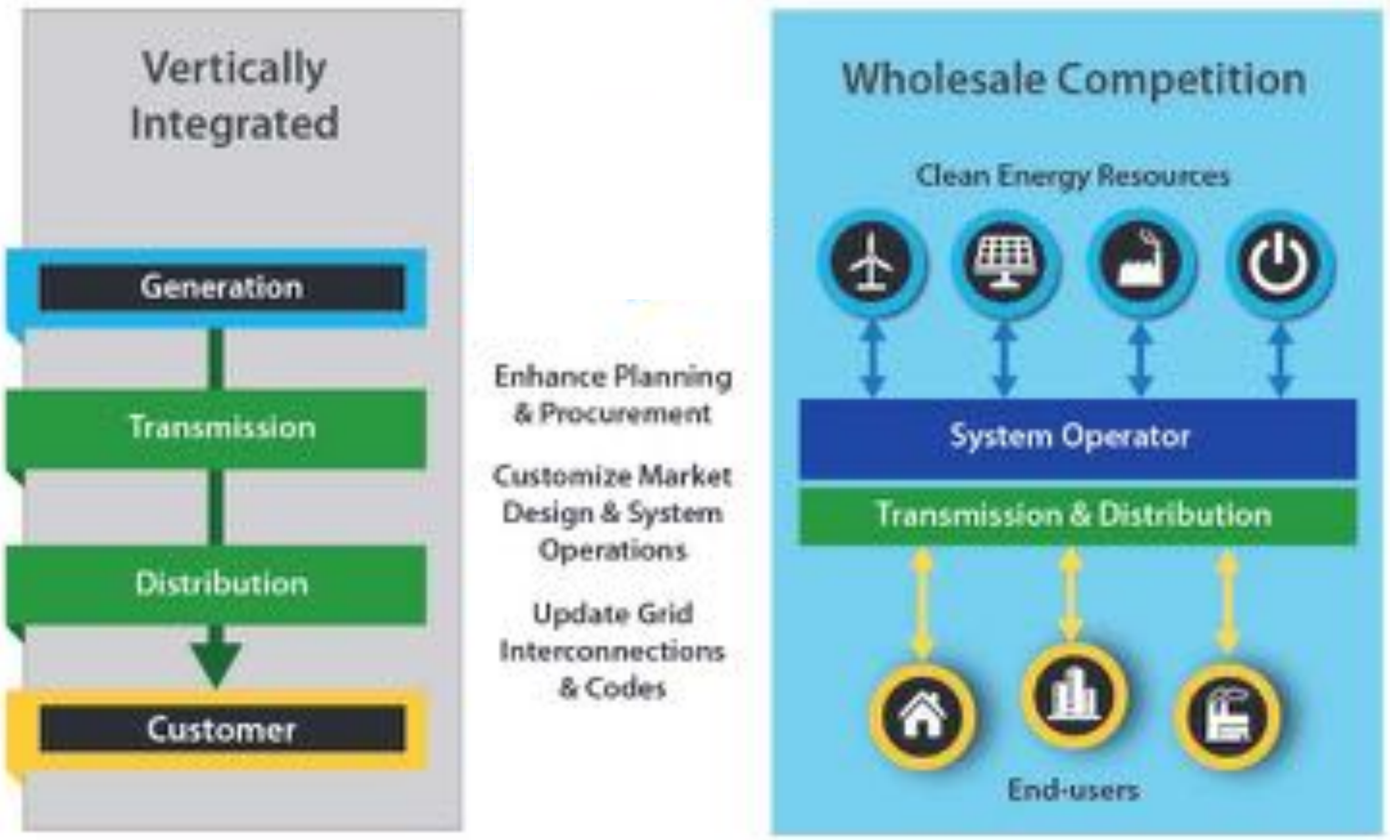
Ensure Electricity Markets Support Clean Energy

Electricity Markets: Traditional vertically integrated utilities and competitive wholesale markets should both support increasing levels of variable renewable energy sources, load flexibility (e.g., demand response), and other clean electricity options.

Paradigm Shift from Thermal to Renewable System

In an electricity market dominated by renewables (vertically integrated or wholesale competition), optimizing for variable cost will not be the main concern.

Lessons for Ministerial Action: Planning (e.g., resource adequacy assessments that include wind and solar data), system operations (e.g., rules for curtailment), and new business models can all support clean energy in various electricity markets.



Source: Shah et al. (2016)

Scale Renewable Energy and Storage via Auctions

Renewable Energy (RE) and Storage Auctions: Bidding process in which developers who meet certain criteria submit project proposals and are selected based on least-cost bids.

- Storage options (e.g., batteries, hydrogen etc.) are increasingly competitive and should be included in RE procurement mechanisms

Advantages	Challenges
Volume control	Requires competition
Competitive pricing	Requires strong institutions
Easier to scale up for multiple projects	Bidders risk not being awarded a contract
Faster project execution	Risk of underbidding and project non completion

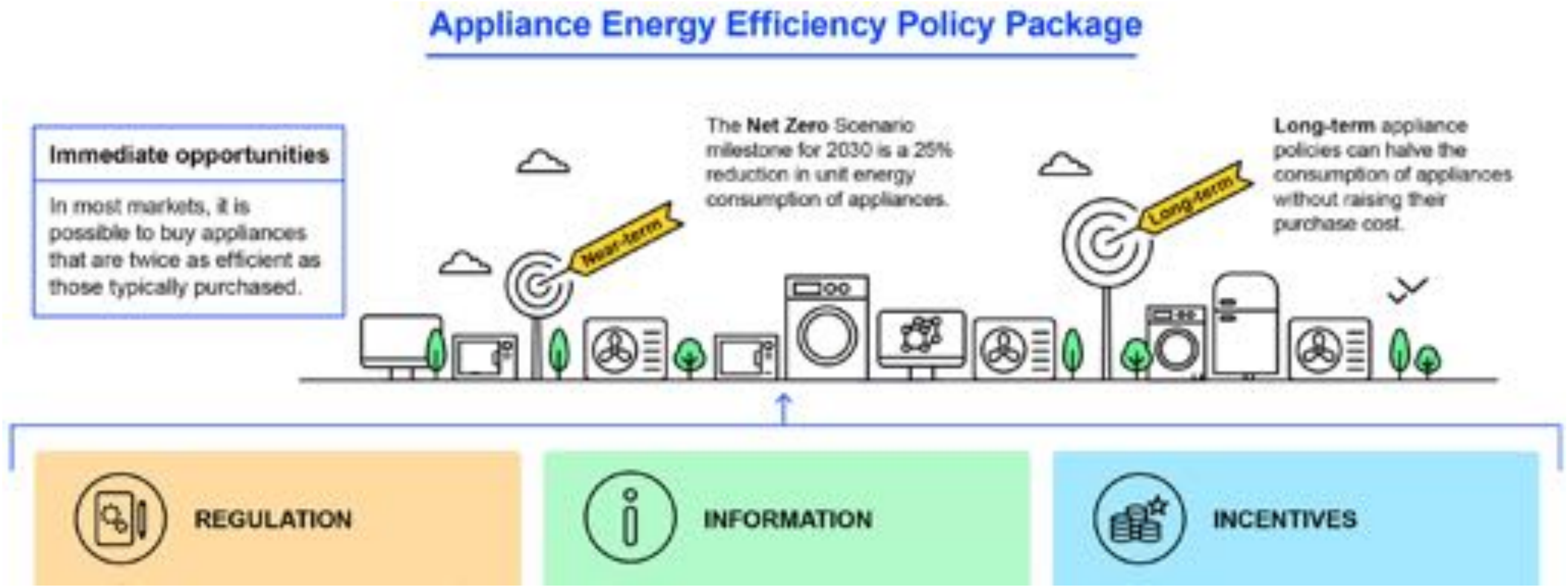
Lessons for Ministerial Action: Auctions, if fully integrated with other regulatory, planning, and economic strategies, can enable efficient deployment of renewable energy and storage capacity with private sector capital.

Core Elements of a Renewable Energy Auction

Source: Azuela and Barroso (2014), Wigand et al. (2019)

DESIGN POLICY PACKAGES TO DEPLOY ENERGY EFFICIENCY

- Policies have helped **halve the energy consumption of key end-uses** in the longest-running programs
- **Building envelope design** is also a key enabler of systematic reductions in energy consumption
- **Minimum Energy Performance Standards** are a highly cost-effective way to improve equipment energy efficiency
- Standards should be accompanied by **mandatory labelling** and targeted **incentives** to deploy the most efficient equipment



Lessons for Ministerial Action:
Design and implement comprehensive Policy Packages (regulation, information, and incentives) to ensure large-scale deployment energy efficiency (e.g., for appliances, etc.)

Source: IEA Appliance Efficiency Policy Package (2022)

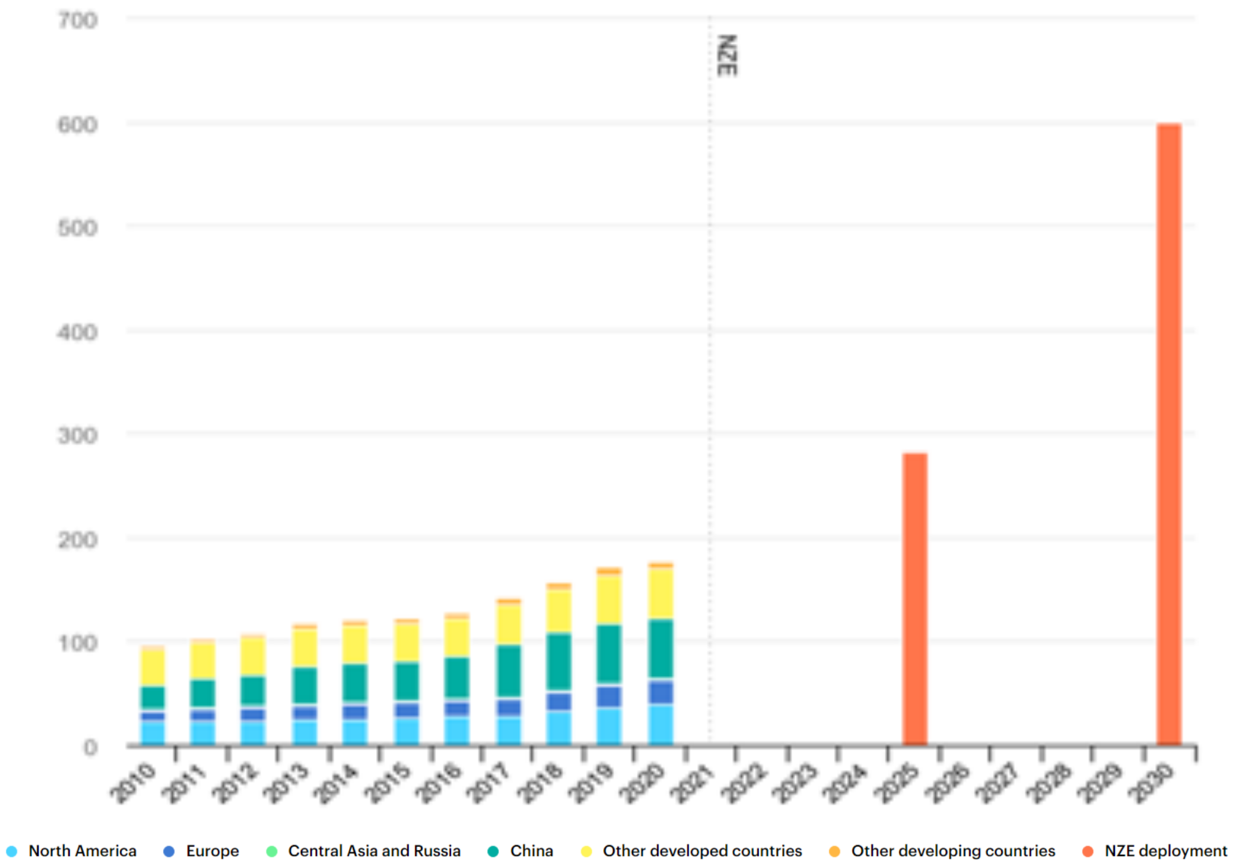
Foster Innovation For Heat Pumps and Industrial Motors

Further innovation is needed to ensure customer access to affordable and high-performing appliances, such as heat pumps, industrial motors, water heaters, etc.

- The most effective way to rapidly improve product efficiency is to apply measures at the point of manufacturing and sales
- Mandating manufacturer responsibility is key to ensure efficiency across the whole supply chain
- Heat pumps: need to reduce upfront costs and phase out refrigerants with high global warming potential
- Industrial motors: need minimum energy performance standards that rely on internationally recognized efficiency levels

Lessons for Ministerial Action: Support technology and policy innovation to guarantee consumer access to affordable and high-performing electricity end-uses (e.g., heat pumps).

Installed and Projected Heat Pump Stock in Net Zero Scenario (2010-2030)



Source: IEA

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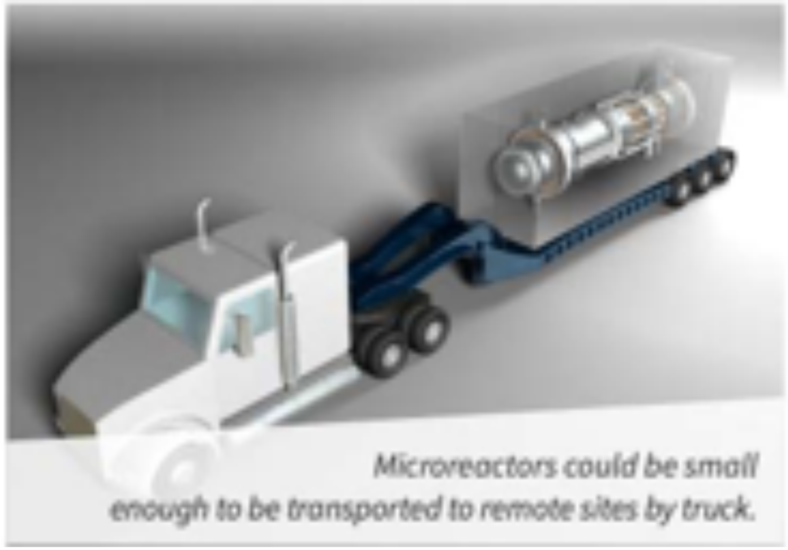
Support Advanced Nuclear Demonstration Projects

Small Modular Reactors: Small-scale reactor options under development range in size from a few megawatts to a few hundred megawatts to support distributed energy demands. These technologies can provide safe and reliable energy to a wide range of applications, both electric and non-electric.

Lessons for Ministerial Action: Policies to support small modular reactor development, demonstration, and deployment can enable economical clean energy, flexibility, and versatility.

Footprints of Various Reactor Types

Ease of Transportation



Source: NICE Future

Develop Carbon Capture Incentives and Hubs

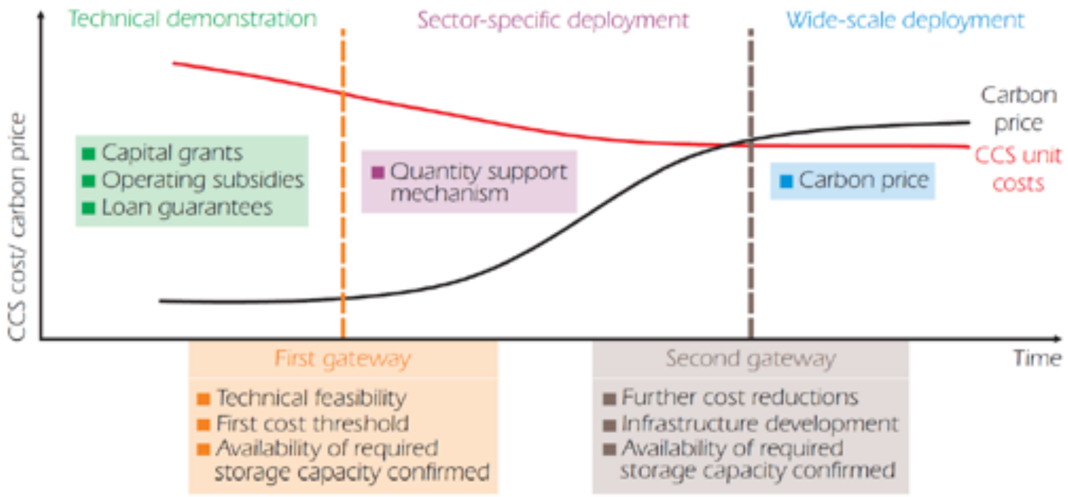
Governments should develop and implement carbon capture, utilization, and storage (CCUS) **incentives that can reduce costs and support research**, and **hubs to leverage shared infrastructure** for storage and transportation.

Lessons for Ministerial Action: Specific, time-limited CCUS incentives along with hub development can boost deployment and lower costs.

Strategic transport and storage hubs can link several emission sources

Source: ACTL, Canada

CCUS-specific incentives can enable wide-scale deployment



Source: IEA

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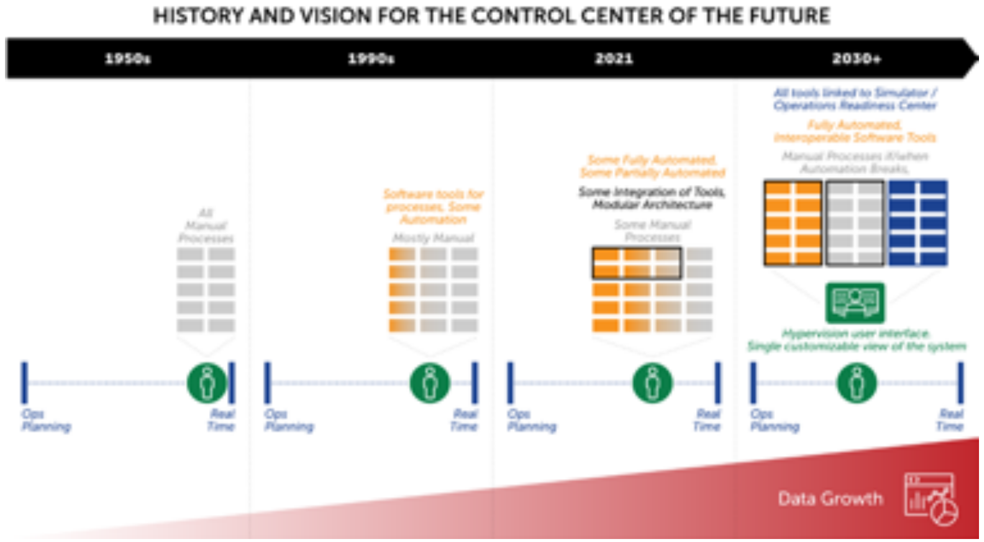
Champion Knowledge Sharing With Peers

Peer learning: E.g., Global Power System Transformation (G-PST) Consortium system operators and technical experts share applied knowledge, operational innovation, and technical skills to enable faster progress toward decarbonization goals.

Lessons for Ministerial Action: Fostering technical knowledge exchange enables faster progress toward national and global clean energy goals.

2030 control center roadmap for Peru informed by peer exchange



Source: COES Control Center of the Future Assessment (2022)

Technical exchanges support operational innovation and strengthen human capital

Source: PLN Power System Learning Series (2021)

Promote Standards and Open-Source Tools

Standards create rules for the procurement, interconnection, and operation of new technologies.

Open-source tools are public, freely available alternatives to commercial solutions for managing the power system.

Lessons for Ministerial Action: Regulatory support for standards and tools implementation accelerates deployment.

Standards create market and operational certainty

Source: NREL IEEE1547-2018 Standard Resource Center

Open-source tools expand the solution set for system operation and planning

Source: G-PST Open Tools Portal

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Endorse Interoperability to Integrate Different Technologies

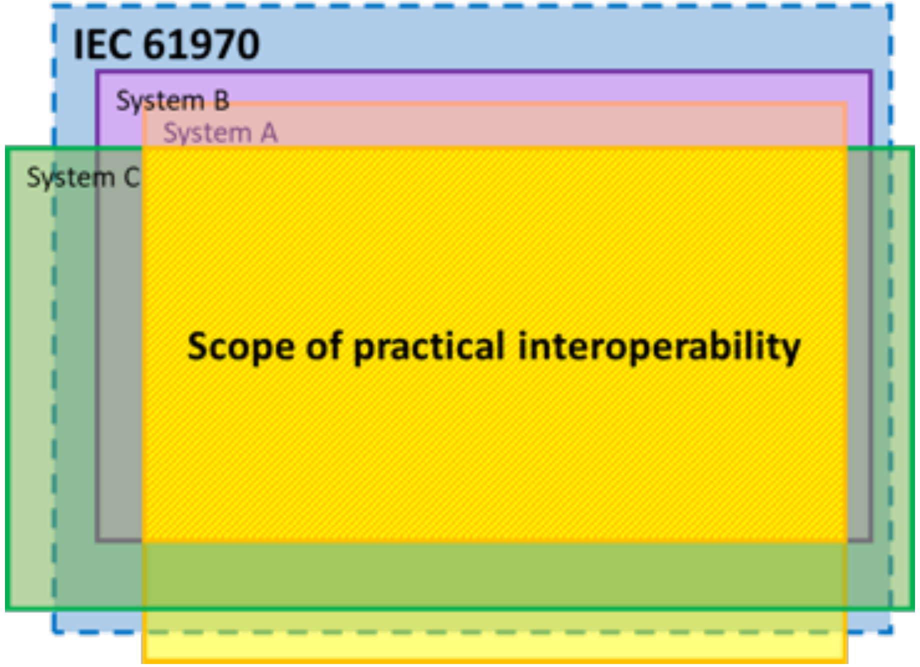
Interoperability requires the development and testing of standards, including both lab and on-system testing and verification. This creates the confidence in performance conducive to the formulation of grid regulations and acceleration of large-scale technology investments.

Interoperability makes it possible to:

1. Exchange information with each other
2. Understand that information
3. Act on that information

Interoperability standardization has not yet been achieved, but a shared understanding of key concepts facilitates coordination of interoperability issues.

Lessons for Ministerial Action: Support sustained collaborative processes to facilitate systems interoperability that can seamlessly integrate digital systems in the energy sector, create mechanisms for power systems testing and results sharing, and support international standardization processes.



Source: DP ISGAN WG 6 - Interoperability of Digital (ICT) Systems in the Energy Sector (2020)

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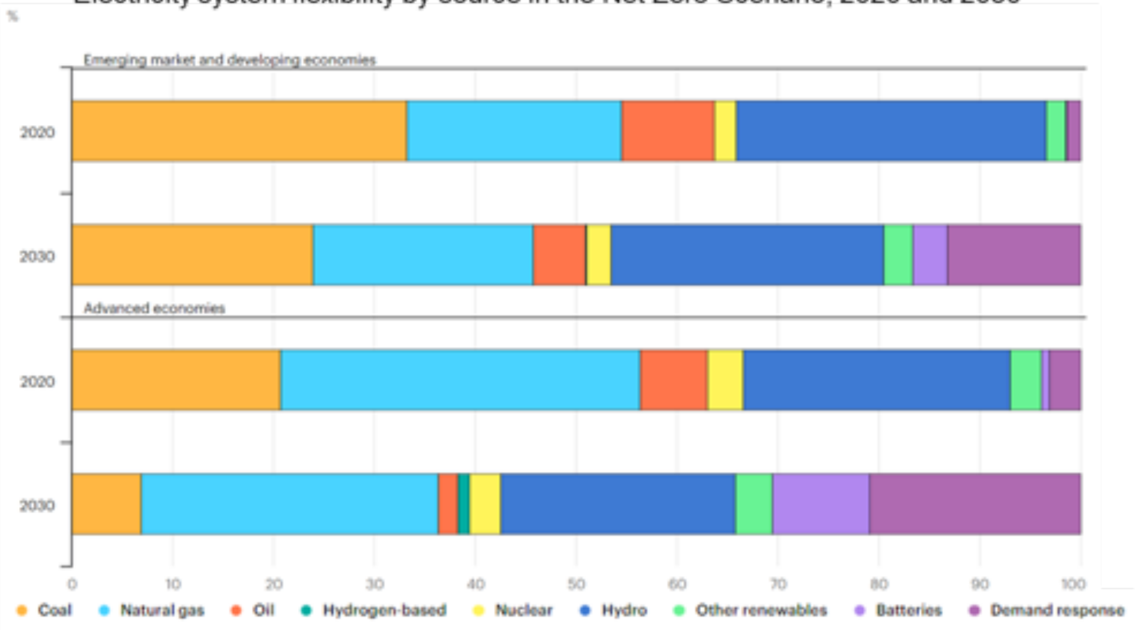
Assure Integration of Flexible Resources, Including Grid-Edge Assets

To achieve decarbonized, resilient, and secure power systems, **all clean flexibility sources (including significant amounts of grid-edge assets)** need to be **understood, considered**, and **appropriately utilized**.

- The global inventory of flexible assets needs to increase ten-fold by 2030.
- Examples of grid-edge assets: behind-the-meter energy storage, electric vehicles, distributed rooftop solar photovoltaics, flexible loads, etc.
- Digitalization, regulatory changes, and market reforms are crucial to enable access, coordination, and control of a growing fleet of flexibility assets.

Electricity system flexibility by source in the Net Zero Scenario, 2020 and 2030



Lessons for Ministerial Action: Set strategies and create regulations to appropriately value and reward demand-side resources (electric vehicles, demand response, behind-the-meter batteries, rooftop solar PV) and enable new business models including aggregation of multiple resources to enable greater power system flexibility.

Source: IEA

Endorse Transmission Interconnections

Case Study: Interconnections Seam Study for the United States evaluated the costs and benefits of strengthening the connection between the Eastern and Western Interconnections.

Key Results

There are substantial positive benefit-cost ratios for increasing transfer capability between the interconnections.

The geographic diversity of resources also increases resilience.

Lessons for Ministerial Action: The benefits of expanding interconnections (or cross-border energy trade for smaller countries) outweigh the costs and increase the efficient utilization of renewable energy resources. The benefits can be even greater during extreme grid conditions.

Macrogrid (a nationwide HVDC transmission network) is built and additional AC transmission and general are co-optimized to minimize system costs

Source: Bloom et al. (2021)

Advocate for State-of-the-Art Metrics, Data, Models and Tools

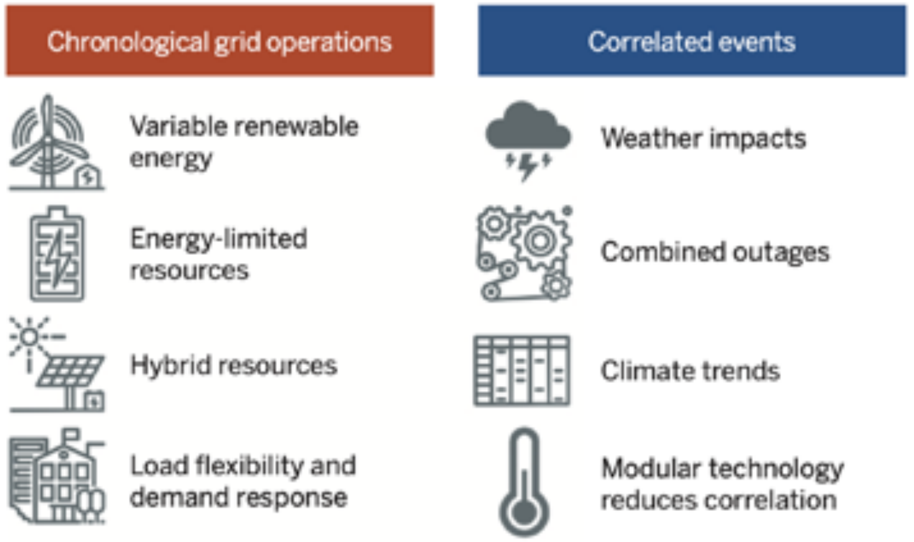
Working groups on **system services, redefining resource adequacy, and grid-forming technologies** (capable of restarting the grid after an outage) have been delivering new approaches for managing power systems under rapidly changing conditions.

Lessons for Ministerial Action: New methods and tools enable system operators to understand the resource adequacy and reliability implications with increased shares of wind and solar in the power system.

Managing increase in inverter-based resources (IBR)

Source: Bialek et al. 2021

Understanding change in factors impacting reliability



Source: Stenclik et al. (2021), Energy Systems Integration Group

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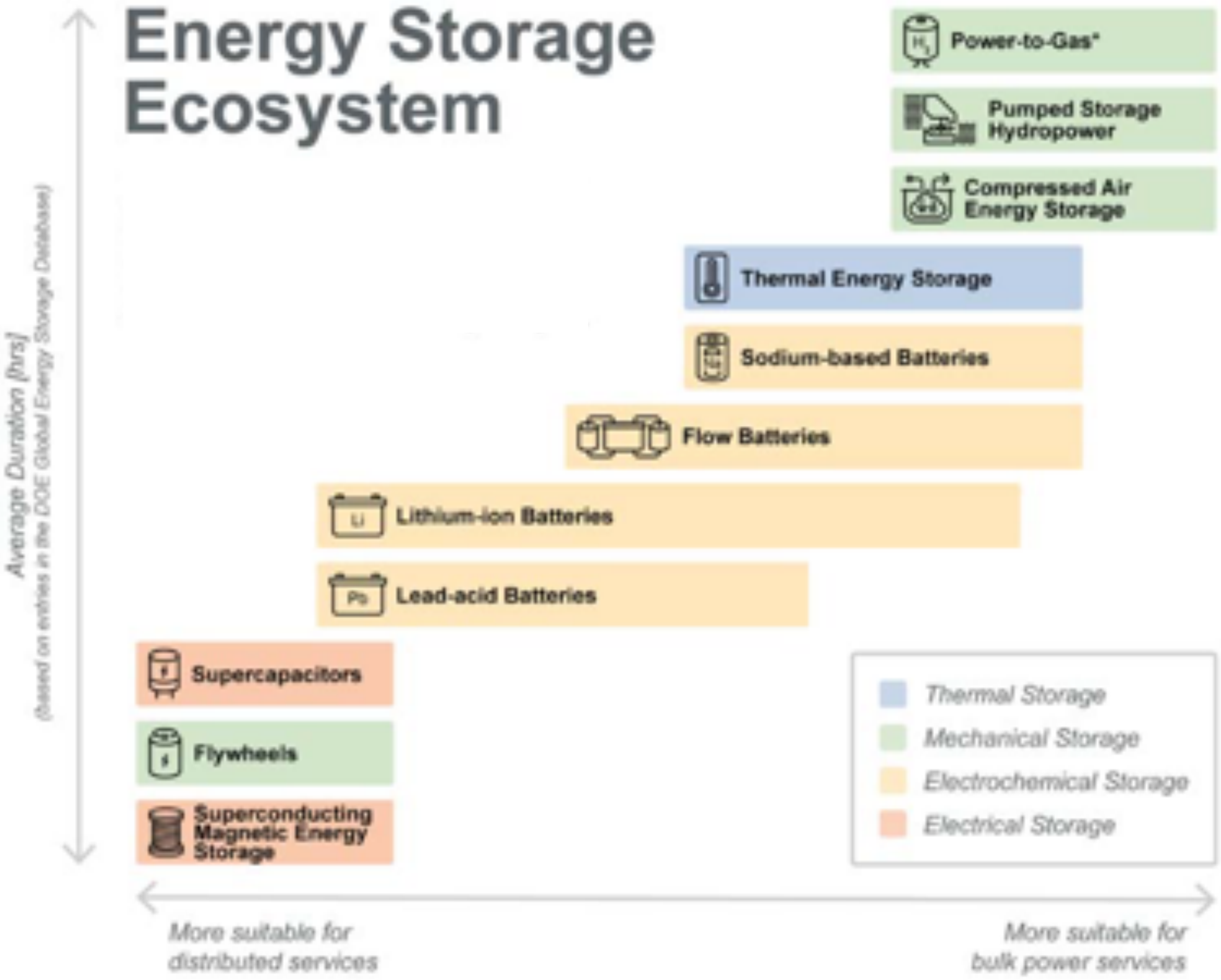
Enable the Various Grid Services of Energy Storage



Power-to-Gas Technologies
Includes green hydrogen (produced by renewable energy) and other low carbon fuels and chemicals such as ammonia. These are a potential source of long-duration energy storage.

Lessons for Ministerial Action: Different types of energy storage (thermal, mechanical, electrical, and electrochemical) can provide a variety of grid services for different durations that are beneficial for operating decarbonized power systems.

Source: Bowen et al., 2021

Assure the Use of Improved Wind and Solar Forecasting Capabilities

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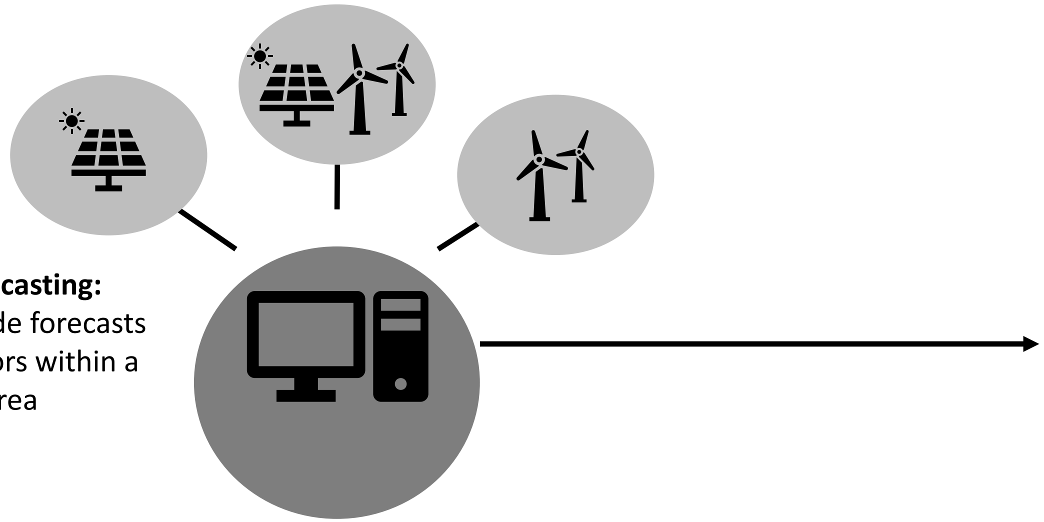
Lessons for Ministerial Action: Integrating variable renewable energy forecasts with real-time system operations requires advanced information technology, standardized data requirements, and certification for forecast-relevant data.

Forecasting Spatial Resolution

Decentralized Forecasting:
Helps inform system operators of potential transmission congestion

Centralized Forecasting:
Provides system-wide forecasts for all VRE generators within a balancing area



Forecasting Temporal Resolution

	Type of Forecast	Time Horizon	Key Applications
Generation	Intra-hour	5-60 min	Regulation, real-time dispatch, market clearing
	Short term	1-6 hours ahead	Scheduling, load-following, congestion management
	Medium term	Day(s) ahead	Scheduling, reserve requirement, market trading, congestion management
	Long term	Week(s), Seasonal, 1 year or more ahead	Resource planning, contingency analysis, maintenance planning, operation management

Source: Tian and Chernyakhovskiy (2016)

Accelerate Deployment of Grid Enhancing Technologies

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Grid Enhancing Technologies (GETs): Hardware and software that increase the capacity, efficiency, and/or reliability of the transmission grid.

Lessons for Ministerial Action: Enabling the use of grid enhancing technologies via regulatory frameworks can allow more clean energy to interconnect to existing transmission infrastructure and reduce congestion.

Power Flow Controllers (PFC):
Hardware and/or software to push or pull power, helping to balance overloaded lines and underutilized corridors in the grid.

Dynamic Line Rating (DLR):
Hardware and/or software to update the calculated power flow limits of existing transmission lines based on real-time and forecasted weather.

Topology Optimization:
Software that identifies reconfigurations in the grid to route power around congested or overloaded segments.

Sources: NewGrid, Smart Wires, Lindsey Systems,, Source for GET definitions: U.S. Department of Energy (2022), Watt Coalition (2022)

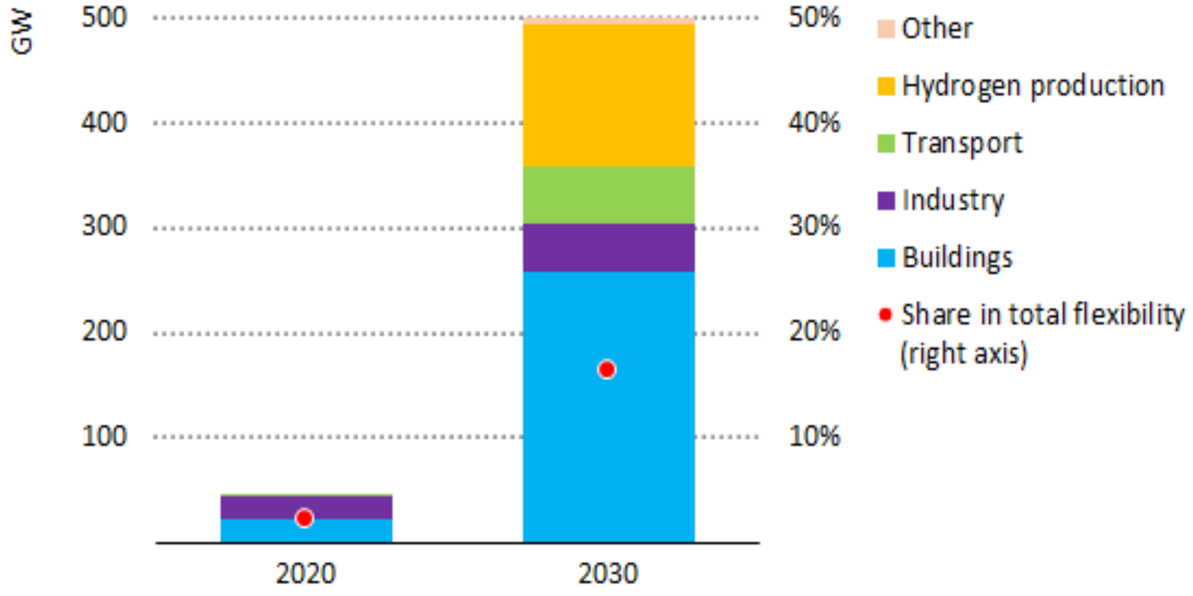
Support Demand Response via Appropriate Regulations and Incentives

Energy-efficient and flexible loads play a key role in grid operations and decarbonizing the power sector.

- Energy-efficient and flexible loads benefit consumers, businesses, and governments.
- Increasing efficiency and flexibility lowers energy costs, enhances energy security, helps expand access to energy services, and reduces harmful emissions.
- Grid interactive loads and demand response can provide flexibility services to the grid to support decarbonization and resilience.

Lessons for Ministerial Action: Promote energy-efficient and grid interactive appliances to provide flexibility services to the grid and support its decarbonization and resilience.

Demand response availability at times of highest flexibility needs and share in total flexibility provision in the Net Zero Emissions by 2050 Scenario [2020 and 2030]



Source: IEA

Annex: Industrial Decarbonization

Lessons Learned for Rapid Decarbonization of Power Sectors

Supplemental lessons on leveraging the power sector to enable industrial sector decarbonization

This section is focused primarily on the coupling between the power and industrial sectors. Therefore, not all industrial decarbonization topics will be covered.

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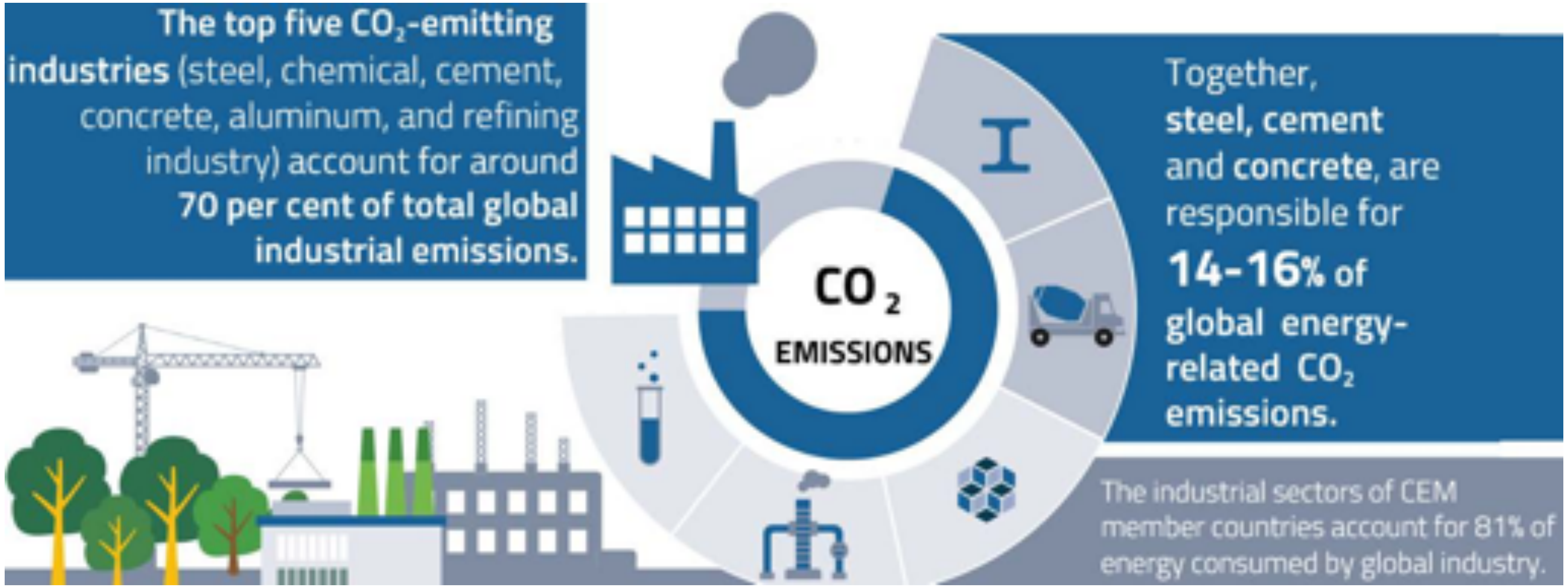
INCORPORATE INDUSTRIAL SECTOR INTO POWER SYSTEM PLANNING

Many industrial **end-uses that currently use fossil fuels can be decarbonized** by leveraging the power sector:

- Electrification of end-uses, using zero-carbon electricity
- Hydrogen for end-uses, using hydrogen generated via zero-carbon electricity

This increased demand for zero-carbon electricity needs to be accounted for by planners and grid operators.



Lessons for Ministerial Action: Account for the increased zero-carbon electricity demand for industrial decarbonization in power system planning to ensure adequate resources and grid infrastructure.

Source: Rissman et al., 2020

Align Standards to Define Low- or Zero-Emission Materials

A decarbonized power sector can facilitate the development of **low-emission materials, which can be defined and verified via global standards**.

- **Standards set out how companies can develop, manufacture, and supply goods in ways that are efficient, safe and sustainable**. They can have a major influence on the environmental characteristics of materials, products, and manufacturing processes.
- **A coherent global framework is fundamental to creating a thriving market for low-emission materials.** This framework must establish what constitutes low and near-zero emission steel, cement, and concrete, and be supported by widely recognized production standards and benchmarks.
- **Agreeing on such standards will instill confidence among steel, cement, and concrete manufacturers to invest in developing low and near-zero emissions products.** Such standards will also make it easier for governments to understand and be confident in their decisions to procure such materials.

Lessons for Ministerial Action: Lead carbon disclosure requirements and standards for materials and support international harmonization.

Source: IDDI

Scale Production of Low-Emission Materials Via Procurement

Through **green public procurement**, governments can use their immense purchasing power to buy low and near-zero emission steel, cement, and concrete, **stimulating the market and rewarding businesses** that develop products with **lower environmental impacts (partially enabled by a decarbonized power sector)**.

Lessons for Ministerial Action: Lead public procurement by implementing best practices in major construction projects and making bold commitments to purchase low-emission industrial materials.

Governments can commit to one of four levels, depending on their national circumstances

Encouraging governments to disclose and reduce embodied carbon emissions in public construction projects.

Ambition level 1	Ambition level 2	Ambition level 3	Ambition level 4
DISCLOSE	**DISCLOSE + NET ZERO**	**DISCLOSE + NET ZERO + 2030 TARGET**	**DISCLOSE + NET ZERO + 2030 TARGET + ZERO EMISSION**
Starting no later than 2025, require disclosure of the embodied carbon in cement/concrete and steel procured for public construction projects.	Starting no later than 2030, conduct whole project life cycle assessments for all public construction projects, and, by 2050, achieve net zero emissions in all public construction projects.	Starting no later than 2030, require procurement of low emission cement/ concrete and steel in public construction projects, applying the highest ambition possible under national circumstances.	Starting in 2030, require procurement of a share of cement, concrete and/or crude steel from near zero emission material production for signature projects.

Source: IDDI

Lessons Learned for Rapid Decarbonization of Power Sectors

Collaborative Report from the Clean Energy Ministerial

Delivered for the Global Clean Energy Action Forum (GCEAF/CEM13/MI7)

September 2022

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