

Locking in Prosperity

Ten practical, evidence-backed actions toward affordable, reliable, and secure power systems

November 2026

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Rocky Mountain Institute (RMI) is an independent, nonpartisan nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to secure a prosperous, resilient, clean energy future for all. In collaboration with businesses, policymakers, funders, communities, and other partners, RMI drives investment to scale clean energy solutions, reduce energy waste, and boost access to affordable clean energy in ways that enhance security, strengthen the economy, and improve people's livelihoods. RMI is active in over 50 countries.

Executive Summary

Who is this report for?

We are writing to the energy leaders charged with delivering affordable, reliable, and secure electricity. The stakes are high for regulators, executives, and civil servants. This report is for the leaders and teams losing sleep over these challenges and seeking near-term solutions.

The stakes are high:

- **Electricity systems are the backbone** of the economy, enabling just about everything when they work, and complicating just about everything when they do not.
- **Outages leave society** — literally and figuratively — powerless.
- **Billions still struggle** to access or afford the electricity they need.
- **Power availability** can determine whether economies and industries succeed or fail in globally competitive markets.



Photo: IEA

What are these leaders up against?

It is a legacy-making time to work in energy, as decision makers chart a path toward a prosperous future amid rapid change and uncertainty .

Tailwinds

Technologies needed to build a prosperous future are ...

- Scaling at unprecedented speed
- Deploying in months, not years
- Delivering more value at less cost

More details start on page 15

Headwinds

Leaders are making long-lived decisions as …

- Load growth is surging but uncertain
- Supply chains are increasingly unpredictable
- The world is facing rising temperatures and climate risk
- Technology adoption is outpacing grid modernization

More details start on page 22

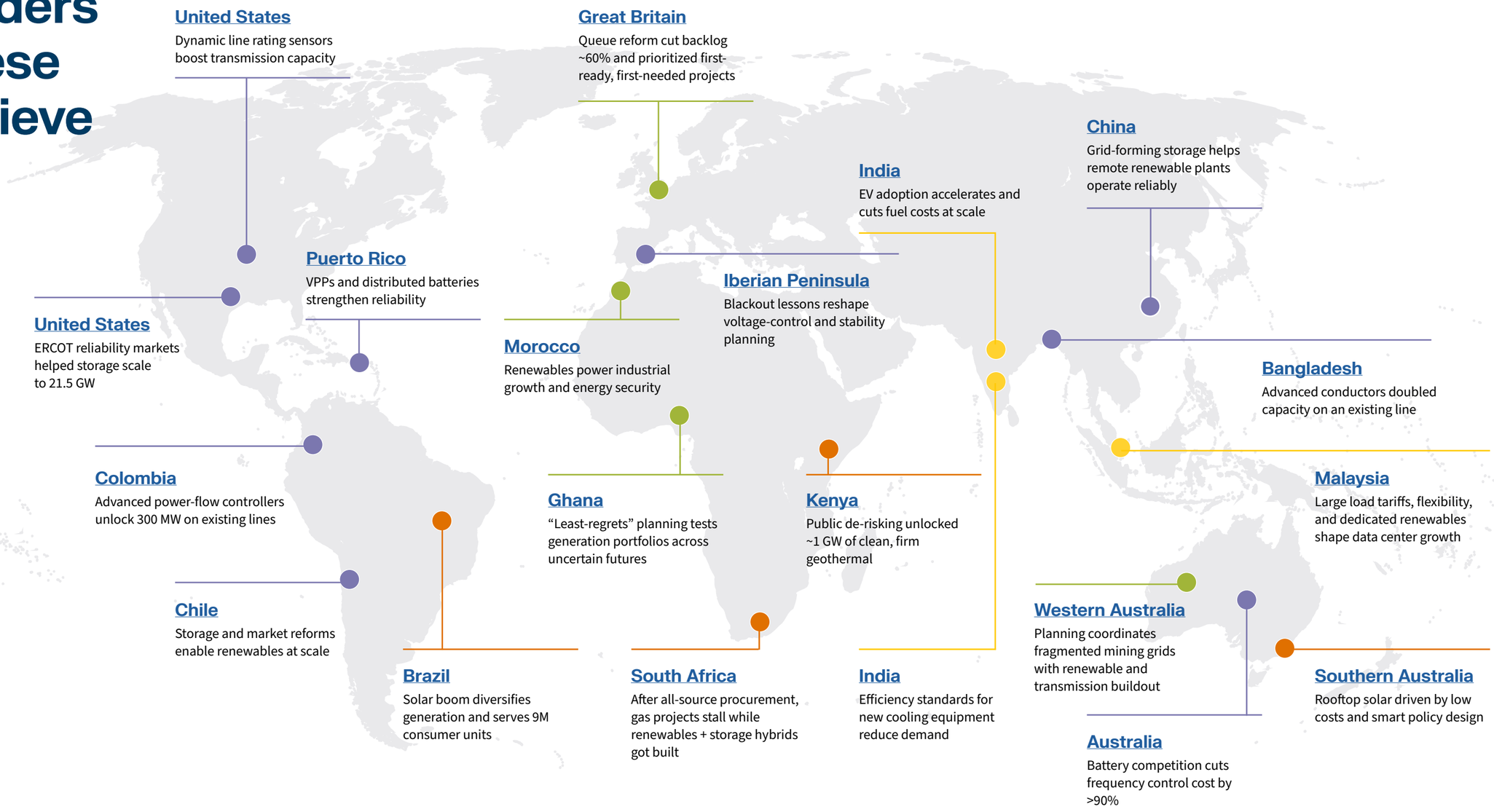
How can energy leaders make progress on the problems keeping them up at night?

Ten Practical Actions address the challenges leaders are facing, are useful even when the future is uncertain, have been widely demonstrated, and can show results in less than 12 months.

Action area	Practical Action	Case studies
Plan Design plans, procurement, and queues for uncertainty	1. **Plan for uncertainty.** Model system risk across a range of fuel cost, demand forecast, and technology cost scenarios, then stage procurement and investment to pivot when circumstances change.	Ghana, Morocco, Western Australia
	2. **Clear queues and improve forecasts.** Apply project planning milestones and financial requirements to clear speculative or stagnant projects from connection queues and forecasts, directing limited study capacity toward the most promising projects, and improving generation and load projections.	Great Britain
Modernize Electrify efficient, responsive loads	3. **Scale efficient cooling.** Set testing standards and labels that differentiate and reward air conditioners delivering efficient real-world performance, and build ecosystem awareness to shift the market toward such products.	India
	4. **Encourage vehicle electrification.** Educate consumers on the real costs and benefits of EVs versus gasoline and diesel vehicles and reduce up-front adoption barriers by streamlining financing and charging.	India
	5. **Make large loads flexible.** Tie large-load connection costs and queue priority to grid impact, so loads that commit to reducing demand during critical hours connect faster.	Malaysia
Balance Deliver reliable power when and where it is needed	6. **Match supply and demand.** Incentivize storage to earn and stack revenues from energy shifting and capacity provision.	Chile, Puerto Rico
	7. **Stabilize the grid.** Create technology-neutral pathways to procure ancillary services with clear technical standards.	Australia, Texas, Iberian Peninsula, China
	8. **Improve grid utilization.** Pilot advanced transmission technologies (ATTs) in high-impact grid segments while embedding ATT evaluation into ongoing transmission planning.	Colombia, Bangladesh, USA
Secure Build low-cost, low-risk generation portfolios	9. **Make distributed solar a grid resource.** Reduce soft costs and implement financially sustainable net-billing rules for distributed solar, keeping connection requirements technology neutral and encouraging solar + storage.	Brazil, Southern Australia
	10. **Level the playing field.** Run all-source, technology-neutral procurement competitions with independent evaluations that weigh resilience and fuel-price risk in addition to cost.	South Africa, Kenya

How are leaders wielding these tools to achieve results?

This report highlights 20 case studies across 15 countries and 6 continents.



United States
Dynamic line rating sensors boost transmission capacity

Great Britain
Queue reform cut backlog ~60% and prioritized first-ready, first-needed projects

India
EV adoption accelerates and cuts fuel costs at scale

China
Grid-forming storage helps remote renewable plants operate reliably

Puerto Rico
VPPs and distributed batteries strengthen reliability

United States
ERCOT reliability markets helped storage scale to 21.5 GW

Iberian Peninsula
Blackout lessons reshape voltage-control and stability planning

Morocco
Renewables power industrial growth and energy security

Bangladesh
Advanced conductors doubled capacity on an existing line

Colombia
Advanced power-flow controllers unlock 300 MW on existing lines

Malaysia
Large load tariffs, flexibility, and dedicated renewables shape data center growth

Ghana
"Least-regrets" planning tests generation portfolios across uncertain futures

Kenya
Public de-risking unlocked ~1 GW of clean, firm geothermal

Chile
Storage and market reforms enable renewables at scale

Western Australia
Planning coordinates fragmented mining grids with renewable and transmission buildout

Brazil
Solar boom diversifies generation and serves 9M consumer units

South Africa
After all-source procurement, gas projects stall while renewables + storage hybrids got built

India
Efficiency standards for new cooling equipment reduce demand

Southern Australia
Rooftop solar driven by low costs and smart policy design

Australia
Battery competition cuts frequency control cost by >90%

- Plan
- Modernize
- Balance
- Secure

Will these solutions work?

Real-world case studies from regulators, civil servants, executives, and engineers around the world show how to leverage renewables, storage, and grid technologies to improve affordability, reliability and security.



Plan

Modernize

Balance

Secure

Puerto Rico

LUMA coordinated 110,000 batteries into a VPP, aligning supply and demand to keep reserves above the critical threshold on 18 high-risk days, preventing island-wide blackouts.

Photo: SunRun

Ghana

Facing supply shortages, Ghana's Integrated Power Sector Master Plan tested multiple scenarios across several criteria to choose a lowest-risk approach to expanding capacity.

Photo: Sustainable Energy for for All

Kenya

Public investment in geothermal resource exploration and workforce development addressed key market barriers, enabling competitively selected IPPs to supply clean firm power at ~0.07/kWh. Today, 90% of Kenya's electricity generation is renewable, including contributions from 1 GW of clean firm geothermal capacity.

Photo: Geothermal Development Company

India

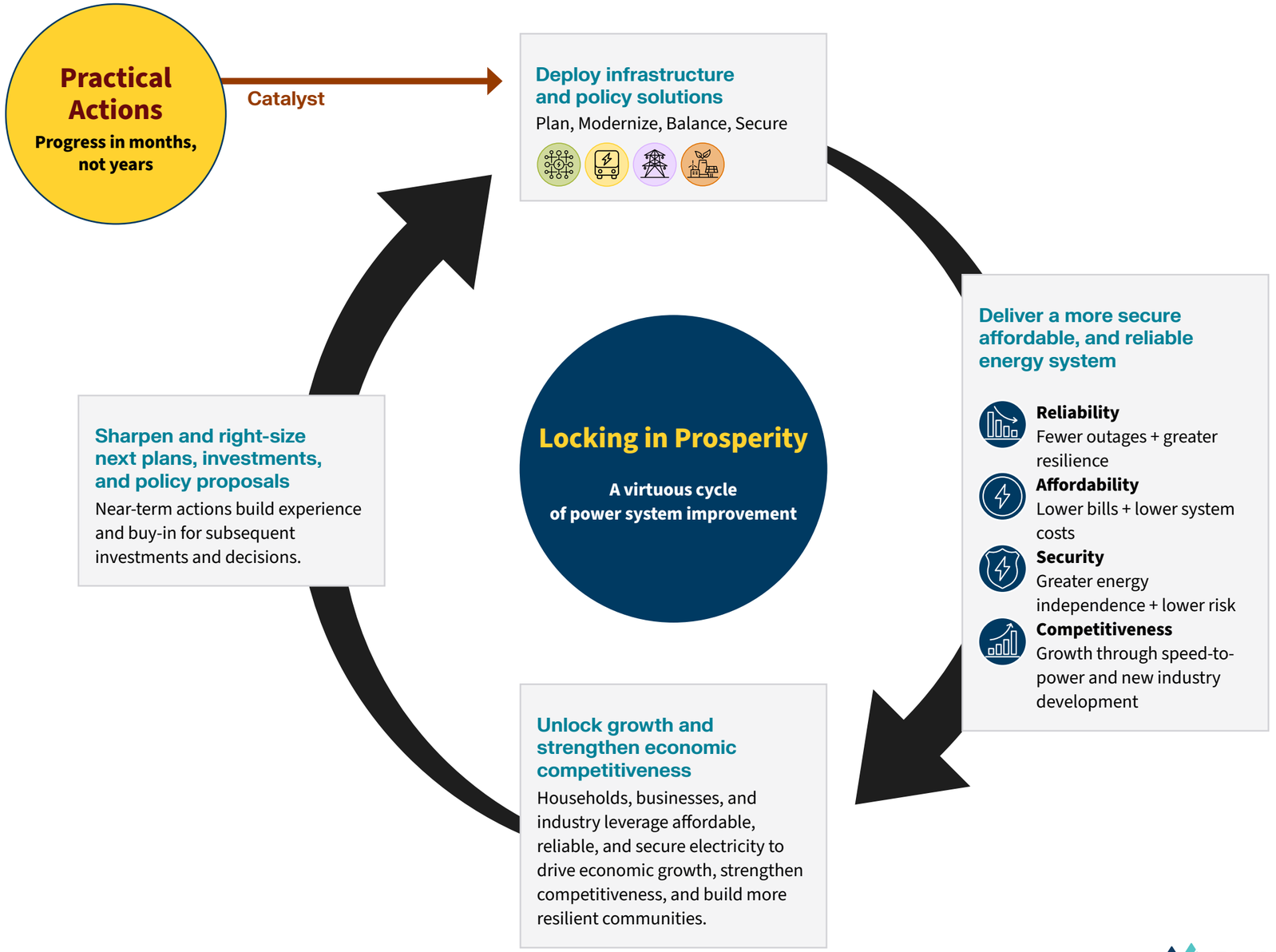
Through subsidies, domestic manufacturing incentives, and charging infrastructure rollout, India has become a global leader in electrifying two- and three-wheeled vehicles. Three in five three-wheelers sold in India today are electric.

How can near-term actions address urgent needs while building toward long-term prosperity?

The 10 Practical Actions in this report can catalyze progress on immediate needs while building the evidence and capability for long-term infrastructure investment and policy decisions.

Pragmatic near-term actions are not substitutes for long-term reform and investment, but they can set the course for better long-term action:

- **Learning:** Pilots and sandboxes test new technologies and reforms in practice, showing what works and how to incorporate in future planning or procurement.
- **Right-sizing:** Near-term measures to increase efficiency, improve demand responsiveness, and better utilize grid capacity can reduce the size of future investments.
- **Buy-in:** Improved grid performance can help build the social license for larger investments and reforms.



How to use this report in your work this year

In this document

This report provides a starting point

Understand the trends driving energy strategy and outcomes

Define shared challenges across the sector, and map solutions to them

Learn practical actions leaders and their teams can explore

Take action

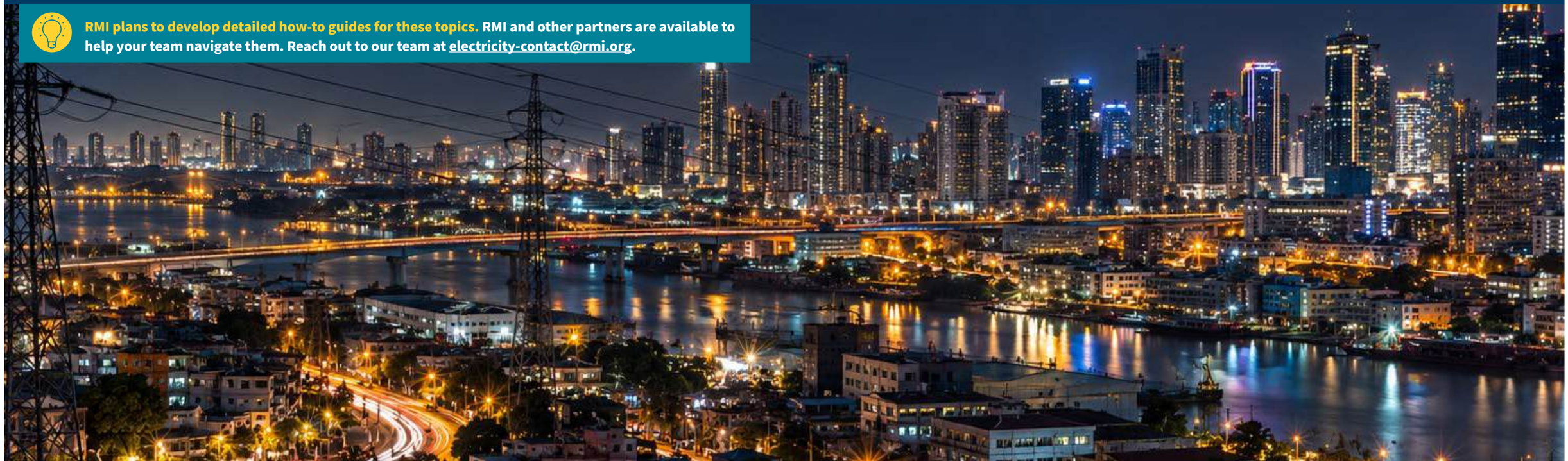
Next steps can include

1. Identify the Practical Action that addresses the problem you are solving

2. Make it somebody's job to act on applying this solution in your context

3. Build on the experience of global peers to move fast

RMI plans to develop detailed how-to guides for these topics. RMI and other partners are available to help your team navigate them. Reach out to our team at electricity-contact@rmi.org.



Introduction

A prosperous future is powered by reliable, affordable, secure electricity

Locking in Prosperity: Enduring actions to lower exposure to volatile fuels, reduce long-term cost and risk, and strengthen economic competitiveness.

INFRASTRUCTURE → **PROSPERITY**

Nimble plans that reduce risk
Planning processes reduce risk to energy supply and infrastructure over time, while accommodating load growth

Responsive, efficient end uses
Electric appliances, ACs, vehicles, computing loads and industrial processes, deliver strong value for low energy cost and respond to grid needs

A grid that delivers
Grid infrastructure moves cheapest energy mix from supply to demand with high reliability and power quality

Dependable, secure energy supply
Most of the energy supply comes from domestic sources with zero marginal cost









Affordability
Energy prices households can pay and industry can compete with

Reliability
Power when people and industry need it, through heat waves, storms, and fuel shocks

Energy security
Reduced exposure to volatile imports, geopolitics, and supply shocks

Economic competitiveness
Enabling growth through timely connection to affordable, reliable, secure power

Assets built and contracts signed today shape costs, risks, and capabilities for decades

"Going forward, is it possible for [Brazil] to lock in long-term gas contracts, which would commit the system to fossil fuel costs for decades? **Or should we use the storage to fill that gap instead?**"



- **Thaissa Avena**, former Technical Advisor at the Advisory for International Relations, Ministry of Mines and Energy

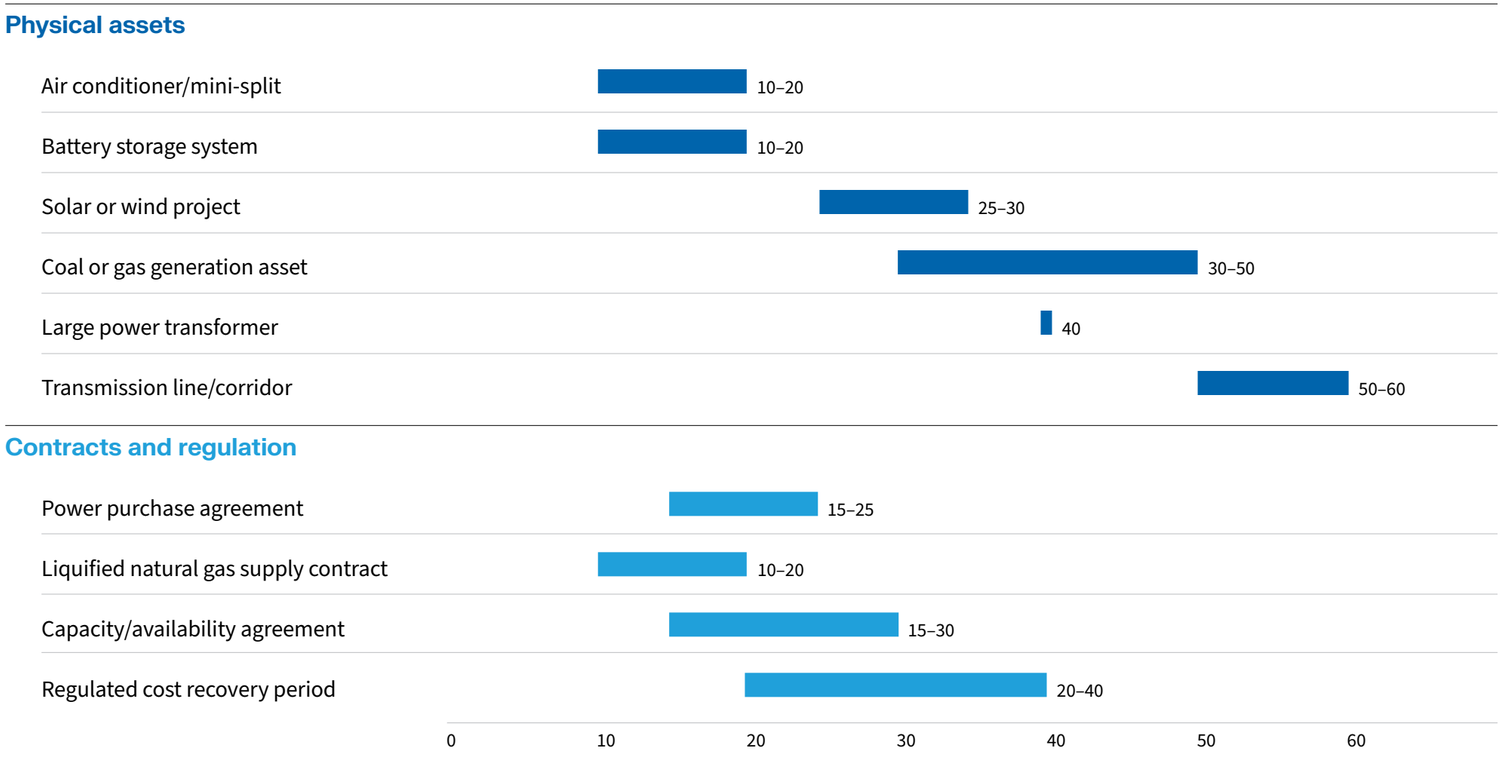
"There is a growing perspective that gas is an important fuel to meet energy needs, in the interim. However, **what you don't want is to lock in unabated gas for the long term**, which risks crowding out the continued transition to renewables."



- **Matt Judkins**, Lead Partner, Deloitte Energy and Climate

Lifespan in years of energy assets, contracts, and regulations

Indicative ranges; actual lifespans and terms vary by technology, jurisdiction, maintenance, financing, and market conditions.



Decisionmakers are faced with adapting century-old grids to meet changing needs in a handful of years

California shows how quickly a grid can evolve from centralized, non-variable generation to a distributed, two-way system, that has brought its own set of wins and challenges.

"(Batteries) are out of view. The footprint is very small. They are out of sight, but not out of mind. **They have been the difference maker.** They are the reason we haven't had flex alerts. These storage facilities have provided an incredible cushion."



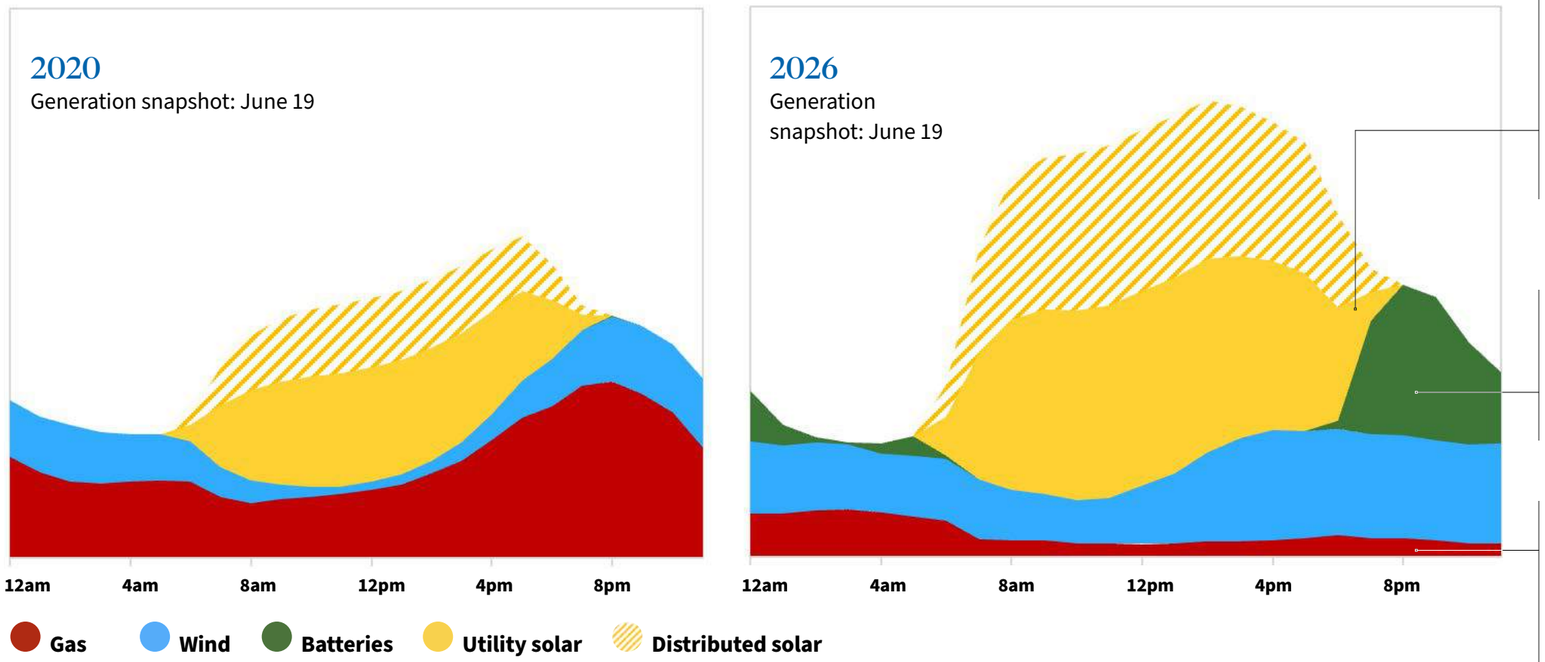
- **David Hochschild** in 2024[1]
Chairman of California Energy Commission

"But we are still very much, I would say, maybe in the second quarter of this transition. And so **we are still having to rely on our entire portfolio of resources**, our hydro, our natural gas, geothermal, our wind, our solar, imports from out of state to be able to keep the lights on."



- **Elliot Mainzer** in 2024[2]
President and CEO of CAISO

California ISO one-day snapshot generation from 2020 to 2026 (GW)



Generation snapshots from California ISO, growth stats are based on system capacity reported on EIA, CAISO, and State of California. Solar utility and distributed generation was broken out using ratio of total installed capacity of each from a single data source of solar generation.

In just six years

2x
Total solar capacity **doubled** from 2020 to 2026. Distributed resources contributed 38% and 45% of 2020 and 2026 solar capacity, respectively.

32x
Battery storage capacity increased from 2020 to 2026, now **36% of peak demand**.

39%
Reduction in natural gas generation through May of each year with only a 2% reduction in generation capacity.

[1] "Giant Batteries a 'Game Changer' for California Power Outages" (2024), https://www.govtech.com/em/safety/giant-batteries-a-game-changer-for-california-power-outages.

[2] "Successfully Managing the Growth of Renewables" (2024) on the ARC Energy Ideas podcast, https://www.arcenergyinstitute.com/successfully-managing-the-growth-of-renewables-with-elliot-mainzer-ceo-of-caiso/.

This future is already emerging around the world

Countries are already demonstrating how modern electricity systems can lower costs, strengthen reliability, improve energy security, and enhance economic competitiveness.

Affordability

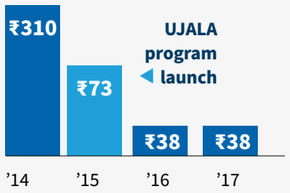
US$2.24 billion+

Annual household electricity bill savings from efficient LED lighting in India

India

- **369 million LED bulbs distributed** through UJALA program, making efficient lighting affordable at scale.
- Bulk procurement **reduced LED bulb prices by nearly 90%**, accelerating nationwide adoption and lowering household electricity bills.

LED procurement price
(INR/bulb)



369 million

LED bulbs distributed

90 million

households reached (~1 in 3.5 homes)

Reliability

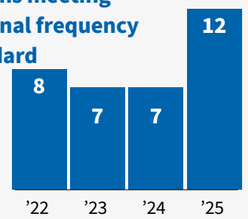
>50%

Of Chile's secondary frequency-control provided by solar & wind + battery energy storage systems (BESS) by late 2025

Chile

- In under three years, Chile **deployed 3.2 GW of battery storage**, enabling BESS to shift surplus solar to periods of higher demand and increasingly provide critical grid-stability services, meeting the national frequency standard every month.
- **Solar and wind now generate around 38%** of Chile's electricity.

Months meeting national frequency standard



Every single month in 2025 met the 97% frequency standard

97.95%

Percent of time within normal 49.8–50.2 Hz band in 2025, up from 96.72% in 2022.

Security

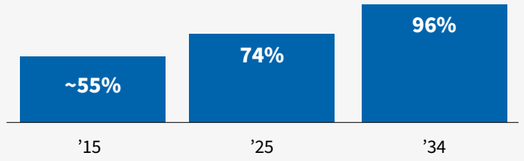
US$12 billion

Avoided imported fuel costs in Pakistan since 2018

Pakistan

- Rapid solar adoption has **reduced dependence on imported liquified natural gas (LNG) and oil** while improving resilience to global fuel price shocks.
- During recent LNG market disruptions, **Pakistan was able to reduce imports** while neighboring countries increased purchases.

Electricity generation from domestic sources



Competitiveness

US$32 billion

Green investment attracted in Morocco (2022–present)

Morocco

- Deliberate policy planning under the "Morocco Offer" has bundled low-cost renewable electricity, 1 million hectares of allocated land, and tax/customs incentives, thereby attracting ~US$32 billion in green industrial investment across hydrogen, fertilizers, EV batteries, and manufacturing.

Brazil

- Brazil is installing roughly 1 GW of solar capacity every month, creating one of the world's fastest-growing clean energy industries.

~1 GW

Solar installed every month in Brazil

1.6 million

Jobs supported in Brazil's solar industry

Source: Government of India / EESL UJALA factsheet; CLASP, Lighting a Billion.

Tailwinds Toward Prosperity

Given the tools available, this future is not just possible, but likely

More options than ever.

Leaders can access options that simply did not exist 10 years ago.

In three years since its launch in 2023, **Puerto Rico's Customer Battery Energy Sharing Program (CBES) has scaled to more than 110,000+ participants** and nearly 600 MW of enrolled capacity.

Faster and cheaper technologies.

Technologies once niche or prohibitively expensive are now cheaper and deployable far faster than traditional infrastructure.

In a pilot project by US utility AES, **42 LineVision dynamic line-rating sensors increased usable capacity by ~61%**, installed across five lines in less than two weeks.

More value from less energy.

Electrified generation and end uses deliver more value with less energy and at lower cost.

Efficient, inverter-based AC units, which can use up to 75% less electricity than traditional units, **grew from 1% to nearly 80% of India's AC stock** from 2015 to 2022.

Less exposure to fuel markets.

Fuel-free generation reduces exposure to continuous fuel supply and price volatility.

Pakistan has **avoided an estimated $12 billion** in imported fuel costs since 2018 as solar reduced LNG and oil dependence.



Drone-installed dynamic line rating sensors can increase capacity in less than six months from project start to finish.

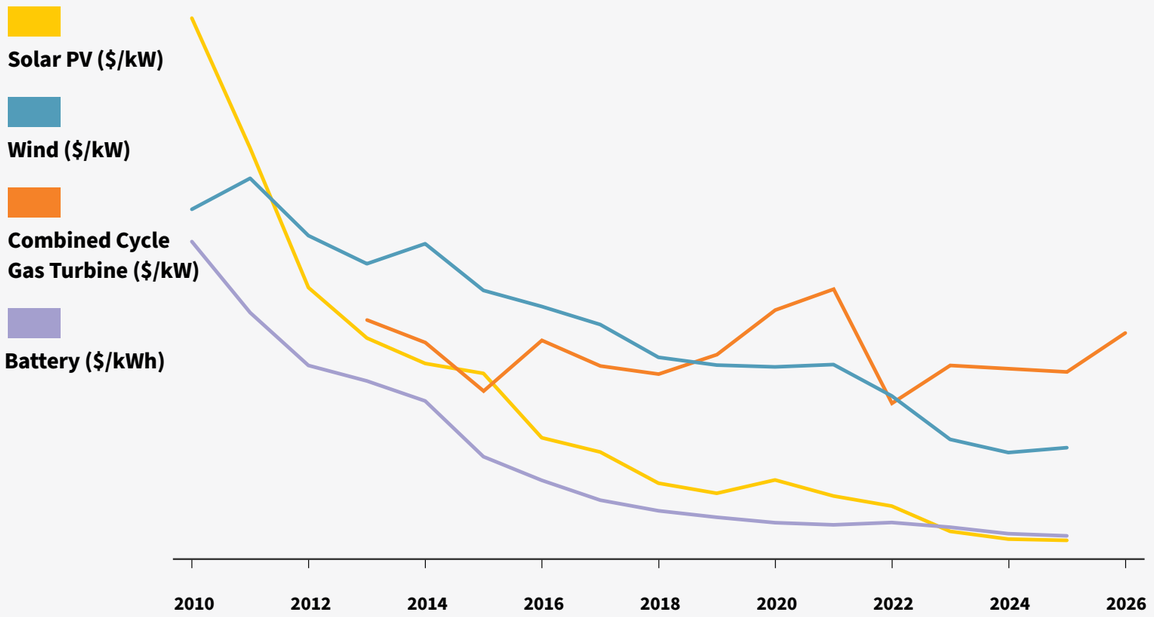
Photo: Heimdall Power

It is a historic time to be an energy leader

The technologies needed to build a prosperous future are scaling at unprecedented speed. Falling costs of renewables and storage are driving rapid uptake of new technologies that are reshaping the grid.

Capital costs of solar, wind, and batteries plummet relative to gas turbines

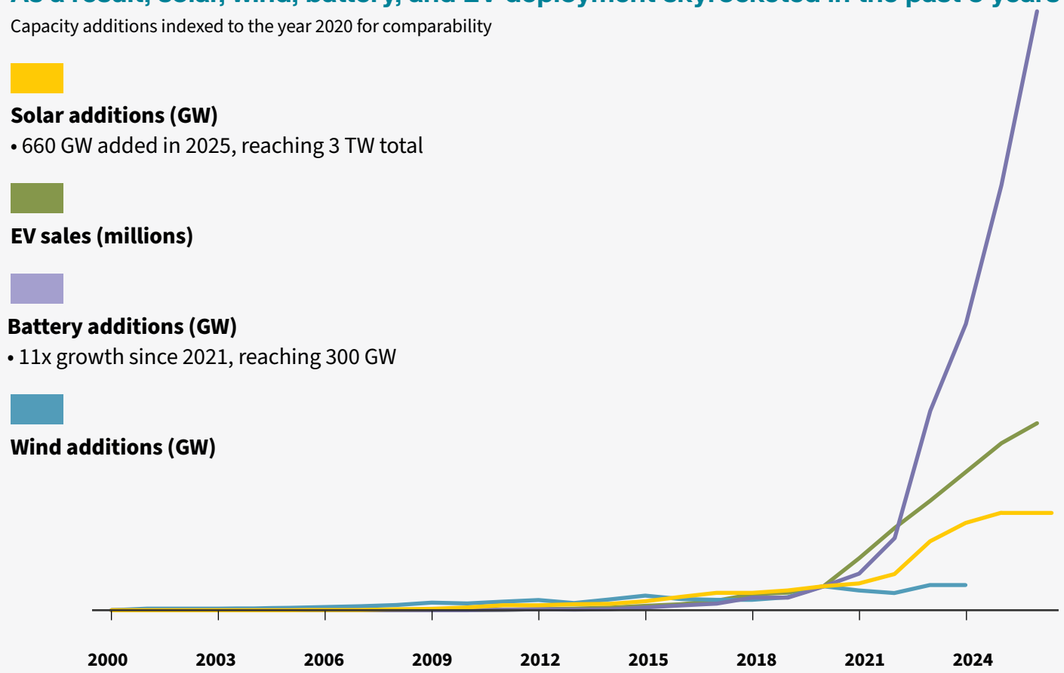
Up-front capital cost per unity of capacity



Sources: EIA, BNEF.

As a result, solar, wind, battery, and EV deployment skyrocketed in the past 5 years

Capacity additions indexed to the year 2020 for comparability



Sources: IEA, IRENA, BNEF.

Fast-to-deploy technologies can deliver power in weeks or months — not years, avoiding hundreds of millions of dollars in delay costs

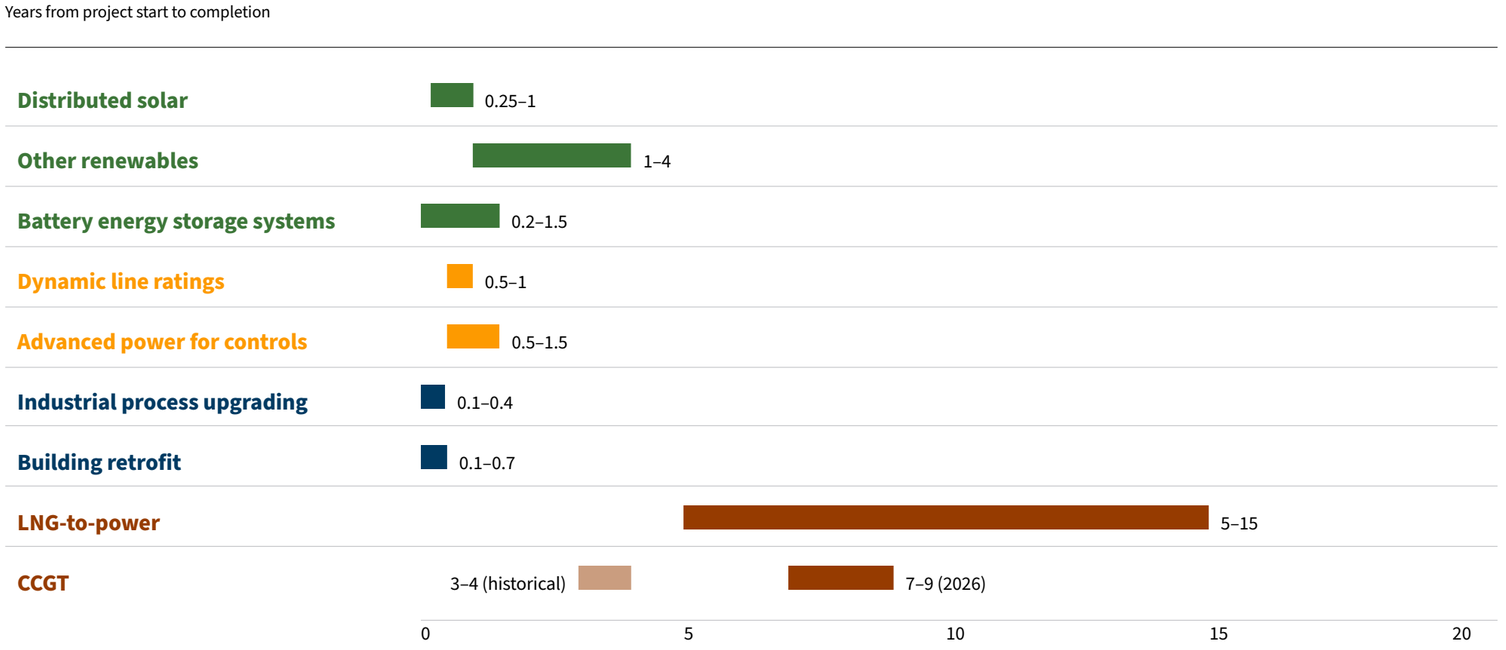
The price of delay is higher than ever in the AI era; the rewards of speed-to-power are that much greater.

In new modeling of large loads, delays are the largest driver of lost returns. **A 1-year delay can reduce the life-cycle value of a 100 MW US AI data center by ~$550M** (~5.5% of total value), which is 25% more than the modeled impact of doubling electricity prices.

Gas turbine lead times exceed 7 years.

New combined cycle gas turbine (CCGT) and coal projects are facing **increasing lead times** with turbine OEM's (e.g., GE Vernova, Mitsubishi Power), holding **a combined backlog of 170 GW**.

Modular renewable technologies, grid enhancement, and efficiency improvements are the fastest options for delivering power



Electrified, efficient, and modern end uses deliver more value with less energy and at lower cost

Energy production

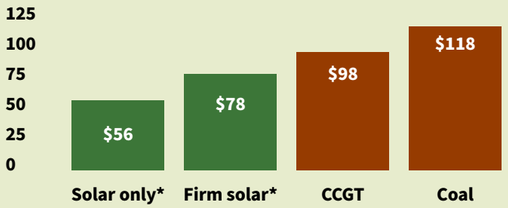
Electricity

Wind and solar
No thermal conversion losses

Fossil thermal
30%–60% efficiency

Thermal plants lose 40–70% of a fuel's energy turning molecules into electrons.

Levelized cost of electricity (LCOE) - $/MWh 2025



Energy use

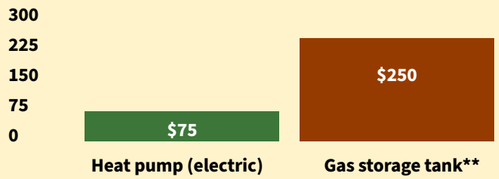
Water heating

Electric heat pump
200%–300% efficiency
3–6x as efficient

Conventional gas storage heater
50%–60% efficiency

Electric water heating is ~3x cheaper than gas heating; electric heating saves ~$170/year per household

Annual water heating cost (same household use)
India heat pump total cost of ownership



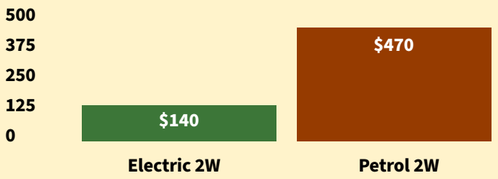
Transport

Electric vehicle
80%–90% efficiency
2–4x as efficient

Internal combustion engine
25%–40% efficiency

Electric two wheeler (2Ws) are ~3x cheaper than petrol 2Ws; electric 2Ws save ~$300/year per vehicle

Annual driving cost (12,000 miles)
India 2W total cost of ownership



The Physics

What drives this gap? Converting heat from burning fuels into electricity wastes energy at every step. By bypassing combustion, motors, resistors, and semiconductors turn electrons to motion, heat, or light with minimal losses. Approximately 75% of all energy wasted today is due to fossil fuel conversion steps; switching to electric has both economic and efficiency benefits.

Note: Solar and wind's 100% efficiency represents the fact that there are no conversion losses from primary to secondary energy.

*Firm solar LCOE is based on IRENA's 24/7 Renewables analysis at 95% reliability averaged for all available regions. **Gas storage tank pricing depends on local gas versus electricity prices.

Source: IEA, IIASA, BNEF, DOE, EPRI, EIA, RMI analysis, adapted from Prof. Tomas Kaberger.

Most economies create more value per unit of energy than they did 25 years ago

How have nations raised energy productivity?

Energy productivity reflects energy use, production, and economic structure. Energy-intensive production has at times shifted from one nation to another, but countries in this dataset **increased energy productivity 45% from 2000 to 2025**.

Energy use

More efficient industrial processes, motors, buildings, appliance, and vehicles reduce input energy required for the same economic and energy output

India

1%
of ACs used more efficient inverter systems in 2015.

77%
of ACs used these inverter systems in 2022

Energy production

Renewable and electric systems avoid substantial thermal losses both during combustion and at end use

Chile

38 TWh
of additional renewable generation in 2025 than 2000 from solar, wind, and bioenergy avoiding thermal losses equal to nearly 3 years of Santiago's electricity consumption*

Change in countries' energy productivity from 2000 to 2025

Energy productivity defined in billion US$ of GDP per EJ of total energy supply

Each bar represents a country's change in the country's energy productivity from 2000 to 2025.

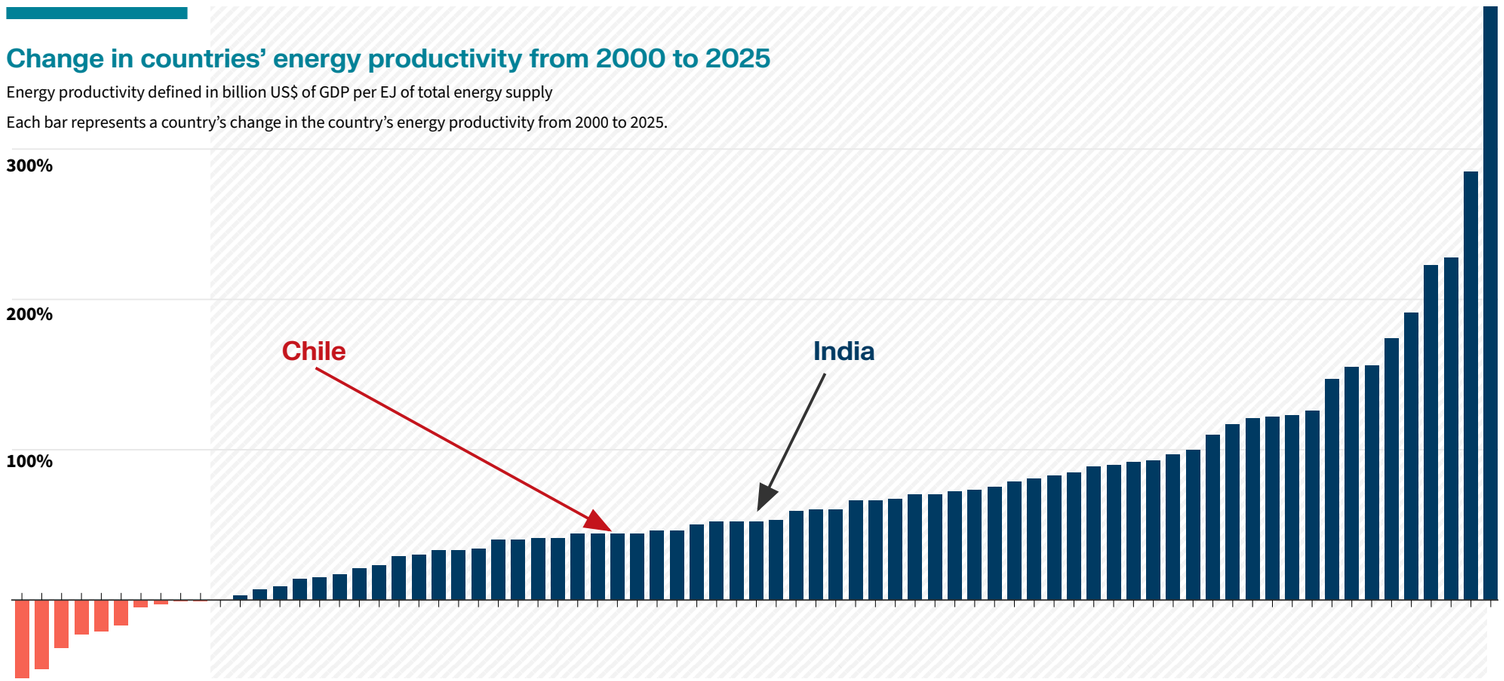


Chart data from Energy Institute and IMF. **Additional sources:** PIB, SEC

85%
of nations had an increase in their energy productivity over the past 25 years

$57T
of additional GDP enabled from the same amount of energy than at 2000 energy productivity levels

338 EJ
of additional total energy supply would have been required to generate 2025 GDP if energy productivity stayed at 2000 levels

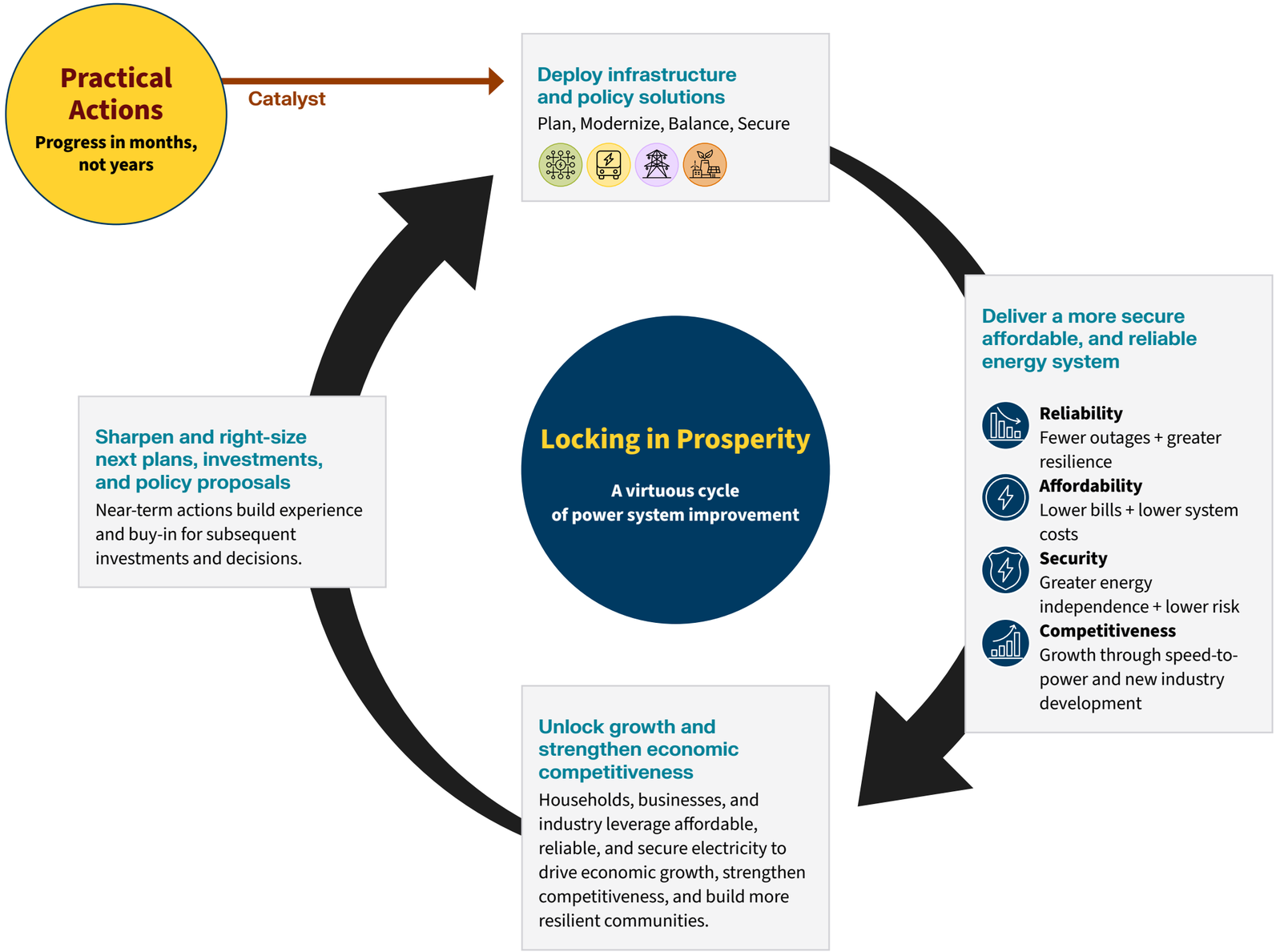
*Assuming 50/50 split of CCGT and coal, summing to 0.15 EJ of fossil generation losses avoided, aligned to current national generation trends. This value also represents Enel Chile's distribution, which covers the majority of the greater Santiago Metropolitan Region

Near-term actions address urgent needs while building toward long-term prosperity

Today's investments in technology, infrastructure, and policy solutions can catalyze a virtuous cycle where near-term actions drive long-term benefits and clarify long-term reform and investment.

Pragmatic near-term actions are not substitutes for long-term reform and investment, but they can set the course for better long-term action:

- **Learning:** Pilots and sandboxes test new technologies and reforms in practice, showing what works and how to incorporate in future planning or procurement.
- **Right-sizing:** Near-term measures to increase efficiency, improve demand responsiveness, and better utilize grid capacity can reduce the size of future investments.
- **Buy-in:** Improved grid performance can help build the social license for larger investments and reforms.



Headwinds Energy Leaders Face

Despite these tailwinds, building the grid of the future is not a simple task in a turbulent era

Demand is surging.

Electricity demand is growing rapidly as cooling, EVs, data centers, and industrial electrification expand.

From 2020 to 2025, **global data center electricity demand rose 92%**, while **EV electricity consumption increased roughly 5x**.

Markets are volatile.

Energy leaders are making long-lived investment decisions while fuel prices and supply conditions can change abruptly.

Contracts and power purchase agreements (PPAs) last decades; **major grid and fuel infrastructure can remain in service for half a century or more**.

Climate risk is growing.

Rising temperatures and more disruptive weather events are creating new pressures on power systems.

Global hydropower capacity factors **fell below 40%** in 2023, their lowest level in at least three decades.

Risks are shifting.

As power systems evolve, exposure is moving from fuel supply toward technology, materials, and system operations.

California's battery capacity **increased 32x** from 2020 to 2026; in Brazil, a new distributed generation asset is installed **every 40 seconds**.



Electricity is projected to become the single largest source of final energy consumption by 2047

Electrification has become an ingrained process in energy development around the world, where future energy demand growth will be largely driven by electricity.

"The electricity grid is becoming the critical interface between ambition and execution."

— **Firdaous El Ghazi**,
Moroccan Agency for Sustainable Energy (MASEN)



Percentage of global final energy consumption



Primary drivers of electricity growth

Air conditioning

Installed cooling capacity is set to **triple by 2050** from 2022 as incomes rise and heat risks intensify.

Electric vehicles

Global EV electricity consumption nearly doubled from 2023 to 2025 and could rise another **6x by 2035**.

Data centers and AI

Global data center demand rose 92% from 2020 to 2025 and could reach **9% of global energy demand in 2050**.

Industrial electrification

Through 2035, industrial electrification is **expected to account for nearly 30%** of electricity growth.

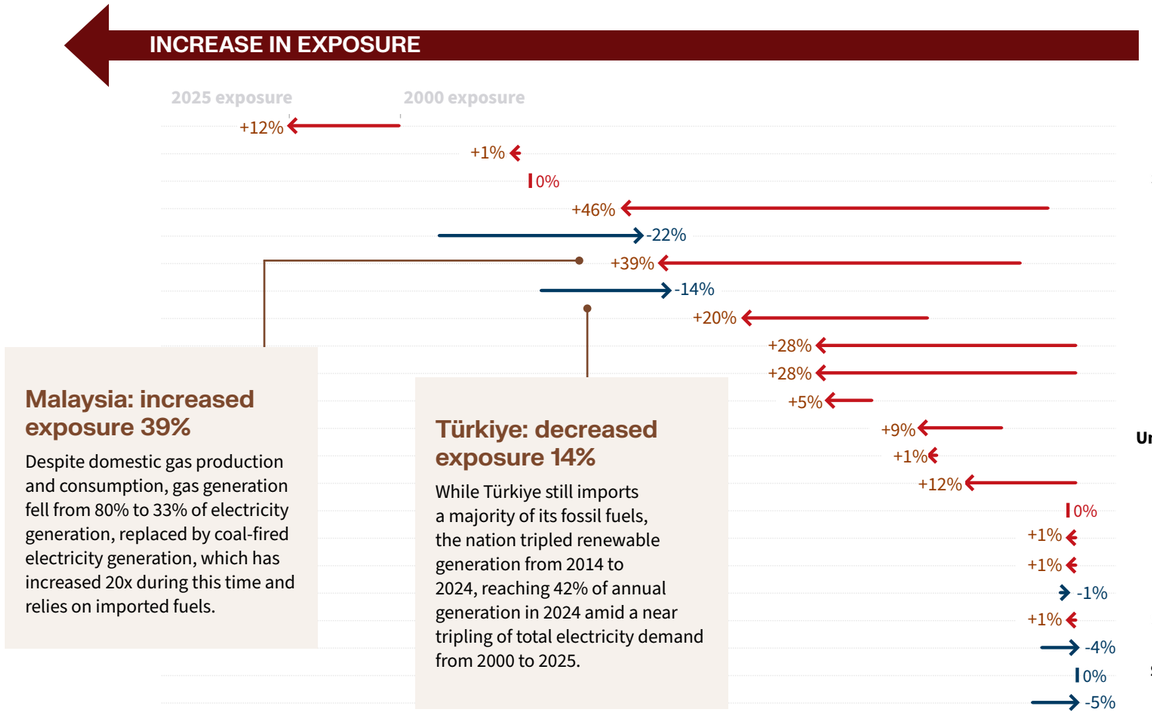
Sources: BNEF, IEA, UNEP, Forbes

Electricity systems have become larger and more dependent on imported fuel in the past 25 years

Leaders are managing both electricity growth and energy security

Exposure to fossil fuel imports for electricity has risen in many countries from 2020 to 2025

Percent of electricity generation dependent on imported gas, coal, and oil*



Malaysia: increased exposure 39%

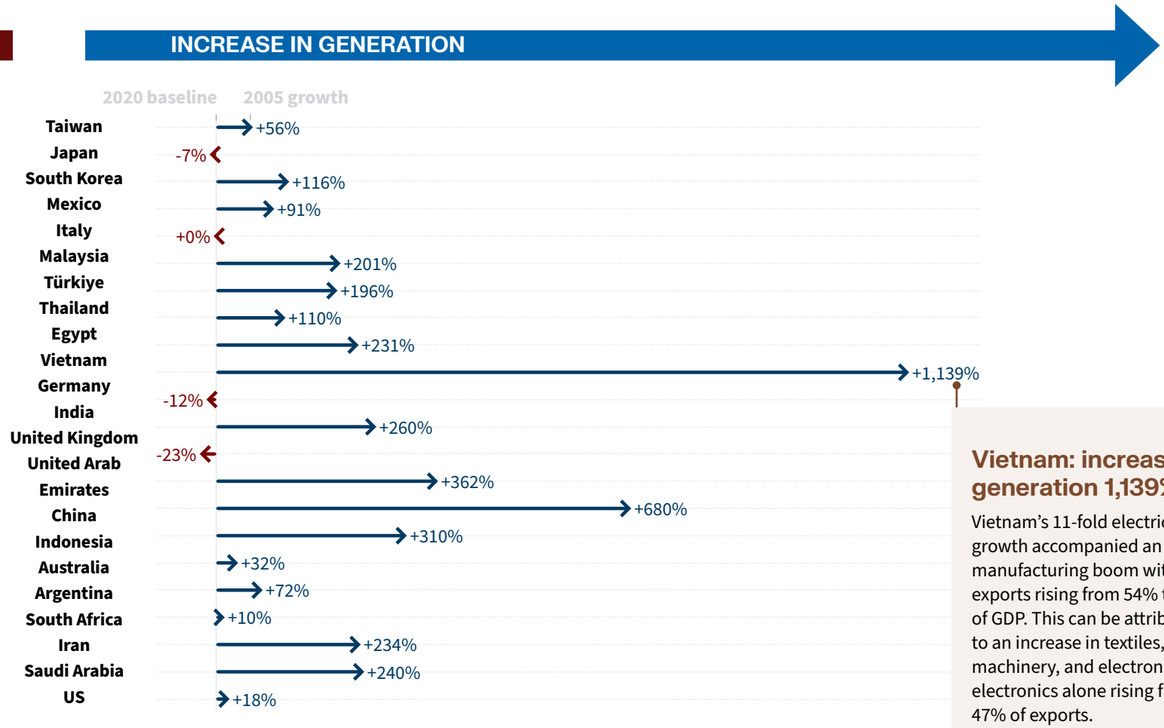
Despite domestic gas production and consumption, gas generation fell from 80% to 33% of electricity generation, replaced by coal-fired electricity generation, which has increased 20x during this time and relies on imported fuels.

Türkiye: decreased exposure 14%

While Türkiye still imports a majority of its fossil fuels, the nation tripled renewable generation from 2014 to 2024, reaching 42% of annual generation in 2024 amid a near tripling of total electricity demand from 2000 to 2025.

Annual electricity generation has grown substantially between 2000 and 2025

Relative percentage change in annual electricity generation



Vietnam: increased generation 1,139%

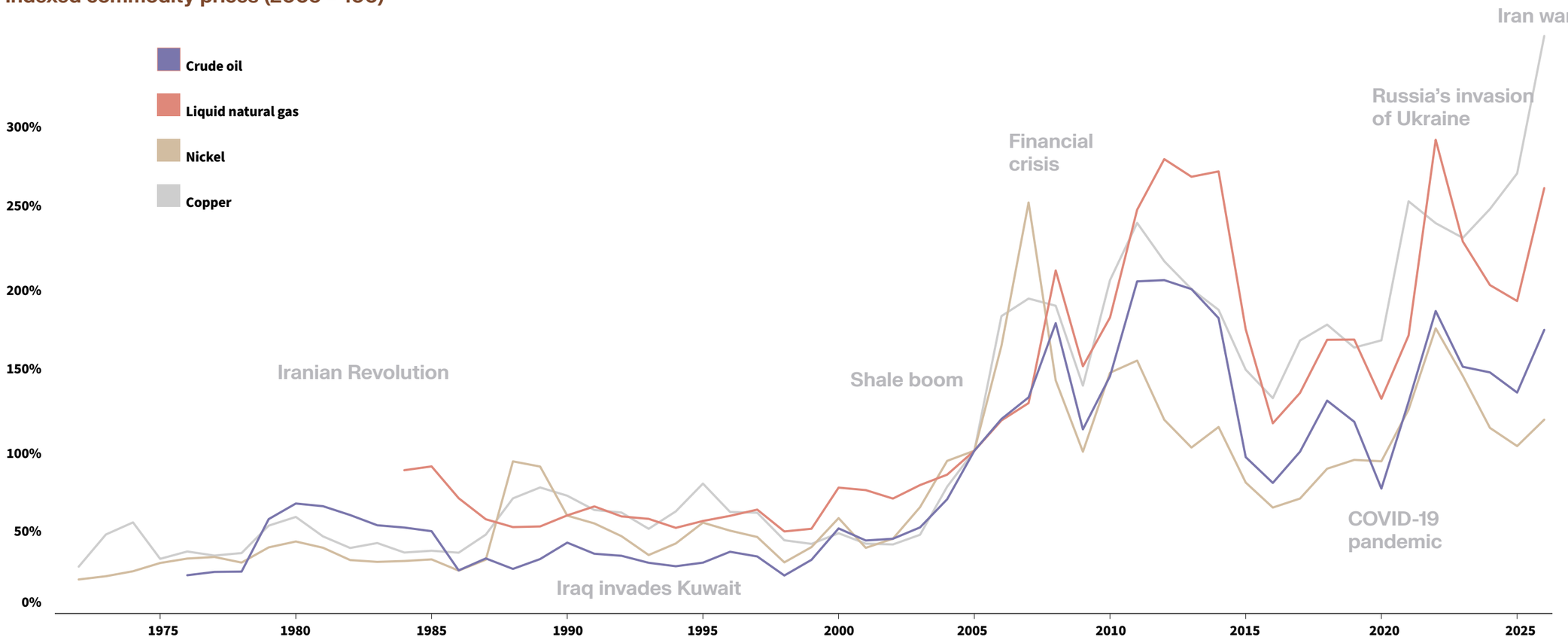
Vietnam's 11-fold electricity growth accompanied an export-manufacturing boom with exports rising from 54% to >90% of GDP. This can be attributed to an increase in textiles, heavy machinery, and electronics, with electronics alone rising from 8% to 47% of exports.

*Calculated with total fuel supply subtracted by domestic production with minimum of zero. Countries included are sample of available data from the Energy Institute 2026 Statistical Review of World Energy. **Additional sources:** IEA, World Bank

Markets are becoming less predictable by the decade

Energy leaders must make long-term decisions amid major, unpredictable disruptions that create technological, economic, and geopolitical uncertainty.

Indexed commodity prices (2005 = 100)



Commodities have swung more in the last 20 years than they did in the previous century's crises, including other global oil shocks sparked by wars in the Middle East.

Notes: Prices indexed to 2005 to compare relative commodity price movements during the modern investment period. 2026 data is from IEA January/February data, 2026 average data and June snapshot from JOGMEC.

Sources: Energy Institute Statistical Review; World Bank Commodity Markets "Pink Sheets"

Rising temperatures increase cooling needed for health and comfort, but growing equipment base can strain grids

Heat risk is rising, non-linear, and deadly

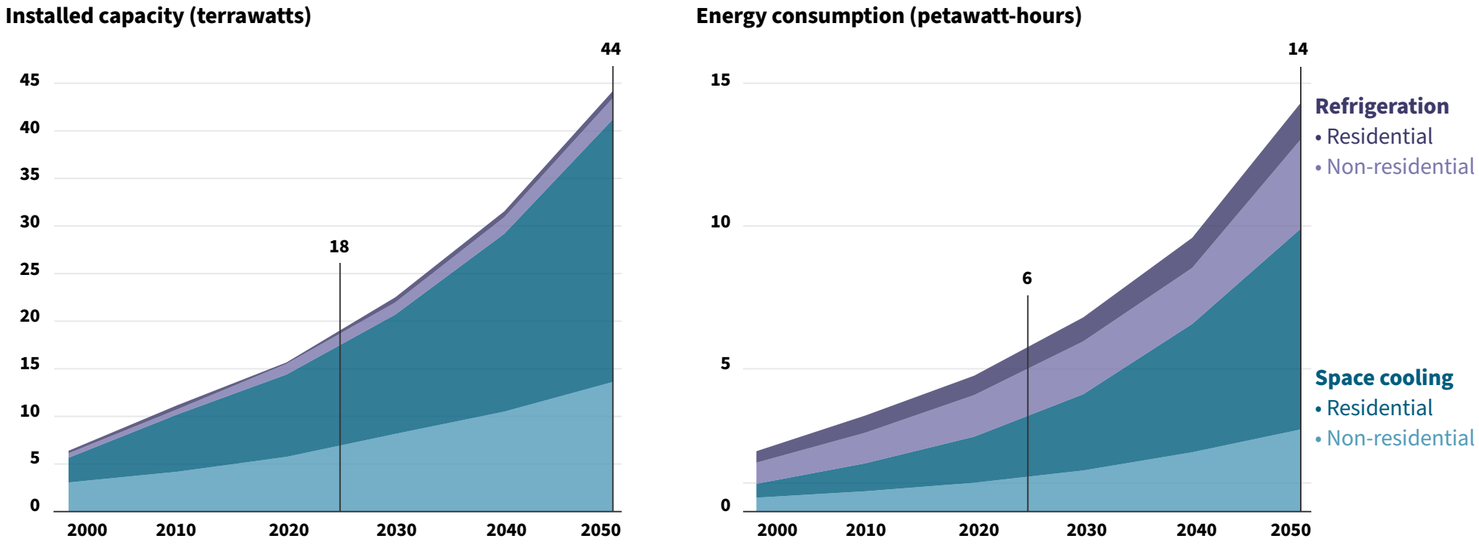
By 2030 ...
Extreme heat could lead to a **$2 trillion loss** in labor productivity worldwide.

By 2050 ...
Extreme heat could cause **240,000 deaths** each year.

By 2100 ...
74% of people globally will experience deadly heat conditions.

Mechanical cooling is one component of an integrated approach to reducing these risks, which also includes measures to reduce urban and building heat gain.

Global energy consumption by space cooling and refrigeration is expected to grow 2.5x by 2050



Note: 1 PW is equal to 1 trillion kilowatts (kW).

Source: UNEP, 2023 "Global Cooling Watch," US EIA

Energy planners will need to anticipate substantially higher cooling demand as temperatures rise, ensuring power systems can reliably meet hotter, higher-demand periods.

Sources: ILO, WHO, Mora et al., 2017

Beyond extreme heat, more frequent weather-related disruptions are challenging power systems worldwide

Climate hazards create distinct and compounding pressures across the power system.

Droughts
Reduce hydropower output and reservoir levels. **Global factors fell below 40%** in 2023, their lowest levels in at least three decades.

Extreme heat
Drives higher cooling demand and system peaks. **Installed cooling could more than triple**, from 850 GW in 2022 to 2,700 GW in 2050.

Wildfires
Damage transmission infrastructure and can force **preventive power shutoffs**.

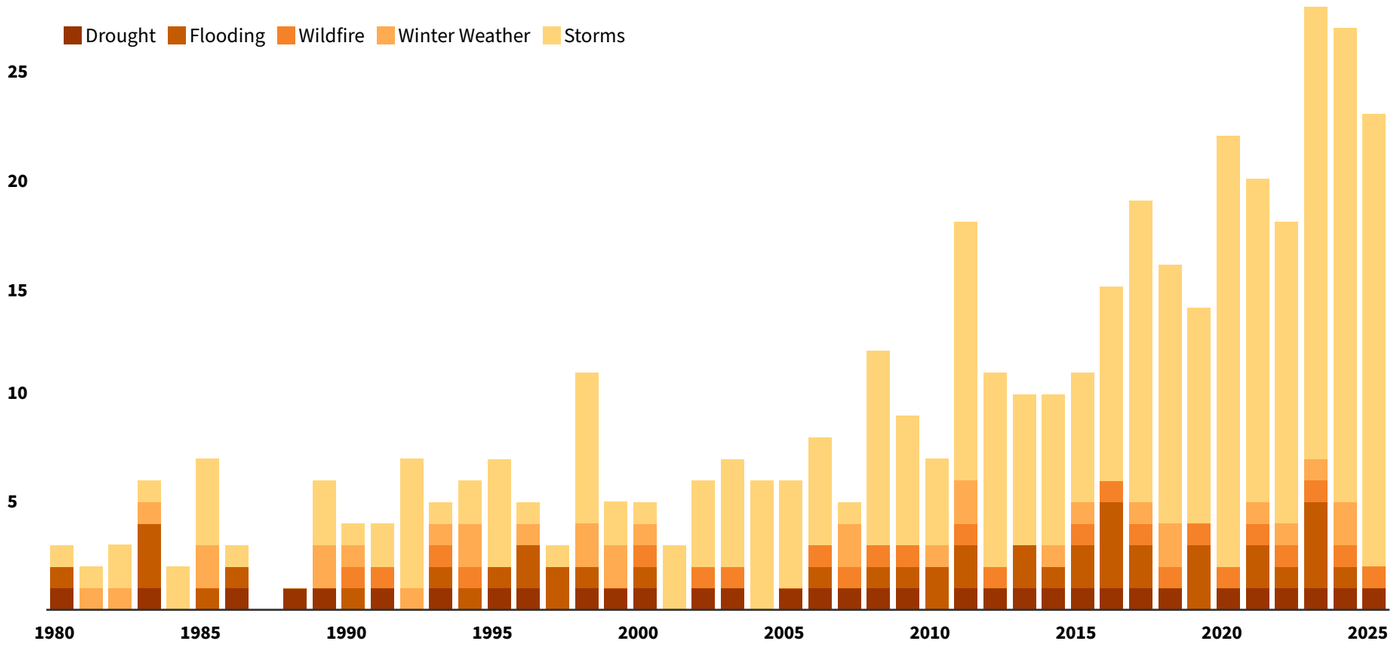
Severe storms
Cause widespread infrastructure damage and prolonged outages. **Hurricane Maria disrupted electricity service across Puerto Rico**, with full grid restoration taking nearly 11 months.

Winter storms
Can simultaneously reduce supply and increase demand. Winter Storm Uri left **55 GW of generation unavailable** in Texas in 2021.

Flooding
Can inundate **substations, power plants, and other critical infrastructure**, causing equipment failures.

Costly climate-related disasters are becoming more frequent

Number of US weather and climate disasters causing at least US$1 billion in damages, 1980–2025



Sources: IEA, Government of Accountability Office, FERC

Though the future promises to reduce vulnerability, leaders face evolving risks as systems transition

Electrification and efficiency trade recurring fuel dependence for manageable technology and infrastructure risks, reducing overall vulnerability over time.

Three types of risk combine to determine overall vulnerability

Commodity flow

Risks from the physical flow of energy commodities across global markets.

- Maritime chokepoints
- Import dependence
- Fuel price volatility

Material and tech stock

Risks from the availability and concentration of critical materials, components, and technologies.

- Critical minerals
- Manufacturing bottlenecks
- Trade barriers
- Export controls

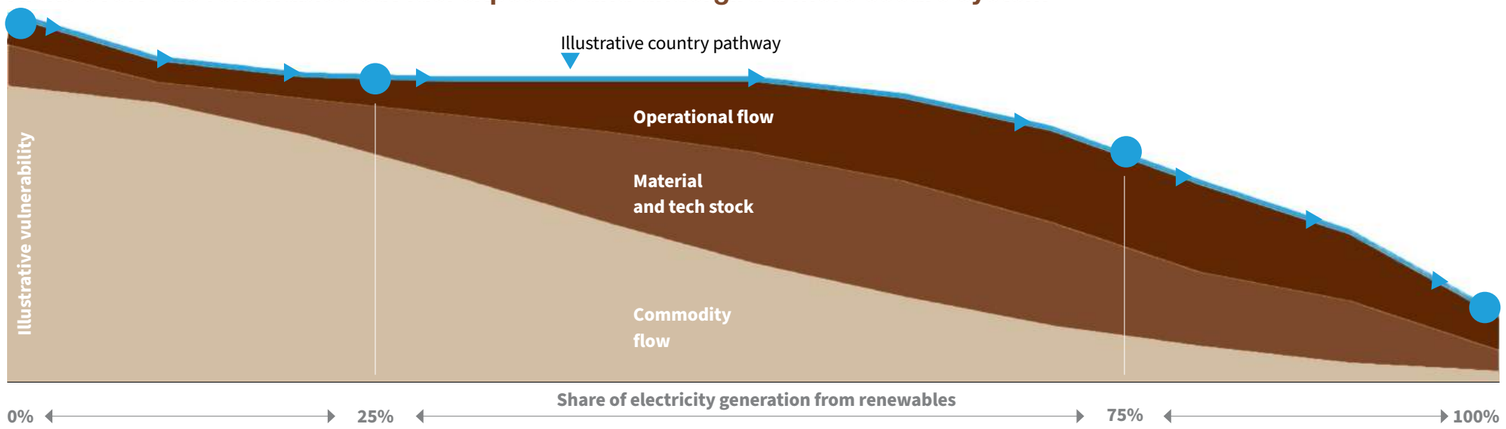
Operational flow

Risks from the real-time operation and coordination of increasingly complex energy systems.

- Grid reliability
- Cyber threats
- Extreme weather

Note: Based on Shepard et al. (2026) framework: https://iopscience.iop.org/article/10.1088/1748-9326/ae8a6d

Risks evolve as renewables cut fuel exposure and undergird a more secure system



Incumbent system
0%–25%
- Fossil import dependent
- **Commodity flow risks dominate**

Reduce exposure
- Efficiency
- Reserves
- Fuel diversification

Messy middle
25%–75%
- Rapid clean-tech deployment, concentrated supply chains
- **All three risks overlap**

Build resilience
- Domestic manufacturing
- Diversification
- Recycling

Coordinated clean system
75%–100%
- Fully electrified, digitally complex
- **Operational risks key to mitigate**

Manage complexity
- Flexibility
- Controls
- Cybersecurity

Amid this uncertainty, energy leaders around the world are facing four common challenges

Utility leaders, agency heads, regulators, and their teams consistently identify four problems facing their grids. These suggest four responses can improve affordability, reliability, and security.

Challenge		Action area
Grid planning under uncertainty	• Established planning tools optimize for lowest cost given fixed assumptions, rather than prioritizing low-risk or high-flexibility paths	**Plan** Design plans, procurements, and queues for uncertainty
Growing and inflexible loads	• Volatile fuel prices burden industry and consumers directly using oil and gas for services that could alternatively be powered by electricity • Grid costs and stress driven by peak demand set by inflexible loads	**Modernize** Electrify efficient, responsive loads
Grid infrastructure to reliably align supply and demand	• Balancing the grid in real time is increasingly difficult as loads grow and variable renewables increase • Grid instability reduces customer quality and hours of service • Grid congestion and inflexible contracts sideline cheapest generation sources	**Balance** Deliver reliable power when and where it is needed
Cost and risk of energy supply	• Meeting growing electricity demand while keeping prices affordable • Global fuel supply disruptions directly affect electricity costs and reliability	**Secure** Build low-cost, low-risk generation portfolios

There is a solution to every problem, and most use renewables, storage, and grid technologies to get there

Action area	Challenge	Solution	Enabling tools
 **Plan** Design plans, procurement, and queues for uncertainty	Established planning tools optimize for lowest cost given fixed assumptions, rather than prioritizing low-risk or high-flexibility paths	Update plans to be iterative, flexible, and risk-aware, and streamline queues to prioritize most-needed projects	• Improved planning processes • Digital metering • Nimble processes for procurement, interconnection, and grid code updates • Grid visibility, monitoring, digital twins
 **Modernize** Electrify efficient, responsive loads	Volatile fuel prices burden industry and consumers directly using oil and gas	Upgrade end uses to electric equipment that delivers more value with less energy	• Efficient end-use equipment (e.g., heat pumps) • Industrial electrification
	Grid costs and stress driven by peak demand set by inflexible loads	Shave peaks with demand response or price signals, especially for large loads.	• Demand response • Dynamic pricing
 **Balance** Deliver reliable power when and where it is needed	Without storage and system buffers, cheap power is curtailed, not delivered	Deploy storage or market products to manage for volume and capacity	• Battery energy storage systems • Virtual power plants • Emergent long duration energy storage
	Grid instability reduces customer quality and hours of service	Normalize inclusion of grid-forming hardware and create markets for ancillary grid services	• Voltage and frequency stabilizing hardware (e.g., grid-forming inverters)
	Congestion sidelines cheap capacity	Boost grid capacity with advanced transmission technologies (ATTs)	• Advanced transmission technologies • Greenfield lines, reconductoring, new interconnects
 **Secure** Build low-cost, low-risk generation portfolios	Meeting growing electricity demand while keeping prices affordable	Equip consumers to bring cheap distributed capacity in alignment with grid needs	• Distributed solar, storage, and other resources
	Global fuel supply disruptions directly affect electricity costs and reliability	Explore clean firm options and optimize thermal generation to fill gaps left by variable sources	• Variable renewables with firming storage • Clean firm sources (e.g., geothermal) • Optimized incumbent generation

Ten Practical Actions Toward Affordable, Reliable, and Secure Power Systems

A starting point: practical actions to meet the moment and evolve grids for the long haul

We used the following criteria to identify practical actions that address leaders' most urgent challenges.

Low-regrets: valuable across uncertain futures, can be staged or adapted, and avoid unnecessary lock-in.

Timely: can deliver results in less than 12 months.

Doable: can be driven by a designated leader or team without requiring whole-system reform or extraordinary resources.

Technology neutral: clearly defining the problem and then inviting solutions, rather than starting with a technology of choice

Applicable: most, if not all, grids around the world can benefit from some form of this action.

Practical actions are a part of a longer path to a prosperous energy future, but not every step along the way fits these narrow selection criteria. We intend these actions as pragmatic starting points for busy leaders, many of which may inform longer-term market reform, planning, or infrastructure investment activities that are also crucial.



How can energy leaders make progress on the problems keeping them up at night?

Ten Practical Actions address the challenges leaders are facing, are useful even when the future is uncertain, have been widely demonstrated, and can show results in less than 12 months.

Action area	Practical Action	Case studies
Plan Design plans, procurement, and queues for uncertainty	1. **Plan for uncertainty.** Model system risk across a range of fuel cost, demand forecast, and technology cost scenarios, then stage procurement and investment to pivot when circumstances change.	Ghana, Morocco, Western Australia
	2. **Clear queues and improve forecasts.** Apply project planning milestones and financial requirements to clear speculative or stagnant projects from connection queues and forecasts, directing limited study capacity toward the most promising projects, and improving generation and load projections.	Great Britain
Modernize Electrify efficient, responsive loads	3. **Scale efficient cooling.** Set testing standards and labels that differentiate and reward air conditioners delivering efficient real-world performance, and build ecosystem awareness to shift the market toward such products.	India
	4. **Encourage vehicle electrification.** Educate consumers on the real costs and benefits of EVs versus gasoline and diesel vehicles and reduce up-front adoption barriers by streamlining financing and charging.	India
	5. **Make large loads flexible.** Tie large-load connection costs and queue priority to grid impact, so loads that commit to reducing demand during critical hours connect faster.	Malaysia
Balance Deliver reliable power when and where it is needed	6. **Match supply and demand.** Incentivize storage to earn and stack revenues from energy shifting and capacity provision.	Chile, Puerto Rico
	7. **Stabilize the grid.** Create technology-neutral pathways to procure ancillary services with clear technical standards.	Australia, Texas, Iberian Peninsula, China
	8. **Improve grid utilization.** Pilot advanced transmission technologies (ATTs) in high-impact grid segments while embedding ATT evaluation into ongoing transmission planning.	Colombia, Bangladesh, USA
Secure Build low-cost, low-risk generation portfolios	9. **Make distributed solar a grid resource.** Reduce soft costs and implement financially sustainable net-billing rules for distributed solar, keeping connection requirements technology neutral and encouraging solar + storage.	Brazil, Southern Australia
	10. **Level the playing field.** Run all-source, technology-neutral procurement competitions with independent evaluations that weigh resilience and fuel-price risk in addition to cost.	South Africa, Kenya



Plan

Design plans, procurements, and queues for uncertainty

Long-term planning can push infrastructure in the right direction for the future while maintaining flexibility. Leaders can improve the resilience, adaptability, and efficiency of planning and procurement with these actions.

Need	Practical Actions	Case studies
Flexible plans that minimize risk	1. **Plan for uncertainty.** Model system risk across a range of fuel cost, demand forecast, and technology cost scenarios, then stage procurement and investment to pivot when circumstances change.	**Ghana** Coordinated planning reduces overbuilding and improves resilience
Responsive connection processes for new electricity generators and users	2. **Clear queues and improve forecasts.** Apply project planning milestones and financial requirements to clear speculative or stagnant projects from connection queues and forecasts, directing limited study capacity toward the most promising projects, and improving generation and load projections.	**Great Britain** Replacing a “first come, first served” connection queue with a “first-ready, first-needed, first-connected” system created a 60% smaller, more manageable pipeline.

Note: These options are not meant to be exhaustive across categories, but they do represent actionable solutions to the needs we have identified across categories in our analysis and stakeholder consultation.



Modernize

Electrify efficient, responsive loads

Efficient, electric end uses wring the most value out of every kilowatt hour, and demand flexibility can mitigate rapidly increasing system peaks. Leaders can drive economic competitiveness while reducing grid stress with these actions.

Note: These options are not meant to be exhaustive across categories, but they do represent actionable solutions to the needs we have identified across categories in our analysis and stakeholder consultation.

Need	Practical Actions	Case studies
Cool households and businesses without breaking the grid	3. **Scale efficient cooling.** Set testing standards and labels that differentiate and reward air conditioners delivering efficient real-world performance, and build ecosystem awareness to shift the market toward such products.	**India** Efficiency standards for new cooling equipment shift market and reduce peak demand
Free drivers from fuel price fluctuations	4. **Encourage vehicle electrification.** Educate consumers on the real costs and benefits of EVs versus gasoline and diesel vehicles and reduce up-front adoption barriers by streamlining financing and charging.	**India** EV adoption accelerates and cuts fuel costs at scale
Shape demand when supply is tight	5. **Make large loads flexible.** Tie large-load connection costs and queue priority to grid impact, so loads that commit to reducing demand during critical hours connect faster.	**Malaysia** Large load tariffs, flexibility, and dedicated renewables shape data center growth



Balance

Deliver reliable power when and where it is needed

Modern grids must balance abundant, variable electricity supply against growing, variable demand. Leaders can bolster reliability, reduce curtailment of low-cost power, and reduce system costs through these actions.

Note: These options are not meant to be exhaustive across categories, but they do represent actionable solutions to the needs we have identified across categories in our analysis and stakeholder consultation.

Need	Practical Actions	Case studies
Match supply and demand across hours	**6.** **Match supply and demand.** Incentivize storage to earn and stack revenues from energy shifting and capacity provision.	**Chile** New revenue pathways in energy arbitrage and resource adequacy strengthened BESS project economics, supporting ~5 GW of deployment
Balance the grid over seconds to minutes	**7.** **Stabilize the grid.** Create technology-neutral pathways to procure ancillary services with clear technical standards.	**Australia** Battery competition cuts frequency control cost by >90%
Move more power through the grid without waiting for new transmission	**8.** **Improve grid utilization.** Pilot advanced transmission technologies (ATTs) in high-impact grid segments while embedding ATT evaluation into ongoing transmission planning.	**Colombia** Advanced transmission technologies unlock cheap renewables and relieve congestion



Secure

Build low-cost, low-risk generation portfolios

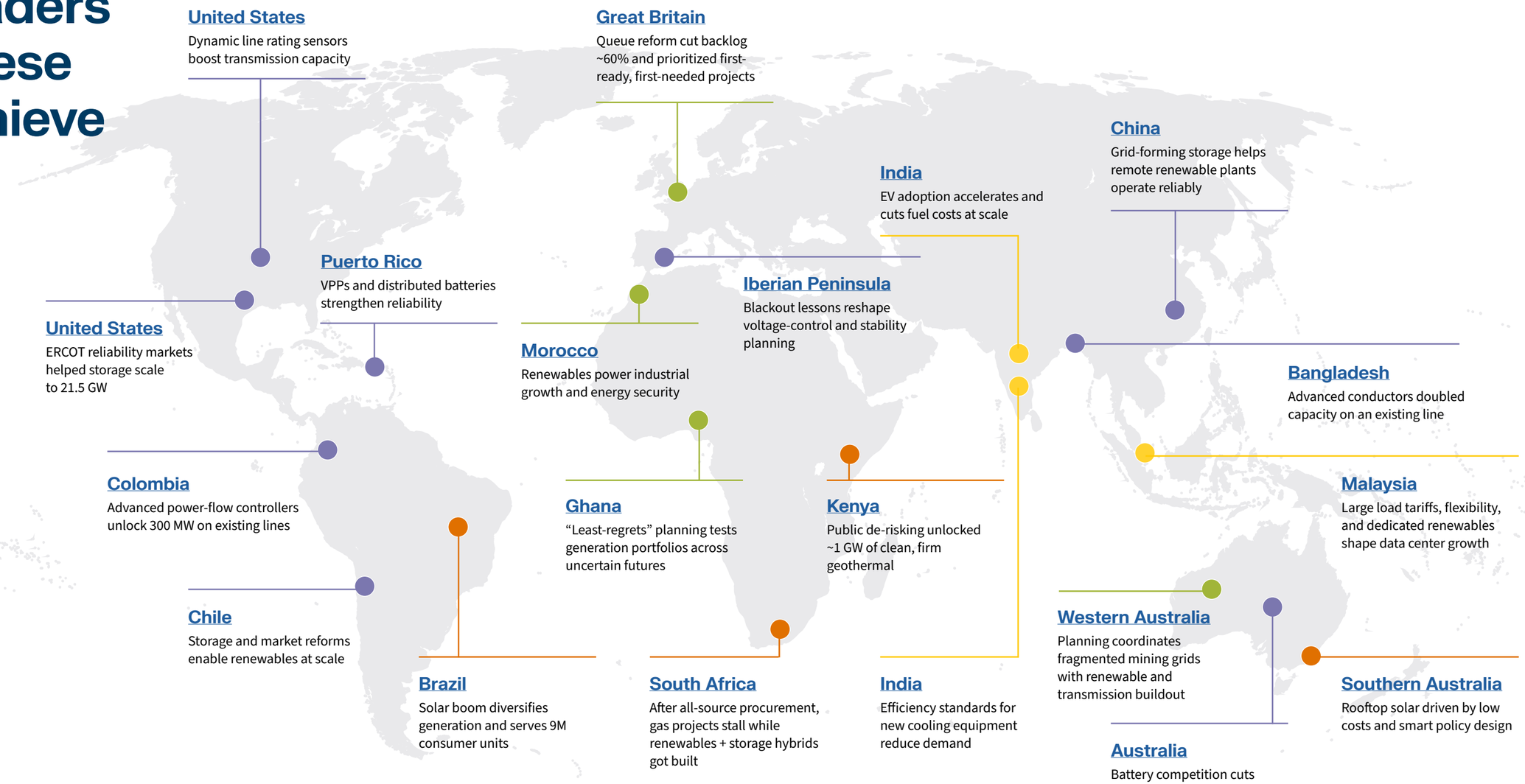
Distributed, secure energy supplies offer independence from market volatility and single points of failure in fuel supplies or physical infrastructure. Leaders can act to harness solar on rooftops as a grid resource and prioritize procurement of low-cost and low-risk sources.

Note: These options are not meant to be exhaustive across categories, but they do represent actionable solutions to the needs we have identified across categories in our analysis and stakeholder consultation.

Need	Practical Actions	Case studies
Affordable, rapidly deployable capacity	**9.** **Make distributed solar a grid resource.** Reduce soft costs and implement financially sustainable net-billing rules for distributed solar, keeping connection requirements technology neutral and encouraging solar + storage.	**Brazil** Distributed solar boom boosts energy security and reliability
Secure energy supply	**10.** **Level the playing field.** Run all-source, technology-neutral procurement competitions with independent evaluations that weigh resilience and fuel-price risk in addition to cost.	**South Africa** All-source procurement brought diverse technologies to the table; renewable-storage hybrids ultimately delivered power as gas projects stalled

How are leaders wielding these tools to achieve results?

This report highlights 20 case studies across 15 countries and 6 continents.



United States
Dynamic line rating sensors boost transmission capacity

Great Britain
Queue reform cut backlog ~60% and prioritized first-ready, first-needed projects

India
EV adoption accelerates and cuts fuel costs at scale

China
Grid-forming storage helps remote renewable plants operate reliably

Puerto Rico
VPPs and distributed batteries strengthen reliability

United States
ERCOT reliability markets helped storage scale to 21.5 GW

Iberian Peninsula
Blackout lessons reshape voltage-control and stability planning

Morocco
Renewables power industrial growth and energy security

Bangladesh
Advanced conductors doubled capacity on an existing line

Colombia
Advanced power-flow controllers unlock 300 MW on existing lines

Malaysia
Large load tariffs, flexibility, and dedicated renewables shape data center growth

Ghana
"Least-regrets" planning tests generation portfolios across uncertain futures

Kenya
Public de-risking unlocked ~1 GW of clean, firm geothermal

Chile
Storage and market reforms enable renewables at scale

Western Australia
Planning coordinates fragmented mining grids with renewable and transmission buildout

Brazil
Solar boom diversifies generation and serves 9M consumer units

South Africa
After all-source procurement, gas projects stall while renewables + storage hybrids got built

India
Efficiency standards for new cooling equipment reduce demand

Southern Australia
Rooftop solar driven by low costs and smart policy design

Australia
Battery competition cuts frequency control cost by >90%

- Plan
- Modernize
- Balance
- Secure

Behind each of these technical solutions is a team who invested in human capacity, clearly defined the problem, and marshaled resources across organizations to solve it

These leaders share their words of wisdom

"**We can't just lock ourselves away and expect to roll things out later.** The strategy was to sit everyone down at a table, everyone, and hold a technical, pre-legislative dialogue."

– **Andrés Romero,**
former Executive Secretary,
National Energy Commission Chile



"Throughout the process, we took stakeholders with us and met regularly so **it's the cumulative working groups and working across industries to make it happen** in NESO."

– **Neil Copeland,**
Connections Strategy Manager, NESO



"We have ample resources, but **without the human capacity** to develop those resources, **we can't move** on."

– **Anastasia Wanjohi,**
Ken Gen, Former Senior Geophysicist



"They just defined … the problem: this is what we need to solve. **Come one, come all, solve it if you can.** And that is what [allowed the] influxes of generation."

– **Joshua Rhodes**,
Research Scientist, University of Texas Austin



"**The clarity of scope and having one gate to handle all subjects is a huge relief** for the investors who are looking for credibility and the clear framework. If it's renewable, electrolysis, water desalinization, port infrastructure, or grid … come to MASEN to coordinate and facilitate."

– **Firdaous El Ghazi,**
Director of Contract Management, Green Hydrogen, Moroccan Agency for Sustainable Energy (MASEN)



"The [Puerto Rico virtual power plant] has proven more reliable than… legacy thermal power plants, with a response time in seconds versus minutes or hours, and no single point of failure. **We would not be here today without** LUMA's program, our trusted local sales and installation partners, our aggregator partners, and **the thousands of Powerwall battery households that routinely share their energy** with the grid today."

– **Kevin Joyce,**
Global VPP and Retail Electricity Lead, Tesla



Ten Practical Actions

For each action, we examine:

1. Benefits
What the action can deliver for people and power systems

2. Evidence
Where leaders have put it into practice

3. Application
Steps leaders can apply in their own contexts

Plan

1.

Plan for uncertainty

Model system risk across a range of fuel cost, demand forecast, and technology cost scenarios, then stage procurement and investment to pivot when circumstances change

Full case studies informing this Practical Action:

Ghana: power-sector planning

Morocco: grid buildout for green industrialization

Western Australia: integrated system planning

What are the benefits?

- **Cost:** Scenario planning can limit costly overbuild by reducing investment into capacity or infrastructure that only is bankable in specific circumstances.
- **Speed:** Redoing conventional integrated resource plans (IRPs) can take years. Adaptive procurement can respond to quickly changing conditions.
- **Reducing risk:** Portfolio planning can identify and reduce exposure to risk and uncertainty in fuel supply, load growth, climate shocks, and national security.

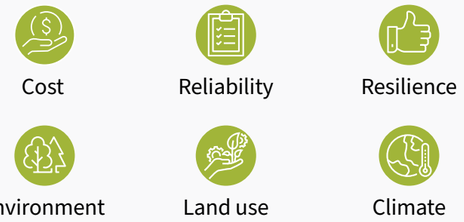
Model scenarios Robust across all futures ▶ **Procure flexibly** Add capacity in stages ▶ **Monitor and pivot** Continue or pivot plan

Ghana

Integrated power sector master plan

- **Context:** After facing supply shortages, fuel constraints, and overcapacity concerns, Ghana's Energy Commission developed an Integrated Power Sector Master Plan that explicitly sought a Least-Regrets Portfolio. Planners tested sensitivities to gas supply, water availability, load growth, capital costs, and fuel costs.
- **Outcome:** In 2023, planners selected a Geographic Diversification strategy through renewables, battery storage, and combined cycle gas plants. They prioritized resilience and balanced performance across five other metrics (below). The new plan aims to reduce overbuild and associated capacity payments over time. It also reduced exposure to risk and uncertainty in fuel supply, load growth, climate shocks, and national security.

Five strategies were evaluated using six metrics:



Practical steps for leaders

- **Establish standing data collection and monitoring** that integrates information from customer commitments, procurement results, project-development milestones, system operations, etc., into future planning assumptions and scenarios.
- **Consider a wide range of fuel price scenarios** and technology costs to establish a clear picture of the risks your power system is facing.
- **Adapt plans and procurement as real-world conditions change.** Procure in stages and condition later additions on signed service agreements, interconnection milestones, and successful delivery of capacity rather than locking-in build out up-front.

Further reading

- Planning for Uncertain Data Center Demand – RMI
- IRP for an Uncertain Future – IRB CoLAB

Plan

2.

Clear queues and improve forecasts

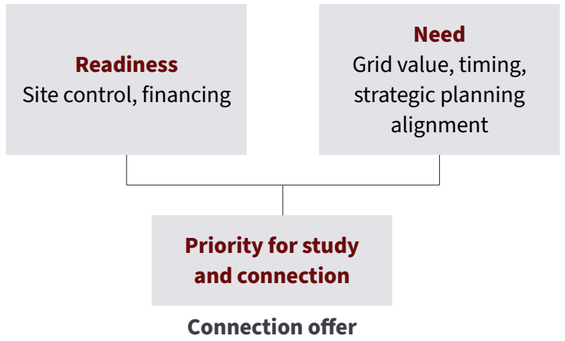
Apply project planning milestones and financial requirements to clear speculative or stagnant projects from connection queues and forecasts, directing limited study capacity toward the most promising projects, and improving generation and load projections.

Full case study informing this Practical Action:

Great Britain: NESO power system reforms

What are the benefits?

- **Cost:** Clearing non-viable projects allows capital to go toward shovel-ready projects, freeing up capital and improving the project financial ecosystem.
- **Speed:** Removing stagnant projects from the queue lets more viable projects move ahead, thereby bringing generation to the market more quickly.
- **Reducing risk:** A bloated queue distorts transmission and generation planning.



Great Britain

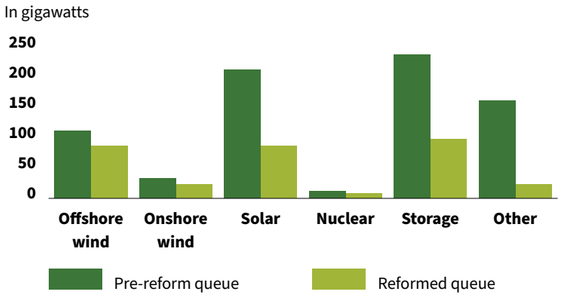
NESO's evidence-based queue reform

- **Context:** Historically, Great Britain faced queue times of up to 10 years with a ~770 GW pipeline of projects that were not located where there was capacity or expected need for growth.

  National Energy System Operator replaced the "first come, first served" queue with a "first ready and needed, first-connected" system. This allowed NESO to enforce milestones in project development, remove stagnant projects, and improve planning.

- **Outcome:** NESO cut the queue by ~60%, down to a ~280 GW pipeline, which more heavily indexes toward renewables; this has freed study capacity and capital to viable projects.

Great Britain connections delivery pipeline



Source: National Energy System Operator

Practical steps for leaders

- **Prioritize requests that align with strategic planning**, for example by providing capacity or grid services at specific nodes that need it.
- **Increase the barrier to new interconnection requests by requiring proof of project readiness** including site control, consents, and financing before projects can enter queue.
- **Retain the right to terminate agreements** if a project doesn't progress after approval; this prevents the queue from re-clogging.
- **Adopt streamlined, energy-only pathways** that are paired with **modern automated study software** to cut interconnection study timelines.

Further readings

- Powering New Loads and Lowering Electricity Costs with Connect-and-Manage Interconnection - RMI
- The Interconnection Queue Continues to Be a Barrier to US Economic Competitiveness - RMI
- Interconnection reforms and processes across the Atlantic: A primer – Clean Air Task Force

Modernize

3.

Scale efficient cooling

Set testing standards and labels that differentiate and reward air conditioners delivering efficient real-world performance, and build ecosystem awareness to shift the market toward such products

Delivering thermal comfort for all requires integrated efforts to passively reduce heat gain by cities and buildings, and then to improve efficiency and responsiveness of mechanical cooling devices.

Full case study informing this Practical Action:

India: cooling efficiency standards

What are the benefits?

- **Cost:** Improving real-world efficiency of air conditioners can halve energy costs for owners.
- **Grid:** Air conditioners designed and optimized for real-world conditions have lower peak power draw. It's possible to lower a building's peak demand by up to 50%, reducing required investments in capacity-constrained areas.
- **Health:** Increasing accessibility of mechanical cooling is essential to reducing heat risks and mortality as temperatures rise.

India

Efficiency standards shift AC market

- **Context:** India's Bureau of Energy Efficiency (BEE) has steadily improved efficiency ratings for air conditioners to remove less efficient products.

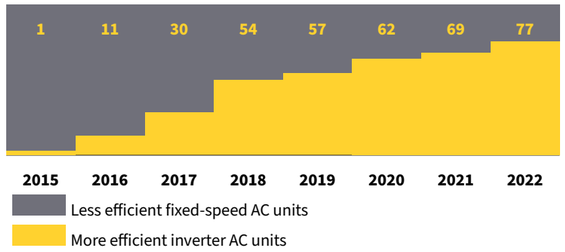
  India's Department of Science and Technology co-led the Global Cooling Prize to demonstrate room ACs with 80% lower climate impact.

  BEE labeling helped more-efficient inverter ACs grow from <1% to 77% of the market (2015–23).

- **Outcome:** Manufacturers engaged to develop next-gen air conditioners.

More efficient inverter ACs have grown to dominate the Indian market in less than 10 years

Percentage share of air conditioners



Source: India Press Information Bureau

Practical steps for leaders

- **Ratchet minimum efficiency standards** to eliminate the worst-performing products.
- **Evolve standards and offer market incentives** to support production and adoption of higher efficiency products that reduce total electricity demand on the grid.
- **Work with buyers and manufacturers** to expedite product development timelines and build market confidence in next-gen products.
- **Create public awareness of the benefits** of efficient cooling and flexible demand.

Further reading

- Global Cooling Initiative – RMI
- Tackling the World's Surging Cooling Demand - RMI
- Leveraging automated demand response to accelerate the clean energy transition - International Growth Centre

Modernize

4.

Encourage vehicle electrification

Educate consumers on the real costs and benefits of EVs versus gasoline and diesel vehicles and reduce up-front adoption barriers by streamlining financing and charging

2/3-wheelers offer an early path to EV scale: their smaller form factor makes them more efficient, cheaper to run, and easier to charge than 4-wheeled EVs. 4-wheeled EVs are also rapidly improving and are already cost competitive with gasoline-powered vehicles in many markets.

Full case study informing this Practical Action:

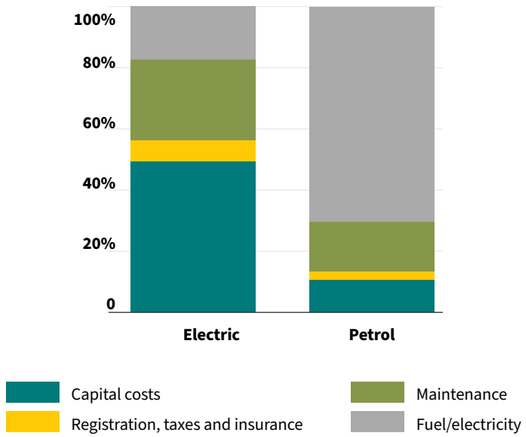
India: 2- and 3-wheeler electrification

What are the benefits?

- **Cost:** Electric 2- and 3-wheelers deliver major lifetime fuel and maintenance savings for consumers relative to gas vehicles.
- **Speed:** Electric 2/3Ws are scaling quickly because of their cost advantage, lower up-front costs, and quicker turnover compared to 4Ws.
- **Reducing risk:** Electrifying 2/3W fleets lowers a country's oil exposure and cushions price shocks for drivers.

Electric two-wheelers shift lifetime costs from fuel to the up-front purchase

Share of total cost of ownership, at 100 km/day



Source: RMI, ICCT*

* Total cost of ownership calculations by RMI using representative Indian data and 100 km/day vehicle utilization.

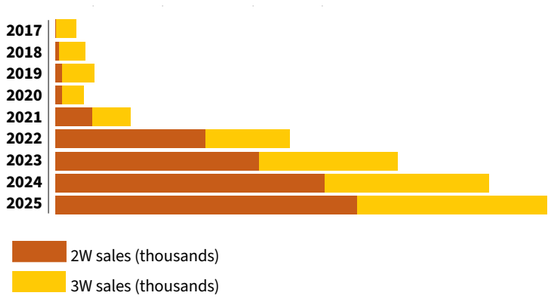
India

Subsidies and tax cuts drive 2/3W EV adoption

- **Context:** India has become the world's largest electric 3-wheeler (E3W) market and second-largest electric 2-wheeler (E2W) market, with comprehensive policy support to subsidize up-front costs, lower goods and services taxation, build charging infrastructure, and incentivize domestic manufacturing.
- **Outcome:** E3Ws account for more than two-thirds of the total 3W market, and E2W adoption is rising, creating a growing demand base for charging, and sheltering millions of drivers from higher oil prices.

2W/3W sales in India, 2017-2025

Vehicles in thousands



Source: RMI, ICCT

Practical steps for leaders

- **Explain the benefits of electric models to consumers,** so people can choose their next purchase considering the costs and benefits of EVs (e.g., Shoonya campaign).
- **Pair vehicle adoption with charging and financial support** so operators can get vehicle, infrastructure, and tax credits together.
- **Clarify charging rules and make them interoperable** between regions so vehicles can charge more seamlessly both in urban environments and in inter-city travel.

Further readings

- Understanding the Grid Impacts of Electric Vehicle Adoption - RMI
- Electric Vehicles: An Economic and Environmental Win for Developing Countries - World Bank
- Electrifying the future: adapting the EV experience for developing nations - Nickel Institute

Modernize

5.

Make large loads flexible

Tie large-load connection costs and queue priority to grid impact, so loads that commit to reducing demand during critical hours connect faster.

Large-load tariffs — which include special contracts, rates, and service agreements between utilities and large-load customers — are a rapid and flexible tool for bringing new load onto the grid while minimizing the risk to ratepayers. They typically include mechanisms to reduce the risk of either overbuilding the system and ending up with stranded assets or underbuilding the system and facing reliability challenges.

Full case study informing this Practical Action:

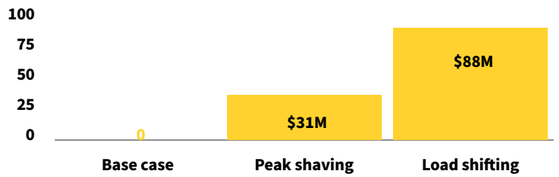
Malaysia: data center growth and strategy

What are the benefits?

- **Cost:** Dynamic cost allocation for large loads (e.g., data centers) recovers grid expansion costs from the customers driving costs rather than residential and small-scale commercial consumers.
- **Speed:** Standardized, pre-approved grid connection terms (e.g., commitment length, advance notice required) replace a slower, case-by-case negotiation-based process, thereby cutting connection timelines.
- **Reducing risk:** Shaping large load demand protects electricity reserves and avoids costly generation overbuild on on the supply side, without negatively affecting overall grid reliability.

System cost savings under different data center flexibility scenarios in Southeast Asia

In US$ millions



Source: RMI

Malaysia

Ultra High Voltage Tariff shapes large load demand

- **Context:** With an anticipated ~26% data center load growth through 2035, Malaysia has instituted an Ultra High Voltage Tariff class to charge cost-reflective rates tied to grid impact; large loads can contract for on-site/off-site renewable generation and treat storage as a bankable asset.
- **Outcome:** The tariff shifted pricing from "activity-based" to "grid-impact-based." The Green Lane Pathway shortened applications from 48 to 12 months, expediting sustainable large load growth.

Grid impact is based on:

- Peak demand contribution (MW)
- Energy consumption
- Load shape/timing
- Required network location
- Flexibility capability

Practical steps for leaders

- **Create a grid impact (e.g., voltage, capacity draw) based cost-framework** to ensure large loads pay for a proportionate part of the grid expansion they cause.
- **Proactively assess how much flexibility is needed**, and include it in resource planning.
- **Standardize flexibility parameters (e.g., notification time, duration, frequency, depth of charge) based on need** so utilities can replicate agreements at scale rather than negotiating custom-made agreements for each large load.
- **Fast-track connections for large loads** that commit to flexibility.

Further reading

- The Importance of Data Center Flexibility in Southeast Asia – RMI
- How Data Centers Can Set the Stage for Larger Loads to Come - RMI
- The billion-dollar case for enabling data center load flexibility - Carbon Direct
- Large Load Tariff Principles - RMI

Balance

6.

Match supply and demand

Incentivize storage to earn and stack revenues from energy shifting and capacity provision.

Full case studies informing this Practical Action:

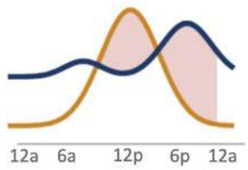
Chile: grid storage boom

Puerto Rico: distributed battery VPP

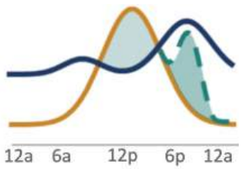
What are the benefits?

- **Decreased balancing costs:** Battery energy storage systems (BESS) combine energy shifting and capacity in a highly flexible resource, with rapidly declining costs improving their competitiveness with thermal alternatives.
- **Speed:** BESS can be deployed more quickly (e.g., 6–18 months) than thermal plants and other new generation assets to meet growing, and often less predictable, peak capacity.
- **Reducing risk:** BESS can shift output in times of peak demand more reliably than hydro or thermal assets that may have more fuel supply and price volatility.

Without BESS



With BESS



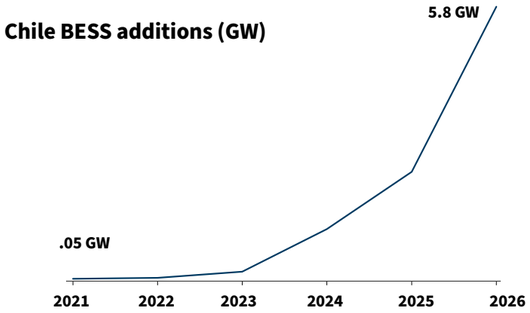
Demand
Solar
Net supply (+BESS)

Chile

Market reforms unlock ~6 GW of BESS and counting

- **Chile's 2022 Storage and Electromobility Law (21.505)** recognized stand-alone storage as a market participant, enabling revenues from energy shifting and capacity provision.
- **Decreto Supremo 70 (2024)** amended the capacity payment framework to credit storage and hybrid systems for resource adequacy, unlocking the capacity revenue stream more predictably.
- **Storage can also provide ancillary services** (e.g., voltage, frequency control) where technically possible, creating additional potential revenue streams.
- **Outcome:** 5.8 GW of BESS is operating or in commissioning — equivalent to ~45% of Chile's peak demand — with another ~5 GW already under construction.

Chile BESS additions (GW)



Source: EMBER

Practical steps for leaders

- **Create dedicated storage compensation mechanisms (e.g., contracts, markets)** for energy shifting, capacity value, and congestion management.
- **Coordinate storage deployment with transmission expansion**, market reforms, and interconnection improvements to maximize system value.
- As storage scales for short-duration flexibility, **market rules should evolve to compensate long duration storage** for multi-day resilience.

Further reading

- Battery Energy Storage Systems as a Resilience Solution – RMI
- Battery storage is scaling up and taking on a larger system role – IEA
- Everything you always wanted to know about battery storage – Agora Energiewende

Balance

7.

Stabilize the grid

Create technology-neutral pathways to procure ancillary services with clear technical standards.

Full case studies informing this Practical Action:

Australia: frequency control ancillary services

Texas: ERCOT reliability improvements in wake of winter storms

Iberian Peninsula: voltage control

China: grid-forming inverters

What are the benefits?

- **Lower ancillary service and system costs:** Opening markets to all capable technologies (including BESS) increases competition; as participation scales, ancillary service prices fall and broader system costs decline.
- **Better reliability:** Faster response to frequency deviations than conventional generators manages disturbances and minimizes system disruption.
- **Enable early deployment of technologies that can meet evolving grid needs:** Ancillary service revenues can support early commercial viability while opening pathways to provide additional services as system needs evolve.



Battery energy storage systems (BESS)



High-voltage direct current (HVDC) converters



Static frequency converters

Australia

Hornsdale BESS delivers first battery-based frequency control ancillary services

- **Context:** South Australia relied on a small pool of conventional generators for locally procured frequency control ancillary services (FCAS), contributing to high and volatile costs. The local FCAS constraint added nearly A$40 million annually in 2016 and 2017.
- **Outcome:** In 2017, the 100 MW Hornsdale Battery was the first FCAS procurement using a technology other than conventional synchronous generation. The Hornsdale BESS asset demonstrated that batteries could provide fast, accurate frequency responses while competing with conventional generators. Improved FCAS has since saved A$116M in system costs and cut procurement costs 90%.

Practical steps for leaders

- **Open ancillary services markets to all technically capable resources** and establish compensation pathways through competitive procurement, obligations, or contracts.
- **Define performance requirements and technical standards** for voltage, inertia, and frequency, to enable providers to compete on their ability to deliver the service needed regardless of their underlying technology.
- **Refine procurement and compensation pathways** to meet emerging system needs, including grid-forming capabilities as they become increasingly valuable.
- **Pilot procurement in areas with known risks** (e.g., high renewables penetration, high outage vulnerability), to demonstrate market value and build regulatory experience.

Further reading

- Procuring and Scaling Grid Flexibility – RMI
- Grid-Forming Inverters for Modern Power Grids – Azo Materials
- The role of grid-forming inverters in enabling high penetration of renewable energy in power systems: standards, ancillary services, current deployment, and future perspectives – Progress in Energy

Balance

8.

Improve grid utilization

Pilot advanced transmission technologies (ATTs) in high-impact grid segments while embedding ATT evaluation into ongoing transmission planning.

Full case studies informing this Practical Action:

Colombia: advanced power flow controls

Bangladesh: reconductoring with advanced materials

United States: dynamic line ratings

What are the benefits?

- **Cost:** Increases transmission capacity at lower cost than new build ($60-70K USD / MW vs $300-600K USD / MW) by increasing efficiency of existing lines; lowers energy costs by fully utilizing assets or minimizing curtailment.
- **Speed:** Technologies are deployable quickly (e.g., 6-18 months), with minimal disruption to existing services; less land, permitting, and construction impact.
- **Reducing risk:** Avoids siting, permitting, and land-acquisition implementation risks that are associated with new infrastructure, while improving visibility of system conditions across geographies.



Dynamic line ratings



Topology optimization



Advanced power flow control



Advanced conductors

Colombia

UPME deploys advanced power flow controls

- **Context:** In the early 2020s, Colombia's Atlántico region faced transmission constraints with more than 1.5 GW of wind and solar projects approved for connection, creating forecast overload risks for several 220-kV circuits.

  Colombia's planning agency, UPME, selected SmartValve, an ATT that mounts directly on transmission lines, to direct electricity flows across the network while avoiding congestion.

- **Outcome:** By evaluating and deploying ATTs alongside traditional transmission expansion planning, UPME was able to defer larger investments and see faster transmission improvements.

12–18 months
Time to deployment

300 MW+
Capacity unlocked

21
SmartValves installed

5
200 kV circuits supported

Source: Smart Wires

Practical steps for leaders

- **Utilize system-wide screening** to identify bottlenecks in existing infrastructure; system operators can then target ATT deployment where it will **yield greatest capacity gains**.
- **Pilot ATTs on small, high-value segments of the network;** smaller substations may clear congestion or queued demand, thereby realizing benefits and building operating experience before wider rollout.
- **Embed the consideration of ATTs into standard utility or grid operator transmission planning processes,** to ensure that these tools are routinely studied and deployed where applicable.

Further reading

- Fast, Efficient Solutions to Meet Electricity Demand Growth – RMI
- Report - Alternative Transmission Technologies Planning Guide – Quanta and RMI
- GETting Interconnected in PJM - RMI

Secure

9.

Make distributed solar a grid resource

Reduce soft costs and implement financially sustainable net-billing rules for distributed solar, keeping connection requirements technology-neutral and encouraging solar + storage.

Full case studies informing this Practical Action:

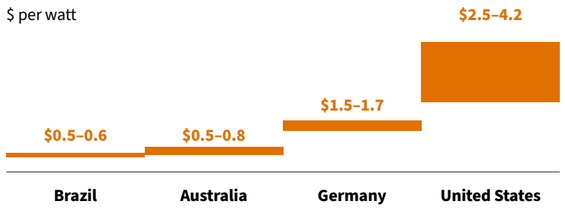
Brazil: distributed solar boom

Southern Australia: reduction in solar soft costs

What are the benefits?

- **Cost:** Solar panel and battery costs have declined 90% in the past decade, making distributed energy on par or cheaper than other sources available to homes and businesses.
- **Speed:** Distributed solar takes weeks or months to deploy versus two to four years for utility-scale generation.
- **Reducing risk:** Distributed solar can add supply resilience during extreme weather (e.g., droughts), supply shocks, and security crises by distributing generation spatially and reducing reliance on depletable inputs (e.g., fuel, water).

Cross-market comparison of installed distributed PV cost per watt



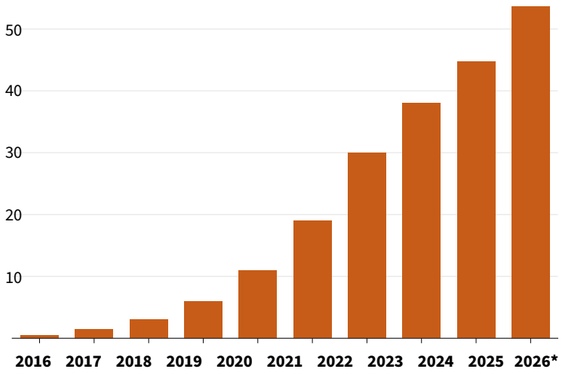
Source: IEA, BN Americas

Brazil

ANEEL's net metering framework scales distributed solar

- **Context:** Following repeated hydro shortages, Brazil diversified its power system. This included unlocking distributed solar by inviting cheap panel imports, incentivizing "prosumers" through predictable net metering incentives that have evolved as the market matured.
- **Outcome:** ~50 GW of distributed solar installed (~23% of Brazil installed capacity), supplying power to ~21M Brazilians as of 2026.

Distributed generation capacity in Brazil (GW)



Note: 2026 data is through June

Source: EIA

Practical steps for leaders

- Maximize customer value through **soft cost reduction** (e.g., South Australia and Brazil solar soft cost reduction).
- **Design compensation to evolve as penetration increases:** early-stage net metering can accelerate adoption at first and can be accompanied by appropriate allocation of grid costs over time.
- **Keep interconnection rules technology-neutral;** define the performance requirement, not the technology (e.g., GB NESO interconnection queue reform).
- **Promote solar-plus-battery systems** to manage fluctuations and maximize resilience (e.g., Chile BESS installations).

Further reading

- Utility-Enabled Distributed Energy Resources Hub – RMI
- From Sun to Roof to Grid – ESMAP
- Smart Rate Design for DERs – RAP

Secure

10.

Level the playing field

Run all-source, technology-neutral procurement competitions with independent evaluations that weigh resilience and fuel-price risk in addition to cost.

Full case studies informing this Practical Action:

South Africa: all-source procurement closes supply gaps

Kenya: opened the door to geothermal by de-risking exploration, enabling competitively selected IPPs to supply clean firm power at ~$0.07/kWh

What are the benefits?

- **Cost:** All-source, technology-neutral competition drives down cost through real-time bid pricing and reduction of fuel price volatility.
- **Reducing risk:** Evaluating the range of supply and demand-side resources may reduce cost and improve grid flexibility by not relying on one technology or ownership structure; all-source procurement allows the system operator to identify the critical grid needs more quickly.
- **Speed:** Open power procurement prioritizes the fastest-to-deploy generation assets, thereby building a cost-competitive electricity portfolio more quickly.

Approach and objectives

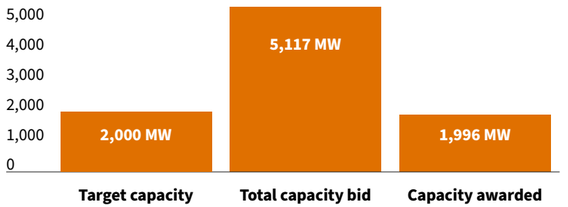
Narrow procurement	Open procurement
Thermal assets only	Renewable, hybrid, storage, demand flex, and thermal assets
Concentrates fuel and implementation risk in a few generation types	Distributes risk across multiple technologies

South Africa

DMRA's RMIPPPP attracts diverse resources

- **Context:** South Africa was facing an urgent power supply gap coupled with a reliance on costly thermal peaker plants. As a result, in 2020, South Africa launched the regions first tech-agnostic performance-based tender process (South Africa's Risk Mitigation IPP Procurement Program, RMIPPPP).
- **Outcome:** The tender attracted 28 bids (~5,100 MW) which was 2.5x the required 2,000 MW; 11 projects were chosen across gas, BESS, wind, and solar to meet the procurement capacity. Though some projects were later abandoned, the urgent supply gap was partially addressed, and no one project bore full liability, thereby diversifying risk across energy sources.

RMIPPPP funnel: target vs. bids received vs. capacity awarded



Source: Renewable News

Practical steps for leaders

- **Require system operators to make procurement decisions tied to integrated planning outcomes** and based on grid service needs (e.g., capacity, flexibility, resilience) rather than specific technologies; this can allow storage and distributed energy to compete.
- **Mandate independent evaluators or regulatory oversight** to ensure that regulators are weighing public interest goals (e.g., grid resilience) with state targets.
- **Require system operators to factor in long-term risks of fuel volatility** when comparing options to arrive at lifetime procurement risk/value.
- For uncertain grid needs, consider **thresholds** (e.g., load commitment stage gates for large loads) **that will necessitate a new procurement cycle**; support choosing resources that can be easily scaled up/down or repurposed to provide other grid services.

Further reading

- All-Source Procurement, Electricity Affordability Toolkit – RMI
- All-Source Competitive Solicitations: State and Electric Utility Practices – Berkeley Lab

Conclusion

Next steps for extremely busy leaders

How to use this report in your work this year

In this document

This report provides a starting point

Understand the trends driving energy strategy and outcomes

Define shared challenges across the sector, and map solutions to them

Learn practical actions leaders and their teams can explore

Take action

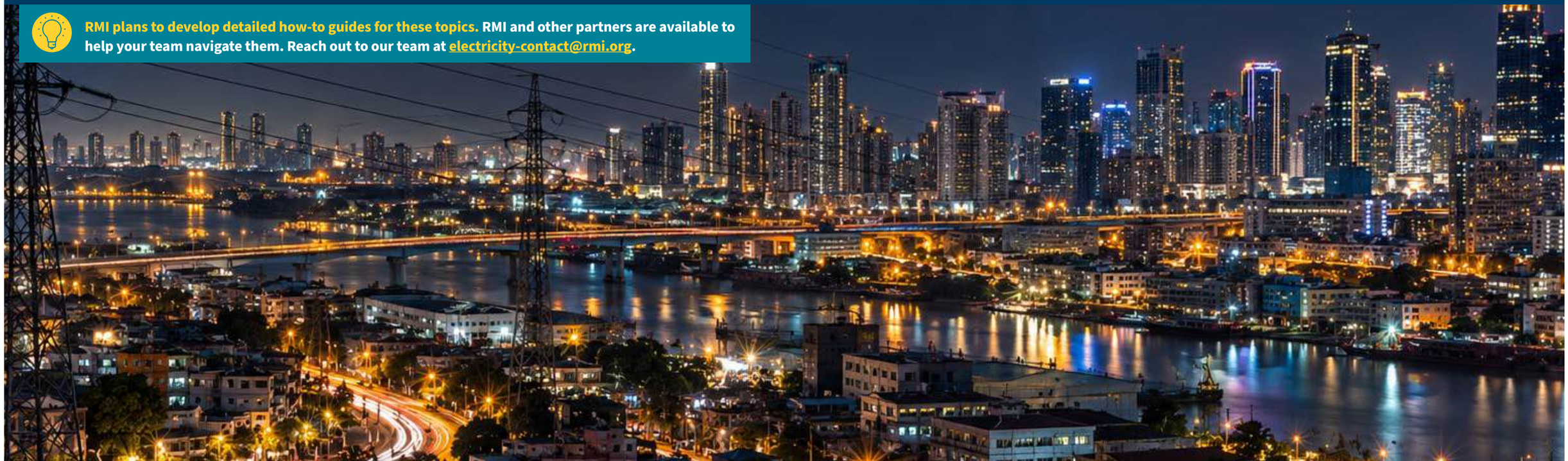
Next steps can include

1. Identify the Practical Action that addresses the problem you are solving

2. Make it somebody's job to act on applying this solution in your context

3. Build on the experience of global peers to move fast

RMI plans to develop detailed how-to guides for these topics. RMI and other partners are available to help your team navigate them. Reach out to our team at electricity-contact@rmi.org.



Appendix:
Case studies

Case study table of contents

Action area	Practical Action	Country or region	Case study
 **Plan** Design plans, procurements, and queues for uncertainty	**1. Plan for uncertainty**	Ghana	Ghana's Energy Commission built a "least-regrets" power system plan by stress-testing portfolios across futures, weighing multiple performance criteria, and validating results with stakeholders
		Morocco	To strengthen green industrial development and investment, the government designated Moroccan Agency for Sustainable Energy as the focal point for the Morocco Offer for Green Hydrogen
		Western Australia	Energy Policy WA is coordinating common-use transmission planning across fragmented grids serving mines and industry in the Pilbara
	2. Clear queues and improve forecasts	Great Britain	Power system reforms cleared connection bottlenecks and brought low-cost demand flexibility online
 **Modernize** Electrify efficient, responsive loads	**3. Scale efficient cooling**	India	The Bureau of Energy Efficiency propelled efficiencies in AC units while the government engaged with manufacturers to start building the next generation of efficient room air conditioners (RACs)
	4. Encourage vehicle electrification	India	PM E-DRIVE Scheme has helped India become a global leader in electrifying 2/3-wheel vehicles, through subsidies, domestic manufacturing, and charging infrastructure rollout
	5. Make large loads flexible	Malaysia	YTL Green Data Center Park is scaling AI infrastructure by co-locating data centers with renewable generation and regional connectivity
 **Balance** Deliver reliable power when and where it is needed	**6. Match supply and demand**	Chile	A 15-year sequence of market reforms and investments unlocked abundant renewable energy; today, surging BESS is helping the grid make the most of these resources
		Puerto Rico	LUMA is improving grid reliability for all customers by coordinating more than 100,000 distributed batteries through a virtual power plant (VPP)
	7. Stabilize the grid	Australia	Hornsdale BESS cut Frequency Control Ancillary Services (FCAS) costs while strengthening grid reliability
		Texas	ERCOT rebounded from winter storm outages through new reliability products as solar, wind and battery storage scaled rapidly
		Iberian Peninsula	ENTSO-E turned a catastrophic blackout into a blueprint for planning and operating a renewables-heavy grid
		China	CHN Energy's Ningdong project shows how grid-forming storage can help remote renewable bases operate reliably and support power exports
	8. Improve grid utilization	Colombia	Advanced power flow controllers unlocked more than 300 MW of transmission capacity on the grid
		Bangladesh	The PGCB doubled transmission capacity on an existing 132-kV line using advanced conductors on existing towers and rights-of way
		United States	AES found that dynamic line ratings (DLRs) could boost capacity of a 345-kV line by 43%, using sensors installable in less than two weeks
 **Secure** Build low-cost, low-risk generation portfolios	**9. Make distributed solar a grid resource**	Brazil	Policymakers drove a two-track solar boom across utility and distributed markets, benefiting 8M consumer units and diversifying a hydro-heavy grid
		Southern Australia	Households enjoy three free hours of midday power, supported by affordable solar installed on 40% of homes countrywide
	10. Level the playing field	South Africa	All-source procurement brought diverse technologies to the table; renewable-storage hybrids ultimately delivered power as gas projects stalled
		Kenya	Public investment in geothermal resource exploration and workforce development addressed key market barriers, enabling competitively selected IPPs to supply clean firm power at ~0.07/kWh

PLAN

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Ghana

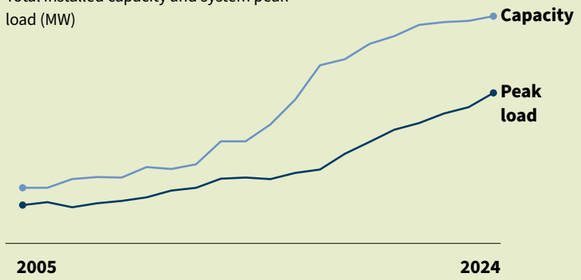
Ghana's Energy Commission built a "least-regrets" power system plan by stress-testing portfolios across uncertain futures, weighing multiple performance criteria, and validating results with key sector stakeholders.

Results

Context: Over the past decade, thermal plants generated 60% of Ghana's electricity, and hydropower accounted for nearly all the rest. Both resources presented challenges to system planners and operators. Hydro resources faced hydrological and climate risk, and the Akosombo reservoir was at times drawn below its minimum operating level. From 2016 to 2022, installed capacity exceeded system peak demand by roughly 60%–100%. By 2020, the government reported paying more than US$500M per year in excess-capacity payments for power it did not use. Ghana's Energy Commission and cross-sector partners responded by developing a "least-regrets" framework to mitigate these challenges and choose a more resilient portfolio.

Ghana's electricity capacity has exceeded demand over the past 20 years

Total installed capacity and system peak load (MW)



Case learnings:

- **Testing a plan against multiple scenarios is critical:** Ghana's Energy Commission evaluated five potential strategies against six performance metrics (e.g., cost, reliability, resilience, environment, land use, and climate) and various assumptions on gas supply, water availability, and fuel costs. The Commission did not pick a plan optimized for a single fuel cost.

- **Collaborative planning processes span institutional siloes:** The IPSMP process engages distribution utilities, the grid operator, regulators, generators, and fuel suppliers to set up and validate the plan.

Key takeaway: Intentional scenario planning while weighing diverse conditions allowed Ghana to pick a resilient power plan that maximizes financial and system stability.

How they did it

1. **Build plans based on comprehensive system-wide needs assessments:** Rather than making the scenario plan based on a non-contextualized view, Ghana's Energy Commission developed a plan in response to historical challenges including supply shortages, fuel constraints, and capacity overpayment.

2. **Weigh strategies on diverse metrics, not just cost:** Ghana's Energy Commission weighed various strategies based on cost, reliability, resilience, environment, land use, and climate, not just based on cost; the tradeoffs across multiple metrics were visible before selection, not just after construction.

3. **Pair diverse generation with storage:** The chosen plan combined renewables, battery storage, and select combined cycle gas plants so that the variable renewable energy output could be firmed up without over-building thermal capacity.

"The importance of coordinated, evidence-based planning cannot be overstated."

- **Adwoa Serwaa Bondzie,**
Acting Executive Secretary, Energy Commission, Ghana (2026)



Sources: Climate Policy Radar, Modern Ghana, GCB Bank, Climate Policy Lab, Richmond University, AB David, RMI, Science Direct

PLAN

Case study table of contents

Morocco

Building on renewable energy to strengthen green industrial development and investment, the Moroccan government designated Moroccan Agency for Sustainable Energy as the focal point for the Morocco Offer for Green Hydrogen.

Results

Context: Morocco has historically imported about 90% of its energy, but the country's plentiful wind and solar resources offered an opportunity to rebuild the economy around generating and using renewable energy. Starting with the 2009 National Energy Strategy, the government has set and sustained this reorientation as a national priority. "

Case learnings:

- **Redirecting fossil fuel subsidies into renewables can rapidly build capacity:** Renewables represented 46% of Morocco's 12.2 GW of installed electricity capacity at the end of 2025. Six green hydrogen projects have been selected under Morocco's green hydrogen strategy, the "Morocco Offer," representing ~$32B in investment.
- **Clean energy can anchor an entirely new industrial export base: :** Morocco's national Green Hydrogen Roadmap projects up to 230 TWh per year of green hydrogen and hydrogen-derived exports by 2050.
- **Morocco's green hydrogen framework incorporates socioeconomic benefits** in project evaluation, aiming to create jobs through integrating local industries, supporting regional development, and generating financial returns for the state.

46%
of 2025 electricity capacity is renewable

$32B
in green hydrogen investment to date

Key takeaway: Intentional subsidy reform and industrial policy turned Morocco's energy liability into a green export platform.

Sources: The Global Economy, World Economic Forum, AENERT, World Bank, IEA, IRENA, World Resources Institute, Green Hydrogen Organization, World Bank, Reuters, Net Zero Circle, Market Screener, Africa Energy Portal, North Africa Post, MASEN, Morocco Head of Government Circular N. 03/2024.

How they did it

1. **Set ambitious national targets and redirected fossil fuel subsidies:** Morocco's National Energy Strategy targeted 52% renewables by 2030 and redirected the 5% of GDP previously spent on fossil subsidies into renewable investment.
2. **Planned generation and grid buildout around future demand:** Morocco's strategy was sized against forecast industrial and export (e.g., hydrogen, EV batteries) demand; aligning renewables, land allocation, and transmission buildout with future load.
3. **Established a coordinated investor framework, with one focal point:** MASEN serves as a one-stop-shop for stakeholders, streamlining approvals and reducing execution risk for developers.
4. **Allocated land at scale for integrated green industrial projects:** The Morocco Offer allocated one million hectares for integrated green hydrogen projects spanning generation, electrolysis, and ammonia production, with a structured investor selection and contracting process, supported by an incentive framework.
5. **Aligned domestic regulation with major export market standards:** Aligning renewable energy production rules with the EU's Carbon Border Adjustment Mechanism (CBAM) guarantees the validity of Morocco's renewables credits internationally and protects export competitiveness.

"**The energy transition is a matter of energy sovereignty in Morocco.** It's a matter of economic resilience. And it's a matter of long-term industrial competitiveness. The idea is not to replace one dependency with another."



- Firdaous El Ghazi,
Director of Contract Management, Green Hydrogen, Moroccan Agency for Sustainable Energy (MASEN)

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Great Britain

Power system reforms cleared connection bottlenecks and brought low-cost demand flexibility online.

Results

Context: Many of Great Britain's grid planning, connection, and balancing processes were designed for a more centralized power system and struggled to keep pace with rapid renewable deployment. Growing wind capacity revealed structural weaknesses in connection, ancillary services procurement, and demand flexibility infrastructure. Additionally, Great Britain faced queue times of up to 10 years with a >770 GW pipeline of projects that were not located where there was capacity for offtake or expected need for growth. From 2023, government, Office of Gas and Electricity Markets (Ofgem), and the system operator launched a series of interrelated reforms to address these problems.

Case learnings:

- **Grid reform can eliminate speculative backlogs and redirect capital to strategic projects:** Great Britain cut its connection queue from >700 GW to a 283 GW pipeline with ~130 GW clean power prioritized for 2030.
- **Demand flexibility can displace expensive thermal balancing at scale:** Two million households shifted 4 GWh across 44 events in winter 2024/2025, saving consumers nearly £500K in balancing costs.
- **Without continued action, gains remain fragile:** Total balancing costs still rose 10% to £2.7B in 2025, driven by thermal constraints and limited transmission upgrades; smart dispatch savings alone are insufficient without transmission buildout

Key takeaway: Queue reform redirected capital to viable clean projects, but congestion costs confirm transmission is the next frontier for change.

How they did it

1. **Created an independent system operator:** Energy Act 2023 separated planning decisions from commercial interests to enable unbiased grid modeling, connection sequencing, and planning.
2. **Overhauled connection queue design:** Shifted from "first-come, first-served" to "first ready and needed, first-connected" so shovel-ready clean projects are no longer stalled by speculative backlog.
3. **De-risked long-duration storage investment:** A cap-and-floor mechanism ensures investors receive a minimum amount of revenue to enable LDES investment, and while returning revenues above a cap to consumers.
4. **Made demand flexibility a permanent year-round tool:** Transitioned emergency winter Demand Flexibility Service (e.g., dynamic EVs, heat pumps, industrial loads) into a continuous balancing resource that pays households and businesses to shift electricity use when the grid needs it.
5. **Built smart metering and half-hourly settlement infrastructure:** Forty million smart meters and an ongoing shift to 30-minute interval settlement unlock time-of-use tariffs and allow residential demand to flex toward wider stability goals.

"The government was involved in engagement and development of new proposals and provided their signaling that this is something that they wanted; they had to do this without undermining investment confidence."



- Neil Copeland,
Connections Strategy Manager, NESO

Sources: Clean Growth Fund, Cambridge Center for Computational Chemical Engineering, Reuters, Ofgem, Science Direct, GT Law, Data Center Dynamics, Electron News, Sources: Government of the United Kingdom, Science Direct, NESO, USwitch

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Western Australia

Energy Policy WA is coordinating common-use transmission planning across fragmented grids serving mines and industry in the Pilbara.

Results

Context: The Pilbara mining region does not have a traditional centralized grid. Instead, the electricity infrastructure grew around individual mines and industrial facilities, creating a patchwork of separately-owned grids. Today, the North West Interconnected System (NWIS) serves around 20% of Pilbara's electricity consumption, but it is comprised of several loosely connected networks owned and operated by separate parties. Energy Policy WA (EPWA) began convening industry stakeholders in 2022 to coordinate improvements to this infrastructure.

Case learnings:

- **Inclusive planning processes have delivered a shared plan toward common goals:** The Pilbara Energy Transition Plan identifies four strategic transmission corridors that can connect industrial demand with renewable resources, and has selected proponents to advance each of them.
- **Common-user transmission infrastructure (CUTI) holds promise for coordinated development that cuts costs:** Modeling by Marsden Jacob Associates shows that shared transmission infrastructure can serve the same modeled load at about A$30B lower system cost through 2050 than a go-it-alone approach with more duplicated transmission, generation, and storage.
- **Clear infrastructure plans help drive next-gen industrial investments:** The Great Sandy Desert Corridor will link the Boodarie Strategic Industrial Area with high-quality renewable resources, aiming to grow the emerging green iron industry in the zone.

A$30B
avoided costs by 2050 by sharing transmission infrastructure

A$3B
pledged government support

Key takeaway: Coordinating common-use transmission across the Pilbara's fragmented grids could cut system costs by about A$30B through 2050 and unlock green industrial investment.

How they did it

1. **Used a consultative process to create a roadmap to address the region's complex electricity infrastructure challenges:** EPWA convened the Pilbara Roundtable in 2022 to build consensus on transmission and renewable buildout, regulatory reform, and load growth from electrification of mining and new industries. Participants ranged from government, to industry, to Traditional Owners.

2. **Modeled load growth, generation expansion, and grid needs together:** EPWA's Pilbara Electricity Transformation Assessment used a spatially explicit least-cost model to identify transmission needs between generation and load centers. Subsequent wholesale electricity market modeling tested the Pilbara Networks Rules against future scenarios with changing capacity mix.

3. **Aligned transmission investments with planned generation and industrial use from private players:** The PET Plan established priority corridors and selected private proponents to advance them. These projects are eligible for consideration for concessional financing. In parallel, major mining players such as Fortescue, Rio Tinto, and BHP are developing or contracting energy generation and storage (e.g., Fortescue's 1.5 GW solar, 900 MW wind, 4-5 GWh battery Pilbara Green Grid project), and new industrial plants such as the 2 Mtpa Port Hedland Iron HBI project at Boodarie are being designed around access to third-party power.

"There's a massive opportunity for Western Australia ... via the right levers, **there is an opportunity to fundamentally transform Western Australia to be an energy and industrial superpower**, transitioning existing industries and growing out new export-oriented industries."

– Matt Judkins,
Lead Partner, Deloitte Energy and Climate



Sources: Energy Matters, Power Magazine, Clean Energy Finance Corporation, Woodside, Rio Tinto Website, Mining Technology, Discovery Alert, Superpower Institute, Institute for Energy Economics and Financial Analysis, PV Tech, Mining Weekly, Renew Economy, World Economic Forum, PV Magazine

MODERNIZE

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India

The Bureau of Energy Efficiency (BEE) propelled efficiencies in AC units in India while the government engaged with manufacturers to start building the next generation of efficient room air conditioners (RACs).

Results

Context: India's cooling demand is projected to grow eightfold between 2017–18 and 2037–38. Cooling already accounts for slightly more than 10% of annual electricity demand and can reach one-third of consumption on hot summer nights. The India Cooling Action Plan calls for "thermal comfort for all," and a whole-of-government approach to AC efficiency aims to drive down the energy required to achieve this ambitious goal.

Case learnings:

- **Effective policy can help boost adoption of more efficient technologies:** The Bureau of Energy Efficiency (BEE) used standards and labeling to boost adoption of more efficient inverter-based RACs, driving their market share from <1% in 2015 to 77% in 2023.
- **Benefits from efficiency span across cost savings, grid stability, and health:** While efficient RAC systems have lowered costs to customers, this efficiency adoption has also reduced peak demand. More efficient RAC units have also become more affordable to access, essential in a nation that experienced 536 heatwave days in the summer of 2024.
- **Working with manufacturers can provide a path forward:** Next generation RAC units have demonstrated the ability for RACs to have 80% lower climate impact and a 75% reduction in electricity use by meeting both humidity and temperature needs rather than temperature alone.

<1% to 77%
Market-share increase of efficient, inverter-based RAC units in 8 years

100,000
RAC technicians trained and certified

80%
Lower climate impact demonstrated by the Global Cooling Prize

Key takeaway: More efficient AC systems with effective policy and deployment strategies reduce customer costs, grid stress, and relieve heat-related health risk.

How they did it

1. **Set and ratchet efficiency standards on all RACs:** The BEE steadily increased efficiency standards from 2009 to 2022. Efficiency improved 43% and 61% for their one-star and five-star RACs, respectively. A voluntary labeling system for inverter ACs launched in 2015 and became mandatory in 2018.
2. **Equipped installers/technicians with resources to limit refrigerant leak:** The government launched a program to train and provide resources to 100,000 RAC service technicians. India's Cooling Action Plan made this training part of their strategy acknowledging the importance of proper installation and maintenance.
3. **Expanded access and affordability of RAC units:** EESL, a government-backed energy service company, used bulk procurement to lower the up-front cost of efficient ACs.
4. **Worked with manufacturers to continue efficiency innovation:** The Government of India co-led the Global Cooling Prize, where monetary prizes fostered a space to identify how to meet their specific cooling needs in the most efficient way possible, namely a combination of temperature and humidity control.

"Taking that first step of advancing controls by making your air conditioner better respond to both temperature and humidity can instantly deliver 15% to 20% savings right off the bat. I feel confident that could happen in a matter of a couple of years."



- **Ankit Kalanki,**
RMI, Volts Podcast: "How to keep people cool without making the planet even hotter"

Sources: PIB, IMPRI India, Clasp, Volts, The Indian Express, Global Cooling Prize, IEA

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India

Prime Minister Electric Drive Revolution in Innovative Vehicle Enhancement (PM E-DRIVE) Scheme has helped India become a global leader in electrifying 2/3-wheel vehicles, through subsidies, domestic manufacturing, and charging infrastructure rollout.

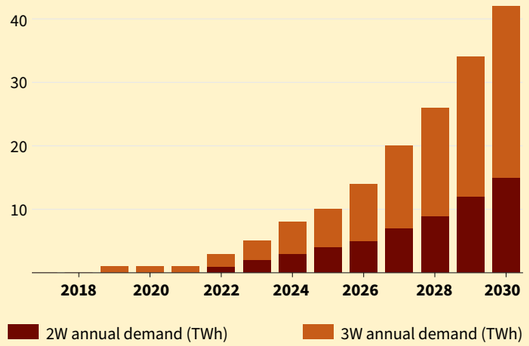
Results

Context: More than 80% of vehicles on the road in India have two or three wheels. Electric 3-wheelers (E3Ws) account for nearly two-thirds of the total 3W market, and 2W adoption is rising — electric 2-wheeler (E2W) registrations are up ~60% YoY in 2026. India is faced with scaling the charging infrastructure and grid capacity to support a boom in electric 2/3W sales.

Case learnings:

- **Electrification unlocks major cost savings for drivers:** Switching to an electric 2W saves consumers 5–6 lakh INR (~$5,700) over the vehicle's lifetime, driven primarily by fuel savings. Switching to an electric 3W saves consumers 4–5 lakh INR (~$4,700) driven by savings in capital costs and fuel.
- **Electrification drives emissions reductions:** Electrification of 2/3Ws eliminates tailpipe emissions, with special air quality benefits in dense urban centers such as New Delhi, where 2/3Ws account for ~50% of road transport's contribution to fine particulate matter (PM2.5) pollution during the post-monsoon season".
- **Grid load from EV charging can grow quickly:** 2/3W charging demand has grown 50x in the past 10 years and will likely quadruple between 2025 and 2030.

Historic and projected annual demand from 2/3W charging (TWh)



Key takeaway: Electrification of small vehicles can yield significant lifetime savings for consumers, driving both economic and environmental benefits.

Sources: RMI, ICCT, Clean Mobility Shift, Mongo et al. (2003) and FADA

How they did it

1. **Used policy to close up-front capital cost disparity:** FAME and PM E-DRIVE schemes provided up-front subsidies for purchasing electric 2/3W vehicles; coupled with state and city purchasing incentives, customers see a 30%-50% up-front cost reduction.
2. **Deployed charging infrastructure via public-private partnerships:** A Delhi program offered public land and electrical infrastructure on concessional terms and competitively selected charging operators based on lowest service charge to EV users. The tender awarded 100 charging sites comprising ~900 charging points. Kerala State Electricity Board Limited (KSEB) has installed ~1,100 pole-mounted chargers (a recent report implies ~70% of the state's total) on its own distribution poles to maximize efficient rollout of charging infrastructure.
3. **Grew domestic manufacturing:** India has Production Linked Incentive Schemes to promote domestic manufacturing of batteries and vehicles (e.g., TVS Motor, Bajaj Auto, Ola Electric); it requires EVs to meet local manufacturing thresholds to qualify for subsidies.
4. **De-risked financing of vehicles:** Banks offer EV loans with similar interest rates as internal combustion engine vehicles. Small Industries Development Bank of India (SIDBI) and Shell Foundation piloted a $6M second-loss facility that supported more than 1,900 EVs and is designed to leverage 13x its capital in commercial lending.

"For people in rural areas, we made these pole-mounted chargers. **With those chargers, these common people would be able to live out their livelihoods easily** without much expenses in going for petrol or diesel vehicles."

– **Director, Generation – Electrical, Civil, REES, SOURA,** Kerala State Electricity Board Ltd. (KSEBL)

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Malaysia

YTL Green Data Center Park is scaling AI infrastructure by co-locating data centers with renewable generation and regional connectivity.

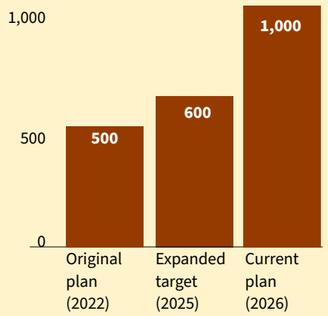
Results

Context: Malaysia's data center boom drove nearly 6 GW of supply agreements with TNB by 2024 and the Johor region has emerged as a hotspot due to its proximity to Singapore, available industrial land, power infrastructure, and international connectivity. An innovative Green Data Center Park in Kulai, developed by YTL Power International, shows how one developer is using a campus approach to phasing large load buildout alongside dedicated renewable generation.

Case learnings:

- **Large-scale data center capacity can be built alongside dedicated renewable generation:** The park originally targeted pairing 500 MW of data center capacity with 500 MW of on-site solar but subsequently announced plans to expand the park to 1 GW.
- **Phased energization enables de-risked operating infrastructure:** The first phase of the park became operational in May 2024, and YTL reported 298 MW of contracted data center capacity by March 2026, with additional phases in development.
- **Data center infrastructure can be designed for flexibility:** YTL's newer Johor facilities incorporate thermal buffer storage alongside chilled-water systems and direct-to-chip liquid cooling, creating the potential to decouple cooling-system operation from instantaneous IT load and manage power demand.

YTL Green Data Center Park planning (in MW)



Key takeaway: Integrated campus planning may smooth the accommodation of new compute demand by coordinating new phases of data center load with power supply, and load flexibility provided by a portfolio of loads and dynamic cooling.

How they did it

1. **Developed the campus around existing infrastructure**: The Kulai site is strategically located near Singapore, with access to national-grid power, water resources, major transport infrastructure, and industrially zoned land. The campus has dedicated dark-fiber connectivity as well, providing low-latency connections to regional digital hubs.
2. **Phased construction:** YTL brought in major customers early, including Sea Limited, which anchored the first phase, and GDS, which agreed to co-develop 168 MW across eight facilities. Subsequent phases have been contracted, enabling staged expansion and construction that reduces risk of infrastructure overbuild.
3. **Designed flexibility into campus facilities:** The campus is structured as a portfolio of data center buildings, providing a larger pool of cooling, electrical, and compute loads that can be coordinated across the campus as operating needs change.
4. **Developed data center load and dedicated generation in parallel:** By developing the campus and associated solar generation within one multi-infrastructure business model, YTL can naturally coordinate power and data-center construction and operation.

"We are driving the expansion of our infrastructure platform to the digital age by **combining our expertise in renewable energy, property development, telecommunications and data centers**."

– **Managing Director,**
YTL Power International

Sources: YTL, MIDA, GDS, Data Center Dynamics

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Chile

A 15-year sequence of market reforms and investments unlocked abundant renewable energy; today, surging BESS is helping the grid make the most of these resources.

Results

Context: Chile's historic dependence on imported fossil fuels coupled with high electricity prices made energy security and affordability urgent national priorities. Yet their exceptional Atacama solar and Patagonian wind resources were far from load centers and investors were not developing them at scale. Regulators made it easier for renewables to compete in power markets and established strategic transmission corridors to bring this power to load centers. Today's challenge is making that abundant renewable power available when and where the grid needs it. Recent reforms enable storage to provide multiple services: shifting bulk power across hours, supporting grid stability, and contributing to capacity reserves.

Case learnings:

- **Renewables can scale to high penetration rapidly:** they now supply roughly two-thirds of Chile's electricity, with solar and wind alone reaching a record 38% in 2025.
- **BESS can scale rapidly:** Chile went from 0.5 GW of BESS capacity in 2023 to 5.8 GW of BESS operating or in commissioning in mid-2026, with another ~5 GW already under construction.
- **Storage can put wind and solar to work:** Ember estimates that in 2025, batteries prevented roughly 2 TWh of wind and solar curtailment. But storage and transmission still lag the renewables buildout: an estimated $562M in renewables revenues has been lost to curtailment since 2022.

Key takeaway: Intentional reform led to the rapid scaling of solar, wind, and BESS from negligible shares in 2012 to major grid contributors today.

How they did it

- **Improved renewable bankability:** Reforms established 20-year PPAs, lengthened development lead times, improved predictability of auctions, and attracted new entrants and private capital.
- **Built transmission links:** Law 20.936 (2016) overhauled transmission planning, and the 2017 interconnection of Chile's northern and central systems allowed low-cost resources in the north to serve central demand centers.
- **Redesigned auctions so new technologies could compete:** Longer contracts, longer lead times, and time-based supply blocks allowed wind and solar to compete effectively; average awarded prices fell from $129/MWh in 2013 to ~$33/MWh in 2017.
- **Created ancillary services markets:** Competitive procurements formalized compensation for frequency response, black start, and other grid services, creating additional revenue opportunities for storage.
- **Recognized storage's energy and capacity value:** Law 21.505 (2022) enabled stand-alone storage to participate in electricity markets; 2024 rules established how storage receives credit for resource adequacy, opening a capacity revenue stream.

"If the objective is to ensure fair competition and to truly allow technologies to compete on their own merits, **there is absolutely no doubt that renewables will come out on top.**"



– **Andrés Romero**,
former Executive Secretary, National Energy Commission Chile

Sources: IEA, ENEL, World Bank, AMI, Coordinador Electrico Nacional, IEA, PV Magazine, Latercera, EMBER, Global Energy Monitor, EIA, Wood Mackenzie, BNEF

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Puerto Rico

LUMA is improving grid reliability for all customers by coordinating more than 100,000 distributed batteries through a virtual power plant (VPP).

Results

Context: Puerto Rico's electric system has faced persistent grid reliability challenges and generation shortfalls, exacerbated by the devastating impacts of Hurricanes Irma and Maria. In response, households and businesses across the island have adopted solar-plus-storage systems to improve resilience during outages. Puerto Rico's grid operator, LUMA Energy, has worked with regulators and industry stakeholders to use this growing fleet of distributed energy resources (DERs) to strengthen the grid and improve overall reliability.

Case learnings:

- **VPPs can deliver at scale:** Puerto Rico's Customer Battery Energy Sharing Program (CBES) has scaled to more than 110,000 participants and over 580 MW of enrolled battery capacity as of July 2026.
- **Utilities can consistently leverage VPPs to reduce blackout risk in island communities:** On 18 days during July and August 2025, LUMA's reserve logs showed that without the ~40–48 MW injection from CBES, the system's operating reserves would have dropped below the 200 MW critical floor. By keeping reserves above this level, CBES helped LUMA reduce the risk of "automatic under-frequency" trips that can lead to wider outages.
- **VPPs can deliver customer affordability benefits while preserving household energy resilience:** LUMA paid an estimated $11 million in participant incentives to aggregators, approximately $9 million of which was passed through to customers. At the same time, enrolled customers allowed an average of 27% of their battery's capacity to be available for CBES events, preserving approximately 73% of their capacity to be used for their own home or business.

110,000+
Participants in Puerto Rico's Customer Battery Energy Sharing Program

~600 MW
Enrolled capacity

$9 million
Paid to customers

How they did it

1. **Built trust through customer-first design:** Since CBES launched, participating aggregators have implemented inclusive customer engagement strategies including bilingual outreach, step-by-step enrollment videos, and dedicated customer support to help customers understand the program and navigate the enrollment process.
2. **Designed VPPs for iteration and regulatory evolution:** LUMA has continued to refine CBES enrollment pathways, capacity increases, incentives, and dispatch structures in partnership with aggregators and regulators to improve reliability and program effectiveness over time.
3. **Partnered with OEMs and aggregators to reduce utility burden.** Third parties have helped to enable the VPP market by reducing barriers to solar-plus-storage adoption through accessible financing, building local installer networks, offering flexible compensation structures, coordinating distributed batteries, and fostering customer trust.
4. **Leveraged auto-enrollment to scale participation:** CBES allows eligible customers to be automatically enrolled through participating aggregators while retaining the ability to opt out of events, reducing enrollment friction and creating a pathway for more customer-sited batteries to participate in the program.

"Home solar and storage's growth across Puerto Rico was born out of **necessity to provide families resilience and peace of mind in a post-Hurricane Maria world.**"

– **Chip Silverman**,
Director, Grid Services & Electrification, Sunrun



Sources: Interview with LUMA Energy, July 2026, Interview with Tesla, June 2026, FY2026 Q4 Consolidated Transition Period Plan and Demand Response Administrative Costs Quarterly Report, August 14, 2026, Photo courtesy of Sunrun

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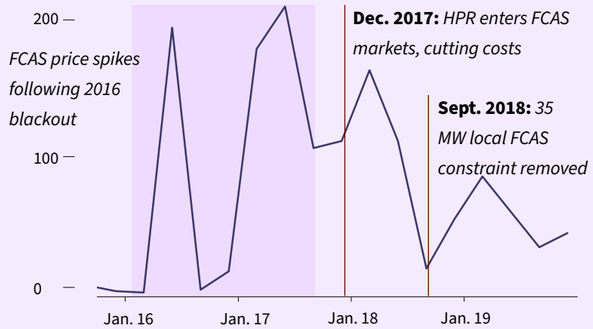
Australia

Hornsdale BESS cut Frequency Control Ancillary Services (FCAS) costs while strengthening grid reliability.

Results

Context: As conventional generators in South Australia's Frequency Control Ancillary Services (FCAS) market retired, a small pool of generators remained to meet the 35 MW local FCAS requirement when the grid was at risk of islanding. Because the few remaining generators were only able to provide this resource under certain operating conditions, it became especially expensive to procure FCAS. Across Australia's National Electricity Market (NEM), operated by the Australian Energy Market Operator (AEMO), FCAS costs reached A$214 million in 2017. The South Australian government turned to battery storage as one new source of grid services, and the Hornsdale Power Reserve (HPR) began operating in late 2017 as a 100 MW / 129 MWh BESS.

Battery competition helped drive down the cost of frequency control in South Australia



Case learnings:

- **Batteries can provide fast, precise grid stability:** HPR entered all eight FCAS markets in 2017, using its rapid response to support system frequency.
- **New competition can reduce ancillary-service costs:** HPR increased Regulation FCAS competition, delivering an estimated A$116 million in system savings in 2019 as Regulation FCAS costs fell by more than 90%; AEMO also removed the costly 35 MW local requirement in 2018.
- **Successful demonstration can unlock broader deployment:** HPR proved batteries could provide essential grid services, helping establish storage as a viable grid resource across Australia.

Key takeaway: Well-designed ancillary service markets can turn batteries into cost-effective grid stability resources by rewarding their fast, flexible response.

How they did it



1. **Opened ancillary-service markets to new technologies:** AEMO enabled batteries like HPR to register and compete alongside conventional generators across all eight FCAS markets.
2. **Integrated batteries into system protection:** AEMO and ElectraNet incorporated HPR into South Australia's System Integrity Protection Scheme, enabling the battery to respond within milliseconds to contingencies and help prevent interconnector separation and load shedding.
3. **Enabled batteries to stack revenues across multiple services:** HPR could earn revenue from FCAS alongside energy-market participation in the system-security services, strengthening the commercial case for battery investment.

"Regulating the **heartbeat of the grid**."

– **Garth Heron**, Head of Development, Neoen (Hornsdale developer and owner)



Sources: AEMO, AER, ARENA, Aurecon

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Texas

ERCOT rebounded from winter storm outages through new reliability products as solar, wind and battery storage scaled rapidly

Results

Context: In 2021, Winter Storm Uri spiked electricity demand while the extreme cold caused widespread generation outages across fuel types. ERCOT shed as much as 20 GW of load to prevent grid collapse, the largest manual load shedding event in U.S. history. 4.5 million customers lost power. In response, ERCOT added new reliability products and Texas raised weatherization standards. At the same time, the ERCOT synchronized 31 GW of solar, 10 GW of wind, 16 GW of battery storage, and 5 GW of thermal capacity from 2021–2025.

Case learnings:

- **New reliability products can quickly incentivize solutions from multiple technologies in parallel:** The ECRS (ERCOT Contingency Reserve Service) invited generators, batteries, and flexible loads to compete to provide capacity deployable within 10 minutes. In 2025, ERCOT deployed up to 1 GW in a single ECRS event, and batteries supplied 42% of the service.
- **Storage can provide meaningful peak support.** During Winter Storm Fern, batteries briefly supplied more than 7 GW — about 9.5% of ERCOT generation — during a morning peak. On a record day in July 2026, solar and batteries worked in concert to meet demand: solar supplied more than a third of generation in the afternoon peak, and batteries helped shift that energy into the evening.
- **Battery energy storage system (BESS) can quickly grow to a meaningful system resource:** BESS operational capacity grew to 21.5 GW by September 2026, giving ERCOT a large pool of fast, dispatchable capacity.

Key takeaway: Technology neutral ancillary market and interconnection queue reforms led to the large-scale BESS rollout seen in ERCOT.

Sources: Texas Tribune, ERCOT, PUC, Texas Comptroller, GridLab, EIA, ERCOT, Modo Energy, RavenVolt, Amperon, FERC

How they did it

1. **Created technology-neutral reliability products:** ECRS and other ancillary services clearly defined grid needs and then invited generators, batteries, and flexible loads to meet them.
2. **Designed competitive markets and revised them as grid needs evolved:** Real-time price volatility and reserve pricing created opportunities for flexible resources to grow and attract private capital. In 2025, ERCOT updated its market with the RTC+B (Real-Time Co-optimization plus Batteries) mechanism to co-optimize energy and ancillary services in real time and better account for battery state of charge.
3. **Scarcity pricing drives investment:** Real-time price volatility during weather events sent a clear investment signal, enabling privately financed storage and renewables projects
4. **Maintained a relatively fast interconnection pathway:** ERCOT's connect-and-manage approach allows projects to connect without first resolving every transmission constraint, managing congestion while grid upgrades are completed.

"The ERCOT market is in fact working. **15+ GW of BESS build was accomplished in 5 years with zero mandates.** Tens of billions of dollars of direct investment. All driven by market participants who saw this demand growth coming and invested in multiple symbiotic technologies ahead of it."



- **Aaron Zubaty**,
Chief Executive Officer, Eolian

"If we had 15 GW of storage during Uri, **it may have been a different story.**"



- **Joshua Rhodes**,
Research Scientist, University of Texas Austin

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Iberian Peninsula

ENTSO-E turned a catastrophic blackout into a blueprint for planning and operating a renewables-heavy grid.

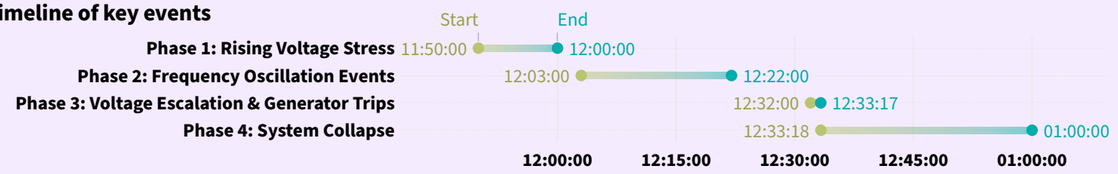
Results

Context: On April 28, 2025, Spain and Portugal experienced Europe's most severe power system incident in more than 20 years. A rapid voltage rise triggered cascading generation disconnections and loss of synchronism with Continental Europe. Nearly 25 GW of load was lost. The collapse followed a morning of difficult voltage management and two major oscillation events, as operators tried to adjust network configuration, cross-border flows, and HVDC settings in an attempt to keep the grid stable.

Case learnings:

- **Traditional planning can miss dynamic grid risks:** Pre-event assessments found the grid could withstand the loss of any single major component, but they did not identify the interacting voltage and stability risks that ultimately drove the blackout.
- **Generation and grid capabilities must be planned together:** As the generation mix and operating conditions evolved, voltage-control and reactive-power practices did not keep pace, leaving the system vulnerable to instability.
- **Adequate stability margins can prevent cascading failures:** Expert Panel simulations found that increased reactive-power margins could have prevented system collapse.

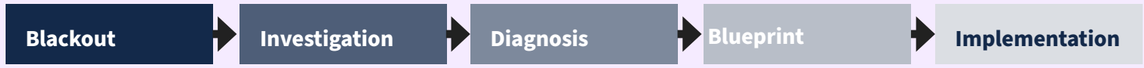
Timeline of key events



Key takeaway: Adequate generation is not enough. Iberia's blueprint translates the blackout's lessons on voltage control and reactive-power margins into future grid planning, requirements, and operating practices.

How they did it

1. **Investigated and built a forward-looking blueprint:** A 49-member Expert Panel brought together transmission system operators, regional coordination centers, and regulators. They combined system data and dynamic modeling to identify the interacting causes of the blackout and translate them into recommendations.
2. **Build sufficient voltage-control capability:** Assess future reactive-power needs, strengthen generator voltage-control requirements, and incorporate sufficient voltage-support resources and monitoring into grid plans, including active generator voltage control and greater automation of reactive-power resources.
3. **Prepare for dynamic stability risks:** Update grid codes, protection settings, and oscillation-management practices, and assess resources such as BESS with advanced controls, STATCOMs, and synchronous condensers where needed, while regularly reassessing oscillation risks as the generation mix evolves.
4. **Implement the lessons through updated requirements and practices:** Translate recommendations into concrete changes to grid rules and operations. Spain, for example, expanded dynamic voltage control to renewables in 2025. By June 2026, 21 GW of capacity was participating, including 8 GW of renewables, cogeneration, and waste-to-energy plants.



"It's not about renewables, it's about voltage control … **There is nothing in the recommendations that cannot be implemented tomorrow** … Voltage control has been known for a long time."



- **Damián Cortinas**, President, ENTSO-E

Sources: ENTSO-E, ICS Investigation Expert Panel (2026), Grid Incident in Spain and Portugal on 28 April 2025 – Final Report; Red Eléctrica (2026)

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China

CHN Energy's Ningdong project shows how grid-forming storage can help remote renewable bases operate reliably and support power exports

Results

Context: China's best wind and solar resources are concentrated in the northwest, far from major demand centers in the east. In Ningxia, high renewable penetration, weak grid strength, and long-distance power exports create stability challenges; the Ningdong project demonstrates how grid-forming storage can help address them.

Case learnings:

- **Grid-forming storage can strengthen weak renewable grids:** Ningdong's 100 MW / 200 MWh battery provides voltage-source behavior, virtual short-circuit capacity, and fast dynamic support.
- **Grid-forming controls can measurably improve system stability:** Project stakeholders report 50% fewer grid-connected oscillations and a 30% improvement in control-code execution efficiency.
- **Grid-forming storage can ride through severe disturbances:** The system was designed to maintain voltage stability through grid-voltage disturbances of 0–130% of rated voltage and phase-angle jumps up to ±60° without disconnecting.

50%
Fewer grid-connected oscillations

3–5 ms
Typical response for grid-forming inverters

Key takeaway: Grid-forming storage can help turn remote renewable resources into reliable power by strengthening weak grids and supporting long-distance electricity transfers.

How they did it

1. **Co-located grid-forming storage with a remote renewable base:** CHN Energy built 100 MW / 200 MWh of grid-forming storage to support its 2 GW Ningdong solar base, where weak-grid conditions create stability challenges.
2. **Used grid-forming controls to strengthen the grid, not just shift energy:** The grid-forming inverter connecting the Ningdong battery to the broader power system provides voltage-source behavior, short-circuit capacity, voltage recovery, damping, and disturbance ride-through. These capabilities reduce oscillatory behavior and improve stability at the renewable base and along the associated export system.
3. **Integrated grid-forming resources in planning:** Grid operators can treat grid-forming storage as part of the infrastructure required to scale remote renewable bases and safely transfer power over long-distance HVDC corridors. As they scale renewable energy exports to other provinces, State Grid Ningxia explicitly plans storage around grid topology, prioritizing renewable-rich areas and key nodes for grid stability reinforcements. The Ningdong project is an early grid-forming example in the region and may inform future standards and plans with real-world data.

"In extreme circumstances, **grid-forming storage can rapidly and autonomously adjust voltage and frequency** and actively participate in grid regulation."

– **Zhang Lei**,
Station Manager, Guoneng Shuguang No. 1 Energy Storage Station

Sources: NEA, CHN Energy, project stakeholder interviews

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Colombia

Advanced Power Flow Controllers unlocked more than 300 MW of transmission capacity on the grid.

Results

Context: In the early 2020s, Colombia's Atlántico region faced transmission constraints with more than 1.5 GW of wind and solar projects approved for connection, creating forecast overload risks for several 220-kV circuits. Rather than relying solely on new transmission construction, UPME (Colombia's Mining and Energy Planning Unit) evaluated alternatives and selected a proposal from transmission company ISA TRANSELCA to deploy Smart Wires' SmartValve technology on the existing network.

Case learnings:

- **Congestion does not always mean more lines are needed:** Existing networks can contain underutilized power flow paths even while other circuits are constrained.
- **Advanced power flow controllers (APFCs) can unlock significant capacity:** 21 SmartValve APFCs across five 220-kV circuits unlocked 300+ MW.
- **Existing infrastructure can support renewable growth while longer-term investments are made:** The project addressed constraints affecting ~1.5 GW of approved wind and solar connections. Advanced PFCs can help delay or avoid the longer permitting and community disruption associated with alternative network options.

1.5 GW
Wind and solar generation approved for connection

300 MW+
Additional capacity enabled

$30 million
Investment

20x
Benefit-cost ratio

Key takeaway: Colombia's government estimated that a ~$30M investment in targeted Advanced PFCs could deliver ~$610M in benefits, a 20x return on cost.

How they did it

1. **Identified grid congestion caused by uneven power flows:** UPME, the Colombia's national planning agency, identified congestion in the Atlántico transmission network, as well as other paths with spare capacity.
2. **Evaluated alternative solutions alongside conventional transmission expansion:** UPME evaluated options to solve the problem, including ISA TRANSELCA's proposal to use Smart Wires APFCs.
3. **Deployed modular controllers on existing circuits to redirect power toward underutilized paths:** ISA TRANSELCA deployed the project across five existing 220-kV circuits, targeting overloaded and underutilized paths within the network.
4. **Used modular equipment that can adapt as grid flows changes:** APFCs can be expanded or relocated as their transmission needs evolve.

"Our collaboration with ISA TRANSELCA exemplifies how strategic investments in APFC can optimize grid capabilities and expedite the adoption of renewable energy."



– **Joaquin Peirano**,
General Manager for the Americas, Smart Wires

Sources: Smart Wires, RMI, Quanta, Colombia Ministry of Mines and Energy

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Bangladesh

Power Grid Company of Bangladesh doubles transmission capacity on existing 132-kV line using advanced conductors.

Results

Context: Bangladesh's installed generation capacity tripled from 2009 to 2017, while transmission line length expanded by just 30%. A transmission study identified the Mymensingh–Jamalpur corridor as a new 132-kV transmission constraint. Rather than constructing a new transmission line, the Power Grid Company of Bangladesh (PGCB) replaced the existing conductors with CTC Global's Aluminum Conductor Composite Core (ACCC®) conductors. This approximately doubled capacity while reusing existing towers and rights-of-way.

Case learnings:

- **Reconductoring can unlock major capacity before building new lines:** Using existing lattice structures, PGCB installed over 330 kilometers of ACCC® Conductor on their 132 kV double circuit Mymensingh to Jamalpur transmission line. This approximately doubled the capacity of the existing Mymensingh–Jamalpur line using ACCC® Conductors.

2x
Capacity increase

330 km
ACCC conductors installed

132 kV
Existing line upgraded

25%–30%
Reduction in power loss

Key takeaway: Upgrading existing transmission lines with advanced conductors can increase capacity without the time, cost, and permitting challenges of new transmission construction.

How they did it

1. **Prioritized reconductoring:** Identified constrained corridors during transmission planning. PGCB and partners identified several such corridors in their 2016 Optimal Transmission Development study.
2. **Considered upgrading an existing corridor before building a new one:** PGCB opted to reconductor the Mymensingh–Jamalpur corridor and specified an advanced conductor — CTC Global's ACCC® Grosbeak — to enhance capacity while suiting existing tower spans and siting.
3. **Procured the upgrade as a turnkey reconductoring project:** PGCB competitively tendered supply, erection, testing, and commissioning of the existing double-circuit line; the contract was awarded in May 2020 to the FJEC–FEPEC joint venture.
4. **Executed the project with an experienced EPC and supply chain:** The project's EPC provider (Power China Fujian Engineering. Co. Ltd.) and conductor manufacturer (Apar Industries) already had experience with ACCC® in the region.

"We are using this advanced conductor on our most critical projects in Bangladesh."



– **Yeakub Elahi Chowdhury**, Executive Director, PGCB

Sources: CTC Global, Quanta, ADB

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United States

AES found that dynamic line ratings (DLRs) could boost capacity of a 345-kV line by 43%, using sensors installable in less than two weeks.

Results

Context: US Utility AES identified several near-term transmission constraints across its Indiana and Ohio systems: prospective large-loads could overload existing lines, some corridors were already experiencing thermal overloads, and outages could force generation curtailment. In 2023, AES partnered with dynamic line rating (DLR) innovator LineVision to assess how grid enhancing technologies (GETs) may increase transmission capacity on the existing power grid. They subsequently deployed 42 sensors across five transmission lines in Indiana and Ohio.

43%
Average increase over SLR

42
Sensors installed

<2 weeks
Sensor installation

Case learnings:

- **Existing high-voltage lines can contain substantial unused capacity:** On the 345-kV demonstration line, DLR provided an average 43% capacity increase over the static line rating (SLR) over a 12-month period.
- **DLR data collection can also identify segments with unexpected limitations:** On one 69-kV line, DLR actually averaged 10% below the winter static rating — in this case the culprit was a half-mile, heavily-vegetated, low-wind section of the line.
- **Deployment can be fast and minimally disruptive:** AES installed 42 sensors across five transmission lines in under two weeks, averaging roughly 30 minutes per sensor without outages.

Key takeaway: DLR can deliver major transmission capacity gains with minimal infrastructure investment, helping utilities defer costly grid expansion while accelerating access to existing capacity.

How they did it

1. **Identified needs during transmission planning:** After transmission plans identified general areas of concern, AES partnered with LineVision to prioritize lines where DLR could unlock additional capacity, or where sensors could provide crucial visibility.
2. **Deployed sensors in concert with the data, software, and processes needed to operationalize the DLR in practice:** Although 42 sensors were installed in less than two weeks, AES and LineVision also did the engineering and analysis required to translate sensor data into trusted ratings. The next phase will integrate these dynamic ratings into AES' transmission energy management system for real-time operation.



3. **Share pilot evidence to inform future rulemaking and scale-up:** AES and LineVision published detailed lessons from the deployment; two months later, FERC cited the project's cost and deployment-time findings in its national DLR Advance Notice of Proposed Rulemaking.

"By deploying DLR technology, we are empowering utilities like AES to maximize the efficiency and reliability of their grid infrastructure while minimizing costs and environmental impact."

– **Hudson Gilmer**,
Hudson Gilmer, Cofounder and Former CEO of LineVision



Sources: AES, Quanta, RMI

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Brazil

Policymakers drove a two-track solar boom across utility and distributed markets, benefiting 8M consumer units and diversifying a hydro-heavy grid

Results

Context: Brazil entered the 2010s with a grid built on hydropower. A 2014–15 drought depleted reservoirs and exposed the cost of relying on more expensive thermal generation for backup, including LNG. Solar offered a hedge against hydro exposure, producing the most during dry seasons when hydro is most constrained. Brazil opened two pathways for scaling solar: 1) a compensation framework for distributed generators, and 2) competitive federal auctions with long-term PPAs.

Case learnings:

- **Competitive auctions with long-term PPAs can invite investment, open a market for lower-cost power, and give way to other contracting schemes as the market matures:** Average solar auction prices dropped by 63% from the first federal auction in 2014 to the last in 2022. Today, 90% of planned 2023–29 generation capacity expansion is through the free market, with a 2025 disclosed deal priced at $33/MWh.
- **Predictable net metering policies and affordable installed costs can spark a distributed solar boom:** These measures helped distributed solar leapfrog utility-scale solar and benefited ~8M consumer units receiving electricity credits. Solar has continued to become more affordable: installed costs of residential systems dropped 64% from 2016 to 2024.
- **Success in both utility and distributed and utility scale solar quickly shifts the challenge from deploying the generation to using it effectively:** Distributed solar now supplies up to 40% of national grid demand at midday but falls away before the evening peak. Meanwhile, an estimated 20% of potential utility-scale solar and wind was curtailed in 2025, contributing to R$6.5 billion in estimated losses. BESS can help address this hourly mismatch, and Brazil is now preparing its first national battery-storage capacity auctions.

Key takeaway: Distributed solar generation has seen compounding growth in recent years, driving a diversification of Brazil's electricity generation mix.

How they did it

1. **Ran competitive federal auctions with long-term PPAs to anchor private investment:** Brazil's federal auctions provided bankable certainty and competition required to bring the first waves of solar investment online at competitive costs.

2. **Maintained access to competitively priced solar equipment:** Policymakers granted import holidays during the solar takeoff, allowing low-cost equipment into the market. Average imported solar module prices fell 73%, from $0.89/Wp in 2012 to $0.24/Wp in 2021. They averaged $0.09/Wp in H1 2026.

3. **Created and evolved a net metering framework to unlock distributed solar:** ANEEL's 2012 regulation established energy compensation for distributed generation, helping the market grow to millions of participants. A 2022 reform modernized the framework by reflecting network costs on prosumer bills while protecting legacy projects through 2045, providing regulatory certainty.

4. **Creating a market for storage to shift abundant midday solar to other hours**: The first large-scale battery auctions are planned for December 2026 and will procure ≥30 MW systems with ≥4-hour discharge on 15-year contracts. By August 2026, nearly 300 GW of projects had registered for the auctions.

"The LNG experience made it undeniable that the country needed a different kind of structural hedge. **What is particularly compelling about solar is that it generates the most during the dry season**, which was our main challenge at the time."



– **Thaissa Avena**,
former Technical Advisor at the Advisory for International Relations, Ministry of Mines and Energy

Sources: MDPI, EIA, Oxford Institute for Energy Studies, EPE, BNDES, ABSOLAR, EMBER, PV Magazine, EIA, Science Direct, Energy Tracker

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Australia

Households enjoy three free hours of midday power, supported by affordable solar installed on 40% of homes countrywide.

Results

Context: Rooftop solar is exceptionally affordable and quick to install in Australia, thanks to simple incentives, a high-volume market, low hardware costs, and efficient permitting and installation processes. 40% of Australian homes have solar, reaching nearly 50% in South Australia. Residential solar and storage are part of the Australian Energy Market Operator's (AEMO) resource plans as they replace an aging coal fleet while electricity demand rises. The 2026 Integrated System Plan treats consumer solar and storage as core resources and projects 87 GW of small scale solar and 35 GW of consumer batteries by 2050.

Key takeaway: In Australia, small scale solar reaches homes and businesses at 25% lower cost than in the US.

Case learnings:

- **Efficient delivery and low-cost system components drive down installed cost, which fell 75% between 2010 and 2025:**
  - **Soft costs**: Installers manage permitting, compliance, and grid connection, and they face penalties when audits reveal problems. Routine projects do not require an on-site utility representative or approval at every step. The system trusts installers and spot-checks them with a real risk of loss of grid connection certification for noncompliance.
  - **Hard costs:** Australia has tapped the world's most competitively priced solar supply chains, with duty-free imports and retail module prices available for roughly A$0.30/W in recent years.
- **Abundant solar can benefit customers without panels on their roofs:** The Solar Sharer Offer gives eligible households, including renters and homes without solar, free electricity for three midday hours each day (up to 24 kWh).

	Australia	United States
Installed cost (pre-incentive)	**$0.83/W** *AEMO 2025 residential cost basis*	**$3.60/W** *LBNL 2025 host-owned median*
Homes with solar	**40%**	**7%**

How they did it

1. **Simple, immediate point-of-sale discounts catalyzed the market:** The Small-scale Renewable Energy Scheme (SRES) allows customers to reduce upfront costs from installers rather than filing for a rebate in the future.
2. **Streamlined quality checks, permits and connections:** SRES requires owners to use accredited installers and equipment from national lists, eliminating project-by-project due diligence for these steps. Additionally, most networks developed automatic or ~1-day connection approvals for ordinary projects. For example, Ausgrid and SA Power Networks auto-approve ≤30 kVA compliant systems, reserving engineering review for constrained or unusual projects.
3. **Storage incentives and flexible export schemes are enabling the power system to catch up to growing solar penetration.** The national Cheaper Home Batteries Program offers discounts around 30% today, to be ratcheted down as battery costs decline. Network operators are also adopting flexible export arrangements with customers, allowing the grid to raise and lower limits based on local conditions.
4. **Planned distributed energy as core power system resources:** AEMO explicitly models rooftop solar, batteries, EVs, flexible demand, and their coordination in its Integrated System Plan. By 2050, consumers' own resources are forecast to meet about 30% of NEM electricity demand.

Sources: Australian Government Department of Climate Change, Energy, the Environment and Water, The Electricity Journal, IEEFA, Renew Economy, Australian Taxation Office, PV Magazine, SurgePV, Clean Energy Council, Australian Bureau of Statistics

"Consumers are continuing to invest in **rooftop solar and home batteries**, which **benefits all consumers** by reducing the need for grid-scale investment."

– **Daniel Westerman**, CEO, Australian Energy Market Operator



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South Africa

All-source procurement brought diverse technologies to the table; renewable-storage hybrids ultimately delivered power as gas projects stalled.

Results

Context: South Africa entered 2020 with an urgent 2–3 GW supply gap and reliance on expensive diesel peakers. In August 2020, the Department of Mineral Resources and Energy (DMRE) launched a technology-neutral, performance-based tender to procure 2 GW of dispatchable power. The Risk Mitigation Independent Power Producer Procurement Programme (RMIPPPP) required bids to meet the grid's needs via a set of dispatchability and performance standards.

Case learnings:

- **Specifying the services needed, rather than the technologies to be used, can maximize competitive bidding:** RMIPPPP required projects to provide energy, capacity, and ancillary services daily from 5:00 a.m. to 9:30 p.m., with at least a 50% annual load factor. They attracted proposals that used gas generation, batteries, wind, and solar — often in combination with each other — to meet these needs. The tender closed with 28 bids totaling 5 GW, and the preferred-bidder portfolio met the 2 GW goal with a diverse portfolio of technology types.
- **Attracting diverse bids can hedge against specific technology risks during development and operation:** Of the 11 selected projects, the four projects including gas plants (totaling 1.42 GW) failed to reach commercial close before the December 2023 deadline. Of the seven renewables plus storage projects, six totaling 428 MW reached financial close.

Big technology type	Contracted capacity (MW)	Advanced by 2026 (MW)
Gas or gas/solar hybrid	1,418	**0** (Zero of four projects reached commercial close)
Renewables and storage	578	**428** (280 MW operational, 148 MW under construction)
Total	1,996	**428** (21% of target)

Key takeaway: A technology-neutral, time-framed tender let the market reveal the cheapest way to close the supply gap, rather than government selection of technologies up front.

How they did it

1. **Set technology-neutral, needs-based service targets:** The 2019 Integrated Resource Plan identified an urgent supply gap, and Eskom set requirements based on grid needs, including dispatchability from 5:00 a.m. to 9:30 p.m., a minimum 50% annual load factor, and provision of energy, capacity, and ancillary services. The IPP Office built the RFP based on these requirements.

2. **Assessed bids using both financial and economic development criteria:** An independent evaluation committee scored bids with a 90% weight on price and a 10% weight on economic development commitments. A normalized "evaluated price" included costs of both energy and ancillary services, and the development score comprised local content, job creation, and other government priorities.

3. **Set and enforced time-bound execution milestones:** The DMRE set deadlines for legal and commercial milestones, and Eskom tied grid reservations to project readiness.

"The **RMIPPPP was unique in approach wherein diverse technologies and their application were allowed to compete**. This approach allowed the Bidders to tailor make solutions that would meet the specification to close the energy and capacity gap."

– **Minister Gwede Mantashe**,



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Kenya

Public investment in geothermal resource exploration and workforce development addressed key market barriers, enabling competitively selected IPPs to supply clean firm power at ~0.07/kWh.

Results

Context: Kenya's first geothermal plan opened in 1981, and it has been building exploration and operating expertise for decades. Today, 90% of Kenya's electricity generation is renewable, including contributions from 1 GW of clean firm geothermal capacity. Historically, generators including state-owned KenGen and private IPPs have primarily sold grid power to Kenya Power and Lighting Company. Recent reforms aim to increase competition by allowing large consumers to contract directly with generators and wheel power across the grid.

Case learnings:

- **Public investment can catalyze a promising geothermal market, while competitive procurement keeps generation affordable:** The creation of the national Geothermal Development Company has accelerated buildout by taking on the risk of exploration before handing wells off to generators. In the Menegai Geothermal Project, the GDC drilled and developed the steam resource, and three IPPs were competitively selected to finance, build, and operate three 35 MW plants. The contracted tariff for clean firm power from Menegai Phase 1 was roughly $0.07/kWh.
- **Geothermal provides clean domestic baseload:** Geothermal supplied ~40% of Kenyan electricity in recent years. In Kenya's renewable-dominated generation mix, these plants are operated as baseload facilities that complement hydro, solar, and wind without exposure to imported fuel prices.
- **Sustained public investment compounds**: Investments in technical training and local workforce (KenGen, GDC) built expertise that drives continued geothermal development.

Key takeaway: Kenya made geothermal a long-term, fuel-free pillar of its electricity system by derisking exploration, establishing a skilled workforce, and attracting private and concessional capital.

How they did it

1. **Created dedicated entity to absorb exploration risk:** Launched in 2008, the Geothermal Development Company has supported private sector entry by reducing the upfront risk and cost of developing geothermal resources. The GDC does this through exploratory studies and well drilling, producing and selling steam to power producers, and supporting workforce development.
2. **Developed derisked resources through both public and private pathways:** Depending on the project state-owned KenGen or private IPPs finance, build, and operate the generation facilities using GDC's steam.
3. **Blended public, concessional, and private capital to make projects bankable:** Public and concessional financing of steam-field development, long-term PPAs, and guarantees against offtaker nonpayment and GDC steam-supply risk made private generation projects bankable. At Menengai, this structure enabled three privately owned 35 MW plants worth roughly KES 39 billion (~US$300 million), with private sponsors providing equity and taking responsibility for financing, construction, and operation.
4. **Integrated growing firm resource into resource plans:** Kenya's 2024–2043 Least Cost Power Development Plan anticipates 3.4 GW of additional geothermal, contributing the largest share of total firm capacity alongside batteries and pumped hydro. All diesel and diesel and other oil-fired plants are expected to be decommissioned by 2035.

"One thing Kenya did well was to develop the capacity to the extent we have established a school at KenGen where **we are training other countries, especially the sub-Saharan countries, on geothermal exploration** and geothermal utilization."

– Anastasia Wanjohi,
Ken Gen, Former Senior Geophysicist



Sources: ThinkGeoEnergy, Africa Oil & Gas Report, IEA, Project Syndicate, Energypedia, Carnegie Endowment, Clean Air Task Force, The Global Economy, IEA, KFW, World Bank, UNIDO, Energy News, Science Direct, Global Energy Monitor, CleanAir Task Force

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https://rmi.org/resources/locking-in-prosperity/

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