Leading in the New Reality
Climate & Sustainability |

Rising to the Challenges of Integrating Solar and Wind at Scale

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BCG | BCG HENDERSON INSTITUTE

Electricity is produced using three types of generators

Conventional power plants

- Nuclear
- Coal
- Natural gas
- Oil

Dispatchable renewable-energy plants

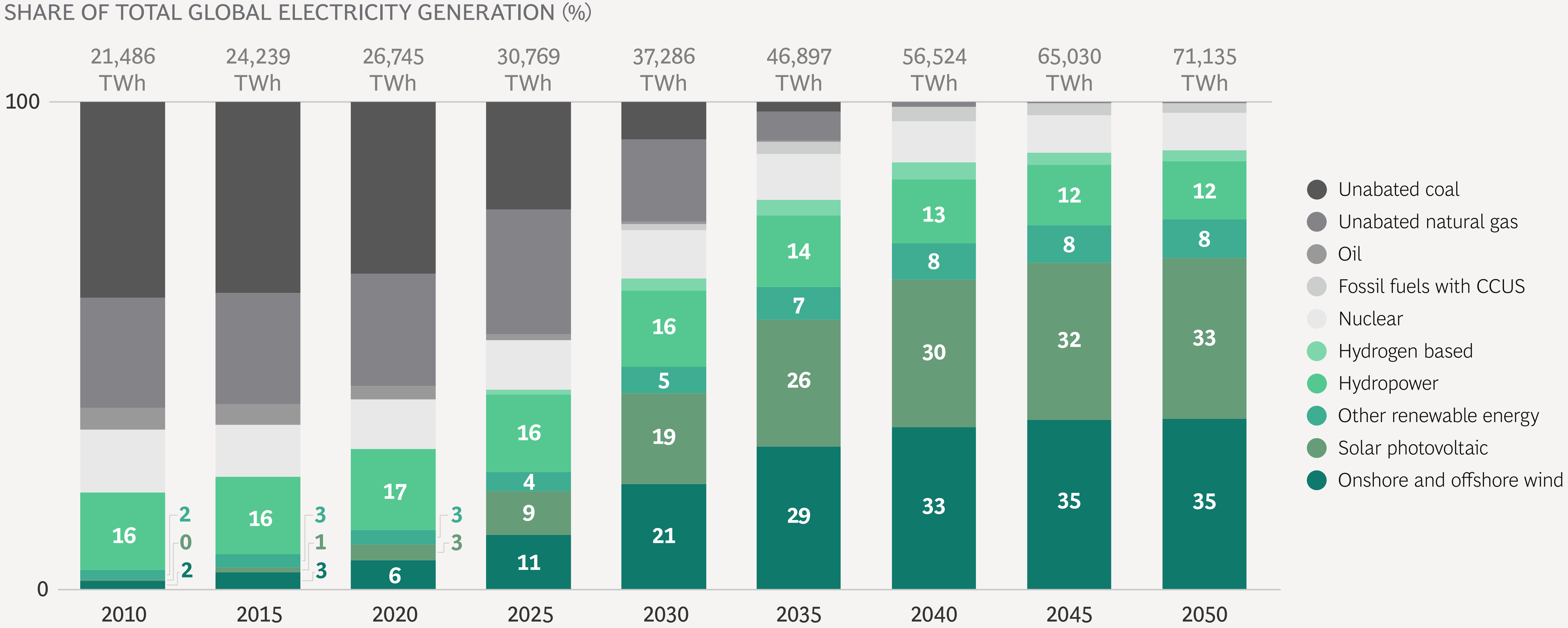
- Hydropower
- Hydrogen based
- Biofuels
- Geothermal

Variable renewable energy (VRE) sources

- Solar photovoltaic
- Onshore wind
- Offshore wind

Source: BCG analysis.
Note: The list of technologies is not exhaustive; it is based on the most common technologies.

VRE sources need to account for about 70% of global electricity generation by 2050



Source: *Net Zero by 2050: A Roadmap for the Global Energy Sector*, 2021, International Energy Agency.
Note: TWh = terawatt-hour; CCUS = carbon capture, utilization, and storage. Unabated refers to power plants that do not have CCUS technology.

Generating VRE is different from producing conventional power in five ways

Variable
Generation depends on the sun shining or the wind blowing; energy is not available on demand

Uncertain
Generation remains challenging to predict perfectly, despite increasingly accurate weather-forecasting tools

Inverter based
Power electronic devices interface solar panels and wind turbines with the grid, changing direct current into alternating current

Distributed
Generators are typically small in scale and distributed broadly across the electrical grid

Zero marginal cost
Cost structures are almost entirely fixed, with few if any variable running costs

Source: BCG analysis.

The characteristics of VRE generation create challenges in four areas that are key to system reliability

Resource adequacy
Having a sufficient portfolio of energy resources to match electricity demand with supply is essential for operating a system reliably

Network adequacy
Adequate grid capacity is needed to transport electricity from generators to consumption centers

Frequency stability
System operators must maintain the system's frequency (typically 50 Hz or 60 Hz) within acceptable limits by instantly balancing supply and demand

Voltage stability
System operators have to maintain the voltage waveform and phase angle at all locations in their electricity system following disturbances

Resource adequacy	Network adequacy	Frequency stability	Voltage stability
Years to hours	Years to hours	Minutes to seconds	Seconds to less than a second

← TIME FRAMES IN WHICH SYSTEM OPERATORS AND DESIGNERS NEED TO ACT IN ORDER TO MEET THESE REQUIREMENTS →

Source: BCG analysis.
Note: Frequency indicates how fast the electricity waveform repeats itself, while voltage indicates the size of the waveform and how its cycle is shifted in time relative to other waveforms in the network.

Some system issues have already appeared in regions with high usage of VRE

Resource adequacy

US

Steeper intraday ramps

During several days in 2018, California's three-hour surge in residual demand around sunset was more than 50% of the daily peak demand; this required flexible plants to ramp up generation quickly

US

Seasonal imbalances

In Texas, wind-powered generation is highest in the spring, but electricity demand is relatively low; this will lead to overcapacity or the need for dispatchable plants that run for only part of the year

GERMANY

VRE droughts

In early 2017, Germany had to rely on conventional power plants to meet its needs because of a ten-day renewables drought (or *dunkelflaute*); conventional plants had to run partly loaded for the rest of the year

Network adequacy

GERMANY

Network congestion

In Germany, most wind-powered generation is in the north and most solar-powered production is in the south; as a result, the cost of redispatching to prevent congestion has risen to more than €1 billion a year in recent years

Frequency stability

AUSTRALIA

Low visibility and controllability

South Australia has about 1.7 GW of behind-the-meter solar capacity; it is neither fully visible to nor fully controllable by participants or the system operator and, thus, acts as a must-run source without further actions

AUSTRALIA

Must-run dispatchable plants

On October 11, 2020, South Australia's solar-powered generation met more than 100% of demand, but the region still had 250 MW of must-run fossil-fuel generators operating at the minimum load to provide grid services

AUSTRALIA

System inertia

In South Australia, synchronous condensers are being installed, and fast-acting frequency-control services are being procured, following inertia shortfalls

AUSTRALIA

Unstable system frequency

VRE's share of electricity generation rose from about 3% to roughly 15% on Australia's east coast from 2011 through 2019, requiring about 20% more operating reserves to ensure a stable frequency

Voltage stability

DENMARK

Unstable system voltage

In 2015, the Danish transmission system operator installed three synchronous condensers to help stabilize the transmission system and system voltage and to support the high amounts of wind-powered generation

Sources: California Independent System Operator; BloombergNEF; AEMO; ENTSO-E; BCG analysis.

Note: Behind-the-meter solar capacity is power that is generated by small-scale rooftop solar systems. These examples are only a few of many worldwide.

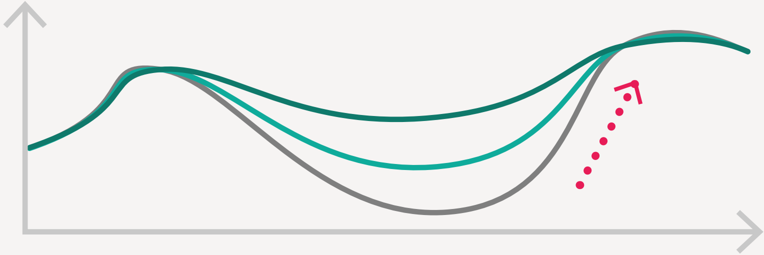
RESOURCE ADEQUACY

High usage of VRE challenges resource adequacy in three ways

Higher intraday variability

Greater usage of VRE can steepen the residual load profile.[1] Because this profile is hard to follow for dispatchable power plants, it brings challenges—and costs—when they have to ramp up assets to generate power or ramp down to reduce power.

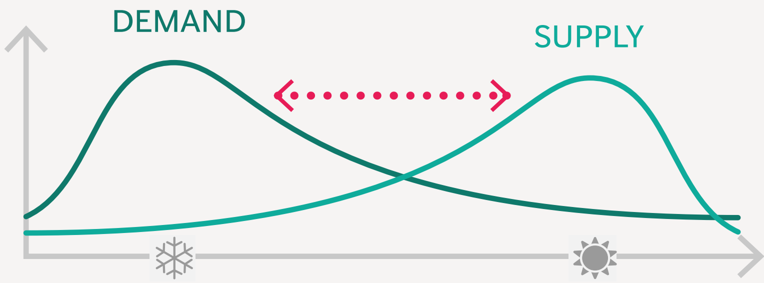
More solar-powered generation deepens the valley of the residual load in the afternoon and steepens the resulting ramp when the sun sets



More seasonal imbalances

The days are longer and sunnier during the summer, and wind speeds vary with the seasons. When combined with seasonal changes in demand, the result can be either an excess generation of VRE or the need for dispatchable plants that run partly loaded.

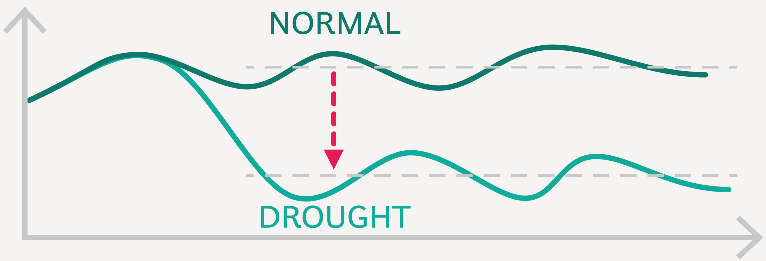
Electricity demand peaks in the winter in some countries, while the supply of solar energy is higher in the summer



VRE droughts

The generation of VRE can vary depending on extreme weather events. A period of reduced sunlight and little to no wind can cause a dip in renewable generation. Such droughts can leave power system operators scrambling to find sufficient generating sources.

Less sun and wind can significantly lower the average supply of VRE beyond normal variations



Source: BCG analysis.

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[1] The residual load profile indicates the power demand to be met by dispatchable generators throughout the day. A steeper residual load profile indicates that the demand for power met by dispatchable generators tended to increase rapidly.

RESOURCE ADEQUACY

System operators and designers can tackle resource adequacy challenges in four ways

	Facilitating demand flexibility	**Storing electricity**	**Generating power flexibly**		**Building interconnections**
Higher intraday variability	Users can curtail and shift their demand, depending on the availability of VRE	Storage and hydropower reservoir operators can help by storing electricity during periods of low residual demand and discharging it during periods of high demand	Dispatchable plants can be ramped up and down to meet demand	VRE providers can only curtail power generation	Operators can import power to meet shortages and export it when surpluses arise; the extent to which interconnections between power systems can help depends on the available physical infrastructure and the willingness of neighboring regions to trade surpluses and excesses
More seasonal imbalances	For most users, it is not practical to shift demand across seasons	Storage and hydropower reservoir operators can address seasonal imbalances and VRE droughts by storing electricity; potential solutions include power-to-gas storage, large pumped-hydroelectric storage, and large conventional hydropower reservoirs	Dispatchable plants can be turned on and off or ramped up and down as needed		
VRE droughts	Users can mitigate the effects of droughts by reducing or shifting demand, or operators can perform load-shedding actions			VRE operators cannot increase the amount of sun or wind	

Source: BCG analysis.
Note: The list may not be exhaustive, but it is based on the most important solutions.

NETWORK ADEQUACY

Shifts in power flows through electrical grids can lead to network congestion

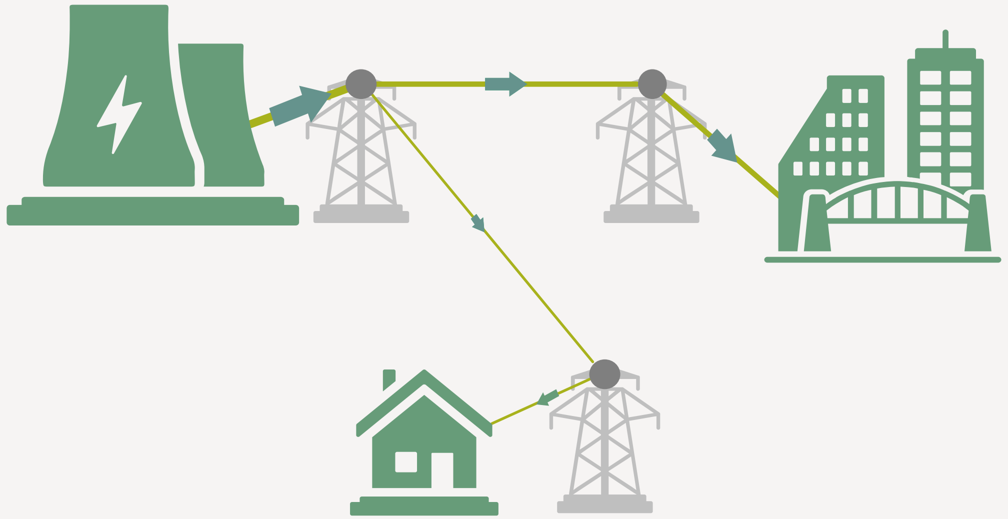
Conventional electricity systems

Large conventional power plants generate the bulk of the electricity, and networks are designed to transport it to consumption centers

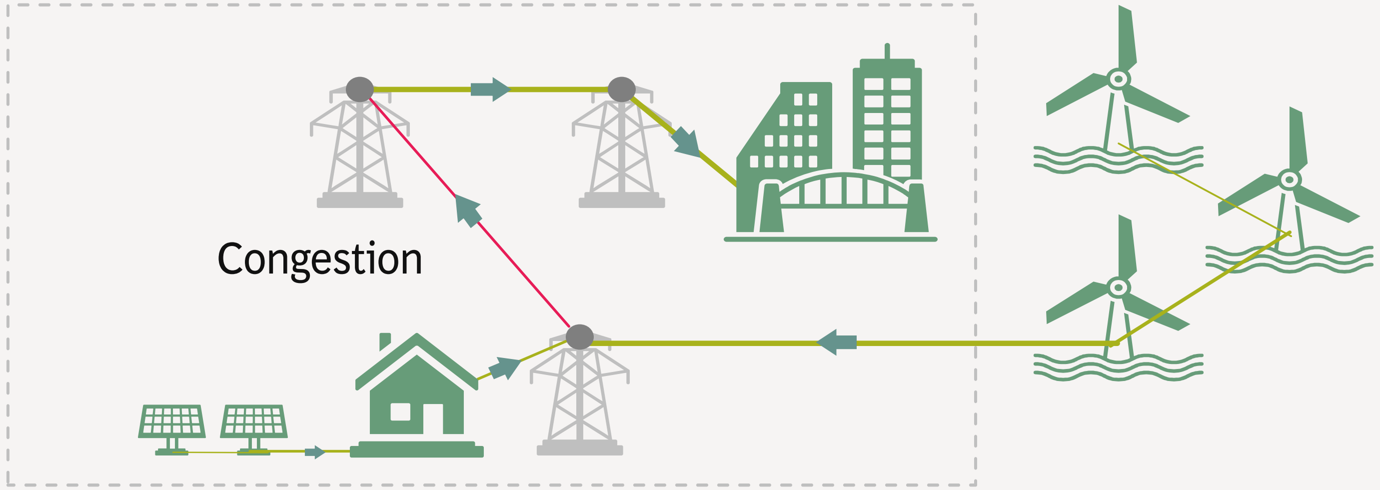
VRE-driven electricity systems

Wind farms and solar systems generate most of the electricity, but they are more distributed and may be in areas with weaker connections to the main electricity grid, resulting in congestion issues[1]

A conventional power plant supplies a city and a village



The city is powered by wind and solar, and a village supplies itself with solar power; such networks can suffer from congestion without line upgrades



Source: BCG analysis.

[1] Congestion occurs when a transmission line operates at its maximum transfer capacity and not all electricity can flow through.

NETWORK ADEQUACY

There are six ways to address the network adequacy challenge

Optimizing the siting of VRE sources

When deciding where to build VRE sources, consider the available network capacity as well as the best location from a yield or generation perspective

Increasing grid capacity

Alter the dimensions of transmission and distribution cables, or lay additional ones, to pass more electricity through

Incentivizing local balances

Implement incentives to match supply and demand locally; not exporting surplus power through the grid can help manage grid congestion

Facilitating demand flexibility

Resolve grid congestion by helping both industrial and residential users to adjust their consumption profile

Storing electricity

Store electricity when networks are congested and discharge it when there is spare capacity

Curtailing VRE

Reduce network congestion by curtailing electricity generation from VRE

Source: BCG analysis.
Note: The list may not be exhaustive, but it is based on the most important solutions.

FREQUENCY STABILITY

To maintain frequency stability, system operators typically activate operating reserves

Supply and demand imbalances

- Instantaneous imbalances, or mismatches between supply and demand, cause an electricity system's frequency to change
- The pace of change in the frequency depends on the inertia in the system; the more inertia, the slower the pace
- System operators typically address imbalances by using so-called operating reserves—mechanisms that support the balance between supply and demand; these mechanisms include asking generators to ramp their assets up or down and asking users to consume more or less

Regulating and contingency reserves

- The causes and durations of imbalances vary, requiring different operating reserves
- The names for and the types of contracted reserves differ by region, but operating reserves typically include regulating and contingency reserves
- **Regulating reserves** help restore frequency stability during normal imbalances, which occur continuously
- **Contingency reserves** help restore frequency stability during more severe and infrequent events, and they have three components: primary reserves that stabilize the frequency, secondary reserves that return the frequency deviation to zero, and tertiary reserves that relieve the primary and secondary reserves

Source: BCG analysis.

FREQUENCY STABILITY

Five VRE-driven factors can disrupt frequency stability

Higher demand for operating reserves

As wind and solar increasingly account for a larger share of the electricity that is generated, a larger part of power generation becomes variable and uncertain. All else being equal, this results in a greater need for operating reserves to compensate for system imbalances.

Lower availability of operating reserves

Operating reserves have traditionally been provided by controllable conventional generators. These are increasingly being phased out following the integration of solar and wind power into electricity systems, eliminating historical sources of reserves.

Minimum-load requirements

When providing reserves, conventional generators are typically spinning. In times of low residual demand because of high VRE generation, they can only reduce their output to a minimum-load level in case they have to remain online to provide grid services. The result is surpluses.

Reduced inertia

Rotating components in conventional generators provide inertia, which slows the effect of frequency changes. As conventional generators are phased out and natural inertia is reduced, compensating actions are required to stabilize the frequency.

Low visibility and controllability

Electricity produced by small-scale solar-powered generation systems (such as those set up on the roofs of SMEs and households) is not fully visible to the system operator and market participants. This makes it hard to control or forecast output, complicating the integration of small-scale solar-powered generation in system planning and operations.

Source: BCG analysis.
Note: SME = small and midsize enterprises.

FREQUENCY STABILITY

Operators and designers have six ways to tackle higher demand and lower availability for operating reserves and minimum-load issues

	Coordinating with neighboring regions	Storing electricity	Facilitating demand flexibility	Curtailing the generation of VRE	Making conventional plants more flexible	Improving advanced forecasting
Higher demand for operating reserves	Operating reserves can be jointly sized by operators in multiple regions	These measures do not reduce the demand for operating reserves				Forecasts that use live and historical weather data will be more accurate and help reduce the need for reserve capacity
Lower availability of operating reserves	Pools of operating reserves can be shared across multiple regions	Storage assets can provide reserve capacity	Users can change or shift consumption to provide reserve capacity	Operators can temporarily curtail VRE generation to rebalance supply and demand	Investments in flexibility can enable power plants to ramp up and down faster	This measure will not boost operating reserves
Minimum-load requirements	Electricity can be exported to relieve minimum-load constraints	Storage charging increases electricity demand and thus relieves minimum-load constraints	Users can temporarily consume more to relieve minimum-load constraints	Operators can temporarily curtail VRE generation to relieve minimum-load constraints	Plants with a reduced minimum-load level can ramp down production further while remaining online	This measure will not address minimum-load requirements

Source: BCG analysis.
Note: The list may not be exhaustive, but it is based on the most important solutions.

FREQUENCY STABILITY

There are five ways to solve the inertia challenge

Maintaining a minimum number of synchronous generators

Keeping a small number of synchronous generators online and spinning can guarantee a minimum amount of inertia, but this is only a temporary solution toward net zero if these synchronous generators use fossil fuels.

Contracting for more or faster operating reserves

Contracting for more or faster operating reserves can mimic inertia. Since system frequency changes more rapidly with less inertia, the operator needs to activate operating reserves faster to stabilize the frequency.

Running synchronous condensers

A synchronous condenser mimics the inertia that a conventional generator provides by means of a similar rotating mass. It behaves like a motor, consuming energy to keep the mass spinning.

Providing synthetic inertia from grid-following inverters

Grid-following inverters take their frequency reference from the network and are often configured to deliver a certain amount of power. They can support system frequency by adjusting their power output. Because of control delays, they behave more like operating reserves than true inertia.

Providing synthetic inertia from grid-forming inverters

Grid-forming inverters have their own internal frequency reference. This allows the inverter to respond instantaneously to frequency changes. Therefore, they are better suited to provide synthetic inertia than grid-following inverters.

Source: BCG analysis.
Note: The list may not be exhaustive, but it is based on the most important solutions.

FREQUENCY STABILITY

Operators and designers have three ways to address the visibility and controllability challenge

Improve the visibility of distributed renewable generators

Operators of electricity networks can collaborate with players that operate distributed renewable-energy systems to aggregate data and improve individual system visibility by leveraging smart meters and information from supervisory control and data acquisition systems.

Increase the controllability of distributed renewable generators

System operators can require new distributed photovoltaic systems to be more controllable. For example, in South Australia, all new rooftop solar installations must have an agent that can carry out remote disconnections and reconnections.

Offer stronger incentives for market participants to keep local balances

Incentives to match supply and demand locally, without exporting surplus power through the grid, can reduce the number of balancing actions the system operator needs to perform to keep the system balanced.

Source: BCG analysis.
Note: The list may not be exhaustive, but it is based on the most important solutions.

VOLTAGE STABILITY

Greater use of inverters can disrupt voltage stability in electricity systems

Reduced share of conventional and dispatchable generation

Conventional and dispatchable generation include synchronous machines, which can inject or absorb reactive power to improve system strength. These capabilities diminish as they are phased out.

SHARE OF CONVENTIONAL AND DISPATCHABLE GENERATION IN SOUTHERN AUSTRALIA (%)

Increased share of inverter-coupled generation

Wind and solar generators are coupled to the network through an inverter. Today, by default, most designs and implementations lack the control systems and hardware that provide reactive power capabilities.

SHARE OF VRE GENERATION IN SOUTHERN AUSTRALIA (%)

Sources: Australia's Department of Industry, Science, Energy and Resources; BCG analysis.
Note: There are two types of power in a power system: active and reactive. Active power is the useful part that provides the energy to serve the load. Reactive power flows are caused by the normal operation of power system components; controllable sources of reactive power can regulate these flows to ensure voltage stability.

VOLTAGE STABILITY

There are five ways to tackle voltage stability issues

Using synchronous generators

Synchronous generators can adjust their reactive power while generating active power under normal operation, or they can be used in a synchronous condensing mode in which they generate only reactive power, not active power

Running synchronous condensers

Synchronous condensers are synchronous motors that can absorb or inject reactive power, allowing them to contribute to voltage stability.

Operating grid-forming inverters

Grid-forming inverters are equipped with hardware and control mechanisms that allow them to inject or absorb reactive power to support voltage stability.

Providing modified grid connections

Modifying the grid’s connections can enhance voltage stability. For example, adding transmission lines can reduce the distance at any point in the grid to large conventional generators and other voltage sources.

Using other electrical devices

A range of electrical devices without spinning parts can provide fast-acting reactive power. These include capacitor banks, static VAR compensators, and static synchronous compensators.

Source: BCG analysis.
Note: VAR = volt-ampere reactive. VAR is a unit of measurement of reactive power. The list may not be exhaustive, but it is based on the most important solutions.

If you would like to discuss this topic, please contact one of the authors:

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