Maintaining future electricity supply reliability in the period of transition of five to ten years

Role of renewable energy

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Energy demand and consumption

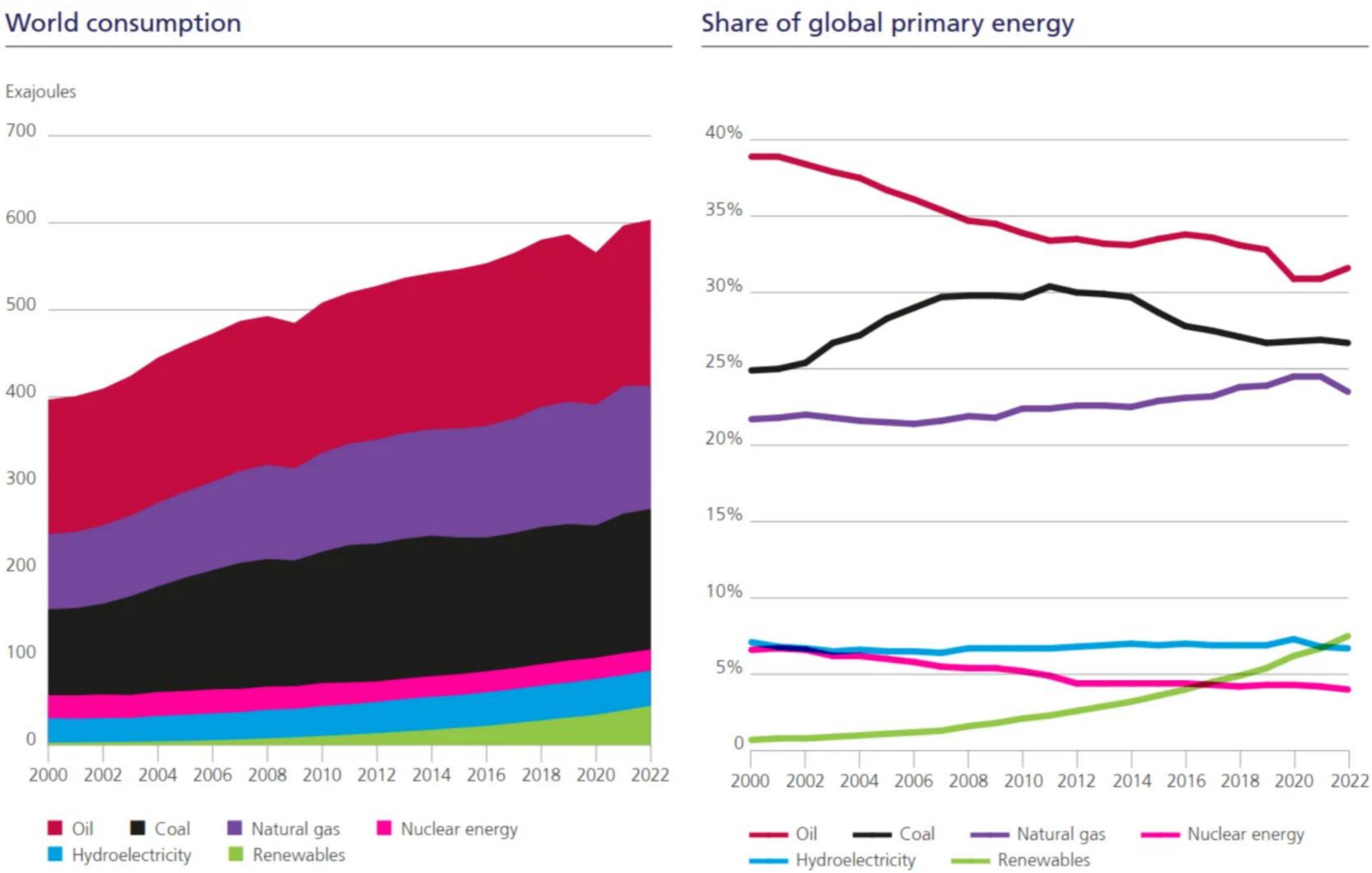


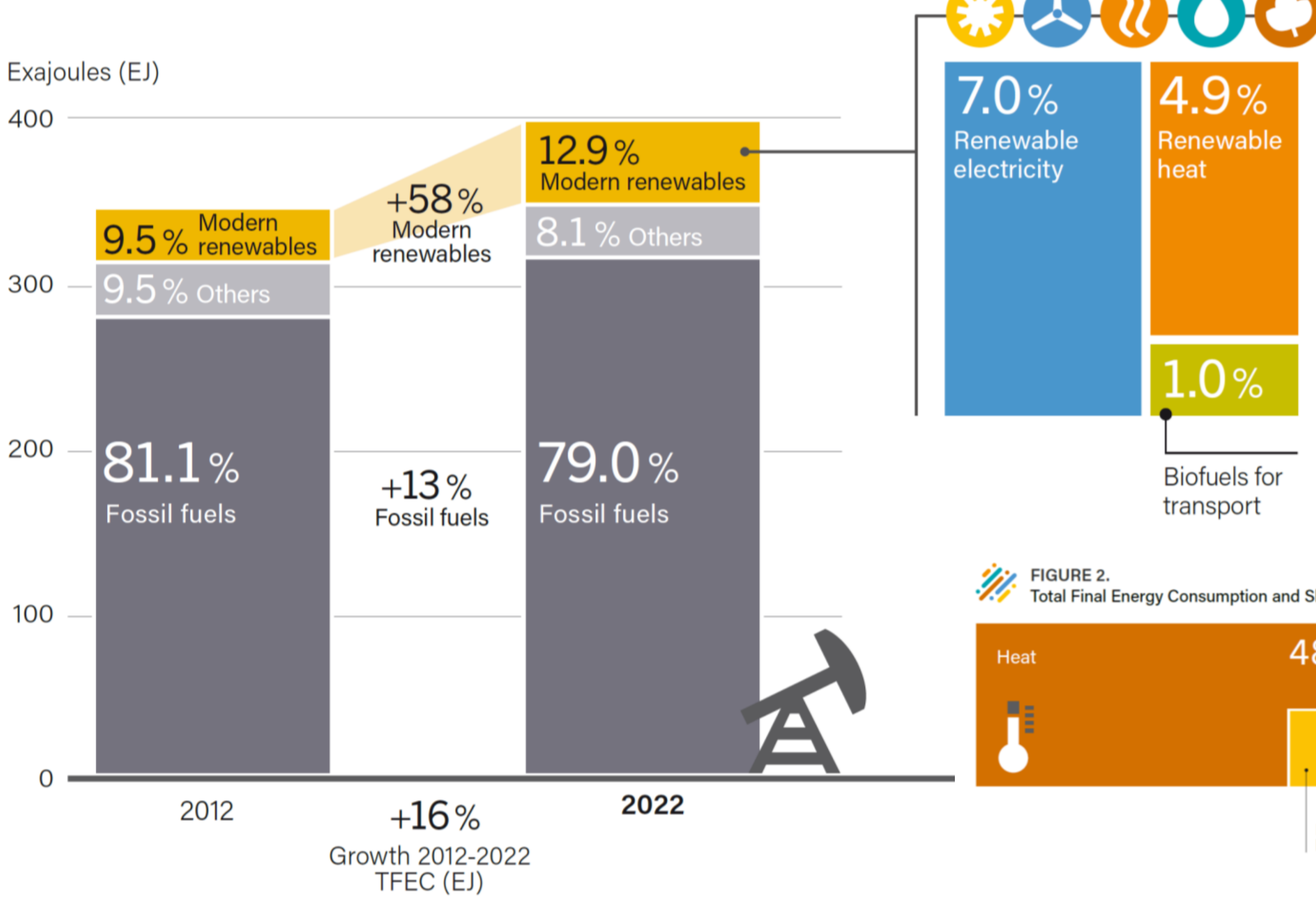
Figure 1. World primary energy consumption by source

Renewables include solar, wind, geothermal, biomass, and waste (Source: Energy Institute Statistical Review of World Energy 2023)

https://dieselnet.com/news/2023/07energyreview.php/

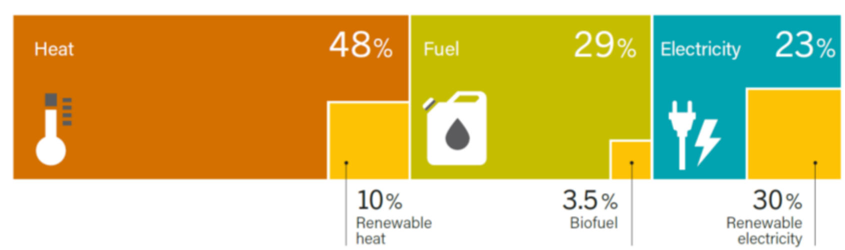
Energy consumption by source and carrier

FIGURE 1.
Total Final Energy Consumption by Source, 2012 and 2022

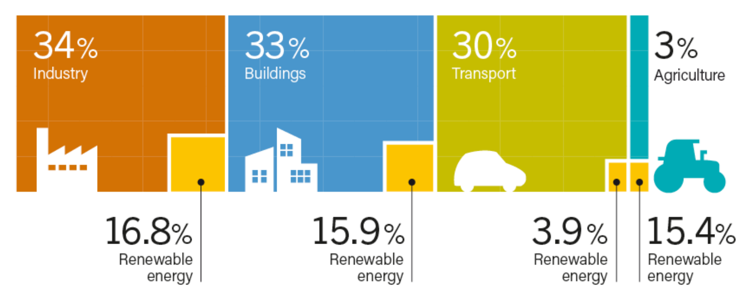


https://www.ren21.net/gsr-2024/

FIGURE 2.
Total Final Energy Consumption and Share of Modern Renewables, by Energy Carrier, 2021



Renewable Share of Total Final Energy Consumption, by Sector, 2021



Pros and Cons of renewables

- **Pros:**

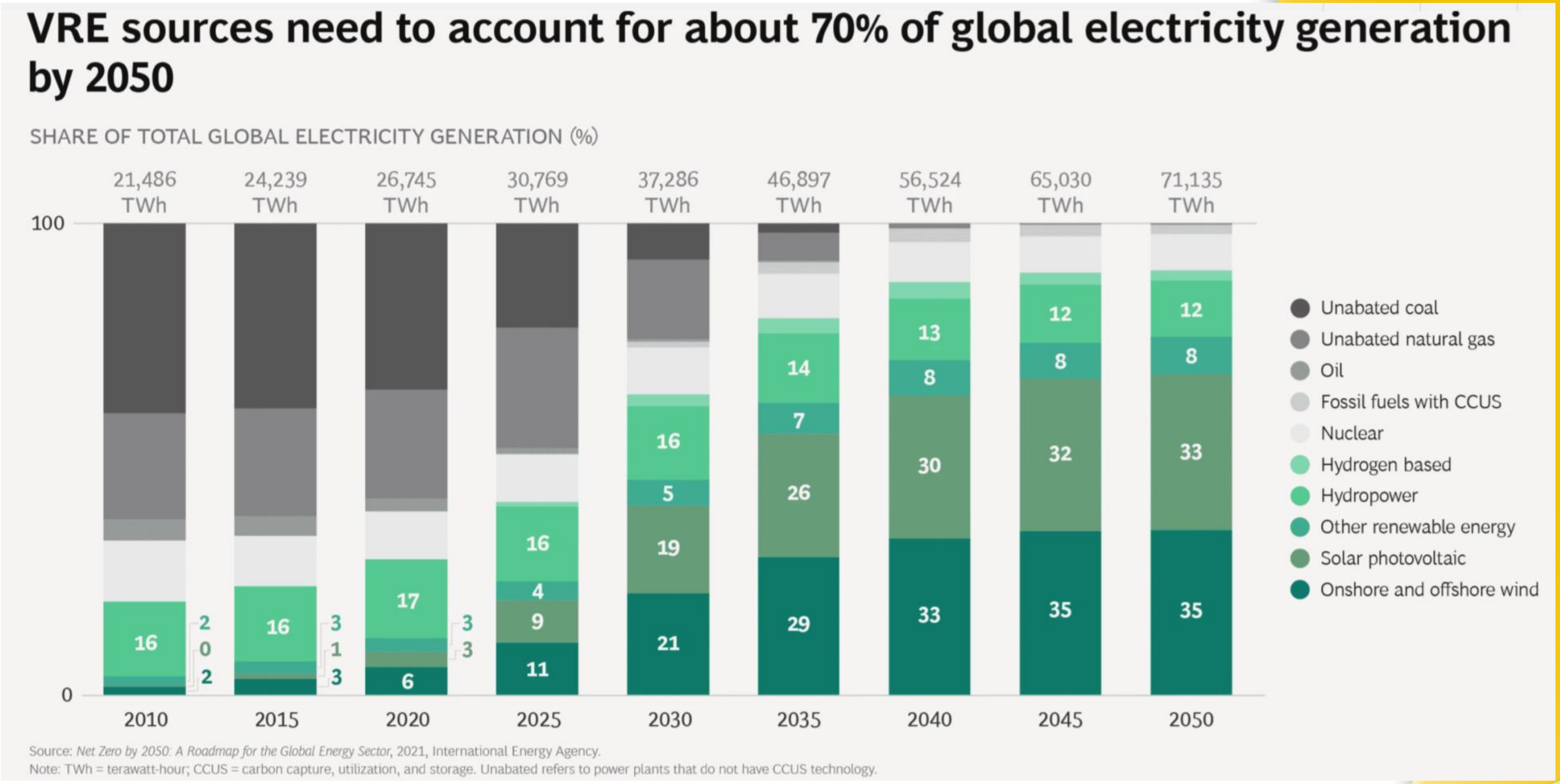
1. **<u>Reduce carbon emissions</u>:** VRES produce little or no carbon emissions, making them an attractive alternative to fossil fuels.
2. **<u>Cost-effective (in non-subsidised markets)</u>:** As technology improves, the cost is decreasing, making them more affordable for consumers.
3. **Zero marginal costs:** cost structure is fixes with few variable costs
4. **<u>Diversifies energy portfolio</u>:** Their use diversifies the energy portfolio, reducing dependence on a single source of energy.
5. **<u>Creates jobs</u>:** Their growth creates jobs in manufacturing, installation, and maintenance of renewable energy systems.
6. **<u>Enhances energy security</u>:** The source of energy is renewable, therefore it increases energy security by reducing dependence on foreign oil and gas.

- **Cons:**

1. **<u>Intermittent supply</u>:** The supply of energy is not always very predictable, making it difficult to rely on them as a primary source of energy in some cases.
2. **<u>Geographic limitations</u>:** They are limited by geography, and some areas may not have enough sunlight or wind to generate a sufficient amount of energy.
3. **<u>Environmental impact</u>:** The production and disposal of some renewable energy technologies may have negative environmental impacts.
4. **<u>Land use</u>:** Large-scale variable renewable energy projects require significant land use, which can be a challenge in densely populated areas.

https://www.linkedin.com/pulse/pros-cons-variable-renewable-energy-sources-modelling-jovanovic-phd/

Net zero



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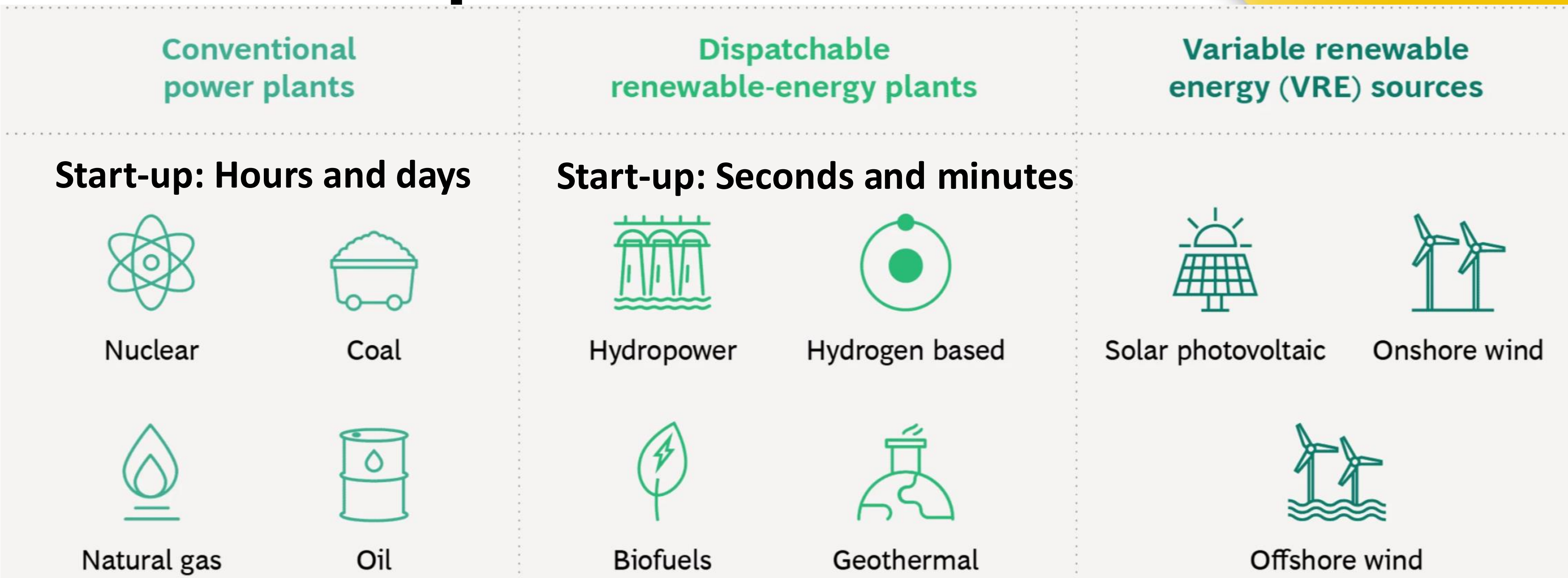
Dispatchable vs variable



- Difference of VRE vs conventional/dispatchable

Variable	Uncertain	Inverter based	Distributed
Generation depends on the sun shining or the wind blowing; energy is not available on demand	Generation remains challenging to predict perfectly, despite increasingly accurate weather-forecasting tools	Power electronic devices interface solar panels and wind turbines with the grid, changing direct current into alternating current	Generators are typically small in scale and distributed broadly across the electrical grid

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VRE-related challenges of 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 →

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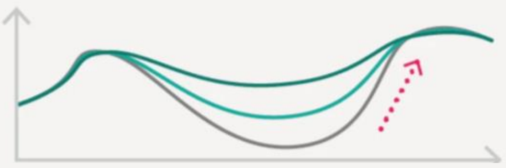
Resource adequacy challenges…

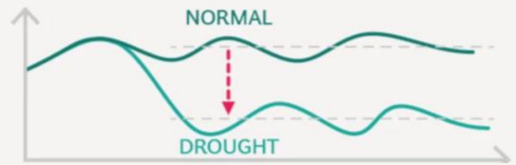


Higher intraday variability

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 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.



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.

- **and solutions**

	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	

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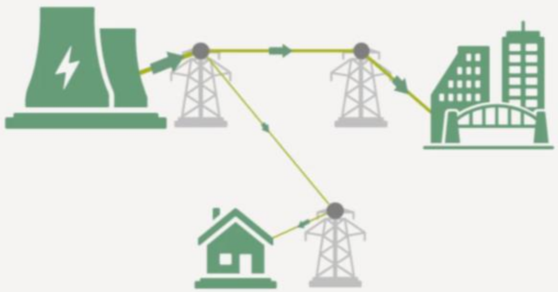
Network adequacy challenges…

Conventional electricity systems

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

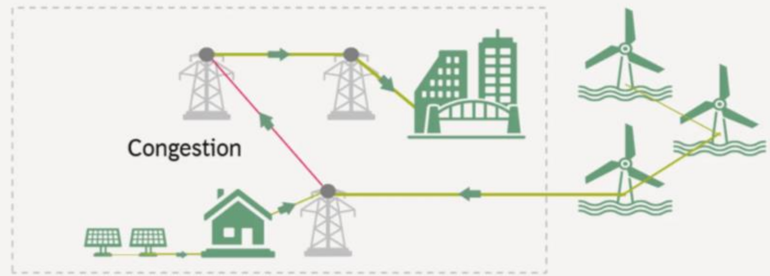
A conventional power plant supplies a city and a village



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]

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



- **and solutions**

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

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Frequency stability challenges…

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

- **and VRE disruption factors**

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.

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Tackling 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

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Solving inertia challenges

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.

- **and addressing visibility and controllability**

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.

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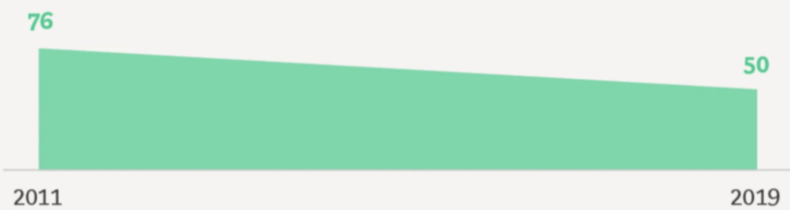
Voltage stability issues

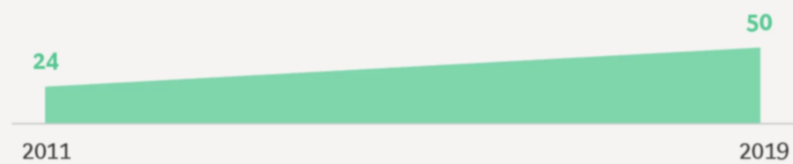
Reduced share of conventional and dispatchable generation
Conventional and dispatchable generation include synchronous machines, which can inject or absorb reactive power to improve system strength. These capabilities diminish as they are phased out.

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 (%)



- **and solutions**

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.

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The views expressed are those of Tatiana Vedeneva and do not necessarily reflect the views of the United Nations

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