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CHAPTER

Integrating renewable energy: Electrical impact on distribution and transmission grids—Part 1

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Learning objectives

After completing this chapter, readers should be able to:

1. Characterize renewable energy variability using quantitative metrics.
2. Analyze the grid integration challenges arising from high renewable penetration.
3. Evaluate energy storage technologies based on their technical characteristics and match them to appropriate grid services.
4. Explain sector coupling concepts and how they enhance grid flexibility and enable long-term energy storage.

1. Introduction

1.1 Global trends in renewable penetration and energy system outlook

The global energy system is undergoing a profound transition toward renewable energy, driven by the imperative to reduce greenhouse gas emissions, ensure long-term energy security, and stimulate sustainable economic growth.[1] This transformation is particularly marked in the electricity sector, where wind, solar, hydropower, geothermal, and bioenergy are rapidly expanding their market shares. According to the International Energy Agency (IEA), renewables are expected to provide nearly 50% of global electricity generation by 2040, with scenarios extending to over two-thirds of the primary energy mix by 2050 under net zero–aligned pathways.[2]

In terms of capacity additions, wind and solar photovoltaic (PV) have been leading globally. The United States, the European Union, and China account for more than two-thirds of annual global additions. China alone installed over 100 GW of solar PV and nearly 70 GW of wind power in 2023, while the European Union and the United States continue to expand their renewables portfolios through both utility-scale and distributed generation. Advanced economies such as Germany, Spain, and Denmark now regularly exceed 40% annual penetration, with hourly values reaching 100% during peak periods.[3,4]

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Environmental benefits are central to the renewable shift. Numerous studies affirm that renewables substantially lower life-cycle greenhouse gas emissions compared to fossil-based systems, while also reducing air and water pollution. Nevertheless, the deployment of large-scale renewables can introduce land-use conflicts and ecological trade-offs, which require thoughtful spatial planning and stakeholder engagement.[5,6] Moreover, the economic implications of this transition are significant. Renewable deployment has contributed to declining electricity costs, increased energy independence, and job creation, particularly in solar manufacturing and wind turbine maintenance.[7] Disparities in technological diffusion and investment persist across regions, often shaped by differences in regulatory frameworks, financing access, and local resource potential.

Crucially, the pace and structure of the transition are strongly influenced by national policy and regulatory environments. The European Union and the United States have established robust policy instruments, such as renewable portfolio standards, tax credits, and carbon pricing schemes, to incentivize clean energy adoption. Europe, through the "Fit for 55" package and subsequent REPowerEU plan, is setting ambitious decarbonization goals for 2030 and 2050. The EU's renewable energy targets include roughly 600 GW of solar PV capacity by 2030, a dramatic increase from current installations. China's central planning model, combined with proactive industrial strategy and infrastructure investment, has made it the global leader in the manufacturing and deployment of clean energy technologies.[5]

Unlike conventional thermoelectric generation, renewable energy sources (RESs) such as wind and solar PVs exhibit inherent variability and intermittency, challenging conventional grid operation and energy dispatch. These characteristics necessitate substantial modifications to both transmission and distribution networks to ensure stability, reliability, and efficiency. Therefore, the increasing share of renewable generation is reshaping grid dynamics, requiring new strategies to accommodate fluctuating power injections, mitigate voltage and frequency deviations, and enhance system resilience.

In this aspect, the role of energy storage systems (ESS) has become pivotal in balancing supply and demand, offering ancillary services such as frequency regulation and peak shaving. Grid modernization efforts, including flexible demand response (DR) mechanisms and power electronic solutions, further contribute to the adaptation of networks to renewable energy integration.

This chapter examines the multifaceted electrical implications of integrating RESs into modern power systems. It provides a comprehensive analysis of the temporal and spatial variability of renewables, introduces quantitative metrics for characterizing their fluctuations, and evaluates the operational and planning challenges arising from their large-scale deployment. The discussion extends across transmission and distribution grids, addressing impacts on power quality, system inertia, and network stability. A central focus is placed on the role of ESSs and their integration into grid architecture, both as technical enablers and market actors. Furthermore, the chapter explores sector coupling strategies that enhance grid flexibility and enable long-term balancing of supply and demand.

2. Characteristics of renewable energy sources

Renewable energy is a bundle of paradoxes from the standpoint of a modern power system operator. Its primary input is inexhaustible and free, yet its electrical output is unpredictable, appearing in bursts and pauses that seldom coincide with the system's instantaneous demand. In traditional fossil energy systems, engineers could schedule generation in half-hour increments and rely on inertia to bridge the

gaps. In a renewable-rich grid, the cadence is dictated not by human dispatch but by cloud shadows across PV power plants and by turbulent vortices whipping wind farms. Intermittency, that is, the on/off availability driven by the resource itself, and variability, that is, the continuous fluctuation of power when the resource is present, combine with technology-specific capacity factors to shape every planning and operational decision, from feeder voltage limits to continental transmission overlays. Moreover, climate change is becoming a growing threat to grid infrastructure. The increasing frequency and intensity of extreme weather events amplify the vulnerability of both generation and grid components, undermining the stability and reliability of future energy systems.[8,9]

2.1 Intermittency and variability

2.1.1 Physical drivers and timescales

Intermittency finds its roots in the geophysical processes and meteorology that govern renewable resources. Within RES, a critical subset is variable renewable energy (VRE), that is, technologies such as wind and solar that are inherently weather-dependent and therefore less predictable than dispatchable renewables like hydropower, geothermal, or bioenergy. Therefore, for different renewables, system operators should pay attention to different production behaviors and timescales.

For solar PV generation, nightfall is a perfectly predictable shutdown, an orbital certainty programmable centuries ahead, yet daylight production is sculpted by the capricious choreography of clouds, aerosols, and atmospheric water vapor columns. A lone cumulus congestus only a kilometer wide, cruising at 10 m/s, can reduce plane-of-array irradiance at a 100 MW facility from 850 to 200 W/m^2 in under 2 min, yanking roughly 60 MW from the grid, far faster than even the nimblest steam control system of a traditional power plant can muster replacement torque.[10] The leading and trailing cloud edges create steep positive ramps as well: irradiance frequently overshoots clear-sky conditions by 10%–15% through cloud-edge lensing, so operators must brace for both deficits and spikes (Fig. 12.1).

Beneath these minute-scale fluctuations lies a rapid subsecond modulation: traveling wavefronts of diffuse irradiance move across rows of PV trackers, causing string-level current variations at frequencies between 2 and 20 Hz.[11] Photovoltaic inverters respond to these variations through kilohertz-rate maximum power point tracking (MPPT) algorithms. However, when many inverters operate simultaneously, their collective output can introduce oscillations into the distribution feeder. These oscillations may interact with low-order harmonic resonances, potentially destabilizing the system unless adequately mitigated by grid-forming control strategies.[12]

In wind energy systems, the variability and smoothing of total power output are strongly influenced by the number of turbines, their geographic distribution, the surrounding topography, and the total installed capacity of the wind farm. Wind generation operates across four nested temporal scales, each transmitting distinct dynamics through the electromechanical conversion chain:

Turbulence ($<$1 s): Eddies shed from upstream obstacles impinge on turbine blades, producing torque fluctuations that excite drivetrain resonances in the 2–4 Hz range.[13] Converter controls must attenuate these disturbances without compromising grid-support functionalities.

Boundary-layer gusts (1–60 s): Gust fronts generated by wind shear can alter the rotor-effective wind speed by more than 3 m/s in less than a minute, causing power output to vary by $\pm$15% (Fig. 12.2). These rapid changes define inverter current limits and impose flicker compliance requirements at the point of common coupling.[14]

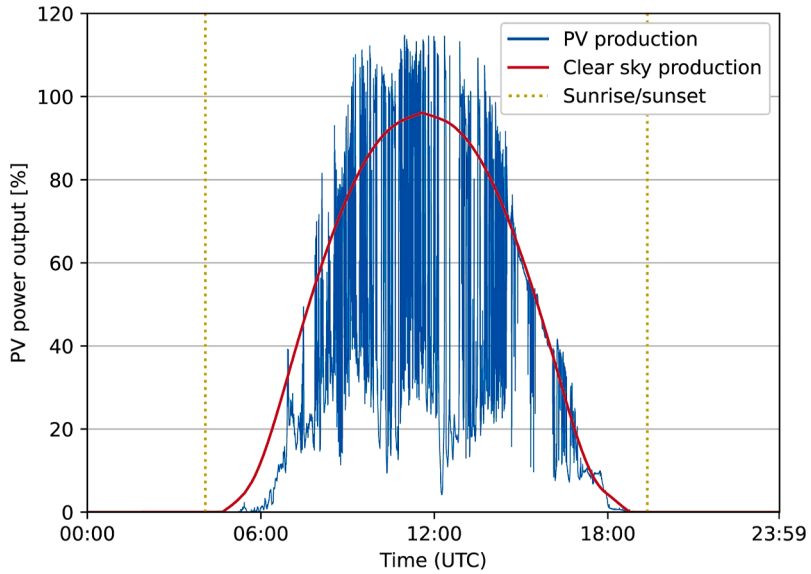

FIGURE 12.1 Variability of PV output under clear-sky and cloudy conditions.

The figure illustrates strong fluctuations caused by passing clouds, leading to rapid ramps in production that deviate significantly from the smooth clear-sky curve. Sunset and sunrise boundaries are also indicated, emphasizing the variability operators must manage within a single day.

From Visser LR, Schuurmans EMB, AlSkaif TA, Fidder HA, van Voorden AM, van Sark WGJHM. Regulation strategies for mitigating voltage fluctuations induced by photovoltaic solar systems in an urban low voltage grid. Int J Electr Power Energy Syst. 2022;137. https://doi.org/10.1016/j.ijepes.2021.107695.

Mesoscale flows (minutes to hours): Diurnal wind patterns, such as sea-breeze circulations or katabatic winds descending mountain slopes, shape medium-term power availability.[15] These effects guide unit commitment strategies and reserve allocations.

Synoptic-scale systems (days): Large-scale weather systems, such as North Atlantic low-pressure fronts,[16] determine the baseline energy yield forecasted on a weekly basis and inform transmission scheduling across interconnectors.

In contrast, run-of-river hydropower presents minimal subhourly variability but exhibits marked fluctuations over weekly to seasonal timescales.[17] For example, the Rhône-Alpine hydro cascade averages 1000 m^3/s of discharge during spring snowmelt but falls to 430 m^3/s in winter.

From an energy system perspective, each region features a distinct mix of renewable technologies, with varying shares of wind, solar, and hydropower. Meteorological conditions affect these sources differently, depending on their nature and local context. Their spatial and temporal responses can either align or diverge, leading to synchronized or desynchronized generation patterns.[18] Notably, when wind and solar outputs fluctuate in opposite phases across locations, their aggregated variability diminishes, a dynamic known as complementarity.[19] A growing body of research highlights the benefits of combining wind, solar, and hydropower within a coordinated portfolio, leveraging the

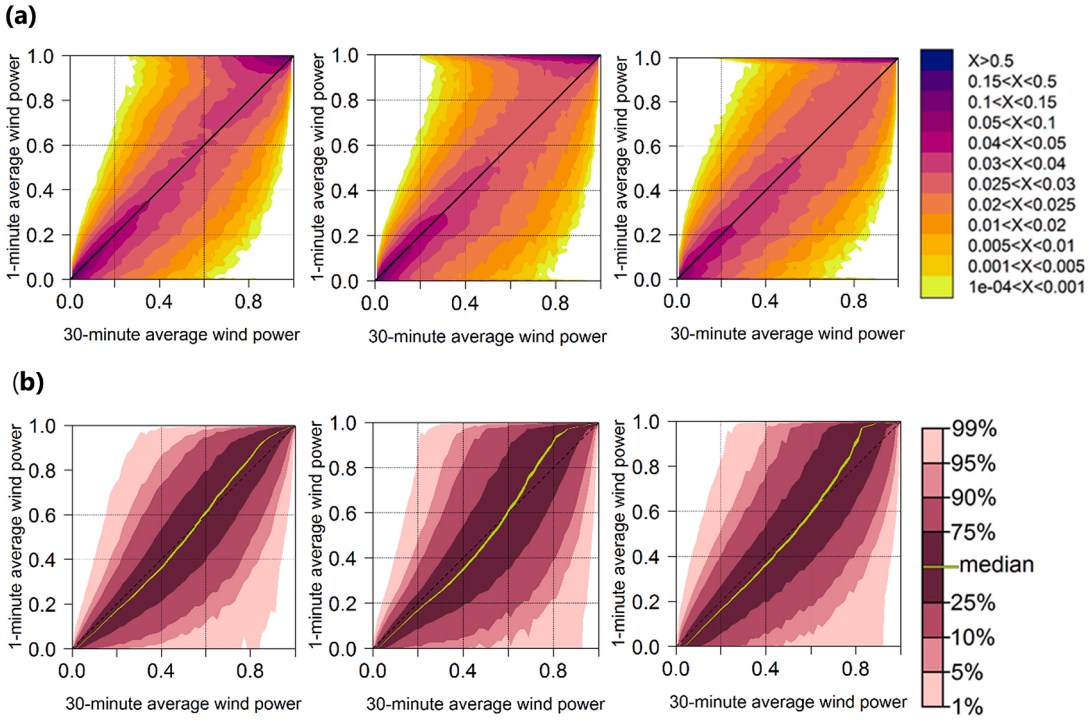

FIGURE 12.2 Conditional probability of short-term wind power fluctuations.

(a) Conditional probability that the 1-min power output within a 30-min period reaches a given value, based on the half-hourly average output. (b) Probability distribution of 10-min power output compared with the 30-min average value. These plots highlight the hidden variability of wind generation when data are aggregated over longer time intervals, underscoring the importance of high-resolution measurements for system integration.

From Ward KR, Bamisile O, Ejiyi CJ, Staffell I. Time-averaged wind power data hides variability critical to renewables integration. Energy Strat Rev. 2023;50. https://doi.org/10.1016/j.esr.2023.101235.

complementary behavior of these resources to mitigate individual intermittencies and improve overall system stability and reliability.

2.2 Quantitative metrics

Achieving high shares of renewable energy, such as wind, solar, and various forms of hydropower, is a central objective in the transition to low-carbon energy systems. Because the output of these resources is highly sensitive to regional meteorological conditions, which vary across locations, engineers rely on a set of compact statistical indices to translate this variability into actionable design and planning parameters.[20] The following subsections introduce and discuss the principal quantitative metrics used in this context.

2.2.1 Coefficient of variation

The coefficient of variation (COV) is a widely employed dimensionless index used to assess the relative variability of power output with respect to its mean.[21] It is particularly relevant in the context of RESs, where fluctuations in generation can challenge the balance and reliability of power systems. The COV is calculated as the ratio between the standard deviation of the power signal over a given interval and the corresponding mean value, typically expressed as a percentage:

$$\mathrm{COV} = \left(\frac{\sigma_1(P_t)}{\overline{P}_{\Delta t}}\right) \times 100\%$$

In this expression, $\sigma_1(P_t)$ denotes the standard deviation of the power output within the selected interval, and $\overline{P}_{\Delta t}$ represents the corresponding mean value. This formulation provides a normalized measure of dispersion, making it suitable for comparing variability across systems with different absolute scales of power production.

Although the COV is commonly applied to quantify wind and solar power variability, it presents notable limitations in capturing the full complexity of stochastic generation. In particular, it does not adequately reflect the spectrum of temporal dynamics associated with renewable sources. The index aggregates variability into a single value, which obscures crucial information about short-term (intrahour or infradiurnal) fluctuations that have significant operational implications for grid stability.[22] Moreover, the COV does not account for spatial variability or correlations across geographically dispersed assets, which are increasingly relevant in high-penetration renewable energy systems.[23]

Different power output profiles may yield identical COV values while exhibiting distinct patterns of fluctuation and ramping behavior. For this reason, relying solely on the COV may lead to an underestimation of the operational challenges posed by highly intermittent resources. A more comprehensive characterization of variability often requires complementary metrics that capture frequency content, ramp events, and the spatial distribution of fluctuations.[24]

Despite its limitations, the COV remains a useful preliminary indicator for assessing relative variability, particularly when used in conjunction with other statistical and spectral tools tailored to the needs of system operators and planners.

2.2.2 Step change index

The step change index is one of the most widely used time-domain indicators to quantify instantaneous variations in renewable energy generation.[19] It captures the difference in wind speed, solar irradiance, or power output between two successive time intervals. The general formulation is given by:

$$\Delta P_t = P_t - P_{t-1}$$

This expression reflects the absolute change in the variable of interest (e.g., power output) between consecutive time steps. To normalize this change, two additional formulations are commonly adopted:

$$\Delta P_c = \left(\frac{P_t - P_{t-1}}{P_c}\right) \times 100\%$$

$$\Delta P_{\max} = \left(\frac{P_t - P_{t-1}}{P_{\max}}\right) \times 100\%$$

In these equations, P_t represents the power output (or meteorological input) at time t, $P_{t\text{-}1}$ is the value at the previous time step, P_c denotes the rated capacity of the system, and $P_{\max}$ indicates the maximum observed value. These normalized indices enable a relative assessment of variability independent of system scale.

Further statistical measures derived from the step change include the average magnitude of fluctuations, the maximum positive and negative excursions, and the standard deviation of changes. These metrics can be applied across a wide range of temporal resolutions, from subminute intervals to multihour or daily scales. The choice of interval depends on both the resolution of the dataset and the specific analytical objectives.

Fig. 12.3 illustrates step changes in wind power output and global horizontal irradiance at different temporal resolutions. As resolution becomes coarser, the magnitude of observed step changes tends to decrease, with large fluctuations appearing less frequently.

These indices serve as valuable tools for system operators and market participants, informing operational decisions such as the provision of ancillary services and the scheduling of energy supply in day-ahead markets.

2.2.3 Ramp rate

The ramp rate represents the rate at which power output or meteorological variables change over a defined time window. It differs from step-based metrics, which focus on immediate point-to-point variations, by considering the cumulative variation between an initial time t and a future time $t + \Delta t$. A ramp event is said to occur when this change exceeds a predefined threshold.

Several formulations are used to define and detect ramp events.[25] A first approach considers the absolute change in power output over the interval Δt and compares it with a threshold value RR_{val}:

$$|P_{t+\Delta t} - P_t| > RR_{\text{val}}$$

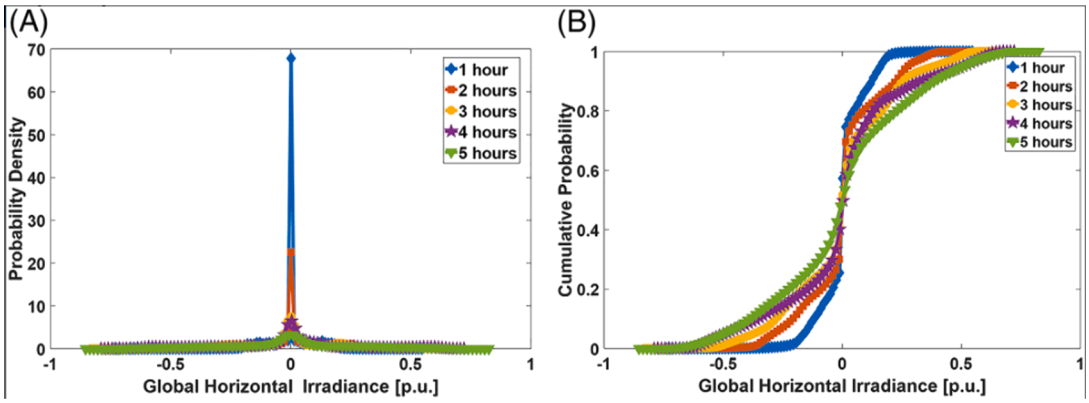

FIGURE 12.3 Step changes in wind power output and irradiance across temporal resolutions.

Distributions of step changes in (A) global horizontal irradiance and (B) wind power output for different temporal resolutions, ranging from subminute to multihour intervals. As the temporal resolution decreases, the magnitude and frequency of large fluctuations decrease, illustrating how temporal resolution strongly influences the characterization of variability.

From Yan J, Qu T, Han S, Liu Y, Lei X, Wang H. Reviews on characteristic of renewables: Evaluating the variability and complementarity. Int Trans Electr Energy Syst. 2020;30(7). John Wiley and Sons Ltd. https://doi.org/10.1002/2050-7038.12281.

An alternative formulation compares the maximum and minimum values of power over a specified time window. If their difference exceeds the same threshold *RR*_val, a ramp event is recorded:

$$\max(P_t) - \min(P_t) > RR_{\text{val}}$$

A more dynamic definition involves calculating the ramp rate itself as the magnitude of change normalized over the interval length Δt and comparing it against a maximum admissible ramp rate RR_{maxr}:

$$RR_{\Delta t}(t) = \frac{|P_{t+\Delta t} - P_t|}{\Delta t} > RR_{\text{maxr}}$$

In these expressions, the ramp thresholds (RR_{val} and RR_{maxr}) are predefined based on system-specific tolerance levels or grid operation criteria. These formulations allow for flexible detection and categorization of ramp events in both generation and resource parameters.

Ramp events may result from atmospheric phenomena such as moving weather fronts, but also from operational disruptions, including scheduled maintenance or unexpected outages. Their impact on power systems is nontrivial, as they introduce sudden imbalances that require fast corrective actions to preserve grid stability.

Ramp events occur in two directions: ramping up, indicating a rapid increase in generation, and ramping down, corresponding to a sharp drop.[26] Downward ramps typically present greater operational challenges, as they necessitate rapid activation of reserves or fast-ramping dispatchable units to compensate for the loss in supply. These corrective measures increase both system risk and cost. In contrast, upward ramps can often be mitigated by curtailing excess renewable output.

Empirical studies have shown that upward ramps in wind power tend to be steeper than downward ones, but the maximum ramp rates in both directions are generally smaller than the magnitudes observed in step changes. As with other variability metrics, ramp rate calculations can be applied across various temporal resolutions, enabling differentiated assessments of short-term and long-term fluctuations. Statistical analyses of ramp rate distributions are also frequently performed to support probabilistic forecasting and reserve allocation strategies.

2.2.4 Spectral decomposition of power variability

Spectral decomposition is a method used to analyze how power output varies over different timescales. Instead of measuring variability with a single number, it shows how much the power output changes at each frequency. This is useful for understanding short-term fluctuations, especially those happening within a day (infradiurnal), which are important for grid stability.[22]

The method starts from the autocorrelation function R(τ) of the power time series, where τ is the time lag. Using the Wiener–Khinchin theorem, this function is converted into the power spectral density (PSD), $S(f)$, through a Fourier transform. To measure the power variability in a specific frequency range, for example, for infradiurnal fluctuations between f_1 and f_2, the following intermittency index is used:

$$I_{\text{spec}} = \frac{\int_{f_1}^{f_2} S(f)\, df}{\overline{P}^2}$$

where $\overline{P}$ is the average power over time. A higher value of I_{spec} means stronger short-term variability.

This method gives more detailed information than standard time-domain metrics, helping system operators and engineers understand not just how much variability exists, but also when and how fast it happens. It is widely used in energy systems, signal processing, and other fields involving time-varying data.

2.2.5 Other metrics for time-varying data

Several other statistical metrics have been developed to characterize the variability of time-varying power output. These indices, while initially designed for renewable energy systems, are broadly applicable to a wide range of dynamic systems governed by stochastic processes.

The average fluctuation magnitude (AFM) offers a straightforward measure of fluctuation intensity. It is computed as the average of the absolute deviations from the mean value, normalized by the number of observations.[27] The mathematical formulation is:

$$\mathrm{AFM} = \frac{1}{n} \cdot \sum \left| P_t - \overline{P} \right|$$

where n is the number of time steps, P_t is the power output at time t, and $\overline{P}$ is the average power over the period considered. This index provides a more intuitive sense of fluctuation scale than variance-based measures, especially when assessing absolute variability without squaring errors.

To capture both the magnitude and the frequency of directional changes in power output, the moving fluctuation intensity (MFI) was introduced. This metric is defined as the product of AFM and the reverse fluctuation count (RFC), which is the number of times the time series changes its trend direction:

$$\mathrm{MFI} = \mathrm{AFM} \times \mathrm{RFC}$$

The RFC component makes MFI particularly sensitive to rapid alternations in trend, which are operationally relevant for assessing control demands in grid systems and are similarly important in time-series applications such as finance and climatology.

Another key index is the deviation from the centered moving average (CMA), which quantifies how much a value deviates from its local trend, computed over a symmetric temporal window centered around each time step:

$$\mathrm{CMA}_{\mathrm{dev}}\ (t) = |P_t - \mathrm{CMA}(t)|$$

This deviation captures the range of local fluctuation while filtering out low-frequency trends, making it a valuable tool in short-term forecasting, anomaly detection, and signal smoothing analyses. The CMA itself is typically computed using a sliding window, such as a 20-min interval (Fig. 12.4), allowing the detection of transient deviations from the local mean.[28]

For evaluating the worst-case variability within a time window, the maximum fluctuation width (MFW) is employed.[29] Unlike point-wise fluctuation indices, MFW identifies the maximum range within a defined period:

$$\mathrm{MFW} = \max(\ P_t) - \min(P_t)$$

This index captures the most extreme fluctuation scenario and is particularly useful in system sizing, reliability assessments, and robustness analyses. A high MFW value indicates a large excursion between the minimum and maximum power outputs, highlighting the need for flexible response capabilities.

These indices, AFM, MFI, CMA deviation, and MFW, are not only instrumental in evaluating the volatility of wind or solar energy production but also represent general tools in the analysis of time-varying signals. They are widely used in disciplines such as econometrics, hydrology, neuroscience, and control theory, where understanding variability and its dynamics is essential. Together, they offer a

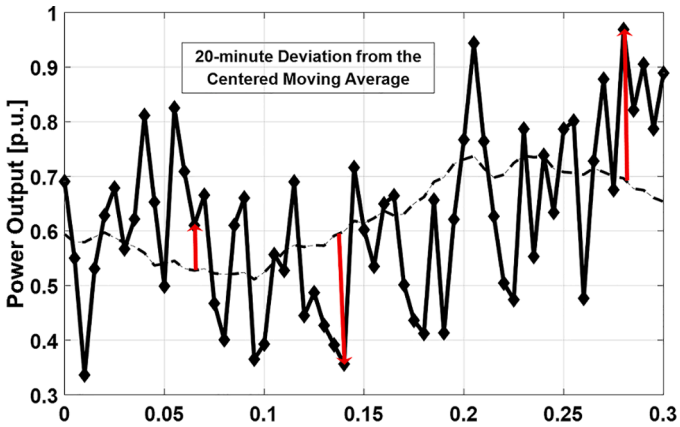

FIGURE 12.4 Deviation from the centered moving average (20-min window).

The CMA_{dev20} index highlights short-term fluctuations around the local mean, effectively capturing transient deviations while filtering out low-frequency trends. This makes it a useful tool for forecasting, anomaly detection, and smoothing analyses.

From David M, Andriamasomanana FHR, Liandrat O. 2014. Spatial and temporal variability of PV output in an insular grid: case of reunion island. Energy Proc. 57;1275–82. Elsevier. https://doi.org/10.1016/j.egypro.2014.10.117.

comprehensive framework to characterize fluctuations across different timescales and signal types, supporting both operational decision-making and theoretical modeling.

2.2.6 Practical use of the variability metric

Each of the metrics discussed offers a different lens through which the variability of RESs can be quantified. Their selection should be guided by the specific operational objective, data resolution, and the temporal characteristics of interest. While scalar indices like the COV and AFM offer quick comparisons, frequency-resolved tools like spectral decomposition provide deeper insight into fluctuation dynamics. Event-based metrics such as step change and ramp rate help assess system response requirements, while moving-window analyses such as CMA deviation and MFW capture local anomalies and extreme events. Table 12.1 summarizes the key features and recommended applications of each metric.

These tools are complementary rather than mutually exclusive. When used in combination, they allow for a multidimensional characterization of variability, balancing simplicity and depth to support both real-time operations and long-term system planning.

2.3 Generation profiles and capacity factors

2.3.1 Temporal signatures of renewable generation

Temporal generation patterns of wind and solar PV and hydropower are strongly shaped by regional climatic conditions, latitude, and local geographic features. These patterns manifest through both diurnal and seasonal cycles, which in turn dictate the operational profile and integration potential of each technology.

Table 12.1 Practical use of variability metrics for renewable energy systems.

Metric	Captures	Main use case	Recommended when
COV	Relative variability (normalized standard deviation)	High-level comparison across systems	Comparing variability regardless of system scale
Step change	Instantaneous variation between steps	Operational planning, ancillary service sizing	Analyzing short-term fluctuations at fixed time resolution
Ramp rate	Cumulative change over Δt	Reserve planning, ramp forecasting	Identifying operational risks from sudden rises/drops
Spectral decomposition	Frequency-specific variability	Diagnosing infradiurnal fluctuations, model calibration	Detailed understanding of fluctuation timescales
AFM	Average magnitude of deviations	Simple variability assessment	Data smoothing or when standard deviation is not robust
MFI	Magnitude $\times$ frequency of direction changes	Grid control stress, regulation needs	Evaluating rapid power direction reversals
CMA deviation	Deviation from local trend	Short-term forecasting, anomaly detection	Capturing local deviations from smoothed output
MFW	Maximum peak-to-peak variation	System design, worst-case scenario analysis	Identifying largest fluctuation in given time window

Solar PV generation follows a predictable diurnal curve (Fig. 12.5), with output rising in the morning, peaking near solar noon, and declining toward sunset. However, actual profiles are modulated by local cloud cover, humidity, and aerosol levels, which can induce high-frequency fluctuations even under partially clear skies.[30,31] Seasonal differences are pronounced, particularly at higher latitudes, where variations in daylight duration and solar elevation angles affect output. For example, in northern and central Canada, summertime solar potential is significantly higher than in winter, requiring careful system design to maintain year-round performance. In colder climates, modules with favorable temperature coefficients may achieve higher efficiencies during cool, sunny periods, partially offsetting winter deficits.[32]

Wind power exhibits substantial intraday and seasonal variability. Diurnally, its output is highly sensitive to evolving weather systems, with fluctuations occurring over short timescales due to turbulence and local atmospheric conditions. Larger wind farms can mitigate this volatility through spatial averaging, particularly for fluctuations on sub-12-h timescales.[33] Seasonally, wind generation in temperate climates tends to peak during winter months due to enhanced wind speeds driven by atmospheric circulation patterns.[34] In northern Europe, for example, wind production correlates better with electricity demand during the colder months than solar energy does.[35] At a broader scale, wind resources vary markedly with latitude and climate: in Ethiopia, for instance, wind speeds follow a diurnal pattern that coincides with peak demand, improving the system's effective capacity credit.[36]

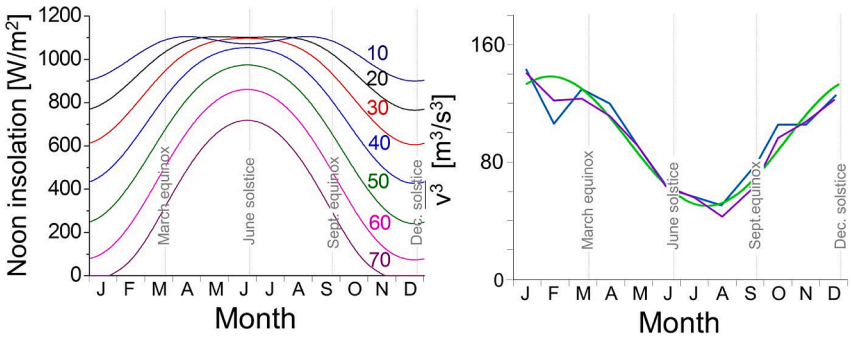

FIGURE 12.5 Seasonal variations in solar irradiance and wind resources.

Left panel: Monthly variation of solar irradiance at noon across different northern latitudes, showing stronger irradiance in summer and weaker values in winter. Right panel: Average of the cubed wind speed (v^3) across US onshore (*blue*) and offshore (*purple*) sites, illustrating seasonal and locational differences in wind resource intensity.

From Mulder FM. Implications of diurnal and seasonal variations in renewable energy generation for large scale energy storage. J Renew Sustain Energy. 2014;6(3). https://doi.org/10.1063/1.4874845.

Hydropower, while less sensitive to intraday meteorological changes, shows strong seasonal modulation depending on precipitation cycles, snowmelt, and reservoir levels. In alpine and snow-fed regions, output typically rises during spring and early summer due to runoff and declines during dry months.[37] In Northern Italy, run-of-river plants demonstrate low hourly variability but exhibit significant changes on daily-to-monthly timescales due to hydrological conditions.[38] In many parts of Africa, hydropower offers a crucial counterbalance during dry periods when wind and solar may underperform.[39] Operationally, hydropower's flexibility and dispatchability allow it to follow load variations more effectively than wind or solar, making it a cornerstone for balancing renewable variability.[40,41]

In Fig. 12.6, the generation profiles of hydropower, wind, and solar PV sources are shown over the course of a typical day. The curves illustrate the average diurnal patterns derived from hourly data, while the shaded areas indicate the corresponding standard deviations, capturing the typical range of variability for each resource. These profiles highlight the distinct temporal dynamics of each source: solar PV follows a predictable daytime pattern centered around midday; wind power tends to exhibit more irregular fluctuations; and hydropower typically reflects operational strategies and water availability rather than direct solar or wind forcing.[36]

2.3.2 Renewable energy source capacity factor

Although generation profiles capture the temporal dynamics of renewable resource availability, they offer only a qualitative perspective on variability. A more synthetic indicator is required to evaluate how effectively an installation exploits its rated capacity over time. This role is assumed by the capacity factor, which quantifies the ratio between actual energy output and the theoretical maximum under continuous full-capacity operation.

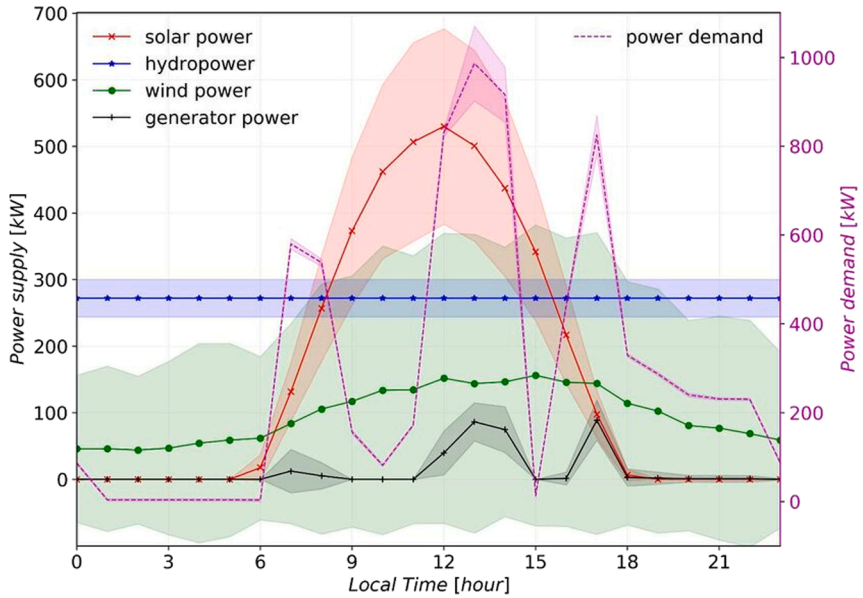

FIGURE 12.6 Diurnal variations in power generation from multiple renewable sources.

Shaded areas indicate the corresponding standard deviations based on hourly measurements, highlighting the variability and complementarity of different renewable energy sources throughout the day.

From Gezahegn GT, Hatiye SD, Ayana MT, Ayalew AT, Minda TT. The hydro, wind and solar hybrid power generation and balancing energy supply-demand for Seyemtribua rural village in northern Ethiopia. Research Square. https://doi.org/10.21203/rs.3.rs-632374/v1.

The capacity factor of a renewable energy system is defined as the ratio between the actual electrical energy produced over a given period and the energy that would have been generated if the system had operated at its full rated capacity continuously during that same interval. It is calculated using the following equation:

$$CF = \frac{E_t}{P_n \times t}$$

where E_t is the total electrical energy generated during the time period t, typically measured in kilowatt-hours (kWh) or megajoules (MJ); P_n is the rated capacity of the system, expressed in kilowatts (kW); and t is the duration of the considered time interval, usually in hours or years.

This dimensionless indicator provides a normalized measure of performance that accounts for both resource availability and technological constraints, and it is instrumental in comparing the productivity of different generation technologies and regions.[42]

Capacity factors vary substantially across renewable technologies. Wind power systems typically achieve capacity factors in the range of 20%–40%, influenced by site-specific wind speed distributions and turbine design. For instance, in the western United States, systems with identical average capacity factors can yield different marginal benefits depending on curtailment and spatial wind patterns,

underscoring the need to evaluate incremental capacity contributions.[43,44] Solar PV systems, constrained by daily irradiance cycles and meteorological variability, generally exhibit capacity factors between 10% and 25%. In countries like Germany, curtailment and grid limitations have been shown to reduce effective capacity factors by up to 70%.[42]

Geographical variation further modulates these values. In the United States, wind farms in the Great Plains benefit from sustained wind regimes and reach some of the highest capacity factors nationally, while solar installations in the Southwest outperform those in northern latitudes due to superior irradiance.[45] In Europe, regional interconnection and crossborder balancing reduce storage requirements and improve renewable utilization, thereby optimizing effective capacity factors.[46] In China, complementary allocation of wind and solar in provinces such as Xinjiang and Qinghai enhances overall system performance by reducing aggregate output variability.[47]

Fig. 12.7 illustrates both the average and weighted-average capacity factors observed globally for different energy technologies.[45] These aggregated values offer a useful benchmark for assessing the general performance of each technology type. As solar and wind power continue to expand and mature, their typical capacity factor ranges have become increasingly well established and reliable.

The capacity factor of wind and solar power plants is governed by a complex interplay of physical, technological, and infrastructural factors. For wind systems, sustained high wind speeds directly enhance energy yield, but the variability and intermittency of wind patterns, especially at low altitudes, can diminish long-term reliability. In solar PVs, the intensity of solar radiation is the dominant input, though elevated ambient temperatures and high humidity can reduce panel efficiency and thereby lower the effective capacity factor.[48]

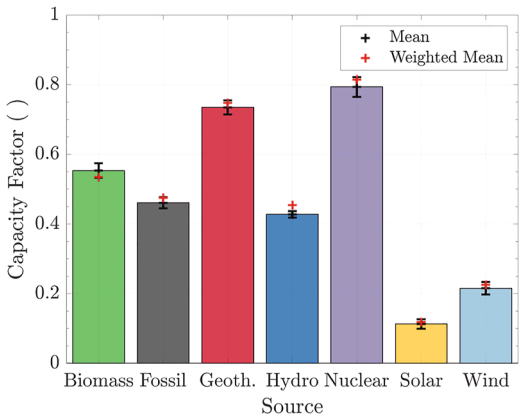

FIGURE 12.7 Capacity factors for renewable and nonrenewable power generation sources.

Comparison of global mean and weighted mean capacity factors for different energy technologies, including biomass, fossil fuels, geothermal, hydro, nuclear, solar, and wind. These aggregated indicators provide a benchmark for evaluating the typical performance and reliability of renewable and conventional generation sources.

From Bolson J, Prieto A, Patzek T. Capacity factors for electrical power generation from renewable and nonrenewable sources. Proc Natl Acad Sci. 119(35), e2205429119. https://doi.org/10.1073/pnas.2205429119.

Geographical siting remains one of the most influential determinants. Wind farms located in areas with high average wind speeds, such as coastal regions or elevated terrains, and solar plants situated in high-irradiance latitudes consistently report superior capacity factors.[49] In contrast, installations in suboptimal locations suffer from derated performance regardless of system design.

Design innovations further modulate energy capture. Solar plants equipped with single- or dual-axis tracking systems can follow the sun's path, significantly boosting daily energy output compared to fixed-tilt arrays, although their effectiveness depends on site characteristics and economic feasibility.[50] For wind turbines, increasing hub height, optimizing rotor diameter, and using advanced blade materials have all contributed to higher extraction efficiencies from turbulent wind flows.

Capacity factors are also sensitive to grid-related constraints. Where transmission infrastructure is limited or inflexible, even well-sited plants may experience significant curtailment, especially during periods of high renewable penetration. This effect is well documented in regions with inadequate interconnection or balancing capacity, where transmission bottlenecks depress the practical capacity factor below its theoretical value.[42,51] High-penetration systems, such as those in Germany, have experienced curtailment levels that diminish the usable capacity factor of wind and solar installations by up to 60% and 70%, respectively.[42] As such, the effective capacity factor must be distinguished from the theoretical maximum, as it reflects real-world constraints and system-level limitations.

Finally, land-use intensity and socioeconomic factors influence large-scale deployment. Wind farms, due to their lower power density, require more land area per unit of energy produced than PV systems, affecting siting decisions and long-term capacity factor expectations.[52] Broader demographic dynamics, such as population growth and urban expansion, reshape load profiles and renewable siting opportunities, indirectly altering achievable capacity factors over time.

Table 12.2 presents the capacity factors for the various technologies and regions. At the global level, the differences between the arithmetic mean and the weighted mean are relatively minor. However, at the regional scale, these differences can be substantial. In some cases, a few dominant energy producers significantly influence the weighted average. For example, in Oceania, the values are largely shaped by Australia's energy production, while in Latin America, Brazil alone accounts for approximately half of the region's total hydroelectric output, heavily affecting the regional average for hydropower.

Table 12.2 Capacity factors by region and technology.

Region	Biomass	Fossil	Geothermal	Hydro	Nuclear	Solar	Wind
Africa	0.32	0.31	0.56	0.44	0.80	0.17	0.26
Asia	0.37	0.41	0.65	0.37	0.72	0.14	0.23
CIS	0.34	0.32	0.60	0.37	0.72	0.10	0.12
Europe	0.53	0.37	0.63	0.38	0.83	0.10	0.21
L. Am.	0.37	0.36	0.67	0.47	0.77	0.20	0.27
N. Am.	0.62	0.44	0.72	0.48	0.85	0.14	0.26
Oceania	0.32	0.40	0.87	0.45	–	0.15	0.22
World	0.55	0.46	0.74				

Adapted from Bolson J, Prieto A, Patzek T. Capacity factors for electrical power generation from renewable and nonrenewable sources. Proc Natl Acad Sci. 2022;119(35), e2205429119. https://doi.org/10.1073/pnas.2205429119.

2.3.3 Variable renewable energy aggregation and spatial smoothing

The geographical distribution of VRE plants, such as wind and solar installations, plays a fundamental role in mitigating generation variability through spatial smoothing effects.

When VRE systems are deployed across diverse locations, as shown in Fig. 12.8, their power outputs, each affected by local meteorological conditions, tend to be only partially correlated. This partial correlation reduces overall variability in aggregated generation profiles.[53–56]

Spatial dispersion ensures that not all plants experience the same weather disturbances at the same time. For instance, a cloud front may shade one solar farm while another, located tens of kilometers away, remains unaffected. Similarly, wind speeds tend to peak at different times across distant sites, particularly in regions with pronounced diurnal or synoptic cycles.[54,57] This temporal diversity spreads generation over time, moderating ramp rates and decreasing dependence on fast-response reserves.

Aggregation across dispersed VRE sites leads to mutual smoothing effects, which are especially pronounced in PV systems.[58] Numerous studies have shown that the combined output of spatially distributed PV units exhibits significantly lower power fluctuation amplitudes than that of individual installations. In regions such as India, where local wind conditions vary on an hourly basis, such aggregation enables diurnal smoothing that is essential for maintaining grid frequency and reducing the need for active control interventions.[59]

The smoothing benefits also extend to system operations. Distributed generation reduces the demand for operating reserves, including regulation, ramping, and load-following services, by decreasing both the amplitude and frequency of power deviations. From a system planning

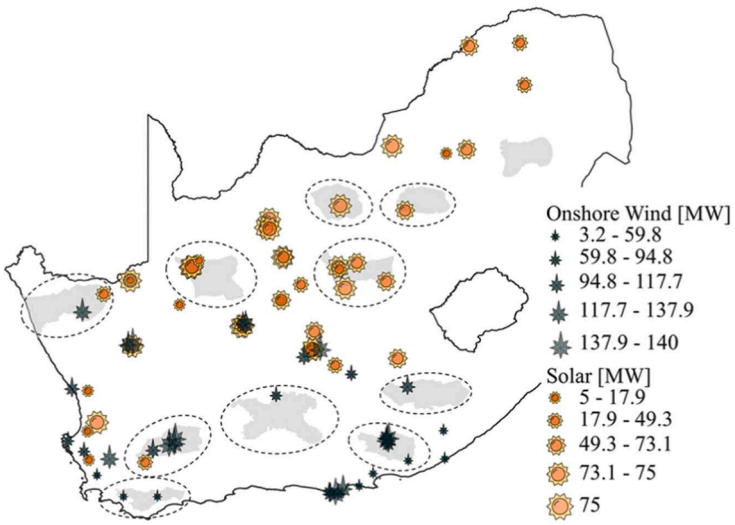

FIGURE 12.8 Geographic distribution of operational wind and solar power plants in South Africa.

Wind installations (measured in MW) and solar plants (measured in MW) are represented with different colored markers, with symbol size indicating installed capacity ranges. The figure highlights the clustering of renewable projects in resource-rich regions.

From van Staden CY, Vermeulen HJ. Geospatial optimisation of wind and solar energy generation: a framework for optimized resource allocation. Sustain Energy Grids Netw. 2024;39, 101389. Elsevier. https://doi.org/10.1016/j.segan.2024.101389.

perspective, optimizing the geographic siting of VRE plants can help mitigate residual load risks and better match generation profiles with demand patterns.[53]

Geographical complementarity between different VRE sources, such as wind and solar, can also be leveraged. Colocating technologies with distinct but complementary generation patterns allows planners to reduce net variability and improve supply reliability. For instance, on calm and sunny afternoons, solar output is typically high while wind tends to be low. The opposite may occur at night or during storm events, creating a natural balancing effect between the two sources.[60]

2.3.4 Challenges of renewable integration on the power network

2.3.4.1 Operational challenges from intermittency

The integration of intermittent RESs, notably wind and solar, introduces multifaceted operational challenges for balancing real-time supply and demand. These challenges arise primarily from the weather-dependent nature of RES and their limited controllability: unlike conventional generators, RES cannot be dispatched on demand, as their output depends on meteorological conditions.[61]

One of the primary concerns is maintaining frequency and voltage stability. Because power generation and consumption must be balanced at every moment, fluctuations in RES output can produce short-term imbalances. If left uncorrected, these can propagate through the system as frequency deviations or localized voltage excursions, undermining the reliability and safety of the grid.[62]

Network congestion is another critical issue, particularly during periods of high RES output combined with low demand or insufficient transmission capacity. Excess electricity injected into the grid can exceed the carrying capacity of local infrastructure, triggering protection mechanisms and necessitating curtailment of renewable output to preserve system integrity.[51]

These dynamics highlight the growing need for operational flexibility, the capacity of the system to respond rapidly to variability and uncertainty (Fig. 12.9). This includes the use of fast-ramping generators, grid-scale ESSs, and responsive demand-side resources that can either absorb excess energy or reduce load instantaneously.[63]

To manage this complexity, power systems must increase their reliance on reserves and ancillary services, such as spinning reserves that can be activated quickly, voltage-support mechanisms, and automated frequency control. These services provide the necessary buffer to handle sudden imbalances between generation and load.[64]

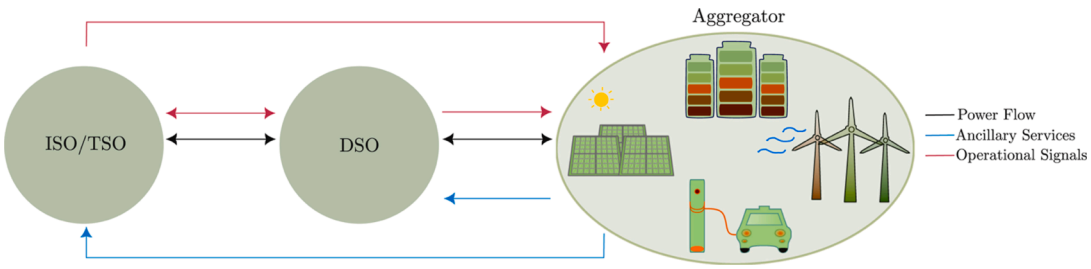

FIGURE 12.9 Conceptual framework for multiactor coordination in power systems.

The diagram shows the role of bidirectional information exchange in enabling the delivery of electricity and grid services through distributed energy resources.

From Viola L, Mohammadi S, Dotta D, Hesamzadeh MR, Baldick R, Flynn D. Ancillary services in power system transition toward a 100% non-fossil future: Market design challenges in the United States and Europe. Electr Power Syst Res. 2024;236, 110885. Elsevier. https://doi.org/10.1016/j.epsr.2024.110885.

Demand response and ESSs play a crucial role in compensating for the variability of RESs. Demand response allows for the flexible adjustment of electricity consumption, shifting loads to match the availability of renewable generation. Energy storage system enables surplus electricity to be stored during periods of high RES output and released when generation drops or demand peaks, enhancing the overall resilience of the grid.[65]

2.3.5 Economic impacts of renewable penetration

The growing share of VRE, such as wind and solar, is not only reshaping the physical operation of power systems but also fundamentally altering the economic logic of electricity markets. Among the most prominent consequences is the merit-order effect, a structural shift whereby renewable sources with near-zero marginal costs consistently outcompete traditional generators in wholesale markets. While this appears advantageous for consumers through lower electricity prices, it also undermines the financial viability of conventional power plants and flexible assets, which remain essential for maintaining grid stability under high-VRE scenarios. This duality reveals a central paradox of the energy transition: decarbonization policies that succeed in lowering market prices may inadvertently discourage the very flexibility and reliability mechanisms on which the system depends.[66,67]

A closely related phenomenon, the cannibalization effect, describes how increased VRE penetration also reduces the market revenues of renewables themselves, particularly solar PV, due to oversupply during peak generation hours.[66] Fig. 12.10 highlights a clear diurnal trend, where increased

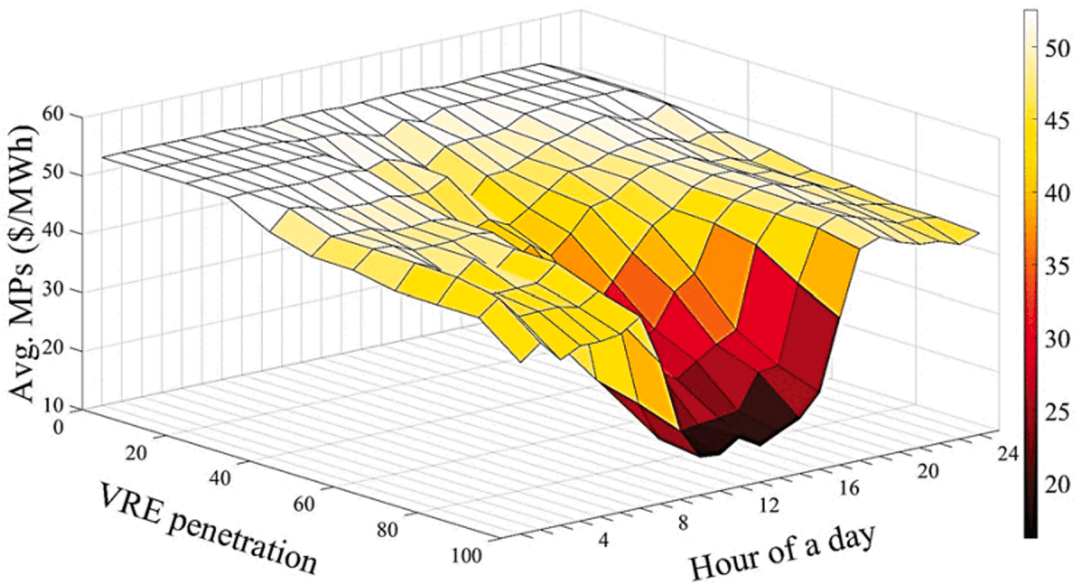

FIGURE 12.10 Impact of variable renewable energy (VRE) penetration on marginal electricity prices.

The figure illustrates how increasing shares of VRE lead to a clear diurnal trend, with higher penetration during sunny or windy intervals associated with downward pressure on electricity prices, reflecting the cannibalization effect observed in liberalized power markets.

From Imcharoenkul V, Chaitusaney S. The impact of variable renewable energy integration on total system costs and electricity generation revenue. IEEE Access, 2022;10, 50167–50182. IEEE. https://doi.org/10.1109/ACCESS.2022.3172284.

VRE shares, particularly during mid-morning hours, coincide with a pronounced reduction in electricity market prices. This has been observed across several liberalized power markets, including PJM and ERCOT, where day-ahead market signals reflect the downward pressure on prices during sunny or windy intervals.

As VRE shares increase, markets exhibit heightened price volatility, with more frequent occurrences of both extremely low and high marginal values of energy (MVEs). This volatility complicates revenue adequacy for all technologies, especially capital-intensive renewables that rely on a limited number of high-price hours to recoup their investment.[68] Without targeted reforms, this revenue uncertainty may jeopardize the financial viability of essential generation and storage assets. Moreover, the integration of VRE introduces additional system costs, including balancing, ramping, and reserve requirements. These integration costs can erode the economic attractiveness of renewables despite their falling levelized cost of energy (LCOE). Analysis shows that while these costs remain modest up to about 70% VRE penetration, they increase nonlinearly beyond that threshold, particularly in systems lacking sufficient flexibility.[69]

Curtailment is another economic inefficiency that emerges in high-VRE systems (Fig. 12.11). It occurs when renewable output exceeds demand or grid capacity, forcing operators to discard usable energy. In extreme cases, marginal curtailment can approach 50%, with significant financial losses. This issue gives rise to market failures, where VRE investors respond to average curtailment signals rather than marginal system impacts. Corrective mechanisms, such as locational marginal pricing or curtailment-adjusted grid fees, are necessary to restore efficiency and signal optimal asset placement.[70]

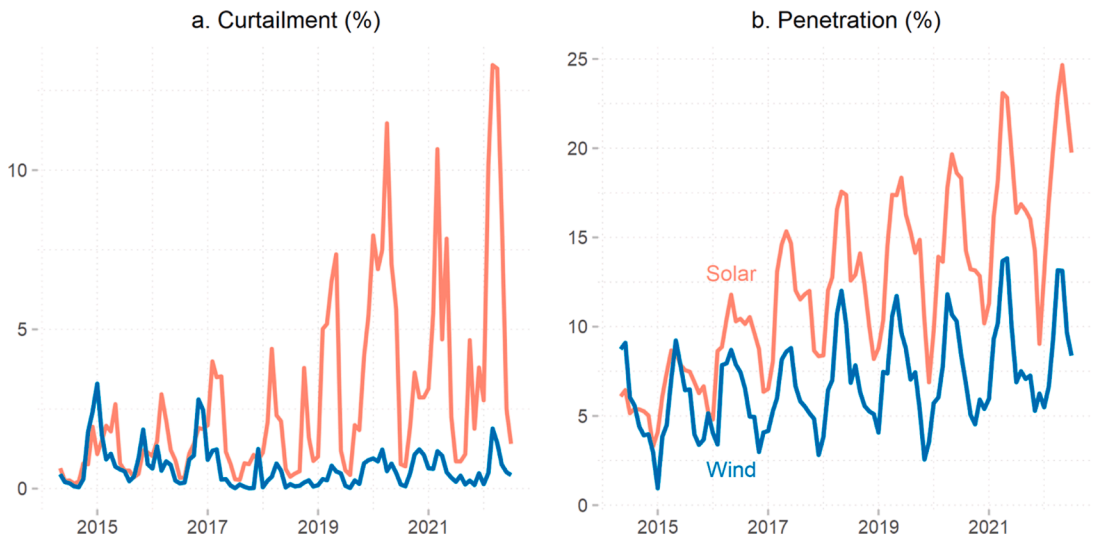

FIGURE 12.11 Monthly curtailment rates and penetration levels of solar and wind in California.

(a) Monthly trends in curtailment rates of solar and wind energy, expressed as a percentage of their potential generation. (b) Penetration levels of solar and wind relative to electricity demand over an 8-year period in California. The figure highlights how higher renewable penetration correlates with increased curtailment, underscoring integration challenges in high variable renewable energy (VRE) systems.

From López Prol J, Zilberman D. No alarms and no surprises: Dynamics of renewable energy curtailment in California. 2023;Energy Econ. 2023;126, 106974. Elsevier. https://doi.org/10.1016/j.eneco.2023.106974.

Therefore, high-VRE penetration reduces electricity prices while supporting decarbonization, but it also destabilizes traditional market structures and revenue models. Addressing these challenges requires innovative market designs that value flexibility, ensure investment adequacy, and align economic signals with system needs.[71]

2.4 Enabling technologies for modern power system flexibility

The integration of VRE sources into modern power systems presents multifaceted challenges, particularly with regard to grid stability, energy storage, and infrastructure adaptability. As the penetration of VRE increases, these challenges become more pronounced, necessitating a systemic transformation through infrastructure digitalization, the deployment of advanced ESSs, and the adoption of digital modernization strategies. These approaches are designed to increase the responsiveness, efficiency, and resilience of power systems while accommodating the inherent variability of renewables.[64]

A foundational component of this transformation is infrastructure digitalization, which refers to the application of digital technologies and data-driven tools to enhance the planning, construction, operation, and maintenance of energy infrastructure. This process enables real-time monitoring, predictive maintenance, and efficient resource deployment through the continuous integration and analysis of data across the asset life cycle. Effective digitalization depends on the standardization and interoperability of data formats, allowing for seamless communication between diverse systems and stakeholders.[72] Tools such as building information modeling (BIM) and digital twins play a central role in this context by creating dynamic, data-rich representations of physical infrastructure. These technologies not only improve coordination during project execution but also support long-term sustainability goals by reducing environmental impacts and extending infrastructure longevity.[73] Furthermore, the digital modernization of power systems has introduced new paradigms for managing distributed and variable energy flows. Virtual power plants (VPPs) enable the aggregation of distributed energy resources, such as rooftop PV, small-scale wind, and battery storage, into a single controllable entity capable of providing ancillary services and participating in electricity markets.[74] In addition, digital twin-enabled traffic shaping in smart urban environments allows for the real-time coordination of energy demand and supply across complex networks, ensuring low-latency responses and enhancing system connectivity.[75]

In parallel, ESSs constitute a foundational element for the successful integration of VRE by addressing the intrinsic temporal decoupling between generation and consumption. Technologies such as lithium-ion batteries, redox flow batteries, and advanced bidirectional power converters allow for the dynamic balancing of energy flows by storing excess electricity during surplus generation periods and releasing it when demand peaks. This capability not only reinforces grid reliability but also mitigates the curtailment of renewable output and enhances the effective utilization rate, that is, the capacity factor, of VRE assets. Moreover, ongoing progress in storage materials, system architecture, and intelligent control algorithms further strengthens the adaptability and economic viability of ESS across diverse grid conditions and temporal scales.[76]

Another essential innovation is virtual inertia control, which addresses the declining physical inertia in inverter-dominated systems. In traditional power systems, inertia is naturally provided by the rotating mass of synchronous generators, which act as a buffer against sudden changes in grid frequency. This inertia slows down the rate of frequency deviation following disturbances, granting operators critical time to respond. However, inverter-based renewable sources, such as solar PV and wind turbines, do not inherently provide such inertial response. Virtual inertia control technologies aim to replicate this function by using advanced power electronics and control algorithms to rapidly inject

or absorb power in response to frequency changes. In doing so, they stabilize system frequency and improve the dynamic response of the grid, ensuring secure and reliable operation even under high shares of nonsynchronous generation.[77]

Despite the clear potential of these solutions, implementation remains uneven. Infrastructure upgrading can provide synergistic benefits for carbon and pollution reduction, as demonstrated by large-scale national programs.[78] However, operationalizing such transitions involves overcoming data heterogeneity, ensuring cybersecurity, and achieving economic viability. Particularly in developing countries, the adoption of digital tools like BIM is constrained by limited technical and financial resources.[79] Addressing these challenges requires coordinated efforts across public and private sectors, supported by sustained investment and adaptive regulatory frameworks.

As the share of VRE continues to grow, the ability to buffer temporal mismatches between generation and demand becomes not only advantageous but structurally necessary. Storage thus shifts from a complementary role to a systemic enabler of operational flexibility, market efficiency, and long-term grid resilience. The following sections explore in detail how storage technologies interact with electrical networks, their integration logics, technical functionalities, and broader implications for a secure and decarbonized energy transition.

3. Integration of storage systems in electrical grids

3.1 Role of energy storage systems

Achieving such high penetration of intermittent RESs in the electricity mix will require a flexible and resilient power grid. In particular, the distribution network, where a growing share of solar PVs and other distributed generators are connected, must be capable of handling intermittent, bidirectional power flows while maintaining power quality and reliability. This necessitates new approaches to balance supply and demand at the local level, beyond the traditional design of passive distribution feeders.

One of the most promising solutions to enhance grid flexibility is the widespread deployment of ESSs in distribution networks. By decoupling the timing of generation and consumption, ESS can buffer the fluctuations of VRE and provide backup capacity to shave peak loads and fill demand troughs. Battery ESSs have become the most prominent solution in recent deployments, owing to their rapid response, modularity, and improved economics.

Utility-scale and behind-the-meter batteries are increasingly used to compensate for the variability of solar and wind, ensuring that a higher share of renewables can be safely and efficiently integrated into the grid.[80]

Among storage options, lithium-ion batteries currently dominate new deployments, thanks to their maturity, high responsiveness, and rapidly declining costs.[81]

In this context, the following sections outline the key operational benefits that ESSs offer to distribution networks, with particular emphasis on their role in providing ancillary services, enhancing load balancing, and reducing peak demand. In addition, the sections discuss the main regulatory and economic barriers hindering large-scale storage deployment. Finally, an overview is provided of the potential of energy storage to act as both an enabler and a catalyst for sector coupling.

3.2 Benefits of storage in providing ancillary services, load balancing, and peak shaving

Beyond their local use to integrate renewables, distributed ESSs play a crucial role in supporting overall grid operations. Energy storage can provide multiple services to the distribution system, often

simultaneously. Key benefits include: (1) peak load shaving and load leveling to manage demand spikes, (2) ancillary services such as frequency regulation, reserves, and voltage support, and (3) improved network performance via loss reduction and power quality control (Fig. 12.12). These functions help transition distribution grids from passive networks to active, flexible systems.

By mitigating demand peaks and balancing daily load profiles, storage reduces stress on distribution infrastructure and postpones the need for costly grid reinforcements.

At the distribution network level, peak shaving by aggregated utility-owned storage can defer costly infrastructure upgrades. Rather than reinforcing a substation or reconductoring lines to meet a few hours of annual peak demand, a battery can supply those peaks and postpone the need for new cables or transformer capacity.

On the other hand, by flattening load profiles (load leveling) across time, storage increases the utilization of existing grid assets and extends their lifetime. In fact, flattening the demand curve over time ensures that no part of the network is either under- or overloaded while generation and consumption are matched.[82] Practically, batteries can contribute to load balancing by shifting energy from times of surplus to times of deficit (also known as energy time shifting or arbitrage). This could mean charging from midday excess PV and discharging in the evening, which supports the grid and improve renewable utilization.[80]

There is also evidence that optimally locating storage maximizes these benefits. Research on loss minimization and voltage support in radial networks suggests that placing ESS at the most sensitive nodes yields the highest reduction in losses per kWh of storage installed. In practice, this means targeting sections of the feeder that heavily contribute to peak flows or voltage drops. Planning tools, using techniques like mixed-integer optimization or sensitivity analysis, have been developed to determine the best size and site for storage in a given network.[83]

In addition to managing energy loads, distributed storage can supply ancillary services traditionally provided by large centralized plants. These services include frequency regulation, spinning reserve, fast contingency reserve, voltage control through reactive power support, and black-start capability. Batteries can potentially contribute to many of these tasks because of their fast response (millisecond-scale inverter controls) and precise output. An ESS can rapidly inject or absorb power to counteract frequency deviations, far faster than conventional turbine generators. Indeed, distributed batteries can collectively act as a flexible reserve that the system operator can use to balance the grid on short

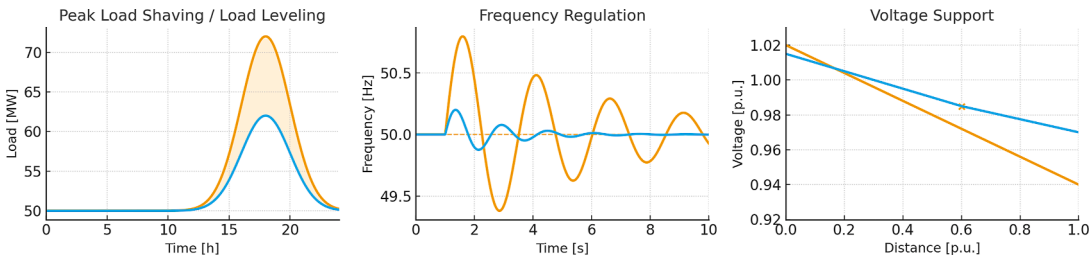

FIGURE 12.12 Benefits of energy storage in power systems.

(Left) Peak load shaving and load leveling: storage smooths demand profiles by reducing peak magnitudes and shifting energy to valleys. (Center) Ancillary services: storage contributes to frequency regulation by rapidly damping deviations around the nominal 50 Hz. (Right) Network performance: storage units located closer to loads improve voltage profiles along feeders and reduce distribution losses. The comparison between scenarios "with storage" (*blue*) and "without storage" (*orange*) highlights the stabilizing role of storage technologies across multiple operational domains.

timescales. For example, in the United Kingdom and Ireland, hundreds of megawatts of battery systems are enrolled in fast frequency response markets, reacting within 1 s to any major imbalance. Their performance has been excellent, helping to bound frequency excursions and stabilize the system during generator trips or sudden demand swings.[84,85]

Allowing distributed storage (including community- or customer-owned batteries) to participate in ancillary service markets opens new revenue streams and can improve the overall economics of ESS projects. Many EU countries have been reforming regulations to enable this. For instance, in Italy the so-called *"UVAM"* (virtually aggregated mixed unit) program allows aggregated batteries and flexible loads (Fig. 12.13) to provide services like frequency regulation and balancing to the grid operator.[86]

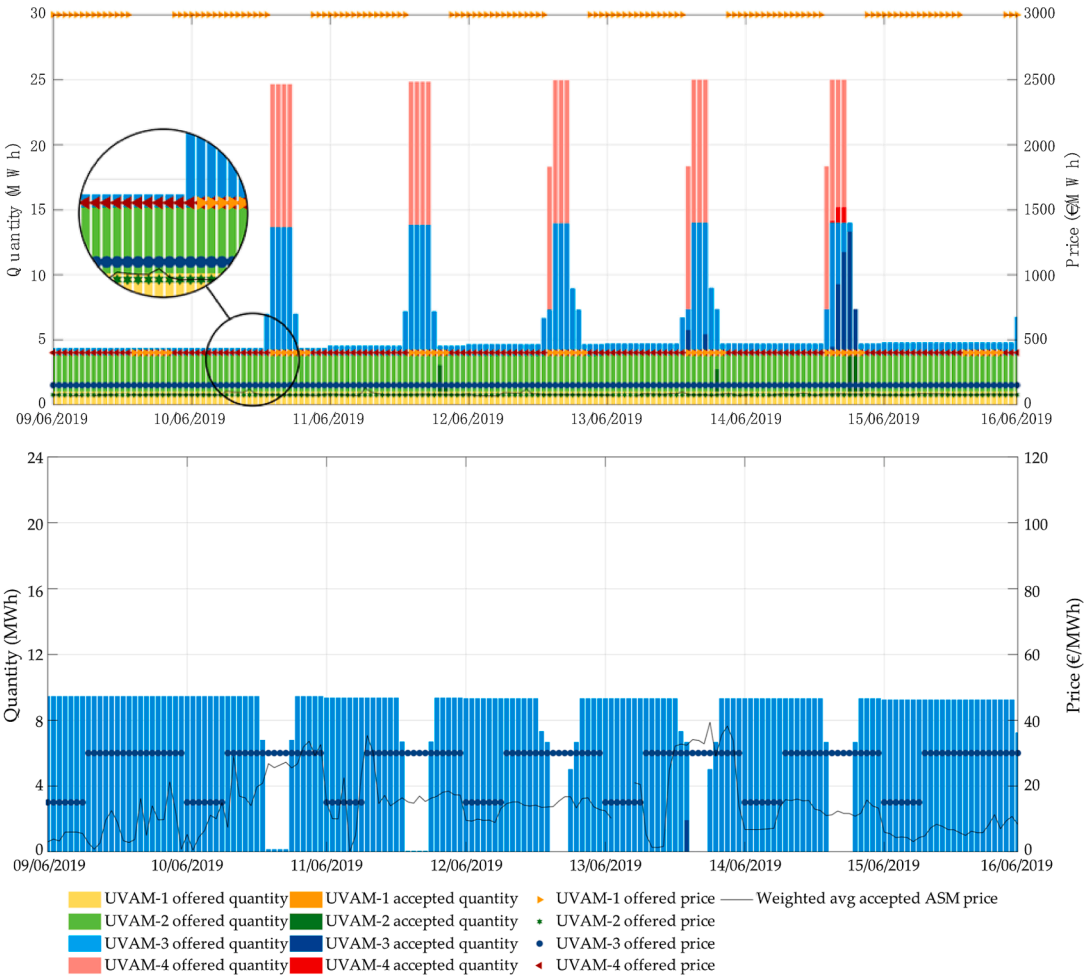

FIGURE 12.13 UVAM participation in the Italian ancillary service market pilot program.

The figure highlights the different offering strategies of aggregated units providing flexibility services with clear differences across hours and weekdays.

Schwidtal JM, et al. Integration of flexibility from distributed energy resources: Mapping the innovative Italian pilot project UVAM. Energies. 2021;14(7). MDPI AG. https://doi.org/10.3390/en14071910.

Besides this and other similar projects, even small batteries behind customers' meters can be potentially pooled by an aggregator to behave like a single power plant on the ancillary market. Early analyses of such setups reveal substantial untapped potential. In one Italian energy community study within the Savona campus, researchers examined a neighborhood-scale battery that primarily stored local PV energy but could also be made available for grid support. They found that if the community battery was allowed to participate in ancillary service provision (while still meeting local energy needs), it created significant additional value, enough to make the battery investment financially viable, whereas it might not be if used only for self-consumption.[87] This finding underscores the importance of stacking multiple value streams: a battery that provides both local peak shaving and grid services earns more and delivers more benefit to the system.

From a system perspective, distributed batteries providing ancillary services also contribute to voltage regulation at the distribution level. Traditionally, keeping voltage within tight limits (e.g., $\pm 10\%$ of nominal) was handled by tap-changing transformers and capacitor banks. Now, battery inverters can actively support voltage by injecting reactive power or real power at key moments. This is especially useful in areas with high PV penetration, where midday solar export can cause overvoltage, and then sudden cloud cover or evening ramp can cause drops. A battery can smooth these fluctuations. In a recent study, the combination of an ESS, smart inverter control, and an optimal tap-position strategy contributed to avoiding real power curtailment.[88]

It is worth noting that the benefits of storage in peak shaving, load leveling, and ancillary services are interrelated. By shaving peaks, batteries inherently provide a local form of capacity firming (which improves reliability), and by contributing to frequency or voltage control, they indirectly enable higher renewable penetration, which feeds back into flattening net-load profiles. In short, distributed storage is a multitool that simultaneously addresses several challenges of a high-distributed energy resources grid. The challenge and opportunity lie in optimizing ESS operation to maximize the stacked value without overly stressing the battery (i.e., managing its cycles).

A further benefit of distributed storage is the improvement of renewable self-consumption and self-sufficiency for end users. In simple terms, a battery enables more of the energy produced by local PV or wind to be consumed on-site (or within a community) rather than spilled to the grid. This not only reduces curtailment of renewables but also lessens the burden on distribution infrastructure by keeping energy local. For individual prosumers, adding a home battery can, even drastically, raise the fraction of solar generation they use themselves. A nationwide analysis in Italy, for example, examined PV-plus-battery scenarios for typical households across various regions. It found that integrating even a small battery size could boost the household's self-sufficiency to 35%–40% (for a given PV size and consumption profile), depending on the territorial area being considered. Similarly, the self-consumption ratio (i.e., the percentage of PV output directly used by the home or stored for later use) rises significantly with a battery, to 70%–90%.[89] These improvements pave the way for more sustainable and autonomous energy systems at the local level.

From an energy community perspective, the same principle applies: distributed storage raises the utilization of distributed generation. Instead of midday solar surplus being sent upstream (and possibly wasted if the grid cannot accept it), community batteries store it and later feed it to local loads in the evening, sharing the PV surplus within the community. This smooths the net demand seen by the higher grid distribution system operator (DSO) levels and reduces instances of renewable curtailment. In a real energy community demonstration in Germany, the introduction of a community-based battery system increased the collective PV self-consumption (or energy sharing) to approximately 90% during

the summer months (by storing excess daytime solar for nighttime use), while also cutting evening peak imports from the main grid by more than half.[90] Such outcomes are highly encouraging as they show storage can enable renewable energy–intensive communities to significantly reduce their reliance on the external grid.

Another benefit tied to this is the reduction of distribution losses. When energy is generated and consumed locally (or when peak power flows are reduced), the power losses on distribution lines diminish. Storage can charge during low-demand periods and discharge locally, which means that less power flows traveling long distances. A study optimizing battery placement in a distribution network quantified this effect: the optimal deployment of ESS in the network could reduce overall line losses by approximately 20% under high renewable penetration scenarios.[91] In another case, an optimally placed peak-shaving battery in a 22-bus distribution system led to power loss reductions up to 20.6%, which corresponds to a substantial improvement in efficiency.[92] Even smaller loss reductions (several percent) are valuable on a system-wide scale, as they translate into energy savings and lower operating costs for the DSO.

Recognizing these benefits, European policymakers and regulators have increasingly turned their attention to energy storage as a key enabler of grid flexibility. Over the past few years, the EU and member states have introduced a range of policies, targets, and incentives to accelerate storage deployment. In 2019, the EU's Electricity Market Directive (recast)[93] formally acknowledged energy storage and mandated that markets be designed to allow storage participation on equal footing. More recently, in March 2023, the European Commission issued detailed recommendations on removing barriers to electricity storage deployment, as part of a broader effort to unlock flexibility resources.[94] These recommendations call for actions such as clearer definitions of storage in regulation, enabling revenue stacking (so storage can earn from multiple services), and ensuring that distribution-level storage can access ancillary service markets. The message from the top level is clear: energy storage must be scaled up rapidly to meet EU climate and energy goals.

As a result, Europe is moving to open up markets and remove regulatory barriers for storage. Historically, one barrier was that many regulatory frameworks did not allow transmission or distribution operators to own storage assets. The EU's Electricity Regulation now explicitly requires system operators to consider storage (and DR) as alternatives before reinforcing the network, effectively making storage part of the planning process. Moreover, electricity markets are being revised to accommodate storage attributes. For instance, products with shorter durations (like 5-min balancing products or fast frequency response) favor batteries. Several EU countries (such as Ireland, the United Kingdom, and France) have introduced fast-response ancillary service products that batteries have eagerly filled. Ensuring that batteries can stack revenues, earning from energy arbitrage, frequency regulation, capacity mechanisms, etc., is seen as vital for their business case. The European Commission has encouraged member states to allow such stacking and to remove double charging of network fees (previously, batteries in some places paid fees both when charging and discharging, which is now widely recognized as unfair since it acts like both load and generator).

Additionally, many EU countries have also responded by setting national storage targets or funding programs. For example, Eurelectric Decarbonization Speedways study[95] estimates that Europe's total storage capacity (including all technologies) needs to grow almost fourfold from around 51 GW in 2023 to 191 GW by 2030, and further to about 486 GW by 2050. Some countries have outlined specific ambitions in line with such trajectories. Germany, through its KfW Development Bank, has offered low-interest loans and grants for home battery systems paired with PV (leading to tens of thousands of installations). France's has introduced regulatory changes allowing distribution system operators to procure storage for grid management under certain conditions. Greece and Ireland held auctions where

grid-scale batteries won contracts for flexibility services, jump-starting new projects. Italy stands out as an early mover in facilitating community-level storage integration. Following the EU's Renewable Energy Directive (RED II),[96] Italy transposed provisions for renewable energy communities (RECs) and introduced supportive measures: citizens and local authorities can form RECs to collectively produce, share, and store energy, with incentives for energy shared within the community. By 2022, this had led to a wave of interest—an independent survey found at least 10,000 REC initiatives in various stages across Europe, and in Italy specifically, dozens of pilot communities had been established.[97] However, progress has not been without challenges; as of early 2024, only 27 RECs in Italy had successfully navigated the bureaucracy to receive the available incentives under the transitional scheme. This indicates that while the policy framework is promising, practical implementation needs to accelerate.

Despite its numerous benefits and strong policy push, deploying storage in distribution networks faces several challenges. Among others, economic viability (ensuring projects can earn enough returns) is still one of the crucial aspects to be addressed to unlock the full potential of distributed storage. Batteries are capital-intensive assets, and their profitability depends on capturing multiple value streams. A standalone business case based on a single service (e.g., arbitraging energy prices or reducing peak charges) can often be marginal under current conditions.[98] For instance, residential PV-plus-battery systems in Italy still have relatively long payback times in most cases, especially when subsidies are absent; the LCOE for solar with storage remains higher in many regions.[99] The same findings have been reported in another study under Italian market conditions: storage profitability, when only a single service is offered, needs to be supported by national grants.[100] This means that, based purely on energy arbitrage (charging when power is cheap, discharging when expensive), many batteries would not break even. However, when stacked with other revenues or savings, the picture improves. We saw earlier that peak shaving can be profitable on its own in some cases; when those same batteries also participate in frequency regulation markets, they can earn additional revenue that significantly shortens the payback period. A German large-scale battery project (identified as a "virtual power plant" aggregator) reported that roughly 60% of its income came from frequency regulation, 30% from arbitrage, and 10% from other services, a diversification that made the project financially viable.[90]

Moreover, to directly support batteries, some countries have implemented dedicated programs.[101] Italy launched a storage rebate in certain regions to encourage residential ESS adoption (covering part of the cost of a battery if paired with a PV size lower than 20 kWp). The UK's regulator, Ofgem, ran the "Innovation Funding Incentive"[102] which supported trials of storage for distribution deferral. Spain's Recovery and Resilience Plan (2021)[103] allocated significant funds to energy storage projects, including behind-the-meter and community storage, seeing it as crucial for absorbing PV surpluses from its rapid solar rollout. At the EU level, the Innovation Fund and Horizon Europe research programs[104] have also financed large-scale demonstrators and research on advanced storage integration, ranging from novel battery chemistries to aggregation platforms.

3.3 Storage systems for grid services

The term *energy storage system* indicates all the systems capable of storing energy at a given time t, making it available at a later time in order to achieve specific goals. These objectives can be either

technical (e.g., aiming to create compatibility between the load/generation and the grid) or economic (the so-called *energy arbitrage*).

The effectiveness of a storage system is evaluated, from a power system point of view, according to elements that depend on both the specific application and the storage technology itself. These elements can be summarized as follows[105]:

Response to *cyclical (and noncyclical) load variations*: Such variations may have short (e.g., daily) or longer (e.g., weekly or monthly) cycles.

Response to *interruptions in nondispatchable resources* (especially solar or wind), as well as to possible *seasonal variations* in hydroelectric generation.

Efficiency, including the round-trip efficiency (RTE), that is, how much energy remains available after a certain time, compared to what was originally stored. This also includes energy losses related to the specific storage medium.

It should be noted that the first two points can be grouped together by stating that storage systems must be able to *cope with cyclical (and noncyclical) variations in the net load*, defined as load minus generation. Focusing on net load, rather than separately on load and generation, reflects the increasing presence of *prosumers*. Storage systems must take into account the nature of the net load, especially in the context of decentralized energy communities.[105,106]

Some storage technologies are more attractive than others, according to their lifetime, storage duration, energy retention losses, charge/discharge efficiencies, and charging/discharging response time. Moreover, when storage is considered as part of a multienergy system, it can also be seen as a means of contributing to the decarbonization of the overall energy system. In this case, factors such as geographical distribution, interaction between different energy vector infrastructures (e.g., electric grids and gas grid), and the presence of loads that can be powered by different energy carriers become essential. In such scenarios, long-term storage is generally required and may involve the feeding of large-scale chemical processes (e.g., for gas/fuel production).[107]

3.4 Storage at the consumer premises

The installation of ESSs at user premises can mitigate power quality issues and facilitate grid connection by adapting the user's load profile through mechanisms such as energy arbitrage and response to price signals.

A special category of distributed storage integration involves electric vehicles (EVs). With the accelerating adoption of EVs, a vast number of mobile batteries are increasingly connected to distribution grids.[108] Through smart charging and vehicle-to-grid (V2G) technologies, EV batteries can function as a flexible storage resource for the grid when plugged in (Fig. 12.14). Managed unidirectional charging (V1G) can already provide load shifting by timing EV charging for off-peak hours or high renewable production periods. More advanced bidirectional schemes (V2G and vehicle-to-home (V2H)) allow EVs to discharge power back to the grid or home, effectively acting as mobile ESSs. When aggregated, a fleet of EVs can help absorb midday solar peaks and provide energy back to the grid at the evening peak, much like stationary storage. This concept has been successfully piloted in several European countries; however, there are technical and regulatory hurdles, such as concerns about battery degradation and the need for V2G-compatible chargers. Some EU member states (e.g., the Netherlands and Denmark) are updating grid codes and incentivizing V2G trials, while regulation in other countries is also evolving to allow V2G services from private EVs.

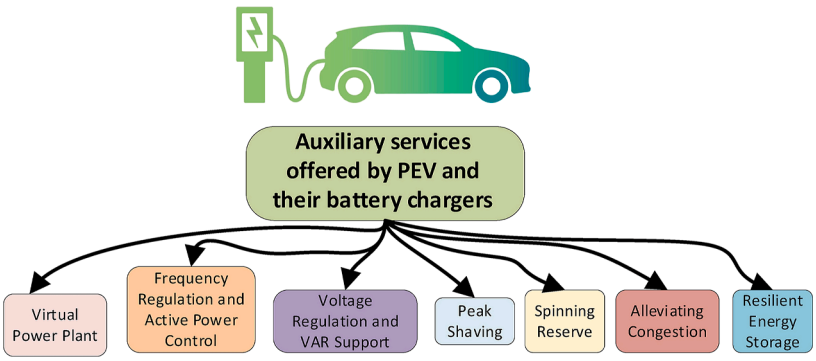

FIGURE 12.14 Potential vehicle-to-grid (V2G) auxiliary services from plug-in electric vehicles (PEVs).

Services include virtual power plant operation, frequency regulation and active power control, voltage regulation and VAR support, peak shaving, spinning reserve, alleviation of congestion, and resilient energy storage.

Ibrahim RA, Gaber IM, Zakzouk NE. Analysis of multidimensional impacts of electric vehicles penetration in distribution networks. Sci Rep. 2024;14, 27854. https://doi.org/10.1038/s41598-024-77662-6.

3.4.1 Power quality and backup services

Using storage systems to solve power quality issues is not a new concept. A common application is the use of uninterruptible power supply (UPS) systems, which are designed to manage short and very short power interruptions while also acting as filters against harmonics affecting the voltage waveform. Storage systems can supply the energy that would otherwise be lost during periods of poor service quality, while also providing a waveform that is acceptable for the connected load.

Table 12.3 lists the most common power quality problems for which energy storage can be used as a mitigation tool.[105,109]

3.4.2 Energy arbitrage

The term *energy arbitrage* refers to actions taken by active users (prosumers) to *modulate* their *net load* in order to benefit from price variations across different time-of-use periods.[110]

Unlike DR, which typically involves limiting or shifting load due to grid constraints, energy arbitrage requires the presence of an ESS. The system can absorb or inject energy depending on the economic convenience; typically, there are no limitations (apart from the technical constraints of the storage itself and the point of common coupling) on how much power can be fed into or withdrawn from the grid. The decision is entirely driven by economic signals. This service typically operates on a daily cycle, with charging during low-price periods and discharging during peak-price hours.[111]

3.5 Storage as an asset for the electric system operation and planning

A storage system directly connected to the electric system for grid service purposes may focus on supporting *frequency* and *voltage,* providing *black-start support*, or being used for *network planning purposes*.

Table 12.3 Overview of the power quality issues.

Type	Description	Voltage level
Interruptions	Transient interruptions ($\leq$1s)	<0.05 pu
	Short interruptions (1 s–3 min)	–
	Long interruptions (>3 min)	–
Short-term voltage variations (10 ms–1 min)	Voltage sags (or dips)	0.1–0.9 pu
	Short overvoltages (swells)	1.1–1.8 pu
Long-term voltage variations ($\geq$1 min)	Sustained interruptions	0.0 pu
	Undervoltages	0.8–0.9 pu
	Overvoltages	1.1–1.2 pu
Repetitive disturbances	Flicker	0.9–1.1 pu
Harmonic distortion	Harmonic distortion	Nonsinusoidal voltage

Compiled by the authors on: Das CK, Bass O, Kothapalli G, Mahmoud TS, Habibi D. Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality. Renew Sustain Energy Rev 2018;91, 1205–1230. https://doi.org/10.1016/j.rser.2018.03.068; CEI EN 50160. Caratteristiche della tensione fornita dalle reti pubbliche di distribuzione dell'energia elettrica. CEI Norme. Retrieved July 30, 2025, from http://mycatalogo.ceinorme.it/cei/item/0000011266.

3.5.1 Frequency support

The frequency (which in Europe has 50 Hz as nominal value) at each moment is directly related to the balance between generated power and total load (including losses). If generation and load are equal, the frequency remains constant; otherwise, it deviates from the nominal value. Significant deviations are not acceptable because they threaten the power system stability. For this reason, control systems are in place and are tuned to limit such deviations within acceptable thresholds, with the frequency required to stay in the range $47.5 \leq f \leq 51$ Hz.[112] The control systems have been traditionally associated with large power plants, which may intervene according to a *hierarchical scheme*, composed of *reserves* aiming to:

Containing frequency deviations within acceptable limits (known at the European level as *FCR—Frequency Containment Reserve*)[113];

Restore the frequency to its nominal value (referred to in Europe as *aFRR—Automatic Frequency Restoration Reserve*).[114,115]

The FCR is typically activated locally by generators based on local measured deviations, while aFRR is dispatched through signals sent from a control center (usually nationwide). Since not all generators are able to provide these services continuously, their usage must be limited over time. Generators initially providing FCR are replaced by those assigned to aFRR. Then, a third service is needed to replace the aFRR providers, namely the *Manual Frequency Restoration Reserve (mFRR)*. This kind of service ensures the availability of aFRR for subsequent events. It is worth noting that some transmission system operators (TSOs) also include an additional, *slower* tertiary reserve service, called *Replacement Reserve (RR)*. Table 12.4 shows an overview of the different frequency support services, with their activation time and response time, their duration and the old terms used to indicate them.

Table 12.4 Overview of grid services classified by type (FCR, aFRR, mFRR, and RR).

Service type	Activation time	Response time	Duration (min)	Previous terminology
FCR	2–3 s after disturbance	<30 s	15	Primary
aFRR	Continuous (1–5 s control signal)	~5 min	15	Secondary
mFRR	>5 min	12.5 min	15	Tertiary
RR	>15 min	30 min	15–60	–

Adapted from Díaz-Londono C, Enescu D, Ruiz F, Mazza A. Experimental modeling and aggregation strategy for thermoelectric refrigeration units as flexible loads. Appl Energy. 2022;272, 115065. Elsevier. https://doi.org/10.1016/j.apenergy.2020.115065 and European University Institute, Meeus L, Reif V, Schittekatte T. The EU Electricity Network Codes: Technical report. Publications Office of the European Union. 2019. https://data.europa.eu/doi/10.2870/188992.

These services are designed to *manage the continuous imbalance* resulting from the load variability and, more recently, from the variability of nondispatchable power plants. In this context, *storage systems can act as buffers*, absorbing generation peaks and releasing stored energy when the load exceeds generation. As a matter of terminology, it is worth noting that the literature contributions distinguish frequency support services into *rotating* and *nonrotating reserves*.[116–118] However, this separation makes sense only if the tertiary reserve is considered outside the frequency regulation domain. In this chapter, and in line with the European regulatory framework, we will not use the rotating/nonrotating terms. Instead, only the RR service will be mentioned, regardless of whether it is provided by rotating or nonrotating units.

The above services were originally designed for power systems with a dominant presence of rotating generators. In such systems, the kinetic energy of rotating masses naturally helps stabilize frequency in the initial moments after a disturbance. For example, in a frequency-drop event (when load exceeds generation), the rotating generators slow down slightly and automatically release more power, which is later compensated for through control systems.

This stabilizing effect is absent in power systems where most generators are interfaced through power electronics, such as PV or modern wind plants using inverters. As a result, the system's overall inertia is decreasing, and it is expected that *synthetic inertia* will become part of FCR services, with storage systems playing a key role.

3.5.2 The evolution of the frequency support: The virtual inertia

The frequency support services mentioned above were originally designed for *power systems with a dominant presence of rotating generators*. In fact, in such systems, the kinetic energy of rotating masses naturally helps stabilize the frequency just after the occurrence of a disturbance that leads the frequency to move from its nominal value. For example, in a frequency-drop event (i.e., when load exceeds generation), the rotating generators slow down slightly and automatically release more power, which is later compensated for through control systems.

This stabilizing effect becomes negligible in power systems where most generators are interfaced through power electronics, such as PV or modern wind plants using inverters. As a result, the system's

overall inertia is decreasing, and it is expected that *synthetic inertia* will become part of FCR services, with storage systems playing a key role. Therefore, additional control systems are needed to adjust the inverter power output based on local frequency measurements.[119] If the control system emulates the torque that rotating generators apply against a frequency drop (with instantaneous activation), we refer to this as *synthetic inertia*. Other fast responses, although similar in purpose, are better classified as fast frequency response (FFR). Hence, synthetic inertia is a special case of FFR, but not the only one. An example of FFR is the Dynamic Containment service introduced in the United Kingdom, which does not require generator-like behavior, only a response within 0.5–1 s.[120]

3.5.3 Voltage regulation support

In transmission networks, voltage regulation relies on reactive power control. However, reactive power is difficult to transmit over long distances and can reduce active power transport capacity. Moreover, inappropriate voltage values can compromise power flow between nodes. Therefore, voltage regulation is typically local, via injection or absorption of reactive power. Well-controlled storage systems can support this, ensuring that voltage remains within acceptable levels.

In low-voltage (LV) distribution networks, where lines are mostly resistive, active power injection also affects voltage. Here, local voltage control through storage is feasible but must be coordinated with higher-level controls (e.g., on-load tap changers in primary substations).

Medium-voltage (MV) networks exhibit a mixed behavior: the conductor parameters (especially in urban cable lines) prevent a clean separation of effects from active and reactive power variations. Thus, a combined variation of both is necessary for effective voltage support.

This service must be fast, with storage systems responding within seconds and typically lasting up to 10 min. Larger deviations require action from centralized control systems.[111]

3.5.4 Black start

In the event of a total blackout, a restart plan is required to bring production units back online and restore load supply within an integrated grid (e.g., see[121] for the Italian system).

Storage may support black-start operations in two main ways[110]:

As a *power source for main generator startup*: Most power plants require auxiliary systems (usually powered by the external grid). If the grid is down, alternative energy sources are needed. These can be diesel generator sets (gensets) or ESSs. The latter enable fuel savings and can be used for other services as long as a sufficient state of charge is kept.[122]

As a *supply source for part of the distribution network*: This requires energy storage units connected to the MV grid, with enough capacity and suitable control to keep frequency and voltage within operational limits. Large-scale deployment would involve many microgrids that must later be resynchronized. While complex, this can be useful during extreme and rare events that isolate parts of the network for hours.

The black-start service typically requires activation within 10 min and may last several hours for significant grid segments.[111]

3.5.5 Network planning purposes

In network planning, storage systems can help avoid grid investments. For instance, if a large non-dispatchable generator is connected to a weak grid section, a storage unit can absorb excess energy (instead of curtailing generation) and release it later.

Although similar to energy arbitrage, this service actually addresses a power injection constraint, where renewable generation would otherwise be curtailed due to grid limitations. In this use case, the goal is to follow the daily cycle of renewable production.

Peak shaving refers to using stored energy to cut the tops off demand peaks, thereby reducing the maximum load seen by the grid. This has immediate economic benefits for large consumers (by lowering demand charges) and also relieves stress on transformers and feeders. In many jurisdictions, industrial or commercial electricity tariffs include hefty fees for the highest power drawn; by discharging an ESS when facility load would otherwise exceed a threshold, those peaks (and fees) can be curtailed. One of the studies in this area found that operating a battery for peak shaving at an industrial site yielded about an 8% reduction in the facility's electricity bill.[91]

A case study on a real 500-bus, MV grid in Spain found that a strategically placed ESS could serve peak loads on the hottest days, allowing the utility to defer building new feeders, and the deferral savings could cover a significant portion of the battery cost. In scenarios with relatively slow load growth, the analysis showed that storage was a cost-efficient alternative to traditional grid reinforcement, since the battery was needed only for peak shaving during a few days per year. This highlights that distribution-connected storage can provide an alternative to expansion, especially when peak demand is infrequent or growing modestly.[82]

3.6 Long-term energy storage and sector coupling

While stationary batteries have garnered much attention, long-term storage requires a broader sector coupling approach, which is increasingly relevant in Europe. Sector coupling integrates electricity with transport, heating, gas, and industry, enabling surplus electricity to be converted, stored, and utilized across sectors (EVs, thermal storage, hydrogen, and power-to-X (P2X)).[123] This approach complements batteries by addressing the need for longer-duration flexibility and enhancing renewable integration at the distribution level.

The main goal is to maximize the energy production from RESs and to store that energy for relatively long periods. Hence, in this case, the storage is not used to *support the grid operation and planning* but to enable an ever-higher penetration of renewables within the energy system. This kind of application requires a *decoupling between power and energy capacity* so that the limitations of the conversion unit (handling incoming electricity) do not compromise the ability to store large energy volumes. The system must be capable of following the nonpredictable profile of renewable generation without being constrained by instantaneous power ratings.

Energy storage in this context requires both *temporal* (energy is used a long time after it is produced) and *geographical* decoupling. The latter aspect highlights the importance of *adequate infrastructure to transport energy* from the storage site to the consumption point. Changing the energy carrier (e.g., electricity to hydrogen or thermal) could help make better use of existing infrastructure and increase overall system flexibility. Currently, *pumped hydro storage* (PHS) represents the main technology used for long-term energy storage, with an installed capacity of about 179 GW worldwide (2017 data[124]). Other technologies (such as flow batteries and systems based on hydrogen production) are presented in the next chapter.

Thermal energy storage (TES) is a powerful sector coupling tool at the distribution level, linking the electricity grid with heating and cooling demands.[125] Technologies such as electric heat pumps, resistive heaters, and thermal storage tanks (e.g., hot water cylinders or phase-change material heat

buffers) allow surplus electrical energy to be converted into heat and stored for hours or even days. This power-to-heat approach provides a form of distributed battery by exploiting the thermal inertia in water or building materials. During periods of excess RES generation or low electricity prices, electric boilers and heat pumps can be turned up to charge thermal stores (heating water or buildings); later, the stored heat supplies space heating or hot water so that electricity demand is reduced during peak hours. In this way, thermal storage offers peak-shaving and load-shifting services to the grid by deferring electric heating loads.

Hydrogen energy storage, often via power-to-gas (P2G) processes, is another cornerstone of sector coupling with growing application in Europe's distribution grids.[126] In a P2G system, surplus electrical power drives an electrolyzer to produce hydrogen. The hydrogen can be used directly as a clean fuel, converted to synthetic methane (by adding captured CO_2) for injection into the gas network, or stored and later reconverted to electricity through fuel cells or gas turbines. This versatility allows hydrogen systems to act as long-duration storage and as a bridge between the electricity, gas, and mobility sectors. At the distribution level, deploying electrolyzers at substations or near distributed generation sites can store local power surpluses (preventing overvoltage or curtailment) by converting electricity to hydrogen, effectively shaving peaks during periods of oversupply. The stored hydrogen becomes a distributed energy reserve that can be used for various purposes: in fuel cell vehicles or buses (linking to transport), fed into local gas pipelines to decarbonize heating, or converted back to electricity in fuel cell units to supply the grid during shortages. In terms of ancillary services, electrolyzers offer highly controllable demand that can ramp up or down quickly, providing a form of fast DR for grid balancing.

Finally, beyond heat and gas, P2X denotes a broad class of solutions converting electrical energy into other forms, such as synthetic liquid fuels, chemicals, or other energy carriers, thereby linking the electricity grid with industries like transport, aviation, and manufacturing.[127] In the context of distribution grids, P2X installations (such as a synthetic fuel pilot plant connected to a local renewable generator) act primarily as controllable high-capacity loads that can be turned on to soak up excess generation. By operating electrolyzers and reactors when local solar/wind output is abundant and power prices are low, P2X systems provide a valuable flexibility service: they mitigate RES curtailment and help balance local supply and demand by shifting energy into the chemical domain.[128] For example, a power-to-heat system for hard-to-abate industries could use hydrogen storage during midday PV peaks, thereby effectively reducing strain on the electrical network and delivering it later to better balance a continuous hydrogen demand.[129] Although most power-to-fuel processes cannot dynamically adjust on a second-by-second basis for frequency control (due to slower chemical process dynamics), they can still participate in slower forms of energy services.[130]

3.7 Technology selection and service suitability analysis

Energy storage systems can be categorized according to the underlying technology into five main groups: mechanical, electrochemical, electrical, chemical, and thermal systems.[117,1]

Fig. 12.15 provides an overview of these categories; several important subtechnologies require further consideration. Within the electrochemical group, conventional batteries include advanced lead–acid devices, lithium-ion cells, nickel–cadmium (NiCd), and nickel–metal hydride (NiMH) systems, each with distinct performance profiles and deployment contexts. Additional high-

[1]The detailed description of these technologies is beyond the scope of this section.

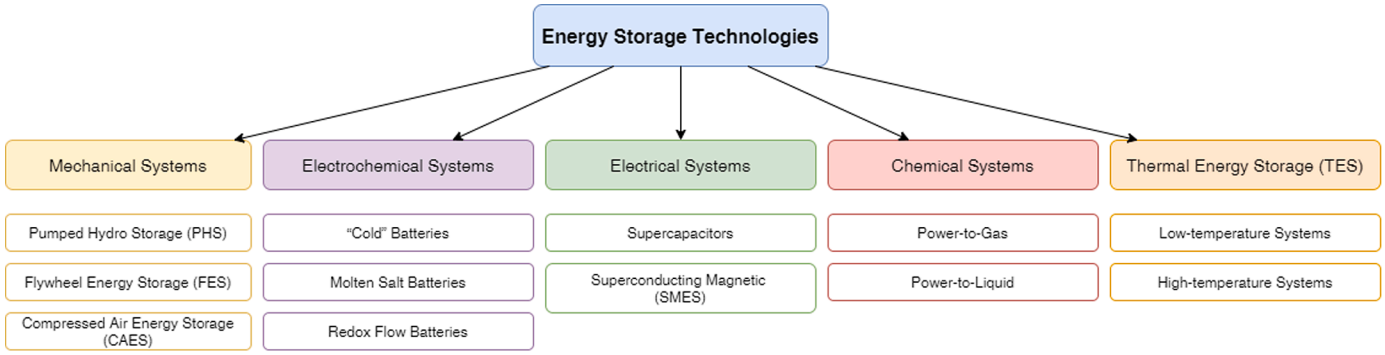

FIGURE 12.15 Energy storage technologies.

Energy storage systems can be broadly categorized according to their underlying technology into five main groups: mechanical, electrochemical, electrical, chemical, and thermal systems.

temperature chemistries, such as sodium–sulfur (NaS) and sodium–nickel chloride (ZEBRA) batteries, as well as redox flow batteries including vanadium redox flow (VRFB) and zinc–bromine (ZBR) systems, further expand the technological landscape. In the chemical category, the P2G pathway involves hydrogen production through electrolysis and its conversion to synthetic methane, while the power-to-liquid route enables the synthesis of renewable liquid fuels for transport and industrial uses. Thermal energy storage is typically divided into low-temperature systems, mainly applied in buildings, and high-temperature systems, which support industrial processes and concentrating solar power. These subcategories complement the high-level taxonomy and highlight the technological diversity that characterizes energy storage research and deployment.

Collectively, the above storage and conversion technologies greatly increase the suite of ancillary services available at the distribution level. Nowadays, thanks to sector coupling and distributed storage, even local energy communities and microgrids can act as "partners to the grid," providing services like peak shaving, voltage regulation, and DR that were once the domain of large power plants. Table 12.5 summarizes how each technology can contribute to key ancillary services in a distribution-grid context.

Every technology shows specific features that make it more or less suitable for a particular purpose or application[2]:

Storage capacity (MW h): the total amount of storable energy
Nominal power (MW): electrical capacity of the interface device (typically the converter) connecting the system to the grid
Energy density (Wh/L): energy stored per unit of volume
Power density (W/L): power output per unit of volume
Charging time: time required for full charging
Discharging time: time needed to discharge at nominal power
Response time: time to begin delivering power once triggered
Lifetime: expressed in years or full charge/discharge cycles
Round-trip efficiency (%): ratio between discharged and charged energy, including all losses
Power–energy coupling: whether power and energy capacities are coupled or decoupled
Self-discharge (% per day): losses inherent to the storage medium
Depth of discharge (%): minimum allowable state of charge to avoid degradation.

Tables 12.6–12.10 summarize the technical features of the various technologies.

For identifying the most suitable technologies for grid services, it is necessary to *define a set of technical parameters* related to every storage system and relevant for the grid service provision (see Table 12.11). Once the services are characterized, it is then possible to match them with the storage technologies, by combining the information included in Tables 16.6–16.10 (about the storage technologies) and Table 12.11 (service characteristics/requirements). The results are then shown in Table 12.12, from which it is possible to get as follows:

There is no single dominant technology that meets all requirements, suggesting that a combination of different storage technologies will be necessary in future scenarios.

[2]We focus here only on technical features, by neglecting the economic aspects due to the technical purpose of the section.

Table 12.5 Contribution of different storage technologies to ancillary services in distribution grids.

Storage type	Frequency regulation	Peak shaving	Load balancing	Voltage control	Black start	Energy arbitrage
EVs (smart/V2G)	✓ Fast response	✓ Discharge at peak	✓ Intraday shifting	✓ Via inverters	~ Possible (V2H)	✓ Buy low, sell high
Thermal storage	~ Load modulation	✓ Avoids electric peaks	✓ Daily load shift	~ Indirect effect	×	✓ Use cheap power for heat
Hydrogen (PtG/fuel cell)	✓ Electrolyzer control	✓ Stores excess as hydrogen	✓ Long-duration balance	~ Limited via fuel cells	✓ With generators	✓ Convert low-price power
Power-to-X (e.g., methanol)	×	✓ Absorbs surplus	✓ Seasonal shift	×	×	✓ Displace peak use

✓ = Suitable; ~ = Partial; × = Not applicable.

Table 12.6 Overview of the storage feature for service coupling: mechanical storage.

Type	Mechanical		
Technology	**PHS**	**CAES**	**FES**
Capacity (MW h)	$(2–80)^{*}10^{2}$	$2^{*}10^{2}–10^{3}$	≤5
Power (MW)	$10^{2}–5^{*}10^{3}$	$5–3^{*}10^{2}$	0,01–20
Energy density (Wh/L)	0.2–2	2–6	20–80
Power density (W/L)	0.5–1.5	0.5–2	$(1–5)^{*}10^{3}$
Charge duration	Min–hours	Min–hours	<15 min
Discharge duration	Hours–days	Hour–days	Sec-15 min
Response time	Minutes	Minutes	Seconds
Lifetime (years)	30–100[33]	20–40	15–20
Lifetime (cycles)	$(1–3)^{*}10^{4}$	$(8–50)^{*}10^{3}$	$>2^{*}10^{4}$
Self-discharge (%/day)	Negligible	0.5–2	20–100
Max depth of discharge (%)	95–100	70	75
Efficiency (%)	65–87	40–80	85–95
P/E ratio (h^{-1})	0.2–0.6	0.1–1.5	<4

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Table 12.7 Overview of the storage feature for service coupling: cold batteries.

Type	Electrochemical—cold batteries			
Technology	**Lead–acid**	**Li-ion**	**NiCd**	**NiMH**
Capacity (MW h)	10^{-3}–100	≤100	<10	10^{-5}–0.5
Power (MW)	0–40	$1^{*}10^{-3}$–50	≤40	10^{-2}–1
Energy density (Wh/kg)	25–35	120–180	15–200	40–300
Power density (W/L)	10–700	$(1.3–10)^{*}10^{3}$	75–700	$5^{*}10^{2}$–$3^{*}10^{3}$
Charge duration	Min–20 h	Min–hours	1 h	2–4 h
Discharge duration	Seconds–hours	10 min–4 h	Seconds–hours	Hours
Response time	<5 ms	<5 ms	<5 ms	<5 ms
Lifetime (years)	5–15	15–20	20	15
Lifetime (cycles)	500–3000	2000–10000	$(1.5–3.5)^{*}10^{3}$	$(3–30)^{*}10^{2}$
Self-discharge (%/day)	0.1–0.3	0.1–0.3	0.2–0.6	0.4–1.2
Max depth of discharge (%)	60–70	80	100	60–70
Efficiency (%)	75–85	90–98	70–75	50–80
P/E ratio (h^{-1})	0–1	≤10	≤6	$2^{*}10^{-2}$–10^{5}

Compiled by the authors on: Argyrou MC, Christodoulides P, Kalogirou SA. Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications. Renew Sustain Energy Rev. 2018;94, 804–821. https://doi.org/10.1016/j.rser.2018.06.044; Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy. 2015;137, 511–536. https://doi.org/10.1016/j.apenergy.2014.09.081; Chatzivasileiadi A, Ampatzi E, Knight I. Characteristics of electrical energy storage technologies and their applications in buildings. Renew Sustain Energy Rev. 2023;25, 814–830. https://doi.org/10.1016/j.rser.2013.05.023; Javed MS, Ma T, Jurasz J, Amin MY. Solar and wind power generation systems with pumped hydro storage: Review and future perspectives. Renew Energy. 2020;148, 176–192. https://doi.org/10.1016/j.renene.2019.11.157; Koohi-Fayegh S, Rosen MA. A review of energy storage types, applications and recent developments. J Energy Storage. 2020;27, 101047. https://doi.org/10.1016/j.est.2019.101047; Farivar GG, et al. Grid-connected energy storage systems: state-of-the-art and emerging technologies. Proc IEEE, 2023;111(4), 397–420. https://doi.org/10.1109/JPROC.2022.3183289.

The technologies that currently enable full coverage of all grid-related services are PHS and Li-ion batteries. Both are also capable of providing energy arbitrage. Lithium-ion batteries can additionally support user-level power quality, while only PHS is able to deliver seasonal energy storage.

Seasonal storage can also be provided by TES and P2G systems, although the latter are currently constrained by scale limitations. The future role of P2G in seasonal storage will depend on the ability to inject hydrogen into the gas grid or to use it in supply chains (e.g., synthetic natural gas or liquid fuel production) that allow long-term storage and reuse, particularly in hard-to-abate sectors such as heavy transport, aviation, and the chemical industry.

Regarding electrolyzer technologies, PEM electrolyzers can provide fast grid services thanks to their response times. Alkaline and solid oxide electrolyzers are more instead suitable for grid planning and long-term energy storage, as well as for decarbonizing specific processes.

Among high-temperature batteries, sodium-based systems can currently provide most grid services, and future developments may enable them to support all the considered applications. However, ZEBRA batteries still require technical improvements to become truly competitive across multiple service areas.

Table 12.8 Overview of the storage feature for service coupling: molten salt and flow batteries.

Type	Electrochemical—molten salt and flow batteries			
Technology	**NaS**	**ZEBRA**	**VRB**	**ZnBr**
Capacity (MW h)	≤600	≤5	≤60	≤4
Power (MW)	0.2–50	<1[32]	≤15	≤10
Energy density (Wh/L)	<400	100–200	16–35	20–65
Power density (W/L)	120–180	250–270	0.5–2	≤25
Charge duration	9 h	6–8 h	Minutes	≤4 h
Discharge duration	6h at nominal power	Seconds–hours	Seconds–hours	Seconds–hours
Response time	<5 ms	<5 ms	<5 ms	<5 ms
Lifetime (years)	15–20	10–14	5–20	5–20
Lifetime (cycles)	≥4500	$\geq 2.5^{*}10^{3}$	$(1.2–1.4)^{*}10^{4}$	$(2–10)^{*}10^{3}$
Self-discharge (%/day)	≈0 [	5	0.15	≤1
Max depth of discharge (%)	90	75–85	100	100
Efficiency (%)	70–80	80–90	75–85	60–80
P/E ratio (h^{-1})	0.14–85	0.2–8.33	$0.5^{*}10^{-3}$–1.5	$1.25^{*}10^{-2}$–$2^{*}10^{2}$

Compiled by the authors on: Argyrou MC, Christodoulides P, Kalogirou SA. Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications. Renew Sustain Energy Rev. 2018;94, 804–821. https://doi.org/10.1016/j.rser.2018.06.044; Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy. 2015;137, 511–536. https://doi.org/10.1016/j.apenergy.2014.09.081; Chatzivasileiadi A, Ampatzi E, Knight I. Characteristics of electrical energy storage technologies and their applications in buildings. Renew Sustain Energy Rev. 2023;25, 814–830. https://doi.org/10.1016/j.rser.2013.05.023; Javed MS, Ma T, Jurasz J, Amin MY. Solar and wind power generation systems with pumped hydro storage: review and future perspectives. Renew Energy. 2020;148, 176–192. https://doi.org/10.1016/j.renene.2019.11.157; Koohi-Fayegh S, Rosen MA. A review of energy storage types, applications and recent developments. J Energy Storage. 2020;27, 101047. https://doi.org/10.1016/j.est.2019.101047.

Table 12.9 Overview of the storage feature for service coupling: electrical and thermal storage.

Type	Electrical		Thermal
Technology	**DLC**	**SMES**	**High T.**
Capacity (MW h)	10^{-4}–10^{-2}	10^{-4}–10^{-1}	
Power (MW)	10^{-2}–1	0.1–100	0.1–300
Energy density (Wh/L)	10–30	0.2–6	
Power density (W/L)	$\geq 10^{5}$	10^{3}–$4^{*}10^{3}$	
Charge duration	Seconds–minutes	Minutes	
Discharge duration	Seconds–minutes	Seconds–1/2 h	Hours
Response time	<5 ms	Milliseconds	Hours
Lifetime (years)	10–30	20–30	5–40
Lifetime (cycles)	$5^{*}10^{4}$–$5^{*}10^{5}$	$2^{*}10^{4}$–10^{5}	
Self-discharge (%/day)	5–40	10–15	$5^{*}10^{-2}$–1
Max depth of discharge (%)	75	100	
Efficiency (%)	84–98	90–98	30–60
P/E ratio (h-1)	$\leq 0.6^{*}10^{3}$	$<6^{*}10^{4}$	

Compiled by the authors on: Argyrou MC, Christodoulides P, Kalogirou SA. Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications. Renew Sustain Energy Rev. 2018;94, 804–821. https://doi.org/10.1016/j.rser.2018.06.044; Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy, 2015;137, 511–536. https://doi.org/10.1016/j.apenergy.2014.09.081; Chatzivasileiadi A, Ampatzi E, Knight I. Characteristics of electrical energy storage technologies and their applications in buildings. Renew Sustain Energy Rev. 2013;25, 814–830. https://doi.org/10.1016/j.rser.2013.05.023.

Table 12.10 Overview of the storage feature for service coupling: chemical systems.

Type	Chemical		
Technology	**Alkaline P2H**	**PEM P2H**	**Power-to-methane**
Capacity (MW h)	–	–	–
Power (MW)	$5.5^{*}10^{-2}$–3.5	$1.2^{*}10^{-2}$–2	1–1000
Energy density (MWh/t)			13.9
Power density (W/L)	–	–	–
Charge duration	–	–	–
Discharge duration	–	–	Some weeks
Response time	Seconds–minutes	Seconds	Seconds
Lifetime (years)	15–30	5–20	30
Lifetime (cycles)	–	–	–
Self-discharge (%/day)	–	–	–
Max depth of discharge (%)	–	–	–
Efficiency (%)	47.2–82.3	48.5–61.1	48–53
P/E ratio (h^{-1})	–	–	

Compiled by the authors on: Mazza A, Bompard E, Chicco G. Applications of power to gas technologies in emerging electrical systems. Renew Sustain Energy Rev. 2018. 92, 794–806. https://doi.org/10.1016/j.rser.2018.04.072; Rozzi E, Minuto FD, Lanzini A, Leone P. Green synthetic fuels: Renewable routes for the conversion of non-fossil feedstocks into gaseous fuels and their end uses. Energies. 2020;13(2), 420. https://doi.org/10.3390/en13020420; Götz M, et al. Renewable power-to-gas: a technological and economic review. Renew Energy. 2016;85, 1371–1390. https://doi.org/10.1016/j.renene.2015.07.066.

Among flow batteries, vanadium-based systems already allow for the provision of several services. Hybrid flow batteries (e.g., Zn–Br) may offer a good alternative in the future, but as of now, they are only suitable for small-scale applications.

Regarding compressed air energy storage (CAES) and flywheel energy storage (FES) systems, it appears that they are largely complementary, which may open opportunities for hybrid configurations. Nevertheless, they require significant physical space, which may limit their deployment.

Reading Table 12.11 row by row, the following observations can be made:

Grid services can generally be provided by a diverse mix of technologies, particularly when it comes to voltage regulation support.

Seasonal storage, on the other hand, can currently be implemented through a more limited set of technologies.

Power quality support remains the service for which the largest number of technologies is available. This is consistent with the fact that it has been one of the first industrial needs historically addressed.

Table 12.11 Main characteristics of the analyzed services.

Type of service	Frequency regulation				Black start	Voltage regulation	Grid planning	Power quality	Arbitrage	Seasonal storage
	FCR	aFRR	mFRR	RR						
Size	10–40 MW	10–40 MW	10–100 MW	10–100 MW	5–50 MW	1–10 Mvar	10–100 MW	<5 MW	1–500 MW	30–500 MW
Response time	2–3 s	1–5 s	>5 min	>15 min	10 min	sec	–	ms	min	min
Discharge duration	15 min	15 min	15 min	15–60 min	≥1 h	–	2–8 h	sec–min	1–10 h	Hours/ weeks
Min. annual cycle	250–1000	250–1000	20–50	20–50	10–20	–	>360	10–200	≥250	1–5

Compiled by the authors on: Díaz-Londono C, Enescu D, Ruiz F, Mazza A. Experimental modeling and aggregation strategy for thermoelectric refrigeration units as flexible loads. Appl Energy, 2020;272, 115065. https://doi.org/10.1016/j.apenergy.2020.115065; Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy. 2015;137, 511–536. https://doi.org/10.1016/j.apenergy.2014.09.081; Akhil A. DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA. 2015. DOE/EPRI.

Table 12.12 Matching technologies/services.

Techn.		Frequency regulation				Black start	Voltage regulation	Grid planning	Power quality	Arbitrage	Seasonal storage
		FCR	aFRR	mFRR	RR						
Mech.	PHS	X	X	X	X	X	X	X		X	X
	CAES			X	X			X		X	X
	FES	X	X				X		X		
Low T Batt.	Lead–acid	O	O				X		X		
	Li-ion	X	X	X	X	X	X	X	X	X	
	NiCd	O	O	X	X	X	X	O	X	O	
	NiMH								X		
High T Batt.	NaS	O	O	X	X	X	X	X	X	O	
	ZEBRA	O	O	O	O	O	X	O	X	O	
Flow Batt	VRB	X	X	X	X	X	X	X	X	X	
	ZnBr	O	O	O	O	X	X	O	X	O	
Electr.	EDLCs	O	O				O		X		
	SMES	O	O				O		X		
Therm.	TES									X	X
P2G	AEL							O		O	X
	PEM	O	O					O		O	X
	P2M							O		O	X

O, *suitable in perspective;* X, *ready.*

Final considerations

The integration of RESs into transmission and distribution grids represents one of the most profound transformations in modern power systems. As detailed throughout this chapter, the inherent intermittency and variability of wind, solar, and hydroelectric resources impose complex operational and planning challenges that traditional grid architectures were not designed to accommodate. These challenges extend beyond issues of power quality and stability; they reshape temporal generation patterns, reduce system inertia, and necessitate a fundamental rethinking of network design and operational paradigms.

To navigate this complexity, a multidimensional response is required. On one front, the development and deployment of robust metrics for variability offer system operators and planners essential tools to characterize, predict, and respond to renewable-induced fluctuations. On another, strategies such as spatial diversification, resource complementarity, and coordinated dispatch across technologies contribute to reducing volatility and enhancing the predictability of aggregated output. Nevertheless, these measures alone are insufficient to guarantee a secure and resilient energy system under conditions of high renewable penetration.

In this evolving context, ESSs emerge as a foundational component of modern grids. By enabling the temporal decoupling of generation and demand, storage technologies enhance system stability, mitigate the need for curtailment, and delay or eliminate costly infrastructure upgrades. Whether deployed at the utility scale or embedded behind the meter, ESS can simultaneously deliver ancillary services, smooth local voltage and frequency fluctuations, support peak shaving, and improve the economic efficiency of distributed energy resources. The ability to stack multiple services, technical and economic, positions storage as both a flexibility provider and a critical infrastructure asset for grids with high renewable penetration.

The successful integration of RESs will ultimately depend on the coherent coordination of infrastructure design, storage deployment, sector coupling strategies, and operational planning. A future-proof power system must combine clean generation capacity with the flexibility and resilience needed to accommodate the inherent variability of renewable resources while maintaining security of supply.

Study questions

Test your understanding of the key concepts covered in Chapter 12. Each question has four options with only one correct answer. After completing the quiz, check your responses against the answer key provided at the end.

1. What is the primary cause of variability in solar photovoltaic (PV) generation during daylight hours?
   - **A.** Changes in the Earth's orbital position
   - **B.** Temperature changes in the solar panels
   - **C.** Fluctuations in electricity demand
   - **D.** Cloud cover, aerosols, and atmospheric conditions
2. Which energy storage technology currently provides the largest share of global long-term energy storage capacity?

A. Pumped hydro storage (PHS)
B. Lithium-ion batteries
C. Compressed air energy storage (CAES)
D. Vanadium redox flow batteries

3. What does the term "synthetic inertia" refer to in power systems with high renewable penetration?
A. The physical mass of wind turbine blades
B. The chemical stability of battery storage systems
C. Control systems that emulate the inertial response of rotating generators
D. Natural frequency oscillations in transmission lines

4. In power-to-gas (P2G) systems, what is the primary function of an electrolyzer?
A. Converting hydrogen back to electricity
B. Generating synthetic methane from biomass
C. Compressing natural gas for pipeline injection
D. Using surplus electrical power to produce hydrogen through water electrolysis

5. Which ancillary service requires the fastest response time (milliseconds) from energy storage systems?
A. Seasonal energy storage
B. Frequency regulation
C. Peak shaving
D. Energy arbitrage

Learning check

Question	Correct Answer	Explanation
1	B	During daylight hours, cloud cover, aerosols, and atmospheric water vapor columns are the primary drivers of short-term irradiance fluctuations, causing rapid power ramps that can exceed 60 MW in under 2 min at large-scale facilities.
2	C	Pumped hydro storage accounts for the vast majority of global installed long-term energy storage capacity, far exceeding lithium-ion, CAES, and flow battery deployments.
3	B	Synthetic inertia refers to control algorithms in power electronic–interfaced generators (e.g., wind turbines and inverters) that emulate the inertial response of conventional synchronous machines, helping stabilize system frequency.
4	C	In P2G systems, the electrolyzer uses surplus electrical power to split water into hydrogen and oxygen through electrolysis, enabling long-term energy storage and sector coupling.
5	C	Frequency regulation requires response times in the millisecond range, making it the fastest ancillary service—significantly faster than peak shaving, energy arbitrage, or seasonal storage.

AI disclosure

During the preparation of this work, the author(s) used OpenAI GPT-5 for proofreading and language refinement. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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