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Integration of Solar PV and Wind Power into Modern Power Grids: A State-of-the-Art Review

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Abstract
Solar photovoltaic (PV) and wind generation now supply a rising share of electricity in many countries, and the systems built around coal, gas, and hydro were not designed for them. Both resources are weather-driven, both connect to the network mostly through power electronics, and both are often located far from load centres. This review examines how these characteristics affect network operation and how the research and industry communities have responded. It covers generation and conversion technologies, the main operational problems (voltage and frequency regulation, falling inertia, power quality, fault behaviour, congestion, and curtailment), and the main remedies: grid-forming converter control, energy storage, hybrid plants, flexible transmission, demand-side flexibility, and data-driven forecasting. The paper adds worked equations, simulated illustrations, and side-by-side comparisons of technologies, control methods, forecasting approaches, and documented system events. Open research problems are identified for networks that must run with very high shares of inverter-based generation. The review is intended as an organized starting point for researchers and engineers working on renewable-rich power systems.
Keywords: *solar photovoltaic, wind power, grid integration, low-inertia systems, grid-forming inverters, energy storage, grid codes, forecasting.*

1. Introduction
Electricity supply is undergoing a structural change. For more than a century, power was produced mainly by large synchronous machines whose rotating mass gave the network a natural resistance to sudden imbalance. Solar PV and wind turbines change this picture. Their output follows irradiance and wind speed, not dispatch instructions, and most of their capacity is coupled to the network through converters rather than through rotating synchronous generators [1], [2]. These differences are not just academic. Operators must now plan for output that can swing within minutes, for networks that have less physical inertia than before, and for power flows that no longer run only from large plants down to consumers. At the distribution level, rooftop PV can push power upstream and raise voltages beyond planned limits. At the transmission level, wind-rich regions can exceed the capacity of the lines connecting them to demand centres [3]. A large body of literature addresses individual pieces of this problem: converter control, storage sizing, forecasting methods, market design, and grid codes. Surveys also exist, but many concentrate on one resource or one technical theme. This paper takes a system-level view of both solar PV and wind together, linking resource behaviour, interface technology, operational effects, and mitigation options in one structure. The remaining sections are organised as follows. Section II describes resource characteristics and their mathematical models. Section III reviews grid-connection technology. Section IV discusses integration challenges. Section V reviews mitigation strategies. Section VI covers forecasting. Section VII summarises grid codes and operating experience. Section VIII identifies research gaps, and Section IX concludes.

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1.1. Related Reviews and Contribution of This Paper

Earlier surveys cover individual parts of the integration problem. As shown in Table 1 lists selected ones and the way their scope differs from that of this paper.

Table 1 lists selected ones and the way their scope differs from that of this paper

Ref.	Year	Focus	Scope relative to this paper
[19]	2020	Challenges and solution technologies for variable renewables	Treats variable sources as one group; this paper compares PV and wind interfaces explicitly
[20]	2010	Technical problems of grid-connected PV	PV only; written before low-inertia operation became a major concern
[21]	2016	Impacts of PV penetration on distribution networks	Distribution level and PV only
[22]	2010	Frequency regulation with renewable sources	Frequency control focus; predates mature grid-forming control
[23]	2017	Inertia response and frequency control for renewables	Frequency stability techniques only
[24]	2020	Renewable penetration and power system flexibility	Operational flexibility focus
[11], [27]	2009, 2012	Grid-code requirements for wind farms	Wind only; earlier than current inverter-based requirements
[25], [26]	2020, 2021	Grid-forming inverter modelling and control	One technology theme
[28]	2015	Electrical energy storage technologies	Storage only
[29]	2016	Wind and solar curtailment	Curtailment only
[15]	2020	Energy forecasting	Forecasting only
[1]	2017	Operating systems with very high renewable shares	Broad overview in magazine format

Studies of PV integration have concentrated on inverter behaviour and on distribution-network effects such as voltage rise, reverse power flow, and protection coordination [20], [21]. The wind

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literature has focused on generator types, power-electronic converters, and grid-code compliance [11], [27], [32]. This separation makes it harder to see which problems are shared by both resources and which belong to only one. Frequency and inertia studies establish that converter-based generation contributes no inertia by default [22], [23], [39]. Later work moves from emulating inertia toward redesigning converter control [25], [26], [41]. Small-signal analyses of low-inertia systems [44] and studies of harmonic stability [36] indicate that interactions among converters, and between converters and the network, can drive instability even when each device meets its own requirements. Reviews of flexibility, storage, and curtailment [24], [28], [29], [45] address how balancing capacity is supplied, while forecasting surveys [15], [51], [52] address how uncertainty itself can be reduced.

The present paper differs in three ways. It treats PV and wind side by side. It links each integration problem to the interface technology that causes it and to the mitigation options reported in the literature. It also draws on documented system events and on simple simulations to show where gaps in requirements have mattered in practice.

2. Characteristics of Solar PV and Wind Generation

2.1.Solar PV

PV output depends on irradiance and cell temperature. On a clear day the daily profile is smooth and predictable, but passing clouds can cut the output of a plant by a large fraction within seconds to minutes. Because panels have no moving parts, there is no mechanical energy stored in the generator, and output can change much faster than that of a thermal unit. Geographic spreading of plants reduces the combined variability, since cloud cover rarely affects distant sites at the same moment. Plant sizes range from household rooftop systems of a few kilowatts to utility-scale plants of hundreds of megawatts. This wide range matters for integration: small systems are usually connected to low-voltage feeders and are not visible to the system operator, whereas large plants connect at transmission level and can be required to provide network support services. The electrical behaviour of a PV cell, and by extension a module, is commonly described by the single-diode model:

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + IR_s}{a}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \qquad (1)$$

where I_ph is the photo-generated current (nearly proportional to irradiance), I_0 is the diode saturation current, R_s and R_sh are the series and shunt resistances, and a=nN_s kT/q is the modified ideality factor of a module with N_s series cells. For system studies, a simpler power model is often sufficient:

$$P_{pv} = \eta\, A\, G\left[1 - \beta\left(T_c - T_{ref}\right)\right] \qquad (2)$$

where η is the conversion efficiency, A the array area, G the plane-of-array irradiance, β the temperature coefficient of power, T_c the cell temperature, and T_ref the reference temperature. As shown in Figure 1(a) and (b) show the I–V and P–V curves obtained from Eq. (1) for a generic 60-cell module at three irradiance levels. The current falls almost in proportion to irradiance, while the voltage at the maximum power point (MPP) changes only slightly. This is why MPPT algorithms mainly track a moving current while the voltage stays within a narrow band [30].

2.2.Wind Power

The mechanical power captured by a wind turbine is

$$P_w = 1/2\ \rho\, A\, C_p(\lambda, \beta)\, v^3, \qquad \lambda = \frac{\omega_r R}{v} \qquad (3)$$

where ρ is air density, A the swept area, C_p the power coefficient (a function of tip-speed ratio λ and blade pitch angle β), v the wind speed, ω_r the rotor speed, and R the rotor radius. Because of the cubic dependence on v, output is highly sensitive to small changes in the resource. In system studies the turbine is usually represented by a power curve defined by cut-in speed v_ci, rated speed v_r, and cut-out speed v_co. A common smooth approximation between cut-in and rated speed is

$$P(v) = \begin{cases} 0, & v < v_{ci} \text{ or } v > v_{co} \\ P_r\,\dfrac{v^3 - v_{ci}^3}{v_r^3 - v_{ci}^3}, & v_{ci} \le v < v_r \\ P_r, & v_r \le v \le v_{co} \end{cases} \qquad (4)$$

Fig. 1(c) plots Eq. (4) for v_ci = 3 m/s, v_r = 12 m/s,

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and v_co = 25 m/s. Variability occurs over many time through ramps lasting minutes to hours when weather fronts pass, to seasonal patterns. Offshore wind generally shows higher capacity factors and smoother output than onshore wind, but needs submarine cable or HVDC connections to shore [4].

scales, from turbulence on the order of seconds,

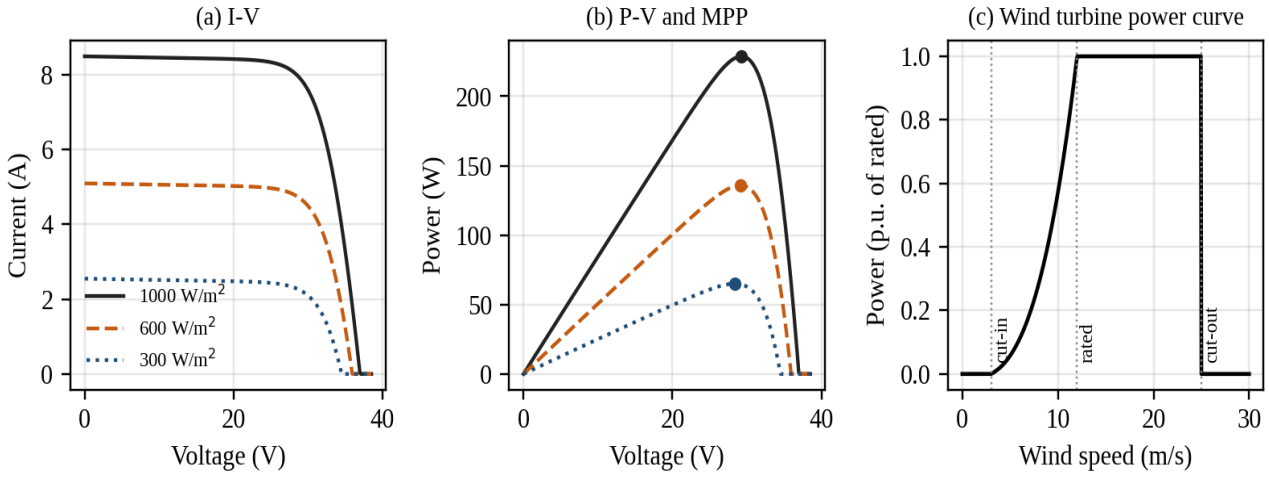


Figure 1 Illustrative resource behaviour: (a) I–V and (b) P–V curves of a generic 60-cell PV module at three irradiance levels, computed from the single-diode model of Eq. (1) at 25 °C; (c) normalised wind turbine power curve from Eq. (4). The MPP power at 1000, 600, and 300 W/m² is about 229, 136, and 65 W

2.3.Complementarity

In many regions the two resources partly offset each other: solar peaks around midday and in summer, while wind is often stronger at night and in winter. Where this complementarity exists, a combined portfolio needs less balancing capacity than either source alone. A common way to quantify it is the Pearson correlation coefficient between the two output series:

$$\rho_{pv,w} = \frac{\mathrm{cov}(P_{pv}, P_w)}{\sigma_{pv}\,\sigma_w} \qquad (5)$$

A strongly negative value indicates that the sources tend to compensate for each other. The profiles in Fig. 2(b) are synthetic and were built only to illustrate the idea; for them, ρ_(pv,w)≈-0.72. The degree of benefit at a real site is location-specific and should be assessed with local measured data instead of assumed. A strongly negative value indicates that the sources tend to compensate for each other. The profiles in Figure 2(b) are synthetic and were built only to illustrate the idea; for them, ρ_(pv,w)≈-0.72. The

degree of benefit at a real site is location-specific and should be assessed with local measured data instead of assumed. As shown in Table 2 compares the two resources on the characteristics most relevant to grid integration.

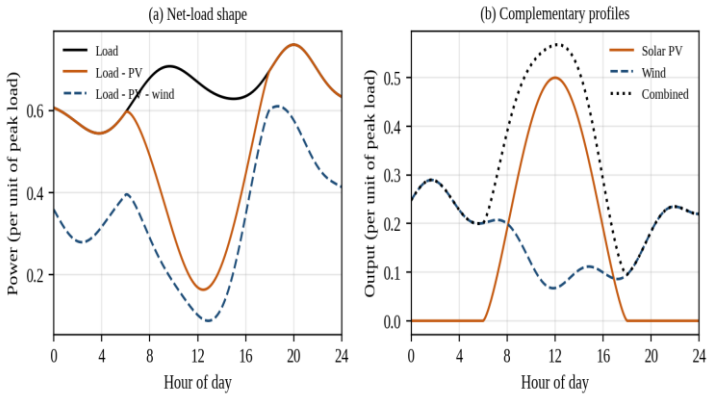


Figure 2 Illustrative daily profiles (synthetic data, not measurements): (a) net-load shape with and without PV and wind, showing the midday

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trough and evening ramp; (b) complementary PV and wind output

Table 2 Comparison of solar PV and wind generation relevant to grid integration

Aspect	Solar PV	Wind
Primary driver	Irradiance, temperature	Wind speed (cubic relation)
Fastest variability	Seconds to minutes (cloud transients)	Seconds to hours (turbulence, ramps)
Predictability	Strong daily pattern, cloud uncertainty	Weather-front uncertainty, ramp events
Interface to grid	Inverter (DC to AC)	Full converter or doubly fed machine
Typical connection level	Low voltage to transmission	Medium voltage to transmission, HVDC offshore
Moving parts in generator	None	Rotating generator, gearbox (some designs)
Inertial contribution	None by default	None by default (can be emulated)
Typical daily peak	Midday	Often night or early morning (site-dependent)
Main siting constraint	Land or roof area, irradiance	Wind resource, access, visual and noise limits

3. Grid-Connection Technologies

Fig. 3 shows a generic configuration in which PV, wind, and storage units connect to a common collector bus and then to the utility grid at the point of common coupling (PCC), under the supervision of a plant controller.

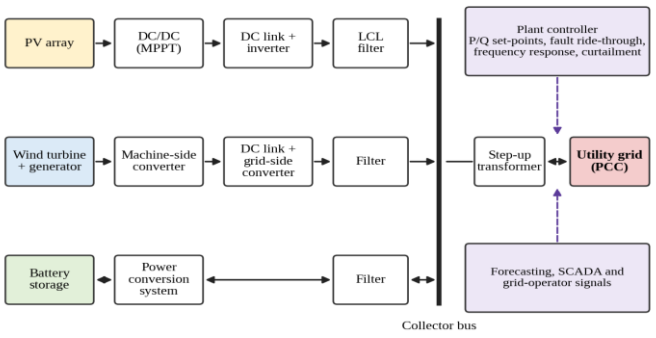


Figure 3 Generic configuration of a hybrid PV–wind plant with battery storage connected to the grid through power-electronic converters

3.1.PV Inverter Topologies

PV plants use inverters to convert DC to AC and to track the maximum power point. Common arrangements are central inverters for large plants, string inverters for medium installations, and microinverters at panel level for small systems. Central units give low cost per watt, while string and module-level units improve energy capture under partial shading and offer finer monitoring. Transformerless designs improve efficiency but need attention to leakage currents [5]. Maximum power point tracking (MPPT) is central to inverter control, and comparisons of tracking algorithms show a trade-off between convergence speed, steady-state oscillation, and implementation complexity [30]. For small installations, single-phase inverter topologies differ mainly in how they decouple the pulsating AC-side power from the DC side, which affects capacitor size and expected lifetime [31].

3.2.Wind Turbine Generator Types

Wind turbines are usually grouped into four types. Fixed-speed squirrel-cage machines (Type 1) and wound-rotor machines with variable rotor resistance (Type 2) are largely historical. The doubly fed induction generator (DFIG, Type 3) uses a partially rated converter on the rotor circuit and has been the dominant onshore design for many years. Full-converter machines (Type 4), using permanent-magnet or electrically excited synchronous generators, pass all power through the converter and offer the greatest decoupling from the grid, which helps with fault ride-through and reactive power control [6]. The DFIG concept uses a converter rated at only a fraction of turbine power, which keeps converter cost low but leaves the stator directly connected to the grid [33]. Reviews of wind power electronics describe the progression toward larger turbines, full-scale converters, and multilevel topologies for high-power and offshore applications [6], [32], [34].

3.3.Converter Control and Synchronisation

Most installed converters are grid-following: they measure the voltage angle at the point of connection, usually with a phase-locked loop (PLL), and inject current accordingly. This works well when the network is strong, meaning it has a high short-circuit level relative to the converter rating. In weak networks, the PLL and the current controller can interact with grid impedance and produce oscillations

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or loss of synchronism [7]. This limitation is a main driver of research on grid-forming control, discussed in Section V. Network strength is usually expressed by the short-circuit ratio (SCR). For a plant of rated power P_r connected to a grid with Thévenin reactance X_g and nominal voltage V, the maximum active power that can be transferred to an ideal source is limited by

$$P_{max} = \frac{V^2}{X_g} = S_{sc}, \qquad \text{SCR} = \frac{S_{sc}}{P_r} \qquad (6)$$

so that, in per unit, the transfer limit equals the SCR itself (Fig. 4). An SCR below about 3 is commonly described as weak and below about 2 as very weak, ranges in which the margin to the transfer limit is small and grid-following control becomes harder to keep stable. As shown in Figure 4 Maximum transferable power of a plant (per unit of its rating) as a function of the grid short-circuit ratio from Eq. (6); shaded areas mark commonly used weak and very weak ranges.

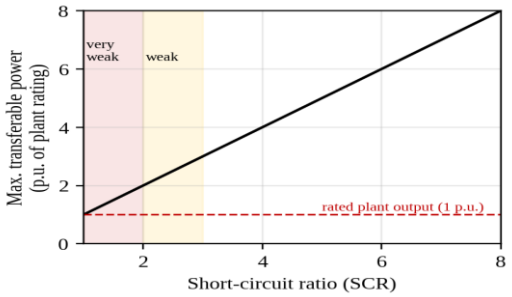


Figure 4 Maximum transferable power of a plant (per unit of its rating) as a function of the grid short-circuit ratio from Eq. (6); shaded areas mark commonly used weak and very weak ranges

Comparative simulations of a network with high inverter penetration indicate that grid-forming units can support voltage and frequency where grid-following units struggle, particularly after the loss of synchronous generation [35]. Beyond synchronisation, interactions at harmonic frequencies between converter controllers and network impedance can cause instability that classical power-quality assessment does not capture [36]. Table 3 compares the two control philosophies.

Table 3 Comparison of grid-following and grid-forming converter control

Aspect	Grid-following (GFL)	Grid-forming (GFM)
Basic behaviour	Controlled current source synchronised to a measured angle (PLL)	Controlled voltage source behind an impedance that sets its own angle and magnitude
Dependence on the grid	Needs a stable voltage reference	Can support weak networks and, in some designs, operate without a synchronous machine nearby
Weak-grid behaviour	PLL and current-loop interaction can cause oscillation	Generally more robust, subject to current limits
Inertial response	None unless supplementary control is added	Fast response possible, needs energy headroom or storage
Fault behaviour	Current-limited; follows a reference	Current-limited; strategy needed to keep voltage-source behaviour
Black-start capability	No	Possible with a suitable energy source and design
Deployment status	Widely deployed	Growing demonstrations and early grid-code requirements

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Page No: 5691 - 5707
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3.4.Transmission Technologies

Large or remote plants often rely on high-voltage alternating current (HVAC) or high-voltage direct current (HVDC) lines. Voltage-source-converter HVDC links are common for offshore wind because they avoid the charging-current limits of long AC cables and can control reactive power independently at both ends. Flexible AC transmission systems (FACTS), such as STATCOMs and static var compensators, are widely used to support voltage near renewable plants. VSC-HVDC technology has been reviewed extensively for offshore and asynchronous interconnections [4], and FACTS devices are covered in detail in standard references [37].

4. Integration Challenges

Table 4 summarises the main challenges, their physical causes, and the usual response. The subsections below describe each in more detail. As shown in Table 4 Integration challenges, causes, and responses.

Table 4 Integration challenges, causes, and responses

Challenge	Main cause	Typical effect	Main mitigation options
Variability and ramps	Weather-driven output	Steep net-load ramps, larger reserve needs	Forecasting, storage, flexible demand, wider interconnection
Low inertia	Converters replace synchronous machines	Faster frequency change, smaller time margin	Grid-forming control, synthetic inertia, fast frequency response, storage
Voltage deviation	Reverse flow, weak grid	Overvoltage on feeders, flicker	Volt-VAR control, tap changers, STATCOM, curtailment
Power quality	Switching converters, resonance	Harmonics, inter-harmonics, flicker	Filter design, damping control, standards compliance
Protection	Limited converter fault current	Under-reach or mis-operation of relays	Updated protection schemes, fault-current contribution from GFM units
Congestion and curtailment	Transmission slower to build than plants	Lost renewable energy, weaker project economics	Reinforcement, dynamic line rating, storage at constrained nodes

4.1.Variability and Uncertainty

Net load, defined as demand minus variable renewable output, becomes steeper and harder to follow as penetration grows:

$$P_{net}(t) = P_L(t) - P_{pv}(t) - P_w(t) \qquad (7)$$

In regions with large PV capacity, the net-load shape shows a deep midday trough followed by a steep evening ramp, often called the “duck curve” [8]. Fig. 2(a) illustrates this with synthetic profiles: adding PV deepens the midday minimum of net load to about 0.16 per unit of peak load, and the evening ramp requires the remaining generators to climb quickly as PV output falls. Operators must hold sufficient fast-ramping resources to cover this ramp and must manage minimum-generation constraints during the trough. The duck-curve analysis for California quantified how overgeneration and steep ramps emerge as the PV share grows [38]. International reviews of curtailment show it to be a common outcome where flexibility or transmission capacity is insufficient [29].

4.2.Reduced Inertia and Frequency Stability

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Page No: 5691 - 5707
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0740

Synchronous generators release stored kinetic energy automatically when frequency falls. As converter-based plants displace them, total system inertia declines, so the rate of change of frequency (RoCoF) after a disturbance increases and the time available for primary reserves to act shrinks [9]. The aggregate inertia constant of a system is the apparatus-weighted average of the individual constants of the connected synchronous machines:

$$H_{sys} = \frac{\sum_i H_i S_i}{S_{sys}} \qquad (8)$$

Only machines that are connected contribute to the sum, so replacing synchronous units by converter-based ones lowers H_sys even if total demand is unchanged. A single-area model of frequency after a power imbalance, with frequency deviation Δf in per unit of f_0, is

$$2H_{sys}\frac{d\Delta f}{dt} = \Delta P_m - \Delta P_L - D\,\Delta f \qquad (9)$$

where ΔP_m is the change in mechanical power from governor action, ΔP_L the lost generation (or added load) and D the load-damping factor. Immediately after the disturbance (ΔP_m=0, Δf=0) the initial rate of change is

$$\mathrm{RoCoF}_0 = \frac{f_0\,\Delta P_L}{2\,H_{sys}} \qquad (10)$$

which is inversely proportional to inertia. Primary frequency response from a governor with droop R and a combined governor-turbine lag T_g can be represented by

$$T_g\frac{d\,\Delta P_m}{dt} = -\frac{\Delta f}{R} - \Delta P_m \qquad (11)$$

and the steady-state deviation after the primary response is

$$\Delta f_{ss} = -\frac{\Delta P_L}{D + 1/R} \qquad (12)$$

Figure 5 shows the solution of Eqs. (9)–(11) for a 5% loss of generation with R = 0.05, D = 2, T_g = 10 s, and f_0 = 50 Hz at four inertia constants. The initial RoCoF ranges from 1.25 Hz/s at H_sys = 1 s to 0.21 Hz/s at 6 s, and the frequency nadir falls from 49.60 Hz to 49.31 Hz as inertia decreases from 6 s to 1 s, while the final deviation (about 0.12 Hz, 49.88 Hz) is the same in all cases because it depends on droop and damping, not inertia. The results show that inertia governs how fast the problem develops, while reserves and control decide where it ends. The literature draws the same distinction [39]. Frequency-support techniques for renewable plants are surveyed in [22] and [23]. Systems with limited interconnection, such as island networks, are most exposed. Frequency stability is therefore a leading concern in the transition to low-inertia operation, and it is now recognised as a stability category alongside the classical ones, with converter-driven stability added in the revised classification [10].

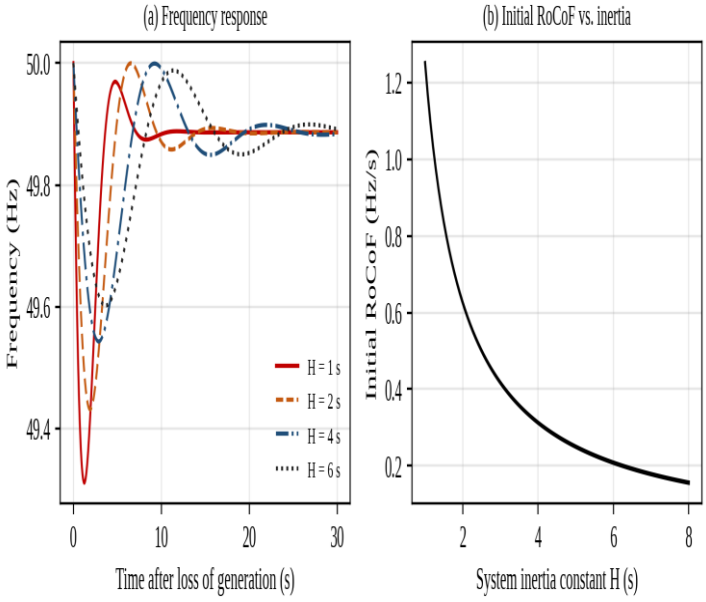


Figure 5 Simulated single-area frequency response (Eqs. (9)–(11)) after a 5% generation loss: (a) frequency for four values of system inertia constant; (b) initial RoCoF from Eq. (10). Parameters: R = 0.05, D = 2, T_g = 10 s, f_0 = 50 Hz. Simplified model for illustration, not a study of any real system

4.3.Voltage Regulation

In distribution feeders, high PV output at times of low demand can raise voltage above permitted limits, causing inverters to trip or curtail. A first-order estimate of the voltage change at the end of a feeder with resistance R and reactance X, carrying injected active power P and reactive power Q at nominal voltage V, is

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$$\Delta V \approx \frac{R\,P + X\,Q}{V} \qquad (13)$$

Because distribution feeders have a relatively high R/X ratio, active power injection raises voltage noticeably, and absorbing reactive power (Q<0) is one of the standard ways for an inverter to bring the voltage back down. In weak transmission areas, wind plants can face voltage fluctuation and flicker. Reactive power capability, on-load tap changers, and coordinated volt-VAR control are standard responses, but they require communication and coordination that older networks lack.

4.4.Power Quality

Switching converters generate harmonics and inter-harmonics, and multiple converters in a small area can interact. Rapid power changes can cause flicker. Standards such as IEEE 519 and IEC 61000 set limits, and modern converters generally meet them individually, but resonance with network capacitance and with other converters remains a practical concern [5].

4.5.Fault Behaviour and Protection

Converters limit their fault current to about 1.1 to 1.5 times rated current to protect semiconductors, whereas synchronous machines can supply several times rated current. This reduces the signal available to conventional overcurrent and distance protection, and it can cause protection to under-reach or mis-operate. Further, plants must stay connected through voltage dips, since mass disconnection during a fault can worsen the event; fault ride-through requirements address this directly [11]. Protection challenges in networks with converter-interfaced sources, including reduced fault current and bidirectional flows, are reviewed for microgrids in [40]; the same issues apply, with adjustments, to distribution feeders with high PV penetration.

4.6.Congestion and Curtailment

Where renewable plants are developed faster than transmission, output must sometimes be reduced to respect line limits. Curtailment wastes low-cost energy and weakens the economics of new projects. Reinforcement, dynamic line rating, and storage placed at constrained nodes are the usual tools.

5. Mitigation Strategies

Figure 6 groups the main families of mitigation measures. Table 6 later in this section compares them.

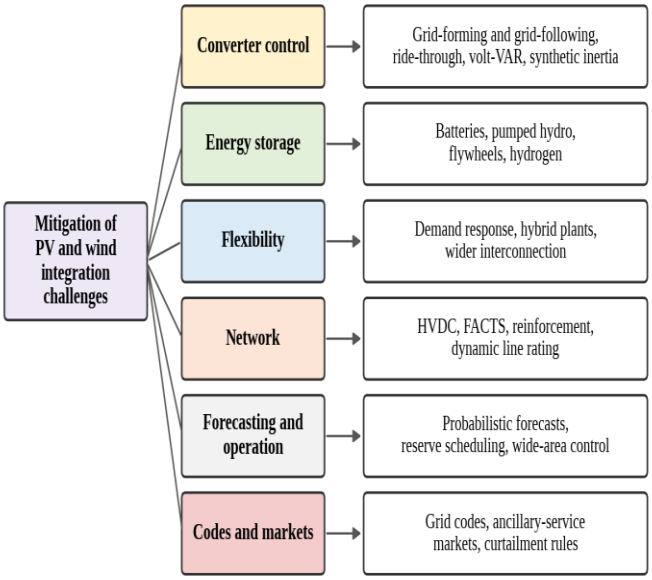


Figure 6 Taxonomy of mitigation strategies for PV and wind integration

5.1.Grid-Forming Converter Control

Grid-forming (GFM) converters regulate their own voltage magnitude and angle, instead of following a measured angle, and so behave as voltage sources behind an impedance. A widely used implementation is droop control, in which frequency and voltage magnitude are adjusted in proportion to active and reactive power:

$$\omega = \omega_0 - m_p\,(P - P_0), = V_0 - n_q\,(Q - Q_0) \qquad (14)$$

where m_p and n_q are the active-power and reactive-power droop gains. A virtual synchronous machine (VSM) instead emulates the swing equation, so that the converter reproduces an inertial response:

$$J\,\omega_0\,\frac{d\omega}{dt} = P_{ref} - P - D_p\,(\omega - \omega_0) \qquad (15)$$

with virtual inertia J and damping coefficient D_p. Well-known approaches include droop control, virtual synchronous machines, and matching control, which differ in how they derive the angle reference from power or DC-link behaviour [7], [12]. GFM units can supply fast frequency response, support weak networks, and in some designs can operate without any synchronous machines nearby.

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Synchronverters, which reproduce the equations of a synchronous machine inside the converter controller, were an early demonstration of this idea [41]. Later work positions grid-forming control as a candidate for enabling very high converter penetration [42], with detailed classifications of control methods and modelling approaches in [25] and [26]. Recent studies also show that grid-following and grid-forming control can be viewed as dual forms of one another [43], and that small-signal studies of low-inertia systems must include converter dynamics alongside network and machine dynamics [44]. Open questions include current-limiting during faults, behaviour when sharing with grid-following units, and standardised grid-code requirements.

5.2.Energy Storage

Battery storage provides fast response for frequency regulation, ramp smoothing, and time-shifting of surplus midday solar to the evening. Pumped hydro offers large energy capacity for longer durations. Other options include compressed air, flywheels for very short duration, and hydrogen for seasonal needs [13]. Operating projects have shown that batteries can respond to frequency events within a fraction of a second, a speed unavailable from most conventional plants. The main constraints are cost, degradation under cycling, and the need for suitable market rules that reward fast response. Grid-scale storage chemistries and their trade-offs are discussed in [45], and a broader comparison of electrical energy storage technologies and their suitability for different power-system functions is given in [28]. Pumped hydro, which holds most of the world's installed storage capacity, is reviewed in [46]. As shown in Table 5. Storage options and typical grid roles.

Table 5 Storage options and typical grid roles

Technology	Response time	Typical duration	Main grid role
Flywheel	Milliseconds	Seconds to minutes	Frequency response, power quality
Lithium-ion battery	Milliseconds to seconds	Minutes to hours	Frequency regulation, ramping, time-shifting
Pumped hydro	Seconds to minutes	Hours to days	Bulk energy shifting, reserves
Compressed air	Minutes	Hours	Bulk shifting
Hydrogen	Minutes	Days to seasons	Long-duration storage, sector coupling

5.3.Hybrid Solar-Wind Plants

Co-locating PV and wind, often with storage, lets the plants share a grid connection and interconnection costs, and the partly complementary output raises the utilisation of that connection. Control must coordinate the units so that the plant meets a single set of grid-code requirements at the point of connection.

5.4.Wind and PV Providing Grid Services

With suitable control, renewable plants need not be passive. Wind turbines can release rotor kinetic energy for a short period to support frequency (synthetic or emulated inertia). PV plants operated below their maximum power point can hold headroom for upward reserve. Both can provide reactive power and voltage control through their converters, sometimes even without generating active power [14]. Early work on wind turbines emulating inertia showed that a temporary release of rotor kinetic energy can support primary frequency control [14]. For PV plants, studies argue that fast frequency response needs either curtailed operation or an added storage element, and that grid requirements should define it explicitly [47]. Active power control from wind plants is also treated in an NREL technical report [48].

5.5.Demand-Side Flexibility and Smart Grids

Controllable loads, such as water heating, cooling,

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 10 October 2026
Page No: 5691 - 5707
https://irjaeh.com
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electric vehicle charging, and industrial processes, can shift consumption to match renewable availability. Advanced metering, distribution management systems, and aggregators allow many small resources to be coordinated as virtual plants. Microgrids add local balancing and can island during upstream disturbances. Demand response and smart-load concepts are reviewed in [49], and the microgrid concept and its control hierarchy are described in [50].

5.6.Network Reinforcement and Flexible Transmission

HVDC, FACTS devices, dynamic line rating, and wider interconnection between regions all increase the ability to move renewable energy and to share reserves. Interconnecting a larger area smooths variability because weather differs across distance. A system-level assessment of options for integrating variable renewables, grouped across technology, market design, and operation, is provided in [57].

5.7.Comparison of Mitigation Options

Table 6 compares the main options on benefit, limitation, and maturity. The maturity column is a qualitative synthesis of the reviewed literature, not a measured quantity, and will differ between countries and markets. As shown in Table 6. Qualitative comparison of mitigation options

Table 6 Qualitative comparison of mitigation options

Option	Main benefit	Main limitation	Maturity (qualitative)
Grid-forming control	Supports weak grids, inherent fast response	Current-limiting and interaction questions, limited standards	Emerging
Battery storage	Fast response, flexible siting	Cost, degradation, limited duration	Commercial
Pumped hydro	Large energy capacity, long life	Site-limited, long lead time	Mature
Hybrid PV–wind plants	Better use of grid connection, smoother output	Needs coordinated control and suitable resource mix	Commercial
Demand response	Low capital cost, shifts load to renewable hours	Depends on participation, market and communication	Commercial, varies by market
HVDC and FACTS	Moves power over distance, voltage support	High capital cost, permitting time	Mature
Synthetic inertia from wind and PV	Uses existing assets	Limited energy, recovery effects, headroom needed	Early commercial
Probabilistic forecasting	Reduces reserve and improves scheduling	Data quality, extreme events	Emerging in operations

6. Forecasting

Accurate forecasting reduces the reserve that operators must hold. Methods range from physical models driven by numerical weather prediction, to statistical time-series models, to machine-learning models trained on historical output and weather data. Hybrid approaches combine physics-based inputs with learned corrections. Very short-term PV forecasting often uses sky imaging and satellite data to anticipate cloud motion, whereas wind ramp forecasting relies on weather model ensembles and turbine data. Probabilistic forecasts that give a range or distribution, not a single value, are increasingly preferred, because they allow reserve decisions to

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 10 October 2026
Page No: 5691 - 5707
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0740

reflect risk [15]. Remaining challenges include rare extreme weather events, transferability of models between sites, and the availability of high-quality data. Reviews of PV forecasting classify methods by horizon, input data, and model type [51], and reviews of wind power forecasting describe a similar progression from physical and statistical methods to hybrid and machine-learning approaches [52]. Deep-learning ensembles have been proposed to produce probabilistic wind power forecasts [53].

Forecast accuracy is usually reported with the root-mean-square error and the mean absolute error, often normalised by plant capacity P_r:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(\hat{P}_k - P_k\right)^2}, \mathrm{nRMSE} = \frac{\mathrm{RMSE}}{P_r} \qquad (16)$$

$$\mathrm{MAE} = \frac{1}{N}\sum_{k=1}^{N}\left|\hat{P}_k - P_k\right| \qquad (17)$$

where P^_k is the forecast and P_k the measured power at step k. RMSE penalises large errors more strongly than MAE and is therefore more sensitive to missed ramps. A forecast is normally compared with a persistence baseline before it is judged useful. Table 7 compares the main forecasting approaches.

Table 7 Comparison of forecasting approaches

Approach	Typical horizon	Strengths	Weaknesses
Persistence	Minutes to hours	Simple, hard to beat at very short range	Fails at ramps and longer horizons
Physical (numerical weather prediction)	Hours to days	Captures weather systems, no site history needed	Coarse resolution, high compute cost, local bias
Statistical time series	Minutes to hours	Fast, interpretable	Weak for non-stationary and nonlinear behaviour
Machine and deep learning	Minutes to days	Learns nonlinear patterns, fuses many inputs	Needs large data, limited interpretability, transfer between sites
Hybrid (physics plus learning)	Minutes to days	Combines weather information and local correction	More complex to build and maintain
Sky imaging and satellite	Minutes to a few hours	Tracks cloud motion for PV	Limited to PV, depends on equipment and coverage

7. Grid Codes and Operating Experience

7.1.Grid-Code Requirements

Grid codes have evolved from simply allowing renewable plants to disconnect during disturbances to requiring them to behave more like conventional plants (Table 8). Typical requirements include operation within defined frequency and voltage ranges, fault ride-through with reactive current injection, active power curtailment and ramp-rate control on command, frequency-response capability, and reactive power range at the point of connection. For distributed resources, standards such as IEEE 1547-2018 added voltage and frequency ride-through and smart-inverter functions [16]. Requirements differ by country and are being updated as penetration rises, with several operators now considering or introducing grid-forming capability requirements. Comparisons of wind-farm grid codes across countries show differences in fault ride-through profiles, reactive power ranges, and frequency-response obligations, and they have motivated calls for harmonisation [11], [27]. In Europe, the Requirements for Generators network code sets common minimum technical requirements for

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 10 October 2026
Page No: 5691 - 5707
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0740

generating units connected to the network [54]. As shown in Table 8. Legacy and modern grid-code requirements for inverter-based resources.

Table 8 Legacy and modern grid-code requirements for inverter-based resources

Requirement	Legacy approach	Modern approach
Behaviour during voltage dips	Disconnect to protect the plant	Stay connected and inject reactive current (ride-through)
Frequency deviations	Disconnect outside narrow limits	Remain connected over wider ranges and provide frequency response
Active power control	Output follows the resource	Curtailment and ramp-rate limits on operator command
Reactive power and voltage	Fixed power factor	Voltage or reactive power control within a defined range
Distributed resources	Passive, not visible to operators	Smart-inverter functions, communication, ride-through [16]
Grid-forming capability	Not addressed	Under discussion or being introduced in some systems

7.2.Lessons from System Events

Several events illustrate integration risks. The September 2016 blackout in South Australia involved a series of faults during severe storms, during which multiple wind farms reduced output through protection settings that counted repeated voltage disturbances, contributing to the loss of supply; the investigation led to changes in settings and requirements [17]. The 9 August 2019 event in Great Britain saw a lightning strike followed by the loss of a gas plant and an offshore wind farm and distributed generation, causing frequency to fall below normal limits and triggering automatic load shedding; the report highlighted the importance of ride-through behaviour and of understanding the behaviour of embedded generation [18]. These cases did not show that renewables are inherently unsafe, but that settings, controls, and requirements must match system needs.

7.3.Disturbances Involving Large Solar PV Fleets

North American investigations offer further examples. After faults during the 2016 Blue Cut Fire in southern California, a large amount of solar PV output was lost, and the investigation pointed to inverter behaviour during faults and to protection settings [55]. Later disturbances in Texas involved reductions in PV output following transmission faults, and the investigation again highlighted converter control and protection settings as contributing factors [56]. Together with the events above, these cases suggest that plant-level controls and settings, more than resource variability, have been an important cause of large unplanned output losses during faults. Table 9 compares the events. As shown in Table 9. Comparison of documented disturbances involving PV and wind plants.

Table 9 Comparison of documented disturbances involving PV and wind plants

Event	Resource involved	Main contributing factors reported	Lesson
South Australia, September 2016 [17]	Wind	Repeated voltage disturbances triggered protection	Review protection and ride-through settings

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 10 October 2026
Page No: 5691 - 5707
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0740

		settings in several wind farms	
California, Blue Cut Fire, 2016 [55]	Solar PV	Inverter behaviour and settings during faults	Verify inverter fault response and settings
Great Britain, 9 August 2019 [18]	Wind, embedded generation	Loss of generation after a lightning strike, ride-through behaviour	Understand embedded generation behaviour
Texas disturbances, 2021 [56]	Solar PV	Output reductions after transmission faults, converter control and protection settings	Improve converter control and commissioning checks

8. Research Gaps and Future Directions

Based on the reviewed literature, several areas deserve further attention.

1. Stability analysis in converter-dominated networks. Classical tools rely on assumptions about synchronous machines. Methods for assessing small-signal and transient stability with many interacting converters, including electromagnetic-transient-level models at scale, need maturing.
2. Standardisation of grid-forming requirements. Specifications for response speed, current limiting, and test procedures are still developing, and harmonised requirements would ease deployment [12].
3. Co-optimisation of storage, hybrid plants, and flexible demand. Sizing and siting methods that account for degradation, market revenue, and network constraints together are still limited.
4. Protection in low-fault-current systems. Protection schemes that do not depend on high fault currents, and their coordination with converter control, require more validation.
5. Data-driven methods with guarantees. Machine learning for forecasting and control shows promise, but operators need interpretable, robust methods with quantified uncertainty and verified behaviour under rare events.
6. Cybersecurity of inverter-based resources. A large number of internet-connected converters expands the attack surface, and secure communication and update practices need to be built into resources and standards.
7. Sector coupling and long-duration storage. Integration with heating, transport, and hydrogen production may provide flexibility, but the system-level benefits and operating rules are not yet fully established.

Conclusion

Solar PV and wind power can be integrated at high shares, but doing so requires a shift in how power systems are planned and operated. The central difficulties come from variability, the replacement of synchronous inertia and fault current by converters, and the mismatch between where resources are located and where power is needed. The reviewed literature, together with the simple models and comparisons in this paper, shows that these difficulties can be addressed by combining several measures: converter control that supports the network, storage and flexible demand, stronger and smarter networks, better forecasts, and grid codes that require plants to contribute to system security. The most pressing open issues are the stability and protection of networks dominated by converters and the standardisation of grid-forming capability. Continued work on these topics, supported by field experience and open data, will determine how

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 10 October 2026
Page No: 5691 - 5707
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0740

reliably and economically renewable-rich grids can operate.

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Vol. 04 Issue: 10 October 2026
Page No: 5691 - 5707
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