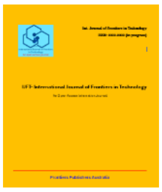
International Journal of Frontiers in Technology
An Open Access International Journal

Journal home page: https://frontierstechnologyjournal.com
ISSN: 0000-0000 (in progress)



Research Article

Flexibility in Energy Systems: Integrating Renewable Energy into the Power Grid

Md Mizanur Rahman and Ahad Ali
IEOM Society International, Sydney, Australia
Email: mizanur1970@gmail.com

Publication history
Received:12 March 2025
Revised: 15 March 2025
Accepted: 25 March 2025
Available online: 25 March 2025

International Journal of Frontiers in Technology, 2025, 02(01), 01-07

Abstract
Over the past three decades, the integration of renewable energy sources (RES) into power grids has grown exponentially, driven by global decarbonization targets and the zero-marginal-cost nature of harvesting ambient energy. However, the intrinsic weather-dependent volatility and spatial-temporal variability f(x, y, t) of these resources present structural stability challenges to legacy grid architectures. In conventional power systems, operational flexibility was natively localized on the supply side through dispatchable fossil-fuel generation. Modern high-penetration renewable grids require multi-dimensional flexibility frameworks across both supply and demand to maintain active power-frequency balance and reactive power-voltage control. This article provides a comprehensive overview of the systemic need for energy flexibility, establishes formal conceptual definitions, and evaluates the state-of-the-art technical, architectural, and market-driven strategies required to mitigate residual load volatility.

Keywords
Flexibility, Energy Grid, Integration, Renewable Sources

1. Introduction

The paradigm shift from deterministic, fossil-fuel-based generation to stochastic, renewable-dominated power systems necessitates a fundamental reassessment of grid resilience. According to the International Energy Agency (IEA), power system flexibility is formally defined as: the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise [1].

From a market-centric perspective, it is characterized as the modification of generation injection and/or consumption patterns in reaction to an external signal—such as a dynamic price indicator or an activation command—to provide a localized or system-wide service within the energy ecosystem [2].

Historically, power grids relied on centralized, dispatchable generation units to dynamically follow a passive, aggregate load profile. In contemporary systems, both supply and demand vary stochastically across spatial dimensions (x, y) and continuous temporal scales (t). The deployment of variable renewable energy (VRE), primarily solar photovoltaics (PV) and wind power, introduces sharp multi-hour ramps and steep net-load declines. This phenomenon is exemplified by the well-documented duck-curve [3], where high solar insolation at midday hollows out the net-load profile, followed by a rapid ramp-up in the evening as solar generation drops off precisely when consumer demand peaks.

To prevent catastrophic system degradation, including unmitigated frequency excursions and voltage instability, modern grids must mobilize a diversified portfolio of flexibility strategies. These solutions span flexible demand response, deep market reforms, sectoral coupling, and advanced electrical, thermal, and chemical energy storage architectures.

2. Market Structures and Smart Grid Digitization

Achieving systemic flexibility requires coordinating millions of distributed energy resources (DERs). This coordination relies on integrating advanced information and communication technologies (ICT) with reformed, non-monopolistic electricity market designs.

2.1 Smart Grid Infrastructure

The digitization of the distribution and transmission networks through Advanced Metering Infrastructure (AMI) enables automated, bidirectional, real-time communication between system operators and end-use devices. By leveraging edge computing and sensor networks, smart grids optimize localized power flows, dynamically increase transmission line network capacity, and reduce the systemic over-allocation of dedicated stationary storage assets.

2.2 Regulatory and Market Decoupling

Legacy utility models built on natural monopolies stifle the financial incentives required to unlock demand-side flexibility. To incentivize market actors to provide grid services, regulatory frameworks must transition to open, transparent, and competitive commodity markets characterized by the following attributes:

a) Generator Disaggregation: Unbundled power systems allowing independent power producers (IPPs) and aggregators to compete directly on an open exchange to serve retail and wholesale loads.
b) Bilateral Contract Freedom: Empowering commercial, industrial, and residential consumers to negotiate dynamic supply and ancillary service contracts across multiple providers.
c) Transparent Price Discovery: Implementing high-granularity spot markets (day-ahead, intra-day, and real-time balancing markets) that accurately reflect the instantaneous marginal cost of production and physical grid congestion.
d) Financial Derivatives Trading: Facilitating robust futures and forward markets to allow market participants to hedge against the extreme price volatility inherent to VRE-dominated wholesale markets.

3. Demand-Side Flexibility and Sector Coupling

Transitioning flexibility from a supply-only mechanism to a bidirectional framework involves mobilizing end-use demand and coupling the electricity sector with transport and heating.

3.1 Demand Response (DR)

Demand response involves modifying consumer load profiles in response to dynamic pricing structures or direct utility signals.

a) Industrial Adjustments: Large-scale industrial plants (e.g., aluminum smelting, chlor-alkali processing, and wastewater treatment plants) can retrofit control systems to dynamically ramp down or shift heavy processes to coincide with peak VRE generation.
b) Residential Optimization: Residential consumers utilize smart home energy management systems (HEMS) to automatically shift deferrable loads, such as heat pumps and dishwashers, to periods with favorable time-of-use (ToU) tariffs or real-time pricing signals.

3.2 Electric Vehicles (EV) and Vehicle-to-Grid (V2G) Systems

The electrification of the transportation sector presents both a notable grid burden and a highly scalable distributed storage resource. Because passenger vehicles remain stationary for approximately 95% of their lifetime, parked EVs can serve as dynamic assets. Installing charging infrastructure at long-duration parking zones (e.g., residential garages and workplace parking lots) allows for two primary paradigms:

Grid-to-Vehicle (G2V / Smart Charging): Automated charging optimization where the charging profile is shifted within the boundaries of total parked duration and battery state-of-charge (SoC) constraints. Mathematically, the total energy delivered E_{\text{total}} over a parking interval [t_{\text{start}}, t_{\text{end}}] can be represented as the integration of the charging power curve:

$$E_{total} = \int_{t=0}^{T} P(t)dt$$

Because P(t) can be freely manipulated between the battery's minimum charging threshold and the maximum capacity of the electric vehicle supply equipment (EVSE), charging can be heavily skewed to match VRE generation peaks or periods of low residual demand.

Vehicle-to-Grid (V2G): A bidirectional framework enabling plug-in electric vehicles (BEVs, PHEVs) to actively inject power back into the distribution network or throttle their charging rates to provide ancillary grid services (e.g., spinning reserves and frequency regulation). Regulatory models indicate that with proper framework support, V2G integration can provide vehicle owners with annual net revenues ranging from approximately 318 to 454, depending on daily driving distances (spanning 32 to 97 km) and local market valuation of fast frequency response services.

3.3 Cogeneration and Sectoral Heat Coupling

Combined Heat and Power (CHP) plants radically improve efficiency compared to conventional thermal generation, which typically rejects 50% to 70% of primary energy as waste heat. Most conventional thermal power stations exhibit efficiencies in the range of 30–37%, while newer combined cycle gas turbine (CCGT) stations still only achieve efficiencies in the region of 47%.

Electricity demand is normally highest during concurrent heating or cooling demand peaks (with cooling demand tracking high solar insolation periods). By operating at thermal-electrical equilibrium, CHP plants meet these simultaneous needs. Integrating large-scale thermal energy storage (TES) units, heat accumulators, and flue gas condensers decouples electricity generation from direct thermal tracking. This allows CHP systems to ramp down electrical output during VRE abundance without interrupting the continuous supply of district heating, cutting harmful air pollution, reducing fuel imports, and improving regional energy security.

4. Power-to-Gas (P2G) Pathways

For long-duration and seasonal energy storage where electrochemical batteries are economically unfeasible, Power-to-Gas (P2G) pathways provide a critical link between the electrical grid and the chemical energy sector. P2G utilizes surplus wind and solar generation to drive water electrolysis, separating water into oxygen and hydrogen gas:

$$2H_2O + Electricity \rightarrow 2H_2 + O_2$$

The generated hydrogen can be stored under pressure, utilized directly in fuel cell vehicles, or processed through a methanation reaction to yield synthetic natural gas (SNG) for injection into existing national gas networks. The operational efficiencies of various P2G pathways are detailed in Table 1.

Table 1. Efficiency Metrics of Power-to-Gas (P2G) Technological Pathways

Pathway Class	Intermediate/Final Product	Efficiency Range (%)	Process Parameters and Conditions
Electricity>Gas	Hydrogen (H2)	54 – 72%	200 bar Mechanical compression
	Methane (SNG)	49 – 64%	Thermochemical/biological methanation
	Hydrogen (H2)	57 – 73%	80 bar natural gas pipeline injection
	Methane (SNG)	50 – 64%	80 bar pipeline injection standard
	Hydrogen (H2)	64 – 77%	Atmospheric operation (no compression)
	Methane (SNG)	51 – 65%	Atmospheric synthesis
Electricity>Gas >Electricity	Hydrogen (H2)	34 – 44%	80 bar compression; up to 60% back to electricity
	Methane (SNG)	30 – 38%	Standard gas turbine re-electrification
Electricity >Gas> Electricity & Heat	Hydrogen (H2)	48 – 62%	80 bar compression; electricity/heat for 40/45%
	Methane (SNG)	43 – 54%	Integrated district heating co-generation

Source: Adapted from Fraunhofer IWES technical evaluation data [4].

5. Electrical and Mechanical Energy Storage Systems

Energy storage systems (ESS) manage supply-demand mismatches across varying operational timeframes, from millisecond-level frequency responses to multi-day load leveling. Renewable energy sources coupled with advanced power electronics can regulate reactive power (and therefore voltage response) even when they are not dispatching active power [5, 4].

By curtailing or storing output, renewables can perform frequency control, while dedicated battery storage can execute fast frequency response services superior to heavy conventional thermal plant governors [6]. Currently, VRE co-located with localized small-scale battery storage is cost-competitive with conventional legacy sources [7, 8], smoothing power output with minimized round-trip energy losses [9] and boosting grid reliability.
However, current battery capacities are insufficient to cover long-duration variations in the regional residual load curve [10]. Thus, residual load flexibility must still be performed mainly by conventional dispatchable sources with the aid of demand response [11]. For example, in simulated summer power profiles for Taiwan, where solar energy represents the dominant VRE capacity, total dispatchable renewable capacity (hydro, pumped storage, bioenergy, and geothermal) sits at approximately 5.5 GW [12]. Yet, the variations of the residual load can ramp up to 18 GW within a swift six-hour window, forcing fossil gas power plants to perform the vast majority of the residual load shifting [13, 14]. The primary technological mechanisms involved in electrical energy storage are categorized below.

5.1 Pumped Hydropower Storage (PHS)

PHS represents the most widely deployed type of grid-scale energy storage facility globally, operating via two vertically separated water reservoirs.

a) Scale and Efficiency: Typically configured in 100–400 MW and 1–2 GW classes, it yields round-trip efficiencies between 70% and 85%, with discharge times ranging from several hours to multiple days.
b) Advancements: Subterranean configurations using disused wells or cavities reduce environmental impacts and human population displacement controversies. Furthermore, pumping sea or river water optimizes spatial pathways; seawater PHS can attain up to 80% efficiency due to short waterway lengths which minimize hydraulic head losses.

5.2 Compressed Air Energy Storage (CAES)

CAES utilizes off-peak electricity to compress ambient air into underground geological formations (e.g., salt caverns) at pressures ranging from 45 to 70 bar. During discharge, the compressed air is expanded through a modified gas turbine to meet bulk energy demands. Traditional diabatic CAES achieves approximately 42% efficiency (e.g., Huntorf, Germany, built in 1978 with a 300,000 \text{m}^3 cavern and a 290 MW unit). However, it consumes 40% less natural gas than conventional open-cycle gas turbines because the mechanical work of compression is performed prior to combustion. Modern configurations, such as the McIntosh facility in Alabama (USA), couple a 100 MW wind farm with a 268 MW CAES unit to mitigate wind volatility.

5.3 Seafloor Concrete Storage Spheres

Developed for deployment adjacent to deep offshore wind arrays, this concept employs hollow concrete spheres (approx. 31 meters in diameter) placed on the ocean floor at depths near 350 meters. Coinciding with VRE surpluses, seawater is pumped out of the internal cavity against hydrostatic pressure, effectively storing energy via a localized vacuum. When grid demand peaks, sea water penetrates the sphere, moving an internal hydro-turbine generator. Each sphere delivers 5 MW of capacity over a 4-hour discharge window, featuring an operational durability of up to 40 years.

5.4 Mechanical Flywheels

Flywheel energy storage systems store kinetic energy within a rotating high-mass cylinder operating between 30,000 and 40,000 rpm. To maximize efficiency, the cylinder is suspended via active magnetic bearings within a vacuum chamber. Flywheels are characterized by rapid response times 5ms for a 0% to 100% full power transition) and minimal standby losses (< 1\%).

The world's largest operational flywheel system (operating since 1985) consists of six disks, each featuring a diameter of 6.6 meters and a weight of 107 tonnes. During a 6-minute charging sequence, thyristor systems ramp the angular speed from 70% to 100% of its rated limit using 19 MW of power, allowing for a high-power discharge of up to 160 MW over approximately 30 seconds.

5.5 Superconducting Magnetic Energy Storage (SMES)

SMES systems store electrical energy directly within the magnetic field generated by circulating a direct current through a cryogenic superconducting coil cooled below its critical temperature. The stored energy E within an inductive coil carrying a current I is mathematically defined by:

$$E = \frac{1}{2}LI^2$$

where L represents the system inductance. Because the electrical resistance of the superconducting loop is zero, energy can be stored indefinitely without conversion losses. Significant losses are restricted solely to the rectifier/inverter processes (AC to DC and vice versa) and cryogenic refrigeration. SMES units provide near-instantaneous power injection, serving specialized industrial applications (such as microchip fabrication plants requiring ultra-clean power) and transient grid stabilization. The primary barrier to widespread deployment remains capital cost.

5.6 Thermal Energy Storage (TES)

TES systems decouple thermal power plants from absolute load tracking by storing energy in material media.

a) Sensible Heat Storage (SHS): Involves heating bulk liquid or solid media (such as molten salts, liquid sodium, or pressurized water) without altering the material's phase state during accumulation. The thermal energy is later extracted via secondary heat exchangers to generate high-pressure steam for turbo-alternator units.

b) Latent Heat Storage (LHS): Utilizes Phase Change Materials (PCMs), such as sodium hydroxide, capitalizing on the high energy density associated with solid-to-liquid phase transitions at near-isothermal conditions.

6. Grid Interconnections and Trans-National Balancing

Expanding physical transmission interconnections between adjacent balancing areas reduces the ramping demands placed on individual domestic generation fleets. Well-interconnected synchronous zones allow localized VRE variations to be averaged out over larger geographical regions. This spatial smoothing lowers wholesale electricity prices by reducing the invocation of expensive, high-marginal-cost peaker plants, an economic metric dictated by the prevailing spark spread [15].

A clear empirical example occurred during the winter of 2016–2017, when a significant portion of France's nuclear fleet was offline for safety inspections. Cross-border electricity imports from the United Kingdom, Germany, and other neighbouring grids stabilized the European transmission network and reduced the need to activate high-emission fossil gas plants within France [20]. Consequently, international grid interconnection represents a mutually beneficial paradigm that enhances transnational cooperation [16, 17, 18].

However, enhanced interconnection can sometimes create conflicting operational incentives. If cross-border transmission capacity is highly available, legacy fossil-fuel generators (such as German lignite/brown coal plants) may opt to export surplus energy at low prices rather than undergoing thermal cycling or shutting down completely. Modelling suggests that German brown coal electricity generation could have dropped by up to 37% during specific historical periods if all additional residual load flexibility had been enforced through domestic generation curtailment rather than regional export pathways.

7. Conclusion

Integrating high penetrations of variable renewable energy requires a coordinated approach to system flexibility. While decentralized battery storage and smart charging configurations are increasingly cost-competitive and effective at managing short-term frequency deviations, they are not yet sufficient to manage seasonal or sustained multi-day net-load ramps.

As a result, modern power systems must use a combined strategy. This involves deploying mechanical and chemical storage systems (such as PHS and P2G), enacting regulatory changes to enable dynamic demand response, and utilizing highly flexible, low-emission dispatchable generation assets to maintain grid stability through the energy transition.

Acknowledgment

The authors express their gratitude to IEOM Society International for providing all out supports to perform this research work.

References

[1] International Energy Agency (IEA). Status of Power System Transformation: System Flexibility and Integration of Renewables. IEA Research Report, Paris, 2024.
[2] European Commission / Regulatory Frameworks. Market Mechanisms for Ancillary Service Procurement and Grid Flexibility. Energy Policy Review Series, 2020.
[3] Agora Energiewende. The German Energy Transition (Energiewende): Insights on Lignite Generation Inflexibility and Regional Export Dynamics. Agora Study Series, 2021.
[4] Battaglini, A., et al. More Interconnection, Less Curtailment: The Strategic Value of Trans-National Supergrids. Energy Policy, 2020.
[5] Kundur, P. Power System Stability and Control. McGraw-Hill Education, 2020.
[6] Blaabjerg, F., et al. Power Electronics Converter Technology for Modern Large-Scale Renewable Energy Systems. IEEE Transactions on Power Electronics, 2019.
[7] Denholm, P., et al. The Role of Fast Frequency Response from Battery Energy Storage in High VRE Grids. National Renewable Energy Laboratory (NREL), 2022.
[8] Lazard's Levelized Cost of Storage Analysis. Comparative Economic Feasibility of Co-located VRE and Electrochemical Storage Systems, 2020.
[9] Taiwan Bureau of Energy. Simulated Power Output Profiles and Residual Load Volatility for Summer 2025/2026 Target Scenarios. Technical Report, 2019.
[10] California Independent System Operator (CAISO). The Duck Curve: Operational Challenges and Flexibility Requirements with High Penetration Solar Photovoltaics, 2021.

[11] Kempton, W., & Tomić, J. Vehicle-to-Grid (V2G) Power Fundamentals: Calculating Capacity and Net Revenue. Journal of Power Sources, 2020.
[12] Lund, H., & Munster, E. Integrated Energy Systems and Sector Coupling: Combined Heat and Power (CHP) and District Heating Optimizations. Energy, 2019.
[13] energypedia. Flexibility in Power Systems: Conceptual Frameworks and Technical Options, 2019. Available: https://energypedia.info/wiki/Flexibility_(Power_System).
[14] Fraunhofer Institute for Wind Energy and Energy System Technology (IWES). Power-to-Gas (P2G) Technological Pathways, Efficiencies, and Grid-Infeed Potentials. Technical Report, Kassel, 2023.
[15] MIT Energy Initiative. Design and Hydrostatic Modeling of Submarine Concrete Storage Spheres for Offshore Wind Integration. MIT Press, 2024.
[16] Aneke, M., & Wang, M. Energy Storage Systems: A Review of Mechanical, Thermal, and Chemical Storage Technologies. Renewable and Sustainable Energy Reviews, 2021.
[17] Schmidt, O., et al. Projecting the Future Levelized Cost of Electricity Storage Technologies. Progress in Energy, 2024.
[18] Ibrahim, H., et al. Energy Storage Systems—Characteristics and Comparative Advantages. Renewable and Sustainable Energy Reviews, 2021.