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Reactivating retired wind turbines as distributed sources of physical inertia for resilient power systems

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Abstract

The transition towards renewable energy systems is introducing a dual challenge, with declining system inertia and the growing accumulation of end-of-life infrastructure. While inverter-based generation reduces the physical inertia required for frequency stability, large numbers of wind turbine generators are reaching retirement despite retaining substantial electromechanical capability. This creates a mismatch between emerging system needs and underutilised resources. We show that retired wind turbine generators can be reactivated as distributed sources of physical inertia, enabling direct electromechanical energy exchange with the grid. By linking frequency-responsive activation to rotor dynamics, these assets provide immediate support during disturbances and recover key features of conventional system behaviour. System-level analysis indicates that reactivated generators consistently improve frequency response across a range of operating conditions. The response arises from the direct utilisation of stored kinetic energy and remains inherently fast and spatially distributed. Beyond the improvement in dynamic performance, this approach offers a pathway for the functional reuse of renewable infrastructure. By extending the operational role of existing assets, it connects system stability with circular resource utilisation. These results suggest that renewable technologies may evolve from single-purpose generation units into persistent system resources, offering a scalable route towards more resilient and sustainable low-carbon power systems.

Introduction

The rapid expansion of renewable energy generation over the past decade has been accompanied by an emerging challenge associated with the large-scale accumulation of end-of-life infrastructure[1]. In particular, early generations of wind turbines are increasingly reaching retirement across major renewable markets, with decommissioning expected to accelerate significantly in the coming decades[2]. While components such as blades have established recycling pathways[3,4], the recovery of wind turbine generators remains more complex[5]. Despite retaining substantial electromechanical functionality, these generators are typically dismantled, creating a growing pool of underutilized assets and raising concerns about the long-term sustainability of wind energy deployment[6].

At the same time, power systems are undergoing a structural transition as inverter-based renewable generation (IBRG) progressively replaces conventional synchronous machines[7]. Unlike synchronous generators, which inherently provide physical inertia and short-circuit capability through rotating mass, IBRGs rely on power electronic interfaces and digital control, leading to fundamentally different dynamic behavior. As their penetration increases, the resulting reduction in system inertia and fault support capability has become a critical challenge for maintaining grid stability[8,9]. Recent large-scale disturbances and blackouts in such systems have further highlighted the urgency of addressing these limitations[10-13].

Existing approaches to mitigate the stability challenges of low-inertia power systems broadly fall into three categories. At the system level, dispatch strategies seek to maintain stability by optimally coordinating synchronous and inverter-based generation under operational and economic constraints[14]. However, their effectiveness diminishes as power systems transition towards near-fully inverter-based configurations, where the availability of synchronous inertia becomes intrinsically limited. At the device level, extensive efforts have focused on emulating inertial response through power electronic control. Virtual inertia schemes, including fast frequency response enabled by energy storage or dc-link capacitors, can reproduce certain aspects of the frequency and power characteristics of synchronous machines[15-21]. Nevertheless, these approaches rely on synthetic responses mediated by converters, resulting in limited short-circuit capability and increased system complexity. In particular, battery-assisted solutions introduce significant cost and lifecycle constraints, raising concerns regarding their long-term scalability and sustainability[17]. More advanced strategies, such as virtual synchronous generator control, further attempt to replicate electromechanical dynamics through converter control laws[22-25]. While effective in shaping system response, such approaches fundamentally remain control-based approximations and may constrain the intrinsic fast-response capability of power electronic systems[26].

These limitations have motivated renewed interest in reintroducing physical inertia through electromechanical means. Solutions such as synchronous condensers provide genuine inertial and fault support by directly coupling rotational energy to the grid[27-30]. However, their deployment is associated with substantial capital and operational costs, limiting their scalability in future power systems[31,32]. Taken together, these approaches expose a critical gap, as existing solutions rely either on synthetic inertia with limited physical fidelity or on dedicated synchronous assets associated with high cost. This tension underscores the need for alternative pathways capable of delivering real, scalable, and economically viable inertia in converter-dominated power systems.

At the same time, as shown in Fig. 1a, the increasing retirement of wind turbine generators is creating a growing pool of electromechanical assets that remain largely underutilized. The convergence of these trends reveals a fundamental mismatch between available resources and system needs. This conceptual mismatch motivates an alternative perspective in which retired wind turbine generators are not treated as waste or merely recycled for material recovery, but instead regarded as distributed sources of recoverable electromechanical functionality, as illustrated in Fig. 1b. By reactivating their inherent kinetic energy and direct grid-coupled characteristics, these assets can provide genuine physical inertia and system strength, thereby improving frequency stability in low-inertia power systems. At the same time, such an approach enables the functional reuse of existing renewable infrastructure, reducing material waste and extending asset lifecycles, and thus contributes to the long-term sustainability of energy system development.

Results

Degradation of system dynamics in low-inertia conditions

As the penetration of inverter-based renewable generation increases, the power system undergoes a fundamental transition in its dynamical regime. As illustrated in Fig. 2a, the system evolves from a synchronous-machine-dominated configuration, in which frequency dynamics are governed by the electromechanical response of rotating masses, to a low-inertia regime characterised by faster and more weakly damped dynamics. In conventional systems, the substantial rotational inertia of synchronous machines provides an inherent energy buffer that moderates frequency excursions and maintains a clear separation between fast electromagnetic and slow electromechanical processes. As this buffering mechanism diminishes, system response becomes increasingly driven by instantaneous power imbalances rather than stored kinetic energy.

This transition is directly reflected in the frequency trajectories shown in Fig. 2b. With increasing renewable penetration, the system exhibits progressively deeper frequency nadirs, more pronounced oscillatory behaviour, and a longer recovery towards steady state. These changes indicate a reduced capability to contain disturbances and to redistribute energy smoothly across the network. The trend is further quantified in Fig. 2c, where the frequency nadir decreases monotonically while the integral of frequency deviation increases consistently with penetration level. These two metrics provide complementary measures of system degradation, capturing both the severity of instantaneous excursions and the cumulative impact of disturbances over time. From a dynamical perspective, a key consequence of this transition is the compression of time scales. As system inertia decreases, the separation between fast and slow dynamics is progressively reduced, leading to more rapid and less coordinated responses to disturbances. This limits the ability of the system to absorb and redistribute energy through gradual electromechanical processes.

Collectively, these results indicate that the observed behaviour is not merely a gradual degradation in performance, but a structural shift in the governing dynamics of the system. The transition from an inertia-dominated to a low-inertia regime weakens the intrinsic coupling between power imbalance and frequency evolution, fundamentally altering the mechanisms that sustain frequency stability.

Reactivation of retired wind turbine generators as system resources

To address the loss of physical inertia, retired wind turbine generators are reactivated as system-level resources. Instead of being dismantled after decommissioning, these electromechanical units are re-integrated into the grid, allowing their rotational dynamics to directly participate in system response. In this configuration, frequency deviations induce a mismatch between electromagnetic and mechanical torque, leading to transient variations in rotor speed as show in Fig. 3c. These variations govern the release or absorption of kinetic energy stored in the rotating mass, thereby establishing a direct energy pathway from mechanical inertia to electrical power support. During a frequency drop, rotor deceleration converts stored kinetic energy into active power injected into the grid, whereas during frequency

recovery the rotor accelerates and reabsorbs energy. This bidirectional exchange is inherently governed by physical dynamics rather than control synthesis, enabling a fast and continuous response at the earliest stage of the disturbance. At the system level, the reactivated units operate as distributed sources of inertia, providing spatially dispersed support that enhances the ability of the network to contain disturbances and redistribute energy.

The effectiveness of this mechanism is demonstrated by the system response shown in Fig. 3. As illustrated in Fig. 3a, the introduction of reactivated wind turbine generators leads to a consistently higher frequency nadir across all renewable penetration levels from 10% to 50%, indicating enhanced resistance to frequency excursions. In addition, the frequency trajectories become noticeably smoother, with reduced oscillatory behaviour during the post-disturbance period, as shown in Fig. 3d, reflecting improved damping characteristics. This trend is further quantified in Fig. 3b, where the frequency nadir increases monotonically with the level of RWTG integration, demonstrating a consistent enhancement in system resilience across different operating conditions. Furthermore, as shown in Fig. 3e, the integral of frequency deviation decreases with increasing RWTG capacity, indicating that disturbance energy is more effectively absorbed and dissipated over the recovery period.

These improvements become increasingly pronounced at higher penetration levels, where the system is more susceptible to inertia deficiency. Collectively, the results demonstrate that the reactivated generators do not merely compensate for performance degradation, but reintroduce physically grounded inertia into the system. This restores key features of conventional electromechanical dynamics, enabling smoother frequency evolution and more coordinated energy redistribution in inverter-dominated power systems.

Sustainability and system-level implications of reactivated wind turbine generators

To further evaluate the broader impact of the proposed approach, its system-level characteristics are examined from the perspectives of economic efficiency, physical response mechanisms, and resource circularity, as illustrated in Fig. 4. The proposed approach leverages existing retired wind turbine generators, thereby avoiding the substantial capital investment associated with battery manufacturing and deployment. As shown in Fig. 4a, the system cost is significantly reduced through the reuse of existing infrastructure, with minimal requirements for new core equipment and supporting components. This fundamentally alters the cost structure of frequency support, enabling scalable deployment without large-scale construction of new assets.

Beyond cost considerations, the two approaches differ fundamentally in their physical mechanisms. As illustrated in Fig. 4b, electrochemical storage relies on control-mediated energy conversion, where frequency deviations are processed through controllers and realised via coupled electrochemical and thermal dynamics, resulting in an indirect and multi-stage response pathway. By contrast, the proposed approach establishes a direct electromechanical energy exchange with the grid as shown in Fig. 4c, in

which frequency deviations induce rotor acceleration or deceleration, leading to the release or absorption of kinetic energy. This physically grounded mechanism enables a continuous and inherently stable response without reliance on complex control coordination.

At the same time, the proposed approach introduces a fundamentally different paradigm of resource utilisation. Electrochemical storage typically follows a linear lifecycle involving material extraction, manufacturing, operation, and eventual disposal, which can impose environmental and recycling challenges. In contrast, reactivating retired wind turbine generators extends the functional lifetime of existing renewable assets, transforming them into active system-supporting resources. This circular utilisation pathway reduces material demand, mitigates decommissioning impacts, and enhances the overall sustainability of energy system development. Collectively, these results demonstrate that the proposed approach goes beyond a conventional technical solution for frequency support. By coupling physically grounded inertia with the reuse of existing infrastructure, it establishes a circular and system-integrated pathway that simultaneously improves dynamic performance and supports a sustainable energy transition.

Discussion

The present study is based on system-level simulations that capture the aggregated dynamics of inverter-dominated power systems. While the results demonstrate the effectiveness of repurposed wind turbine generators in restoring inertial response, practical implementation will require careful consideration of grid integration constraints, control coordination, and site-specific operating conditions. In particular, the interaction between reactivated generators and existing converter-based resources may introduce additional dynamic couplings that warrant further investigation. Beyond these implementation aspects, the proposed approach points towards a broader shift in how inertia is provisioned in future power systems. Unlike synthetic inertia strategies realised through power electronic control, the reactivated generators contribute through direct electromechanical energy exchange, restoring a physically grounded mechanism that has largely diminished in inverter-dominated grids. This distinction suggests that inertia provision need not rely exclusively on emulation or newly installed assets, but can instead be partially recovered through the functional reuse of existing infrastructure.

More broadly, this work highlights the potential of integrating system stability requirements with circular resource utilisation. By extending the functional lifetime of retired renewable energy assets, the proposed approach establishes a link between power system dynamics and sustainable infrastructure management. Such a perspective opens new opportunities for co-optimising stability, cost, and environmental impact in future energy systems.

Future research may further explore large-scale deployment strategies, including the coordination of heterogeneous inertia sources such as reactivated generators, energy storage, and grid-forming converters. Understanding the interactions among these resources will be critical for designing resilient and scalable solutions in renewable-dominated power systems.

Methods

System configuration and simulation framework

The dynamic performance of the proposed approach is evaluated on a representative medium-scale transmission network based on the New England 39-bus system. A progressive transition from a synchronous-machine-dominated network to an inverter-dominated structure is emulated by replacing conventional generation with converter-interfaced renewable resources, including wind and photovoltaic units. The penetration level of inverter-based resources is defined as the fraction of total generation capacity they supply, and varied across scenarios to represent different low-inertia conditions.

System dynamics are analysed in the time domain using a detailed electromechanical representation, capturing the dominant processes governing frequency stability. Disturbances are introduced as step changes in active power to emulate sudden generation loss or load increase, with identical magnitudes applied across all scenarios to ensure consistent comparison. System frequency is evaluated using the frequency of the largest synchronous generator as a proxy for system-level dynamics. Key transient characteristics, including frequency nadir, recovery trajectory, and the integral of frequency deviation, are extracted to quantify system performance.

Electromechanical inertia representation of retired wind turbine generators

Retired wind turbine generators are represented as grid-connected electromechanical units that preserve their intrinsic rotational inertia, such that system dynamics are governed predominantly by the kinetic energy stored in the rotor. During frequency disturbances, variations in rotor speed enable direct energy exchange with the grid, providing a physically grounded source of inertial support. From a system-level perspective, the support provided by the reactivated generators originates from the release of rotor kinetic energy, which can be expressed as

$$\Delta E = \frac{1}{2} J (\omega_1^2 - \omega_2^2) \qquad (1)$$

where J denotes the equivalent rotational inertia and ω is the rotor angular speed. This expression shows that the amount of energy exchanged with the grid is directly determined by variations in rotor speed. As rotor speed dynamics are inherently coupled to system frequency, this establishes a direct link between frequency deviation and the availability of inertial energy support. This bidirectional energy exchange reflects a physically grounded inertial response, distinguishing the proposed approach from synthetic inertia implementations that rely on control-mediated power injection.

Control and activation strategy

The control strategy is formulated to establish a physically consistent coupling between system frequency dynamics and rotor energy exchange. A frequency-dependent feedforward pathway is introduced and embedded within the rotor speed control loop, enabling frequency disturbances to be directly mapped into electromechanical response. The resulting regulation signal follows a piecewise formulation that distinguishes between disturbance amplification and recovery regimes. The output of the frequency adjustment module is defined as

$$\Delta f_{out} = \begin{cases} k_{pf}\Delta f, & \Delta f\,\dot{\Delta} f > 0 \\ k_{pi}\int \Delta f\, dt, & \Delta f\,\dot{\Delta} f < 0 \end{cases} \tag{3}$$

where Δf denotes the system frequency deviation and $\Delta \dot{f}$ its rate of change. The proportional term governs the response when the deviation increases, enabling rapid suppression of frequency excursions, whereas the integral term becomes active during recovery, providing sustained energy support. This frequency-dependent signal is incorporated into the rotor speed control loop as a feedforward term, thereby modulating the power reference of the system. The resulting power command is expressed as

$$P_{ref} = k_{sp}\Delta\omega + k_{si}\int \Delta\omega\, f dt + \Delta f_{\text{out}} \tag{4}$$

where $\Delta\omega$ represents the deviation of rotor speed from its reference value. The first two terms correspond to the conventional speed control loop, ensuring stable tracking and recovery of rotor dynamics, while Δf_{out} introduces an additional frequency-driven component that directly links system disturbances to power output. Through this structure, frequency deviations are mapped into a control signal and then injected into the electromechanical dynamics via the speed loop. This establishes a direct pathway from system-level frequency variation to rotor kinetic energy exchange. During a frequency drop, the feedforward signal increases the power reference, inducing rotor deceleration and releasing stored kinetic energy to the grid. Conversely, during recovery, the integral action supports gradual restoration of rotor speed and replenishment of kinetic energy.

The inner current control loop of the RWTGs is implemented using grid-forming strategies, providing a fast and stable electrical interface that enables the outer control loops to shape the system dynamic response. This coordinated mechanism ensures that the overall control action remains consistent with the underlying physical inertia of the system. Unlike synthetic inertia approaches that rely solely on externally imposed control laws, the proposed strategy preserves the intrinsic coupling between rotor motion and power exchange. When multiple units are deployed, their responses are naturally aggregated through the network, enabling a distributed and scalable form of inertia support.

Data analysis and performance metrics

System frequency is evaluated using the frequency of the largest synchronous generator, which serves as a representative indicator of system-level dynamic behaviour due to its dominant inertial contribution.

The frequency nadir is defined as the minimum frequency reached following a disturbance, reflecting the severity of instantaneous frequency excursions. In addition, the integral of frequency deviation over time is used to quantify the cumulative impact of disturbances, providing a measure of the system's ability to absorb and dissipate imbalance energy during the recovery process. The rate of change of frequency is also examined during the initial stage of the disturbance to characterise the short-term dynamic response. ss

Declarations

Author Contributions Statement

Y. Hu supervised the project and provided overall guidance. Y. Huang and Y. Hu conceived the concept and designed the study. Y. Huang carried out the modelling, time-domain simulations, and data analysis. J. Xu contributed to the design and implementation of the control strategy. Y. Huang drafted the manuscript, and all authors contributed to the interpretation of the results and revision of the manuscript.

References

1. International Energy Agency. *Renewables 2023: Analysis and forecast to 2028*. IEA (2024).
2. Meng, F., Hawkin, J. L., Gast, L. *et al.* End-of-life management for wind turbines. *Nat. Rev. Clean Technol.* 1, 677–698 (2025).
3. Wang, B., Chen, G., Dong, Y. *et al.* Wind turbine blade recycling for greener and sustainable wind energy. *Nat. Rev. Mater.* 10, 330–331 (2025).
4. Yang, J., Meng, F., Zhang, L. *et al.* Solutions for recycling emerging wind turbine blade waste in China are not yet effective. *Commun. Earth Environ.* 4, 466 (2023).
5. Ortegon, K., Nies, L. F. & Sutherland, J. W. Preparing for end of service life of wind turbines. *J. Clean. Prod.* 39, 191–199 (2013).
6. Liu, P. & Barlow, C. Y. Wind turbine blade waste in 2050. *Waste Manag.* 62, 229–240 (2017).
7. International Renewable Energy Agency. *Innovation landscape for a renewable-powered future*. IRENA (2019).
8. Schwarz, S., Sahoo, S., Stoffers, M. *et al.* Resilient low-inertia power systems through asynchronous energy balancing. *Nat. Rev. Electr. Eng.* (2026).
9. Ulbig, A., Borsche, T. S. & Andersson, G. Impact of low rotational inertia on power system stability and operation. *IFAC Proc. Vol.* 47, 7290–7297 (2014).

10. North American Electric Reliability Corporation. *1200 MW fault induced solar photovoltaic resource interruption disturbance*. NERC (2017).
11. Australian Energy Market Commission. *Review of the system black event in South Australia on 28 September 2016*. AEMC (2019).
12. Yan, R., Masood, N.-A., Saha, T. K., Bai, F. & Gu, H. The anatomy of the 2016 South Australia blackout: A catastrophic event in a high renewable network. *IEEE Trans. Power Syst.* 33, 5374–5388 (2018).
13. National Grid ESO. *Technical report on the events of 9 August 2019*. National Grid ESO (2019).
14. Gu, H., Yan, R., Saha, T. K. *et al.* System strength and inertia constrained optimal generator dispatch under high renewable penetration. *IEEE Trans. Sustain. Energy* 11, 2392–2406 (2019).
15. Engels, J., Claessens, B. & Deconinck, G. Combined stochastic optimization of frequency control and self-consumption with a battery. *IEEE Trans. Smart Grid* 10, 1971–1981 (2019).
16. Bowen, T., Chernyakhovskiy, I. & Denholm, P. L. *Grid-scale battery storage: Frequently asked questions*. National Renewable Energy Laboratory (NREL), Golden, CO (2019).
17. Casals, L. C., Amante García, B. & Canal, C. Second life batteries lifespan: Rest of useful life and environmental analysis. J. Environ. Manage. 232, 354–363 (2019).
18. Rajan, R., Fernandez, F. M. & Yang, Y. Primary frequency control techniques for large-scale PV-integrated power systems: A review. *Renew. Sustain. Energy Rev.* 144, 110998 (2021).
19. Xin, H., Liu, Y., Wang, Z., Gan, D. & Yang, T. A new frequency regulation strategy for photovoltaic systems without energy storage. *IEEE Trans. Sustain. Energy* 4, 985–993 (2013).
20. Omran, W. A., Kazerani, M. & Salama, M. Investigation of methods for reduction of power fluctuations generated from large grid-connected photovoltaic systems. *IEEE Trans. Energy Convers.* 26, 318–327 (2010).
21. Rajan, R. & Fernandez, F. M. Power control strategy of photovoltaic plants for frequency regulation in a hybrid power system. *Int. J. Electr. Power Energy Syst.* 110, 171–183 (2019).
22. Zhong QC, Weiss G. Synchronverters: Inverters That Mimic Synchronous Generators. *IEEE Transactions on Industrial Electronics* 58, 1259–1267 (2011).
23. Wu H, *et al.* Small-Signal Modeling and Parameters Design for Virtual Synchronous Generators. *IEEE Transactions on Industrial Electronics* 63, 4292–4303 (2016).
24. Pan D, Wang X, Liu F, Shi R. Transient Stability of Voltage-Source Converters With Grid-Forming Control: A Design-Oriented Study. *IEEE Journal of Emerging and Selected Topics in Power Electronics* 8, 1019–1033 (2020).
25. Ge P, Tu C, Xiao F, Guo Q, Gao J. Design-Oriented Analysis and Transient Stability Enhancement Control for a Virtual Synchronous Generator. *IEEE Transactions on Industrial Electronics* 70, 2675–2684 (2023).
26. Milano F, Dörfler F, Hug G, Hill DJ, Verbič G. Foundations and Challenges of Low-Inertia Systems (Invited Paper). In: *2018 Power Systems Computation Conference (PSCC)*) (2018).

27. Nguyen HT, Yang G, Nielsen AH, Jensen PH. Combination of Synchronous Condenser and Synthetic Inertia for Frequency Stability Enhancement in Low-Inertia Systems. *IEEE Transactions on Sustainable Energy* 10, 997–1005 (2019).
28. Zhou G, *et al.* Synchronous Condenser Applications: Under Significant Resource Portfolio Changes. *IEEE Power and Energy Magazine* 17, 35–46 (2019).
29. Wang Y, Wang L, Jiang Q. Impact of Synchronous Condenser on Sub/Super-Synchronous Oscillations in Wind Farms. *IEEE Transactions on Power Delivery* 36, 2075–2084 (2021).
30. Hadavi S, Rathnayake DB, Jayasinghe G, Mehrizi-Sani A, Bahrani B. A Robust Exciter Controller Design for Synchronous Condensers in Weak Grids. *IEEE Transactions on Power Systems* 37, 1857–1867 (2022).
31. Marrazi E, Yang G, Weinreich-Jensen P. Allocation of synchronous condensers for restoration of system short-circuit power. *Journal of Modern Power Systems and Clean Energy* 6, 17–26 (2018).
32. Jia J, Yang G, Nielsen AH, Muljadi E, Weinreich-Jensen P, Gevorgian V. Synchronous Condenser Allocation for Improving System Short Circuit Ratio. In: 2018 *5th International Conference on Electric Power and Energy Conversion Systems (EPECS)*) (2018).

Figures

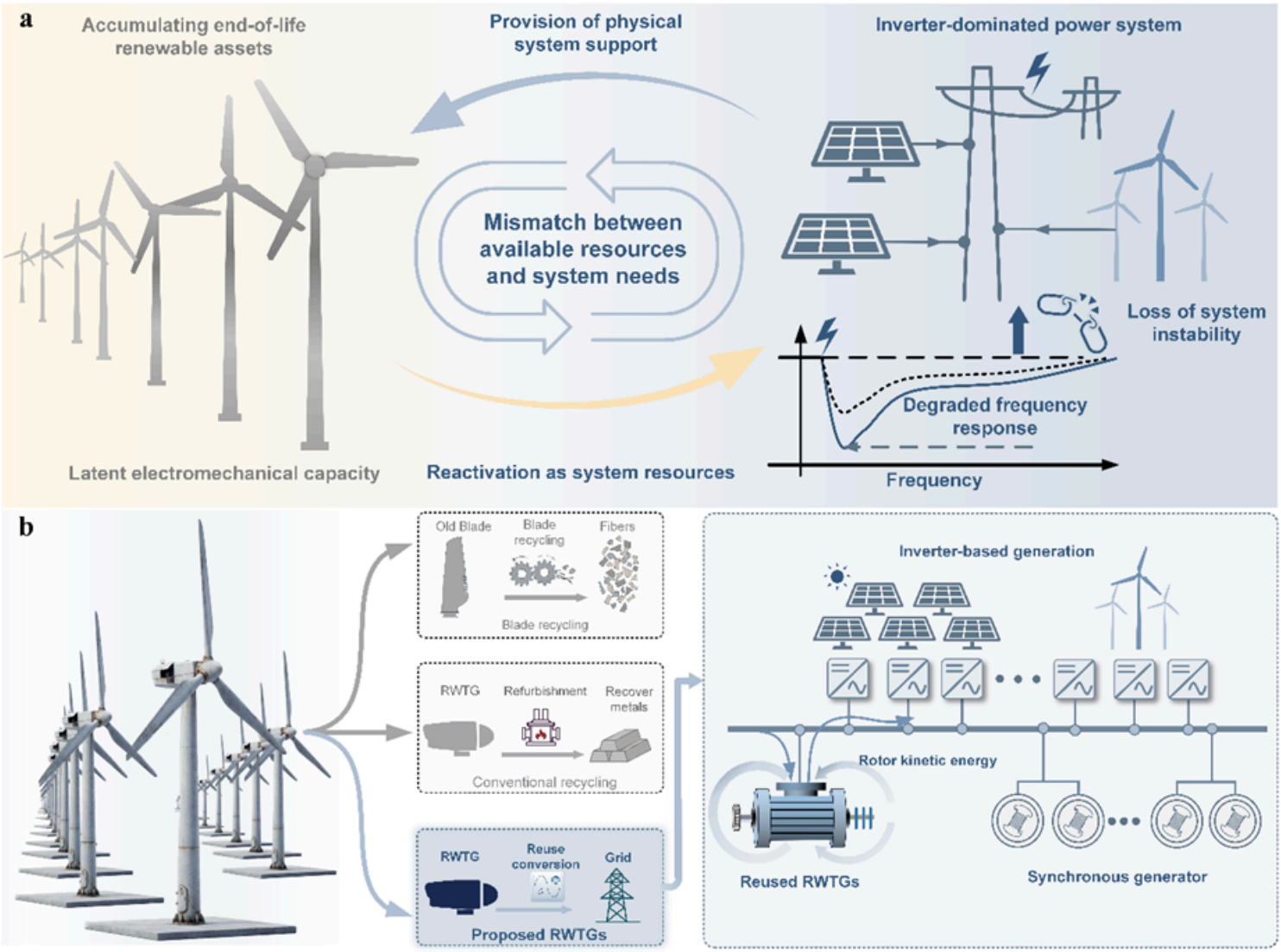


Figure 1

Reactivation of electromechanical inertia in inverter-dominated power systems. a Conceptual illustration of the emerging mismatch between resource availability and system requirements. The global energy transition is simultaneously leading to the accumulation of end-of-life wind turbine generators with latent electromechanical capacity and the increasing prevalence of inverter-based power systems characterized by reduced physical inertia and degraded frequency response. **b** Proposed pathway for reactivating retired wind turbine generators as distributed system-supporting resources. Instead of conventional material recycling, the retained kinetic energy and grid-coupled characteristics of these assets are utilized to provide physically grounded inertia and system strength, thereby improving frequency stability while enabling the functional reuse of existing renewable infrastructure.

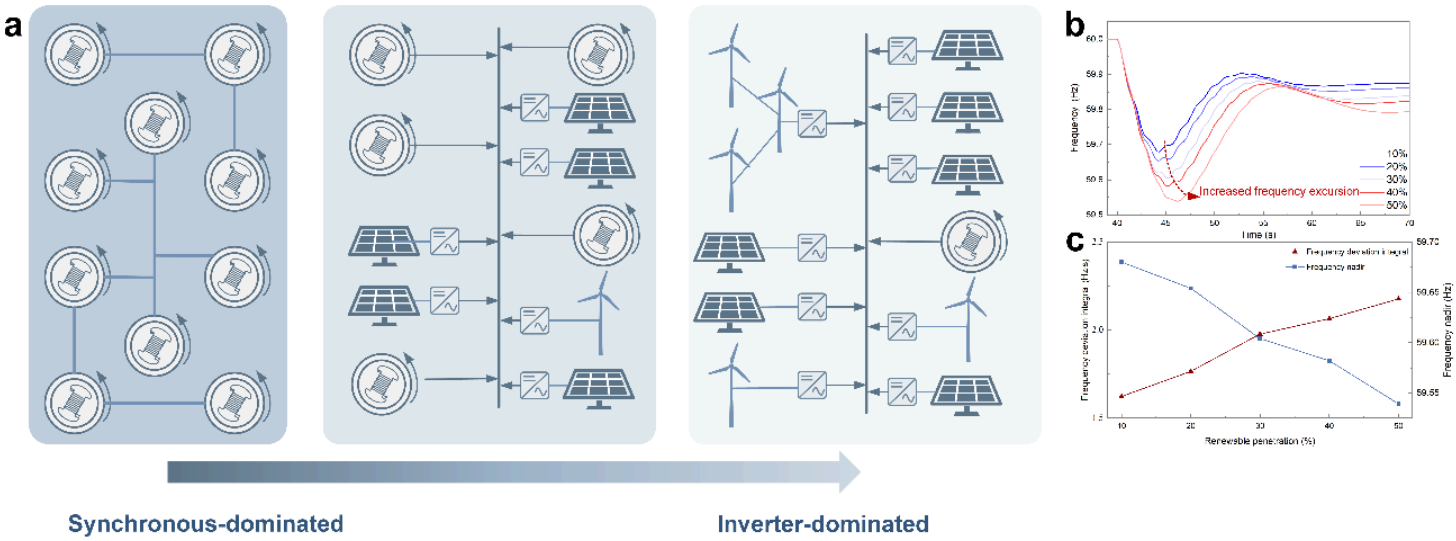


Figure 2

Degradation of system dynamics with increasing inverter-based generation. a. Conceptual illustration of the transition from a synchronous-dominated to an inverter-dominated power system. The progressive displacement of synchronous machines reduces the contribution of rotating mass, leading to a loss of inherent inertial support. **b**. Frequency response under different levels of inverter-based generation. Higher penetration results in a lower frequency nadir and slower recovery following a disturbance. **c.** Frequency nadir and cumulative frequency deviation under different penetration levels. Increasing inverter-based generation leads to a lower frequency nadir and larger cumulative frequency deviation, indicating more severe frequency excursions and reduced disturbance absorption capability.

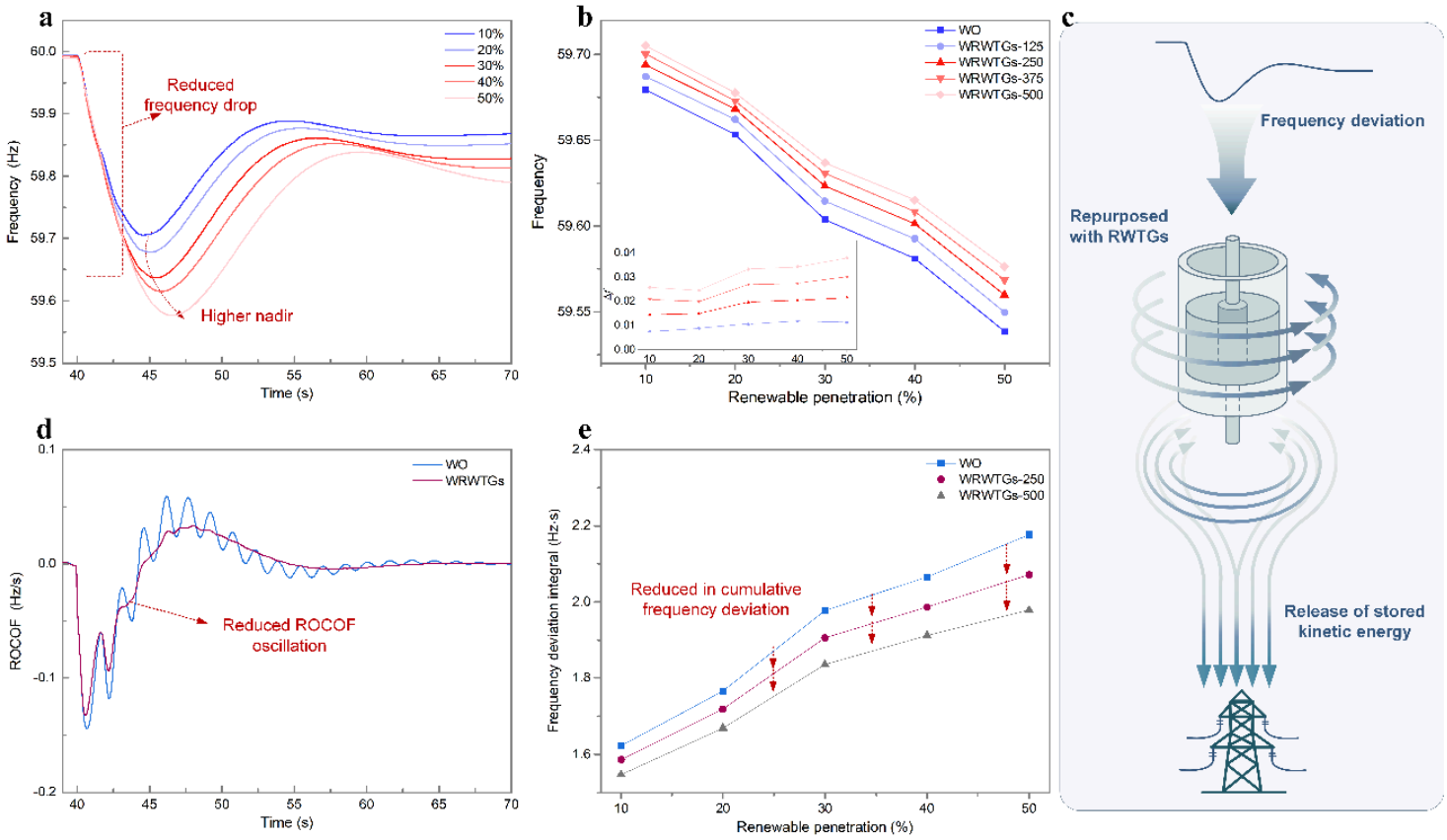


Figure 3

Reactivation of wind turbine generators for physical inertia restoration. a. System frequency trajectories under different renewable penetration levels. The introduction of reactivated wind turbine generators leads to a higher frequency nadir and reduced frequency drop following disturbances. **b.** Frequency nadir as a function of renewable penetration. Compared with the case without RWTGs (WO), all RWTG configurations consistently increase the minimum frequency, demonstrating improved resistance to frequency excursions. **c.** Schematic illustration of the inertial response mechanism of RWTGs. Frequency deviations induce rotor speed variations, enabling the release of stored kinetic energy to the grid and providing physically grounded inertia support. **d.** Rate of change of frequency response. The RWTG-supported system exhibits reduced ROCOF oscillations, indicating enhanced inertial buffering and improved damping of transient dynamics. **e.** Integral of frequency deviation over time. The cumulative frequency deviation is significantly reduced with RWTG support, indicating more effective absorption and dissipation of disturbance energy.

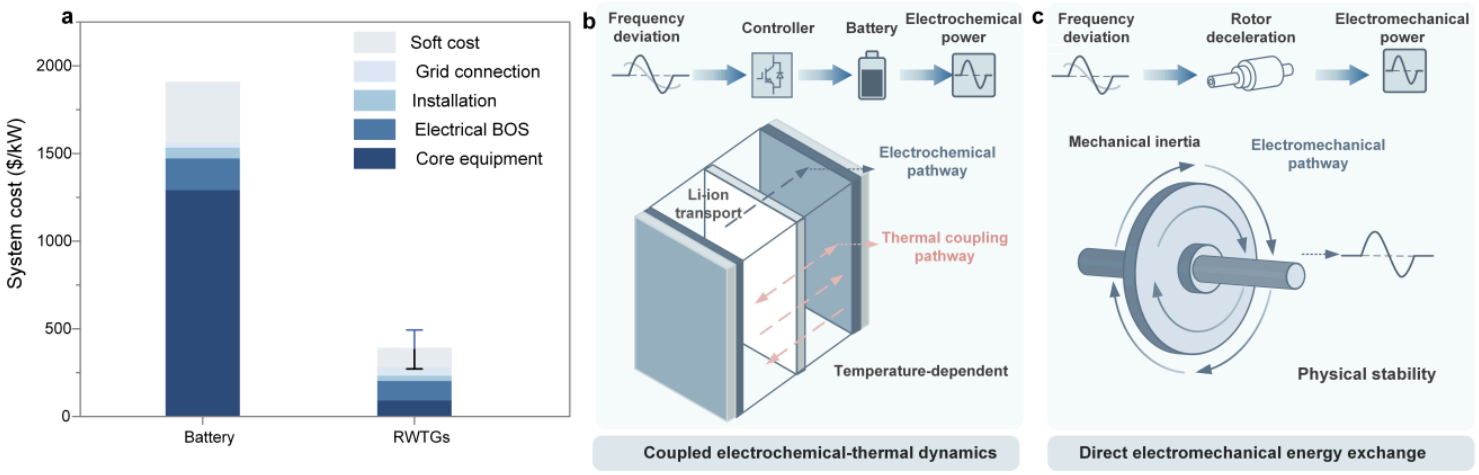


Figure 4

System-level cost and physical mechanisms of electrochemical storage and electromechanical inertia. **a.** Comparison of system cost for battery energy storage and reactivated wind turbine generators. The total cost is decomposed into core equipment, electrical balance of system, installation, grid connection, and soft costs. RWTGs exhibit substantially lower overall system cost, reflecting the reuse of existing infrastructure and reduced capital requirements. **b.** Electrochemical storage pathway. Frequency deviations are detected and processed through control systems, triggering battery response via power electronic interfaces. Energy exchange is governed by coupled electrochemical and thermal dynamics, including ion transport and temperature-dependent processes, resulting in indirect and multi-stage response characteristics. **c.** Electromechanical inertia pathway enabled by RWTGs. Frequency deviations directly induce rotor deceleration or acceleration, leading to release or absorption of kinetic energy. This establishes a direct electromechanical energy exchange with the grid, providing physically grounded inertia and contributing to inherent system stability.