Integration of renewables and storage for maximum flexibility: a digital design of low-carbon grids (smart grids)

Július Šimčák[1*], *Vladimír* Szomosi[1], *Ardian* Hyseni[1], *František* Margita[1], *Kristián* Glajc[1], and *Dušan* Medveď[1]

[1]Technical University of Košice, Department of Electric Power Engineering, Košice, Slovakia

Abstract. The transition to a low-carbon energy system is conditioned by the successful integration of highly variable, yet advanced, renewable energy sources (RES). This paper analyzes the transformative synergy between the next generation of RES, the increasing capacity of Battery Energy Storage Systems (BESS), and the development of intelligent electricity networks (Smart Grids). We focus on how the deployment of distributed BESS and centralized storage solutions not only stabilizes fluctuations in generation from advanced solar and wind sources but also provides critical network services, such as frequency regulation and optimized power flow. We examine the role of Smart Grids, which serve as the digital backbone enabling two-way communication, predictive load management, and efficient resource allocation in real-time. The paper presents a quantitative analysis of the impact of these three technologies on reducing operational costs, minimizing transmission capacity losses, and accelerating decarbonization. In conclusion, we emphasize the regulatory and investment reforms necessary to fully utilize the potential of these technologies, demonstrating that their synergy is essential for creating a resilient, flexible, and fully decarbonized energy infrastructure of the future.

1 Introduction

The current global energy landscape is undergoing its most profound transformation since the widespread adoption of alternating current in the late 19th century. This change is not merely a technological replacement of components, but a fundamental shift in the operational paradigm with significant environmental consequences. Historically, electrical grids were built on a deterministic principle: large, centrally controllable sources (coal, gas, nuclear, hydro) were dispatched to match a relatively predictable and inelastic consumption curve. The stability of this system was dictated by the physics of rotating masses—massive generators provided kinetic inertia that served as an immediate buffer against grid perturbations. From an environmental perspective, however, this model required maintaining a significant portion of capacity in "spinning reserve," which meant burning fossil fuels even when not directly needed to cover demand, solely to maintain frequency stability.

The current era is characterized by a transition to stochastic complexity. This shift is driven by three vectors: the imperative of deep decarbonization to mitigate climate change, the aging of transmission and distribution infrastructure, and rapid digitalization. The result is a grid that must accommodate variability on both ends of the "wire." On the supply side, renewable energy sources (RES) such as photovoltaics (PV) and wind introduce intermittency dependent on meteorological conditions, not operator decisions. On the demand side, the electrification of transport and heating transforms passive consumers into active "prosumers" with bidirectional energy flows.

This report provides a comprehensive analysis of the technological triad enabling this transition: RES, Battery Energy Storage Systems (BESS), and Smart Grids. The analysis goes beyond surface-level trends to examine the algorithmic foundations of grid control, the electrochemistry of storage, and the environmental footprint of digitalization, synthesizing evidence on how these technologies interact to create a resilient and low-carbon infrastructure.

2 Methodology

To provide a comprehensive analysis of the technological triad enabling the energy transition (RES, BESS, and Smart Grids), a systematic literature review was conducted. Peer-reviewed articles, industry reports, and quantitative case studies published between 2015 and 2026 were sourced from scientific databases, including IEEE Xplore, ScienceDirect, and Web of Science. The selection criteria focused on studies providing concrete quantitative data on grid losses, battery degradation mechanics (e.g., V2G impacts), and the ecological footprint of digital infrastructure. A comparative analysis was then employed to synthesize the environmental tradeoffs, contrasting the material intensity of physical infrastructure upgrades with the

* Corresponding author: julius.simcak@tuke.sk

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

energy consumption of advanced digital solutions like Edge Computing.

3 The hierarchy of modern grid architectures

To understand the ecological impacts of integration, it is essential to define the spatial and operational hierarchy of the modern grid. The monolithic grid is fragmented into a cellular structure, allowing for the application of the principle of

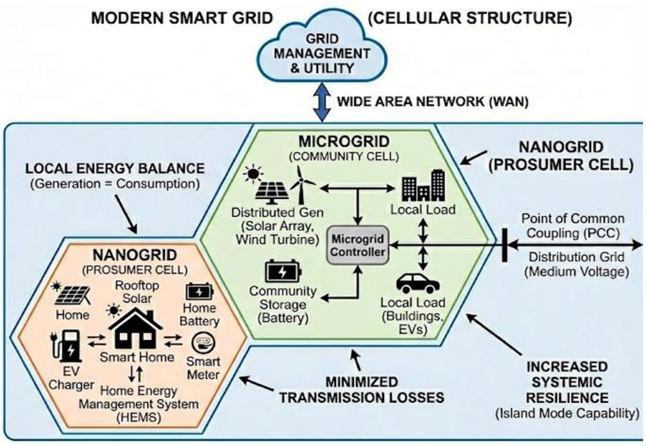

Fig. 1. The hierarchical architecture of a modern Smart Grid

"Energy subsidiarity“ resolving the energy balance at the lowest possible level, thereby minimizing transmission losses and the environmental burden of infrastructure.

3.1 Nanogrids and microgrids: reducing losses and increasing resilience

The smallest building blocks are nanogrids, typically limited to a single building or a small cluster of loads (e.g., a smart home with rooftop PV and an EV charger, totaling <50 kVA). Their primary goal is self-consumption. From an ecological standpoint, maximizing self-consumption is crucial as it eliminates losses associated with transforming and transmitting energy to higher voltage levels and back. Losses in the transmission and distribution system can reach up to 18% in some regions, representing approximately 1 gigatonne of CO2 emissions annually globally [1]. These high losses (up to 18%) occur primarily in developing economies with rapidly expanding infrastructure, such as parts of India, Brazil, or Sub-Saharan Africa, whereas modernized European grids maintain losses between 4–6% [18]. Optimizing flows at the nanogrid level reduces this footprint by minimizing the distance between generation and consumption, bypassing multiple voltage transformation stages where the highest Joule losses occur. However, this decentralization increases management complexity and requires higher initial investments in local control systems and sensors.

Operating at a higher level are microgrids, which aggregate multiple distributed energy resources (DERs) and loads within a defined electrical boundary (e.g., a university campus). A defining feature of a microgrid is the ability to island—disconnect from the main grid and operate autonomously. This capability has profound environmental implications in the context of climate change adaptation. During extreme weather events that often disable the centralized grid, microgrids can keep critical infrastructure running using local RES and batteries, eliminating the need to deploy emission-intensive diesel generators, which are the standard solution for crisis situations. Instead, operators are turning to Stochastic Dynamic Programming (SDP), Convex Programming (CP), and bio-inspired metaheuristics to navigate the uncertainty of the new energy paradigm. These methods are primarily utilized by Distribution System Operators (DSOs) for voltage management and Transmission System Operators (TSOs) for real-time balancing. Stochastic Dynamic Programming (SDP) is typically applied for long-term scheduling of large-scale storage, while Convex Programming (CP) is used for real-time optimal power flow (OPF), and metaheuristics are employed for the optimal sizing of distributed resources [19].

3.2 Active distribution networks (ADN) and virtual capacity

Active Distribution Networks (ADN) transform the "last mile" of the grid from a passive pipeline into a dynamic marketplace. Unlike traditional grids, ADNs actively manage voltage and power flows using distributed generation and storage. This allows for the integration of a higher share of RES without the need for massive reinforcement of physical infrastructure (cables and transformers). The production and installation of physical infrastructure carry a significant carbon footprint (embodied emissions in steel, aluminum, concrete). By utilizing software and control to optimize existing lines, ADNs effectively "virtualize" grid capacity, reducing the material intensity of the energy transition. Case studies in regions such as California and the United Kingdom have demonstrated that smart grid software can increase existing line capacity by 15–30% [20]. This directly reduces the material intensity of the energy transition by avoiding the manufacturing of thousands of tons of steel and aluminum for new physical infrastructure.

4 The physics of flexibility: battery energy storage systems (BESS)

Batteries are a key element of the flexible grid, capable of functioning as both source and a load. However, their deployment is a complex optimization problem bounded by electrochemical degradation and lifecycle environmental risks.

4.1 Electrochemistry and environmental risks: LFP vs. NMC

Dominant lithium-ion battery technologies, particularly those based on Nickel-Manganese-Cobalt (NMC) cathodes, present an environmental challenge. The mining of cobalt and nickel is associated with high toxicity, water pollution, and ethical issues. Furthermore, these chemistries are more prone to thermal runaway, leading to fires that are extremely difficult to extinguish and release toxic gases (e.g., hydrogen fluoride) and pollutants into the surroundings [2].

The modern trend is shifting towards the use of Lithium Iron Phosphate (LFP) batteries for stationary applications. From an environmental perspective, LFP offers significant advantages [3]:

Absence of Cobalt and Nickel: Eliminates the most toxic elements of the supply chain [3].

Thermal Stability: LFP has a higher decomposition temperature, radically reducing the risk of fire and subsequent emissions [3].

Longer Lifespan: A higher number of cycles means the battery serves longer before becoming waste, reducing the frequency of recycling and raw material extraction.

4.2 Comparison with pumped hydro storage (PHS)

Although BESS dominates discussions on short-term flexibility, pumped hydro storage (PHS) still accounts for most of the global storage capacity (over 90% of domestic storage in some regions). The environmental comparison of these technologies is complex [4]:

Greenhouse Gas (GHG) Emissions: Life Cycle Assessment (LCA) studies show that closed-loop PSH often has lower GHG emissions per stored kWh over its lifetime compared to batteries, primarily due to the extremely long lifespan of the infrastructure (50-100 years vs. 10-15 years for batteries) [4].

Land Use: Batteries are more spatially efficient. While PSH requires specific geography and occupies large areas (2 m²/MWh), which can disrupt ecosystems, flow batteries and Li-ion systems occupy more per unit (3-5 m²/MWh) but can be sited in industrial zones without additional land intake [5].

4.3 Second-life batteries and circular economy

The concept of "second life" for electric vehicle (EV) batteries is crucial for reducing the environmental footprint of storage. Batteries that have degraded to 70-80% capacity are unsuitable for EVs due to reduced range but are still perfectly functional for stationary applications where the weight-to-energy ratio is not critical [6].

Research shows that reusing batteries can reduce CO2 equivalent emissions by 450 tons per installed MWh compared to manufacturing new systems [6]. This approach delays the entry of batteries into the recycling stream and maximizes the return on the "carbon investment" made in their original production. Furthermore, the Li-ion battery recycling market is expected to reach $23.9 billion by 2030, with new methods (such as direct recycling) promising to reduce emissions from the recycling process by 58-81% compared to mining new materials [7].

4.4 Recycling and future trends

Given the projected increase in battery waste (over 3 million tonnes annually by 2045), recycling is becoming an imperative. Innovations in hydrometallurgy and direct regeneration of cathode materials allow for the recovery of up to 95% of critical metals (lithium, cobalt, nickel, copper) with high purity. The European Union is introducing strict regulations (e.g., "Battery Passport") that will require transparency in composition and high recycling rates, making the pressure for eco-design of BESS not only ethical but also legislative and economic [7].

5 Vehicle-to-Grid (V2G): mobile power plants and the degradation paradox

Vehicle-to-Grid (V2G) technology represents one of the greatest opportunities for RES integration but also raises concerns about vehicle battery longevity.

5.1 Environmental benefit: displacing fossil fuels

Studies unequivocally demonstrate that smart charging and V2G can significantly reduce energy sector emissions. Demand flexibility (smart charging) leads to a reduction in generation from high-marginal-cost gas turbines by 2.5 MWh for every MWh of EV charging. With full V2G, this effect is deepened gas is displaced even more aggressively and replaced by wind and solar, leading to a net reduction in system emissions [8]. Specifically, V2G can reduce greenhouse gas emissions by 0.08 $MtCO_2$/year within local distribution networks depending on the energy mix [9].

5.2 Degradation analysis: calendar vs. cyclic aging

A key economic and ecological question is whether V2G destroys batteries prematurely. Detailed analysis of electrochemical models reveals a surprising fact: for many usage scenarios, the dominant degradation factor is calendar aging (aging over time), not cyclic wear.

Degradation of capacity can be modeled by a combination of Arrhenius kinetics for calendar aging and charge-throughput models for cyclic aging. Research indicates that calendar aging can account for up to 67% of total degradation in low annual mileage scenarios (e.g., 10,000 km).

If a car is parked and fully charged (100% SoC), it degrades faster due to high voltage on the electrodes, which accelerates parasitic electrolyte reactions. A smart V2G system can "discharge" the battery to a healthier level (e.g., 60%) by supplying energy to the grid during peak times and then charging it just before departure. In this way, V2G not only provides grid services but can paradoxically extend battery life compared to "dumb" charging and parking at 100% SoC [10].

Table 1. V2G impact on battery degradation.

Aging Type	*Calendar*	*Cyclic*
Cause	Time, Temperature, SoC (State of Charge)	Cycle count, Depth of Discharge (DoD)
V2G Impact	Can reduce degradation if V2G maintains the battery at an optimal lower SoC (e.g., 50%) instead of fully charged.	Increases wear due to additional cycles.
Ecological Implication	Extending battery life delays the need for new production and reduces waste.	Optimized "shallow" cycling minimizes this impact.

5.3 Economic viability and regional differences

The environmental benefit of V2G is closely tied to its economic viability. In regions with low price volatility (e.g., Shanghai, Ontario), arbitrage is often unprofitable because the profit does not cover even minimal battery degradation costs.1 Conversely, in regions with high price differentials (Australia, California), V2G is strongly incentivized. This means regulatory policy (dynamic tariffs) is a key tool for unlocking the ecological potential of millions of EV batteries.

6 Hydrogen and power-to-gas: seasonal anchor and environmental dilemmas

While batteries excel within the day, they are economically unsuitable for inter-seasonal energy shifting (from summer to winter). Hydrogen (H_2) and Power-to-Gas (P2G) technology appear to be essential solutions for the "last mile" of decarbonization.

6.1 Power-to-gas as a virtual pipeline

P2G utilizes RES surpluses for water electrolysis. The produced hydrogen can be injected into the existing gas grid. Research confirms that pipelines can safely tolerate admixtures of 15-20% hydrogen by volume without the need for appliance modification.

- Ecological Benefit: This solution effectively transforms fossil infrastructure into a massive "battery." Utilizing existing pipelines eliminates the need to build new tanks and lines, representing massive material savings and reduced landscape impact.
- Dunkelflaute: Hydrogen stored in salt caverns is the only technology capable of covering demand during long periods of low wind and sun (so-called Dunkelflaute), making it a critical insurance policy against the collapse of a RES-dominated grid.

6.2 Hydrogen's water footprint: myth and reality

Criticism of hydrogen often focuses on water consumption. Green hydrogen production requires approximately 9 kg of water per 1 kg of H_2, while real consumption (including cooling and water treatment) can be higher-up to 45-95 liters per kg of hydrogen according to some sources. A large plant can consume millions of gallons of water annually [11].

- Context: Despite these figures, comparative studies show that water consumption for hydrogen production is still lower than or comparable to water consumption in coal and nuclear power plants (for cooling and mining) [12].
- Solution: Using desalinated seawater or wastewater is technically feasible and economically viable, as water costs constitute only a fraction of the hydrogen price. Circular systems that capture water produced during hydrogen combustion (e.g., in the steel industry) can further reduce the water footprint [12].

6.3 Hydrogen leakage and indirect greenhouse effect

A more serious and less discussed risk is leakage. Hydrogen is the smallest molecule, extremely prone to leaking through seals and materials. Although hydrogen is not a direct greenhouse gas, in the atmosphere it reacts with hydroxyl radicals, thereby reducing their availability to break down methane. Through this mechanism, it extends the lifetime of methane in the atmosphere and increases its warming potential.

- GWP of Hydrogen: Some models attribute a Global Warming Potential (GWP) to hydrogen up to 11-35 times higher than CO2 over a 20-100 year horizon [11].
- Benefit Threshold: If leakage rates across the entire chain exceed approx. 1-3%, the climate benefit of hydrogen compared to fossil fuels may be lost or significantly reduced [13].
- Implication: Hydrogen infrastructure must be built with extremely strict standards for tightness, monitoring, and maintenance. Blending hydrogen into old gas pipelines may increase the risk of leaks of methane itself (due to pressure changes and mixture properties), requiring a cautious approach [11].

7 Smart grids: digital nervous system and its footprint

Integrating fluctuating RES is physically impossible without parallel digital infrastructure—the "Internet of Energy" (IoE). This layer allows for real-time monitoring, prediction, and control.

7.1 From "dumb" wire to algorithmic infrastructure

The traditional grid was "big and dumb" (high inertia, simple control). The Smart Grid is "distributed and smart."

- Reducing Losses: Digitalization and flow optimization can reduce technical losses in grids. It is estimated that reducing global grid losses to around 5% could save over 400 Mt CO2 annually [1].
- Reducing Curtailment: Algorithms for weather forecasting and demand management allow the use of energy that would otherwise be discarded. In California, solar energy curtailment reaches gigawatt-hours—this energy can be redirected to batteries or EVs thanks to the Smart Grid, directly replacing fossil fuels [14].

7.2 Virtual power lines (VPL) and non-wire alternatives

An innovative concept with massive ecological benefit is Virtual Power Lines (VPL). VPL pairs two battery systems at opposite ends of a congested line. Mathematically, VPL operation is governed by the following conditions:

$$P_{SU_DN1}(t) + P_{SU_DN2}(t) = 0 \quad (1)$$

where $P_{SU_DN1}(t)$ is the instantaneous power of the battery system at node 1 at time t, and $P_{SU_DN2}(t)$ is the power at node 2. This balance ensures net energy transfer without physically overloading the line at critical times. From a biodiversity perspective, these "Non-Wire Alternatives" (NWA) allow for avoiding the construction of new physical lines through sensitive ecosystems, forests, and bird migration routes, which often fragment habitats and create barriers for wildlife. By eliminating the need for heavy steel, aluminium, and concrete for new pylons, the carbon footprint of the grid itself is radically reduced.

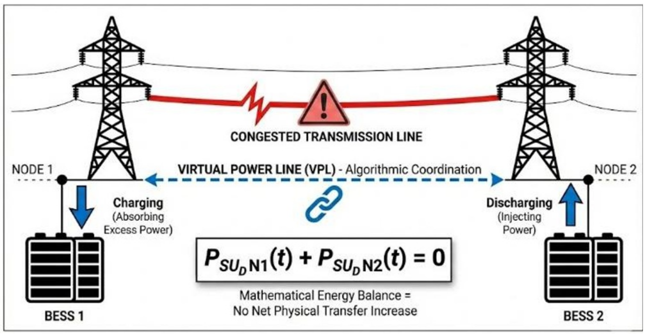

Fig. 2. Virtual Power Line (VPL) Concept utilizing BESS to relieve congestion.

- Biodiversity: These "Non-Wire Alternatives" (NWA) allow avoiding the construction of new physical lines through sensitive ecosystems, forests, and bird migration routes. Physical infrastructure often fragments habitats and creates barriers for wildlife [15].
- Embodied Carbon: By eliminating the need for heavy steel, aluminum, and concrete for new pylons, the carbon footprint of the grid itself is radically reduced [15] [16].

7.3 Environmental price of digitalization

Digitalization, however, is not "immaterial." Sensors, servers, and data transmission consume energy.

Data Center Consumption: Energy consumption of data centers (powered also by AI for grid management) is expected to grow massively, with AI training and inference being energy-intensive processes with high water consumption for cooling [17].

Edge vs. Cloud: From an ecological perspective, Edge Computing (processing at the edge) is more advantageous. Instead of sending terabytes of raw sensor data to a central cloud, data is processed locally, and only the result is sent. This is particularly critical for Phasor Measurement Units (PMUs), which provide high-speed grid data sampling (e.g., 60 samples per second). By processing this data at the edge, the energy intensity of communication networks is reduced, and latency is minimized, which is critical for real-time grid stability [21].

E-Waste: The deployment of millions of smart meters (AMI) and sensors creates a new stream of electronic waste. The lifespan of these electronics (10-15 years) is shorter than that of power infrastructure (40+ years). LCA studies show that the environmental benefit of AMI (via energy savings) outweighs their production footprint, but only if recycling and component life extension are prioritized.

7.4 Cybersecurity as an ecological factor

The Smart Grid is a cyber-physical system. A cyberattack (e.g., False Data Injection - FDI, where an attacker spoofs data) can lead to physical equipment damage and blackouts. A blackout triggers the immediate startup of high-emission diesel backup generators and failure of critical filtration systems. Real-world incidents, such as the 2015 cyberattack on the Ukrainian power grid, demonstrate how vulnerabilities in digital infrastructure can lead to direct physical disruptions and environmental risks [22].

8 Conclusion: integrated approach to sustainability

The analysis confirms that the path to a low-carbon future leads through the synergistic interconnection of RES, BESS, and Smart Grids. However, this integration must be managed with a deep understanding of secondary and tertiary environmental impacts.

Key findings and recommendations:

1. Localization is Key: Supporting nanogrids and microgrids minimizes losses and increases

resilience. Energy subsidiarity is an ecological imperative.

2. Batteries with Prudence: Massive deployment of BESS must be accompanied by a transition to safer chemistries (LFP), support for recycling, and intelligent use of existing EV batteries (V2G) with regard to minimizing calendar aging.
3. Leak-Free Hydrogen: Hydrogen is indispensable for seasonal accumulation, but its infrastructure must meet strict emission standards for leakage; otherwise, it will become a climate liability.
4. Digital Efficiency: Smart Grids must be designed to minimize the energy consumption of the IT infrastructure itself (Edge Computing) and address the e-waste problem.
5. Algorithms Instead of Concrete: Prioritizing "Non-Wire Alternatives" (VPL, flexibility) over building new physical lines is one of the most effective tools for protecting biodiversity and the landscape.

The future of energy lies in the intelligent orchestration of millions of devices, where every algorithm, every battery, and every panel plays a role in maintaining the planet's ecological balance.

Acknowledgement: This work was supported by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic (ME SR) and of Slovak Academy of Sciences (SAS) under the contract No. VEGA 1/0385/23, 1/0627/24 and 1/0647/26.

References

1. IEA, *Sustainable recovery* (IEA, Paris, 2020). Available: https://www.iea.org/reports/sustainable-recovery
2. U.S. Environmental Protection Agency, Battery energy storage systems: Main considerations for safe installation and incident response. Available: https://www.epa.gov/electronics-batteries-management/battery-energy-storage-systems-main-considerations-safe
3. H. Weinstein, BESS pros and cons (Clean Coalition, 2024). Available: https://clean-coalition.org/news/bess-pros-cons/
4. T.R. Simon, D. Inman, R. Hanes, G. Avery, D. Hettinger, G. Heath, Life cycle assessment of closed-loop pumped storage hydropower in the United States. Environ. Sci. Technol. **57**, 12251–12258 (2023)
5. D.V. Nemova et al., Life cycle analysis of energy storage technologies: A comparative study. E3S Web Conf. **511**, 01040 (2024)
6. Connected Energy, Second life EV battery energy storage: Making a sustainable impact (2024). Available: https://connected-energy.co.uk/industry-insights/second-life-ev-battery-energy-storage-making-a-sustainable-impact/
7. Green Li-ion, Future trends in Li-ion battery recycling for 2025 and beyond. Available: https://www.greenli-ion.com/post/future-trends-in-li-ion-battery-recycling-for-2025-and-beyond
8. M.F. Bortotti, P. Rigolin, M.E.M. Udaeta, J.A.B. Grimoni, Comprehensive energy analysis of vehicle-to-grid integration with the power grid. Appl. Sci. **13**, 11119 (2023)
9. J. Chen, M.T. Craig, J. Michalek, M. Bruchon, P. Vaishnav, Negative electric vehicle emissions: Vehicle-to-grid can incentivize enough wind and solar investment to reverse EV charging emissions. Environ. Sci. Technol. **59**, 21090–21101 (2025)
10. L. Timilsina, A. Moghassemi, E. Buraimoh, A. Arsalan et al., Impact of vehicle-to-grid on battery degradation in a plug-in hybrid electric vehicle. SAE Technical Paper 2024-01-2000 (2024)
11. Clean Energy Group, Green hydrogen's impact on water supplies – Fact sheet (2024). Available: https://www.cleanegroup.org/wp-content/uploads/Green-Hydrogen-Fact-Sheet.pdf
12. D.J. Lampert et al., Development of a life-cycle inventory of water consumption associated with the production of transportation fuels (Argonne National Laboratory, 2015). Available: https://doi.org/10.2172/1224980
13. MIT Energy Initiative, New climate chemistry model finds non-negligible impacts of potential hydrogen fuel leakage (2024). Available: https://news.mit.edu/2024/new-climate-chemistry-model-finds-non-negligible-impacts-potential-hydrogen-fuel-leakage-1216
14. A.A. Chien et al., As grids reach 100% renewable at peak, growing curtailment of 8 gigawatts looms as a challenge to decarbonization. Institute for Climate and Sustainable Growth Working Paper (2024). Available: https://climate.uchicago.edu/working-papers/as-grids-reach-100-renewable-at-peak-growing-curtailment-of-8-gigawatts-looms-as-a-challenge-to-decarbonization/
15. A.J. Bennett, D.M. Watson, M.J. Watson, Positive and negative impacts of electrical infrastructure on animal biodiversity: A systematic review. Oecologia **207**, 142 (2025)
16. R. Saidur, N.A. Rahim, M.R. Islam, K.H. Solangi, Environmental impact of wind energy. Renew. Sustain. Energy Rev. **15**, 2423–2430 (2011)
17. Environmental and Energy Study Institute, Data center energy needs could upend power grids and threaten the climate (2025). Available: https://www.eesi.org/articles/view/data-center-energy-needs-are-upending-power-grids-and-threatening-the-climate
18. World Bank, Electric power transmission and distribution losses (2023). Available: https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS

19. A.F.A. Zaidi et al., Machine learning and optimization in energy management systems for plug-in hybrid electric vehicles: A comprehensive review. Energies **17**, 3059 (2024)
20. Idaho National Laboratory, A guide to case studies of grid enhancing technologies (2023). Available: https://inl.gov/content/uploads/2023/03/A-Guide-to-Case-Studies-for-Grid-Enhancing-Technologies.pdf
21. Y. Chen et al., Synchrophasor data anomaly detection on grid edge by 5G communication and adjacent compute. *IEEE Trans. Smart Grid* 15, 4123–4134 (2024)
22. D.E. Whitehead et al., Ukraine cyber-induced power outage: Analysis and practical mitigation strategies, in Proceedings of the 70th Annual Conference for Protective Relay Engineers (2017), 1–8