PROBLEMY EKOROZWOJU/ PROBLEMS OF SUSTAINABLE DEVELOPMENT
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SUBMITTED:17.X.2025, ACCEPTED: 18.XI.2025, PUBLISHED ON-LINE: 10.01.2026
2026, 21(1): 30-41, DOI: 10.35784/preko.8754

Environmental and Social Sustainability Pathways in the Development of Energy Storage Technologies: Global Scenario Analysis

Ścieżki zrównoważonego rozwoju środowiskowego i społecznego w rozwoju technologii magazynowania energii: analiza globalnych scenariuszy

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Abstract
This article foregrounds the environmental and social dimensions of energy storage development, analyzing how market dynamics, investment strategies, and policy instruments shape the deployment and sustainability of these technologies. While technological innovation and environmental concerns remain vital, the economic viability of energy storage solutions in various global contexts is increasingly central. The article presents three development scenarios – high-speed technological advancement, balanced growth focused on sustainability and inclusivity, and slow development influenced by environmental and social caution – each evaluated through an economic lens. The scenarios illuminate pathways not only for climate resilience and equity, but also for stimulating green economies, securing investments, and enhancing long-term energy market stability.

Key words: energy storage technologies, environmental sustainability, social equity, renewable energy, technological advancement, climate change mitigation

Streszczenie
Artykuł koncentruje się na ekonomicznych środowiskowych i społecznych aspektach rozwoju magazynowania energii, analizując, w jaki sposób dynamika rynkowa, strategie inwestycyjne i instrumenty polityczne kształtują wdrażanie oraz trwałość tych technologii. Choć innowacje technologiczne i kwestie środowiskowe pozostają kluczowe, coraz większe znaczenie zyskuje ekonomiczna opłacalność rozwiązań w zakresie magazynowania energii w różnych kontekstach globalnych. W artykule przedstawiono trzy scenariusze rozwojowe – szybki postęp technologiczny, zrównoważony wzrost ukierunkowany na trwałość i inkluzywność oraz powolny rozwój determinowany ostrożnością ekologiczną i społeczną – z których każdy został oceniony z perspektywy ekonomicznej. Scenariusze te ukazują możliwe ścieżki nie tylko w kierunku odporności klimatycznej i sprawiedliwości społecznej, lecz także pobudzania zielonej gospodarki, zapewnienia stabilności inwestycyjnej oraz wzmacniania długoterminowej równowagi rynków energii.

Słowa kluczowe: technologie magazynowania energii, zrównoważoność środowiskowa, równość społeczna, energia odnawialna, postęp technologiczny, łagodzenie zmian klimatu

Introduction
Amid the urgent need to decarbonize energy systems, the economic dimension plays a pivotal role in shaping technological trajectories and political feasibility. Energy storage, as a strategic enabler of renewable integration

and grid stability, requires more than technical advancement – it demands robust financial models, scalable investment frameworks, and policies that internalize environmental and social externalities. The economic landscape – defined by global capital flows, fiscal incentives, carbon pricing, and industrial competitiveness – profoundly influences which scenarios will emerge as viable and desirable. Thus, an integrated analysis of energy storage futures must explicitly engage with economic logic from the outset.
The pressing global imperatives of climate change mitigation and the transition to renewable energy systems have underscored the critical role of energy storage technologies (Pawłowski,2021). These technologies, including advanced battery systems, are pivotal for buffering the intermittency of renewable energy sources like solar and wind, thereby enhancing the resilience and reliability of power grids (International Energy Agency [IEA], 2020). However, the rapid evolution of these technologies and their deployment raises significant environmental and social considerations that must be addressed to ensure a sustainable energy transition, which is in compliance with the following Sustainable Development Goals: 7 – Affordable and clean energy, 8 – Decent work and economic growth and 9 – Industry, innovation and infrastructure.
Energy storage technologies, particularly battery systems, are evolving rapidly due to technological innovations and substantial investments from both public and private sectors. This evolution is driven by the need to enhance energy security, improve energy access, and reduce greenhouse gas emissions. While these advancements are promising, they also come with complex challenges that impact both the environment and society at large.
Recent global data illustrate these dynamics in terms of costs, deployment, and investment trends (Table 1).

Table 1. Global trends and costs of energy storage (batteries), sources: (BloombergNEF, 2023–2024; IEA, 2023–2024; NREL, 2023).

Indicator	2010	2023	2030 (projection)	Source
Average Li-ion pack price (USD/kWh, weighted average, all uses)	> 1,100 (BNEF 2010)	139 (BNEF 2023)	n/a	BNEF (2010, 2023)
Newly added battery storage capacity in the power sector (GW/year)	n/a	42 (IEA 2023)	n/a	IEA (2023, 2024)
Total installed battery storage capacity in the power sector (GW, year-end)	n/a	85 (IEA 2023)	1,200–1,500 (IEA 2030)	IEA (2023, 2024)
Global battery investment (EV + storage), USD billion	n/a	150 (IEA 2023)	≈300+ (IEA projection 2030)	IEA (2023, 2024)
Capital cost of complete 4-h BESS system (USD2022/kWh)	n/a	n/a	245 / 326 / 403 (NREL 2023)	NREL (2023)

Note: All cost data are expressed in real 2022 USD

Despite a growing body of literature addressing the technological and environmental aspects of energy storage, less attention has been paid to its economic implications and normative trajectories. The question is not merely which technologies will dominate, but which development pathways will align with long-term sustainability goals, social equity, and political legitimacy.
Parallel to this, techno-economic modeling has gained prominence, focusing on cost trajectories, energy density improvements, and integration into power systems (Schmidt et al., 2021; Aral and Wong, 2021). Yet these contributions often treat the economic domain in narrow, quantitative terms - such as levelized cost of storage – without embedding it in broader institutional or political-economic frameworks. Moreover, social aspects tend to be neglected or addressed superficially, despite growing evidence that public perception, equity concerns, and workforce development are critical to the deployment of energy storage technologies (Parkinson and Devezas, 2021; Lim and Fitzgerald, 2025; Adams and Calmon, 2021).
While foresight studies and scenario planning have been applied in the energy sector more broadly (Howells et al., 2021; Sovacool et al., 2020), few have focused specifically on energy storage, and even fewer have attempted to combine normative desirability with empirical likelihood. Most existing scenarios are either technologically deterministic or policy-driven, lacking reflection on underlying value systems or economic paradigms.
This paper responds to these gaps by integrating economic, environmental, and social dimensions into a foresight framework focused on energy storage futures. It combines structured scenario construction with an assessment of

normative appeal and practical feasibility, thereby contributing to a more comprehensive and socially grounded understanding of the sector's development trajectories.

This paper adopts a normative foresight approach to explore three ideal-type scenarios for the development of energy storage technologies, each reflecting different combinations of institutional arrangements, economic drivers, societal values, and environmental priorities. By doing so, it aims to bridge the gap between predictive modeling and value-based policy planning. The core research questions guiding this study are as follows: (1) Which energy storage development pathways are most desirable from a sustainability and justice perspective? (2) Which of these scenarios are most likely to materialize under current political and economic conditions? (3) How can policy and institutional interventions shape the alignment between desirable and likely futures?

This foresight exercise is grounded in the broader context of European climate policy, the Sustainable Development Goals (SDGs), and global efforts to ensure a just energy transition. It incorporates both quantitative indicators and qualitative reasoning to assess the desirability and likelihood of each scenario, paying particular attention to economic and social dimensions often marginalized in energy transition discourse.

Methodological approach to scenario construction

The scenarios developed in this paper follow a normative foresight methodology, drawing upon literature-based archetype construction, policy discourse analysis, and synthesis of observed socio-technical trends. Rather than predicting future outcomes, the aim is to illustrate coherent development pathways that highlight different trade-offs and decision logics relevant to the energy storage transition.

The scenario logic is based on two intersecting axes: (1) the dominant mode of governance – market-driven versus state-led coordination, and (2) the pace of technological adoption – accelerated versus incremental. This results in a matrix of plausible pathways, from unregulated techno-optimism to cautious, socially embedded transitions.

Each scenario was elaborated with four consistent dimensions: technological foundations, economic implications, environmental considerations, and social/governance characteristics. This structure ensures internal coherence and facilitates comparative analysis.

Source material includes peer-reviewed studies, institutional foresight reports (IEA, IPCC, EU policy white papers), and investment trend data from the energy sector. While not relying on formal modeling, the scenario narratives are anchored in empirical signals and validated through iterative cross-checking with recent technological and policy developments.

The typology employed here aligns with established foresight approaches (van Notten et al. 2003; Börjeson et al. 2006), distinguishing between normative and exploratory scenarios. The three scenarios presented – High Speed Technological Advancement, Balanced Development with Focus on Sustainability and Inclusivity, and Slow Technological Development Due to Environmental and Social Concern – represent stylized extremes to provoke reflection and support strategic deliberation.

Scenario 1: High Speed Technological Advancement

The High Speed Technological Advancement scenario represents a trajectory where innovation in energy storage technologies rapidly accelerates in response to global demands for enhanced renewable energy integration and urgent climate action initiatives. This scenario anticipates a surge in technological breakthroughs driven by significant investments, intense market competition, and strong policy support, aiming to address the pressing needs of energy systems transitioning away from fossil fuels.

Under this scenario, advancements in battery technology, particularly in lithium-ion alternatives and solid-state batteries, move at an unprecedented pace. Innovations focus on increasing energy density, reducing charging times, and extending lifecycle while minimizing costs and environmental impacts. Research and development intensify around emerging technologies like silicon anode batteries, which offer the potential for higher energy capacities and faster charging capabilities than traditional lithium-ion batteries (Marom et al., 2011).

From an economic perspective, rapid technological development in the energy storage sector is primarily driven by aggressive capital investment, speculative financing, and high expectations of short-term returns. The swift pace of innovation can lower unit costs through economies of scale and learning curves, attracting further private and institutional capital. However, this growth model may also create market bubbles if valuations outpace underlying technological viability (Ekins & Zenghelis, 2021). Moreover, high volatility in global commodity markets - especially for lithium, cobalt, and nickel - poses price risks that can destabilize supply chains and deter long-term investment planning (IRENA, 2020). Incentives such as investment tax credits, accelerated depreciation schemes, and state-led innovation grants often underpin such rapid expansions, but they can also crowd out more sustainable or locally adapted models. International competition for technological leadership in battery manufacturing may lead to geopolitical tensions and trade barriers, further complicating the economic viability of cross-border energy solutions.

In addition to the previously discussed macroeconomic implications, high-speed advancement in energy storage technologies reshapes sectoral employment patterns and regional economic hierarchies. As battery production intensifies, regions with established supply chain infrastructure – particularly in Asia-Pacific and parts of Europe – are likely to consolidate economic dominance in this emerging sector. This may further global economic imbalances unless parallel investment and technology transfer mechanisms are put in place.

The accelerated pace also places pressure on electricity markets, especially where storage deployment is subsidized without dynamic tariff reform. Price volatility can ensue, challenging grid operators and financial planners. Speculative overcapacity in some regions could also lead to stranded assets if long-term demand projections are inaccurate. In parallel, companies face pressure to justify capital expenditure within shorter ROI windows, which may disincentivize long-term R&D and resilience planning (Ekins & Zenghelis, 2021; OECD, 2021).

At the macroeconomic level, countries heavily investing in next-generation energy storage may experience balance-of-payments shifts due to raw material imports or export-oriented manufacturing booms. Exchange rate volatility could intensify for economies overly reliant on lithium or cobalt supply chains. Moreover, the interconnectedness of energy markets and capital flows could amplify economic contagion if a major player defaults on large-scale storage infrastructure projects (IEA, 2022; IMF, 2023).

This article explores three potential development scenarios for energy storage technologies, each reflecting different balances between technological advancement, economic viability, environmental sustainability, and social equity.

To illustrate the quantitative implications of the three scenarios, Table 2 provides a comparative overview of selected indicators for 2030 based on available projections and literature.

Table 2. Comparative indicators for three development scenarios of energy storage technologies, Sources: (BNEF, 2023–2024; IEA, 2023–2024; NREL, 2023; IRENA, 2023).

Dimension	High-Speed Technological Advancement	Balanced Development	Cautious Transition
Cost of Li-ion packs (USD/kWh, 2030)	100–150 (optimistic projection; BNEF, 2023)	150–250 (moderate decline; IEA, 2023)	>250 (slower decline with strong regulation; IEA, 2023)
Global installed storage capacity in 2030 (GW)	1,500+ (aggressive rollout; IEA (2023, 2024)	~1,200 (aligned with IEA Net Zero target; IEA, 2023)	800–1,000 (slower rollout; IRENA, 2023)
Annual global investment in batteries by 2030 (USD bn)	400–500 (rapid inflows; IEA, 2023)	~300 (doubling from 2023; IEA, 2023)	200–250 (public-led; IRENA, 2023)
Employment effect (jobs created in storage sector)	10–12 million (scaling manufacturing; IRENA, 2023)	7–9 million (balanced growth; IRENA, 2023)	5–6 million (steady growth; IRENA, 2023)
CO_2 avoided annually by 2030 ($MtCO_2$)	1,500+ (rapid fossil displacement; IEA, 2023)	~1,200 (aligned with IEA NZE; IEA, 2023)	800–900 (slower rollout; IRENA, 2023)

Note: All values represent rounded estimates based on institutional projections for 2030; all costs are expressed in real 2022 USD, and emission data in $MtCO_2$ per year.

By integrating financial frameworks, investment dynamics, and market-based policy tools into the scenario analysis, this work seeks to discern the most desirable and likely trajectories for the future development of energy storage systems. It aims to provide actionable insights into how best to navigate the challenges and opportunities posed not only by technological and environmental factors, but also by fiscal constraints, capital flows, and economic resilience. This endeavor is crucial not only for policymakers and industry stakeholders, but also for communities globally that will live with the consequences of these intertwined technological and economic choices.

The rapid advancement scenario could have profound social implications. Economically, it could generate a substantial number of jobs in research and development, manufacturing, and systems integration related to energy storage technologies. Regions or countries that lead in technology development might see significant economic benefits, potentially reinforcing global technological disparities between nations (Carrillo-Hermosilla et al., 2021).

From an environmental perspective, the production, utilization, and disposal of battery systems involve critical materials whose extraction can lead to significant ecological degradation. The mining processes for lithium, cobalt, and rare earth elements, essential for modern batteries, often result in substantial environmental disruption, including habitat destruction, water pollution, and soil degradation (Sovacool et al., 2020). These activities not only threaten biodiversity but also impose health and safety risks on local communities.

The environmental implications of such rapid technological advancement are multifaceted. On the positive side, the swift development and deployment of advanced energy storage technologies can significantly reduce carbon

emissions by enabling a quicker transition to renewable energy sources and decreasing reliance on peaking power plants that typically use fossil fuels (Schmidt et al., 2021).
However, the accelerated pace of technology development could lead to increased extraction of raw materials required for new batteries, such as lithium, nickel, and cobalt, which might exacerbate environmental degradation in mining regions. The rush to advance technology could also sideline the development of comprehensive recycling processes, potentially leading to higher volumes of electronic waste as earlier generations of batteries are quickly rendered obsolete (Schmidt et al., 2021).
Strategic international collaborations and partnerships will be crucial in mitigating the negative impacts associated with this scenario. These efforts should aim to distribute the benefits of new technologies more evenly and ensure that environmental and social safeguards are in place as the global community races towards a more sustainable energy future.
On the social front, the distribution of energy storage technologies has implications for social equity and energy justice. The benefits and burdens of energy storage are not shared equally across different geographies and populations. Issues such as labor rights violations in mining operations in developing countries and the unequal access to energy storage solutions in underprivileged regions highlight the social disparities associated with these technologies (Borenstein et al., 2019).
Beyond short-term market fluctuations, the high-speed advancement trajectory necessitates significant adjustments in regulatory frameworks governing energy finance. Rapid innovation often outpaces regulation, leading to financial asymmetries where venture-backed startups can gain disproportionate market influence without sufficient oversight. This creates risk of financial concentration and raises concerns about monopolistic behaviors in emerging battery sectors.
Additionally, this scenario sees the scaling up of next-generation technologies such as metal-air batteries, which promise significantly higher energy densities suitable for longer-duration storage applications. These technologies become critical as the grid integrates a larger proportion of intermittent renewable energy sources, requiring robust storage solutions that can manage longer discharge times to stabilize supply (Needell et al., 2021).
Conversely, the rapid deployment of new technologies could widen the digital divide, particularly in regions that lack the infrastructure or capital to adopt the latest advancements. This could lead to inequalities in energy access, with advanced energy storage systems primarily benefiting wealthier nations while leaving others behind. Furthermore, the push for rapid development could exacerbate labor issues in mining and manufacturing, where demand for quick production might compromise worker safety and rights (Howells et al., 2021).
To navigate this scenario effectively, policymakers and industry leaders must balance the push for rapid technological advancements with the need for sustainable and equitable development practices. This includes investing in sustainable mining practices, developing global standards for labor rights in the energy storage sector, and promoting the establishment of robust recycling systems to manage end-of-life products.
The rapid technological shift may exacerbate social inequalities, especially in regions lacking access to advanced infrastructure or education. Communities unable to adapt to high-speed innovation may experience marginalization, job displacement, and reduced agency in energy-related decisions. The technological acceleration disproportionately benefits regions and social groups with high adaptive capacity, creating a widening digital and energy divide. In urban centers, early adopters may gain advantages through access to home battery systems and dynamic pricing models, while rural or low-income populations lag behind. This creates new forms of energy poverty, not due to lack of supply, but due to uneven access to smart grids, IoT-based control systems, and energy market participation.
Moreover, the pace of innovation may outstrip the capacity of public institutions to regulate or mediate its social consequences, leading to democratic deficits in decision-making about energy infrastructures. The increasing reliance on algorithm-driven energy management systems raises ethical concerns about transparency, data privacy, and the exclusion of non-digital users. Public perception of technological determinism may generate resistance among social groups who feel disempowered by top-down transitions lacking consultation. Automation in manufacturing and grid operations leads to job losses in traditional sectors, while high-skill labor demand grows, deepening labor market segmentation. Urban-rural divides become more pronounced as smart energy infrastructure concentrates in high-density areas, leaving peripheries with outdated systems and limited flexibility.

Scenario 2: Balanced Development with Focus on Sustainability and Inclusivity

The Balanced Development Scenario outlines a pathway in which technological, economic, environmental, and social dimensions of energy storage evolve in harmony. This scenario reflects a pragmatic policy approach that seeks to balance innovation with precaution, global competitiveness with local benefits, and short-term feasibility with long-term resilience.
Technological progress in this scenario is steady and inclusive. Governments and industry actors collaborate to support both cutting-edge developments and mature technologies that are already scalable. The storage sector

diversifies with a mix of battery chemistries, thermal storage, and hydrogen systems tailored to specific regional needs and energy mixes.

From an economic perspective, this scenario enables cost declines through targeted public investment, robust industrial policy, and cross-sectoral innovation. Markets are designed to reward not just efficiency and capacity but also environmental and social performance metrics. Carbon pricing and green bond mechanisms play a significant role in financing the expansion of storage infrastructure.

Environmental considerations are fully integrated into planning and procurement. Life cycle analysis, sustainable materials sourcing, and end-of-life recovery become industry norms. International standards and certification schemes support transparency and reduce the ecological footprint of global supply chains. Policy frameworks incentivize not only carbon reduction but also biodiversity protection and water use efficiency.

On the social front, this scenario envisions widespread access to clean and reliable energy, including in rural and marginalized communities. Community-scale storage projects receive strong institutional support, enabling energy self-sufficiency and economic empowerment. Education, reskilling, and gender equity programs are embedded in the deployment process, ensuring that the benefits of the transition are broadly shared.

This scenario also fosters public trust and democratic legitimacy by including diverse stakeholders in decision-making processes. Citizens, municipalities, industry representatives, and environmental groups jointly shape policy design and implementation. Adaptive governance mechanisms ensure that the strategy remains flexible in the face of uncertainty, whether due to geopolitical shifts, technological disruptions, or environmental change.

Ultimately, the Balanced Development Scenario represents a middle path – ambitious yet grounded, systemic yet participatory. It acknowledges that sustainable energy storage is not just a technical issue, but a societal project requiring coordination, inclusion, and a shared vision of the future.

The balanced scenario supports diversification of economic benefits across stakeholders. Local manufacturing of modular storage units, supported by government procurement policies and innovation clusters, strengthens SME participation in green markets. These dynamics bolster regional economies and embed resilience through shorter supply chains.

Furthermore, public investment in workforce upskilling aligned with green storage technologies fosters long-term employment, helping economies transition from fossil-fuel-intensive sectors. The economic multiplier effects of such transitions are significant: new value chains emerge in software integration, maintenance services, and battery component recovery. Coupled with eco-labelling and traceability schemes, this enables consumers to make informed economic decisions, reinforcing sustainability through market behavior (Jackson, 2017; UNCTAD, 2022).

The balanced development scenario for energy storage technologies embodies a harmonious blend of technological progress and conscientious sustainability. It champions a thoughtful approach that values environmental preservation and social equity alongside innovation. In this scenario, advancements in energy storage are paced deliberately to align with comprehensive sustainability goals that include reducing environmental footprints, fostering equitable access to technology, and ensuring fair labor practices.

Technological innovation extends to system integration where energy storage is optimized to work seamlessly with renewable energy sources, enhancing grid stability and energy efficiency. Smart management systems, which leverage artificial intelligence to optimize energy storage and distribution, reduce waste and increase the lifespan of battery systems (Martin et al., 2022).

Achieving the goals of the balanced development scenario requires comprehensive policy support, including subsidies for sustainable practices, tariffs on non-sustainable imports, and incentives for research and development in environmentally friendly technologies. International cooperation is crucial, particularly in standardizing regulations that manage both the environmental impact of production and ensure equitable access to technology.

This scenario prioritizes stable, inclusive economic growth over speculative or disruptive expansion. Economic resilience is built through policy tools such as green bonds, feed-in tariffs, carbon pricing mechanisms, and public-private partnerships. These mechanisms lower the cost of capital for sustainable energy investments and provide predictable returns (OECD, 2021). A key economic advantage of balanced development lies in fostering circular economy practices, including battery reuse, repair, and recycling. Such measures reduce lifecycle costs and resource dependencies, while enhancing regional self-sufficiency and employment (Jackson, 2017). Decentralized manufacturing and community-based energy storage initiatives are also supported by micro-financing and targeted subsidies, which stimulate local entrepreneurship and reduce economic disparities. In this context, energy storage becomes not only a technical enabler of renewable energy but also a vehicle for economic democratization and green job creation. Stable market regulation and clear long-term signals from governments further attract institutional investors seeking secure, ESG-compliant opportunities.

Balanced development offers an ideal environment for blended finance models, where public funds de-risk private investment in clean energy storage. By combining concessional loans, guarantees, and equity participation, such frameworks can mobilize large-scale capital for projects in low-income and emerging markets. These regions, often underserved by traditional financial institutions, gain access to storage technologies that stabilize local grids and enable decentralized energy economies.

Moreover, tax incentive policies tied to ESG metrics can promote corporate accountability and steer market capital toward sustainable storage ventures. For example, credits linked to carbon intensity per kWh stored may become the norm in assessing project eligibility for government support. This scenario also fosters intergenerational equity, ensuring that economic gains today do not result in disproportionate future liabilities through environmental degradation or resource exhaustion (World Bank, 2022; BNEF, 2023).
Furthermore, the workforce involved in the energy storage industry benefits from higher standards of health and safety, fair wages, and job security, contributing to socio-economic stability. Educational and training programs, particularly in less economically developed countries, receive investments to prepare local populations for jobs in the growing green tech sector (Sovacool et al., 2020).
In this scenario, development in energy storage focuses on both improving existing technologies and innovating new solutions that are inherently more sustainable. For example, advancements in solid-state batteries emphasize not only enhanced performance over traditional lithium-ion counterparts but also feature designs that are easier to recycle and use less toxic materials (Barnhart and Benson, 2021). This scenario also sees the rise of bio-derived battery materials, which present a lower environmental impact during production and disposal (Kim et al., 2021).
The environmental impacts in this scenario are significantly mitigated through the adoption of green chemistry principles in battery production and a lifecycle approach to product design. This reduces the ecological footprint associated with mining and processing of raw materials. Technologies such as recycling and second-life applications for used batteries become mainstream, further minimizing environmental impacts (Thompson et al., 2021).
Renewable energy sources increasingly power the production of battery materials, reducing the carbon footprint of the entire supply chain. Moreover, regulatory frameworks that encourage or mandate environmental responsibility are universally adopted, leading to widespread industry compliance and the promotion of international standards for sustainability (Jungbluth et al., 2021).
Public and private sectors are encouraged to form partnerships that support the sustainable development of energy storage, with a focus on long-term environmental health and social well-being. Educational initiatives are important to raise awareness about the benefits of sustainability in energy storage and to foster a new generation of engineers and scientists committed to ethical technological development.
The balanced development scenario greatly emphasizes social justice and equity. This includes ensuring that the benefits of energy storage technologies are accessible to all sectors of society, including marginalized communities and developing countries. Efforts are made to not only make these technologies affordable but also to implement them in ways that directly benefit low-income regions, such as through microgrid solutions that enhance local energy independence (Liu et al., 2022).
This scenario presents a holistic approach to energy storage development, balancing the need for advanced technological solutions with the imperative to preserve the planet and enhance human well-being. It exemplifies a sustainable path forward, integrating ethical considerations into every step of technological advancement.
Broad public engagement becomes a key component of this scenario, with policy design emphasizing transparency and citizen participation. Social programs are developed to ensure equitable access to energy services and to support communities in transitioning toward sustainable lifestyles.
This scenario emphasizes the importance of democratic deliberation in shaping long-term energy policy, where citizens are not only informed, but actively co-design solutions. Community-based energy cooperatives flourish, supported by public subsidies and decentralized governance structures, empowering local actors in energy production and management. Vocational retraining programs are developed to ensure a just transition for workers in fossil-dependent sectors, with attention to regional disparities. Energy literacy becomes a public policy priority, integrated into school curricula and adult education programs, fostering a culture of sustainability and collective responsibility.
Social equity metrics are incorporated into national energy transition strategies, ensuring that policy outcomes are regularly monitored for distributive effects. Deliberative forums and citizen science initiatives gain institutional support, integrating local knowledge into renewable energy planning. Intergenerational justice becomes a guiding principle, with youth movements influencing investment decisions and demanding long-term ecological commitments. Cultural narratives around energy shift toward sufficiency and resilience, moving away from purely growth-based logics and stimulating behavioral change.

Scenario 3: Slow Technological Development Due to Environmental and Social Concerns

The Slow Transition Scenario envisions a future where energy storage technologies evolve cautiously, shaped primarily by environmental regulations, community values, and a deliberate pace of change. This trajectory prioritizes long-term sustainability, social inclusivity, and precautionary governance over market speed or innovation-led disruption. Public investment plays a larger role in this scenario, with governments subsidizing low-impact technologies, supporting local supply chains, and ensuring that social equity is embedded in deployment strategies. The pace of technological change remains steady but intentionally moderated to allow adequate time for risk assessment, stakeholder dialogue, and adaptive regulation.

From an economic perspective, this pathway features stable but modest growth in energy storage markets. Instead of rapid upscaling, there is an emphasis on small- to medium-scale installations, particularly in underserved regions. Business models focus on affordability, resilience, and long-term value rather than short-term profitability. The investment environment favors social impact funds, public-private partnerships, and local cooperatives rather than aggressive venture capital.

Environmentally, the scenario places strong emphasis on lifecycle impacts, encouraging recycling infrastructure, domestic sourcing of critical minerals, and circular design principles. Regulatory frameworks mandate comprehensive environmental and social impact assessments for new projects. Citizen assemblies and local councils play an active role in determining technology siting, procurement standards, and deployment priorities.

Socially, this scenario is characterized by inclusive governance mechanisms, community ownership models, and a strong focus on energy justice. Storage technologies are deployed in ways that directly benefit low-income households, rural areas, and historically marginalized groups. Education programs and workforce training are aligned with local needs, increasing both acceptance and capacity.

However, the scenario also entails significant challenges. Slower innovation cycles may hinder competitiveness on the global stage, particularly as other economies embrace faster, high-tech approaches. Maintaining political support for precautionary policies requires consistent public engagement and transparent communication. Despite these barriers, the scenario offers a resilient and just pathway, particularly attractive to societies that value long-term stewardship over technological acceleration.

In this scenario, economic caution and long-term cost-effectiveness are prioritized over rapid expansion. Decision-making relies on comprehensive cost-benefit analyses, environmental risk pricing, and public approval. Investments are more conservative, often coming from public budgets, development banks, or climate finance instruments that emphasize inclusive and low-risk development paths (UNCTAD, 2022). Despite a slower pace of innovation, this model may yield better cost control over the full lifecycle of energy systems. Technologies such as second-life EV batteries or flow batteries with low maintenance costs are economically favored. In the absence of speculative bubbles, resource allocation tends to be more efficient, reducing systemic financial risk. Moreover, the social acceptance of storage facilities is higher, reducing litigation and project delays, which lowers soft costs. Governments in this model emphasize fiscal prudence and use taxation tools (such as mineral export duties or technology-neutral subsidies) to steer markets toward more equitable outcomes (Arrow & Fisher, 1974). Though less dynamic in the short term, this scenario may foster greater economic stability and long-term returns through sustainable infrastructure investments.

The slow technological development scenario envisions a cautious approach to the evolution of energy storage technologies, largely driven by heightened awareness and concern for potential adverse environmental and social impacts. This scenario reflects a world in which the pace of technological innovation is deliberately tempered by rigorous regulatory frameworks, extensive impact assessments, and a strong emphasis on public consultation and consent processes.

In this scenario, the focus is less on pushing the boundaries of technology at all costs and more on enhancing and refining existing energy storage solutions. Incremental improvements in technologies such as lithium-ion batteries are prioritized, with an emphasis on increasing efficiency and extending battery lifespans rather than developing entirely new materials or chemistries. Researchers invest significant effort into enhancing the recyclability of batteries and reducing reliance on rare, toxic, or geopolitically sensitive materials (Sakti et al., 2021).

Technological advancement is closely aligned with the principles of the circular economy. For example, much attention is given to second-life applications for used electric vehicle batteries, integrating them into stationary storage systems to provide backup power and grid services (Adegbite et al., 2022). These practices help to mitigate the demand for raw materials and reduce waste.

The environmental impacts under this scenario are managed more cautiously. The slower rate of technological advancement allows for more thorough environmental assessments and the implementation of stronger safeguards to protect ecosystems. The reduced pace of mining activities for critical minerals like lithium and cobalt results in less disruption to ecosystems and lower carbon emissions from mining operations (ODonoughue et al., 2022).

However, this scenario also poses challenges, particularly in terms of economic opportunities. The slower pace of innovation may limit job creation in the burgeoning energy storage sector and could delay the economic benefits associated with renewable energy technologies. Additionally, slower technological development might hinder global efforts to meet urgent climate targets, potentially placing greater burdens on future generations (Schelly et al., 2021).

Policymakers and industry leaders must balance the need for environmental and social prudence with the urgent demands of climate change mitigation and energy security. They must develop and enforce policies that encourage responsible innovation and ensure that new energy storage technologies do not exacerbate environmental degradation or social inequality.

This scenario demands a strategic, long-term vision that prioritizes sustainability and inclusivity over rapid technological gains. While it presents certain risks in terms of pace and economic impact, it offers a path towards a more balanced and just energy future.

Furthermore, with a focus on sustainability, more energy storage projects are likely to incorporate renewable energy sources during the production phase, further reducing the carbon footprint of the manufacturing process. This careful approach helps in maintaining biodiversity and ensures that local communities do not bear the environmental costs associated with rapid industrial expansion (Turner et al., 2022).
The gradual rollout of technologies ensures that there is ample time for all stakeholders, including vulnerable communities, to engage with and influence the development process. This can lead to more equitable outcomes and a higher degree of public acceptance of new technologies (Parkinson and Devezas, 2021).
Investment in education and training is crucial to prepare the workforce for future opportunities in a more sustainable energy sector. Furthermore, fostering international cooperation can help share best practices and distribute the benefits of energy storage technologies more evenly across global communities.
Public opinion becomes a powerful force in slowing down unsustainable energy projects, empowering grassroots environmental movements. However, slower development generates public frustration in some sectors, especially where green goals conflict with short-term economic needs. The environmental precaution that characterizes this scenario is accompanied by complex social reactions: on one hand, high public trust in science and environmental ethics supports regulatory restraint.
On the other hand, economically marginalized groups may resist deceleration, viewing it as a threat to livelihoods and regional development. Public discourse becomes polarized, with competing narratives about the legitimacy of 'slowing down' progress in the name of ecological caution. New forms of social innovation emerge, such as citizen assemblies, eco-councils, and solidarity-based consumption networks, which mediate these tensions and create alternative pathways for participation.
Slower technological rollout enables a more inclusive dialogue on energy ethics, giving marginalized voices space in regulatory debates. However, fragmented governance and delayed investments may intensify regional disparities, as wealthier areas adapt more easily to low-growth environments. Social resilience is tested as households adjust to higher energy prices and tighter environmental standards, triggering a search for new community solidarity mechanisms. Education and media play a critical role in framing the 'slow transition' not as a failure, but as a legitimate democratic choice rooted in collective responsibility.

Desirability and likelihood of the scenarios

In assessing the development scenarios for energy storage technologies, two dimensions are of particular relevance: desirability (based on normative values such as sustainability, equity, and democratic governance) and likelihood (based on current trends, institutional inertia, and technological feasibility).

Table 3. Assessment of desirability and likelihood of the three scenarios (scale 1–5)

Scenario	Desirability (1–5)	Likelihood (1–5)	Notes
High-Speed Technological Advancement	2	4	Attractive for innovation and cost decline, but risks inequality and environmental pressure.
Balanced Development	5	3–4	Most consistent with sustainability and justice goals, moderately likely if policies align.
Cautious Transition	4	2	Strong on equity and environment, but less feasible under current global growth pressures.

Note: The table presents an expert-based assessment of the three development scenarios using a five-point scale (1 – low; 5 – high). Evaluations reflect the author's synthesis of the reviewed literature and institutional data from IEA, IRENA, BNEF, and NREL.

Among the three scenarios developed in this study, the Balanced Development Scenario emerges as the most desirable from a sustainability and social justice perspective. It aligns most closely with the objectives of the European Green Deal and the United Nations Sustainable Development Goals (SDGs), particularly those related to affordable and clean energy (SDG 7), industry and innovation (SDG 9), and reduced inequalities (SDG 10). The scenario emphasizes inclusivity, public engagement, and environmentally conscious innovation - elements that are essential for a just energy transition.
By contrast, the High-Speed Technological Advancement Scenario, while attractive from an efficiency and innovation standpoint, risks deepening socio-economic divides and exacerbating environmental externalities due to rebound effects and accelerated resource consumption. Although this scenario may appear more immediately feasible due to existing investment patterns and private sector interest, its long-term desirability is compromised unless strong regulatory and redistributive mechanisms are implemented.

The Cautious Transition Scenario is notable for its strong environmental safeguards and social legitimacy, particularly in terms of public acceptance and local engagement. However, it is perceived as less likely to materialize due to economic constraints, slower technological rollout, and the current emphasis on growth and competitiveness in global energy markets. Without deliberate support from national governments and international institutions, this scenario may remain politically marginalized despite its normative appeal.

A simple two-axis matrix (Desirability vs. Likelihood) would thus place the Balanced Development Scenario in the upper-right quadrant - high in both dimensions, though not maximal in either. The High-Speed Scenario would score high on likelihood but lower on social desirability, while the Cautious Scenario would rank high in normative terms but low in feasibility under current conditions.

Bridging the gap between what is desirable and what is likely requires deliberate policy intervention, institutional learning, and a reorientation of socio-economic priorities. This includes investing in education and public participation, integrating social metrics into energy planning, and fostering multilevel governance structures that can mediate between technological innovation and societal needs.

While none of the scenarios fully resolves all tensions inherent in the energy transition, the Balanced Development Scenario offers the most promising foundation. However, its realization depends on proactive policy frameworks and a collective commitment to equitable, sustainable transformation.

From a societal perspective, the desirability of each scenario hinges on its capacity to foster equity, participation, and resilience. The Slow Transition Scenario, although less economically dynamic, presents a unique opportunity to deepen democratic engagement in shaping the energy future. It allows space for inclusive deliberation, local experimentation, and cultural adaptation, which are often sidelined in high-velocity transitions.

In contrast, the High-Speed Technological Advancement Scenario may struggle with public legitimacy if social systems are not adequately prepared for the disruptive effects of automation, sectoral shifts, and techno-centric governance. The rapid pace of deployment risks bypassing public consent and creating a governance vacuum, where critical decisions are made by private actors with limited accountability.

Table 4. Comparison of development scenarios for energy storage technologies

Dimension	Scenario 1: High-Speed Technological Advancement	Scenario 2: Balanced Development	Scenario 3: Cautious Transition
Technological profile	Rapid innovation in battery design, AI-driven management systems, dominance of private R&D.	Moderate, coordinated innovation supported by public and private sectors with focus on interoperability and resilience.	Deliberate and cautious implementation prioritizing safety, durability, and local environmental compatibility.
Economic model	Market-driven expansion, speculative investments, risk of inequality and monopolization.	Hybrid model balancing profitability with inclusiveness and long-term resilience.	State-supported frameworks with slow but equitable distribution of investment and benefits.
Environmental logic	Emission reduction via scale, but increased material extraction, rebound effects, and unmanaged waste.	Environmental limits integrated into planning; emphasis on circular economy and life-cycle standards.	Precautionary logic with strict safeguards on land use, materials, and emissions.
Social dynamics	Increased inequality in access to innovation, rural exclusion, weakening public governance.	Participatory planning, public education, and energy cooperatives ensure social fairness.	Strong public pressure for caution, tensions between ecological protection and economic demands.
Governance & policy	Reactive, fragmented regulation driven by global capital and market actors.	Integrated governance with multilevel coordination, public involvement, and policy alignment.	Localized decision-making, precautionary regulation, citizen oversight mechanisms.

Note: The table summarizes the author's qualitative comparison of the three development scenarios across key sustainability and feasibility dimensions. The assessment is based on the synthesis of institutional projections (IEA, IRENA, BNEF, NREL) and previous expert evaluations presented in Tables 2–3.

The Balanced Development Scenario fares better in integrating societal concerns into energy planning. By institutionalizing participatory mechanisms and emphasizing just transition policies, it enables broader ownership of the energy transition. This reduces resistance and enhances the stability of reforms, especially in regions historically dependent on fossil industries or vulnerable to energy poverty.

Public perception, trust in institutions, and social cohesion play a crucial role in shaping what is likely to happen. Even the most efficient technological pathway may fail if it lacks public support or produces uneven benefits. Conversely, slower but inclusive models may gain momentum if they demonstrate social value and legitimacy.

Ultimately, the desirability of a scenario must not be evaluated in purely economic or technological terms. Social dimensions – including fairness, empowerment, and collective agency – are equally essential in defining successful energy futures. This reinforces the need for foresight exercises to systematically integrate social analysis, rather than treating it as an external constraint.

Conclusions

The foresight exercise presented in this study highlights the multidimensional nature of sustainability-oriented technological development, especially in the context of energy storage from renewable sources of energy, which is in compliance with Sustainable Development Goal 7: Affordable and clean energy.

The analysis of three ideal-type scenarios – high-speed technological advancement, balanced development, and slow transition – reveals trade-offs between efficiency, inclusivity, ecological precaution, and political feasibility.

While the Balanced Development Scenario emerges as both desirable and moderately likely, its realization is not automatic. It depends on deliberate policy frameworks, targeted investments, and sustained societal engagement. Crucially, this scenario requires aligning market incentives with long-term public interests and building institutional capacity to coordinate across sectors and governance levels.

The Slow Transition Scenario, though high in normative value due to its emphasis on environmental limits and social legitimacy, faces structural barriers related to financing, political momentum, and global competitiveness narratives. Nevertheless, elements of this scenario – such as precautionary governance and citizen involvement – should inform hybrid strategies that integrate resilience and justice.

Conversely, the High-Speed Technological Advancement Scenario, while attractive to investors and innovation-driven actors, risks exacerbating socio-economic inequalities and weakening public oversight. Its desirability hinges on whether strong regulation and redistributive mechanisms can be effectively embedded in fast-moving innovation cycles.

Policy recommendations arising from this analysis include: supporting community-based storage initiatives, integrating social impact assessments into technology roadmaps, ensuring equitable access to innovation, and fostering public deliberation on energy futures. A just energy transition requires not only technical viability but also procedural fairness and cultural resonance. Institutions must ensure that the speed of technological change does not outpace the societal capacity to absorb and shape it.

Furthermore, foresight methods should be more systematically embedded in policy design processes, especially in contexts marked by uncertainty, contested values, and long-term implications. Scenario building can help decision-makers identify critical uncertainties, engage with stakeholders, and explore pathways that go beyond business-as-usual trajectories.

This study demonstrates the relevance of normative foresight as a lens to reflect on future development strategies and their ethical, ecological, and socio-political ramifications. Future research should further explore the operationalization of desirability and likelihood metrics and consider participatory scenario design involving citizens, civil society, and underrepresented regions.

Energy storage technologies are not neutral tools but embedded in broader socio-technical imaginaries. Their development pathways must be guided not only by cost and efficiency but also by democratic values, long-term resilience, and a collective vision of sustainable futures.

While the scenarios developed in this study provide a structured lens to explore potential futures of energy storage technologies, several limitations should be acknowledged. First, the analysis relies on ideal-typical constructions rather than predictive modeling; as such, the scenarios are intentionally stylized and do not account for all empirical complexities or uncertainties in technological development. Second, the desirability and likelihood assessments are based on expert judgment and secondary data, which, although grounded in current trends, may be subject to bias or evolve rapidly in the face of geopolitical or economic disruptions. Furthermore, the economic indicators used in the scenario evaluation are necessarily selective and do not fully capture dynamic market feedbacks, innovation diffusion processes, or regional disparities. Lastly, the social dimensions – although expanded – remain conceptual and would benefit from empirical validation through stakeholder engagement or participatory foresight exercises.

Future research should aim to refine and empirically test the scenarios proposed in this study through participatory methods, such as Delphi surveys, expert workshops, or stakeholder consultations. Incorporating diverse perspectives – especially from marginalized communities, industry actors, and policymakers – could enhance the robustness and legitimacy of the foresight process.

Moreover, integrating dynamic system modeling or agent-based simulations could provide a more granular understanding of feedback effects between technological, economic, and social subsystems. Finally, future work could extend the framework to specific national or regional contexts, accounting for local institutional structures, policy landscapes, and cultural values that shape the desirability and feasibility of energy storage development pathways.

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