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Beyond the Grid: Earth Observation Enabled Energy Storage Pathways for Renewable Powered Resilient Energy Systems: A PRISMA-Based Systematic Review

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Abstract

Energy storage systems are increasingly treated as core infrastructure for renewable-energy transitions, yet much of the literature still evaluates storage as a technology or market asset rather than as a spatially situated, climate-risk-sensitive system that can be improved through Earth observation and geospatial intelligence. This PRISMA-based systematic review examines how satellite data, remote sensing, GIS, digital tools and energy-storage technologies can be integrated to support renewable-powered resilient energy systems. Searches were conducted across Scopus, Web of Science, ScienceDirect, IEEE Xplore, Google Scholar and institutional sources from 2018 to 2025. From 170 identified records, 25 sources were included in qualitative thematic synthesis and evidence mapping. The review identifies five connected themes: Earth-observation-enabled siting and resource assessment, storage technology diversification, techno-economic and lifecycle sustainability, governance and market design, and digitalization through AI, IoT and digital twins. The findings show that Earth observation can strengthen energy-storage planning by locating renewable-resource variability, land-use constraints, climate hazards, grid-access conditions and equity risks, while storage technologies provide the temporal flexibility needed to transform variable renewable generation into dependable supply. The main research gap is the limited integration of geospatial evidence, storage dispatch, lifecycle assessment and justice-oriented policy within a single decision framework. The paper proposes a geospatial socio-technical transition model and a future research agenda for storage-enabled renewable systems aligned with Sustainable Development Goals 7, 11 and 13.

1 Introduction

Global energy systems are moving from centralized fossil-fuel generation toward renewable electricity, electrified transport, decentralized generation and digitally managed grids. Solar and wind power are central to this transition, but their output is shaped by weather, seasonality, land conditions and infrastructure constraints. Energy storage systems (ESS) are therefore not only supporting technologies. They are the mechanism through which variable renewable generation can be converted into flexible, dispatchable and resilient energy supply [2, 7–9]. The importance of storage is now visible at system scale. The International Energy Agency reports that global energy storage capacity must increase to about 1,500 GW by 2030 in the Net Zero Emissions Scenario, with batteries contributing about 1,200 GW of that total [2]. This scale-up requires more than battery chemistry and project finance. It requires spatial evidence about where renewable generation is strongest, where grid congestion and land-use conflicts occur, where climate hazards threaten infrastructure, and where communities face unequal access to clean energy. These questions sit directly within the domain of Earth observation (EO), remote sensing, GIS and spatial decision support. Earth observation has already transformed renewable resource assessment, land-suitability analysis, coastal and offshore energy planning, urban energy mapping and environmental monitoring [4–6]. Satellite imagery, reanalysis datasets, digital elevation models, land-cover maps and geospatial platforms such as Google Earth Engine can support energy planning at scales that conventional site surveys cannot easily cover [4, 5]. However, EO-informed renewable-energy studies often focus on generation potential, while energy-storage studies tend to

focus on electrochemical performance, cost, degradation, dispatch optimization or market design. The connection between these two fields remains underdeveloped. The original version of this paper examined the critical role of ESS in a renewable-powered future, with emphasis on technological innovation, economic viability, policy mechanisms and practical applications. For submission to Discover Earth Observation, the present version reframes and strengthens that work around EO-enabled and geospatially explicit storage planning. This reframing is necessary because a storage-only review would be only indirectly related to the journal's scope, whereas an EO-storage synthesis contributes to the journal's interest in remote sensing, geovisualization, spatial decision support, climate action and sustainable infrastructure. This review therefore asks: how can Earth observation and geospatial intelligence improve the planning, deployment and governance of energy storage in renewable-powered energy systems? It addresses four research objectives: (1) to synthesize storage technologies and their roles in renewable integration; (2) to identify how EO and GIS can support storage siting, resource complementarity and resilience assessment; (3) to evaluate economic, lifecycle, policy and justice constraints; and (4) to propose a theoretical model and research agenda for EO-enabled storage transitions.

1.1 Research gap and contribution

Three gaps motivate the review. First, storage reviews provide detailed comparisons of lithium-ion batteries, flow batteries, pumped hydro, hydrogen, compressed air and thermal storage, but they rarely explain how satellite-derived land, weather, water, hazard and infrastructure data can improve storage decisions [8, 9]. Second, EO and GIS studies provide strong evidence for renewable-resource mapping and site selection, but most stop at generation potential rather than linking spatial variability to storage sizing, dispatch, lifecycle cost and grid resilience [5, 6]. Third, policy and justice discussions frequently consider energy access and market reform without operationalizing spatial evidence on exposure, vulnerability, community energy needs and environmental burdens [10, 11]. The contribution of this paper is fourfold. It provides a PRISMA-structured review process, an explicit geospatial socio-technical transition model, evidence maps that visualize the review corpus, and a submission-ready appendix containing search strings, screening criteria, coding fields and quality-appraisal criteria. These additions make the paper more transparent, more reproducible and more closely aligned with the expectations of a high-quality review article.

2 Theoretical and conceptual model

This review uses a geospatial socio-technical transition framework. The model combines three strands of literature: socio-technical transition theory, which explains energy transformation as the co-evolution of technology, institutions, markets and user practices [10]; energy justice, which emphasizes distributional, procedural and recognition dimensions of energy decisions [11]; and EO-based spatial decision support, which uses satellite, GIS and computational data to locate environmental resources, risks and infrastructure conditions [4–6]. The model treats storage deployment as a four-layer decision system. The first layer is EO and geospatial evidence, including satellite imagery, land-cover products,

digital elevation models, reanalysis weather data, climate-risk information, grid-proximity layers and demand proxies. The second layer is analytical integration, where GIS-MCDM, AI/ML, digital twins and complementarity metrics translate spatial evidence into decision variables. The third layer is the storage-deployment layer, where planners select technology, location, capacity, dispatch strategy and lifecycle-management pathway. The fourth layer is the outcome layer, where storage-enabled renewable systems affect grid flexibility, resilience, emissions, affordability and energy justice. The framework also contains a governance feedback loop. Policies, permitting rules, market incentives, open-data standards, cybersecurity safeguards, recycling regulations and community participation influence how geospatial evidence becomes real infrastructure. In this sense, ESS is not only a technical response to intermittency; it is a socio-spatial infrastructure that must be planned through data, institutions and equity.

3 Methods

The review followed the logic of the PRISMA 2020 statement, which improves transparency in systematic review reporting through explicit identification, screening, eligibility and inclusion steps [1]. Because the purpose was to synthesize technological, geospatial, policy and sustainability evidence rather than to calculate a pooled effect size, the review used qualitative thematic synthesis and structured evidence mapping.Searches were conducted in Scopus, Web of Science, ScienceDirect, IEEE Xplore and Google Scholar, supported by institutional sources from IEA, IRENA, the World Bank, UNEP and related energy-transition repositories. The search window covered publications from 2018 to 2025 to capture recent developments in batteries, hydrogen storage, AI-enabled smart grids, EO platforms and storage policy. Earlier foundational works were added when necessary for theory or method, including PRISMA 2020, socio-technical transition theory, energy justice, and foundational energy-storage reviews [1, 8–11]. The search combined energy-storage, renewable-integration and EO/geospatial terms. Core strings included: ("energy storage" OR battery OR hydrogen OR "pumped hydro" OR "flow battery") AND (renewable OR solar OR wind OR microgrid OR "grid flexibility") AND ("Earth observation" OR "remote sensing" OR GIS OR geospatial OR satellite OR "spatial decision support"). Institutional searches used shorter combinations such as "battery storage renewable integration", "renewable energy GIS", and "storage policy grid flexibility". Studies were included if they: (1) addressed energy storage, renewable integration, EO/geospatial planning, smart-grid digitalization, or policy-governance mechanisms; (2) provided analytical, conceptual, empirical or methodological insight; (3) were peer-reviewed articles, conference papers or credible institutional reports; and (4) were available in English. Studies were excluded if they focused only on fossil-fuel systems, provided no analytical connection to storage or renewable integration, lacked methodological clarity, or were duplicate versions of the same work. Data extraction captured bibliographic details, study type, geography, storage technology, EO/geospatial relevance, policy relevance, lifecycle consideration, digital component, key findings and limitations. Each study was coded against six themes: storage technologies; EO/GIS planning; economic and lifecycle sustainability; policy and governance; digitalization through AI/IoT; and justice/community implications.

Multiple codes could be assigned to one study. The coding was used to create the evidence distribution chart and the qualitative evidence-readiness heatmap.

4 Results

4.1 Profile of the review corpus

The search identified 170 records. After removal of duplicates and clearly ineligible source types, 145 records were screened by title and abstract. One hundred and twenty full-text records were assessed for eligibility, and 25 sources were included in the final qualitative synthesis. The final corpus includes systematic and narrative reviews, technology assessments, grid-integration studies, EO/GIS renewable-resource studies, smart-city energy studies, microgrid analyses, EV-storage integration work and institutional reports. The evidence base is strongest in storage technology and renewable-grid integration. It is moderate in EO/GIS planning and economic/lifecycle sustainability, and weaker in justice-oriented storage deployment and integrated EO-storage-policy models. This pattern supports the central research gap: the fields of storage technology, EO-based renewable assessment and governance studies are advancing, but they are still insufficiently integrated.

4.2 Earth observation and geospatial intelligence for storage planning

EO and GIS are most directly used in the reviewed literature for renewable-resource assessment, offshore renewable planning, land-suitability analysis, environmental monitoring and geovisualization [4–6]. These uses are highly relevant to storage planning because storage requirements emerge from spatial and temporal mismatch. Solar and wind are not equally available across landscapes or seasons; grid access, slope, water constraints, land use, protected areas, hazard exposure and demand centers shape whether a storage project is technically and socially feasible. The review shows that EO can support at least five storage-planning functions. First, satellite and reanalysis data can identify where renewable-resource variability is strongest and where complementarity between solar, wind, hydro or offshore resources reduces storage needs [7]. Second, land-cover and elevation data can support siting of pumped hydro, utility-scale batteries, hybrid renewable-storage hubs and transmission-linked storage. Third, hazard maps can reveal where heat, flood, wildfire, sea-level rise or storms may threaten storage assets. Fourth, nighttime-light, building-footprint and urban-expansion data can support demand-side and community-storage planning. Fifth, open geospatial platforms can make storage planning more transparent to communities and regulators [4].

4.3 Storage technology diversification

The storage literature confirms that no single technology can meet all renewable-integration needs. Lithium-ion batteries dominate short-duration and fast-response applications because of high efficiency, modularity and falling cost, while flow batteries, hydrogen, pumped hydro, compressed air, flywheels and

thermal storage address different duration, scale and lifecycle requirements [8, 9, 16, 17]. Long-duration and seasonal storage remain especially important where renewable generation varies strongly across seasons or where isolated microgrids cannot rely on large interconnections [12]. Hydrogen and power-to-gas options are repeatedly presented as promising for long-duration balancing, industrial applications and sector coupling, though they still face efficiency, cost and infrastructure constraints [16]. Pumped hydro remains mature and scalable but is geographically constrained and environmentally sensitive. These differences make EO and geospatial evidence essential: storage technologies are spatially dependent, and their suitability depends on terrain, water availability, land-use constraints, hazards, proximity to renewable generation, and proximity to grid or demand centers.

4.4 Economic viability, lifecycle sustainability and circularity

Economic viability is a consistent concern across the review. Battery costs have declined substantially and storage deployment has accelerated, but lifecycle sustainability remains a critical limitation [2, 14]. Material extraction, supply-chain concentration, battery degradation, end-of-life management and recycling capacity determine whether storage produces net sustainability benefits. Cost reductions alone cannot answer these questions. The evidence suggests that lifecycle assessment should be integrated with spatial planning. EO can contribute indirectly by identifying land-use change, water stress, transport accessibility, climate exposure and ecosystem sensitivity around storage sites. However, few studies combine EO-based siting, storage dispatch models and lifecycle/circularity metrics in a single framework. This gap is significant because a storage project can be technically useful for grid balancing while still producing local environmental or social burdens.

4.5 Policy, governance and market mechanisms

Policy and governance shape whether storage can move from demonstration to system infrastructure. The reviewed literature emphasizes investment incentives, grid codes, market rules for ancillary services, interconnection policy, tariff design, renewable-storage procurement, regional cooperation and international knowledge sharing [21, 22, 25]. Where policy is uncertain, storage projects face revenue risk and permitting delays. Where markets fail to reward flexibility, storage value is underestimated. The EO dimension adds an additional governance issue: data access and transparency. Storage planning can be improved when regulators and developers use open, traceable geospatial layers for siting, risk assessment and community consultation. Without transparent data governance, EO-enabled planning can reinforce technocratic decision-making rather than participatory energy transition. This finding connects directly to energy justice because communities affected by storage and renewable infrastructure should be able to understand, contest and shape spatial decisions [11].

4.6 Digitalization, AI, IoT and smart-grid integration

Digital technologies link EO data, storage assets and grid operations. IoT sensors, digital twins, AI forecasting and cloud analytics can improve state-of-charge management, predictive maintenance, renewable forecasting, load shifting and grid resilience [15, 18]. At the same time, these technologies

introduce cybersecurity risks, interoperability challenges and data-governance questions. The strongest opportunity is to connect satellite-derived resource and hazard information with operational storage control. For example, weather and cloud forecasts can inform short-term battery dispatch; wildfire, flood and heat-risk layers can influence resilience planning; and urban growth data can inform distribution-level storage placement. Yet the evidence base remains fragmented. Most studies analyze either geospatial planning or operational control, not both.

5 Discussion

The findings reposition energy storage as geospatial infrastructure. In conventional energy-storage reviews, the central question is often which technology is most efficient, cheapest, safest or most mature. This remains important, but it is incomplete. A storage asset becomes valuable only when it is connected to a particular renewable resource, grid node, demand pattern, policy regime and environmental context. EO and GIS provide the spatial evidence needed to make these connections visible. The theoretical model developed in this paper also shows why storage cannot be planned solely through engineering optimization. Socio-technical transition theory explains that energy systems change through interactions between technology, markets, regulations, user behavior and infrastructure [10]. Energy justice adds that the distribution of benefits and burdens matters [11]. EO adds the ability to observe and map environmental and infrastructural conditions at relevant scales. A robust storage-transition framework therefore needs all three: technology, governance and spatial evidence.For Discover Earth Observation, the key scientific contribution is not a new battery chemistry or a new dispatch algorithm. It is the integration of EO-supported spatial decision-making with energy-storage transition research. This is relevant to the journal's scope because storage planning now requires remote sensing, geovisualization, spatial decision support, climate-risk assessment and SDG-aligned infrastructure evaluation. The framework can support studies that combine satellite-derived solar and wind variability, land-use constraints, hazard exposure and storage siting in one reproducible workflow. The review also clarifies why PRISMA and visual evidence mapping strengthen the manuscript. A narrative review can describe storage as important, but it does not show how the literature was selected or where evidence is concentrated. The PRISMA flow diagram makes selection transparent; the thematic distribution chart shows the structure of the corpus; the evidence-readiness heatmap turns qualitative synthesis into a visible decision map; and the IEA storage-capacity chart grounds the topic in a measurable policy challenge.

5.1 Practical and policy implications

For policymakers, the review suggests that storage incentives should be tied to spatial evidence. Subsidies and auctions can prioritize projects that reduce curtailment, improve resilience in hazard-prone areas, support underserved communities and minimize land-use or ecological conflict. Geospatial screening can also make permitting more transparent by identifying exclusion zones, high-suitability zones and community-benefit opportunities before project approval. For grid operators, EO-supported storage planning can improve forecasting and resilience. Satellite and reanalysis data can strengthen

renewable output forecasts; hazard maps can identify vulnerable substations and storage sites; and urban EO data can help distribution utilities locate storage near demand growth. For researchers, the review indicates a need for integrated models that combine EO data, storage sizing, dispatch simulation, lifecycle assessment and justice metrics.

6 Limitations

The review has three limitations. First, the corpus is limited to English-language publications and credible institutional reports from 2018 to 2025, with a small number of earlier foundational works. Second, the review uses qualitative thematic synthesis rather than meta-analysis because the included studies differ widely in method, technology, geography and outcome measures. Third, the PRISMA screening log is based on the manuscript search protocol and reported screening counts; authors should verify the final database export and deduplication file before submission to ensure exact reproducibility. These limitations do not weaken the central conceptual contribution, but they define the boundaries of the claims. The paper does not claim that EO can solve all storage-planning challenges, nor that one storage technology is universally superior. It argues that storage planning becomes more scientifically defensible when spatial evidence, lifecycle assessment, policy design and community considerations are integrated.

7 Future research agenda

Research need	Recommended approach	Expected contribution
EO-storage co-optimization	Combine satellite/reanalysis renewable-resource data with storage sizing and dispatch models	Quantifies how spatial variability changes storage requirements
Climate-risk-aware storage siting	Overlay flood, heat, wildfire, storm and sea-level-rise layers with grid assets	Improves resilience and avoids maladaptation
Lifecycle and circularity mapping	Link material supply, transport distance, recycling access and land-use impacts to storage projects	Prevents narrow cost-only evaluation
Energy justice integration	Use spatial vulnerability, access and community-benefit indicators	Makes storage deployment more equitable
Open geospatial workflows	Publish code, data sources and GIS criteria in supplementary materials	Improves reproducibility and policy trust

Future studies should move from general arguments about storage importance toward reproducible EO-storage workflows. A strong next step would be a case study using satellite-derived solar and wind variability, grid layers, hazard data and land-use constraints to identify storage-suitable zones, followed by storage sizing, lifecycle assessment and policy-scenario analysis. Such a study would directly match the empirical expectations of Earth observation journals.

8 Conclusion

Energy storage is a foundation of renewable-powered energy systems, but it should no longer be treated only as a technology, cost curve or grid asset. It is spatial infrastructure whose success depends on location, climate exposure, renewable-resource variability, grid connection, policy design and social acceptance. Earth observation and geospatial intelligence can make these conditions visible and measurable. This PRISMA-based review identified 25 sources and synthesized them into a geospatial socio-technical transition framework. The findings show that EO can support storage siting, renewable complementarity assessment, hazard-sensitive resilience planning, demand mapping, environmental screening and transparent governance. At the same time, gaps remain in integrated modeling, lifecycle-circularity assessment, justice metrics and open geospatial workflows. The paper concludes that a renewable-powered future requires not only more storage, but better spatially informed storage.

Declarations

Funding: No funding was received for this study.

Competing interests: The author(s) declare no competing financial or non-financial interests.

Ethics approval: Not applicable. This study is a systematic review of published and publicly available secondary sources and does not involve human participants, animals, private data or biological materials.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

Data availability: All data used in this review are derived from published literature and publicly available institutional sources. The search strategy, screening criteria, coding framework and evidence-mapping structure are provided in the appendices. Authors should archive the final screening spreadsheet as supplementary material before submission.

Author contributions: [Author initials] conceptualized the study, conducted the literature search, screened sources, performed thematic coding, prepared figures and wrote the manuscript. All authors reviewed and approved the final manuscript.

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Figures

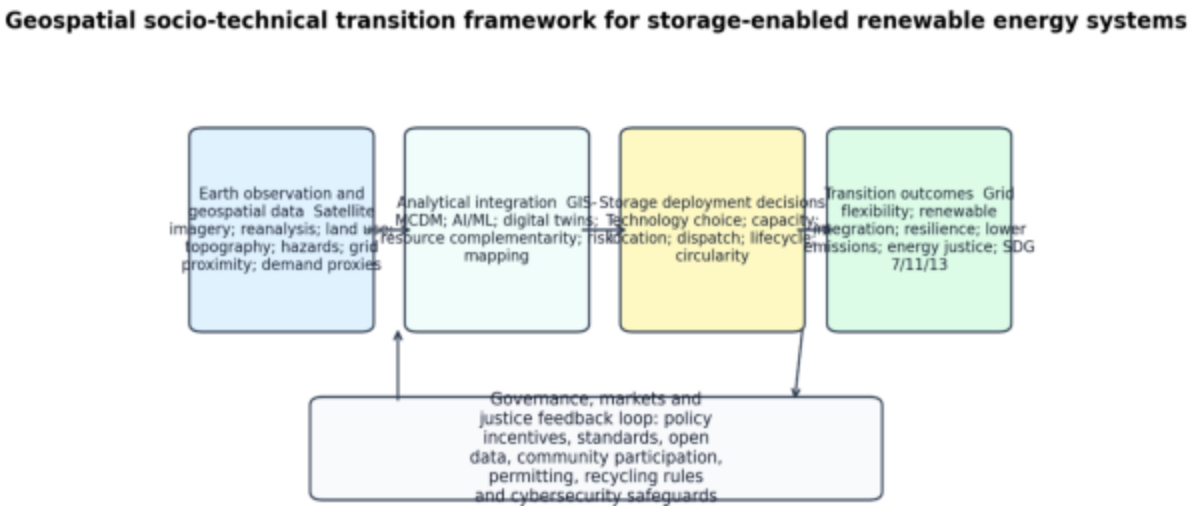


Figure 1

Geospatial socio-technical transition framework for EO-enabled energy storage planning

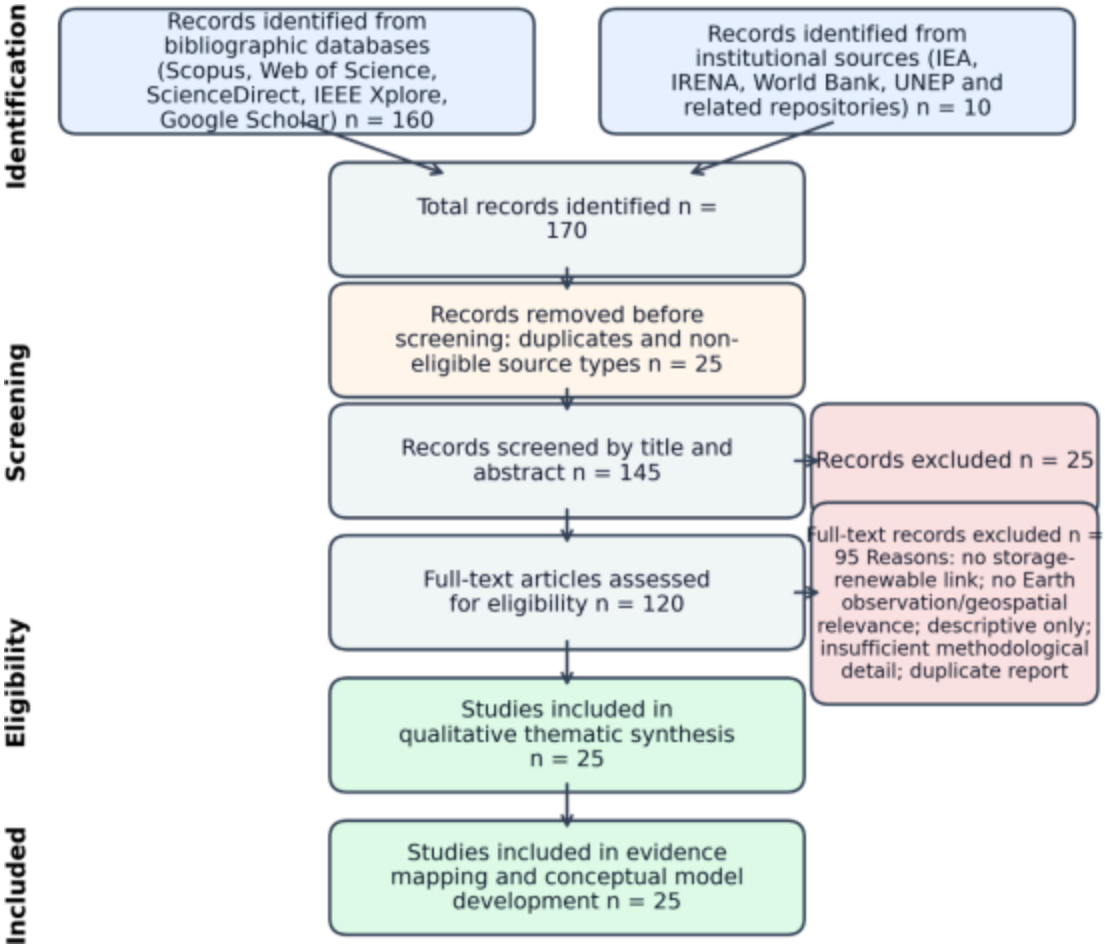


Figure 2

PRISMA flow diagram for study identification, screening, eligibility assessment and inclusion

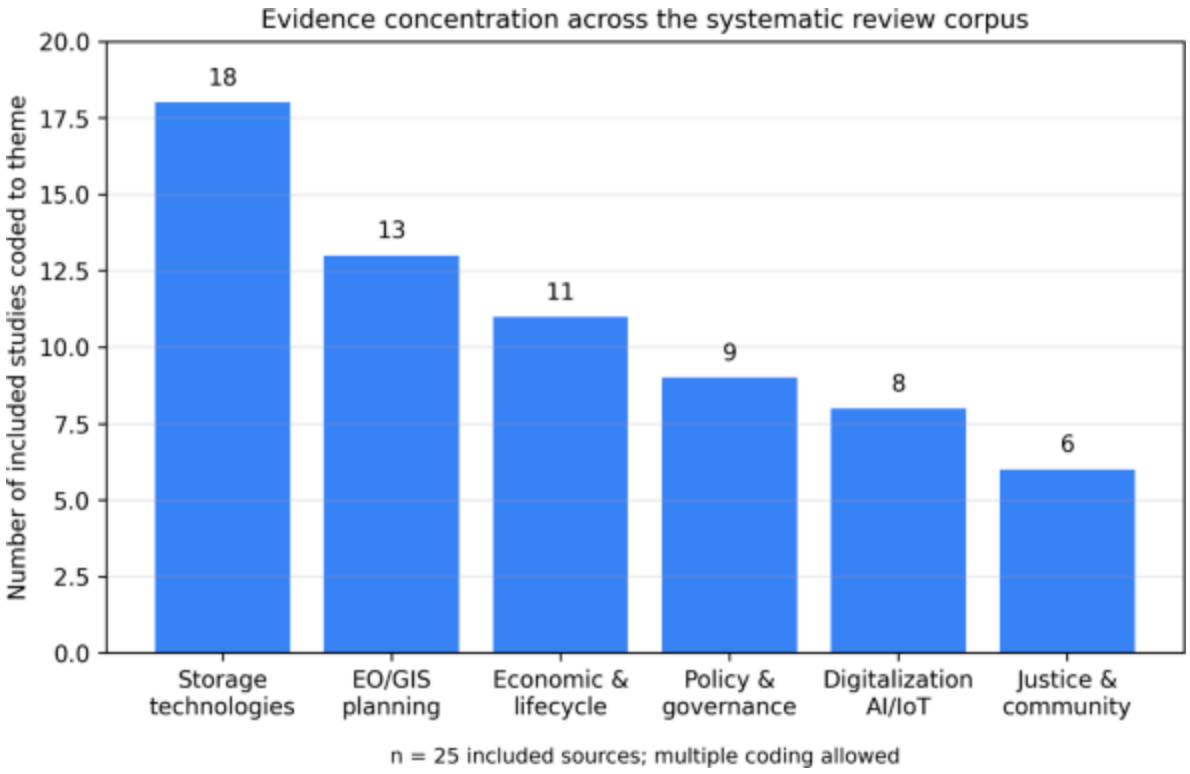


Figure 3

Thematic concentration of the 25-source review corpus; one study could receive more than one code

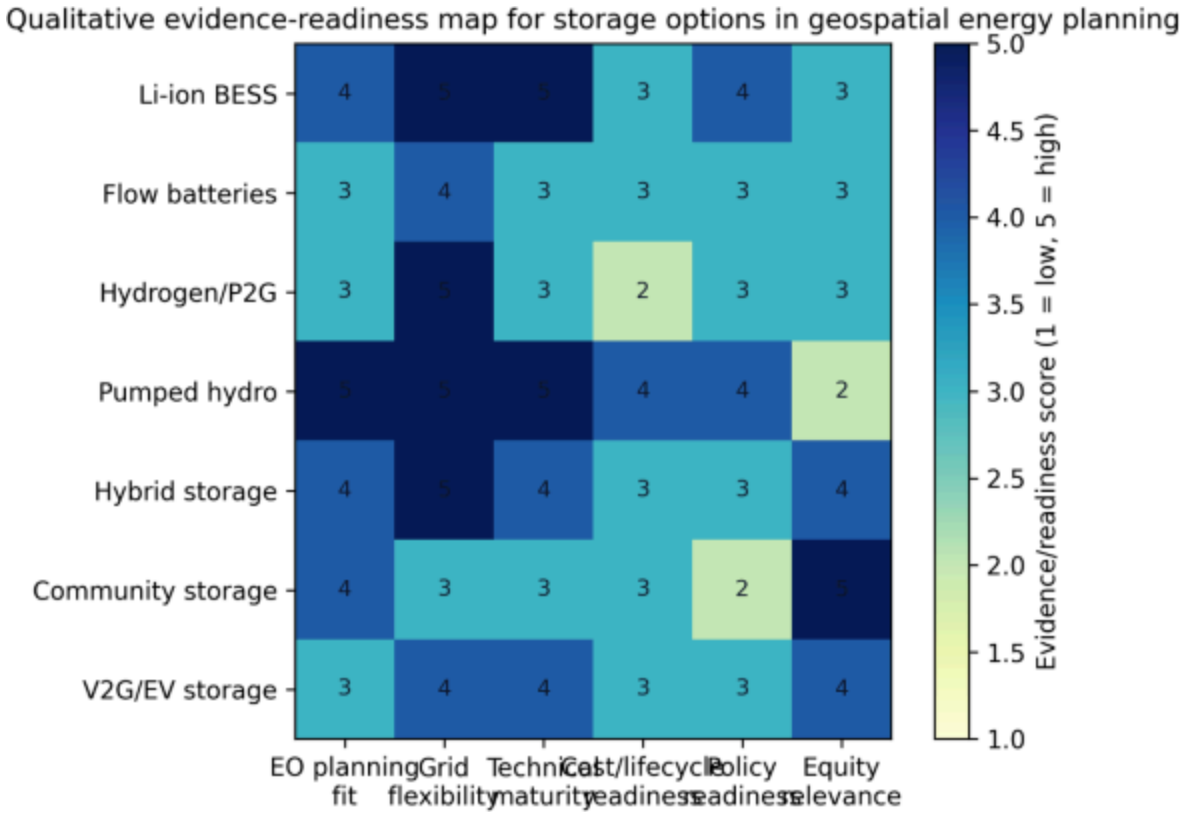


Figure 4

Qualitative evidence-readiness map for storage technologies in geospatial energy planning

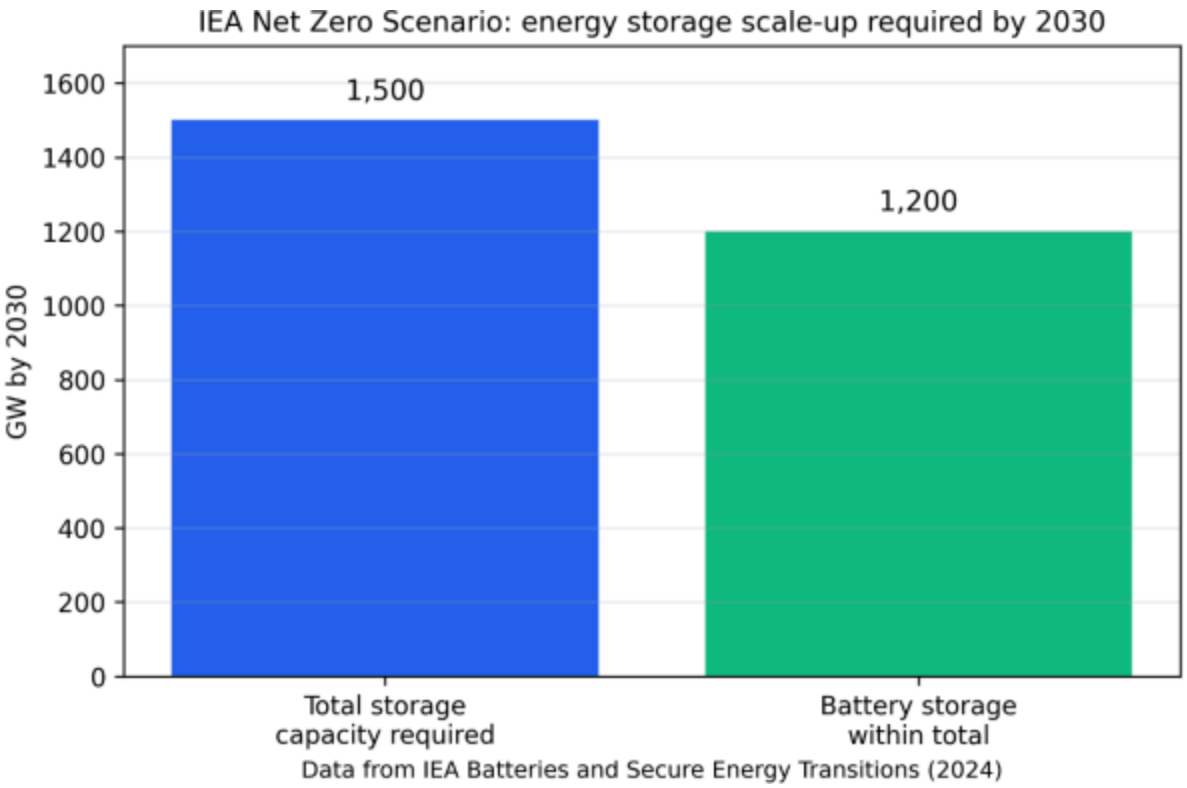


Figure 5

IEA Net Zero Scenario storage capacity requirements by 2030, showing the scale of total storage and battery-storage deployment required

Supplementary Files

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- Appendix.docx