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Geothermal Energy for Resilient Energy Systems: A Systematic Literature Review

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ABSTRACT
This systematic literature review investigates how geothermal energy contributes to energy resilience across electricity, heating, cooling, urban infrastructure, and industrial applications. Guided by PRISMA 2020, the review identified 365 Scopus records using geothermal- and resilience/sustainability-related terms. After filtering English-language journal articles published during 2015–2025 and screening titles, abstracts, full texts, and accessibility, 10 studies were included. Thematic synthesis identified four resilience pathways: dependable baseload and thermal supply; long-term resource stewardship through reinjection and thermal recharge; technological adaptability through ground-source heat pumps, aquifer modelling, hybrid systems, and repurposed wells; and economic-environmental robustness through lower emissions, reduced fuel-price exposure, and infrastructure reuse. Persistent constraints include high upfront costs, geological uncertainty, reservoir degradation, fragmented regulation, and limited social acceptance. Geothermal energy is therefore a strategic resilience asset, but its benefits depend on integrated technical, financial, institutional, and community-governance arrangements.

Keywords:
geothermal energy; energy resilience; energy security; sustainability; systematic literature review

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INTRODUCTION

The transition toward low-carbon energy systems requires technologies that can simultaneously support decarbonization, supply reliability, affordability, and long-term energy security. Geothermal energy is distinctive within the renewable-energy portfolio because subsurface heat can provide electricity and thermal services with limited dependence on daily weather variability. This operating profile enables geothermal facilities to complement variable renewable resources and to reduce exposure to fossil-fuel supply disruptions (Budiono et al., 2022; Liu et al., 2024; Sircar et al., 2022).

Energy resilience extends beyond the simple availability of energy. It concerns the capacity of an energy system to anticipate disturbances, absorb shocks, maintain critical functions, recover from disruption, and adapt to changing environmental, economic, and institutional conditions. Geothermal energy can contribute to these capacities through baseload electricity, direct heat, district heating and cooling, building-scale heat pumps, and hybrid energy systems. Evidence from geothermal-powered district networks indicates that stable local heat resources can strengthen urban energy security while reducing emissions and dependence on imported fuels (Kassem & Moscariello, 2024).

The resilience potential of geothermal energy has expanded through enhanced geothermal systems, closed-loop configurations, improved reservoir management, advanced drilling, and digital monitoring. Enhanced systems can broaden access beyond conventional hydrothermal reservoirs, whereas closed-loop technologies may reduce dependence on reservoir permeability and direct fluid-rock interaction (Budiono et al., 2022; Sircar et al., 2022). Recent reviews further show that expertise from petroleum engineering, well integrity, machine learning, and smart building management can improve project predictability and operational performance (Elshehabi & Alfehaid, 2025; Eze et al., 2025).

These advantages do not eliminate the constraints associated with geothermal development. High upfront capital requirements, exploration risk, long lead times, uncertain subsurface conditions, induced-seismicity concerns, permitting complexity, and limited public acceptance can delay or prevent deployment. The interaction among technical, financial, and socio-political risks means that resilience cannot be achieved through engineering performance alone; effective governance, risk-sharing mechanisms, and community legitimacy are also required (Kassem & Moscariello, 2024; Liu & Lin, 2025).

Indonesia provides a particularly relevant context because it combines substantial geothermal resources with continuing dependence on fossil fuels and growing demand for secure, affordable energy. Empirical evidence indicates that geothermal-energy consumption can contribute to lower carbon dioxide emissions in Indonesia, while transition-oriented research emphasizes the need to address policy, supply-chain, technological, and institutional barriers (Idroes et al., 2024; Yudha et al., 2022). The Indonesian case therefore illustrates how geothermal energy may support both national decarbonization and resilience objectives.

Existing research, however, remains fragmented across reservoir engineering, urban hydrogeology, building systems, environmental performance, adoption determinants, business competitiveness, and energy-transition governance. This fragmentation limits a coherent understanding of the mechanisms through which geothermal utilization strengthens energy resilience. A systematic synthesis is therefore needed to connect technological performance with resource longevity, economic robustness, environmental benefits, and institutional capacity.

Accordingly, this review addresses three research questions: (1) Through which mechanisms does geothermal energy strengthen energy resilience? (2) Which technologies and resource-management practices enable these contributions? and (3) Which barriers and research gaps constrain the resilience value of geothermal development? By answering these questions, the study reframes geothermal energy not merely as a renewable-energy option, but as a multidimensional resilience asset whose performance depends on coordinated technical and governance arrangements.

METHOD

The study employed a systematic literature review guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework. PRISMA was used to structure the identification, screening, eligibility assessment, and reporting of the included evidence (Page et al., 2021a, 2021b). A systematic review was appropriate because geothermal-resilience research spans engineering, environmental science, economics, policy, and urban-energy studies.

Scopus was used as the sole bibliographic database because it provides multidisciplinary coverage and structured metadata for peer-reviewed literature. The search string was: TITLE ("geothermal energy" OR "geothermal power" OR "geothermal resource*") AND TITLE-ABS-KEY (resilience OR sustainability). The search identified 365 records.

Eligibility criteria were specified before the final synthesis. Studies were included when they were (1) written in English, (2) published as journal articles, (3) published between 2015 and 2025, and (4) substantively concerned with geothermal utilization in relation to resilience, sustainability, energy security, low-carbon transition, or long-term system performance. Conference papers, book chapters, non-English publications, items outside the specified period, and papers lacking direct relevance were excluded.

Applying the language, document-type, and publication-year filters reduced the dataset from 365 to 141 articles. The remaining records were screened through titles and abstracts, followed by assessment of article content and full-text accessibility. Studies were retained when they provided explicit evidence on geothermal technologies, resource management, adoption, environmental performance, economic implications, or energy-system resilience. This process produced a final corpus of 10 articles. Figure 1 summarizes the selection pathway.

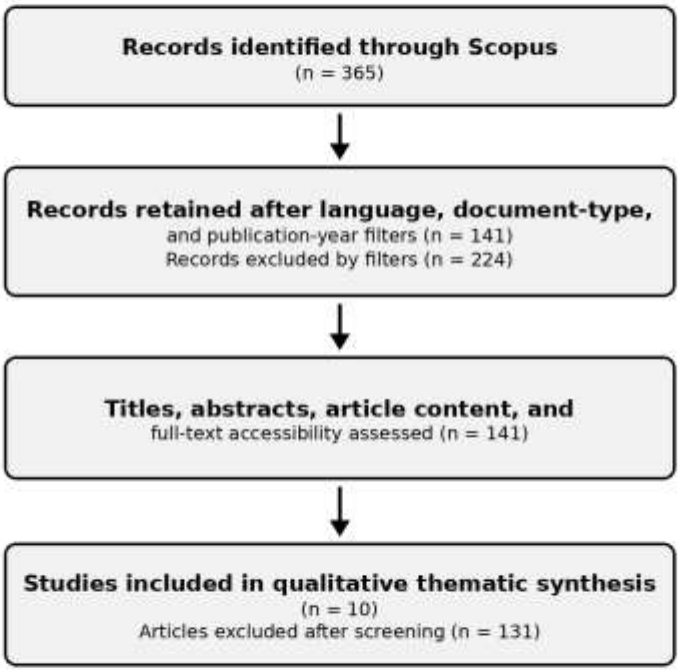

Figure 1. Study selection process based on the available review records.

A structured extraction matrix was used to record authorship, publication year, study context, research design, geothermal application, principal findings, and relevance to resilience or sustainability. Because the included studies used heterogeneous methods, quantitative meta-analysis was not appropriate. The evidence was therefore integrated through qualitative thematic synthesis, which identifies recurring descriptive themes and develops higher-order analytical interpretations across diverse studies (Thomas & Harden, 2008).

Coding was organized around four analytical dimensions: (1) reliability and continuity of energy services; (2) sustainable resource management and adaptive capacity; (3) technological and infrastructural flexibility; and (4) economic and environmental robustness. Institutional and social conditions were treated as cross-cutting enablers because they influence all four dimensions.

The final studies were appraised for topical relevance, clarity of research objective, transparency of method, adequacy of evidence, availability of full text, and direct contribution to the geothermal-resilience discussion. The appraisal was used to support interpretive credibility rather than to calculate a numerical quality score.

Conclusions were drawn only when supported by convergent evidence or clearly identified as context-specific findings.

RESULTS AND DISCUSSION

1. Profile of the Included Studies

The 10 included studies covered macroeconomic analysis, cross-country sustainability assessment, firm-level adoption, decision modelling, hydrogeological simulation, building-energy modelling, plant-level environmental assessment, reservoir-management analysis, infrastructure repurposing, and borehole heat-exchanger modelling. This methodological diversity demonstrates that geothermal resilience is not a single technical outcome. Instead, it emerges from interactions among energy continuity, resource stewardship, infrastructure adaptability, environmental performance, economic feasibility, and institutional support.

Table 1. Characteristics and resilience contributions of the included studies

Study	Context	Method	Application	Principal resilience contribution
Idroes et al. (2024)	Indonesia; national energy consumption	FMOLS/DOLS and causality analysis	Geothermal consumption and carbon emissions	Geothermal consumption reduced CO_2 emissions and supported carbon-neutrality policy.
Berta and Taddia (2024)	Urban aquifer, Torino, Italy	Geological and hydrogeological modelling	Open-loop geothermal district heating	Aquifer modelling supports reliable urban heat supply and sustainable groundwater use.
Li et al. (2024)	Onshore abandoned oil and gas wells	Integrated sustainability assessment	Repurposed wells for geothermal power	Infrastructure reuse can reduce drilling, environmental burdens, and development costs.
Alam et al. (2024)	Emerging-economy national grid	Delphi, fuzzy TISM, and fuzzy MICMAC	Adoption determinants	Investment, employment, affordable renewable energy, and policy support drive adoption.
Aljundi et al. (2024)	University building, Aveiro, Portugal	Monitoring and calibrated EnergyPlus simulation	Shallow geothermal building system	The system reduced heating/cooling energy use and lifecycle CO_2 emissions.
Wang and Alsaleh (2023)	European countries	Cross-country empirical analysis	Geothermal power sustainability	Innovation, governance, market efficiency, and investment conditions shape sustainable development.
Bruscoli et al. (2015)	Flash geothermal plant, Italy	Plant-level environmental and process assessment	Complete reinjection and hybrid configuration	Reinjection lowers atmospheric emissions but may involve output trade-offs.
Doğdu and Çelmen (2023)	Geothermal fields, Türkiye	Technical assessment of reinjection and well siting	Reservoir pressure and fluid management	Balanced production and reinjection protect long-term reservoir productivity.
Arcuri et al. (2025)	Italian business sector	Firm-level empirical analysis	Business adoption of geothermal energy	Use was associated with lower costs, lower emissions, and stronger competitiveness.
Receveur et al. (2024)	Vertical borehole heat exchangers, UK	Analytical and numerical heat-balance modelling	Shallow geothermal resource sustainability	Seasonal heat reinjection is needed to limit depletion and user interference.

Note. FMOLS = fully modified ordinary least squares; DOLS = dynamic ordinary least squares; TISM = total interpretive structural modelling; MICMAC = cross-impact matrix multiplication applied to classification.

2. Reliability and Continuity of Energy Services

The most consistent resilience contribution identified in the literature is the capacity of geothermal systems to provide stable electricity or heat. Cross-country evidence indicates that geothermal development can support sustainable power systems when it is reinforced by innovation, competitive markets, effective governance, and investment capacity (Wang & Alsaleh, 2023). At the organizational level, geothermal adoption can reduce exposure to energy-price volatility and improve energy security, operating costs, and environmental performance (Arcuri et al., 2025).

The same mechanism is visible at urban and building scales. Open-loop groundwater systems can support district heating when aquifer characteristics and groundwater flows are properly modelled (Berta & Taddia, 2024). Shallow geothermal systems can also maintain thermal services while substantially reducing heating and cooling demand relative to conventional configurations (Aljundi et al., 2024). These applications distribute resilience across multiple scales: power systems gain dependable generation, cities gain locally anchored thermal networks, and buildings gain efficient year-round heating and cooling.

Reliability should nevertheless be interpreted as a system property rather than an inherent and unconditional feature of the resource. A geothermal installation can provide continuous service only when wells, reservoirs, pumps, heat exchangers, and supporting networks remain technically and financially operable. Thus, dependable supply is the visible outcome of sustained resource management, preventive maintenance, adequate finance, and institutional competence.

3. Sustainable Resource Management and Adaptive Capacity

Long-term resilience depends on maintaining the pressure, temperature, and chemical condition of geothermal resources. Reinjection is central to this objective because it returns produced fluids to the subsurface, supports reservoir pressure, limits disposal impacts, and can extend productive life. Evidence from Türkiye shows that reinjection-well placement and the balance between production and reinjection are critical for avoiding pressure decline, cooling, subsidence, and loss of productivity (Doğdu & Çelmen, 2023).

Environmental control and resource longevity are closely connected. In flash geothermal plants, complete reinjection of fluids and non-condensable gases can reduce emissions of carbon dioxide, hydrogen sulfide, and mercury, although environmental gains may involve trade-offs with net power output (Bruscoli et al., 2015). This finding demonstrates that resilience decisions may require balancing short-term production with long-term environmental and social performance.

Shallow geothermal resources present a related thermal-balance challenge. Modelling of vertical borehole heat exchangers in the United Kingdom shows that natural geothermal, solar, and radiogenic recharge may replace only a small fraction of annual heat extraction under heat-only operation. Seasonal reinjection, borehole thermal-energy storage, solar-thermal integration, or waste-heat recovery may therefore be required to prevent long-term thermal depletion and interference among neighbouring users (Receveur et al., 2024).

Urban open-loop systems similarly require adaptive monitoring of groundwater levels, flow paths, temperature plumes, and water quality (Berta & Taddia, 2024). Across deep and shallow applications, the common principle is that renewable classification does not automatically guarantee sustainable operation. Resilience depends on extraction rates that remain compatible with hydraulic and thermal recovery, supported by monitoring and corrective management.

4. Technological Innovation and Infrastructural Flexibility

Technological innovation expands both the geography and the functional scope of geothermal energy. One of the clearest examples is the repurposing of abandoned oil and gas wells. Integrated sustainability assessment indicates that reuse of existing wells can reduce drilling requirements, land disturbance, material consumption, and development costs while creating a productive use for legacy infrastructure (Li et al., 2024). This circular-economy pathway can accelerate deployment and lower entry barriers, although well integrity and site-specific thermal performance remain essential.

Digital and numerical tools also improve resilience by reducing uncertainty before and during operation. Hydrogeological modelling can identify sustainable abstraction and reinjection configurations for urban aquifers (Berta & Taddia, 2024), while calibrated building-energy models can assess performance under different climates and operating scenarios (Aljundi et al., 2024). Injectivity testing, tracer analysis, pressure monitoring, and chemical surveillance support adaptive reservoir management and early detection of performance decline (Doğdu & Çelmen, 2023).

Hybridization further strengthens flexibility. Flash-Organic Rankine Cycle configurations, thermal storage, solar-assisted recharge, waste-heat integration, and multi-source heating networks can increase useful-energy recovery or compensate for resource imbalances (Bruscoli et al., 2015; Receveur et al., 2024). The broader literature likewise identifies hybrid geothermal systems and smart controls as important pathways for integrating geothermal energy with variable renewables and building-management systems (Eze et al., 2025; Liu et al., 2024).

5. Economic, Environmental, and Institutional Dimensions

Geothermal energy contributes to environmental resilience by lowering greenhouse-gas emissions and reducing dependence on carbon-intensive fuels. In Indonesia, geothermal-energy consumption was associated with lower carbon dioxide emissions in long-run econometric estimates, and causality tests indicated that changes in geothermal consumption preceded changes in emissions (Idroes et al., 2024). Plant-level and building-level studies likewise report emissions reductions through advanced reinjection and lower heating and cooling demand (Aljundi et al., 2024; Bruscoli et al., 2015).

Economic resilience arises from more predictable operating costs, reduced fuel-price exposure, and the reuse of existing assets. Italian business-sector evidence associates greater geothermal use with lower energy expenditure and improved competitiveness (Arcuri et al., 2025), while repurposed wells can reduce the capital and environmental burdens of new drilling (Li et al., 2024). These advantages are strategically important for organizations and countries exposed to imported-fuel volatility.

High upfront expenditure remains the most persistent economic barrier. Exploration, drilling, well completion, and network construction concentrate risk before revenue is generated. Cross-country evidence suggests that innovation systems, governance quality, market efficiency, and investment conditions influence whether geothermal potential becomes sustainable capacity (Wang & Alsaleh, 2023). In emerging economies, decision-modelling research further identifies investment and employment opportunities, affordable renewable supply, stakeholder participation, and supportive policy as central adoption drivers (Alam et al., 2024).

Institutional and social capacity therefore operate as cross-cutting resilience conditions. Clear permitting, credible monitoring, transparent risk communication, community participation, and appropriate financial instruments are needed to convert technical potential into durable public value. Without these arrangements, projects may remain vulnerable to delay, opposition, financing failure, or weak operational oversight even when the underlying resource is technically attractive.

6. Integrated Geothermal-Resilience Framework

The evidence supports an integrated interpretation in which geothermal energy strengthens resilience through four mutually dependent pathways. First, stable generation and thermal output support continuity of essential services. Second, reinjection, recharge, and monitoring protect resource productivity over time. Third, modelling, hybridization, shallow systems, and infrastructure reuse improve adaptability and scalability. Fourth, emissions reduction, cost stability, and lower fuel dependence strengthen environmental and economic robustness.

These pathways are connected rather than additive. Reliable output cannot persist without resource stewardship; technological innovation cannot scale without financing and regulation; and low emissions do not guarantee legitimacy without transparent environmental safeguards. The resilience value of geothermal energy is therefore best understood as a socio-technical outcome created through alignment among subsurface science, engineering design, financial capacity, policy consistency, and community governance.

Table 2. Integrated dimensions of geothermal energy resilience

Dimension	Resilience mechanism	Enabling practices	Principal risks
Supply continuity	Stable electricity, heating, and cooling	Baseload generation; district networks; GSHPs	Equipment failure; network constraints; financing gaps
Resource longevity	Maintaining pressure, temperature, and recharge	Fluid reinjection; thermal recharge; continuous monitoring	Cooling, depletion, subsidence, contamination
Technological adaptability	Expanding usable resources and operating flexibility	Hybrid systems; modelling; digital controls; repurposed wells	Well integrity; modelling uncertainty; technical capacity
Economic-environmental robustness	Lower emissions, fuel dependence, and cost volatility	Efficient operation; infrastructure reuse; lifecycle management	High upfront cost; uncertain returns; externalities
Cross-cutting governance	Coordinating risk, legitimacy, and investment	Clear regulation; risk sharing; stakeholder participation	Permitting delays; weak institutions; social opposition

7. Research Gaps and Future Directions

First, long-term empirical evidence remains limited. Many studies rely on individual projects, specific aquifers, particular reservoirs, or national contexts. Comparative monitoring across different geological conditions is needed to establish optimal reinjection ratios, sustainable extraction limits, thermal-recharge requirements, and reliable indicators of reservoir recovery.

Second, geothermal integration with other renewable and storage technologies requires more systematic evaluation. Hybrid geothermal-solar systems, geothermal-supported district networks, thermal-energy storage, industrial waste-heat recovery, and flexible sector coupling should be assessed using common technical, economic, and resilience metrics.

Third, evidence from developing countries remains comparatively scarce despite substantial untapped resources. Future research should compare financing constraints, local supply chains, institutional capacity, ownership models, and regulatory performance across developed and emerging economies. Innovative de-risking instruments, public-private investment structures, and insurance mechanisms deserve particular attention.

Fourth, social acceptance and distributive outcomes require deeper investigation. Research should evaluate how induced-seismicity concerns, groundwater risks, land use, benefit sharing, and community participation influence project legitimacy. Transparent monitoring and participatory decision-making should be studied as operational components of resilience rather than as peripheral communication activities.

Finally, standardized geothermal-resilience indicators are needed. A common framework should combine availability, recovery time, resource longevity, lifecycle emissions, affordability, exposure to external fuel markets, adaptive capacity, governance quality, and social legitimacy. Such indicators would improve cross-study comparison and support evidence-based project selection.

8. Review Limitations

This review has several limitations. It used Scopus as the sole database, restricted the search to English-language journal articles, and required geothermal terminology in the title. Relevant studies indexed elsewhere or using different terminology may therefore have been omitted. The final corpus of 10 studies was methodologically heterogeneous, which prevented statistical meta-analysis. In addition, the available selection records did not permit a detailed numerical breakdown of every full-text exclusion reason. The findings should consequently be interpreted as a structured thematic synthesis rather than a comprehensive estimate of effect size.

CONCLUSION

This systematic literature review demonstrates that geothermal energy can strengthen energy resilience through dependable electricity and heat supply, long-term resource stewardship, technological and infrastructural adaptability, and economic-environmental robustness. The 10 included studies show that reinjection, aquifer and reservoir modelling, ground-source heat pumps, borehole heat exchangers, hybrid systems, and the repurposing of abandoned wells can extend geothermal applications while reducing emissions and exposure to fossil-fuel volatility.

The central contribution of the review is to show that geothermal resilience is not produced by resource availability alone. It is a socio-technical achievement that depends on aligning subsurface management, engineering reliability, investment capacity, regulatory quality, and community legitimacy. High upfront costs, geological uncertainty, reservoir degradation, fragmented policy, and limited social acceptance remain significant constraints. Future research should develop standardized resilience indicators, expand long-term comparative monitoring, evaluate hybrid renewable configurations, and test financing and governance models in both developed and developing economies.

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