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Geothermal Energy and Public Health: Opportunities, Risks, and Emerging Research Directions

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ABSTRACT

Geothermal energy stands at a pivotal moment in its development trajectory, with installed global capacity rising steadily, an expanding pipeline of enhanced and next-generation geothermal systems, and growing recognition of the technology's potential contribution to global decarbonization and public health goals. A complete public health assessment of this expansion, however, requires weighing genuine and substantial opportunities—reduced air pollution relative to fossil fuel alternatives, reliable baseload power supporting broader health-relevant development outcomes—against a persistent, only partially resolved set of health and environmental risks, together with a rapidly evolving technical research frontier that is actively reshaping the field's risk profile. This article synthesizes recent systematic reviews on geothermal energy risk and opportunity, chronic and community health epidemiology, and emerging enhanced geothermal systems research, to characterize the current state and future trajectory of geothermal energy's public health implications. It draws on subsurface reactive transport modeling and reactive heat exchanger engineering relevant to long-term geothermal reservoir performance, machine learning-enhanced geomechanical characterization relevant to induced seismicity and wellbore stability risk, and heterogeneous reservoir management principles from analogous subsurface energy operations, and further considers how AI-driven precision public health, predictive analytics, and economic impact assessment frameworks developed for national healthcare systems could inform emerging public health research directions for the geothermal sector. The article concludes by identifying priority research gaps at the intersection of next-generation geothermal technology and public health, and proposes a forward-looking research agenda for the field.

Introduction

Geothermal energy occupies an increasingly prominent position within global clean energy strategy, offering reliable, dispatchable baseload generation with a substantially lower lifecycle carbon footprint than fossil fuel alternatives. The field is simultaneously undergoing rapid technical evolution, with enhanced geothermal systems (EGS) advancing from demonstration toward commercial-scale deployment, next-generation geothermal technologies extending resource access beyond traditional hydrothermal settings, and a growing global research output reflecting intensifying academic and policy interest in the technology's potential. This technical evolution carries direct implications for public health assessment: the risk profile associated with next-generation geothermal systems differs in important respects from that of conventional hydrothermal power plants, even as many of the field's foundational public health questions—chiefly, chronic hydrogen sulfide exposure among nearby communities—remain incompletely resolved.

A forward-looking public health perspective on geothermal energy must therefore hold two things in view simultaneously: the substantial and well-documented opportunities that geothermal energy offers relative to

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continued fossil fuel reliance, including meaningfully reduced emissions of the air pollutants most directly implicated in cardiovascular and respiratory disease, and the persistent, evolving risk landscape that recent systematic reviews continue to identify as requiring further research and mitigation attention, spanning induced seismicity, groundwater contamination potential, and the chronic, low-level chemical exposure pathways that have proven difficult to characterize with precision even after decades of epidemiological study.

This article synthesizes recent research on the opportunities, risks, and emerging research directions at the intersection of geothermal energy and public health, integrating recent systematic literature reviews on geothermal energy risk (Kassem et al., 2025) and geothermal energy's sustainability opportunities (Nkinyam et al., 2025) with the community health epidemiology evidence base (Bustaffa et al., 2020; Nuvolone et al., 2019; Stoppa et al., 2023) and quantitative environmental risk assessment frameworks (Chen et al., 2020). It draws on subsurface reactive transport modeling relevant to long-term geothermal reservoir fluid chemistry evolution, reactive heat exchanger engineering relevant to enhanced geothermal energy recovery, machine learning-enhanced geomechanical characterization relevant to induced seismicity and wellbore stability risk, and heterogeneous reservoir management principles from analogous subsurface energy operations, and further considers how AI-driven precision public health, predictive analytics, and economic impact assessment frameworks developed for national healthcare systems (Nguyen, 2026a, 2026c, 2026d) could inform emerging public health research directions for the geothermal sector. The objective is to provide a forward-looking synthesis for researchers, industry practitioners, and policymakers navigating geothermal energy's rapidly evolving opportunity and risk landscape.

Opportunities: Public Health Co-Benefits of Geothermal Energy Expansion

Emissions Reduction as a Public Health Opportunity

The principal public health opportunity associated with geothermal energy expansion lies in its capacity to displace fossil fuel-based generation and its associated emissions of sulfur oxides, nitrogen oxides, particulates, and other air pollutants directly implicated in cardiovascular and respiratory disease. Nkinyam et al. (2025) conducted a systematic review characterizing geothermal energy as a sustainable energy source with substantial untapped potential, noting that despite currently accounting for a small fraction of global energy contribution, installed geothermal generation capacity has grown substantially over the past decade and a half, with more than thirty countries actively developing geothermal resources—a growth trajectory that, to the extent it displaces fossil fuel generation, carries meaningful public health co-benefits through reduced population-level air pollution exposure.

Reliability as a Development and Health-Relevant Opportunity

Beyond direct emissions displacement, geothermal energy's capacity to provide continuous, weather-independent baseload power represents a distinct opportunity with indirect but genuine public health relevance, particularly in developing regions where reliable electricity access supports health-relevant infrastructure including refrigeration for medical supplies, water treatment and pumping, and healthcare facility operations. This development-oriented framing of geothermal energy's public health opportunity complements, without substituting for, the direct emissions-reduction case, and is particularly salient in rapidly developing geothermal markets where energy access itself constitutes a public health priority.

Emerging Technology Expanding the Opportunity Space

The technical evolution toward enhanced and next-generation geothermal systems is expanding the geographic and geologic scope within which these public health opportunities can be realized, extending viable geothermal resource access beyond the traditionally favorable volcanic and tectonically active regions that have historically hosted geothermal development toward a substantially broader range of geologic settings, thereby extending the potential public health co-benefits of geothermal energy expansion to a correspondingly broader range of communities and regions.

Risks: A Systematic View of the Evolving Risk Landscape

Systematic Characterization of Geothermal Project Risk

Kassem et al. (2025) conducted a systematic literature review explicitly focused on navigating risk in geothermal energy projects, synthesizing the accumulated evidence on the technical, financial, environmental, and social risk dimensions that geothermal developers and communities must navigate across the project lifecycle; this systematic risk characterization complements the more narrowly health-focused epidemiological literature by situating chemical exposure and geomechanical risk within the broader risk landscape that shapes how, where, and how safely geothermal projects are ultimately developed and operated.

Chronic Chemical Exposure Risk Remains Unresolved

Despite the systematic risk assessment progress reflected in reviews such as Kassem et al. (2025), the foundational public health risk question of chronic, low-level hydrogen sulfide exposure among communities near geothermal facilities remains genuinely unresolved. Bustaffa et al. (2020) documented substantial inconsistency across the accumulated epidemiological evidence from New Zealand, Iceland, and Italy, while Nuvolone et al. (2019) and Stoppa et al. (2023) extended methodologically rigorous chronic cohort and objective spirometric evidence from the Mt. Amiata geothermal district without resolving this underlying inconsistency, with the latter study notably failing to confirm an association between exposure and chronic obstructive pulmonary disease despite its comparatively strong study design.

Geomechanical and Seismic Risk

Chen et al. (2020) formally incorporated seismic hazard alongside human health, ecological damage, and economic loss within a quantitative environmental risk assessment framework for geothermal energy, reflecting the field's growing recognition that induced seismicity constitutes a distinct, quantifiable risk category meriting dedicated assessment methodology—a recognition of particular importance for enhanced geothermal systems, where the hydraulic stimulation techniques used to create or enhance reservoir permeability have been directly associated with induced seismic events in several documented projects, motivating substantial research attention toward risk mitigation strategies specific to this emerging technology class.

Risk Evolution with Next-Generation Technology

Because enhanced and next-generation geothermal systems involve engineering interventions—hydraulic and thermal stimulation, deeper drilling, novel working fluids in some configurations—not present in conventional hydrothermal power generation, the risk landscape characterized by earlier public health and environmental assessments of conventional geothermal technology cannot be assumed to transfer unmodified to these emerging system types, underscoring the importance of the systematic, technology-specific risk characterization that Kassem et al. (2025) and related emerging literature provide.

Subsurface Science as a Foundation for Risk-Informed Opportunity Realization

Reactive Transport Modeling for Long-Term Fluid Chemistry Forecasting

Numerical modeling of reactive transport processes in geothermal reservoirs provides a scientific basis for forecasting how reservoir fluid chemistry, including the hydrogen sulfide and trace element concentrations relevant to community exposure risk, may evolve over a geothermal facility's multi-decade operational lifetime, offering a mechanistically grounded complement to the retrospective, empirical epidemiological evidence that has historically dominated efforts to characterize geothermal energy's chemical exposure risk.

Reactive Heat Exchanger Engineering for Enhanced Recovery

The development of reactive heat exchangers for enhanced geothermal energy recovery illustrates how coupled thermal and geochemical processes can be engineered and optimized at the wellbore scale to improve energy extraction efficiency, a class of engineering advance directly relevant to the emerging enhanced geothermal systems research frontier and to the broader opportunity of extending geothermal energy's public health co-benefits to a wider range of geologic settings through improved recovery technology.

Machine Learning-Enhanced Geomechanical Characterization for Proactive Seismic Risk Management

Machine learning-enhanced geomechanical characterization and wellbore stability assessment methodologies, integrating stress field estimation, rock strength prediction, and operational parameter analysis into a proactive risk-management workflow, have been demonstrated in offshore energy reservoir settings as a means of anticipating and managing geomechanical instability before it manifests as an operational or safety incident. Extending such proactive, data-driven geomechanical characterization approaches to enhanced geothermal systems, where induced seismicity risk is particularly consequential, represents an important emerging research direction directly responsive to the risk dimension that Chen et al. (2020) and Kassem et al. (2025) both identify as a priority concern.

Heterogeneous Reservoir Management for Risk-Aware Development

Principles of heterogeneous subsurface reservoir management developed in analogous energy contexts, including the optimization of fluid injection strategies to manage pressure distribution and containment risk in heterogeneous depleted gas reservoirs, offer transferable methodological insight for geothermal reservoir management in structurally complex geologic settings, supporting the broader emerging research goal of extending geothermal development into a wider range of geologic conditions without proportionally increasing geomechanical or chemical exposure risk.

Emerging Research Directions at the Intersection of AI and Public Health

Precision Public Health for Resolving Persistent Exposure Uncertainty

National-scale AI frameworks developed for precision public health illustrate how predictive analytics can integrate diverse individual-level data streams to support continuously updated, individually informed risk assessment rather than relying on periodic, population-wide screening alone (Nguyen, 2026a). Applying this precision public health paradigm to the persistent, unresolved chronic hydrogen sulfide exposure question documented across the Mt. Amiata research program represents a promising emerging research direction, potentially enabling the individually resolved exposure assessment that Bustaffa et al. (2020) identify as the central methodological limitation constraining the field's ability to draw confident conclusions from decades of accumulated epidemiological research.

Predictive Analytics for Emerging Technology Risk Stratification

National-scale predictive analytics frameworks applied to Medicare and Medicaid populations demonstrate how AI-driven risk stratification can identify high-risk populations for targeted follow-up from large, heterogeneous datasets (Nguyen, 2026d). An analogous predictive analytics approach, applied to the emerging enhanced geothermal systems risk landscape characterized by Kassem et al. (2025), could support risk-informed siting and monitoring resource allocation decisions as these technologies scale into new geologic and geographic settings, directing limited monitoring resources toward the specific projects and communities facing the highest predicted combined risk.

Economic Justification for Emerging Research Investment

Economic impact analyses of AI adoption in healthcare, quantifying national-scale cost savings and productivity gains attributable to AI-driven predictive modeling, offer a template for constructing the economic case for investing in the emerging public health research directions outlined in this article (Nguyen, 2026c). As geothermal energy's public health opportunity case rests substantially on its comparative advantage over fossil fuel alternatives, demonstrating that proportionate investment in resolving persistent risk uncertainties and characterizing emerging technology risk profiles is itself economically justified reinforces, rather than undermines, the broader public health case for continued geothermal energy expansion.

Challenges and Limitations

Despite an actively evolving research landscape, several challenges continue to constrain a fully resolved public health assessment of geothermal energy.

Persistent chronic exposure uncertainty despite methodological advances. Even the most methodologically sophisticated available evidence, combining chronic cohort, case-crossover, and objective physiological study designs from the Mt. Amiata research program, has not resolved the fundamental question of whether and to what degree chronic, low-level hydrogen sulfide exposure affects community health outcomes, a persistent gap that systematic risk reviews such as Kassem et al. (2025) implicitly acknowledge remains unaddressed.

Uncertain transferability of conventional risk evidence to emerging technologies. Much of the available public health evidence base was generated in the context of conventional hydrothermal power generation, and the extent to which this evidence transfers to enhanced and next-generation geothermal systems—which involve materially different subsurface engineering interventions—remains an open and actively developing research question.

Underutilization of mechanistic subsurface science in public health assessment. Reactive transport and reactive heat exchanger modeling capable of forecasting long-term reservoir fluid chemistry evolution (Williams, 2023, 2024) and machine learning-enhanced geomechanical characterization capable of anticipating induced seismicity risk remain largely disconnected from applied public health risk assessment practice, representing a substantial and currently underexploited opportunity for mechanistically grounded, forward-looking risk characterization.

Fragmented integration of opportunity and risk assessment. Systematic reviews addressing geothermal energy's sustainability opportunities (Nkinyam et al., 2025) and systematic reviews addressing its project risk landscape (Kassem et al., 2025) have largely developed as separate literatures, complicating the kind of integrated, net-assessment public health perspective that policymakers and communities ultimately require to weigh geothermal energy's benefits against its risks in a single coherent framework.

Rapidly evolving technology outpacing assessment methodology. The pace of technical innovation in enhanced and next-generation geothermal systems is such that public health and environmental risk assessment methodology risks perpetually lagging behind the technology it is meant to evaluate, a structural challenge common to emerging energy technologies more broadly but particularly acute given geothermal energy's currently accelerating research and deployment trajectory.

Future Directions

Future research should prioritize the direct integration of systematic opportunity assessment (Nkinyam et al., 2025) and systematic risk assessment (Kassem et al., 2025) methodologies into a single, coherent net public health assessment framework capable of supporting genuinely balanced policy and community decision-making, rather than allowing these complementary literatures to continue developing along largely separate tracks. Extending rigorous, multi-design epidemiological research—of the kind exemplified by the Mt. Amiata program (Nuvolone et al., 2019; Stoppa et al., 2023)—explicitly to enhanced and next-generation geothermal system deployments represents a priority research direction given the uncertain transferability of conventional geothermal health evidence to these emerging technology classes.

Integrating reactive transport and reactive heat exchanger modeling of long-term geothermal reservoir performance and fluid chemistry evolution (Williams, 2023, 2024) and machine learning-enhanced geomechanical characterization of induced seismicity and ground stability risk directly into applied public health and environmental risk assessment practice represents a promising avenue for developing genuinely forward-looking, technology-adaptive risk characterization capable of keeping pace with the field's rapid technical evolution. Finally, adapting AI-driven precision public health, predictive analytics, and economic impact assessment frameworks developed for national healthcare systems (Nguyen, 2026a, 2026c, 2026d) toward resolving persistent chronic exposure uncertainty and stratifying emerging technology risk offers a concrete, near-term research direction capable of meaningfully advancing the field's public health evidence base.

Conclusion

Geothermal energy's relationship to public health is best understood not as a settled question but as an actively evolving assessment challenge, shaped simultaneously by substantial and genuine emissions-reduction and development-relevant opportunities, a persistent and only partially resolved chronic chemical exposure risk profile, growing formal recognition of geomechanical and seismic risk dimensions, and a rapidly advancing technical research frontier that is actively reshaping the field's risk landscape even as foundational questions about conventional geothermal technology remain open. Systematic reviews characterizing both geothermal energy's sustainability opportunities and its project risk landscape have advanced considerably in recent years, yet these complementary literatures have not yet been integrated into the kind of coherent, net public health assessment framework that policymakers and communities ultimately require. Subsurface reactive transport and reactive heat exchanger modeling, machine learning-enhanced geomechanical characterization, and AI-driven precision public health and predictive analytics frameworks developed for national healthcare systems together offer a mechanistically grounded, forward-looking pathway for closing this integration gap and for resolving the persistent chronic exposure uncertainty that has constrained confident public health conclusions for decades. Advancing this field will require sustained investment in integrated opportunity-risk assessment methodology, technology-specific public health evidence for enhanced and next-generation geothermal systems, and AI-driven surveillance capacity capable of keeping pace with a rapidly evolving and expanding global geothermal energy sector.

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