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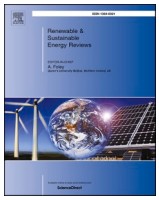

Culture in geothermal energy research: A systematic literature review

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ABSTRACT

Culture is increasingly recognised as shaping public perceptions of energy technologies, yet its role in geothermal energy development remains poorly understood. This systematic review examines how culture is conceptualised, operationalised and studied in geothermal energy research to understand its influence on public perceptions and project development. Two research questions guide the structure of the review: how culture is defined, delineated and studied in geothermal energy contexts, and what empirical insights exist regarding culture's influence on public perceptions. Analysis of 29 peer-reviewed papers shows that culture is broadly described rather than analytically operationalised, with limited definitional consensus. Through thematic analysis, the empirical papers reveal two pathways through which culture shapes perceptions of geothermal projects. The culture-driven pathway highlights how pre-existing cultural frameworks shape perceptions through experiences of the underground, place-based identities, governance traditions, and historical experiences. The project-driven pathway illustrates how geothermal developments impact and transform culture through identity erosion, new cultural practices, and trade-offs between economic benefits and cultural preservation. The findings challenge the view that culture is a barrier, demonstrating that it can support energy transitions. Critical research gaps include the need for systematic frameworks to measure local culture, a cross-regional comparison of the influence of local culture on communities' perceptions of energy projects and how project developers' cultural assumptions shape energy projects. These insights can inform culturally sensitive community engagement for just energy transitions.

1. Introduction

When communities face the introduction of complex or unfamiliar energy technologies into their living environment, they often rely on their cultural norms, values and beliefs in their sensemaking and evaluation of these technologies. Community acceptance of such technologies and projects is thus not only shaped by the characteristics of the technologies nor by the psychological traits and preferences of community members, but also by shared understandings of local culture and how technology implementation aligns with those.

Culture and how it relates to energy technology vary significantly across locations, not in the least due to the uniqueness of places, people, and histories, but also because of spillovers from experiences with other technologies, regional controversies, and historical events [1]. These cultural differences may help explain why the acceptance of identical energy technology projects varies between regions. For example, in Italy, focus group participants in Palermo framed geothermal energy as an opportunity for economic revitalisation, while participants in Viterbo opposed it to protect environmental conservation and agricultural traditions [2], [3], [4]. Geothermal energy (GE), frequently an unfamiliar or newly introduced technology, presents a particularly compelling case for examining culture's role in technology acceptance because this energy source operates locally but largely invisibly beneath the surface. This makes communities heavily reliant on cultural frameworks to interpret unfamiliar subsurface processes in their local context. In addition, the subsurface itself is often granted cultural value and meaning by communities, with connections to religious rituals, local folklore and burial of deceased loved ones. The combination of technological unfamiliarity and uncertainty, reliance on cultural cognition, and the fit to local place may explain why GE can enjoy broad acceptance at the national level while support often varies and can diminish at the local scale [5], [6], [7], [8], [9]. While this pattern might suggest simple NIMBY (Not In My Backyard) dynamics, examining geothermal perceptions across different localities may reveal that proximity alone does not fully determine acceptance and that distinct local cultures may drive varying community responses to identical geothermal projects.

The importance of cultural considerations in geothermal development is increasingly recognised at multiple levels (e.g. Ref. [10]). The

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EU emphasises the need to understand "how the utilisation of geothermal resources aligns with the cultural values and contextual settings at local to regional level" and calls for increased "responsiveness of geothermal energy to diverse societal interests and concerns" through "inclusive, early and continuous societal engagement" [11, p. 1]. Despite this recognition, existing research from a social science and humanities perspective tends to be descriptive in nature and lacks analytical diversity [11]. This creates a knowledge gap: while individual case studies are documented, we lack a systematic understanding of how local culture operates within the GE context.

This article aims to address that gap and reports the findings of a systematic review of academic papers examining the role of culture in GE research. The objective of this review is to (1) assess the extent to which local culture is considered in GE research, (2) explore how culture is understood and conceptualised in these studies, including its scope and analytical boundaries, and (3) evaluate the methodological approaches employed to study cultural dimensions and their empirical foundations. We aim to answer the following research questions:

1. How is (local) culture defined, delineated, operationalised, and studied in research on geothermal energy?
2. What insights has existing empirical research generated with regard to the influence of local culture on public perceptions of geothermal energy?

While we focus explicitly on GE, our contributions extend beyond improving our understanding of the role of culture in social acceptance of GE projects. Energy transitions increasingly involve a shift toward decentralised and distributed renewable energy production (e.g. photovoltaic and wind) within local communities [12], [13]. As a consequence, (indigenous) communities are increasingly confronted with technologies and projects that may misalign or infringe upon their traditional beliefs, local knowledges, or cultural connections to their place, or may threaten the reliance on the natural resources and traditional livelihoods [14], [15], [16], [17], [18]. Culture operates across all three interrelated dimensions of social acceptance as conceptualised by Wüstenhagen et al. [19]: community acceptance, socio-political acceptance and market acceptance. However, this paper focuses on the first two. Community acceptance refers to how residents and local authorities respond to the siting decisions, and socio-political acceptance describes the acceptance of technologies within broader institutional frameworks and governance structures by the public, policymakers and key stakeholders [19], [20]. We focus on understanding how culture shapes socio-political and community acceptance, which may be crucial for project success, and cumulatively, for the success of the energy transition.

The structure of the review is as follows. The next section presents the method, and Section 3 discusses the literature and presents findings. Further analysis, discussion, and implications for future research are elaborated in Section 4. Finally, the conclusions are presented in Section 5.

2. Methodology

To answer the research questions in Section 1, we conducted a systematic literature review methodology for data collection following the PRISMA 2020 flow diagram. The PRISMA statement consists of a four-phase flow chart: identification, selection, eligibility, and included articles. We discuss the resulting article selection and analysis in Section 2.1 and Section 2.2 respectively.

2.1. Data collection

Our search strategy included a broad set of search terms to cover relevant literature. Beyond basic synonyms and variations of 'culture', we incorporated terms reflecting belief and knowledge systems to address epistemological dimensions, alongside terminology from related disciplines such as social geography and anthropology. Terms from socio-technical imaginaries literature (social visions of a desirable future that shape and are shaped by technological projects) and place theory (locations as having multiple symbolic interpretations beyond visual considerations with meaning linked to identity and belonging) were included, as these enable critical considerations of culture, power and sustainability [11], [21]. Through an iterative process, we refined these key search terms and the Boolean operators to narrow the search. A NOT-term was incorporated into the search strategy to exclude papers where the term 'culture' referred to bacterial cultures rather than social science concepts (see Table 1 for the complete list of search terms).

The final search string was systematically applied across two databases: Web of Science and Scopus. These databases were selected for their extensive coverage of scientific and peer-reviewed literature. Database-specific operators and symbols were adapted while maintaining consistent search terms across all queries. The identification and search for literature concluded in July 2025. Table 2 shows the number of papers resulting from each source consulted. To filter the 781 identified papers, the PRISMA selection process comprised four sequential rounds: database filtering, duplicate removal, title/abstract screening, and full-text screening.

Fig. 1 illustrates the paper selection process. Initial database filters restricted results to: (a) English-language publications to ensure accessibility to an international audience, and (b) a full-text version of a peer-reviewed journal article, a peer-reviewed book chapter or a peer-reviewed conference paper. Duplicate removal was conducted using Covidence software supplemented by manual verification, resulting in 564 unique publications for screening. During title and abstract screening, papers were assessed for explicit discussion of culture in relation to GE. This process identified 159 potentially relevant publications. However, thirty-nine publications were inaccessible due to paywalls, lack of institutional access, broken DOIs, or unavailability of older publications, leaving 120 papers for full-text review.

The final screening involved full-text evaluation of the remaining 120 papers. On a paper-by-paper basis, the authors assessed the content of each study. We excluded four papers that the databases wrongly

Table 1
Search string for papers on culture-in-geothermal energy research.

Terms	Search string	
Geothermal-related terms	("Geothermal" OR "Earth energy" OR "Geoenergy" OR "Subsurface energy" OR "Heat from the earth" OR "Underground Energy" OR "Crustal Energy" OR "Geothermic" OR "Earth-based energy")	
Culture-related terms	General cultural terms	("cultur*" OR "cross-cultur*" OR "intercultur*" OR "trans-cultur*" OR "multicultur*" OR "bicultur*" OR "subcultur*" OR "encultur*" OR "accultur*" OR "unicultur*" OR "monocultur*" OR "pluricultur*" OR "polycultur*" …
	Disciplinary perspectives	OR "anthropolog*" OR "ethnograph*" OR "ethnolog*" OR "human geograph*" OR "Social geograph*" OR "sociocultural" OR "sociological" OR "socio-cultural" OR "belief system*" …
	Belief and knowledge systems	OR "local knowledge" OR "epistemolog*" OR "lived experiences" OR "worldview*" OR "value system*" …
	Place theory	OR "imaginaries" OR "place identity" OR "place attachment" OR "sense of place" OR "place dependence" OR "place meaning" OR "place-based" OR "place-making" OR "Placemaking" OR "place theory" OR "place-theory" OR "place perceptions" OR "spatial identity" OR "territorial identity" OR "symbolic place" OR "lived space" OR "place narratives")
Exclusion	NOT ("Bacteria")	

Table 2
Total search results (by database) for papers on culture-in-geothermal energy research.

Database	Number of Results
Web of Science	353
Scopus	428
Total	781

identified as peer-reviewed journal articles or English-language publications. We then applied content-specific exclusion criteria focused on our research objectives.

We excluded fifty-three papers that mentioned culture in relation to GE but failed to provide an original analytical contribution, instead merely paraphrasing existing sources or listing culture without further elaboration. This category also included papers primarily focusing on geotourism, as our analysis examines broader cultural dimensions beyond tourism applications. Finally, we excluded 34 papers that mentioned culture but described GE only as an example, while the papers' focus was on the broader energy transition or other renewable technologies. This systematic screening process resulted in 29 papers for final inclusion, with publication years ranging from 2002 to 2025 across various disciplinary journals and regions.

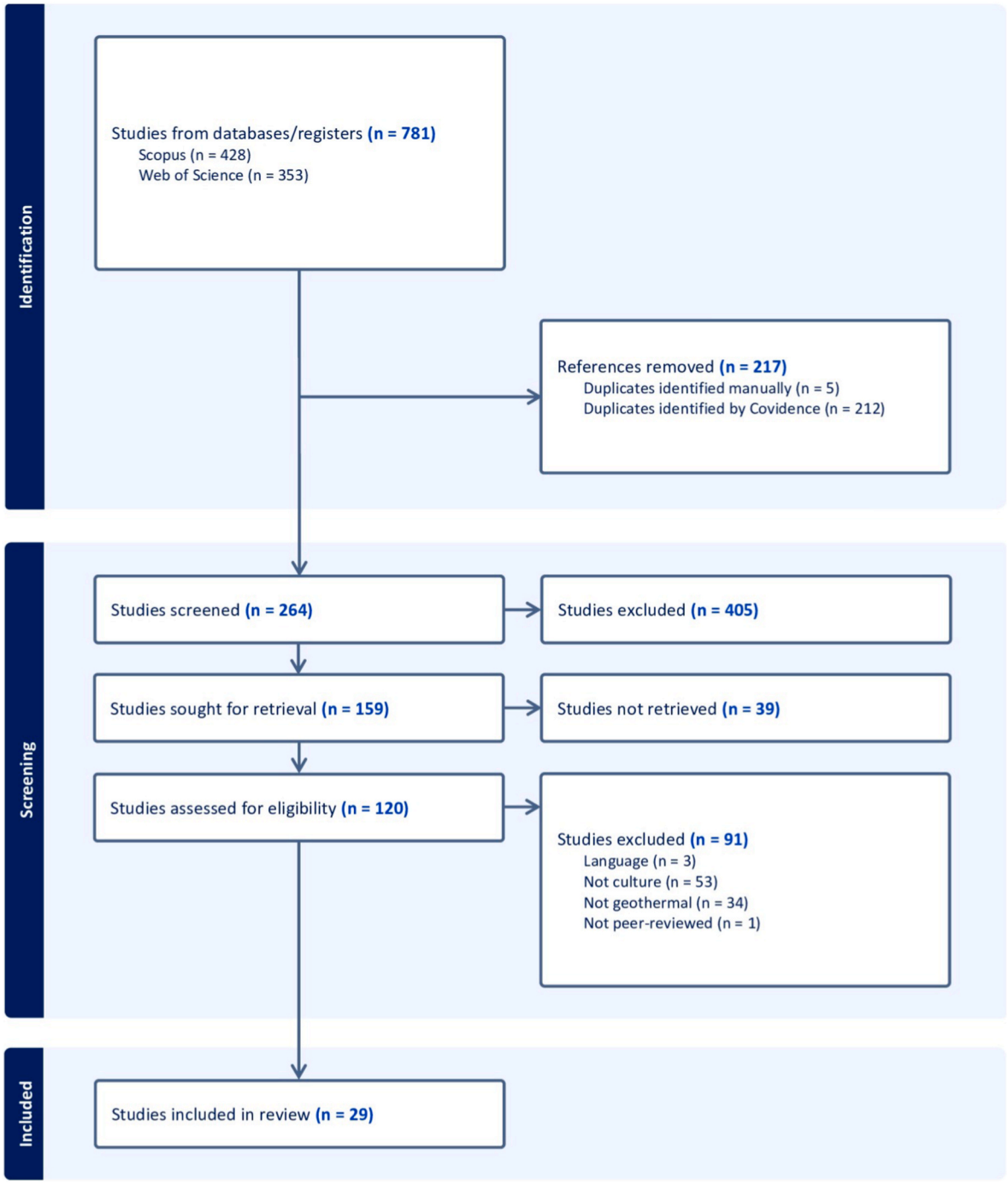

Fig. 1. PRISMA flowchart of the study selection for papers on culture-in-geothermal energy research.

2.2. Data analysis of selected papers

We analysed the selected papers to identify the theoretical and methodological patterns underlying the understanding of the role of culture in GE (RQ1) and the empirical findings of the influence of culture on public perceptions of GE (RQ2).

For the first research question, we divided the analysis into three parts. Firstly, we analysed how culture was defined and conceptualised across the papers. We extracted the authors' definitions, concepts and theoretical frameworks used to understand cultural aspects. We then conducted a thematic analysis in Excel using an inductive, bottom-up coding approach, guided by the question: how do authors conceptualise and define culture in the context of GE? Each paper was coded by the first author, with initial codes assigned to capture distinct cultural definitions and concepts. Codes were then clustered into six themes related to the discipline cluster and four themes related to the conceptualisation. The themes were subsequently validated in a discussion between the three authors (see Appendix C for an overview of the codes and themes). Secondly, delineation of culture: we examined how studies defined the boundaries of culture. This delineation was categorised by geographic scale (i.e., whether the papers discussed local, regional, or national cultures) and social scope (i.e., community or stakeholder cultures). When delineation was not explicitly stated, it was inferred from the study design and sample characteristics. Thirdly, operationalisation and study of culture: we reviewed the methodologies applied in the selected papers, extracting all cultural aspects and frameworks that were operationalised for empirical measurement (i.e., translated from abstract cultural concepts into concrete, measurable indicators). Additionally, we noted the data collection methods and analytical techniques used to study culture.

For the second research question, we refined our dataset by excluding papers without empirical data (e.g., purely theoretical or conceptual works). From the remaining empirical studies, we applied the same inductive coding approach as for RQ1, guided by the question: how does culture influence public perceptions of GE projects? We extracted findings relevant to culture and GE; the first author catalogued, coded, grouped by similarity and refined them into broader themes. The themes were validated through discussions with the co-authors (see Appendix D for an overview of the codes and themes). Two main categories emerged, further discussed in Section 3.2.

3. Findings

Figs. 2–5 provide overviews of the focus of the 29 publications included in this review in terms of geographical distribution, geothermal application, drilling depth of the GE projects studied and methods applied. Information on the authors, the journal and the year of publication is presented in Appendix A, and an overview of the meta-analysis is given in Appendix B.

Fig. 2 shows the global heat flow, indicating that most studied project sites are in areas of high surface heat flow. Iceland, Kenya and New Zealand are the most frequently studied countries ($N = 4$ each; see Fig. 2). Most studies focus on a single country ($N = 22$), while four have no specific geographical focus. Comparative country studies include Japan and Iceland [23] and East Africa [24], while two studies applied a comparative regional analysis: Chavot et al. [25] examine four regions within France and Ratio et al. [9] compare two regions in the Philippines.

Fig. 3 shows the distribution of geothermal applications in the literature; nearly half of the publications (N = 13) focus on electricity generation, including one study on geothermal electricity with lithium extraction [26]. Seven studies focus on both heating and electricity, and five examine direct heating applications such as ground-source heat pumps [27], [28], [29]. The remaining studies did not specify the application type ($N = 4$). Among comparative technology studies, Thórhallsdóttir [30], [31] provide data analysis comparing

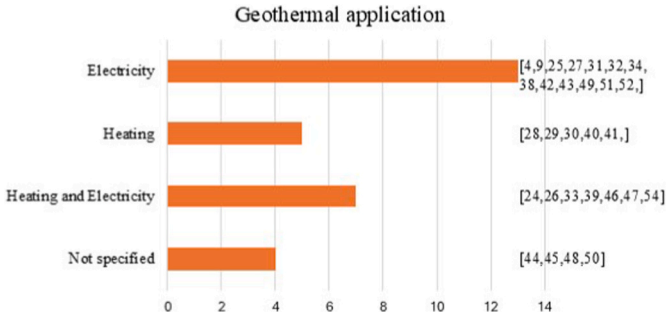

Fig. 3. Application types of geothermal energy in culture-in-geothermal energy studies, the numbers refer to the papers listed in the References.

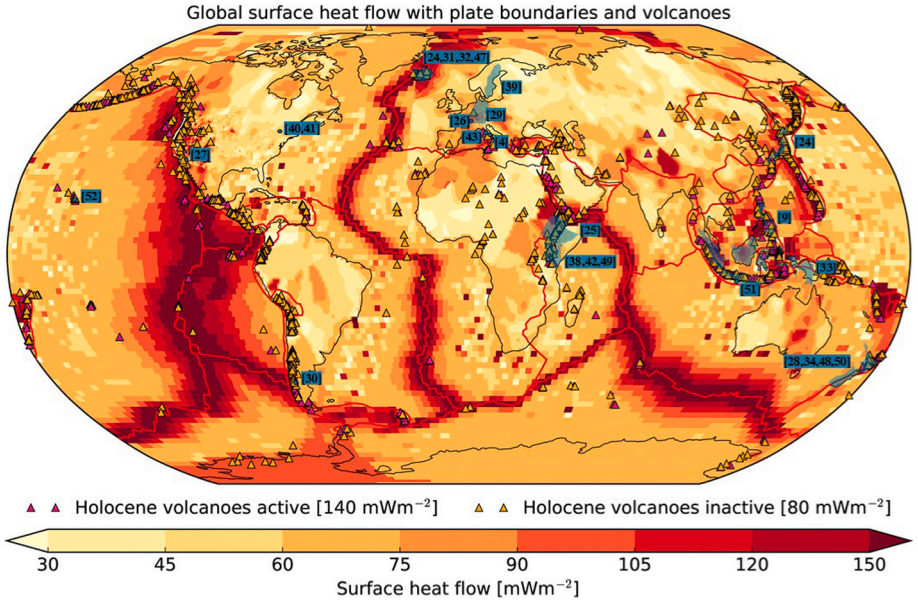

Fig. 2. Global heat flow map (source: Limberger et al. [22]) with an overlay of study locations for culture-in geothermal energy studies (added by author), the numbers refer to the papers listed in the References.

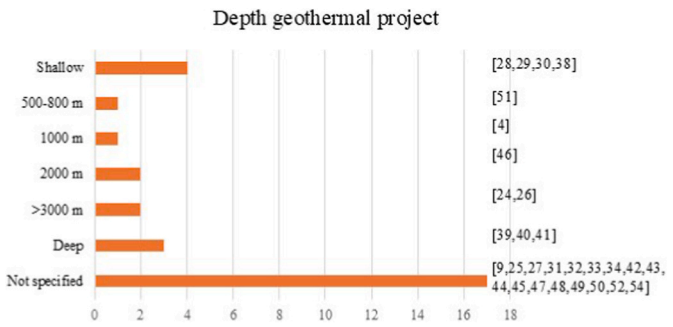

Fig. 4. Depth of the geothermal energy projects in culture-in-geothermal energy studies, the numbers refer to the papers listed in the References.

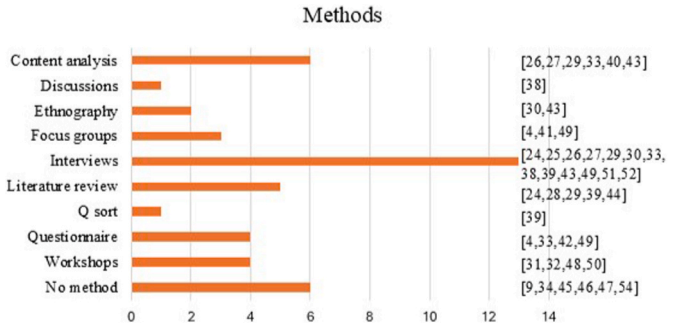

Fig. 5. Methods applied in culture-in-geothermal energy studies, the numbers refer to the papers listed in the References.

hydroelectric and geothermal developments. Nursanty et al. [32] and Guan et al. [33] examine geothermal alongside other renewables using secondary literature. Vargas-Payera et al. [29] compare ground-source heat pumps with traditional heating systems.

Depth characteristics are relevant alongside application types, as both influence project feasibility. However, there is no consensus on what constitutes “shallow,” “deep” or “ultra-deep” GE, with definitions varying according to depth, temperature or application [34]. Depth is nonetheless emphasised because it serves as a practical proxy for project characteristics in public discourse. Public risk perceptions are often depth-related, with "deep underground" associated with greater danger and unpredictability (e.g. Refs. [35], [36]). Fig. 4 shows the depth of the geothermal wells; some indicate ranges of depths, while others describe ‘shallow’ [37], ‘deep’ [38] or EGS technology [25], [39], [40]. Most studies ($N = 17$) do not specify a depth. It is important to note that depth does not necessarily indicate geothermal application, nor does the application type alone determine depth, as the relationship between the two depends strongly on the geothermal gradient and local geological conditions.[1] For this reason, the results of Fig. 3 should be interpreted in relation to Fig. 4.

An overview of the methodologies employed in the selected literature is presented in Fig. 5. Thirteen studies applied one method, five studies applied two, and five studies applied three. Interviews represent the most common approach ($N = 13$), with survey-interview combinations more frequent than standalone quantitative approaches. Mahamoud Abdi et al. [41] diverge from this trend by operationalising culture quantitatively through binary variables (gender-based isolation, elder reliance) and scaled measurements (Likert scales for religious practice disruption). Two distinctive approaches include Q-methodology, in which participants rank-order opinion statements followed by statistical factor analysis to identify distinct cultural worldviews in technology-nature relationships [38], and ethnographic fieldwork combined with interviews to document current practices of how GE technologies disrupt cultures [29], [42].

The following analysis is structured around the research questions: first, how culture is conceptualised, delineated and studied in GE literature (Section 3.1), and second, the empirical insights regarding culture in GE development (Section 3.2).

3.1. How culture is defined, delineated, operationalised and studied in geothermal energy literature

To address how culture is defined, delineated, operationalised and studied in GE research (RQ1), this section examines the theoretical and methodological approaches in the publications. The analysis is structured in terms of how culture is defined in Section 3.1.1, how cultures are delineated in Section 3.1.2, and how culture is operationalised and studied in Section 3.1.3.

3.1.1. Definitions of culture

Firstly, through thematic analysis, we identified six clusters of articles sharing a similar cultural focus, which appear to reflect the disciplinary background of their authors (see Table 3). *Architecture* studies focus on the preservation of culturally and geologically significant features, emphasising tangible elements that connect communities to their environment. The *Cultural ecosystem* approach highlights the cultural benefits arising from human-environment interactions such as spiritual or recreational values associated with geothermal resources. Studies in *Place and imaginaries* focus on place-based identities across local, regional and national scales. Closely aligned with that focus, *Identity* studies examine how cultural identities are formed and disrupted by GE. *Cultural adoption* studies examine how cultural factors influence behavioural change and technology adoption. Lastly, the *Professional culture* study examines how the assumptions of technical and policy professionals shape GE development.

Secondly, despite the overlap in disciplines, the analysis also noted considerable conceptual diversity in how culture is described in the context of GE, with seventeen distinct cultural concepts identified (detailed in Appendix C). This diversity reflects culture's systemic

Table 3
Disciplinary approaches to culture in culture-in-geothermal energy studies.

Disciplinary field	Authors	Cultural focus	Key concepts
Architecture	[30], [31], [32]	Preservation and significance of cultural/ geological features	Cultural heritage; city authenticity
Cultural ecosystems	[43], [44]	Cultural benefits from human-environment interactions	Cultural ecosystem services; cascade models
Place and Imaginaries	[26], [39], [40]	Collective visions and place-based identities	Sociotechnical imaginaries; place attachment; place-technology fit; visions of energy futures
Identity studies	[25], [42], [45]	Cultural identity formation through place attachment and social group membership, and how environmental changes disrupt them	Cultural identity; biocultural identities; solastalgia; social identities and social worlds
Cultural adoption	[23], [27], [29]	Cultural factors in behavioural change and technology adoption	Energy cultures framework; social practices; national culture
Professional culture	[38]	Professional frameworks and assumptions in geothermal development	Petro-cultural assumptions

[1] Depth in isolation is insufficient to characterise geothermal field types: a high-geothermal-gradient location may reach 200 °C at less than 1 km depth, creating a vastly different resource profile compared to a geothermal field that reaches only 40 °C at 1 km depth.

nature: it is simultaneously material, social, location-specific and political, and cannot be reduced to a single dimension. Further analysis of these concepts led to the identification of four novel cross-disciplinary processes of culture, indicating that culture is emerging through interactions between communities, environments and GE projects. These four analytical processes, summarised in Table 4, shape how culture is defined and redefined across all studies, independent of disciplinary background.

The first process, *anchoring culture*, describes how communities are established and maintained through their dependencies on the natural and social environment. The natural environment (the physical landscape, biodiversity and ecosystems) shapes cultural beliefs and practices such as sacred sites and economic and cultural reliance on natural resources. The social environment (community structures) holds religious or political convictions that shape cultural expression such as language, rituals and livelihood systems.

The second process, *materialising culture*, captures how collectively held understandings of the environment become embedded in tangible and intangible cultural heritage. Tangible aspects refer to physical, human-made elements such as archaeological sites, historical buildings and material artefacts. Intangible aspects concern the environments' immaterial, symbolic and experiential aspects such as sense of place, place identity and place attachment. When the environment is subject to change, these intangible and tangible aspects are actively shaped and reinterpreted.

The third process, *collective meaning-making*, describes how these social and natural environments become institutionalised through shared understandings, knowledge systems and group orientations rather than individual perspectives [23]. Through this process, a community generates a common commitment to priorities and visions of desirable futures [25], [39]. Such collective orientation helps groups navigate decision-making and establish what is considered important within their culture, including their stance toward GE projects [25].

Finally, the process of *cultural transformation* recognises that culture continuously evolves in response to social, natural and technological changes (such as with GE developments). This process can generate new cultural practices and social interactions [27], [29] [46], while potentially also causing cultural disruptions when developments threatened familiar environments [42].

3.1.2. Delineation of culture

Different cultures shape distinct perceptions of GE projects, making delineating culture a methodological necessity in empirical studies of this relationship. Rather than implying hard boundaries, culture is inherently fluid, with overlapping and shifting boundaries. Two approaches to cultural delineation emerge from the literature: the geographical and the sociological. The geographical approach maps cultural differences across scales from national to local, with local cultures embedded within broader regional or national cultural contexts. The sociological approach identifies cultural distinctions among social groups whose interests lead them to attribute disparate meanings to geothermal landscapes; indigenous communities, for instance, often assign spiritual and environmental significance, while industry and governments prioritise economic or energy interests [47]. This section first addresses cultural delineation across geographical scales, then explores social group boundaries.

3.1.2.1. Culture delineated by geography. Fig. 6 Shows that studies operate at different geographical scales, ranging from national to local. Vargas Payera et al. [29] study how ground-source heat pumps foster new cultural practices in facilities such as schools and greenhouses; these facilities act as boundary-making mechanisms that define the people connected to them as cultural groups. Lambert [39] examines multiple scales including campus, local, regional and national; these shape negotiations over GE acceptability through distinct cultural

Table 4
Processes of culture to conceptualise culture in culture-in-geothermal energy studies.

Process of culture	Cultural mechanisms	Definition in the geothermal context	Examples
Anchoring culture	Shared social environment	"Religious or political convictions" [26]	Images, language, and stories express the communally shared meanings [40]
	Natural environment	"Biocultural identities" where "local populations are economically and culturally reliant on the natural environment, biodiversity and the cultural significance associated with them" [43]	Japanese onsen culture combines natural hot springs with the tourism economy [24]
Materialising culture	Tangible heritage	"Archaeological remains, sites of historical importance and legends" [31,32] and "materialities (artefacts)" [28,30]	Historical sites can be affected by geothermal energy projects [31,32]
	Intangible heritage	"City authenticity" [33] and "sense of place" [43]	Place identity, place attachment, territorial sovereignty
Collective meaning-making	Shared understanding	"Collectively imagined forms of social life and social order" [27] and "collective understandings of a distinct place, drawing on both narratives of the past and visions of what the future should look like" [40]	Sociotechnical imaginaries creating collective visions of energy futures, influencing community reactions to geothermal developments [41]
	Shared knowledge systems	"Collectively based Traditional Knowledge" [44] and "sharing a body of knowledge" within "social worlds" [26]	"Diverse knowledges that situate characteristics within bioregional constructs" informing geothermal understanding [43]
	Group orientation	"Common commitment to priorities about what is important and what needs to be done" [26] and shared senses of legitimacy, narratives and visions of the energy future that shape public perceptions of geothermal energy [40,41]	"Statutes, arguments and resources intended to support the legitimacy of actions and knowledge" navigate decisions and establish what is considered important within the culture [26]
Transforming culture	Cultural innovations	"Social practices" with three elements: experiences or empirical knowledge, materialities and cultural meanings that enable "change and sustained adoption" [30]	"Interactions between energy technologies, people and their environments" creating new behaviours [28]
	Cultural disruptions	Vulnerable to "solastalgia," a form of distress induced by negative environmental changes in which the comfort of feeling 'at home' is lost" [43]	"Attack on the sense of place" when familiar environments are altered by geothermal development [43]

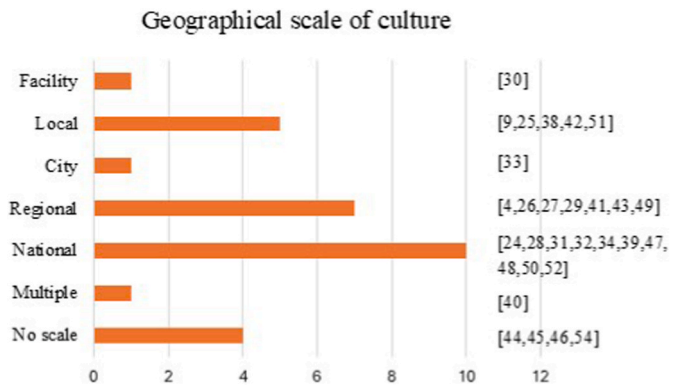

Fig. 6. Geographical focus in culture-in-geothermal energy studies, the numbers refer to the papers listed in the References.

narratives about energy and place between the scales [39].

For national culture approaches, cultural delineation aligns with national administrative borders. Within this perspective, each country has a broadly shared set of cultural values that influence how GE development occurs. Shortall & Kharrazi [23] demonstrate this by contrasting Iceland's higher risk appetite, which "fosters innovation through learning from past mistakes", with Japan's lower risk tolerance that has resulted in "slower leveraging of geothermal capacity", most critically post-Fukushima. Similarly, Barr & Talwar [27] treat New Zealand households as a relatively homogeneous culture, though they acknowledge that socio-economic differences between households lead to varying rates of ground source heat pump adoption.

Analytical approaches to regional culture often assume that cultural boundaries exist within a country, reflecting diversity across counties, provinces or other subnational areas. For instance, in France, distinct regional social worlds and identities shape how regional communities engage in decision-making about GE developments [25]. Similarly, in Italy, regional differences in environmental values and perceptions of industrial development have led to contrasting views to GE developments [42]. However, the delineation of regional cultures is rarely explicit; rather, it emerges through methodological choices. For instance, document analyses delineate regional cultures based on available sources, such as regional administrative documents [42], online discussions [28], public comments and records from town hall inquiries [25], [26]. Interview-based studies delineate regional cultures through stakeholder networks, such as municipal and regional administrators [27], and representatives of community and environmental groups involved [26], [40], [48]. Survey-based research delineates regional cultures according to administrative units corresponding to respondents' residences [4], [48]. Thus, the delineation of regional cultures depends more on methodological pragmatism than on fixed cultural criteria.

Local cultural approaches recognise heterogeneity even within seemingly unified cultural groups. Taute et al. [47], [49] illustrate this by describing Māori culture as a broadly unified system, while acknowledging that tribal iwi and hapū (Māori sub-tribes and clans) observe distinct cultural protocols shaped by their unique histories and local environments. Similarly, Ibrohim et al. [50] highlight differing beliefs about the sanctity of Mount Lawu. Some communities consider the entire mountain sacred, while others consider only certain areas sacred, complicating consultation processes. However, the delineation of local cultures is rarely explicit. For example, some studies (e.g., Mahamoud Abdi et al. [24] and Taute et al. [47], [49]) provide maps showing geothermally active areas. In contrast, Ibrohim et al. [50] rely on administrative sub-districts or zones identified as most affected, and Mariita [37] defines a 10 km radius around the geothermal plant as the boundary of the Maasai community most affected. Yet, several studies do not provide a delineation of local culture (e.g. Mahamoud Abdi et al. [24] and Ratio et al. [9]).

3.1.2.2. Culture delineated by social groups. The included literature examines different cultural groups to understand how each perceives and interacts with GE (see Fig. 7). Indigenous communities are the most frequently identified cultural group ($N = 9$). Although the literature does not explicitly state criteria for defining a cultural group (e.g. Indigenous or local community) in relation to GE, certain defining elements can be identified. For instance, Taute et al. [47], [49] position Māori values and knowledge systems as cultural frameworks. In the case of the Kenyan Maasai, cultural delineation is implied through elements such as language, ethnicity, patterns of community participation and pastoralist traditions, which together shape perceptions of GE [24], [37], [41], [48]. Around Mt. Lawu in Indonesia, local community culture is delineated based on the significance attached to heritage sites including temples, religious ritual spaces and holy water springs, threatened by GE developments [50]. Furthermore, the Native Hawaiian community culture is characterised by the importance placed on Kanawai (natural law) and the protection of Akua (deified natural entities) [51].

Yet even seemingly unified cultural systems contain internal tensions. Mahamoud Abdi et al. [24] show that in Maasai communities, patriarchal decision-making structures exclude women and children, prompting dissatisfaction with unbalanced power dynamics that influence perceptions of engagement in GE developments. Such heterogeneity underscores the importance of clearly defining cultural criteria that encompass all members involved in the culture.

For other actor groups, cultural delineation is primarily based on geographical residence (national, regional, local inhabitants) or their connection to the facilities, with no further explicit cultural criteria described in the literature. The predominance of Indigenous and geographically defined groups in cultural research suggests that 'culture' in GE studies is often associated with traditional or place-based communities. One exception is professional culture ($N = 1$), which is defined by institutional position within the energy sector [38].

3.1.3. Operationalisation and study of culture

Operationalising culture for methodological implementation requires translating cultural concepts and definitions into concrete research methodologies. Most studies employ inductive approaches, in which cultural themes emerge from empirical data rather than being predefined by theoretical frameworks or concepts, and are subsequently quantified by counting theme frequency (e.g. Refs. [24], [37], [48]). However, studies examining cultural impacts on local communities lack clarity about specific questions asked (e.g. Refs. [24], [50], [51]). Mariita [37] is an exception, explicitly stating interview questions on socio-economic and cultural issues directly affecting the Maasai community.

Three deductive methods for applying culture were identified. Firstly, four studies operationalise culture through established

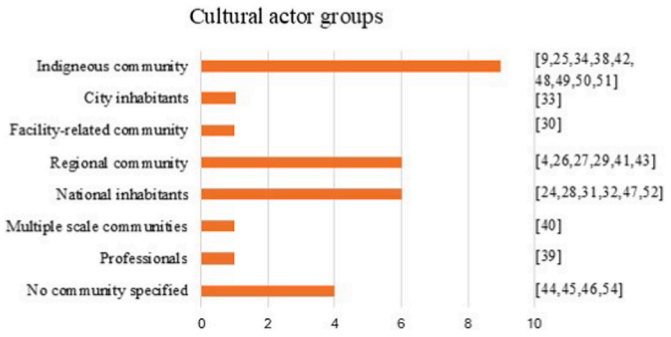

Fig. 7. Cultural actor groups in culture-in-geothermal energy studies, the numbers refer to the papers listed in the References.

theoretical frameworks. Barr & Talwar [27] and Shortall & Kharrazi [23] apply the Energy Cultures Framework (material culture, norms, practices, external influences) and Hofstede's cultural dimensions (e.g., long-term vs short-term orientation, indulgence vs restraint, and uncertainty avoidance [52]), respectively, to examine national-level technology adoption patterns. Vargas Payera et al. [29] employ Social Practices Theory through ethnographic fieldwork and interviews focusing on materialities, competences and the cultural meanings attached to heating practices, to measure cultural change in technology adoption. Cook et al. [44] categorise cultural ecosystem services using the Common International Classification of Ecosystem Services framework, operationalising seven cultural dimensions. These include spiritual enrichment, aesthetics, inspiration, education, archaeological heritage, recreation and existence and bequest value to assess how GE development affects diverse types of human-environment cultural relationships. Cook et al. [43] assess which cultural impacts have been incorporated within existing literature on multi-criteria decision analysis (MCDA) for trade-offs between cultural consequences and social and economic impacts in geothermal development.

Secondly, four studies build frameworks that measure the impact of GE on culture through workshop-based participatory methods. Thórhallsdóttir [30], [31] facilitate workshops with institutions, NGOs and the public to expand the MCDA to accommodate cultural heritage (cultural heritage accounts for 10% of the total weighting, with non-living nature at 50% and living nature at 40%) through six weighted attributes: diversity/richness, rarity, completeness, information value, symbolic value and scenic value. Taute et al. [47], [49] collaborate with Māori communities to develop a "Māori Cultural Impact Assessment Tool" with four cultural dimensions (spiritual connection, protocols, integrity/prestige and ancestral belonging) using a five-point Mauri scale.

Thirdly, six studies operationalise culture through spatial and identity-related concepts using qualitative methods. Lambert [39] employs place and sociotechnical imaginaries (collectively cultural visions of how technologies should work and what kind of society they should create) and place-based identities across geographical scales through document analysis. Lambert & McComas [40] extend this with interviews through place attachment, community identity and local history. Similarly, Britton et al. [26] use hydro-social territories (how water and society shape each other, revealing how cultural meanings of water interact with GE) and sociotechnical imaginaries to examine how places are shaped and understood. Chavot et al. [25], Lampredi [42] and Pellizzone et al. [4] focus on community identity operationalisations examining social worlds, biocultural identities (the reliance on the natural environment and biodiversity) and local identity themes, respectively.

3.2. Empirical insights: the cultural lens and impacts of geothermal energy

To address how local culture influences public perceptions of GE (RQ2), this section examines findings from the 22 studies that provided empirical data on culture–GE relationships. Through collecting and creating an overview of all empirical insights, two distinct pathways emerged that demonstrate different causal relationships between culture, GE projects and public perceptions, as illustrated in Fig. 8.

The culture-driven pathway (indicated by the solid black arrow) describes how pre-existing cultural frameworks function as interpretive lenses through which communities make sense of and evaluate proposed GE developments. Culture here functions as an independent variable shaping perceptions. The project-driven pathway (indicated by the black dashed arrows) captures how GE projects (potentially) impact and transform local culture, with communities' perceptions shaped by their evaluations of these cultural impacts. Here, GE projects function as independent variables that affect local culture, which in turn influences public perceptions.

The four cultural processes identified in Section 3.1, *anchoring culture*, *materialising culture, collective meaning-making* and *transforming culture*, provide the analytical foundation for understanding the empirical findings presented in this section. The first three processes operate as pre-existing interpretive filters in the culture-driven pathway. In the project-driven pathway, these same processes are mechanisms through which cultural transformation is experienced: *Transforming culture* describes the outcome when GE development reconfigures *anchoring culture, materialising culture* and *collective meaning-making*, with the direction of that reconfiguration being disruption or innovation depending on its alignment with these processes.

Based on the thematic analysis detailed in Appendix D, three themes related to the culture-driven pathway are discussed in Section 3.2.1. and three themes corresponding to the project-driven pathway are discussed in Section 3.2.2.

3.2.1. The culture-driven pathway

Empirical evidence shows that culture informs cognitive schemata through which communities interpret and respond to GE projects. Three themes emerged, each grounded in specific cultural processes.

Firstly, *cultural identity and experience of the underground* captures how pre-existing cultural meanings and practices, operating through *anchoring culture* and *materialising culture*, create cognitive schemata

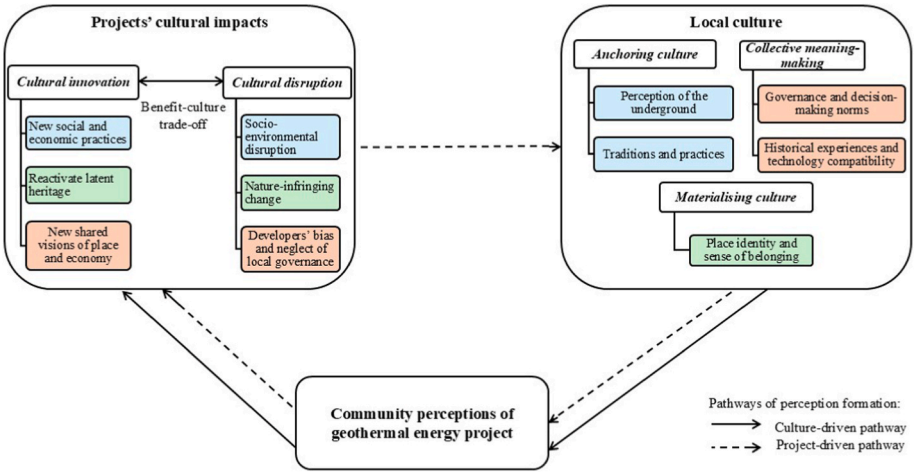

Fig. 8. Conceptual model of local culture and perceived geothermal projects' cultural impacts on perceptions of geothermal energy. The culture-driven pathway illustrates three cultural processes as interpretive frameworks shaping community perceptions. The project-driven pathway illustrates how geothermal is perceived to transform local culture shaping community perceptions.

through which communities understand and evaluate subsurface technologies. Across indigenous communities, geothermal heat is understood not as an energy source but a manifestation of ancestral or divine presence [24], [26], [42], [50]. For Māori, geothermal resources represent the bond between the physical and spiritual realms [49]. In Hawaii, geothermal resources are viewed as a gift from the gods [51]. In contrast, in East Germany, a pre-existing socialist-era perception of the geological underground as an energy resource led to significant adoption of shallow geothermal heat pumps [27]. Beyond the meanings of the underground, economic dependence on geothermal landscapes anchors culture in a different way: in Japan, the onsen tradition has led communities to be concerned about the depletion of culturally and economically vital resources, which generated opposition [23].

Local identity and place attachment further influence how communities evaluate local character compatibility through *materialising culture*: multiple co-existing identities, e.g. rural vs academic, create conflicting views on GE's compatibility with the place [39], [40]. In France, a region where local identity is centred on environmental policy traditions, the community experienced meaningful geothermal participation that aligned with their sustainable development values. In contrast, communities whose local identity emphasised democratic engagement experienced limited participation, contradicting their *collective meaning-making* norms of decision-making involvement, leading them to feel that GE disrupted their social identity [25]. Such governance expectations and their role in shaping GE perceptions are further examined in the second theme.

Secondly, *cultural governance and decision-making norms* examines how traditional governance systems, decision-making processes and power structures influence public responses, with *collective meaning-making* as the primary process. Communities form organised collectives whose shared norms about legitimate authority and appropriate decision-making determine how engagement is expected. A pattern arises from the collision between formal consultation and traditional authority structures, leading to selective inclusion and perceived manipulation. In Maasai communities, engagement through patriarchal structures concentrated on decision-making among elders, dividing communities between co-opted insiders and excluded members who experienced the process as favouritism [41]. Taute et al. [49] demonstrate an alternative: structuring workshops aligned with indigenous governance norms, fostering a sense of belonging and formality among participants, and integrating this at the forefront of the practical management and development of geothermal projects. At national scales, *collective meaning-making* through shared orientations toward risk and consensus shapes structural development conditions: higher cultural risk tolerance supports faster GE development through learning from mistakes, while consensus-seeking culture and public risk aversion slow decision-making and adoption [23], [27]. The cultural context influences how communities utilise risk discourse in GE governance, thereby affecting project development: one community emphasised risks to legitimise opposition aligned with their identity of reducing hazardous installations, while neighbouring municipalities strategically foreground risks to justify compensation demands from operators [25], illustrating that technical information activates different understandings depending on the collective meaning-making frameworks communities bring to it.

Thirdly, *historical experience and technology compatibility* captures how past energy project experiences and historical technology relationships influence perceptions towards new energy projects. Here, *anchoring culture* and *collective meaning-making* reflect internalised norms and governance relationships. In Hawaii and New Zealand, earlier GE projects that disregarded indigenous concerns created lasting perceptions of distrust: future projects are evaluated against cultural memories of prior governance failures rather than solely on their own merits [51] [49]. Technology compatibility further shapes *anchoring culture*: in New Zealand, the norm is often to forgo indoor thermal comfort and put up with being cold, reflecting a heating norm that reduces openness to heat pump adoption [27].

3.2.2. *The project-driven pathway*

The empirical evidence suggests that GE projects can impact and transform culture; however, how this is perceived depends on the community's priorities and values. Three themes describe how this dynamic operates, each reflecting a different mode through which GE development reconfigures the cultural processes.

The first theme, *identity erosion and cultural loss*, reflects *transforming culture* in its disruptive mode, which is triggered when GE development destabilises *anchored* and *materialised culture*. While geothermal facilities typically have minimal surface footprints and are less visually intrusive than other renewable technologies [32], the socio-cultural disruptions they generate can still profoundly impact communities. Lampredi [42] documents how residents experience distress when their sense of belonging is perceived as being replaced by the so-called 'geothermal culture', which represents broader socio-environmental disruption and nature-infringing change driven by technology. Indigenous communities can feel threatened by encroachment on ancestral land that impedes the practice of their traditional way of life [9], [48]. A less visible but significant form of erosion operates through the professional cultural assumptions embedded in development practices themselves. For instance, progressive marginalisation of indigenous cultural values by modern geothermal management practices [37], [47], [49]. When geothermal projects fail to meaningfully engage with culturally rooted local concerns and offer only minimal participation, communities may perceive them as top-down impositions and reject these GE developments [25]. GE stakeholders may inadvertently reproduce petro-cultural assumptions from the fossil era, reducing GE development to questions of finance, geology and technical innovation [38], thereby enacting a form of *transforming culture* that displaces the collective meaning of affected communities without recognising them.

Second, the *creation of cultural meanings and practices* describes transformations in traditional practices, routines and social behaviours. This reflects *transforming culture* in its innovative mode, when GE reorganises rather than dismantles existing *materialising* and *anchoring culture* processes. The most significant evidence comes from Chile, focusing on how the adoption of geothermal heat pumps reorganised the anchored culture in daily life: social gathering spaces around stoves and traditional clothes-drying practices stopped, ventilation practices changed, and new agricultural knowledge became necessary for year-round geothermal greenhouse farming [29]. In Iceland, geothermal resources are culturally integrated beyond energy production, supporting social practices through public swimming pools and wellness tourism [23]. At a larger scale, GE development can reactivate latent *materialising processes*: in Italy, the volcanic landscape provided a cultural substrate to reconsider the area's underutilised thermal spa heritage [4].

Third, *economic benefits versus cultural preservation* characterises how GE development creates (economic) benefits that compete with traditional cultural activities, putting weight on community priorities and values. This operates at the intersection of *transforming culture* and *collective meaning-making* as geothermal proposals can activate communities to articulate the meaning of place, competing visions for their place's future and the impact of GE on these future visions [4], [39]. Whereas in Iceland, community benefits such as swimming pools were broadly accepted, similar mechanisms in Italy were perceived as economically locking communities into industrial development and replacing biodiverse landscape identity [42]. In Kenya, resettlement for geothermal development presented Maasai communities with modern housing. The majority of respondents were excited about the prospect of owning new modern houses, yet acceptance of this benefit coincided with the gradual erosion of nomadic pastoralism practices and traditional housing values [48]. De Jesus [53] concludes that sharing of meaningful benefits can support a development that is culturally appropriate to the local community.

4. Discussion

In this review, we assessed the current body of knowledge on the role of culture in perceptions of GE. Reviewing 29 scientific publications, we identified diverse definitions, delineations and operationalisations of culture, and empirical evidence confirming the relevance of studying culture for a better understanding of community perceptions of geothermal projects in the local place. Amongst others, we find that culture rarely occupies a central analytical position, as most papers pursue other research objectives.

Culture is not a singular phenomenon; it has developed to signify quite different things over its long history, reflecting its complex, dynamic, and emergent nature. Existing frameworks have been insufficient to capture the dynamics involved, particularly how cultural meanings are continuously renegotiated in response to, for instance, technological change at the local level. Four processes were inductively derived from the reviewed literature that illustrate the dynamics: *anchoring culture, materialising culture, collective meaning-making* and *transforming culture*. While each process resonates with established theories from cultural anthropology, sociology, and geography, together they constitute a novel cross-disciplinary contribution by capturing place-specific interactions among communities, environments and technologies. *Anchoring culture* connects to Geertz' interpretive theory of culture as a semiotic system of meaning [[54], p. 311], extending it by describing how those meanings are rooted in dependencies on the natural and social environments. *Materialising culture* draws on cultural heritage theory, which has evolved from a focus on tangible objects to the recognition that heritage is defined not solely by its material aspect [55]. This aligns with place theory through place attachment and place identity, which capture the emotional and symbolic bonds that communities form with their physical environment [56]. The identified process moves beyond the relational bond between people and place by focusing on how cultural meanings become embedded in tangible and intangible heritage that are actively drawn upon and reinterpreted as environments change. *Collective meaning-making* connects to Bourdieu's notion of doxa, through which the social order forms shared assumptions and perceptions of what is natural and legitimate [[57], p. 471]. The identified process extends to capturing not only the unconscious reproduction of shared assumptions but also the active, forward-looking construction of collective visions and governance norms through which communities negotiate what constitutes appropriate development. *Transforming culture* most directly addresses the recognised gap in existing frameworks by capturing how culture continuously evolves in response to technological change, simultaneously eroding existing cultural practices and generating new ones, reflecting its dynamic, complex and emergent nature. Whether transformation is perceived as a disruption or an innovation depends on its alignment with the other three identified processes.

The four cultural processes capture the internal dynamics of culture. The analyses further reveal the directionality of these processes in relation to GE projects, constituting a second analytical contribution. Our findings indicate that culture plays a dual role in GE development: through our review, we identified two pathways that demonstrate how culture influences perceptions of geothermal projects (Fig. 8). This observation differs from how culture is often portrayed in renewable energy literature: namely, as a barrier to project development (e.g. Refs. [26], [29], [42]). We argue that while the two pathways should not be treated as independent processes, analytically distinguishing them reveals different causal mechanisms through which culture may shape perceptions of energy projects. These can improve how practitioners communicate and engage with communities with more cultural sensitivity.

The culture-driven pathway examines how pre-existing culture, such as cultural beliefs [58], imaginaries [59], local knowledge [60], governance structures [61], and historical experiences with other industries [1], [58], [62], shapes perceptions of energy projects. The pathway is likely to be prominent during project planning phases, when pre-existing cultural frameworks are most salient, and in communities with strong cultural markers such as sacred sites, established governance traditions or historically grounded energy visions. In practice, this pathway is typically considered when assessing whether local culture would support an energy project. The project-driven pathway indicates that geothermal projects and project developers also impact culture and simultaneously shape community perceptions of GE projects [25], [49], in line with the broader energy transition (see e.g. Ref. [58]). This pathway is likely to become prominent as projects progress beyond the planning stage, as communities experience and evaluate cultural transformations in their daily practices and environments. In practice, this means assessing how project development will impact and transform local culture, rather than only whether a community's culture accepts the project.

Positioning these findings within the social acceptance framework of Wüstenhagen et al. [19], both pathways operate primarily within the community acceptance dimension, where cultural dynamics are most tangible and have been most studied. Yet community and socio-political acceptance are interrelated through the identified process of *collective meaning-making*: the shared values, visions and knowledge systems that shape how local communities evaluate GE projects also operate at the levels of governance traditions, planning institutions and professional cultures, thereby influencing broader institutional legitimacy. How culture shapes the socio-political acceptance remains comparatively underexplored in the reviewed literature.

We make the following observations about the empirical literature that treats culture as something static and pre-existing, and as being threatened by projects. Firstly, when infringement upon local culture appears unavoidable, communities ought to be compensated or given alternative means and modes through which they can practice traditional livelihood activities or religious rituals, amongst others. One apparent risk of viewing culture as a somewhat static baseline is overlooking that place-based transformations can also strengthen place attachment, particularly when the cultural meanings of the place and the project development align [59]. In other words, a focus on impacts to be avoided and cultures to be protected may fail to recognise that culture can also govern, support and accelerate energy transitions [60], [61]. For instance, Hanna et al. [58] highlight that the Brazilian Lajeado Dam's compensation program inadequately compensated for cultural losses and created negative impacts, suggesting that a more appropriate strategy would be to engage with local stakeholders in ways that respect their traditional governance structures by incorporating community participation and cultural sensitivity with a social license to operate [58], [62].

There is ample opportunity to consider culture not as a barrier, but as an enabler of energy transitions; as something that can be drawn upon to give shape to locally meaningful energy projects that fit with the fabric of community identity, governance norms and people's sense of place, and that are not only likely to be more acceptable, but might also help communities to advance culturally appropriate, progressive futures for themselves. In the geothermal context specifically, the literature warns against unjustifiably reducing people's understanding of GE to simple misconceptions or ignorance of the subsurface and geological processes. Instead, cultural imaginations of the underground, for example, could be considered and how these may complicate critical questions of public opposition or support [63]. Amongst others, this calls for shifting communication with communities on technical issues with the intent of educating them, to speaking with them about the matters that concern them [64].

Secondly, we observe in this literature, as well as in the broader energy transition literature, that cultural impact assessment (CIA) approaches do not always ensure adequate community involvement. Viewing culture as impacted and transformed by energy projects is evident in impact assessment research, systematic evaluations that measure social, environmental, and cultural consequences of proposed

developments. This approach treats culture as an evaluative dimension to be measured, monitored, and preserved as much as possible [30], [31], [43], [65]. However, standardised "checklists" are often insufficient to capture the complexity and dynamism of local culture and may fail to genuinely incorporate community voices into decision-making.

Strategies are needed that allow communities to indicate, early and continuously, with respect for their traditional governance structures, what their community and place imaginaries are, without intervention from project developers who may inadvertently impose their own ideas and perceptions of local culture and community, thereby guiding project development. This is particularly important because project developers are often unaware of their own cultural assumptions and consequently may overlook how their practices disrupt local cultural dynamics. When practitioners instrumentalise local place meaning in engagement merely to construct an appearance of place-technology fit, this can result in projects that reflect practitioners' place imaginaries rather than community-held ones [66]. Practitioners may be unaware of how their own imaginaries shape their understanding of the community's place, which may produce the opposite of the intended effect: generating perceptions of threat rather than perceived technology fit.

Meaningful engagement with local communities should consider both the subjective aspects of place [66] and the project (developers') impact on local culture to construct projects that meaningfully align with locally held visions of the place. Achieving this dual attention requires addressing two critical gaps in the literature: how to measure the local culture (Section 4.1) and the tendency to treat non-community stakeholders as acultural, rational actors rather than culturally embedded ones whose assumptions influence project development (Section 4.2). We end this section by discussing the limitations and implications for future research to support culturally sensitive engagement in energy projects (Section 4.3).

4.1. Methodological challenges

A second striking observation of our review is the substantial heterogeneity in how culture is conceptualised and operationalised, reflected in seventeen distinct cultural concepts with limited shared frameworks or reproducible methodologies across studies. This heterogeneity could stem from the interdisciplinary nature of the field (e.g. architecture, place studies, engineering; see Table 3), which brings different theoretical lenses and methodological traditions to bear on cultural phenomena. Additionally, researchers invoke culture to explain phenomena as diverse as individual risk perceptions and local identity to governance forms [67].

The heterogeneity also reflects culture's inherently context-dependent nature, as evidenced by most studies that relied on inductive approaches in which cultural themes emerged from empirical data without predetermined theoretical grounding. Culture is predominantly discussed descriptively rather than operationalised and measured systematically. Only four studies employed an established theoretical framework or theories deductively [23], [27], [29], [44]. Two arguments may explain this descriptive preference.

From an epistemological perspective, this descriptive preference reflects a philosophical split between "erklären" (explaining) versus "verstehen" (understanding), with researchers implicitly recognising culture as a phenomenon that must be understood rather than merely explained through causal mechanisms [68], [69]. Culture is inherently context-bound in ethnographic research (e.g. Refs. [26], [29], [42]); cultural meanings and valuations vary significantly between communities. In this view, contextual specificity is not a methodological weakness but a characteristic of cultural phenomena as each culture is different (e.g. Ref. [47]). This raises a critical question: should we necessarily strive for homogeneous and consistent approaches to studying culture, or does the pursuit of universal frameworks risk reducing culture to oversimplified categories that fail to capture its essential contextual nature? If culture is defined in context-specific rather than general terms, empirical insights into comparable cultural phenomena may have completely different meanings for distinct groups, limiting systematic knowledge accumulation and, in turn, how culture is measured.

From a methodological perspective, the conceptual ambiguity may have contributed to the lack of consensus on which cultural aspects to measure and how, leading to a lack of agreed-upon cultural indicators and struggles to balance analytical rigour with culture's context-dependent nature. Without standardised frameworks for measuring culture, researchers often default to descriptive approaches that document cultural phenomena. This manifests in a tension between qualitative and quantitative methods: qualitative approaches capture cultural nuances and place-specific dynamics but fragment knowledge into isolated case studies with limited transferability. Conversely, quantitative research approaches can facilitate systematic cross-cultural comparisons and identify why acceptance is significantly lower in some areas than in others. However, standardised indicators risk misrepresenting stakeholder concerns and cultural subtleties, particularly for intangible cultural assets [65]. Cross-regional comparisons remain scarce [11], leaving the field trapped between fuzzy descriptions that resist generalisation and hard measurements that may distort cultural realities. This tension is reflected in theory development: greater abstraction expands scope but reduces analytical precision, while increased complexity aids understanding but resists empirical operationalisation [70].

Without analytical precision, culture risks becoming an explanatory catch-all that obscures rather than clarifies the mechanisms through which social contexts shape energy project outcomes. This mirrors broader critiques of culture's role in sustainability research, where culture is often described as part of social sustainability without systematic analytical integration [71]. Without specification, it becomes difficult to distinguish between cultural factors and other social variables, potentially leading to misattribution of social phenomena to cultural causes when alternative explanations might be more appropriate.

If researchers avoid standardised cultural frameworks because culture is inherently context-specific, the field cannot develop comparative knowledge to distinguish context-dependent cultural aspects from generalisable ones. While the observed fragmentation may reflect early-stage domain development rather than conceptual impossibility, progress requires researchers willing to propose and test standardised local culture frameworks across multiple community contexts.

4.2. The othering of culture

A third and final important insight from our review is that the literature predominantly focuses on local communities as cultural actors, neglecting other stakeholders such as developers, engineers and policymakers. This is also reflected in the disciplinary concentration of the included studies: the literature drew from social geography, anthropology and policy studies, with engineering and technical disciplines largely absent. Culture research in the latter discipline could reveal how cultural values shape scientific facts and technological artefacts and how these determine what counts as valid knowledge and acceptable uncertainty.

The narrow focus risks reproducing an othering of culture: while culture is treated as something local and indigenous communities have, other actors are implicitly treated as rational, interest-driven actors rather than as actors shaped by cultural frameworks. This pattern of concentrating on local communities is also visible in the broader literature on controversies in renewable energy technologies, where studies tend to concentrate on actors that are seen as potentially problematic: opponents that might try to stop project development, the public who might not accept a technology, or local communities that may turn into "NIMBYs" once hearing of development plans in their area [72]. This constitutes a gap: rather than recognising that all actors bring cultural assumptions to geothermal development, existing knowledge about cultural dynamics remains largely confined to local communities.

Attention to this gap is critical, as geothermal development is influenced by the cultural assumptions of all actors involved, not just local communities. For instance, engagement processes are shaped by organisational cultures, place, project partners' social networks, and organisational dynamics within partnerships [73], [74], [75]. Yet, existing GE research asks developers to explain project delays but rarely investigates how their own assumptions, biases and decision-making processes may have contributed to them (e.g., Ref. [41]). This suggests that the acultural framing of developers, engineers and policymakers in the literature warrants explicit attention, as it obscures how their cultural assumptions influence project development in practice.

When project developers' cultural assumptions and subsequent communication strategies misalign with how communities experience their local culture and how they expect to be engaged, prioritising project approval over genuine dialogue, this can quickly erode trust and reduce acceptance [76], [77]. For instance, geothermal proponents who adopt masculine rhetoric inspired by the oil industry, emphasising patriarchal values and practices, to appeal to conservative policymakers, risk losing the support of local communities whose cultural values conflict with such extraction narratives [78]. The problem potentially intensifies when practitioners engage through their own cultural assumptions without recognising how these frameworks may clash with local values and priorities, inadvertently deepening the very opposition they seek to overcome.

4.3. Limitations, implications and future research

During our research, we recognised certain limitations of the present study. First, our methodological choices limit the generalisability of findings across the global geothermal industry. Our final sample of 29 papers over a period of twenty-four years reflects strict inclusion criteria prioritising explicit cultural analysis over broader social acceptance or community values literature, English-language publications without paywalls or access barriers and exclusion of geotourism and broader energy transition papers. These choices likely missed cultural dynamics captured indirectly and underrepresented scholarship from non-English publications (Indonesian, Portuguese and Spanish [79]) in geothermally significant regions such as Indonesia, the Philippines and Latin America. Furthermore, the literature is heavily focused on countries with long-established geothermal sectors, which may differ from those where communities lack established cultural frameworks for interpreting subsurface technologies and governance around GE development. Consequently, the findings apply most confidently to contexts with strong cultural markers, where cultural dynamics are articulated explicitly in support of or opposition to dedicated geothermal projects, rather than embedded in broader cross-technology and energy contexts. Therefore, researchers and practitioners should treat the identified cultural processes and pathways as a starting point for applying local culture in their work.

Second, the included studies vary in design, analytical depth and reporting transparency. While all papers were peer-reviewed, the findings should not be interpreted as equally supported across studies. Notably, however, the themes identified in this review draw most extensively on studies employing multiple complementary methods, such as combinations of interviews, ethnography and content analysis, which carry stronger evidentiary weight. This review highlights patterns reflected across a diverse evidence base, with the most recurrent themes supported by the most methodologically robust studies.

In sum, our findings have important implications for practitioners and researchers in GE development. For practice, these findings can inform culturally sensitive engagement strategies that treat culture as a potential enabler rather than a barrier. Practitioners are encouraged to engage in genuine dialogue that considers both pathways: mapping pre-existing cultural frameworks before project planning begins and continuously monitoring how project development transforms local culture during and after implementation. Concretely, this implies three steps. First, before engagement begins, the practitioner could conduct a cultural scoping exercise to identify the cultural processes: what place identity, perceptions of the underground and practices are associated with the project area; what governance traditions shape legitimate decision-making; and what prior experiences have shaped local trust. Second, engagement processes should respect local governance. Co-creative workshops can facilitate mutual learning, shared expectations and partnership ownership, ensuring that designs reflect local, situated knowledges [80], as demonstrated by the M ā ori-based approach of Taute et al. [49]. Critically, practitioners should remain alert to how their own cultural assumptions, including techno-economic framings inherited from fossil fuel industries, may inadvertently shape their imagination of the community. Third, CIAs could move beyond standardised checklists toward participatory monitoring of both tangible dimensions (heritage sites, landscapes and practices) and intangible ones (place identity, sense of belonging and energy visions), attending to both pathways: whether pre-existing local culture is respected and how project development itself activates or reactivates new cultural impacts.

For research, two priorities emerge. First, addressing the observed heterogeneity requires moving beyond description towards shared analytical starting points. We propose developing systematic frameworks to measure the dynamic, complex and emergent role of culture in energy projects. This requires clearly defining which cultural dimensions are examined, developing validated measurement instruments that balance analytical rigour with cultural sensitivity and conducting comparative studies aiming to explain how specific cultural factors influence project responses differently across locations. To make such frameworks operational, future studies should at minimum, report the following aspects when addressing culture in energy research: (1) the criteria used to delineate culture (e.g., geographic, social, institutional); (2) the conceptualisation of culture, whether it is treated as a pre-existing interpretive lens, as dynamic and shaped by projects, or both; (3) the cultural dimensions examined and whether these are derived inductively or deductively; (4) the actor groups under consideration and the extent to which intercultural dynamics are addressed; and (5) the implications of the method and data collection for comparability.

Second, research should expand beyond the dominant community focus to examine the cultural assumptions of project developers, policymakers, engineers and other stakeholders, particularly how these shape engagement approaches. Methods such as Q-methodology [38] and behavioural systems mapping to analyse actor behaviours [80] can explore cultural biases, cultural misunderstandings, and intercultural dynamics between stakeholder groups. Analysing such engagement practices across diverse project contexts can help establish broader guidelines for culturally sensitive engagement.

5. Conclusion

Although geothermal energy plays a significant role in the energy transition in some countries, it remains underutilised globally. This study investigated the role of culture in geothermal energy projects within the broader energy transition. The analysis, based on a systematic literature review, adds to the intensifying scientific and practical debate on how to improve cultural sensitivity in energy projects, an improvement that is increasingly being put on the agenda.

In terms of answering the first research question, "How is (local) culture defined, delineated, operationalised, and studied in research on geothermal energy?", the three research objectives are addressed. Local culture is increasingly considered across disciplines, but it rarely occupies a central analytical position, with most studies treating it as a contextual background rather than the main analytical focus. Culture is conceptualised through seventeen distinct concepts with limited definitional consensus. Through thematic analysis, four processes of culture were identified that explain how culture, in relation to geothermal energy, can be understood: *anchoring culture*, *materialising culture*, *collective meaning-making*, and *transforming culture*. Together, rather than being

static, these processes show how culture emerges and changes through the interaction between communities, environments and technologies. The conceptualisation of the included studies did not inform the scope or analytical delineation of cultures; delineation operates across geographical scales and social groups, but it is often unclear and driven by methodological convenience rather than by cultural criteria. The methodological approaches employed are predominantly inductive and qualitative, particularly interviews. Deductive theoretical frameworks, quantitative measures and cross-regional comparative designs remain scarce, limiting cumulative knowledge-building and the field's capacity to distinguish context-specific from generalisable cultural dynamics.

In terms of answering the second research question, "What insights have existing empirical research generated with regard to the influence of local culture on public perceptions of geothermal energy?", two pathways between culture and geothermal projects were identified. Three themes describe how pre-existing cultural frameworks shape perceptions of geothermal projects: cultural identity and experience of the underground; cultural governance and decision-making norms; and historical experience and technology compatibility. Three themes characterise how geothermal development transforms culture, with outcomes ranging from disruption to innovation: identity erosion and cultural loss, creation of cultural meanings and practices, and trade-offs between economic benefits and cultural preservation.

The findings trigger three broader discussions, suggesting the need for further research. First, the conceptual and methodological state-of-the-art and heterogeneity reflect the inherently context-dependent nature of culture. The critical question is not whether to impose uniform approaches, but how to balance analytical rigour with the recognition that cultural meanings are locally situated and may resist universalisation, thereby contributing to cross-regional comparison. Second, culture simultaneously shapes community responses and is transformed by the project (developers), challenging the view of culture as merely a barrier to overcome. This demonstrates that meaningful engagement must recognise culture as potentially governing, supporting and accelerating energy transitions [60], [61], recognising that communities' concerns extend beyond technical misconceptions to deeper cultural imaginations and values. Third, the predominant focus on local communities obscures the cultural assumptions of project developers and other stakeholders, which may shape project implementation and engagement processes. Understanding these stakeholder cultures can help identify sources of misalignment that erode trust. Advancing emerging technologies requires not only focusing on technological fit but also understanding the cultural dynamics throughout project development and incorporating cultural sensitivity into community engagement processes in energy transitions.

Future research would benefit from moving beyond its current methodological state-of-the-art to develop comparative, validated methodological frameworks across different contexts, while also broadening the scope of inquiry beyond local communities to include the cultures of other stakeholders, whose decisions shape energy projects. This includes extending the scope to non-English geothermal contexts, other renewable energy technologies and the broader energy transitions.

Data statement

No new data were generated.

CRediT authorship contribution statement

Fabiën Dekker: Conceptualisation, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualisation, Writing – original draft.

Toyah Rodhouse: Conceptualisation, Methodology, Supervision, Writing – review & editing.

Gerdien de Vries: Conceptualisation, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Overview publications included in literature review

Table A.1
Papers included in the systematic literature review on the role of culture in geothermal energy research.

Author(s)	Year	Title	Journal	Link
Barr, A., & Talwar, S.	2025	Understanding energy cultures of space heating in Aotearoa New Zealand: A desktop review of slow ground source heat pump uptake.	*Kotuitui*.	https://doi.org/10.1080/1177083X.2024.2445828
Bleicher, A., & Gross, M.	2016	Geothermal heat pumps and the vagaries of subterranean geology: Energy independence at a household level as a real world experiment.	*Renewable and Sustainable Energy Reviews*, *64*, 279–288.	https://doi.org/10.1016/j.rser.2016.06.013
Britton, A., Olmedo, L., Torres, C. A., & Blair, J. J. A.	2024	Hydrosocial imaginaries of green extractivism: Water-energy transitions and geothermal lithium development at the Salton Sea in Imperial Valley, California.	*The Extractive Industries and Society*, *20*, 101567	https://doi.org/10.1016/j.exis.2024.101567
Chavot, P., Heimlich, C., Masseran, A., Serrano, Y., Zoungrana, J., & Bodin, C.	2018	Social shaping of deep geothermal projects in Alsace: Politics, stakeholder attitudes and local democracy.	*Geothermal Energy*, *6*(1), 26.	https://doi.org/10.1186/s40517-018-0111-6

(*continued on next page*)

Table A.1 (*continued*)

Author(s)	Year	Title	Journal	Link
Cook, D., Davíðsdóttir, B., & Malinauskaite, L.	2020	A cascade model and initial exploration of co-production processes underpinning the ecosystem services of geothermal areas.	*Renewable Energy*, *161*, 917–927.	https://doi.org/10.1016/j.renene.2020.07.155
Cook, D., Fazeli, R., & Davíðsdóttir, B.	2019	The need for integrated valuation tools to support decision-making – The case of cultural ecosystem services sourced from geothermal areas.	*Ecosystem Services*, *37*, 100923.	https://doi.org/10.1016/j.ecoser.2019.100923
de Jesus, A. C.	2016	7—Environmental benefits and challenges associated with geothermal power generation.	*Geothermal Power Generation* (pp. 477–498).	https://doi.org/10.1016/B978-0-08-100337-4.00017-6
Guan, Y., Post, S., Zhao, D., Zhang, S., & Becker, S.	2025	Overview of the application status and development trends of hydropower and geothermal power in New Zealand.	*Energy and Built Environment*, *6*(3), 564–584.	https://doi.org/10.1016/j.enbenv.2024.06.003
Ibrohim, A., Prasetyo, R. M., & Rekinagara, I. H.	2019	Understanding Social Acceptance of Geothermal Energy: A Case Study from Mt. Lawu, Indonesia.	*IOP Conference Series: Earth and Environmental Science*, *254*, 012009.	https://doi.org/10.1088/1755-1315/254/1/012009
Jónsson, Ö. D., & Rastrick, Ó.	2017	Enjoying the outdoor pool in a cold climate: Appropriate technology, utilisation of geothermal resources and the socialisation of everyday practices in Iceland.	*Geothermal Energy*, *5*(1), 2.	https://doi.org/10.1186/s40517-017-0060-5
Kamana, N., & Vaughan, M.	2024	Improving collaboration between native Hawaiians and energy professionals to explore geothermal energy potential in Hawai'i.	*Frontiers in Sustainability*, *5*, 1443407.	https://doi.org/10.3389/frsus.2024.1443407
Kong'ani, L. N. S., Wahome, R. G., & Thenya, T.	2021	Variety and management of developmental conflicts: The case of the Olkaria IV geothermal energy project in Kenya.	*Conflict, Security & Development*, *21*(6), 781–804.	https://doi.org/10.1080/14678802.2021.2000806
Lambert, C. E.	2022	Beneath your feet and in your place: Multi-scalar imaginaries of energy, place, and local geothermal development.	*Energy Research & Social Science*, *94*, 102856.	https://doi.org/10.1016/j.erss.2022.102856
Lambert, C. E., & McComas, K. A.	2020	Public Attitudes Towards Enhanced Geothermal Heating: The Role of Place, Community, and Visions of Energy Futures.		
Lampredi, G.	2024	Solastalgia as Disruption of Biocultural Identity. The Mount Amiata Geothermal Conflict.	*Society & Natural Resources*, *37*(11), 1508–1527.	https://doi.org/10.1080/08941920.2024.2381204
Mahamoud Abdi, A., Murayama, T., Nishikizawa, S., & Suwanteep, K.	2024	Social acceptance and associated risks of geothermal energy development in East Africa: Perspectives from geothermal energy developers.	*Clean Energy*, *8*(5), 20–33.	https://doi.org/10.1093/ce/zkae051
Mahamoud Abdi, A., Murayama, T., Nishikizawa, S., Suwanteep, K., & Obuya Mariita, N.	2024	Determinants of community acceptance of geothermal energy projects: A case study on a geothermal energy project in Kenya.	*Renewable Energy Focus*, *50*, 100594.	https://doi.org/10.1016/j.ref.2024.100594
Mariita, N. O.	2002	The impact of large-scale renewable energy development on the poor: Environmental and socio-economic impact of a geothermal power plant on a poor rural community in Kenya.	*Energy Policy*, *30*(11), 1119–1128.	https://doi.org/10.1016/S0301-4215(02)00063-0
Meller, C., Schill, E., Bremer, J., Kolditz, O., Bleicher, A., Benighaus, C., Chavot, P., Gross, M., Pellizzone, A., Renn, O., Schilling, F., & Kohl, T.	2018	Acceptability of geothermal installations: A geoethical concept for GeoLaB.	*Geothermics*, *73*, 133–145.	https://doi.org/10.1016/j.geothermics.2017.07.008
Nursanty, E., Cauba Jr, A. G., Rusmiatmoko, D., & Destiawan, W.	2024	Green Metropolis: Balancing Sustainable Energy Innovations and Authentic Urban Landscapes.	*E3S Web of Conferences*, *547*, 03010.	https://doi.org/10.1051/e3sconf/202454703010
Pellizzone, A., Allansdottir, A., De Franco, R., Muttoni, G., & Manzella, A.	2017	Geothermal energy and the public: A case study on deliberative citizens' engagement in central Italy.	*Energy Policy*, *101*, 561–570.	https://doi.org/10.1016/j.enpol.2016.11.013
Ratio, M. A., Gabo-Ratio, J. A., & Tabios-Hillebrecht, A. L.	2019	The Philippine Experience in Geothermal Energy Development.	*Geothermal Energy and Society* (Vol. 67, pp. 217–238).	https://doi.org/10.1007/978-3-319-78286-7_14
Roos, A.	2024	Renewing the Subterranean Energy Regime? How Petroculture Obscures the Materiality of Deep Geothermal Energy Technology in Sweden.	*Ecological Economics*, *219*, 108129.	https://doi.org/10.1016/j.ecolecon.2024.108129
Shortall, R., & Kharrazi, A.	2017	Cultural factors of sustainable energy development: A case study of geothermal energy in Iceland and Japan.	*Renewable and Sustainable Energy Reviews*, *79*, 101–109.	https://doi.org/10.1016/j.rser.2017.05.029
Taute, N., Morgan, K., Ingham, J., Archer, R., & Fa'aui, T.	2022	Māori values in geothermal management and development.	*AlterNative: An International Journal of Indigenous Peoples*, *18*(4), 548–555.	https://doi.org/10.1177/11771801221118629
Taute, N., Morgan, T. K. K. B., Ingham, J., Archer, R., & Fa'aui, T.	2023	Cultural sustainability thresholds to measure the mauri of Indigenous Māori values impacted by geothermal engineering projects.	*Environmental and Sustainability Indicators*, *20*, 100303.	https://doi.org/10.1016/j.indic.2023.100303
Thórhallsdóttir, T. E.	2007a	Environment and energy in Iceland: A comparative analysis of values and impacts.	*Environmental Impact Assessment Review*, *27*(6), 522–544.	https://doi.org/10.1016/j.eiar.2006.12.004
Thórhallsdóttir, T. E.	2007b	Strategic planning at the national level: Evaluating and ranking energy projects by environmental impact.	*Environmental Impact Assessment Review*, *27*(6), 545–568.	https://doi.org/10.1016/j.eiar.2006.12.003
Vargas-Payera, S., Ibarra, C., & Hurtado, N.	2023	Social and cultural aspects in the adoption of geothermal heat pump systems to replace wood-burning heaters in educational spaces: The Chilean Patagonian case.	*Journal of South American Earth Sciences*, *128*, 104426.	https://doi.org/10.1016/j.jsames.2023.104426

Appendix B. Meta-analysis of included in literature review

Table B.1
Overview of the selected papers' characteristics on culture-in-geothermal energy research.

Author (s)	Location	Application, depth	Concept/theory	Actor	Scale	Method
[4]	Viterbo, Italy	Electricity 1000m depth	Culturally sustainable innovation for energy societies framework	Community in region	Regional	Focus groups and questionnaire
[9]	Mindanao, Philippines	Electricity No depth specified	No concept or theory related to culture	Indigenous community	Local	No method specified
[24]	Iceland, Japan	Heat & electricity Japan: 3000m	Hofstede cultural dimensions. National culture	National habitants	National	Literature review and interviews
[25]	East Africa	Electricity No depth specified	Local culture	Indigenous community	Local	Interviews
[26]	Eurometro-polis of Strasbourg, France	Enhanced geothermal systems, heat & electricity >3000m depth	Social worlds, social identities, locally anchored and unbound projects	Community and politicians in regions	Regional	Content analysis and interviews
[27]	Salton Sea region of California, United States	Electricity with direct lithium extraction No depth specified	Sociotechnical imaginaries, hydrosocial imaginaries	Residents in region	Regional	Community-based participatory research: content analysis and interviews
[28]	Aotearoa (New Zealand)	Ground source heat pumps Shallow depths (5-200m)	Energy Cultures Framework	Households and businesses	National	Literature review
[29]	Germany	Ground source heat pumps Shallow depth	No concept or theory related to culture	Households in regions	Regional	Interviews, literature review and content analysis
[30]	Aysén Patagonia, Chile	Ground source heat pumps, heating Shallow depths	Social practices: competence, materialities and cultural meanings.	People in specific facilities	Facilities	1. Interviews 2. Ethnography
[31,32]	Iceland	Electricity No depth specified	Cultural heritage	National habitants	National	Workshops
[33]	Cities in Indonesia and the Philippines	Electricity & heat No depth specified	City authenticity, cultural preservation	Community in city	City	Interviews, questionnaire and content analysis
[34]	New Zeeland	Electricity No depth specified	Māori culture	Indigenous community	National	No method specified
[38]	Rift Valley region, Olkaria, Kenya	Electricity Shallow depths	No concept or theory related to culture	Indigenous community in 10 km range	Local	Interviews and discussions
[39]	Sweden	Heat & electricity Deep depth	Petrocultural assumptions	Geothermal energy professionals	National	Literature review, Q-sort and interviews
[40]	Campus of Cornell University, US	Enhanced geothermal, deep depths Heating	Place imaginaries, sociotechnical imaginaries	Residents across geographical scales	National, regional, local and campus	Content analysis
[41]	Tompkins County, New York	Enhanced geothermal, deep depths Heating	Place attachment, place-technology fit, visions of energy futures	Residents in region	Regional	Focus groups
[42]	Kenya, Olkaria	Electricity No depth specified	No concept or theory related to culture	Indigenous community	Local	Questionnaire
[43]	Mount Amiata, Tuscany, Italy	Electricity No depth specified	Biocultural identities, solastalgia	Residents in region	Regional	Ethnography, interviews and informal conversations and content analysis
[44]	No specific location	No application and depth specified	Cultural ecosystem services	Individuals	No scale specified	Literature review
[45]	No specific location	No application and depth specified	Cultural ecosystem services	Individuals	No scale specified	No method specified
[46]	No specific location	Electricity & heat 2000 m depth	Cultural identity	Individuals	No scale specified	No method specified
[47]	Iceland	Heat & electricity No depth specified	Pool culture, culture adoption	National habitants	National	No method specified
[48,50]	New Zealand	No application and depth specified	Cultural sustainability indicators	Indigenous community	National	Workshops
[49]	Olkaria, Kenya	Electricity No depth specified	No concept or theory related to culture	Indigenous community	Regional	Questionnaire, focus groups and interviews
[51]	Mount Lawu, Indonesia	Electricity 500-800m depth	No concept or theory related to culture	Indigenous community	Local	Interviews
[52]	Hawaii	Electricity No depth specified	Cultural identity and beliefs	Island inhabitants	Island	Interviews
[54]	No specific location	Heat & electricity No depth specified	No concept or theory related to culture	Individuals	No scale specified	No method specified

Appendix C. Overview of themes per culture definition

Table C.1
Concepts and definitions of culture in the culture-in-geothermal energy studies for thematic analysis of culture definitions.

Author	Concept	Explicit definition	Field	Codes in cultural processes
[24], p. 101]	National culture	"Cultural characteristics can be defined as socially constructed phenomena resulting in collective meanings in a shared social environment. Common cultural characteristics within a nation, including perception of identity, values, and history can be defined as embodying a national culture [9,16]. Cultural factors are deeply rooted in a society, are slow to change, and determine the behaviour of individuals and groups towards risk, conflict resolution, and the social and institutional capacity for sustainable transformations [81,16,41,42,53]."	*Cultural adoption*	Anchoring: shared social environment, group behaviour Meaning-making: group orientation Transforming: slow to change
[26], p. 4]	Social identities	"a set of beliefs, practices, cultural elements, constitutive of a way of living and experiencing a living space that is robust enough to withstand exogenous threats."	*Identity studies*	Anchoring culture: beliefs, practices, way of life Materialising: living space Transformation: withstand exogenous threats
[26], p. 5]	Social worlds	"Garrety (1997) defines "social worlds" as relatively structured social units sharing a body of knowledge. These are characterized by a common commitment to priorities about what is important and what needs to be done. Each actor participates in different social worlds organized around religious or political convictions and the worlds of work, leisure, and community life. However, social worlds are not fixed entities but are constantly re-configured and re-organized. One of the main characteristics of social worlds is their supply of statuses, arguments, and resources intended to support the legitimacy of the actions and knowledge of the actors."	*Identity studies*	Anchoring: social environments Meaning-making: group orientation, shared knowledge Transforming: reconfigured and re-organized
[27], p. 3]	Sociotechnical imaginaries	"Jasanoff and Kim (2009, p. 120) define sociotechnical imaginaries as "collectively imagined forms of social life and social order reflected in the design and fulfilment of nation-specific scientific and/or technological projects."	*Place and Imaginaries*	Meaning-making: social life, social order
[28], p. 8]	Energy cultures framework	"The Energy Cultures Framework (ECF), developed by Stephenson et al. (2010), provides a widely used conceptual lens to study interactions between energy technologies, people, and their environments. The ECF explores energy behaviour through the interplay of cognitive norms (beliefs and perceptions), material culture (technologies and infrastructure), and energy practices (daily activities). Rooted in systems theory, the framework offers a heuristic rather than prescriptive model to explain energy-related behaviours (Stephenson et al., 2010). Politically, the framework's value lies in highlighting hierarchical structures in energy ownership and decisionmaking processes."	*Cultural adoption*	Anchoring: norms, energy practices Materialising: tangible technology and infrastructure
[30], p. 4]	Social practices	"As Shove et al. (2012) argue, social practices are composed of three key elements: experiences or empirical knowledge (competence), materialities (artefacts/technologies) and cultural meanings."	*Cultural adoption*	Materialising: tangible technology Transforming: interaction
[32], p. 553]	Cultural heritage	"Archaeological remains, sites of historical importance, and legends Farm ruins, cairns, goose pens, historical inland routes, battlegrounds, and cursed sites."	*Architecture*	Materialising: tangible and intangible heritage
[33], p. 1]	City authenticity	"The concept of city authenticity, though often subjectively interpreted, broadly encompasses the preservation of tangible and intangible heritage that gives a city its unique character and identity [3]. Authenticity can be influenced by various factors, including architectural styles, historical landmarks, urban layout, and the lived experience of the city's inhabitants [4]."	*Architecture*	Materialising: tangible and intangible heritage, city authenticity
[39], p. 3]	Petro-cultural assumptions	"Studies have shown how assumptions encouraged by fossil metabolism (henceforth "petrocultural assumptions") inhibit the understanding of today's fossil dependency, while also limiting the scope of emancipatory imaginaries (Szeman and Petrocultures Research Group, 2016)."	*Professional culture*	Not applicable
[40], p. 2]	Sociotechnical imaginaries	"Sociotechnical imaginaries are "collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology" [6,p.4]; they encode what is viewed as both achievable and societally desirable through technology. The term "imaginaries" refers to systems of meaning that are communally shared, are expressed through images, language, and stories, and generate common understandings and shared senses of legitimacy [27], [28]. Sociotechnical imaginaries can explain divergences in energy policies, research and development investments, and preferences for different forms of technology; underlying energy imaginaries shape weighting of risks and benefits, priorities, and visions of decarbonization, leadership, and innovation [3], [29]."	*Place theory and imaginaries*	Meaning-making: institutionalised, shared understanding
[40], p. 3]	Place imaginaries	"Place imaginaries encompass collective understandings of a distinct place, drawing on both narratives of the past and visions of what the future should look like for the place [4,52]."	*Place and Imaginaries*	Materialising: understanding of place

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Table C.1 (*continued*)

Author	Concept	Explicit definition	Field	Codes in cultural processes
				Meaning-making: group orientation
[41], p. 693]	Place attachment, place-technology fit, visions of energy futures	"Place theory has been used to explore the influence of emotional bonds to a place (place attachment) and the meanings attributed to a place on residents' reactions to local changes and disruptions brought on by energy developments. Place attachment can be a driver of opposition to land use changes, due to the perceived threat of disruption (Jacquet and Stedman, 2014); whether a technology is viewed as a potential threat is related to how consistent the symbolic interpretation of the technology is with symbolic meanings of place (Devine-Wright, 2009; McLachlan, 2009). This concept of "place-technology fit" proposes that opposition is driven by perceived contradictions between interpretations of place and technology. Besides the interaction of subjective interpretations of place and technology, also relevant is the interaction between perceptions of an individual energy technology like EGS and visions of energy futures in a community. The overarching visions and narratives held around energy transitions shape how development unfolds and the decisions that are made in choosing among alternatives (Sovacool, 2019)."	*Place and Imaginaries*	Materialising: place attachment Meaning-making: shared understanding
[43], p. 1512]	Solastalgia	"Solastalgia is a form of distress induced by negative environmental changes in which the comfort of feeling "at home" is lost. The disturbance of one's way of being at home can result in social, psychological, and moral damage to individuals. The discomfort is produced by environmental changes in individuals who are linked to that environment on a daily basis. It is an attack on the sense of place, causing an erosion of the sense of belonging that people experience emotionally."	*Identity studies*	Materialising: sense of place Transforming: disruption
[43], p. 1513]	Biocultural identities	"When local populations are economically and culturally reliant on the natural environment, biodiversity, and the cultural significance associated with them, these elements become integral to the identities of local people (Cavaliere and Branstrator 2024; Bridgewater and Rotherham 2019). If biocultural identities consist of "the intertwining of social-ecological relationships and diverse knowledges that situate characteristics within bioregional constructs" (Cavaliere and Branstrator 2024, 217) extends to concepts such as place identity (Daneri, Krasny, and Stedman 2021), place attachment (Devine-Wright 2009), and sense of place (Rajala, Sorice, and Thomas 2020), making the link between socio-ecological relationships (with vegetation, crops, endangered animals, landscapes, etc.) more explicit, as well as the tacit and situated cultural knowledge that is involved in these socio-ecological practices."	*Identity studies*	Anchoring culture: reliance on natural environment Materialising: place attachment, place identity Meaning-making: knowledge systems
[44], p. 4]	Cultural ecosystem services	"Preferences for cultural ES, such as spiritual enrichment, are often formed collectively based on Traditional Knowledge (Martín-López et al., 2014), involve interactions with formal and informal governance institutions (CAFF, 2015), and occur through direct relationships with an environment rather than instrumental or intrinsic associations (Chan et al., 2016). In these cases, which are often common in indigenous communities where notions of the sacredness of land are important, willingness to pay for a particular service is likely to be zero, yet these individuals will still hold a value in socio-cultural terms (Cooper, 2009; Zeppel, 2009; Martín-López et al., 2014)."	*Cultural ecosystems*	Materialising: sacredness of land Meaning-making: knowledge systems
[45], pp. 919-920]	Cultural ecosystem services	"cultural ES will often concern with direct or indirect interactions between human beings and an ecosystem, in addition to value attribution connected to its existence."	*Cultural ecosystems*	Transforming: interactions
[46], p. 136]	Cultural identity	"Identification in a spatial context denotes the mental and cultural fitness or matching of the proposed project with the familiar natural and social environment."	*Identity studies*	Anchoring: social environment Materialising: place identity

Appendix D. Overview of included studies in thematic analysis of empirical insights per theme

Table D.1
Empirical findings in the selected papers on the role of culture in geothermal energy fitting to the theme "cultural identity and experience of the underground"

Study	Statement relating to *cultural identity and experience of the underground*
[9], p. 229]	"The project is located within a national park and an ASEAN heritage area while it was also considered the ancestral home by indigenous cultural communities/ indigenous people (ICC/IP) who believed that their god resides in the mountain. The project was charged with violation of Philippine National Park Laws and its international commitment to ASEAN."
[24], p. 108]	"Given the opposition of onsen owners to geothermal development in Japan due to fears of resource depletion, this is a tactic that could also be used by Japan in the future, if geothermal energy is to be expanded in popular onsen areas."
[25], p. 27]	"Rural communities usually have high cultural, religious, and sentimental attachments to land. Involuntary resettlement to new land can be refused by community members if the new land is not per their expectations or activities in their land."

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Table D.1 (*continued*)

Study	Statement relating to *cultural identity and experience of the underground*
[26], p. 19]	"In Illkirch Graffenstaden and Northern Alsace, geothermal energy fits with long-lasting environmental policies and actions—engagement in local climate plans, for instance—and sustainable economic development, consistent with local social identities. On the opposite, in the western municipalities of EMS and in the Robertsau sector, the geothermal project disrupts the local communities' sets of values, practices and engagements, starting with the attachment to local democracy and to the right to have a say in environment and urban development projects."
[27], p. 6]	"This is our spiritual home. So when you're doing your geothermal thing, please think about that, that steam is the spiritual essence of the people of this earth. That is a healing process, not an economical game thing."
[40], p. 5]	"Local leadership as a climate-forward, sustainable community, "sustainable but practical" energy transition relying on a mix of proven technologies Maintaining rural place character Opposing fracking Clean energy jobs, economic growth, and revitalization."
[41], p. 695]	"In all five focus groups, the central challenges and opportunities that participants identified for the area focused on land use and development, inequality, transportation and growth overall. While the rural nature of the area was often cited as one of the characteristics that participants most valued, discussions of changing land use in the county identified tensions between farming, housing, and energy projects, with concerns about reductions in agricultural acreage changing the rural character. A desire of "keeping farmland" expressed by some was countered by acknowledged needs to address local housing shortages. Other concerns that were raised involved impacts from climate change, local vs. outside ownership, and balancing increased opportunities and growth with changes to local character."
[43], p. 1516]	"The mountain hosts a variety of centers of worship (not only Christian), all of which are connected in some way to the subterranean warmth of the mountain. This is the very same heat that is used by geothermal plants to produce electricity."
[48], p. 3]	"Mauri as the binding force between the physical and the spiritual, where if actions impact negatively upon the mauri of something then the essential bond between its physical presence and its spiritual liveliness is weakened."
[50], p. 553]	"These discussions concluded that geothermal resources are often perceived as a physical representation and a point of remembrance for some of the historical occurrences described in Māori mythology. As such, geothermal resources facilitate a spiritual connection between Māori, their ancestors, and the gods."
[52], p. 6]	"Some interviewees emphasized the uniqueness and cultural significance of geothermal resources they felt should be viewed as a gift from the Akua (Gods) that can be utilized for the betterment of Hawai'i's people."

Table D.2
Empirical findings in the culture-in-geothermal energy studies fitting to the theme "cultural governance and decision-making norms."

Study	Statement relating to *cultural governance and decision-making norms*
[4], p. 566]	"Local and distributed knowledge is also mentioned as an important resource for energy choices. The formation of experts that are both educated and local people could form competent, conscious and reliable people that can be consulted in case of necessity: "In my opinion, we should collect information from experts and people living here that have a local knowledge. This could be strategic" (Environmental focus group)."
[24], p. 107]	Japan: "Its slow decision-making process has been more so attributed to the need for consensus between levels rather than things being decided from the top down." "Iceland has more appetite for risk while Japan does not, which means that Iceland's approach may lead to unintended consequences, but at the same time it may foster more innovation based on learning from past mistakes and the fulfilment of its geothermal energy capacity. Japan on the other hand has been slower in leveraging its geothermal capacity, most critically after the Fukushima calamity, to diversify and progress towards more sustainable energy resources."
[26], p. 19]	"However, the emphasis on the risks involved in the GP debate may serve different logics. In La Robertsau, it enabled the banishment of the GP from the industrial zone of the oil port in order "not to add risk to risk". In that case, dealing with risk and the desire to reduce the number of risky installations in the neighborhood is inscribed in the social identity of La Robertsau residents, in effect legitimizing the opposition to the GP. In the western communities of the EMS, publicity about the risks involved plays a more rhetorical role. It provides the necessary foundation for a set of demands by the small municipalities directed toward the operator and EMS. Because the installation of a geothermal power plant is "costly" in terms of risks, the municipality can ask for compensation, which can be financial (sharing royalties) or political."
[28], p. 21]	"Combined, these findings suggest that the legacy of inadequate space heating, dominance of alternative space heating options, government favouring of other sustainable technologies, low levels of awareness and public risk aversion, have worked to limit the growth of the GSHP industry in New Zealand."
[41], p. 696]	"Trust in the university varied considerably and was central to the discussions of the Earth Source Heat project; a lack of trust in how the project would be managed and how much input the public would have enhanced participants' perception of the potential for negative impacts."
[42], p. 11]	"The survey results reflect the particularities of the pastoral communities affected by the project. However, the collision between exclusive community reliance on the elderly and corporate interests in developing a particular project can lead to favoritism, elitism, and corruption, resulting in feelings of isolation and powerlessness among the other members of the community."
[50], p. 549]	"The adopted research methodology followed the principles of a traditional educative Māori gathering, known as wānanga (Māori-based workshops). Wānanga is the term used to describe any interaction between Māori in which the development of further understandings of mōhiotanga Māori is the goal. Wānanga may be considered a form of participatory action research (Dickens & Watkins, 1999). However, wānanga are unique in that their structure incorporates Māori protocol to establish a sense of belonging in the participants, a sense of relationship, and a sense of formality to differentiate wānanga as a legitimate research methodology rather than casual discussion."

Table D.3
Empirical findings in the culture-in-geothermal energy studies fitting to the theme "historical experience and technology compatibility."

Study	Statement relating to *historical experience and technology compatibility*
[28], pp. 15, 21]	"A norm the research suggests is that New Zealanders often forgo indoor thermal comfort and 'put up' with being cold.", "New Zealand homeowners have low levels of awareness of GSHP technology and uses of low-temperature geothermal energy." "However, risk aversion towards new, and innovative and sustainable energy solutions, across both residential and non-residential population clusters remains high."
[29], p. 10]	"The differences in the distribution of shallow geothermal energy installations may be rooted not only in different institutional developments since the early 1990s but also in a fundamentally different way of perceiving the geological underground as a place for energy utilization stemming from the pre-1990 socialist era."
[40], p. 6]	"Prior experiences with solar and wind projects in the area also led to concerns about lack of proper governance of energy projects and impacts to the county's rural character through loss of agricultural land."
[50], p. 552]	"In discussions regarding the history of conflict between Māori and non-Māori, it was described that despite the early definition of Māori sovereignty in Aotearoa's founding document, Te Tiriti ō Waitangi (The Treaty of Waitangi) 1840, hereafter Tiriti, such sovereignty was seldom respected by the European settlers who breached the Tiriti numerous times to acquire land and natural resources."
[52], p. 6]	"All interviewees articulated the need to rebuilding collaboration and trust lost due to past developments, including early geothermal projects, failing to include indigenous communities, acknowledge their concerns, and respect local and cultural knowledge." "*Trauma from (the overthrow and) settler colonialism is never ending …*"

Table D.4
Empirical findings in the culture-in-geothermal energy studies fitting to the theme "identity erosion and cultural loss."

Study	Statement relating to *identity erosion and cultural loss*
[9], p. 227]	"Since most geothermal sites are located in mountainous areas in ICC/IP ancestral domain, major cultural impacts are encroachment to ancestral lands, desecration of ancestral sites, and hindrance to practice their traditional way of life (i.e. nomadic lifestyle, hunting and gathering, among others)."
[25], p. 28]	"geothermal energy development can also have social risks, including forced displacement of local communities, involuntary resettlement, traditional and cultural loss, and social exclusion."
[26], p. 19]	"Projects that appear to be disconnected from local concerns or to only involve minor participation of elected officials and local citizens risk being perceived as imposed from the top down and thus potentially rejected."
[33], pp. 4, 6]	"Geothermal plants have a low surface footprint, which makes them less intrusive compared to other renewable technologies, thereby supporting the preservation of urban authenticity in terms of landscape and cultural heritage." "Most geothermal facilities are located underground or at least have a minimal surface footprint, making them one of the least intrusive forms of sustainable energy in terms of physical and visual impact."
[38], pp. 1125, 1126]	"Their cultural values being eroded by outsiders." "To a large extent the project has opened up this community "to the outside world'' by the construction of infrastructure such as roads and telecommunication, making access to markets and other facilities possible."
[39], pp. 3, 6, 7]	"All viewpoints identified access to capital as the most important prerequisite for deep geothermal development" "Notably, the viewpoints unanimously prioritize access to capital over access to physical resources, even if the energy needed for the drilling requires >70% of the capital expenditures." "This form of nafthism abstracts the biophysical implications of drilling thousands of meters into the Earth, reducing it to questions of finance, geology, and technological innovation." "Nafthism takes on a myriad of other expressions, which can all be understood as variations on an alienated subjectivity with a difficulty accounting for the material requirements of commodities, technological progress, and economic development."
[43], pp. 1518–1519]	"The identity of Mount Amiata disappears once and for all. Our sense of belonging will disappear and will be replaced by the geothermal culture and landscape, while we already have a solid economy linked to tourism and the quality of agri-food products. This cultural shift is already happening. They're coming into our schools saying, "We're going to give you a new school, a swimming pool, projects and more." (Sara, resident activist)"
[49], p. 796]	"But contrary to the cultural value that the Maasai have traditionally placed on *manyattas*, the majority of the respondents were excited about the prospect of owning new modern houses at the RAPland site. However, the new arrangement was not compatible with tradition where each wife and mature son owned and lived in individual *manyattas*. Forethought and better planning would have provided for customarily acceptable relocation units for the respondents that catered to the different needs of daughters, sons, wives and husbands."
[50], p. 553]	"The discussions finally highlighted many injustices that had occurred to Māori and provided justification for Māori distrust and scepticism towards modern geothermal management regimes. While this Māori scepticism may look like innate opposition, this scepticism arises from a concern that decision makers responsible for modern geothermal management and development may not consider the impacts of their decisions as holistically as Māori do. Many Māori today are open to progress via geothermal utilization, appreciating many of the same benefits commonly aspired to by non-Māori. However, given the holistic ethos of Māori, such benefits would be subject to the preservation of spiritual and customary values."

Table D.5
Empirical findings in the selected papers on culture-in-geothermal energy studies fitting to the theme "creation of cultural meanings and practices."

Study	Statement relating to *creation of cultural meanings and practices*
[4], p. 567]	"In this general framework, on the one hand geothermal energy is partially described as an intrinsic component of the environmentaland culturallocal heritage, interconnected with local tradition and promising for the development of new economic initiatives."*We live in a volcanic context, propaedeutic to geothermal studies and investments*" (Stakeholder focus group); "*Our land is full of hot underground waters, but it is not exploited, at least in the Viterbo Province, except from thermal baths*" (Students focus group). Given the local thermal resources, several participants underline that the touristic development of spas is also underdeveloped if not neglected. "*I wonder why they don't renew the old baths. For sure it would be reasonable for the Viterbo*" (Students focus group)."
[24], p. 106]	"Larger scale man-made bathing facilities using geothermally heated water are more common and are found in most settlements around the country. These man-made swimming pools, often also have steam baths or saunas and are a popular location for socializing, especially during the winter months."
[30], pp. 6, 7]	"This difference caused social resistance among users, especially students who usually come to school with wet clothes due to the weather conditions. In this sense, they need a large amount of heat to satisfy their needs. At the same time, the students started their day in the morning around the wood stove as a point of warmth, but also as a meeting point. In this sense, the wood heater was perceived as a place for meeting and socializing. This interaction changed with the introduction of fan coils in the classroom." "In both study cases, several new cultural practices were qualitatively observed. In the case of the geothermal greenhouse, the cultivation and agricultural practices prior to the project were based on highly traditional techniques, so the new system involved new social representations that directly influenced the perception of the project and the integration of agricultural knowledge. In this project, the aim of the geothermal heat pump system was to maintain production in winter, which is not common in the Aysen region due to weather conditions. Thus, year-round farming requires the implementation of new actions as sowing, germination and harvesting were not common in the winter season." "In the first case, important cultural adjustments were ventilation and operating practices. For example, students and teachers used to keep the windows open even when the temperature outside was below zero degrees Celsius. This practice was common because burning wood creates a hot spot. This practice changed with the GHP system, which requires controlled ventilation. Students and teachers changed their practice to ventilate only during breaks." "In this sense, because the GHP system was programmed five degrees lower, the initial perception was marked by social resistance among students and teachers during the first year of project implementation, then this change was not highlighted by the participants in the Coyhaique school." "The routine during the day was to maintain the fire in each classroom. This routine changed with the centralized GHP system. The operator started his routine of checking that the system was working properly, visiting each room, checking the temperature and the windows."
[38], p. 1123]	"A large part of the *Maasai* community as a whole is still entrenched in their traditional way of living; many of their traditional practices are largely intact and the cultural transformation has been slow. Change has occurred in those *Maasai* communities who have come into contact with other communities from other parts of the country, schools, missionaries and development projects. Alteration or destruction of a cultural resource may impair its value. Since cultural resources are unique and non-renewable they require some level of protection."
[43], p. 1519]	"In the municipalities, the economic compensations enabled the construction of a local swimming pool, reduced kindergarten costs, guaranteed catering services in schools, and facilitated various infrastructure projects. These are all services that have a great impact on the quality of social life, in a small community (field diary, November 2021). These services have helped make geothermal energy more acceptable to a part of the local population by significantly reducing costs related to energy and services. However, these initiatives are viewed with anguish and suspicion by anti-geothermal groups, who argue that these services have the dual purpose of: a) increasingly constraining the population economically, making any form of future decommissioning of geothermal power plants impossible; b) imposing a "cultural shift," from a biodiverse landscape (based on conservation of flora and fauna, agrodiversity, agrotourism, natural reserves, thermal centers, etc.) to a

(*continued on next page*)

Table D.5 (*continued*)

Study	Statement relating to *creation of cultural meanings and practices*
	geothermal one. The perception of losing biocultural identity is a source of anguish and frustration. It is the perception of a substitution of culture, from the culture of biodiversity and conviviality to the "geothermal culture" of larger-scale interests spread through a "colonial attitude" and a "predatory philosophy."

Table D.6
Empirical findings in the culture-in-geothermal energy studies fitting to the theme "economic benefit versus cultural preservation."

Study	Statement relating to *economic benefit versus cultural preservation*
[4], pp. 566, 567]	"*Viterbo used to be an agricultural, rural, city. Today it may be different. It has become an industrial city, but with the crisis some industries have declined. Concerning the touristic sector I don't think there is the will to pin on tourism, it is enough to see how scruffy the roads are*" (Citizens focus group). Some participants explicitly asked about the "mission" of the area: "*Where do we want to go? We don't know. We would have the resources: the mountains are close, the sea, the lake, the enviable climate condition …*" (Citizens focus group). However, according to the focus group discussion a clear vision for the future is absent and the local government is not perceived as oriented towards a precise goal. The local University (Università della Tuscia) is also mentioned as a potential interesting sector for the future of the area." "In this general framework, on the one hand geothermal energy is partially described as an intrinsic component of the environmentaland culturallocal heritage, interconnected with local tradition and promising for the development of new economic initiatives."*We live in a volcanic context, propaedeutic to geothermal studies and investments*" (Stakeholder focus group); "*Our land is full of hot underground waters, but it is not exploited, at least in the Viterbo Province, except from thermal baths*" (Students focus group). Given the local thermal resources, several participants underline that the touristic development of spas is also underdeveloped if not neglected. "*I wonder why they don't renew the old baths. For sure it would be reasonable for the Viterbo*" (Students focus group)."
[40], pp. 6, 7]	"These benefits were stated in more concrete terms in the one aspect of an envisioned geothermal future that was shared across all four levels: EGS as the foundation for a clean energy industry fueling job creation, economic growth, and local and regional revitalization." "A focus on innovation and scientific endeavor as key aspects of the project is used to distance EGS from fracking and the oil and gas industry, but is also the source of tension and frustration for local residents whose sense of sustainability leadership includes the need to protect local place character through immediate, pragmatic climate action. Multiple dimensions of local place identity – of the county as rural community, as home to innovation and sustainability, and as site of anti-fracking activism – are exposed and made salient in response to the dominant imaginaries of EGS development, leading to different reactions to the EGS project and to different preferences for future energy development in the area."
[49], p. 796]	"The excitement at the prospect of owning modern houses at RAPland is perhaps an indication of gradual erosion of the Maasai's nomadic pastoralism and cultural values. More evidence of cultural erosion took the form of small-scale farming, where the PAPs planted a variety of food crops including maize, beans, vegetables, bananas and pawpaws, to supplement their main source of livelihood. The seasonal Maasai migration of livestock traditionally enabled them to crisscross different areas including the new site in search for pasture and water for their livestock."

Data availability

No data was used for the research described in the article.

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