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Perspective

Out of steam? A social science and humanities research agenda for geothermal energy

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ABSTRACT

The potential of geothermal energy for energy transition is increasingly recognized by governments around the world. Whether geothermal energy is a sustainable source of heat and/or electricity depends on how it is deployed in specific contexts. Therefore, it is striking that there is only limited attention to geothermal energy from a social science and humanities (SSH) perspective. Geothermal energy is largely conceptualized as a technological and/or geological issue in both science and practice. This perspective article aims to go beyond such conceptualizations by positioning social science research as an important lens to explore the promises and pitfalls of geothermal energy. We first provide an overview of the current state of geothermal energy as a decarbonization strategy. Second, we move on to review the existing literature. This review shows that studies that do address geothermal energy from an SSH perspective tend to be of a descriptive nature and lack analytical diversity. Third, we discuss three complementary theoretical approaches that are used in the social sciences to observe and address other forms of energy and energy transition. We believe that socio-technical assemblages, systems, and imaginaries can provide fruitful analytical lenses to study the promises, pitfalls and spatialization of geothermal energy. We conclude the paper with a research agenda and call for further engagement with this topic in SSH research, with attention to specificities of global South and North contexts.

1. Harnessing the heat below our feet: the need for social science of geothermal energy

The heat from the core of the Earth can offer an almost limitless supply of renewable energy if it is accessed in a feasible, efficient, and sustainable manner. Geothermal energy is broadly defined as “the thermal energy stored underground, including any contained fluid, which is available for extraction and conversion into energy products” (p.1 [1]). It is a renewable source of energy which is not affected by weather and seasonal variations[1] and, therefore, it can produce a stable base-load capacity. Geothermal energy can be used in a flexible manner to assist variable renewable energy sources such as solar and wind power [1–4]. It offers much potential for ongoing energy transitions in many countries. This potential is recognized in practice by many governments and private sector actors, who show a (renewed) interest in geothermal energy as part of their decarbonization strategy [2,5]. After the invasion of Ukraine, the European imperative to reduce and eventually phase out Russian natural gas gave further impetus to the heating question with increased attention to geothermal energy [6].

Geothermal energy is not necessarily sustainable or effective in

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[1] In the case of shallow geothermal heat pumps that use horizontal loops (also called ground source heat pumps) there can be influence of seasonal variations. Below 15–20 m depth the temperature remains constant throughout the year [167].

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meeting the imperative of decarbonizing energy systems [7]. This mirrors the increasingly recognized issues of unevenly distributed social and environmental problems related to the expansion of renewable energy systems (e.g. [8]). Sustainable use of geothermal energy requires a balance between the consumption and generation rate to avoid extensive cooling of the original aquifer and mitigation of various impacts on the environment [1,2,9–12]. Moreover, the social sustainability[2] of geothermal energy is largely overlooked in existing studies despite a growing body of literature focusing on social acceptance (see e.g., [13]). Engagement with existing debates in energy transition literature related to energy justice and energy democracy (e.g., [14–16]) has been very incipient within geothermal studies. In sum, geothermal energy has received surprisingly little attention in social science studies, and is mainly perceived and dealt with as a technological and/or geological problem [1,17,18].

Social science approaches are uniquely suited for providing critical perspectives on the burdens and benefits of the production and consumption of electricity and heat from geothermal systems. These insights are also necessary for the more normative goal of developing energy policy and decision-making procedures surrounding geothermal energy that are equitable and fair towards communities, and the environments they live in [19]. Such insights are key to understanding and operationalizing geothermal energy as a decarbonization strategy. If we truly want to live in a socially just and ecologically sustainable future, social science perspectives on geothermal systems are fundamentally necessary.

Aiming at tackling this gap in the literature, our perspective article responds to and extends the call for more social science and humanities (SSH) research into geothermal energy as a decarbonization strategy [1,13,20]. In Section 2, we focus on the promise of geothermal energy, followed by a general review of social science literature on geothermal energy in Section 3. Building on the three complementary theoretical approaches of socio-technical assemblages, systems, and imaginaries in Section 4, we discuss a social science research agenda on geothermal energy in Section 5. Section 6 provides some concluding remarks and calls for further engagement with this topic.

2. The promise of geothermal energy as a decarbonization strategy

Geothermal energy can be used directly for heating or indirectly for electricity generation. A distinction is usually made between technologies that use the thermal stability of the underground (shallow) and those that make use of temperatures above the annual mean air temperature (deep geothermal) [1]. However, the threshold between shallow and deep geothermal is not unanimously defined: for instance, while some authors, such as Hähnlein, et al. [21], set 400 m depth as the threshold, others such as Limberger et al. [22] move it to 100 m beneath the ground. In this paper, we will generally focus on deeper geothermal systems rather than on shallow ones, while staying aware of the blurriness of the distinction. Indirect use of geothermal energy for electricity generation usually requires temperatures of over 100 °C to be profitable and effective [1], but technological developments might reduce this limitation [12]. Lower temperature reserves can also be used for other (direct) purposes including industrial processes, aqua- and horticulture, recreational uses, and residential heating [2].

The global capacity of geothermal electric power was almost 16 GW in 2020 [23,24]. This is minor compared to other renewable sources (e.g. the installed capacity of both solar PV and wind power surpassed 700 GW in 2020 [24]). A recent IRENA report [2] states that the estimated technical potential for geothermal electricity is up to 200 GW. The economic potential of current technologies for exploiting these resources is projected at 70 GW [2]. However, being a dispatchable source of renewable electricity generation, geothermal energy can provide crucial services in balancing energy from variable sources such as solar PV and wind power [2,25]. It is important to notice that some of the sources used in the geothermal industry and IRENA report seem to be outdated. This is also indicative of the fact that information on geothermal energy is scattered and different countries and market players use various indicators to report their use of geothermal resources, thereby making it difficult to compare these numbers across contexts [12].

According to IEA [26], global geothermal expansion is not on track with the 2050 Net Zero Emissions scenario, “which requires 13% annual increase in generation over 2021-2030, corresponding to average annual capacity expansions of approximately 3.6 GW”. There are biophysical and spatial limits to this expansion since geological conditions determine how much heat is available in certain places. The existing clusters of geothermal power generation are predominantly located in areas with high tectonic and seismic activity. Fig. 1 shows that in 2020, over 90 % of power generation capacity from geothermal energy came from only 10 countries, which are distributed among various continents located both in the global South and North [12,23]. However there are territories with significant potential that have not been significantly exploited (e.g., Chile [13]).

The economic side of exploiting geothermal energy also requires attention. The costs related to the exploration of geothermal energy are high, making geothermal technology a capital-intensive investment with significant perceived risks [1,12]. These risks vary depending on the geology of the region, the quality of the geothermal resource, existing infrastructure and the social acceptance of different geothermal technologies [1]. Once past this stage, the operational costs of geothermal energy are relatively low [2]. The economic feasibility of geothermal energy systems can be further boosted through alternative revenue streams. For example, there are opportunities for cascade schemes in operating geothermal plants, where heat with decreasing temperature is shifted to other purposes such as horticulture or (existing) district heating systems [2]. Geothermal energy systems are considered a good option for reducing the costs of off-the-grid energy systems [27]. Another opportunity that is currently being studied is the potential for mineral recovery, particularly lithium, from geothermal brines [28].

The benefits of geothermal energy are widely recognized and emphasized, for example by the World Bank which renewed its ESMAP Geothermal Electricity Development Program in 2020 [5]. Nonetheless, IRENA [2] suggests that global geothermal expansion requires increased awareness and collaboration among stakeholders, sound legal frameworks and risk-sharing mechanisms aimed towards the particularities of geothermal energy. This is what initiatives such as World Bank's Global Geothermal Development Plan (GGDP) and EBRD's Early-Stage Private Sector Geothermal Development Framework (PLUTO) seek to address [29,30]. Geothermal plants are claimed to enhance regional economic development and are sometimes presented as opportunities for community investments. A well-known example is the Maori-owned Nga AWA Purua power plant in New Zealand [1,2,31]. Other authors discuss the potential environmental and socio-economic impacts of geothermal energy systems for remote and rural communities in British Columbia [9] and for indigenous communities in Kenya [32].

A growing number of studies also point at the drawbacks of geothermal energy, including runaway emissions, water pollution, seismic activity, and potentially low net energy returns [4,7,9,12,33]. It is therefore timely to note that the geothermal sector [12], IRENA [2], the World Bank [5,30] and the European Bank for Reconstruction and Development (EBRD) [29] differ in how they portray the promises and

[2] According to the UN global compact website “Social sustainability is about identifying and managing business impacts, both positive and negative, on people” [168]. Our definition, instead, is rooted in the political ecology tradition and focuses on equity (the unequal distribution of burdens and benefits), access (to energy and decision making) and ownership (who controls and makes profits).

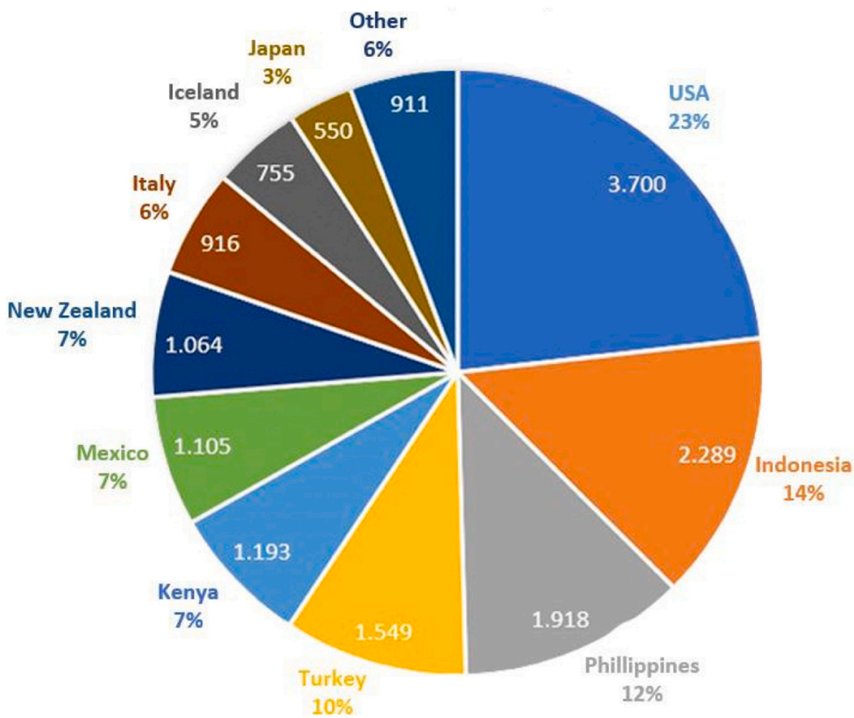

Fig. 1. The ten countries with the highest installed capacity (MWe) of geothermal power generation in 2020. Source: authors, based on data from Huttrer [23].

pitfalls of geothermal energy as a decarbonization strategy. To better contextualize this landscape, we now turn to the scholarly literature on geothermal energy from a social science perspective.

3. Exploring the social in geothermal: perspectives from social sciences and humanities

Despite initial engagement in the 1980s with pioneering works from researchers like Martin Pasqualetti [34–36] and Penelope Canan [37,38], social scientists' interest in geothermal power is relatively recent and limited. This section illustrates how geothermal energy is flying low under the radar of energy and environmental social scientists and is perceived as a technological and biophysical issue (as also observed by [1,17,18]). Here we provide a narrative review [39] of the existing body of work.

While attention for direct use of geothermal energy is gaining traction (see [40] for a review of this literature), deep geothermal energy remains in the domain of the geological. Bobbette & Dononvan [17] call for critical engagement with the political side of geology in general, including geothermal energy. Some initial insight into the social science dimensions of geothermal energy from various disciplines (e.g., geography, policy, economics) are provided by [1,10]. However, these accounts remain relatively general, providing an overview of geothermal technology and pointing towards issues and cases that could be explored in more depth.

The majority of literature on geothermal energy presents national cases and development trajectories in an unmistakably descriptive manner [41–46]. These studies, focusing on availability, affordability, exploitability, and eventually legal issues, often result in policy recommendations regarding administrative systems, financial policy measures, and instruments necessary for further deployment of geothermal energy. There are only a few cross-country comparisons [3,47,48]. Studies that explicitly address government policy focus predominantly on the benefits and drawbacks of various fiscal policies (e.g., [11,49–51]). Two notable exceptions are a study by Ejderyan et al. [52] which analyses how federal and local governance surrounding geothermal energy in Switzerland is both a bottom-up and top-down effort, and a study by Horn et al. [53] regarding the need for governance for sustainable management of near-surface geothermal energy systems.

Existing social science and humanities perspectives on geothermal energy focus primarily on public perception, participation and social acceptance [3,13,20,54–63]. These studies often result in policy advice regarding public communication on risks and benefits related to geothermal energy development. A related strand of literature analyzes how media and social movements frame geothermal energy (e.g., [64–70]). Unlike other renewable sources of energy such as solar and wind power, geothermal energy has barely been associated with major discourses in energy transition literature regarding energy governance, energy decentralization, energy democracy, and energy justice (see e.g., [14,16,71–73]). Some notable exceptions are Shortall et al. [7] and Soltani et al. [4], who provide a review of geothermal energy from an integrated sustainability perspective. These authors hint at the connections between geothermal energy and issues such as energy poverty (see also [47] for a discussion on cultural dimensions in geothermal energy). Benediktsson's [74] critical study on the “nature imaginary” of geothermal energy technology and Guðmundsdóttir et al.'s [75] inquiry into the political ecology of Iceland's geothermal energy development also represent notable exceptions calling for further research.

The existing body of literature shows that there are opportunities to expand the lenses used to explore geothermal energy, paying attention to how the production of geothermal spaces is intertwined with an intricate convergence of different epistemologies, imaginaries, constellations of political economic actors, and the production of specific socio-natures (see Section 4). An interesting side of this debate can also be found in the synergies sought between politics of expertise flowing between geothermal and fossil fuel sectors (see [76]).

In sum, there appears to be a lacuna in terms of the analytical diversity of approaches from social science and humanities engaging critically with geothermal energy in its materialities, temporalities, and spatialities. The studies that do exist demonstrate the urgent need for further critical engagement with geothermal energy systems from a social science and humanities perspective. Despite some studies hinting at opportunities and drawbacks of geothermal energy for a specific location or a specific community (e.g., [9,31,32]) we argue that there is room to expand geothermal debates with emphasis on issues such as equity, access and ownership and make explicit links with larger energy transition governance discussions. In the following we illustrate three theoretical approaches that may be particularly promising, discuss their interlinkages, and explore how they may be applied to geothermal energy.

4. Theoretical reflection on geothermal energy from a social-technical perspective

Energy transition is often conceptualized as a socio-technical transition, focusing on the interrelations between actors, networks, institutions, and technologies across levels and scales [77–79]. Thus, pushing geothermal energy studies beyond the technical-geological domain requires recognition of geothermal energy as an explicit part of the socio-technical transition of energy systems, including a critical perspective on its promises and pitfalls. In this section, we discuss the key concepts, relevance, and potential operationalization of three complementary approaches that have been used in the social sciences to observe and address other forms of energy and energy transition: (1) socio-technical assemblages, (2) socio-technical systems, and (3) socio-technical imaginaries.

4.1. Socio-technical assemblages

The key purpose of assemblage thinking is to focus attention on how phenomena are shaped through multiplicities of contingent and heterogeneous elements (e.g., human and non-human, material and non-material) that are related at a certain moment in time [80–83]. An assemblage can be broadly understood as a 'fragmentary whole', where the various elements can be rearranged and recombined to change its nature [81]. This enables researchers "to remain deliberately open as to the form of the unity, its durability, the types of relations and the human and non-human elements involved" (p.124 [83]). In socio-technical assemblages, the material aspects are placed in relation to the social and cultural networks surrounding it.

Using an assemblage perspective in the context of energy transition, Van Veelen [84] argues that "'energy' [is perceived] not as a singular, self-evident object of analysis, but rather as a phenomenon that is composed of plural social, political, and material actors and processes; and […] how this assemblage (re)produces the more-than technical aspects that make up our lives" (p.3). Elements of energy-related assemblages include, for example, political-institutional structures, energy markets, material infrastructures, and socio-cultural discourses [82]. Assemblage thinking is increasingly used to explore and explain energy systems [82,85]. Haarstad & Wanvik [82], for example, explain the existing carbonscape as a collection of "smaller assemblages that are partially integrated in other assemblages of different scales" (p.442). They argue that assemblage thinking is particularly suited to exploring change processes and potentials (see also [83,86]). Thereby, they make the connection to energy transition literature. Examples where assemblage thinking has been applied to study energy transition include topics such as green financing for low-carbon agriculture [87], energy democracy [88], the electric mobility transition [89], energy efficient cities [90], and the potential of solar energy for enhancing energy access [91]. We argue that with its focus on the dynamic relation between material and non-material aspects of geothermal energy, insights from assemblage thinking can provide novel apertures to expand this field into the domain of new materialism and beyond.

Existing research into fossil fuel assemblages can also help explore the interwoven linkages between the matter and the social. Haarstad & Wanvik [82] make a useful distinction between assemblages surrounding resource exploitation zones, distribution infrastructure, and sites of consumption in oil landscapes. In a similar manner, Sheller [92] distinguishes between objects, infrastructures and practices embodied in assemblages when studying aluminum's relation to the energy sector. When applied within geothermal energy assemblages, such distinctions can help connect resources and energy across sites and scales. Therefore, assemblage thinking is particularly suited for exploring issues of equity, access, and ownership related to geothermal energy. This is exacerbated by the heat component associated with geothermal energy. This heat component creates incentives for cascading systems with various users of heat in relatively close proximity to extraction sites to ensure optimum use of geothermal resources. Taking into account the whole heat chain is particularly pressing in countries where geothermal energy is seen as part of an ongoing transition from natural gas to other heating sources (e.g., the Netherlands) [93,94].

Assemblage thinking is also useful in studying how geothermal systems are embedded in the wider material and spatial repertoire of energy transition in both the global South and North. This relates to questions on how assemblages of geothermal energy are related to and potentially reconfigure, adapt and convert related assemblages around other types of energy production. Such assemblages intentionally or unintentionally leave some subjects out of the equation. Kathryn Yusoff [95] suggests that "voiding subjects was also about voiding a relation to earth that was embodied, organized, and intensified by those relations to place; taking place is also taking ways in which people realize themselves through the specific geologies of a land" (p.4).

Tracing methodologies have been used to analyze assemblages [92,96,97] and can provide insight into the role and position of geothermal energy assemblages in (trans)national energy assemblages that are embedded in objects/materials, infrastructures and practices. Particularly given the absence of a body of work on geothermal energy grounded in social sciences and humanities, assemblage thinking can demonstrate and prove novel regroupings of material and social relations with its "capacity to deal with coexisting complexities, keeping open their multiplicities, without reducing them to singularities" (p.12 [98]). For instance, the geothermal boom in Turkey since 2010s, which catapulted the country to the position of fourth largest producer globally, can also be read as an uncanny assemblage of international climate finance, overlapping exploration permits over a major fault line, dubious environmental impact assessment procedures, struggle over land rights, specific geological formations with a high-carbon content, and techno-utopian visions to commercialize CO_2 released from these reservoirs [99,100]. As such, assembling geothermal energy as a complex field of material and non-material relations can help analyze the multiplicity of elements and relations that condition geothermal energy deployment as a decarbonization strategy in different contexts, as well as the potential conditions for change [101].

4.2. Socio-technical systems

The concept of socio-technical systems points to a heterogenous and interdisciplinary scientific community adopting a systems-theoretical [102] approach to study processes of technological change, especially sustainability-related. It heralds the need for an integrated perspective to understand innovation as emerging from the complex interplay of multiple, partly autonomous elements and processes (e.g., technologies, regulations, practices, markets, cultural meanings, and networks of distribution and support) at different scales [103,104].

Socio-technical systems literature comprises two main strands: the first strand is analytical and studies past transitions to understand their dynamics. It spawns from a gradual broadening in perspective of science and technology studies since the 1990s, leading to an integrated perspective on how technical and social processes interact in promoting or hampering technological change [105]. This change cannot be fully directed or predicted in advance, but emerges from iterative processes of variation, selection, and retention, depending on existing social and technical structures [106,107]. One of the most successful approaches, the multi-level-perspective (MLP), observes transitions as non-linear processes emerging from the interactions between niches (protected spaces where radical innovations occur), regimes (semi-coherent sets of rules and structures which provides stability to the systems) and landscapes (slowly changing variables and trends influencing socio-technical actors but unvarying in the short run [106]). The regimes tend to produce inertia in the momentum [108] of technological change, causing it to suffer path dependency [109] and lock-in along predetermined pathways (e.g., around fossil fuel technologies). Regimes can be changed when alternative solutions developed in the niches reach a critical mass breaking down the inertia of incumbent structures, an insight that can be used to accelerate transitions [110–114].

The second strand aims at devising processes to deliberately promote the transition of innovation systems towards more collectively desirable equilibria, such as those fostering sustainable development [115]. One of the most known approaches within this strand is transition management (TM), a new form of long-term policy-making, focused on driving desirable transitions in socio-technical systems (especially energy) [116]. As MLP, TM acknowledges that any socio-technical transition is emergent - it results from the interactions between multiple groups, and thus, cannot be steered at will by public authorities [117] - it may even be unclear what the problem is and which actors should be involved [118]. It is conscious that policy designs may have unpredictable and unintended effects, causing new problems while striving to solve others [119–121].

Socio-technical systems approaches are not immune from criticisms [122]. Scholars have called for more attention to the political and value-laden character of transitions [116,123], citizen participation [124] and ensuring that the field maintains overture to new perspectives, challenges and contexts [114], especially with other forms of systems-thinking, such as those connect with resilience [104,125,126]. Other scholars have noted the need for this approach to consider the role of social elements, such as trust, in transitions [127], and more fundamentally, to provide a clearer definition on the socio-technical nature of the systems [128]. Studying the social sustainability of geothermal energy can also progress the theoretical development of socio-technical systems approaches.

Socio-technical systems approaches have been used extensively in the energy field, and there are many studies examining the drivers and barriers to the energy transition. Very few of these studies (e.g., [129–132]) explicitly mention geothermal power among renewable alternatives. Kinchy et al. [133] argue in favor of a socio-technical system approach to analyze subterranean resource development, as an opportunity to integrate materialities and controversies in areas such as mining and energy. Moreover, existing studies have explored possible synergies between geothermal power and other energy debates such as carbon capture and storage [134,135], complementarities with the oil and gas sector [136] or geothermal's potential role in green hydrogen [137]. Ejderyan et al. [52] mention the importance of socio-technical systems perspectives when comparing different pathways to foster geothermal energy in Switzerland, concluding on the need for more coordination across levels to promote its development. Socio-technical systems approaches have also been used to highlight the possible future pathways for geothermal energy in Indonesia [138] and potential side effects of near-surface geothermal development in Germany [53]. Other studies employ the notion of socio-technical systems in a more metaphoric fashion, to offer an integrated view on issues such as public perception [74,139,140] or public engagement [59,124] regarding geothermal power. While the application of socio-technical systems to geothermal power is very incipient, the few cases in which it has been used, plus its robust trajectory in analyzing other kinds of renewable energy sources, grant it a strong potential to provide an integrative overlook on the dynamics and governance challenges of geothermal power and its interaction with other technologies.

4.3. Socio-technical imaginaries

The concept of socio-technical imaginaries is commonly attributed to Jasanoff & Kim's [141] seminal study on how the political cultures of the U.S. and South Korea informed divergent visions of nuclear power. Defined as “collectively imagined forms of social life and social order reflected in the design and fulfillment of nation-specific scientific and/or technological projects” (Ibid. 120), an imaginary is a type of social vision of a desirable future. The central task in the study of socio-technical imaginaries is to analyze how such social visions are constituted by and constitutive of scientific or technological projects. Researchers have now examined the imaginaries of a variety of technologies, social groups, environments, and geographical regions at multiple scales. Much research has been carried out to understand the imaginaries implicated in both renewable energy systems (e.g., [76,142–144]) and fossil energy systems (e.g., [145–148]). While these represent two different streams of research, we argue that it is auspicious to consider insights from both streams to understand the imaginaries of geothermal energy projects in energy transitions.

Existing studies have uncovered a rich variety of imaginaries implicated in renewable energy systems. Even so, structural similarities can be observed. For instance, deeper ideographs such as progress, environmental sustainability, and autonomy recur across cases, as well as themes of conflicting visions such as ecological modernization vs. degrowth, utopian vs. dystopian, or incremental vs. transformative [144,149]. Beyond identifying cross-regional patterns, the study of socio-technical imaginaries includes critical considerations of culture, power, and sustainability. One study revealed that imaginaries were “used to attract heavy industry investment” [75] for geothermal energy in Iceland. This study demonstrated how imaginaries of geothermal energy as a renewable resource may be interwoven in political and economic interests which perpetuate problematic perceptions of nature and justify social inequalities (see also [74]). In a study on solar energy in Senegal and South India, Jasanoff & Simmet [150] similarly concluded that alternative visions of social life, nature relations and collective energy are demoted in the face of hegemonic imaginaries of large-scale renewable energy development. Drawing on progenitors of socio-technical imaginaries research [151], we may ask to what degree such imaginaries are inherent to advanced geothermal energy development which often requires large capital investments.

Studies on imaginaries implicated in fossil energy systems make up a rich body of research, pivotal for work on energy transitions within fields such as energy geography, ecological economics, and energy humanities. This stream considers how imaginaries derive from human-environmental relations and the biophysical composition of fossil fuels. Notable insights from this literature include how access to highly energy-dense fossil energy carriers have influenced modern notions of space, time, energy, progress, money, and economic growth [145,152–155]. It also includes the modern notion of technology, which was closely knit to the surge in fossil fuel consumption during the 20th century [156,157]. As such, even if socio-technical imaginaries of renewable energy technology may challenge fossil-based systems, they may rely on notions of reality symptomatic of fossil imaginaries. Studying the imaginaries of geothermal energy projects, we may ask how different social groups in the world struggle for representation of alternatives to such fossil imaginary lock-in.

The notion of energy and space presents another fruitful area for researching the imaginaries of geothermal energy projects. Recent literature has demonstrated how modernity has developed an uncritical distinction between access to land and access to energy [158–160]. These studies unanimously show how the turn to renewable energy represents a return to land as a crucial factor of production. This includes not only the land implicated at the site of energy harnessing, but also the land implicated in the production of renewable energy carriers and their infrastructure [15]. Chateau et al.'s [161] integration of socio-technical imaginaries and “spatial imaginaries” may be useful to understand how actors generate competing imaginaries of the space and scale of geothermal energy projects. The deep geothermal energy project driven by the corporation E.ON in Malmö (Sweden) [162] may be studied to understand how the imaginaries of the developers form scalar imaginaries of geothermal energy which include or exclude environments and peoples implicated in the global production of the infrastructure. Using methods such as Q methodology (see [163]) or story-completion method (see [164]), this may bring interesting results to discuss in relation to geothermal energy, fossil imaginary lock-in and environmental justice.

5. Towards a steaming research agenda for the social science of geothermal energy

The three theoretical approaches discussed in this perspective article have all been fruitfully applied in energy transition studies. A fundamental commonality in each of these approaches is the socio-technical perspective, which focuses attention on how geothermal energy projects necessarily include both material/immaterial and biotic/abiotic relations of the world, prompting the need for interdisciplinarity scholarship. These approaches see geothermal energy projects fundamentally as relations. This relational approach is particularly suited for studying geothermal energy, where cases are characterized by multiple actors, components, and transformative potential in various contexts, both in the global South and North.

Besides these commonalities there are some notable differences between the theoretical approaches (see Table 1). Each of these approaches has a slightly different drive and focus. Assemblage thinking is more focused on creating an understanding of the relations between material and immaterial, human and non-human elements that shape current geothermal energy systems in various contexts. Socio-technical systems literature specifically focuses on the rather pragmatic question of understanding what makes a transition towards geothermal energy possible and how to better foster it. Imaginaries strive to analyze how social visions of desirable futures are constituted by and constitutive of geothermal energy projects. As such, these perspectives have a complementary temporal focus.

These theoretical approaches also place different emphasis on immaterial (or cultural) aspects in shaping geothermal energy projects. However, we argue that they are complementary in this regard as well. For example, fossil-based imaginaries of geothermal energy technology might help to explain the tacit assumptions that inform governance and influence social-technical systems. Similarly, multi-scalar and multi-sited assemblages of geothermal energy infrastructure might help to problematize geothermal imaginaries often emerging within the confines of specific regions. This will help shed light on issues of equity, access and ownership which, despite being the focal point of much existing energy transition research [16,72], have been understudied in relation to geothermal energy.

One way of synthesizing these approaches in a case study is to focus on one approach and use the two other approaches as complementary explanations. Identifying and analyzing stakeholder imaginaries through interviews (or other methods of data collection) may be sufficient, but could be further contextualized by assemblage and systems approach for a more holistic understanding of the imaginary. The assemblage approach may provide conceptual tools for understanding how the geothermal imaginary is emerging within given social and natural conditions, i.e. provide materialist nuance to understanding its social-ecological context. The systems approach may provide a deeper understanding on how the imaginary is constructed by the major stakeholders to meet the challenges of deep geothermal energy systems transcending the level of niche to regime. The geothermal imaginary takes its shape in the complex interplay of actors operating with specific interests within the confines of a system. For instance, in a case we are currently investigating in Sweden, it is possible to see that the major stakeholder is currently forming advertisements and communicating a geothermal imaginary to cater to the assemblage as well as their aspiration to take deep geothermal to the regime level. Thus, the geothermal imaginary is better understood by including considerations of how the assemblage and system dictates its form. A multitude of such case studies may transcend the conceptual boundaries of each of the approaches and form a new understanding of geothermal energy systems.

Table 1
Comparison between three socio-technical approaches and their relevance to social science and humanities research on geothermal systems. Source: authors.

Approach	Definition of socio-technical relationships	Analytical drive (guiding question)	Temporal focus	Spatial focus	Example of application to geothermal energy	Example of potential cases
Socio-technical assemblages	Heterogenous material relations embedded in socio-cultural contexts	Theoretical (understand relations between material and immaterial, human and non-human elements)	Past to Present (how assemblages emerge and operate)	Mostly local (assemblages are context-dependent)	Understanding how geothermal energy systems in a certain context emerged and operate as a result of interrelations between xthe natural characteristics of the local geothermal resources, the technologies deployed, the actors involved, their roles and impact on decision-making, and the institutional context.	The geothermal energy ‘boom’, its recent slowdown and the associated social conflicts in Turkey [29,165], the difficulties in geothermal power generation in Chile [13], or barriers and enablers to geothermal heating systems in the U.S. [48]
Socio-technical systems	Changes in social structures driving or hampering technological innovations	Pragmatical (understand how transitions may occur and how to foster them)	Past (analytical) to future (prescriptive), long-term oriented	Multi-level (local niches to regional and national landscapes)	Understanding how geothermal energy systems are shaped by developments on the niche, regime and landscape level, and what changes are necessary on these various scales to foster sustainable development of geothermal energy as part of wider energy transition debates.	A cross-country comparison of the niche, regime and landscape level context and how these levels have affected geothermal energy development, e.g. in Chile [13], Turkey [45], Indonesia [138], or Kenya [32].
Socio-technical imaginaries	Semantic-semiotic constructs interweaved in technology developments	Critical-reflexive (observe relationship between projects and social visions of desirable futures)	Future (imaginaries) into the Present (projects)	Local to global (imaginaries span geographies)	Understanding divergent imaginaries on geothermal energy projects, their scalar dimensions, and their position as a decarbonization strategy, including how these imaginaries are used to justify the (unequal) distribution of benefits and burdens.	The divergent imaginaries on geothermal energy projects in Büyük Menderes Graben, Turkey [165], the role of geothermal in heat transition in the Netherlands [94], or the deep geothermal energy project driven by E.ON in Malmö (Sweden) [162].

6. Conclusions: full steam towards a sustainable approach to geothermal energy

In this paper we discuss the renewed interests in geothermal energy systems as part of countries' decarbonization strategies, both in the global South and North. The reduction and eventual phase out of Russian natural gas after the invasion of Ukraine has heightened the sense of urgency for this issue, particularly in Europe [6]. Despite the previous contribution of several authors, we noticed a lack of critical social science and interdisciplinary scholarship on geothermal energy systems. The available literature demonstrate a need to further consider geothermal energy systems from social science and humanities perspectives. This is especially important in the context of an increased interest in the potential of geothermal energy technology as a decarbonization strategy. As emphasized in a recent article in this journal, geothermal energy has been "predominantly studied by 'hard' sciences (e.g., engineering)" (p.5 [18]). Our perspective article responds to and extends the call for more social science and humanities (SSH) research into geothermal energy as a decarbonization strategy and discusses three theoretical approaches to better understand geothermal energy systems with a focus on how they arise from and give rise to specific social, technical and ecological relations. We show that the three approaches elaborated here can provide critical perspectives on the promises and pitfalls of geothermal systems across time and scales, taking into account issues such as equity (the unequal distribution of burdens and benefits), access (to energy and decision making) and ownership (who controls and makes profits). Such considerations must be taken into account if geothermal energy is to become part of sustainable decarbonization strategies.

We call on researchers to engage with a broader spectrum of theoretical approaches to critically discuss and explore the use of geothermal energy as a decarbonization strategy. It is high time for social science and humanities researchers to consciously engage with the particularities of deep (and shallow) geothermal systems, as well as the direct and indirect use of geothermal energy. This requires researchers to work in interdisciplinary research teams. We also join the call by another recent piece in this journal [166] for reconfiguring energy governance as a commons, in which we see an explicit role for the study of geothermal energy systems. Such an approach offers key opportunities for single country case studies and cross-country comparisons regarding the development trajectories of geothermal energy systems, policies, and their embeddedness in locally-grounded, internationally-relevant, fair and equitable decarbonization strategies.

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.

Data availability

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

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