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Review

Geothermal Energy and Its Potential for Critical Metal Extraction—A Review

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Abstract: In an era of accelerating energy transition and growing demand for critical metals essential for clean technologies, the innovative integration of geothermal energy with critical metal extraction stands as a paradigm shift in sustainable resource utilization. This comprehensive review unravels the synergistic potential of coupling geothermal energy systems with critical metal extraction, thereby transforming a dual crisis of energy and resource scarcity into an opportunity for circular economy. Through rigorous analysis of existing geothermal technologies, and extraction methodologies, the study establishes a coherent framework that merges energy production with environmental stewardship. It scrutinizes current extraction techniques, and evaluates their compatibility with geothermal brine characteristics, proposing optimized pathways for maximum yield. Through detailed case studies and empirical data, the paper elucidates the economic and environmental advantages of this multifaceted approach, from reduced carbon footprint to enhanced energy efficiency and resource recovery. It concludes that combined heat and mineral production technology can open new, unexplored resources, increasing the supply of previously untapped resources, while the potential of geothermal energy for sustainable mineral extraction and energy production is in line with Sustainable Development Goal 7, which aims to ensure access to affordable, reliable, sustainable and modern energy for all.

Keywords: geothermal energy utilization; critical raw materials (CRM); Combined Heat Power and Metal extraction (CHPM); Petrothermal Enhanced Geothermal System (PEGS)

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1. Introduction

Geothermal energy is a reliable, weather-independent, and renewable source of energy with significant potential for contributing to a sustainable energy future [1]. The Intergovernmental Panel on Climate Change has emphasized that geothermal energy has the potential to provide a significant portion of the world's electricity demand [2–5]. Furthermore, Finster et al. detailed the characteristics of geothermal-produced fluids and emphasized the role of geothermal in energy generation [6]. In addition to heat and electricity production, geothermal energy can also be utilized to extract critical raw materials essential for manufacturing various products [6–8].

Raw materials are essential to EU industry and are at the beginning of every value chain. Among the non-energy, non-agricultural raw materials the assessed by the European Commission, some have been identified as critical on the basis of objective criteria, including their economic importance and supply risk [9] (Figure 1). For instance, there is an increasing need to explore alternative and sustainable sources of lithium to meet the growing demand in energy, manufacturing, and medical sectors. Innovative extraction technologies for lithium from geothermal brines and seawater are emerging as a potentially viable and environmentally friendly solution [10]. A recent study further highlighted that deep geothermal plants can offer a low-carbon alternative to conventional lithium extraction methods [11]. G. Balaram explored potential future alternative resources for rare earth elements and presented the opportunities and challenges associated with them [12]. More specifically, Sanjuan et al. provided an update on the geochemical characteristics of lithium-rich geothermal brines in Europe and discussed their implications for potential lithium resources [13,14].

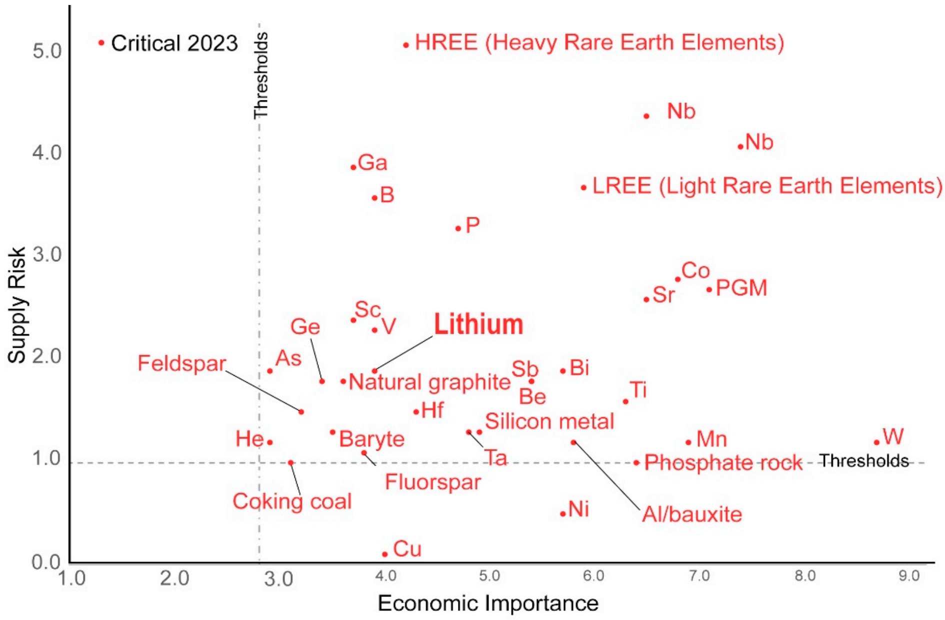

Figure 1. The critical raw materials of the 2023 criticality assessment of EU, lithium is highlighted. Copper and nickel do not meet the CRM thresholds, but are on the CRM list as Strategic Raw Materials (based on [9]).

The negative environmental impacts associated with traditional mining practices for valuable minerals are significant [14–16]. The mining industry is responsible for 4–7% of greenhouse gas emissions [17]. As a result, there is a need for more sustainable and environmentally friendly options for chemical elements extraction. Geothermal brine fluids are gaining attention for their potential applications, and research has shown that their use can lead to a significant reduction in CO_2 emissions compared with traditional hard rock lithium procurement methods [11]. Savinova et al. have critically assessed the global cobalt supply, focusing on geological, mineral processing, production, and geographic risk profiles, suggesting the need for alternative sources of minerals [18]. Similarly, Yu et al. delved into the complexities of the global mineral market, emphasizing the vital role of resource wealth during the energy transition and the need for sustainable extraction methods [19]. The initiative 'CRM-geothermal' further supports this notion, highlighting the potential of utilizing geothermal brine fluids for mineral extraction as a sustainable and environmentally friendly alternative to traditional mining practices [20].

This review paper explores the potential of geothermal energy to extract critical metallic minerals and contribute to Europe's energy security and sustainability. Specifically, we investigate the development of "orebody-Enhanced Geothermal Systems" (EGS) that allow for the cogeneration of energy and metals from metal-containing geological formations. Previous studies have investigated the technical feasibility of this approach, highlighting its potential for reducing the environmental impact of geothermal mining practices [16,17]. However, challenges such as silica scaling necessitate specific water treatments to make this scientific approach practically viable [21]. Recent research has demonstrated that effective silica removal from geothermal fluids can be achieved through a chemical process that forms Calcium-Silicate-Hydrate (C-S-H) phases, significantly reducing the risk of silica scaling [21].

The planned technology manipulates these formations to optimize energy and metal production in response to market needs. Several studies have explored the potential market demand for critical metallic minerals and highlighted the need for more sustainable and environmentally friendly extraction methods [15,18,19].

The paper provides a detailed overview of the nature and classification of geothermal energy and its potential for energy storage, as well as its potential for chemical elements extraction. We also examine the role of metals in human history and their extraction technologies, highlighting the limitations and negative impacts of traditional mining practices. Numerous studies have investigated the environmental and social impacts of traditional mining practices and highlighted the need for more sustainable and socially responsible approaches [8,20].

This study is primarily based on the results of the completed CHPM2030 project [22] and the plans for the CRM-geothermal project that is now being launched [7]. The core of the paper is focused on the possibilities of combined metal and heat production that have been explored so far rather than on a technological overview.

This review paper, guided by the methodology outlined in Figure 2, discusses the economic aspects and potential applications of the proposed technology for industries and governments. Specifically, through a series of research questions, literature reviews, information synthesis, integration and framework development, impact assessments, and case studies, we conduct a cost–benefit analysis to assess the financial feasibility of the technology. This includes evaluating expected costs, revenues, and potential profits for various stakeholders. Our conclusion and recommendations are built upon several studies that have explored the economic feasibility of geothermal energy and chemical elements extraction, highlighting the potential for cost savings and revenue generation [23,24].

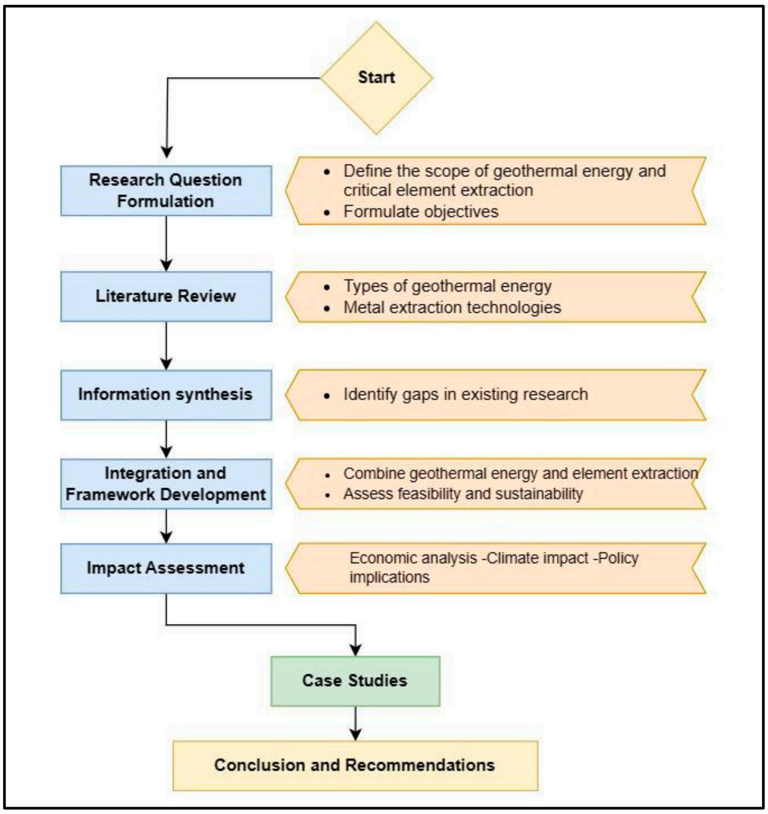

Figure 2. Flowchart of methodological framework.

In addition, we explore the potential of geothermal energy to contribute to the energy transition and address climate change. We highlight the significance of fluid-rock interaction for mineral production and the potential advantages of extracting elements from geothermal brine fluid over traditional mining methods. A number of studies have highlighted the potential of geothermal energy to contribute to the transition to a low-carbon economy and address climate change [25,26].

Altogether, this review paper provides a comprehensive overview of the potential of geothermal energy to contribute to energy security and sustainability through critical metals extraction and the cogeneration of energy and metals. By addressing existing research gaps and highlighting the potential of geothermal energy for sustainable mineral extraction and energy production, this paper contributes to ongoing discussions on the future of energy and natural resource management.

2. The Role of Metals in Human History and Their Extraction Technologies

2.1. Importance of Metals

The imperative for metals in human civilization is deeply rooted, tracing back to prehistoric eras [27]. Most of these metals are found in metal-rich geological formations and are primarily extracted by mining. While mining has historically been carried out close to the surface, technological advances have allowed a significant increase in the depth of extraction, as illustrated by [28–30]. Contemporary mining operations can reach remarkable depths, with Table 1 illustrating key examples. In particular, the Mponeng gold mine in South Africa represents a pinnacle, reaching a depth of 4.0 km, making it unparalleled in the field of deep mining.

The intricacies of deep mining operations are particularly resource intensive and challenging. The mining industry is constantly challenged by resource depletion and environmental concerns, while adapting to fulfill the supply of raw materials within the complex supply and demand and socio-environmental system [31,32]. Human activity in these underground tunnels requires rigorous cooling and ventilation systems. The gold-rich regions of South Africa are fortunately characterized by low geothermal gradients [33,34], which mitigate in situ temperatures at extreme depths. However, other logistical aspects, such as the extraction and transportation of metal-bearing rock material from these depths, present their own set of challenges and associated high costs [31]. Remarkably, the vast majority of mining activities are limited to depths of around 1 km within the Earth's crust, resulting in a notable lack of data from deeper layers to inform reserve calculations [32].

Table 1. The deepest operating mines worldwide from [35].

Mine Name	Depth (km)	Country	Metal Mined
Mponeng Gold Mine	4	South Africa	gold
TauTona Mine	3.9	South Africa	gold
Savuka Gold Mine	3.7	South Africa	gold
East Rand Mine	3.59	South Africa	gold
Driefontein Mine	3.42	South Africa	gold, uranium
Kusasalethu Mine	3.39	South Africa	gold
Empire Mine	3.36	United States	gold
KDC Mine	3.35	South Africa	gold, uranium
Blyvooruitzicht Mine	3.21	South Africa	gold, uranium
Kolar Gold Fileds	3.2	India	gold

The transition toward renewable energy necessitates a radical augmentation of renewable sources, such as wind, solar, geothermal, and biomass, in contrast to fossil fuel-based energy systems [36]. This shift implicates a diverse array of minerals and metals essential for energy production, conversion, and storage technologies, as delineated in Figure 3a. The specific mineral composition required is contingent on both the type of renewable energy in question and its stage of technological readiness [37,38].

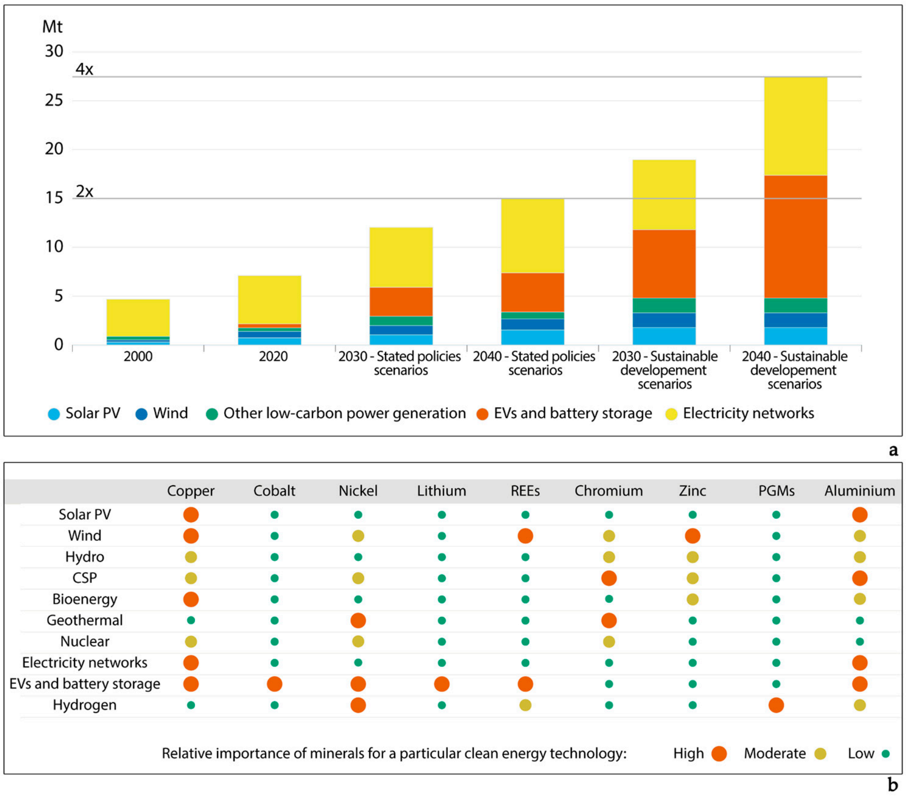

Figure 3. Top (**a**), Critical elements needed for clean energy technologies, from [37] modified bottom (**b**), total mineral demand for clean energy technologies by scenario, 2010–2040 (2020 is the base year). From [37], modified.

To maintain our standard of living, each person needs 15 to 20 tonnes of minerals per year, excluding hydrocarbons [32]. The International Energy Agency (IEA) has formulated two contrasting scenarios to elucidate the prospective aggregate demand for mineral resources in clean energy production. The first, known as the IEA's Specific Policy Scenarios (STEPS), projects a more conservative trajectory of resource utilization. The second, referred to as the IEA's Sustainable Development Scenarios (SDS), posits a more ambitious outlook and includes factors such as low-carbon energy generation from solar, wind, and other renewables, as well as nuclear energy, electricity grids, electric vehicles, and hydrogen storage [37].

Projections indicate that the worldwide pivot toward clean energy will profoundly impact mineral demand in the ensuing two decades [39]. Under the STEPS framework, this demand is expected to double by 2040, whereas under the SDS scenario, it is anticipated to quadruple (as illustrated in Figure 3b). In both models, electric vehicles and battery storage technologies are projected to account for approximately half of the surge in mineral demand. According to STEPS, the demand for these minerals will increase tenfold, while SDS projects a more than thirtyfold increase by 2040. Notably, lithium is predicted to experience the most precipitous growth, with its demand potentially escalating over 40-fold within the SDS framework [37]. These forecasts collectively underscore the burgeoning role that clean energy technologies will play in driving global demand for critical elements.

Unlike fossil fuels, whose production and trade are globally dispersed and generally accessible across continents, the extraction and refinement of critical elements such as lithium, cobalt, and select rare earth elements are heavily concentrated within a small number of countries. Remarkably, the top three producers account for over 75% of the global supply [38]. This concentration exacerbates the vulnerability of supply chains, which are often intricate and lacking in transparency, thus elevating the risks associated with physical disruptions, trade restrictions, or geopolitical developments in major producing nations.

Moreover, although raw material scarcity is not an immediate concern, the declining quality of accessible reserves poses a challenge. As the most easily extractable deposits are depleted, the cost of production escalates, further complicating the economic dynamics of resource extraction [40].

2.2. A New Method for Metal Extraction

The CHPM2030 project envisions a groundbreaking technological approach for the integrated extraction of Combined Heat, Power, and Metal (CHPM) from ultra-deep ore bodies, targeting the operationalization of pilot-scale systems by 2030 (Figure 4). Funded by the European Commission, this 42-month Horizon 2020 initiative aims to combine energy and strategic metal extraction into a single, interlinked process. Its central objective is to augment conventional deep metal mining techniques by eliminating the need for host rock excavation and surface ore processing. This is achieved through an intricate in situ 'leaching' petrothermal Enhanced Geothermal System (EGS), employed in ultra-deep, metal-rich geological formations. The metals are leached in situ and transported to the surface in a fluidic form, obviating the need for large-scale solid rock transportation. CHPM2030 aims to deliver proof of concept for the technological and economic feasibility of this innovative approach, offering a new kind of geothermal facility that turns the extreme content of dissolved metals and high temperatures into an advantage [41]. Such an approach offers multiple benefits: it eliminates the need for deep mine access, replaces traditional excavation with in situ chemical leaching, and mitigates labor standards concerns. These attributes are particularly beneficial in ultra-deep mining scenarios.

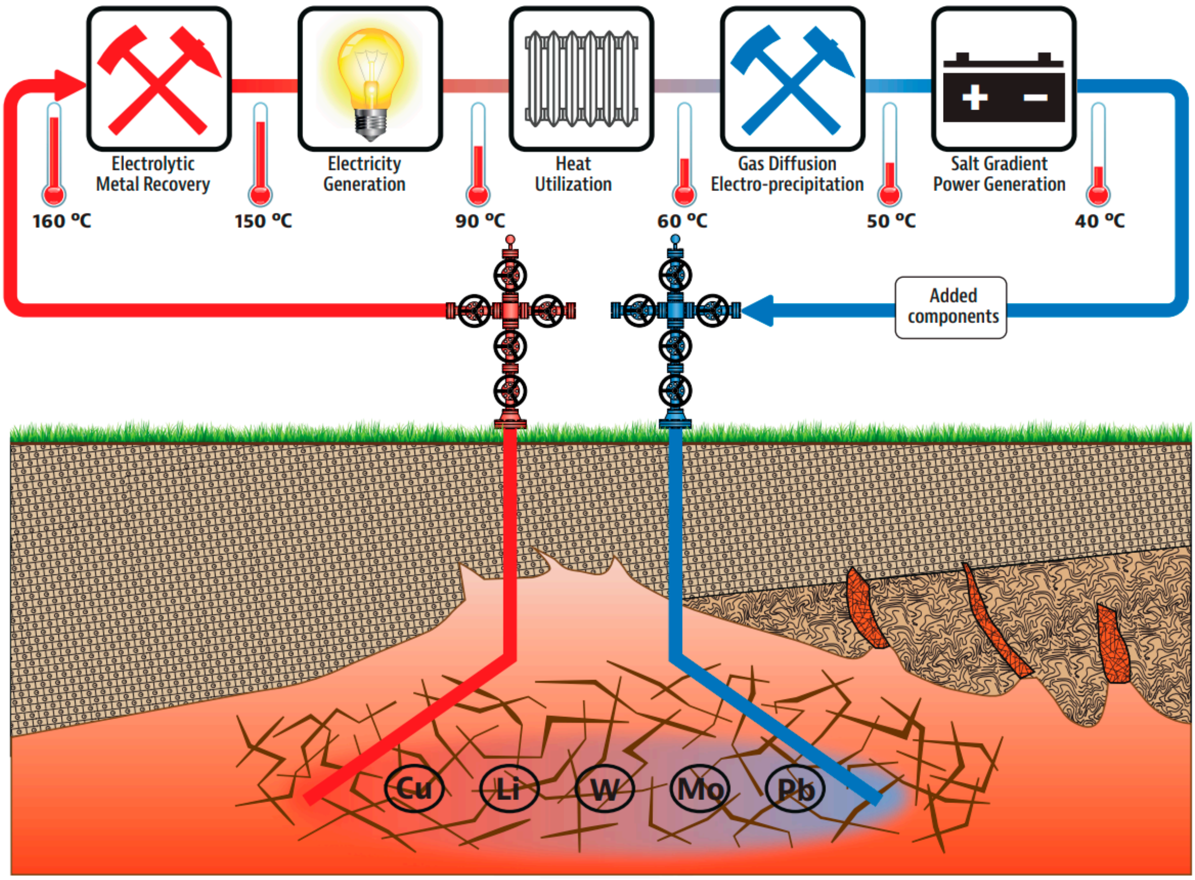

Figure 4. Schematic diagram of the overall CHPM system showing the surface technological components. From [41], modified.

Initial steps prior to CHPM implementation involve the precise location of prospective metal ore bodies, a task that can only be accomplished through comprehensive geophysical surveys. Although various geophysical methods have been employed for decades in mining exploration, they have primarily been applied to relatively shallow depths. Magnetotelluric (MT) techniques have emerged as the most promising for identifying ultra-deep ore bodies. Utilizing naturally occurring electric and magnetic fields, MT techniques can probe the electrical conductivity structure of the Earth's subsurface. Both audiomagnetotelluric (AMT) and broadband magnetotelluric (BBMT) methods are capable of exploring depth ranges from several tens of meters to tens of kilometers [42], thus making them ideal for investigating deep-seated mineral deposits ranging between 500 and 4000 m [43].

Notably, these techniques are particularly effective due to the low electrical resistivities characteristic of metallic ore mineralizations, which usually hover around or below 1 km [44]. While some studies, such as Di et al., have successfully used MT methods to explore deep-seated gold deposits, other studies have consistently identified low-resistivity zones indicative of surrounding metalliferous formations [45]. Advanced numerical procedures for interpreting MT measurements are also readily accessible, as exemplified by [42], which showcases a low-resistivity body at an approximate depth of 2 km (Figure 5). Advanced 3D inversion tools further enrich the MT data interpretation framework [46]. Collectively, MT techniques and their corresponding interpretative models represent a promising avenue for locating ultra-deep ore bodies and catalyzing the subsequent application of CHPM.

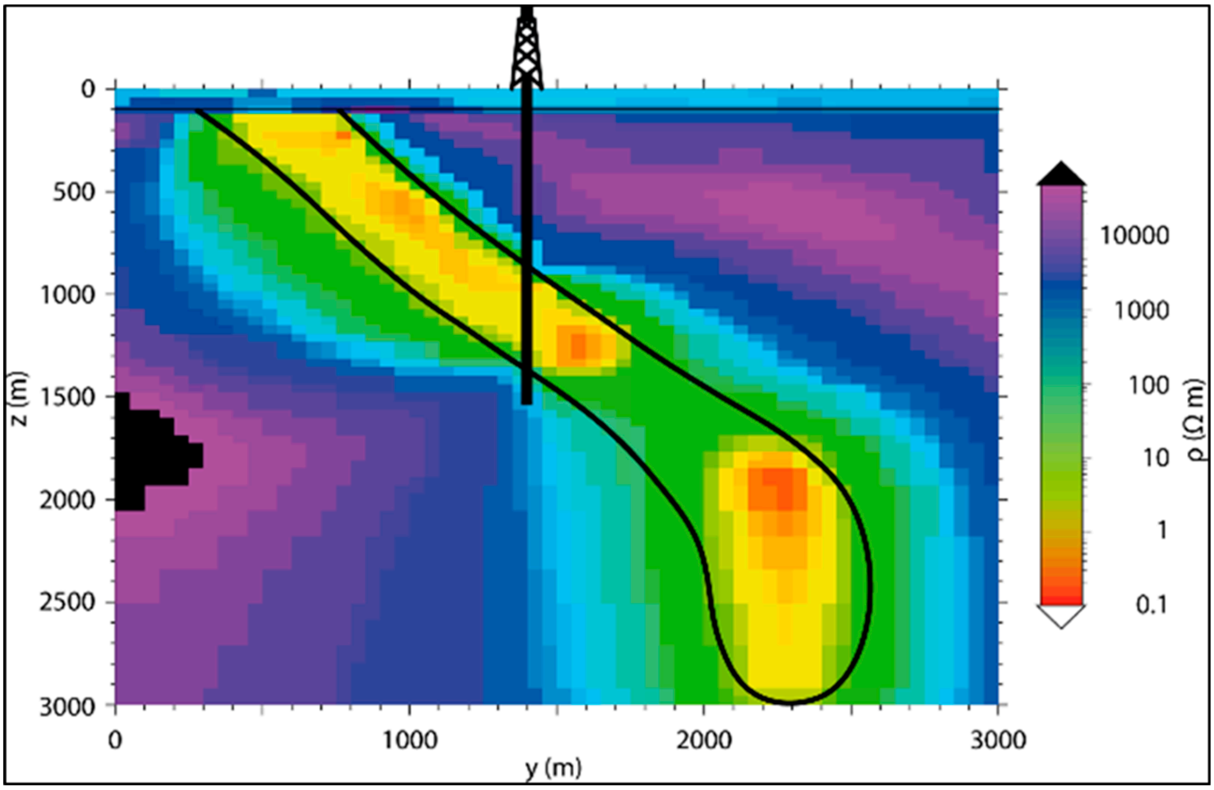

Figure 5. The numerical 2D inversion result of magnetotelluric data reveals a low-resistivity body at 2000–3000 m depth. From [42], modified.

3. The Nature and Classification of Geothermal Energy

3.1. The Source of Geothermal Energy

The underpinning of geothermal energy lies in Earth's prodigious thermal reservoir and the elevated temperatures that characterize its core and mantle. Remarkably, an estimated 99% of Earth's volume harbors temperatures exceeding 1000 °C. This abundant thermal resource allows Earth to dissipate heat into the atmosphere at an astonishing rate of 42 million MWth (Megawatt-thermal) without any discernible temperature decline. This magnitude of thermal power is comparable to the combined output of approximately 13,000 nuclear power plants, each with a capacity of 1 GWe (Gigawatt-electric). More conservative calculations, focusing exclusively on the surface area of continents (approximately 2×10^{14} m^2) and extending to a depth of 1 km within the continental crust, yield a substantial heat content of 3.9×10^8 EJ.

Given the global primary energy consumption of 540 EJ (Exajoule) in 2021 [47], this more confined thermal resource would suffice to meet human energy needs for nearly a million years. Moreover, even if this heat were entirely extracted, the Earth's natural geothermal replenishment mechanisms would restore this energy store in approximately 10^{31} J (Joule) years, further validating the sustainability and abundance of this resource. Among renewable energy options, geothermal energy presents the most considerable potential, as detailed in Table 2 [48].

Table 2. The potential of renewable energies. From [40].

Energy Source	Capacity (EJ/yr)
Geothermal	5000
Solar	1575
Wind	640
Biomass	276
Hydro	50
TOTAL	7541

3.2. Sustainability, Renewability

In the nascent stages of geothermal energy development, power plants were primarily engineered with a 30-year operational lifespan in mind, prioritizing maximum output to expedite return on investment [49]. This approach led to rapid depletion of the geothermal resources. However, contemporary frameworks increasingly mandate sustainable production paradigms, which aim to stabilize energy output over extended periods.

What distinguishes geothermal resources is their innate regenerative capacity. Unlike mineral or fossil fuel extractions where resources are permanently depleted, geothermal systems exhibit natural recuperative capabilities [50]. Heat and/or fluid extraction from subterranean reservoirs generate localized thermal or hydraulic deficits. These deficits induce steep thermal and pressure gradients, which, in turn, instigate a natural backflow mechanism that gradually restores the depleted resources. This is elaborated upon in greater detail in references [51,52].

The mechanics of this system are characterized by an initial drop in the geothermal resource's temperature during the extraction phase, followed by a gradual increase upon cessation of extraction. This temperature change follows an asymptotic trajectory, displaying a rapid initial change that diminishes over time. Rybach [53] has delineated this thermal dynamic through a diagram elucidating the temperature fluctuation in a geothermal heat pump system. Figure 6 extends this concept to Enhanced Geothermal Systems (EGSs), demonstrating that the thermal dynamics remain remarkably consistent irrespective of the enthalpy levels.

In summary, geothermal resources possess a regenerative quality akin to biomass. To maintain this renewability, it is imperative to adhere to moderated extraction rates, commonly referred to as the 'Sustainable Production Level', as detailed in [54].

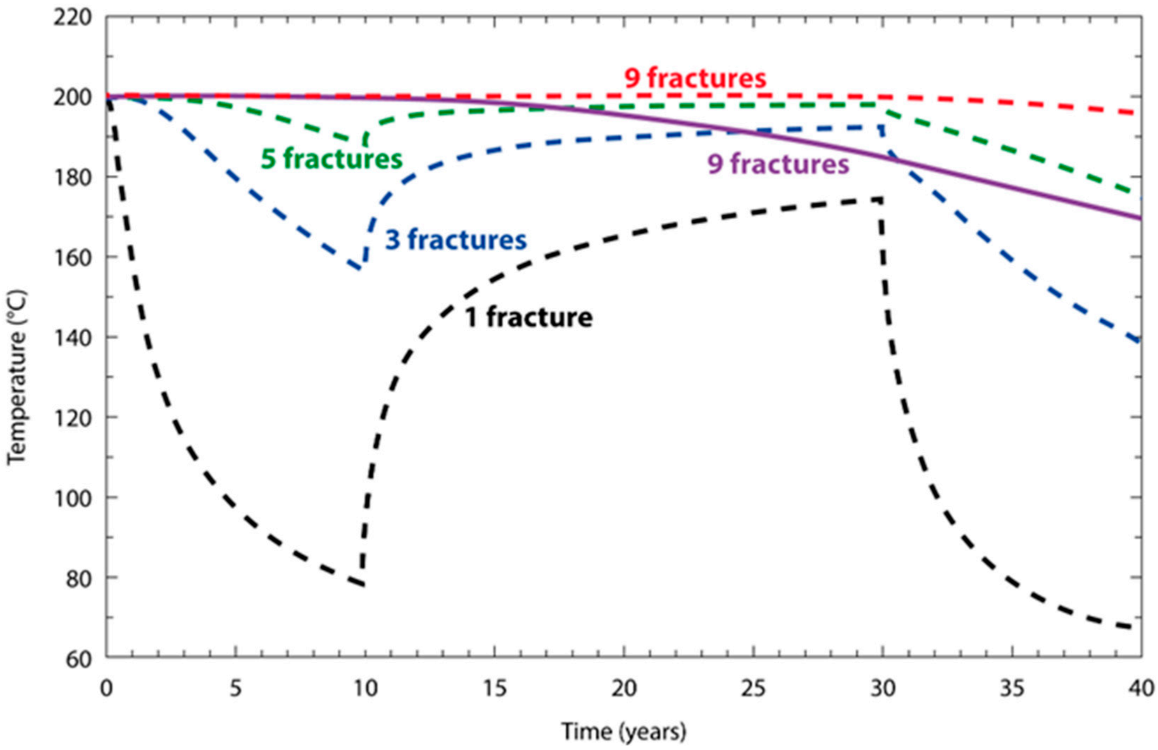

Figure 6. Production fluid temperature results from a multi-fractured PEGS reservoir with different fracture densities; dashed line: periodic extraction; solid line: continuous extraction. From [55], modified.

3.3. Types of Geothermal Energy

Geothermal resources can be systematically classified along multiple axes: depth (shallow versus deep), heat characteristics (hydrothermal versus petrothermal), temperature gradients (low, medium, high), and energetic status (low- or high-enthalpy). In the ensuing sections, this paper aims to concentrate on three salient categories of geothermal systems: specifically, Shallow, Hydrothermal, and Petrothermal Systems. Each will be rigorously assessed in terms of their unique resource compositions, affiliated technologies for utilization, accomplished milestones, and projected future developments [56].

3.3.1. Shallow Systems

Shallow geothermal resources are typically situated within the upper 400–500 m of the subsurface, with regulatory constraints defining the lower boundary at 400 m in countries like Germany and Switzerland [57]. The predominant technology for exploiting these resources is Geothermal Heat Pumps (GHPs), also known as ground-source heat pumps [57]. These pumps are functional up to a depth of 100–150 m, where ground temperatures rarely exceed 30 °C. Notably, the impact of global warming is evidenced by a gradual temperature increase at these depths [58].

In terms of key utilization technologies for shallow resources, Geothermal Heat Pumps serve as the cornerstone. These systems employ an array of configurations including closed-loop (vertical and horizontal), open-loop (groundwater), energy piles, and geothermal baskets. The thermal characteristics of the upper 400 m of the subsurface are such that it is warmer during winter and cooler during summer compared with ambient air. As a result, GHP systems offer dual functionality, providing heating in the winter and cooling in the summer [59]. Comprehensive details pertaining to the design, installation, and operational aspects of these systems can be found in [60,61]. In contemporary settings, GHPs are increasingly deployed across various types of buildings, residential, educational, industrial, as well as public and commercial establishments [62].

Significantly, Geothermal Heat Pumps represent one of the most rapidly expanding segments within renewable energy technologies globally, and unquestionably the fastest within the realm of geothermal technologies [62]. Figure 7 elucidates this exponential growth by charting the rise in global heat supply facilitated by GHP systems from 1995 to 2020. While GHPs are part of the broader Geothermal Direct Use category, their remarkable growth and unique resource base warrant an independent discussion in this paper.

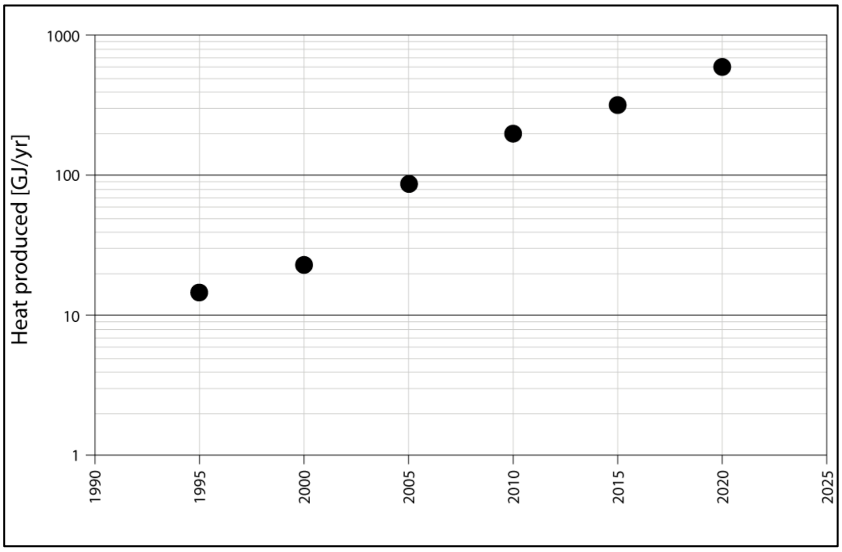

Figure 7. Global heat delivery of GHP systems in 2020. From [63], modified.

3.3.2. Hydrothermal Systems

Hydrothermal resources represent a deeper and hotter subset of geothermal assets compared with their shallow counterparts [64]. Characterized by naturally occurring fluids at elevated temperatures, these resources serve as heat carriers, which can be extracted from subterranean reservoirs via boreholes. However, it is important to note that hydrothermal resources, such as deep aquifers, are contingent on a unique set of geological and hydrogeological conditions, making them relatively scarce. These fluids can attain temperatures of several hundred degrees Celsius and are primarily deployed for two key applications: Geothermal Power Generation and Geothermal Direct Use. The demarcation between these two applications typically lies within a temperature range of 100 to 150 °C. Due to the scope of this paper, these applications will be discussed only in brief.

Geothermal Power Generation

This technology represents a specialized avenue for power generation, employing particular machinery, primarily turbines, to convert heat into electrical power. Fields exhibiting high temperatures, exceeding 200 °C at depths less than 2 km, are predominantly found in volcanic regions and thus are relatively rare [65]. The mean capacity of these plants approximates 50 MWe. Notably, the largest existing hydrothermal facility, situated at Toanga (formerly known as Nga Awa Purua) in New Zealand, features a singular 140 MWe turbine unit and is fueled by a mere six production wells. Advancements such as binary power plants [66] now allow heat-to-power conversions even at reduced fluid temperatures of 100–120 °C. However, the conversion efficiency at these lower temperatures is proportionally modest, averaging around 10%, and plant sizes are consequently restricted, usually not exceeding a few MWe [65].

It is worth noting that geothermal power plants consistently produce base-load electricity, outpacing the annual global average availabilities of solar photovoltaic and wind power, which stand at 68%, 14%, and 21%, respectively [49]. Although the annual increase in global geothermal electricity supply is positive, its growth rate lags behind those of solar PV and wind energy (Figure 8). A multitude of publications exists on the topic of geothermal power generation; however, the limited citations here [67,68] are not intended to diminish the value of other scholarly works.

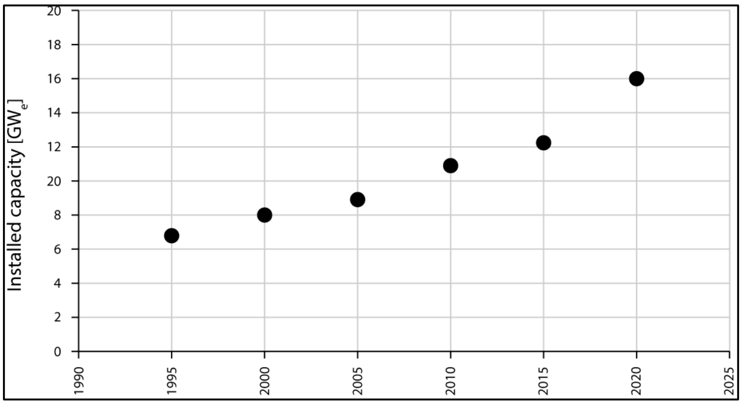

Figure 8. Growth of globally installed capacity of geothermal power plants 1990–2020. From [63], modified.

Geothermal Direct Use (Besides GHPs)

Low-temperature hydrothermal resources are characterized by their permeable, stratified formations that consist of either aquifers or fracture and karst systems. These are particularly useful for geothermal direct-heat applications [69]. The suite of technologies that exploit these resources serve multiple purposes, such as space heating, especially when implemented through geothermal doublets for district heating, which now also offers cooling capabilities. These technologies also find applications in recreational facilities like spas, as well as in industrial, agricultural, and aqua-cultural settings like fish farms [70]. Significantly, over half of the heat generated for direct use originates from Geothermal Heat Pumps (GHPs), followed by 18% from bathing and swimming facilities, and 16% from district space heating systems [53].

Worth noting in this context is the phenomenon observed in various geographical locations where thermal springs naturally convey hot water to the Earth's surface. In these systems, meteoric water infiltrates the surface, travels to greater depths where it gains heat, and then ascends back to the surface, often via permeable fractures [71]. Such systems exemplify the concept of geothermal sustainability as they have proven to deliver consistent heat outflows over extended periods.

The trend in heat delivery from the aforementioned direct systems, excluding GHPs, is depicted in Figure 9, covering the span from 1995 to 2020. While the growth has been remarkable, it is worth noting that the trajectory has been linear rather than exponential.

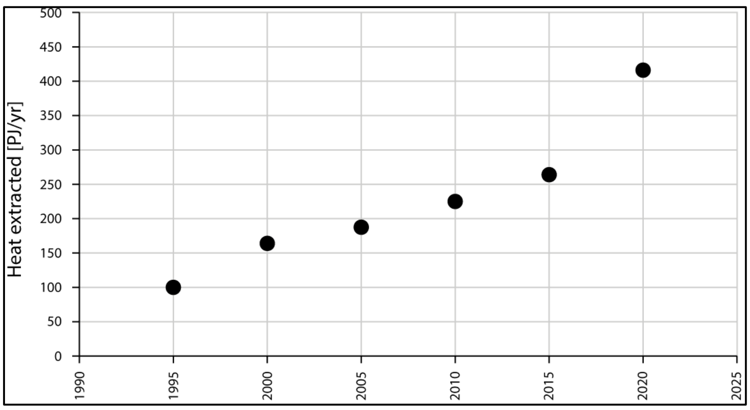

Figure 9. Growth of direct-use heat delivery 1995–2020 from deep resources (i.e., without GHPs). From [63].

3.3.3. Petrothermal Systems

In the depths of the Earth, primarily in basement-type rocks like granites, gneisses, and schists that constitute the continental crust, vast reserves of heat exist with increasingly elevated temperatures [72]. Although these geothermal resources are theoretically ubiquitous, they often lack naturally occurring hot fluids.

The Combined Heat, Power, and Metal extraction (CHPM) technology leverages an underground heat exchanger as its driving force (Figure 6). While this heat exchanger is integral to the heat delivery process, it is insufficient on its own; the extracted heat must subsequently be transported to the surface. Figure 10 elucidates the core components of an Enhanced Geothermal System (EGS), a term here primarily used to denote petrothermal resources. To avoid ambiguity, the term Petrothermal Enhanced Geothermal System (PEGS) will be employed herein. Although extensive literature exists on EGS, only a couple of references are cited for illustration [55,73].

The schematic diagram of a PEGS, as represented in Figure 10, features the underground heat exchanger comprised of a network of permeable fractures. These fractures are created via hydraulic stimulation executed through a centralized injection borehole. Given that these fracture networks must exist at significant depths to capitalize on elevated rock temperatures, cold water is then circulated through this centralized borehole, passing through the heat exchanger to absorb heat, and in the context of a CHPM system, to dissolve metals. This heated, metal-rich fluid is then channeled through two extraction boreholes to the surface, where its heat is converted into electricity, and metal content is extracted.

There is a consensus regarding the specifications for an economically viable, technically feasible deep PEGS heat exchanger. Table 3 delineates these criteria, highlighting key parameters such as heat exchanger volume, surface area, and flow impedance suitable for a standard 5 MWe module.

Notably, despite the immense and theoretically omnipresent nature of petrothermal resources, their development has been limited. Although estimates suggest a recoverable PEGS potential exceeding 210,000 MWe for the U.S. alone [55], as of now, only one commercial PEGS plant is operational, located in France. The Soultz power plant has an installed capacity of 1.7 MWe, while the Riffershofen PEGS plant is primarily focused on supplying industrial heat with a capacity of 24 MWth [74].

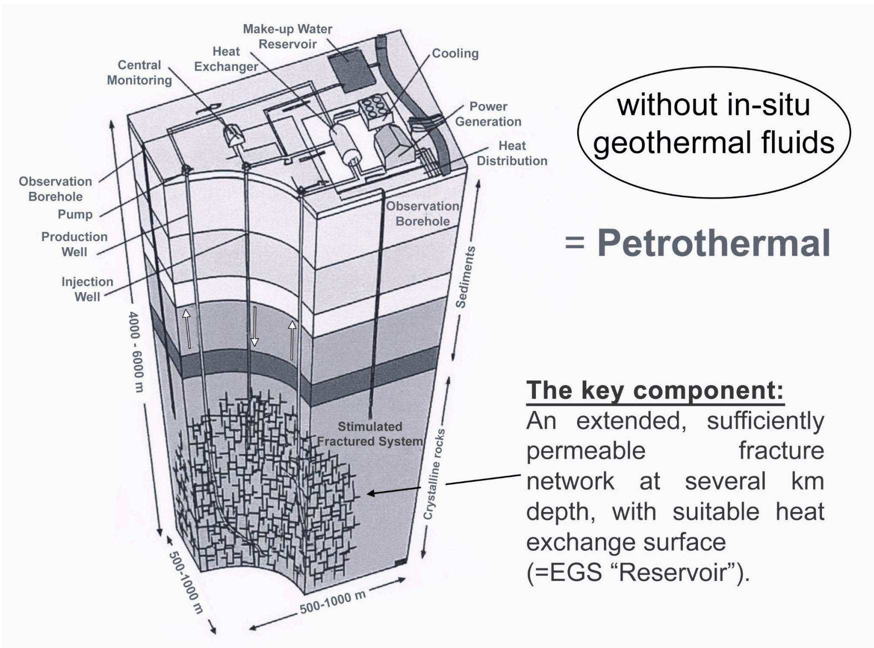

Figure 10. Schematics of a PEGS installation for power generation and district heating. From [75], modified.

Table 3. Requirements of a standard, 5 MWe module PEGS heat exchanger. The most relevant properties are heat exchanger volume, surface area, and flow impedance. From [75].

Parameters	Values
Fluid production rate	100 kg/s
Fluid temperature	150–200 °C
Separation between wells	600 m
Flow impedance	<0.1 MPa/kg/s
Water loss	<10%
Heat exchanger rock volume	>300 × 10^6 m^3
Total heat exchanger surface area	>10 × 10^6 m^2

Field-scale investigations into Petrothermal Enhanced Geothermal Systems (PEGSs) have spanned over five decades, originating at the Los Alamos Scientific Laboratory in the USA and extending across several countries including Australia, France, Germany, Japan, Sweden, Switzerland, and the United Kingdom [76]. Over this period, a myriad of challenges have surfaced. Notably, seismic activities induced by hydraulic stimulation—most prominently, the earthquake in Basel, Switzerland with a local magnitude (ML) of 3.4 in December 2006 [77], and a more damaging event in Pohang, South Korea with a moment magnitude (MW) of 5.5 in November 2017 [78]—have led to significant local damage and ignited public opposition that can potentially halt PEGS development.

Consequently, PEGS technology remains in the 'Proof of Concept' stage, necessitating considerable R&D investments to validate its feasibility [79,80]. Several key objectives must be met to advance this technology:

- The development of custom-designed PEGS heat exchangers that can be strategically located and are capable of functioning under varying local subsurface conditions (lithology, temperature, stress field, natural seismicity, etc.), with minimized induced seismicity;
- Evaluation of the long-term performance metrics of PEGS heat exchangers, particularly with regard to productivity and environmental impact;
- Assessment of the recovery factors of PEGS, defined as the ratio of extractable heat to the total heat in place. Contemporary estimations, such as those by Ladislaus Rybach [80], posit a mere 2% recovery factor, which is economically nonviable;
- Resolving scaling issues that affect both near-wellbore regions and the casing and tubing infrastructure;
- Enlarging the plant capacity from a modest few MWe to a more industrially relevant range of several tens to hundreds of MWe.

The realization of these goals, among other research, development, and demonstration initiatives, requires substantial financial backing and represents a long-term commitment.

4. Combined Geothermal Energy and Mineral Extraction

4.1. Reservoir Stimulation

In the preceding discussion, we established that Petrothermal Enhanced Geothermal Systems (PEGS) rely on natural heat sources while featuring engineered or artificial fluid reservoirs. Extending from this premise, thermal wells with artificially enhanced heat exchanger surfaces or augmented yields can also be categorized under 'engineered' environments.

The formation of these artificial pathways for fluid movement is termed 'stimulation', encompassing three primary methodologies:

- Hydraulic Fracturing or Hydroshearing;
- Chemical or Acid Treatment;
- Thermal Fracturing (Secondary Treatment).

During hydraulic fracturing, high-pressure fluids, commonly water in geothermal applications, are injected into the rock to either create new fractures or expand existing ones [81]. The term 'hydroshearing' is employed when the fracture system principally exploits natural fractures and lower pressures are sufficient, thus mitigating the risk of induced seismicity [76].

Chemical treatments serve as supplementary or alternative approaches to hydraulic fracturing, particularly effective in carbonate rocks or in fractures filled with soluble minerals [82,83]. Commonly used chemicals include hydrochloric acid, hydrofluoric acid, and various chelating agents.

Thermal fracturing is predominantly used in high-enthalpy geothermal fields. This method leverages the cooling effect of injected water to induce thermo-elastic stress in the rock around the wellbore, facilitating the expansion of existing fractures. The magnitude of this artificially induced stress is influenced by factors such as the shape and thermal properties of the cooled rock, temperature differentials, and injection direction [84].

In the engineering of a geothermal reservoir, three principal limiting factors are of paramount importance: heat, rock type, and stress regime. Granitoid rocks of the crystalline basement are preferred for their negligible in situ porosity and permeability. The stress field plays a dual role, influencing both the feasibility of reservoir creation and its subsequent management [84].

When discussing the economic dimensions of PEGS, drilling and downhole fracturing emerge as the primary cost drivers. Although the petroleum industry has made significant strides in deep and high-temperature drilling, geothermal energy extraction demands larger well diameters and often higher temperatures, necessitating specialized equipment [84].

In summary, the hydraulic fracturing procedure stands as a complex, high-risk endeavor requiring meticulous planning and execution. The generated fracture system must adhere to specific quality criteria, positioning the quality of hydraulic fracturing as a potential risk factor in the development of an Enhanced Geothermal System.

4.2. Metal Leaching Technologies

The exploration of geothermal energy's economic viability through the secondary utilization of brines has a rich history, tracing back over half a century. Lithium emerged as the inaugural mineral extracted from geothermal fluids [85]. Noteworthy developments in lithium extraction were first initiated in felsic magmatic terrains in New Zealand [86,87], extending subsequently to diverse magmatic settings in the United States, including granitoid environments [88,89].

Studies focusing on leaching or elemental mobilization deploy source and reservoir rocks subjected to aqueous media, commonly termed 'mild leaching agents'. Historically, the Frasch process for sulfur recovery has demonstrated similarities in methodology and depth, offering a relevant point of comparison for modern lithium extraction from geothermal brines [90]. These conditions are orchestrated to replicate the high-temperature, high-pressure attributes of the native reservoir. The primary aim is to elucidate the dynamics between water-rock interactions and determine the range and volume of elements that can be either mobilized or precipitated from the rock matrix [43,84].

Emerging technologies, such as those delineated in the CHPM2030 project, envisage the manipulation of metal-bearing geological formations. This allows for a synergistic co-production of both energy and metals, with adaptive potential to respond to fluctuating market demands. Natural conduits of hydraulically conductive, metallic mineral veins serve as novel 'heat-exchanger surfaces' in Enhanced Geothermal Systems (EGS), designed to exploit the dual benefits of geothermal heat and ore potential at depths exceeding 4 km [41].

In addition to water, a variety of environmentally benign fluids, such as EDTA, acetic acid, and SDS, are under exploration for their potential to enhance economic efficiency. These agents are examined for their efficacy in leaching metals from ore bodies at economically viable concentrations over extended periods [85]. Concurrently, experiments are exploring the use of CO_2 as an alternative heat transfer medium due to its advantageous thermal properties and solubility attributes for certain minerals [91]. The mobility of specific metals under controlled conditions is contingent on their geochemical behavior. Some metals, such as iron, exhibit diverse characteristics and can engage in multifaceted associations with minerals of varying stability profiles [92].

One of the pivotal challenges lies in the extraction of chemical elements from geothermal fluids in a form that is industrially viable, employing both bio- and chemical sorption methodologies [90,93].

4.3. New Technologies

The design of the heat-exchanger surface constitutes a critical component in Enhanced Geothermal Systems (EGSs), necessitating both rigorous evaluation of existing technologies and the incubation of innovative stimulation techniques [84,94].

Among the nascent stimulation technologies, heat-shock fracture generation has emerged as particularly salient [84,94]. This technique can be executed either at a temperature exceeding that of the host rock, utilizing mechanisms such as plasma or laser, or at significantly lower temperatures. Recent findings by Strabo Ltd (New York, NY, USA). demonstrate that in ultra-high-temperature reservoirs ($T > 500$ °C), the injection of sub-100 °C water can induce substantial rock fragmentation [94].

Advancements in laser technology now permit the deployment of low-energy-loss, high-power laser devices (HPLD) at substantial depths, facilitated by next-generation high-carrying-capacity optical fibers [95]. ZERLUX Hungary Ltd. (Kecskemét, Hungary) employs a system consisting of a high-power laser generator paired with a bespoke, directionally controlled laser drilling head. Preliminary data suggest that laser technology holds promise for economically viable drilling of short lateral boreholes in rock substrates. The induced thermal stress from the laser beam initiates microfractures in the immediate vicinity of the laser-impacted area. Within the framework of the CHPM2030 project [96], ZERLUX Ltd. utilized a laser with a beam power output of 1.5 kW. Subsequent destructive rock mechanics tests have shown that laser treatment results in rock failure at reduced stress levels [96]. Should this methodology prove efficacious, the next frontier would be the development of specialized laser devices designed to augment crack propagation during hydraulic fracturing, while obviating the need for increased pressure applications.

4.4. Reservoir Operation

In the context of Petrothermal Enhanced Geothermal Systems (PEGS), a reservoir, including the enhanced host rock, may either serve as a resource conservatory or function as an active deliverable system. In scenarios where resource delivery is the focus, the deep heat exchanger emerges as a pivotal component. Within the framework of the Combined Heat, Power, and Metal extraction (CHPM) system, this heat exchanger is doubly tasked with not only facilitating metal production but also generating the requisite electricity for metal extraction processes.

As elucidated in Section 3.3.3, a multitude of countries have undertaken comprehensive explorations into the operational dynamics of PEGS, with particular emphasis on the deep heat exchangers. These explorations primarily aim to elucidate the feasibility and efficacy of constructing and operating such deep heat exchangers, along with quantifying their yield potential. The experiments have been executed at full scale, encompassing both depth and temperature variables. These aggregated findings have been meticulously analyzed, synthesized, and presented by Keith Evans in Section 4.2 [97].

One of the most groundbreaking field stimulations to date occurred in Northern Nevada in 2023, spearheaded by Fervo Energy. Uniquely, Fervo's design philosophy eschewed the traditional approach of constructing a complex fracture network. Instead, the company applied fracturing design methodologies that have demonstrated empirical efficacy in shale formations [98]. Key findings from this initiative have been compiled and presented in Table 4.

Table 4. Results of numerous PEGS field experiments. From [97,98].

Reservoir (Depth)/Year	Country	Well Separation (m)	Circ. Duration (Days)	Q_{prod} (l/s)	Reservoir Impedance (MPa/Kg/s)	Thermal Break-Through	Swept Volume 1000 m^3	Loss (%)
Fenton Hill 2-well (2.8 km): 1980	USA (New Mex)	200	282	5.5	0.2	Slight	0.4–1.3	10
Fenton Hill 2-well (4.2 km): 1992	USA (New Mex)	200∓50	183	5.5	4	No	2.2–5	16
Rosemanowes 3-well (2.2 km): 1988–89	UK	120/150–250	200	3/16	3.3/0.6	Yes	13–19	21
Hijiori 4-well (1.8 km): 1991	Japan	40/50/55	90	12.8	0.4–0.7	No	23	23
Hijiori 3-well (2.2 km): 2000	Japan	90/130	300	5.8	1.4/2.1	Yes	64	64
Soultz, 2-well (3.5 km): 1997	France	450	135	25	0.2	No	16	0
Soultz, 3-well (5 km): 2005	France	600	150	12	0.6	No	10.4/0.1	0
Soultz, 2-well (5 km): 2009	France	600	60	3	~0.55	No	0	0
Fjällbacka, 2-well (~0.5 km): 1989	Sweden	100	40	1	4.9	No	45	45
Le Mayet, 2-well (0.8 km): 1987	France	100	66	5.2	1.7	No	38	38
Habanero, 2-well (4.2 km): 2009	Australia	560	60	17	0.7	No	18.5	0
Fervo Energy 2-well (2.3 km): 2023	USA	100	37	~40/max. 63	Not specified	No	*	0

* productive lateral section ~1000 m.

The primary insights gleaned from our investigations can be outlined as follows:

- While pre-existing, highly permeable fracture zones and fault lines have been intermittently observed, their incidence is not consistent across all sites;
- There is a general trend indicating an enhancement in fluid injectivity and productivity within the investigated boreholes. However, this is substantiated predominantly in the immediate vicinity of the wells;
- The conditions beyond the immediate perimeter of the heat exchangers remain ambiguous;
- Three-dimensional mapping of microseismic activities during the hydraulic stimulation process has provided critical insights into the spatial expansion and morphological development of the heat exchanger, extending up to a kilometer from the injection well;
- Anomalies such as thermal breakdowns or loss of circulated water have also been documented;
- There were substantial variances in the heat exchanger volumes, which translated into production flow rates ranging between 1 and 25 L per second;
- Importantly, none of the field-scale experiments resulted in adverse environmental consequences, such as groundwater contamination, in contrast to what is often observed in shale-gas fracking operations.

The question of long-term sustainability of production from the heat exchangers remains a subject of ongoing inquiry. A comprehensive summary of the existing limitations is presented in [96]. It posits that the lack of field-scale experience regarding the temporal evolution of PEGS heat exchangers presents an empirical gap. Factors such as permeability enhancement—potentially from new fractures induced by cooling cracks or mineral dissolution—can amplify the recovery factor. Conversely, reductions in permeability, perhaps due to mineral deposition or short-circuits in the system, can compromise efficiency. In the absence of long-term, field-scale data, any economic projections pertaining to production and maintenance costs must be viewed as provisional.

5. Economic and Climate Impacts, Future Opportunities

5.1. Geothermal Energy and Sustainable Mining for SDG 7

The convergence of geothermal energy's potentialities with the United Nations' Sustainable Development Goal (SDG) 7, a mandate for universal access to affordable, reliable, sustainable, and contemporary energy resources, holds profound implications [2]. The employment of 'Orebody-Enhanced Geothermal Systems' not only allows for the co-production of electrical energy but also facilitates the sustainable extraction of critical metallic minerals, thereby contributing to cleaner, more renewable energy paradigms [16,99].

This multifaceted approach has the capacity to significantly mitigate carbon emissions, diminish reliance on fossil fuels, and augment resource efficiency [14]. Notably, strategic elements like lithium can be sustainably harvested through this system, contributing to the advancement of a circular economy [100].

According to calculations presented in [101], employing similar methodologies for the extraction of Rare Earth Elements (REEs) from geothermal brines can result in an annual recovery of approximately 1071 kg of REEs, thereby fulfilling roughly 0.006% of domestic REE demand. The estimated economic footprint of geothermal energy production falls within the range of USD 0.04 to USD 0.10 per kWh, with initial capital expenditures hovering around USD 2500 per installed kilowatt. If the extraction of REEs can offset operational expenses and create additional revenue streams, the sale of Rare Earth Oxides (REOs) might contribute up to 0.11% of the operational budget.

Furthermore, the inherent weather-resilient nature of geothermal energy provision ensures a continuous and stable supply of clean energy. In summation, the integrative application of geothermal energy and sustainable mineral extraction mechanisms has the potential to radically transform the energy sector and substantiate the objectives of UN SDG 7 [2].

5.2. Achieving a Low-Carbon Economy and Sustainable Mining Practices

In juxtaposition to conventional mining techniques, geothermal energy offers a paradigm shift toward environmental sustainability. Through the deployment of 'Enhanced Geothermal Systems' (EGS), the extraction of critical elements such as lithium and tungsten becomes far less ecologically detrimental [16]. The methodology employed in mining geothermal brines obviates the necessity for invasive excavation, thereby mitigating adverse effects on land quality, water resources, and local biodiversity. The simultaneous cogeneration of both energy and valuable metals from these geothermal reservoirs augments resource optimization, bolsters efficiency, and substantiates the principles of a circular economy [12].

A comprehensive survey was conducted to assess the escalating trend in globally operational lithium brine extraction sites. For this endeavor, data from various countries, such as the United States, Argentina, Chile, and China, were aggregated from the Mineral Commodity Summaries published by the United States Geological Survey (USGS) [102–108]. Additionally, an analysis of global lithium production metrics was sourced from Statista.com (accessed on 21 March 2023), providing a longitudinal view of production escalation over past decades [109].

A salient milestone was observed in 2018 when lithium production experienced a significant uptick, coinciding with a burgeoning demand for electric vehicles [92]. Utilizing a linear regression forecast model, predictions for lithium production for the years 2030, 2040, and 2050 were extrapolated based on historical trends. The precipitous rise in electric vehicle adoption serves as a pivotal variable in the surging lithium demand; specifically, the utilization of lithium in fabricating heavy-duty batteries for these vehicles substantially outpaces its application in portable electronic devices [10].

Figure 11 offers an instructive panorama of lithium production's potential trajectory in upcoming years, emphasizing the instrumental role electric vehicles are expected to play in this expansion. It should be noted, however, that the data visualized in the graph amalgamates both conventional and brine extraction modalities, while not delineating the proportion attributable to each method.

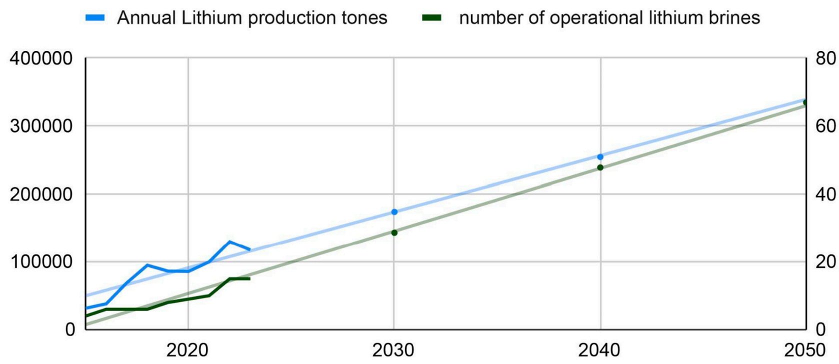

Figure 11. Forecast of Annual Lithium production and worldwide number of operational lithium brines, left axis lithium production (t), right axis number of operational lithium brines; based on [102–107].

5.3. Stakeholder Collaboration for Effective Geothermal Energy Governance

The deployment of geothermal energy for both mineral extraction and energy production is not without its hurdles; however, a suite of viable solutions stands ready to surmount these challenges. The initial capital outlay, primarily devoted to drilling activities and infrastructural enhancements, can be significantly ameliorated by the long-term reductions in operational costs and the prospective revenues garnered from mineral extraction [110–112]. Advanced exploratory measures, refined drilling methodologies, and the utilization of Enhanced Geothermal Systems (EGSs) can serve as effective countermeasures to the finite availability of high-quality geothermal resources. Additionally, issues related to equipment scaling and corrosion can be assuaged through advancements in materials science and the adoption of novel extraction methodologies [113,114].

Moreover, potential environmental ramifications, such as induced seismic activities, substantial water usage, and the inadvertent release of greenhouse gases from geothermal reservoirs, can be comprehensively addressed. This can be achieved by the instatement of rigorous monitoring frameworks, the continual improvement of drilling practices, and the incorporation of advanced reservoir management strategies [115].

Geothermal energy projects hold a multi-faceted potential for a diverse range of stakeholders. On an industrial level, these projects can escalate resource efficiency and boost profit margins. Concurrently, governing bodies can exploit these energy solutions as strategic avenues to achieve climate action milestones, attenuate the reliance on fossil fuels, and invigorate both local and national economies. At the community level, the benefits are manifold, encompassing stable and clean energy provision, prospective reductions in energy costs, and the amelioration of living standards. In summary, the strategic deployment of geothermal energy serves as a robust lever to advance resource efficiency, buttress sustainability initiatives, and stimulate economic prosperity, all while minimizing adverse environmental impacts [116,117].

5.4. Future Challenges and Opportunities

While geothermal brine mining promises a plethora of environmental and economic benefits, it concurrently poses a gamut of challenges that necessitate comprehensive solutions for its long-term feasibility and broad adoption. One salient impediment resides in the considerable upfront expenditures required for project development, encompassing drilling, exploration, and the procurement of sophisticated surface equipment [118,119]. This initial financial outlay can serve as a formidable barrier to entry, particularly for small-to-medium enterprises or regions characterized by fiscal constraints [120].

The intricacies and ambiguities associated with subsurface geological configurations further amplify the inherent risks and complicate the predictability of project outcomes [88]. Technological complexities represent another layer of challenge; mineral extraction from geothermal brines demands specialized apparatus and a high level of expertise [121]. Citing the work of Kavanagh et al., 2018, the extraction of lithium from depths approaching

2 km poses considerable technical and economic hurdles. Moreover, the caustic chemical composition of certain geothermal brines exacerbates the difficulties, raising significant concerns regarding equipment corrosion, scaling, and operational inefficiencies [118]. These factors collectively compromise the equipment's overall efficiency and longevity, thereby augmenting maintenance expenditures and operational downtimes.

From an environmental vantage point, though geothermal brine mining generally exhibits a lower ecological footprint compared with conventional mining practices [122], concerns persist. These encompass the potential release of greenhouse gases, the consumption of significant water resources, induced seismic activities [123,124], and the requisite management of waste byproducts [10,119]. Formulating efficacious strategies to mitigate these environmental ramifications is pivotal for ensuring both the long-term sustainability and societal acceptability of geothermal brine mining initiatives.

Navigating these challenges will necessitate a multi-disciplinary collaborative approach, integrating the expertise of scientists, engineers, industrial stakeholders, and policymakers. Advancements in exploratory technologies, drilling methodologies, and resource extraction techniques hold the promise of cost reductions and efficiency improvements [10]. Regulatory frameworks must evolve to offer incentives and robust backing for sustainable geothermal brine mining endeavors. By concertedly addressing these multifaceted obstacles, geothermal brine mining can be strategically positioned as a viable and appealing avenue for both sustainable mineral extraction and renewable energy production.

6. Projects, Future Options

The optimal geological substrates for the concomitant production of geothermal energy and critical elements are predominantly high-temperature, metal-bearing formations. Excluding volcanic regions, these formations are generally situated at depths exceeding 4 km [41]. Within the framework of the CHPM project, European deposits were taxonomically categorized into distinct metallogenic domains, corroborating the strong correlation between such deposits and their underlying tectonic environments [41,125]:

- Precambrian Fennoscandian Shield province;
- Early Paleozoic Caledonian province;
- Late Paleozoic Variscan province;
- Mesozoic–Cenozoic Alpine province.

In the strategic planning of Potential Exploitable Geothermal Systems (PEGSs), it is imperative to consider both the metal concentration within the ore bodies and the mineralogical phases. These factors collectively dictate the methodologies deployed for metal mobilization and subsequent extraction. Importantly, in hydrothermal contexts, fluids rich in dissolved metal content may be encountered even in reservoir rocks exhibiting low metal concentrations, a phenomenon attributable to metal transport processes.

Current research endeavors are centered on deposits situated at depths compatible with geothermal energy exploitation, where metals have demonstrated solubility in heated aqueous solutions. Sanjuan et al. conducted a comprehensive review of European geothermal and hydrocarbon fields, identifying six principal geothermal regions with notably high lithium concentrations, ranging between 125 and 480 mg/L, notably in Italy, Germany, France, and the United Kingdom [14] (Figure 12). This study places particular emphasis on three regions due to their advanced stage of development: the Upper Rhine Graben at the Franco-German border, Cornwall in southeastern England and Latium Geothermal Area in central Italy. Beyond the European context, investigations have also been conducted in North America—specifically in Nevada and Utah [126], as well as in California's geothermal fields [118]—and in other continents like Asia and Africa, particularly with regard to lithium extraction [127,128].

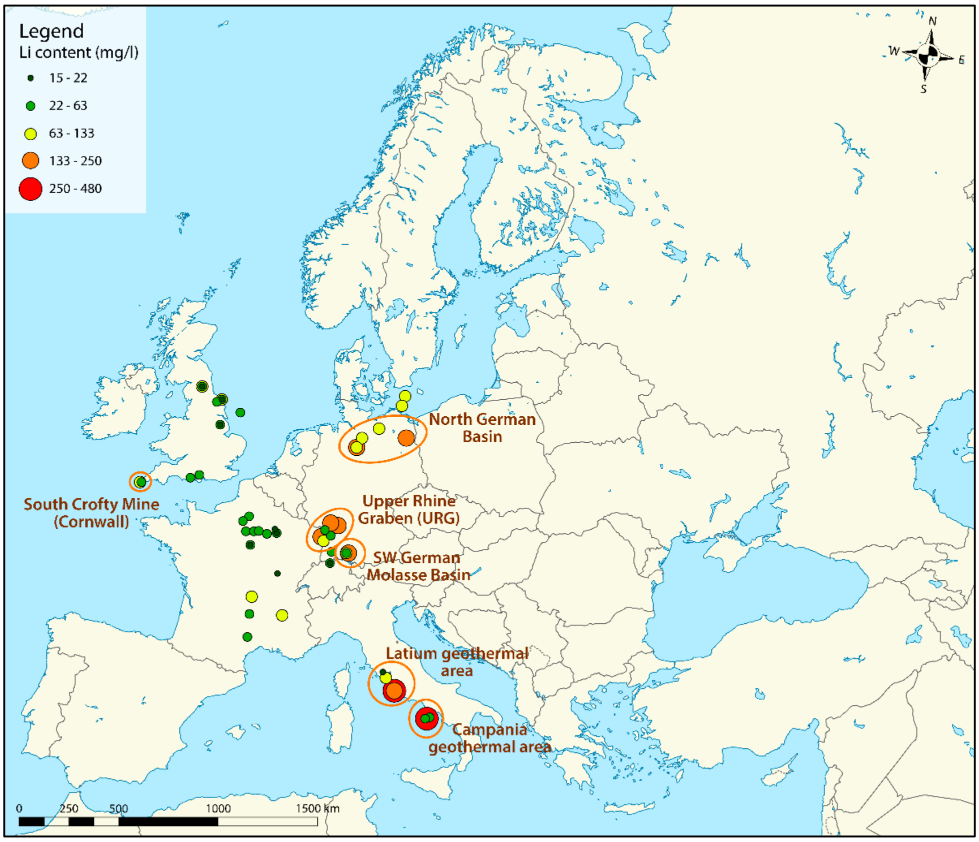

Figure 12. Map of Europe showing the six main geothermal areas with Li-rich fluids (Orange circles) and Li-concentration ranges in such fluids. From [14], modified.

6.1. Upper Rhine Graben

In the landscape of high-temperature geothermal fluids within Europe, the Upper Rhine Graben (URG) has emerged as a highly promising locus for lithium extraction from geothermal brine. The European Geothermal Lithium Brine Project endeavors to harness lithium from existing geothermal wells situated in the URG. The primary source of lithium in this region, which registers temperatures approximating 225 °C at reservoir depths, is conjectured to be evaporite minerals embedded within the Triassic Buntsandstein mica continental sandstone strata, which can extend up to 450 m in thickness. Additionally, the presence of lithium from granitic bedrock cannot be categorically dismissed. Lithium concentrations in this region have been reported to exceed 150 mg/L with promising yields [14].

The overarching objective of the project is to identify a material that exhibits selective affinity for lithium and chloride under specific thermo-hydrodynamic conditions (20 bar pressure and 80 °C temperature). According to estimates by Sanjuan et al., the ongoing and short-term planned geothermal projects in URG are projected to collectively generate between 21,300 and 32,000 metric tons per year of lithium carbonate equivalent, under the assumption that current lithium concentrations and production rates remain stable over extended periods [14].

Amplifying the scale of ambitions is the Vulcan Zero Carbon Lithium™ project of Vulcan Energy Company (Karlsruhe, Germany). According to its final phase-one feasibility analysis, this initiative anticipates a fluid production rate of 900 L/s from the URG region, sourced from two distinct project sites: Lionheart and Taro. Assuming an average lithium concentration of 181 mg/L, the project envisions an annual energy production of approximately 308,000 MWh of electricity and 252,000 MWh of heat, alongside 24,755 metric tons of Lithium Chloride (LiCl) in Lithium Hydroxide Monohydrate (LHM) equivalent [129]. Beyond lithium, the production line is engineered to generate two additional marketable by-products: hydrochloric acid (HCl) and sodium hypochlorite (NaOCl). The economic model factors in an average realized price of EUR 30,283 per metric ton of LHM over a 20-year span and accounts for a yearly lithium dilution rate of approximately 1.6% at each well site. With capital expenditures estimated at EUR 1.496 billion and annual operating expenses approximating EUR 112 million, 80% of which pertains either directly or indirectly to lithium production, the projected average annual revenue for the project's initial phase stands at EUR 704.4 million [129]. Vulcan aims to inaugurate its multi-dimensional production facility by the conclusion of 2025.

6.2. Cornwall

The Cornubian granite batholith situated in Southwestern England has been recognized as one of the United Kingdom's most promising provinces for geothermal energy production. Preliminary estimations indicate that temperatures at a depth of 5 km can significantly exceed 200 °C [130]. Notably, the initial discovery of lithium in this region was incidental to the identification of economically viable deposits of other metals like tin (Sn), copper (Cu), lead (Pb), zinc (Zn), and tungsten (W) in Variscan-age batholiths.

The Cornish Lithium company has engaged in exploratory drilling activities beneath historical mining sites to investigate the lithium potential of geothermal waters generated by water-rock interactions. Although there is a paucity of publicly available data, preliminary measurements suggest that lithium concentrations can reach levels as high as 125 mg/L [14].

Currently, the United Downs project serves as the flagship initiative for Cornish Lithium (Penryn, UK), earning the distinction of being the United Kingdom's inaugural geothermal electricity project. The production well, which has been drilled to a depth of 5057 m, successfully accessed a permeable fractured zone with temperatures approximating 180 °C and recorded lithium concentrations of 274 mg/L. Consequently, Cornish Lithium has set ambitious targets for the scalable production of lithium [131].

6.3. Latium Geothermal Area

The Latium Geothermal Area in central Italy emerges as a noteworthy focus for lithium extraction coupled with geothermal energy production. The region's geothermal reservoirs display temperatures above 200 °C and depths around 4 km, similar to those in the Upper Rhine Graben and Cornwall (Figure 12). These reservoirs are distinguished by their lithium concentrations, ranging from 50 to 200 mg/L, and low Mg/Li ratios, enhancing the economic viability of lithium extraction [9].

The primary lithium source is thought to be complex silicate minerals like spodumene and lepidolite, prevalent in the intrusive rocks. Ongoing projects in the area aim to produce lithium carbonate alongside geothermal energy, indicating the Latium Geothermal Area as a promising venture in dual resource extraction.

However, like other European endeavors, the project faces social and regulatory hurdles. Achieving community engagement and establishing a socially accepted framework remains crucial for the successful exploitation of these geothermal resources [1,9].

7. Discussion

7.1. Challenges in Upscaling: Spatial Constraints and Operational Limitations

While laboratory findings demonstrate promising results in the efficient extraction of critical minerals from geothermal brines, the transition to industrial-scale operations presents multifaceted challenges, including flow rate limitations [85,128], the transition to industrial-scale operations presents multifaceted challenges that extend beyond spatial constraints. Specifically, flow rate limitations emerge as a critical issue when upscaling the technology. While laboratory settings allow for controlled, efficient extraction, the operational expectations at an industrial level demand significantly higher flow rates to yield economically viable outcomes. Thus, it is not solely the spatial considerations that pose a barrier, but also the complex operational variables intrinsic to industrial applications. Future research should not only explore spatially efficient techniques but also address these operational challenges, potentially through the optimization of flow rates and other key parameters.

7.2. Gaps in Deep Ore Body Understanding

Our research underscores a crucial limitation in existing geoscientific literature, while there is abundant information on near-surface ore bodies, the characterization of deep subsurface ore reserves remains insufficiently explored [125]. Traditional ore mapping methodologies primarily rely on surface and near-surface markers and often overlook extra deep subsurface deposits, which may lack such readily identifiable indicators. This shortfall hampers not only the accurate quantification of mineral reserves but also affects the economic viability of extraction projects. To ameliorate this knowledge gap, it is vital to leverage advanced geophysical methods such as seismic, gravity, and magnetotelluric techniques. These methods can provide more comprehensive subsurface mapping and thereby offer a more nuanced understanding of deep ore bodies [42,43,132]. Importantly, recent research on thermal parameters of sedimentary rocks in Central Europe suggests that specific rocks, such as fine-grained quartz sandstones of Middle Cambrian from the Leba Elevation, may offer favorable conditions for Enhanced Geothermal Systems (EGS), further underscoring the necessity for targeted, in-depth subsurface studies [133].

7.3. Challenges in Resource Longevity

Our research highlights a time-sensitive constraint, revealing that resources in petrothermal systems are more susceptible to depletion over time due to leaching compared with their hydrothermal counterparts [85]. This differential implies that while the co-production of geothermal energy and minerals presents an innovative approach to resource utilization, its long-term sustainability is more finite in petrothermal systems, so the whole life cycle assessment study must prove the viability of the technology [85]. As such, there is an urgent need for ongoing exploration into innovative and sustainable extraction techniques tailored to the specific constraints of petrothermal systems to mitigate the risk of resource depletion.

7.4. Economic Barriers to Implementation

Economic feasibility remains a complex issue that extends beyond initial capital costs. Our preliminary cost analyses reveal that both the substantial capital expenditure (CAPEX) and operational expenditure (OPEX) associated with the technology are potential obstacles that can deter prospective investors. Considering the importance of lithium for energy storage technologies, advancements in lithium-specific extraction methods have the potential to alter the economic landscape of geothermal mineral extraction [41,85,134]. Considering the dual challenges of CAPEX and OPEX, it becomes imperative to examine diverse financial avenues. These can range from public-private partnerships and governmental subsidies to venture capital investments, all aimed at mitigating the economic challenges inherent in both the setup and ongoing operation of such technologies.

7.5. The Necessity of a Geothermal Drilling Mitigation Risk Fund

A frequently underestimated risk factor in both geothermal energy projects and associated critical metal extraction is the potential for drilling failures. Our experience indicates that a drilling failure can critically undermine a project's objectives, causing delays and, in extreme cases, rendering the venture nonviable [135,136]. These setbacks can have a cascading effect, disrupting not only energy production but also the extraction of valuable minerals. Consequently, the establishment of a Geothermal Drilling Mitigation Risk Fund is of paramount importance. The geothermal market at national level is too small to keep such a fund alive and it should be created at European level We strongly recommend that European Union bodies take the initiative in creating such a fund to mitigate the risks associated with drilling failures that cannot achieve desired flow rates or temperatures. Providing such a safety net can significantly accelerate technological innovation and commercial investment in this sector by reducing the risk profile of these high-stakes projects.

8. Conclusions

The depth of ore exploration rarely exceeds 1 km due to current mining technologies, so we have only a guess at reserves up to 5–6 km deep. Combined heat and mineral production technology can tap a new, unexplored source, boosting the supply of previously untapped resources. This is also the aim of the CRM-geothermal project [20], based on the CHMP2030 project [41], to develop an economically viable technology for combined heat and critical raw materials co-production from geothermal reservoirs. This co-production avoids visible large-scale installations above ground, and it has minimal environmental footprint. It should be implemented under careful and transparent environmental control to ensure public acceptance, in which case positive social and economic impacts can be expected.

All in all, geothermal energy utilization has evolved beyond its focus on the energy production to encompass a wider range of applications within critical metalextraction, including the sustainable production of critical raw materials. These features make geothermal energy a cost-effective and weather-independent source of renewable energy and mineral resources at the same time. The geothermal sector, based on technological innovations, can be capable of producing critical minerals with a more equitable geographical distribution of resources.

Currently, in Europe, particularly in the Upper Rhine Graben and Cornwall, large-scale combined heat, power, and critical metal extraction technology projects have been launched that can set the future direction of development.

However, the challenges facing this field are multi-dimensional, confirming that there is no one-size-fits-all solution nor a single critical parameter to ensure compatibility. Each application needs to be evaluated on a case-by-case basis, including the mode of thermal energy utilization. Adding another layer of complexity is the geopolitical dimension of resource availability, notably the EU's heavy dependence on world markets for critical metals. This reliance makes the supply chain especially vulnerable, posing potential setbacks in the progress toward achieving UN Sustainable Development Goal 7 (Affordable and Clean Energy). Investment in our proposed method offers a dual assurance: it not only promises a more sustainable approach to geothermal energy production but also offers a degree of resilience against market volatility in critical metals. In this way, our method contributes to strengthening both the energy and raw material supply chains, enhancing their robustness against external shocks and uncertainties.

Author Contributions: J.S. played a pivotal role in the manuscript's conceptualization visualization, as well as the reviewing and editing of the written content. L.R. was instrumental in conceptualizing the study, designing its methodology, and drafting the original manuscript. H.A.A., in addition to providing key visualization insights, was responsible for the curation of relevant data. Their combined efforts have resulted in a comprehensive review that sheds light on the advancements and potential of geothermal energy. All authors have read and agreed to the published version of the manuscript.

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