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King Abdullah Petroleum Studies and Research Center

Discussion Paper

Geothermal Energy – A Rising Powerhouse?

A Global Technical Review and Applications for Saudi Arabia



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Key Points

The Earth's core, which is as hot as the sun, contains a large amount of thermal energy insulated by impermeable rocks. This energy, totaling 15 million zetta[1] joules, dwarfs traditional energy sources such as coal and gas. However, only a fraction of this energy has been utilized, with global geothermal operations contributing just 16 gigawatts (GW), or less than 0.5%, of renewable energy in 2021. Barriers such as high upfront costs, long revenue gestation periods, technical limitations, and social/administrative constraints impede its widespread adoption.

Driven by the imperative to shift from unabated fossil fuels to clean energy, geothermal energy holds promise as a global solution. By leveraging their financial resources, operational excellence, and technological advancements to overcome some of these barriers, medium-sized to large oil and gas (O&G) companies and service providers can play pivotal roles in advancing geothermal energy. Accelerating the adoption of geothermal energy requires clear and streamlined regulatory frameworks and conciliary risk mitigation schemes to create a level playing field for all players and entice investments in this sector.

This study examines the current and potential contributions of geothermal energy, including those in Saudi Arabia, and explores the interests of O&G firms and energy service providers in the sector. This work also delves into technological innovations and how changes in market dynamics and government policies shape geothermal development, especially in Saudi Arabia. With decades of experience in O&G exploration and development, Saudi Arabia is in a favorable position to exploit geothermal energy, which requires appropriate and coherent policies and regulations. The reason for this is that the country already has the infrastructure, supply chains, and workforce required to advance and deploy geothermal technologies at the rapid rate required to meet its national energy and decarbonization targets. To achieve these goals, a fit-for-purpose technology roadmap has been proposed for Saudi Arabia.

The key takeaways from this paper include the following.

Status and Prospects for Geothermal Energy Development:

- Geothermal energy, as a clean and sustainable energy source, is slated for significant growth in the coming years due to a combination of factors, including technological breakthroughs, especially in geothermal exploration and exploitation; capital mobility; the increased entry of O&G companies into the geothermal realm; intensified global actions against climate change; concerns over energy security; and the urge to diversify the energy mix.
- The development and implementation of clear and consistent regulations and policies can encourage geothermal energy development and address potential investor concerns. Risk mitigation schemes such as insurance, capital grants, and low-interest loans may also help in this regard.
- Key technologies that are likely to fuel growth in geothermal energy extraction and usage in the coming years include engineered geothermal systems (both advanced and enhanced systems), binary cycles, ground-source heat pumps, geothermal absorption chillers, and the repurposing of O&G wells for geothermal energy.

Breaking New Ground for Geothermal Energy in Saudi Arabia:

- The western region of Saudi Arabia features prominent geological characteristics on its surface that suggest the presence of geothermal resources. These resources are characterized predominantly by low-to-medium temperature gradients, except for Jizan and Wadi Al-Lith, where temperature gradients appear appreciably higher.
- Given the country's dry and hot climate, geothermal energy has the potential to contribute significantly to water desalination and space cooling in the coming years. Other potential applications for geothermal energy in Saudi Arabia include the cogeneration and conversion of O&G wells for geothermal energy, carbon capture and storage, and mineral extraction.
- Establishing national geothermal targets for cooling and power generation can help the country overcome development challenges and capitalize on opportunities. These targets guide policy formulation, customized technology development, in-house capacity building, planning, and investments.

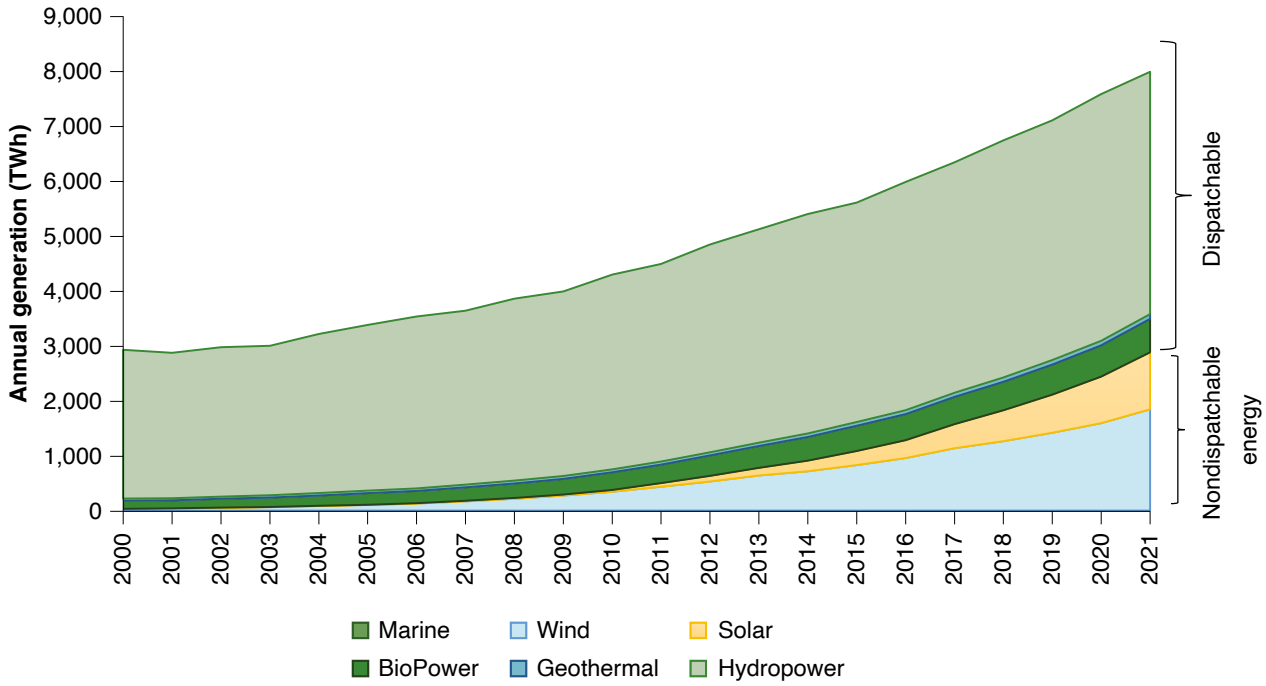
Introduction

Energy has been the driving force behind human progress, evolving from wood burning to the use of fossil fuels, nuclear power, and renewables such as hydropower, solar, and wind. Nevertheless, traditional energy sources will dominate for the foreseeable future. However, climate change, population growth, and shifts in the O&G sector are pushing for alternative energy sources. Geothermal energy, stored in the Earth's crust, remains vastly untapped, despite its potential. With similarities to O&G drilling techniques, the entry of oil companies into geothermal environments could spark a boom akin to the shale revolution. However, while sharing drilling expertise, the two industries differ significantly in terms of market structure and scale.

Although geothermal power has been around since 1913, it remains a niche player, providing less than 0.5% of renewable energy in 2021 (see Figure 1). Although this contribution appears small, geothermal energy plays a critical role in the energy mix of a handful of countries, including Iceland and Kenya, owing to their unique geological characteristics and active utilization of this resource. Geothermal energy offers numerous advantages, from electricity generation to heating and cooling, and, in some cases, value added mineral extraction and green hydrogen production. Furthermore, geothermal energy can also help foster cross-industry synergies, including renewable energy and carbon capture and storage.

This paper aims to inform national energy policies to promote geothermal development and explores its potential contributions, the growing interest of O&G firms, technological trends, and policy impacts. Structured into six sections, this paper first discusses the uses of geothermal energy; its attributes, advantages and challenges; and the transformative relationship between the O&G and geothermal industries. Then, this work explores distinctive geothermal technology ecosystems and technological trajectories that are set to influence the future of geothermal energy. This study highlights the great yet vastly untapped potential of geothermal energy in Saudi Arabia and suggests desirable interventions and technological roadmaps to spur geothermal energy development.

Figure 1. Historical annual power generation from different renewable energy sources (2000-2021).



Source: Authors' analysis based on the IRENA (2024).

1. Geothermal Energy Use Cases

Geothermal energy offers a wide array of applications, including direct use and electricity generation. Direct use involves utilizing geothermal heat, typically below 90°C, directly for activities such as bathing, cooking, and heating. This method is employed globally, with 83 countries harnessing geothermal heat for various purposes, totaling 107.4 GW of thermal (GWth) capacity in 2020, concentrated mainly in Asia Pacific (in countries such as China and New Zealand), Northern and Eastern Europe (in countries such as Türkiye and Iceland), and North America (in the U.S. and Canada).

High-temperature geothermal resources, which usually exceed 90°C, are located primarily near plate boundaries[2] (subduction zones such as the Pacific Ring of Fire), mid-oceanic ridges (such as Iceland), and rift valleys (such as the East African Rift in Kenya) (Figure 2), where most conventional geothermal developments have occurred. Heat extracted from hot water and steam is converted into electricity and other forms depending on the resource temperature and technology chosen — heating and cooling in buildings, agriculture, and industries through district energy networks and the use of ground-source heat pumps and the generation of zero-carbon electricity through geothermal power plants. The three main technologies used are *dry steam*, *flash steam*, and *binary cycle plants*. Dry steam plants utilize high-pressure steam directly for electricity generation, whereas flash steam plants rapidly depressurize geothermal fluids to produce steam. Binary cycle plants use low-temperature geothermal fluids to heat a secondary fluid, which drives turbines to generate electricity.

In recent years, there has been a consistent increase in the installed capacity of binary cycles. The reason for this is mainly that developers are increasingly moving from hot "sweet spots" characterized by high levels of enthalpy[3] to developing reservoirs with temperatures below 120°C in sedimentary basins and shallow ground. This shift requires a binary cycle that efficiently converts electricity from these relatively lower temperature regimes. One drawback of binary cycle plants is that they are somewhat more expensive than are flash or dry steam plants because of the complexity of their design and the cost of equipment and installation (Aguilera et al. 2024).

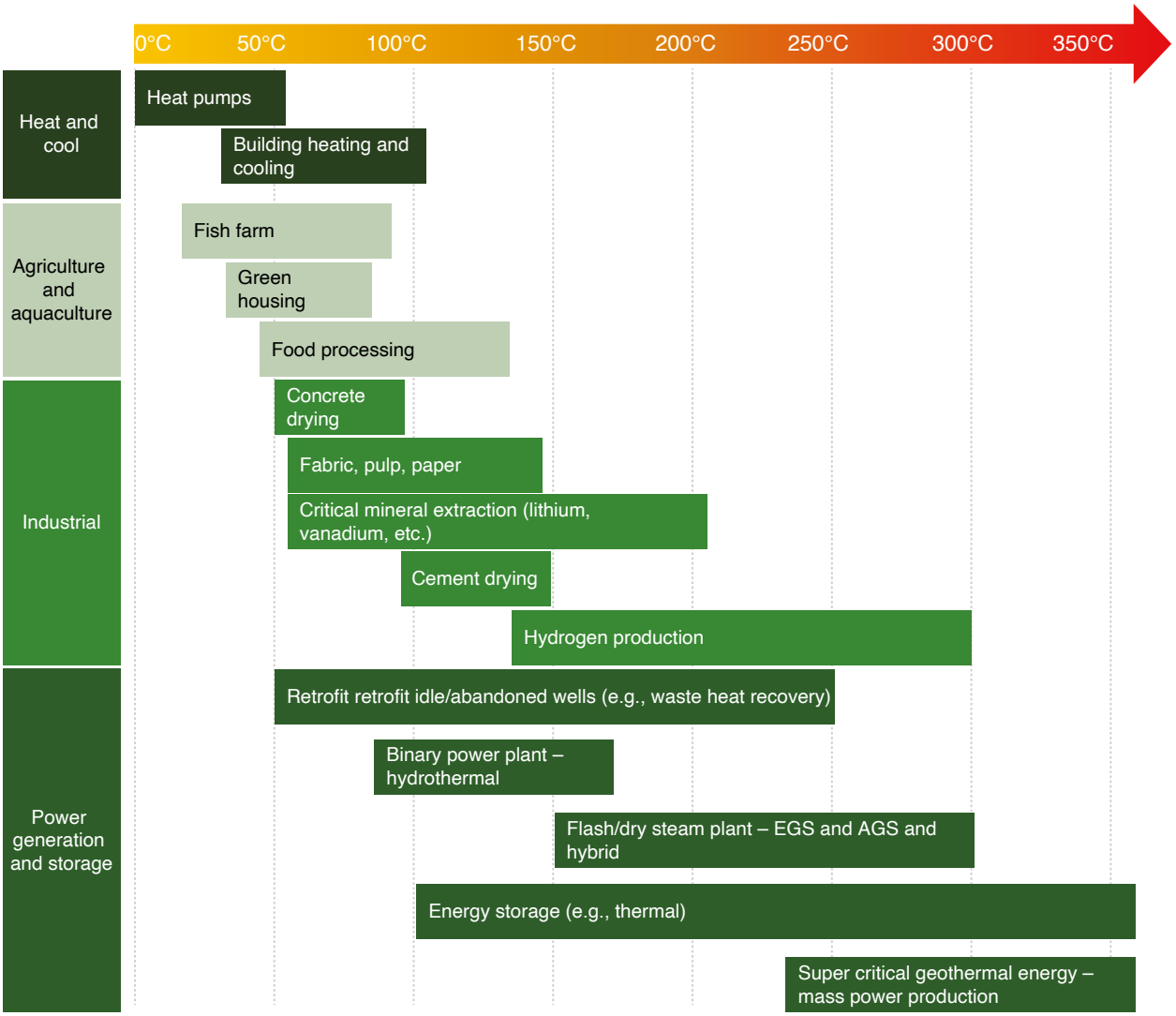
Geothermal energy offers a versatile value chain across a range of temperatures. In low-reservoir temperature applications (below 100°C), this energy powers building heating and cooling, aquaculture, and food processing. As temperatures rise, this energy enables industrial uses like concrete drying, fabric manufacturing, and mineral extraction in the 100-200°C range. Beyond 150°C, geothermal energy supports hydrogen production and repurposes wells for waste heat recovery. High-reservoir-temperature geothermal energy, over 200°C, drives power plants and energy storage solutions. Supercritical geothermal energy, whose temperatures exceed 400°C, which is yet to be discussed, may generate massive electrical output. This spectrum showcases geothermal energy as a key type of sustainable energy, meeting various needs from household to industrial, advancing society's energy goals (Figure 3) (see Appendix 1).

Figure 2. Global tectonic plate boundaries.



Source: British Geological Survey (2024).

Figure 3. Geothermal value chain – cross-cutting industries.



Source: Hoxha et al. (2023).

2. Geothermal Attributes, Benefits, and Challenges

The global deployment potential yet to be realized from conventional geothermal systems[4] stands at 160 GW (Zhou and Goldie-Scot 2022). Despite a modest annual increase of 3.4% in electricity generation over the past decade, the installed capacity reached approximately 14.6 GW-electric (GW_e) in 2022, representing approximately 10% of the world's potential. However, limitations such as the scarcity of exploitable sites and their remote locations, which are often distant from demand centers, have hindered global geothermal energy growth.

Although geothermal energy has not received as much attention as have solar and wind power in international discussions, its potential is being increasingly recognized. Thirty countries have mentioned geothermal energy in their nationally determined contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCC), focusing on its role in meeting energy demand and decarbonizing energy grids. Notable examples include Dominica, which leverages large-scale geothermal development to achieve energy independence and export excess electricity to neighboring islands. In its NDC, Saudi Arabia, too, identified geothermal energy as one of the enablers of the Kingdom's energy transformation journey.

While some energy outlooks have historically underestimated the potential of geothermal energy, recent studies by organizations such as the U.S. Department of Energy (DOE) (2022) and Bloomberg have forecasted a larger role for geothermal energy in the future energy mix. This shift in perception reflects growing levels of investment in geothermal technology and a more favorable regulatory environment.

Geothermal energy projects encounter various challenges, including securing funding for exploration and drilling, power plant construction, technological constraints, long revenue gestation periods, inadequate legislation and policy frameworks, and social and administrative barriers. This section examines the attributes and benefits of geothermal energy, alongside the technical, institutional, and financial obstacles that have thus far impeded its widespread adoption.

Geological and Geographical Constraints

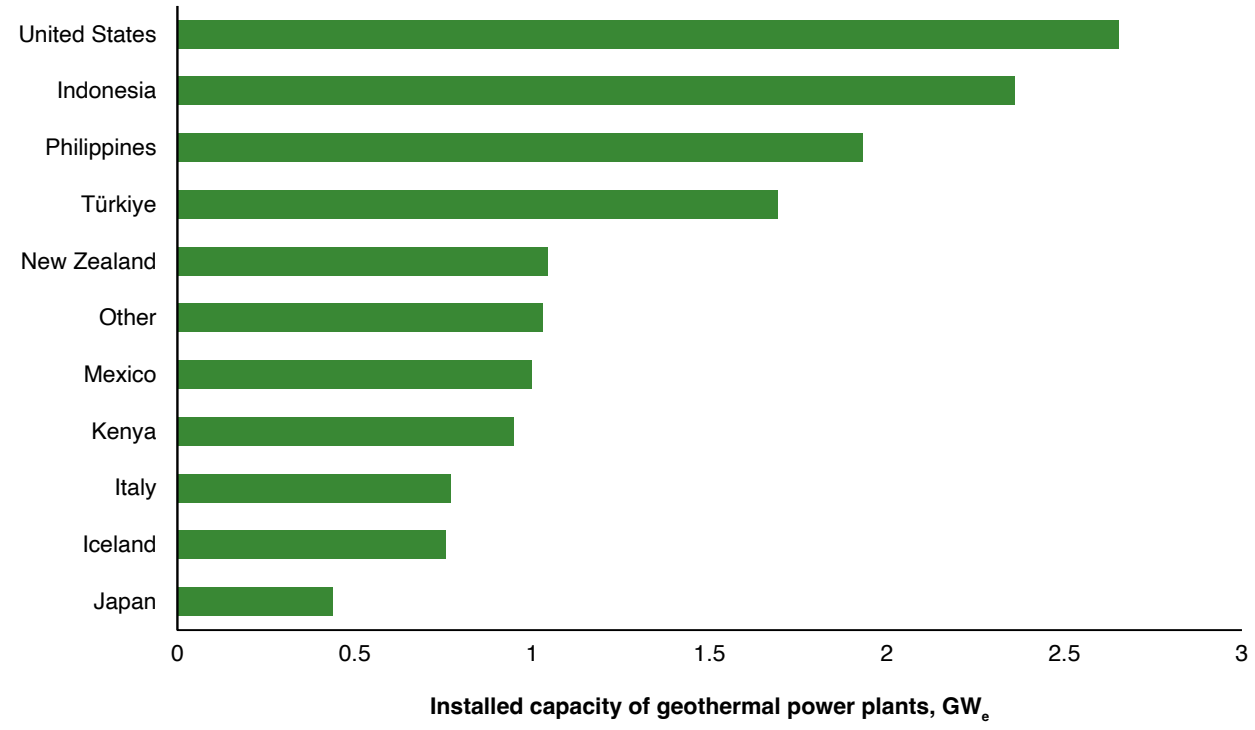
Success in the geothermal market hinges on location, technology, and capital. Currently, developed and vigorously explored geothermal systems are concentrated in tectonically and volcanically active regions such as the Pacific Ring of Fire and the East African Rift (see Figure 2). These areas offer high-yield,

low-risk prospects with high temperatures and shallow depths due to the thin Earth crust, driving exploration and exploitation efforts. However, geological and geographical constraints have restricted geothermal development in many regions, rendering it a niche market. Despite these limitations, there endeavors to tap into energy from hot sedimentary aquifers or hot, dry strata outside traditional geothermal areas are emerging. Innovative technologies, such as engineering geothermal systems or closed-loop geothermal systems, are being explored. These technologies, reminiscent of shale booms in the U.S. O&G sector, may soon position the U.S. as a leader in geothermal development. This technology could spill over and attract a larger number of O&G companies, particularly state-owned and hybrid companies, to explore geothermal opportunities in sedimentary basins where they currently operate.

Historically, the geothermal power market has thrived along the Pacific Ring of Fire, a region characterized by volcanic and tectonic activity stretching from New Zealand through Southeast Asia and Japan, and down the west coast of the Americas (see Figure 2). The resource temperature in this belt is more than 200°C. Outside this belt, countries such as Iceland, Kenya, and Türkiye have emerged as prominent geothermal power producers. Türkiye, with an installed capacity of 1.7 GWe, ranked fourth globally in 2022 (Figure 4).

The Arabian Tectonic Plate, illustrated in Figure 2, is located predominantly in the Middle East, contains the entire country of Saudi Arabia and extends into parts of Jordan, Iraq, Iran, and Syria. This plate is surrounded by several other tectonic plates – the Eurasian Plate, the African Plate, and the Indian Plate. Owing to volcanism, the western side of the plate may harbor considerable geothermal energy potential. Subsequent analysis focuses on Saudi Arabia as the likely epicenter of upcoming applications.

Figure 4. 2022 installed capacity of geothermal power plants.

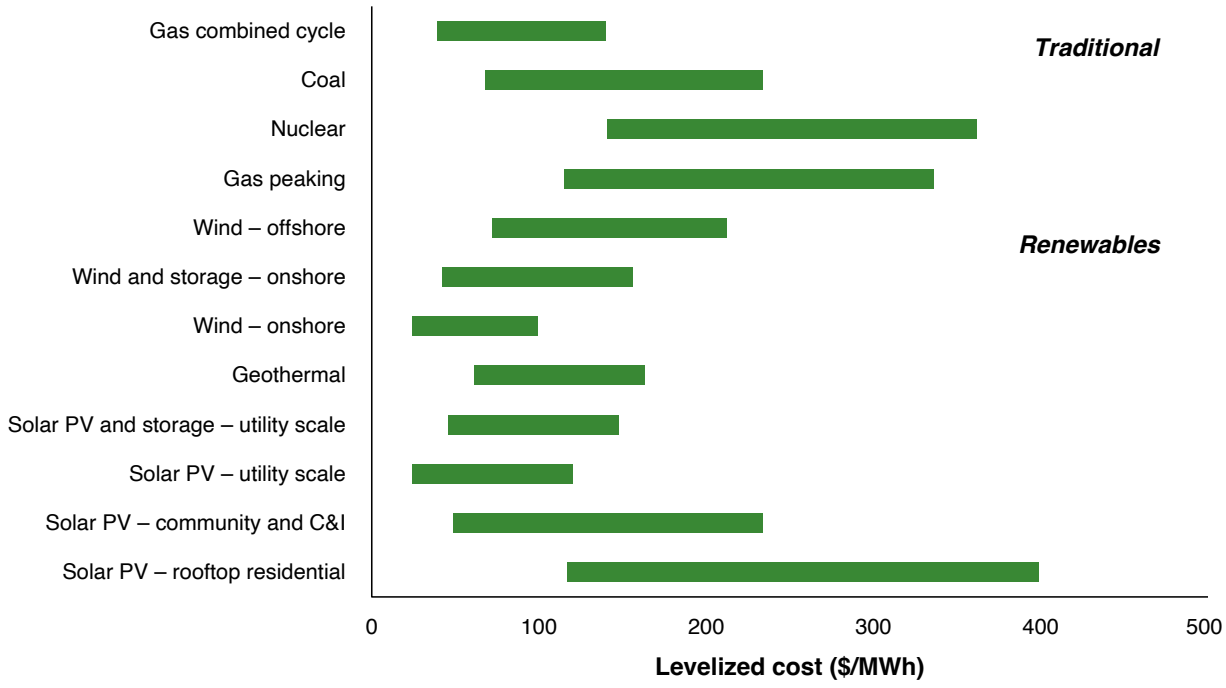


Source: IRENA (2024).

Affordability and Efficiency

Geothermal energy offers a domestically sourced, low-carbon, and reliable baseload energy option that competes favorably with other renewables. The levelized cost of electricity (LCOE)5 for geothermal projects varies with factors such as plant size, well depth, and temperature. The weighted average LCOE is $81.5 per MWh, which is higher than that of solar photovoltaic (PV) and onshore wind energy but comparable to that of renewables that integrate storage and still lower than that of conventional energy sources, as shown in Figure 5 (Lazard 2023). This relatively high cost is due to upfront exploration and development expenses. However, with increasing levels of participation, especially from O&G firms, economies of scale and scope are expected to drive down costs, mitigating project risks and reducing overall development expenses.

Figure 5. Levelized cost of electricity (LCOE) for traditional and renewable energy technologies.



Source: Lazard (2023).[6]

Energy Security and Resiliency

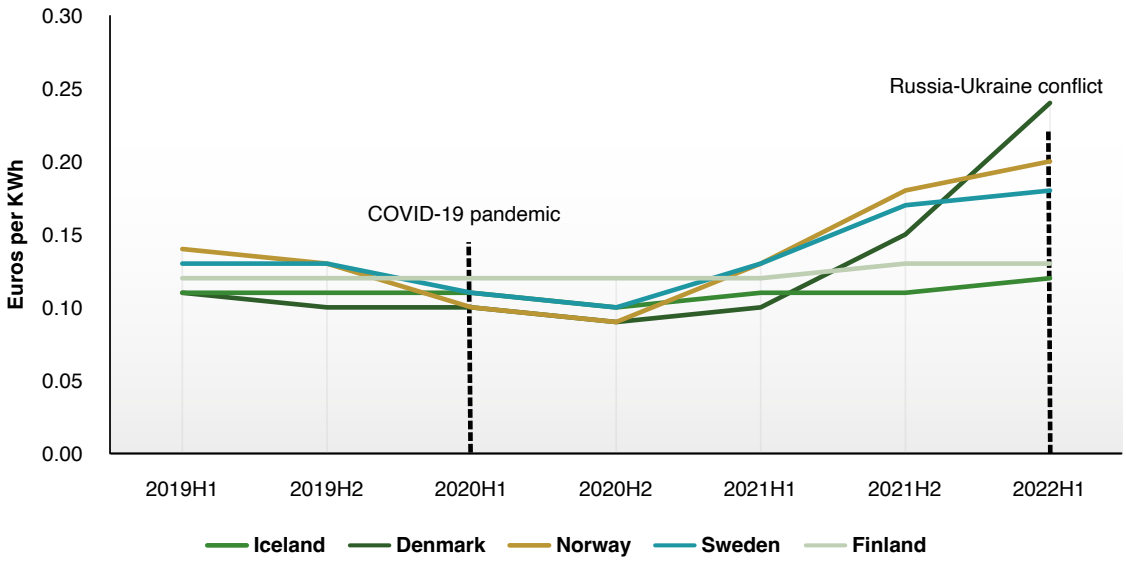
Geothermal energy offers continuous baseload power with capacity factors7 of at least 70%, exceeding solar and wind energy but being slightly lower than nuclear power (Bolson, Prieto, and Patzek 2022). With effective reservoir management, geothermal power plant capacity factors may even exceed 80% (IRENA and IGA 2023). These factors provide dispatchable baseload electricity and ancillary services, supporting the integration of intermittent renewables such as solar and wind power.

Geothermal electricity is insulated from electricity price volatility because the sales of electricity are linked to either feed-in-tariffs or long-term power purchase agreements (PPAs)[8], typically spanning the plant's 30- to 50-year useful lifespan, which also reduces the degree of risk faced by project revenues (Energy Sector Management Assistance Program 2024). This situation enhances the level of energy security, shielding against supply and demand shocks, and increases liquid fuel and gas prices. For example, in Iceland, where electricity is derived mainly from hydro- and geothermal sources, household electricity prices have remained stable for eight years (Statistics Iceland 2022) (see Figure 6).

The utilization of geothermal energy fosters socioeconomic stability and energy security by reducing the degree of reliance on costly fossil fuel imports. Indonesia, a net oil importer since 2004, has harnessed its geothermal potential to offset declining hydrocarbon production, aiming for 5 GW of geothermal generation by 2025, despite COVID-19 disruptions (Koty 2022). With a nameplate capacity of 2.3 GWe, Indonesia is currently the world's second-largest geothermal power producer, eclipsed only by the U.S.

Kenya, faced with declining hydropower due to erratic rainfall, has increased its use of geothermal energy

Figure 6. Electricity prices in Nordic countries for consumption ranging from 2,500 to 5,000 KWh.



Source: Statistics Iceland (2022).

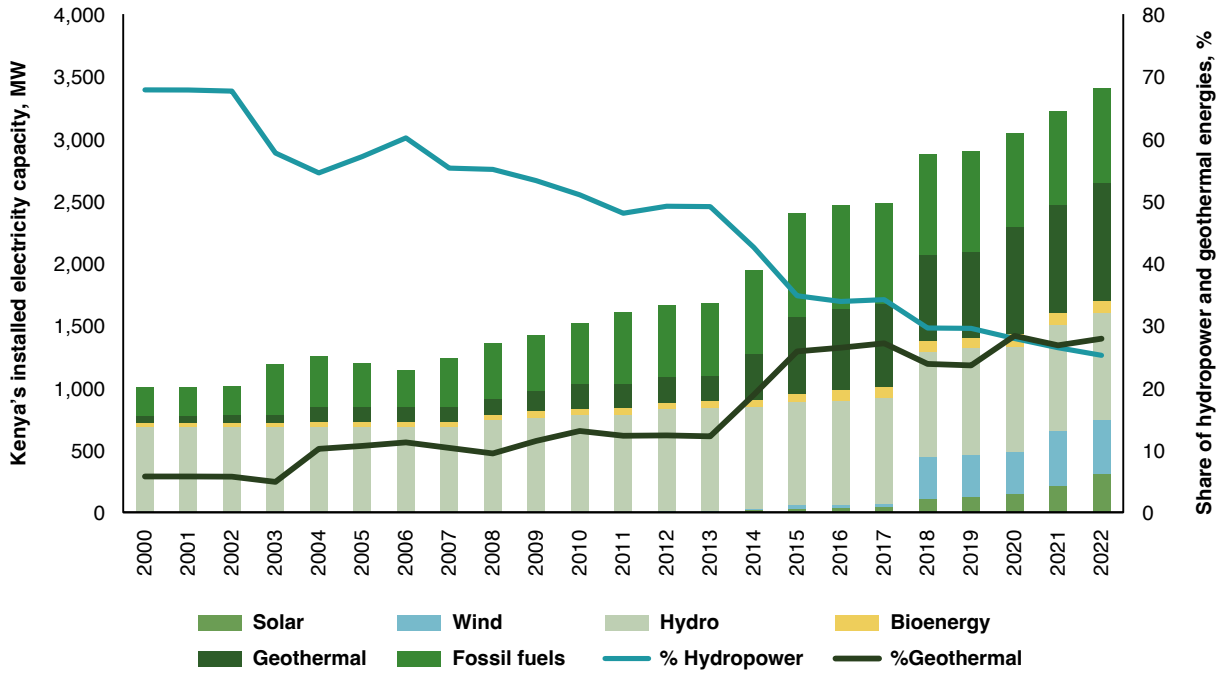
(Gavin 2022). Instead of relying on energy imports to offset this outage and meet the rising demand, the country has opted to develop its geothermal energy resources. The share of geothermal energy in the installed electricity capacity rose from 6% in 2000 to approximately 30% in 2022 (see Figure 7). Kenya's installed geothermal energy capacity now stands at 865 MWe. The country plans to double its geothermal electricity capacity to 1.6 GWe by 2030 (Burkhardt and Herbling 2021). This quick snapshot illustrates how governments can progress and achieve the United Nation's (UN's) Sustainable Development Goal of achieving universal electricity access by 2030.

Materials and Resource Requirements

Compared with other renewables, geothermal energy requires fewer minerals but drives a significant demand for specific metals, such as nickel, chromium, molybdenum, and titanium, which are crucial for transporting hydrothermal fluids and generating power. According to the Sustainable Development Scenario proposed by the International Energy Agency, by 2040, geothermal energy could be responsible for 75% of the demand for nickel, almost half of the total demand for chromium and molybdenum, and 40% of the demand for titanium among low-carbon power projects (IEA 2021). These metals are vital for producing the corrosion-resistant alloys needed to handle the extreme conditions in geothermal reservoirs. Fortunately, these minerals have plentiful reserves and are geographically diverse, including locations in Saudi Arabia, thus mitigating the security risks caused by concentration risks associated with other critical and rare Earth minerals.

Additionally, geothermal brines contain valuable minerals such as lithium, providing a secondary revenue stream and improving project finances. This dual benefit addresses one of the barriers to wider geothermal adoption.

Figure 7. Kenya's installed electricity capacity and the share of hydropower and geothermal energies in Kenya's energy mix.

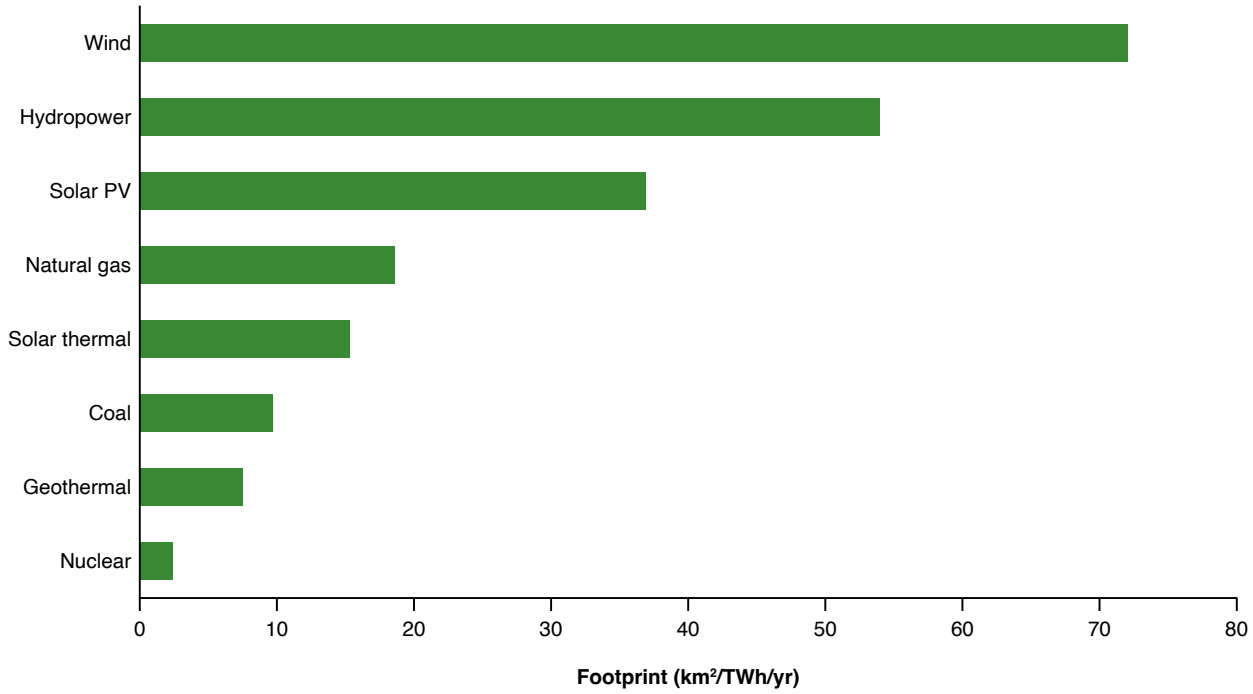


Source: Authors' analysis based on the IRENA (2024).

Environmental Footprint and Carbon Intensity

Geothermal energy stands out for its efficiency in land use, requiring just 7.5 square kilometers per terawatt hour per year (km^2/TWh/yr), which is far less than that of other renewables. Its consistent output contrasts with the variability of wind and solar power, thus increasing its reliability. Compared with fossil fuels, geothermal energy not only is cleaner but also occupies less land and has fewer environmental impacts (Figure 8). Unlike nuclear power, which is the only option with a smaller footprint, geothermal energy offers a safe and sustainable energy option without any problems regarding waste disposal.

Figure 8. Footprint comparison of different energy sources (km^2/TWh/yr).



Source: Ritchie (2022).

A geothermal power plant that produces one megawatt hour (MWh) of electricity requires only 1 km^2 of land, whereas a solar farm needs 8.4 km^2 for the same amount of electricity (National Geographic 2023). This smaller footprint translates to a lower level of demand for critical minerals, addressing concerns about the environmental and social impacts associated with increased mining.

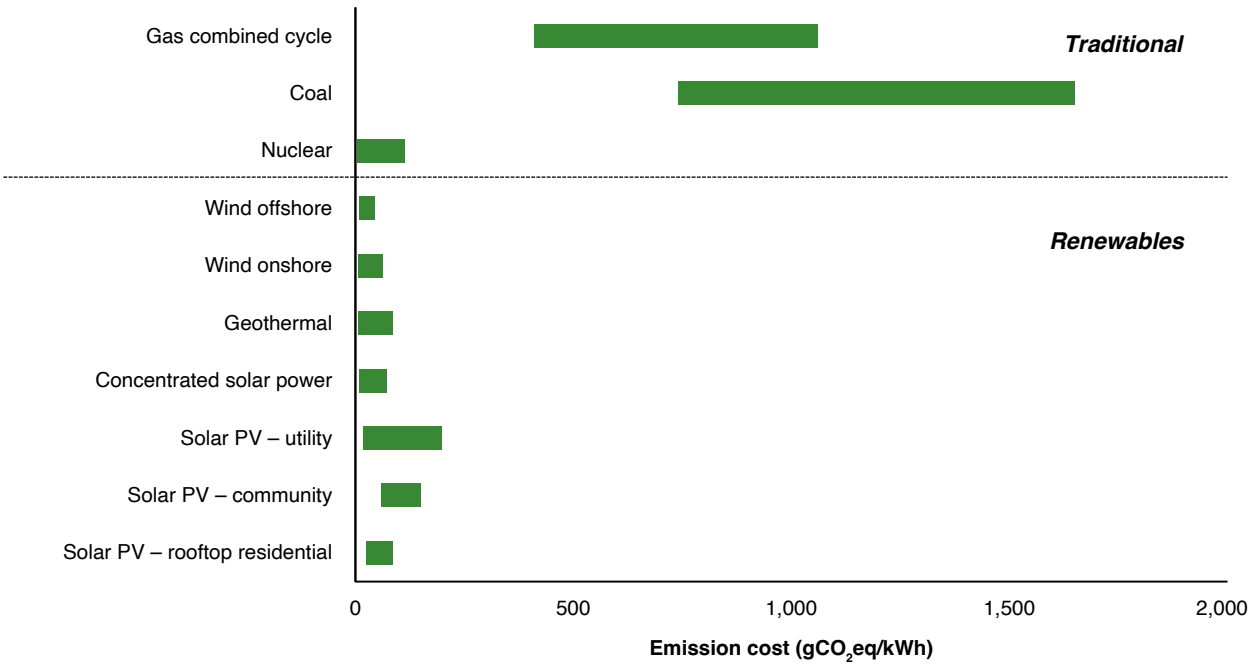
Geothermal energy is environmentally friendly and plays a vital role in combating climate change. This energy has one of the lowest life cycle greenhouse gas (GHG) emission levels, emitting 97% less acid-rain-causing sulfur compounds and approximately 99% less carbon dioxide than fossil fuel plants of similar size (U.S. Energy Information Administration 2022). Most of the emissions released from a geothermal power plant are water vapor, which is a small portion of the steam that is captured and recycled back into the reservoir.

In the quest to limit global temperature increases as per the Paris Agreement, all cost-effective measures must be pursued to accelerate the transition to carbon-neutral and net-zero emission energy systems. Geothermal energy is recognized as a promising solution for achieving this transition while ensuring affordable and reliable energy access. With its minimal carbon footprint and steady generation profile, geothermal power offers a compelling option for aggressive decarbonization efforts (see Figure 9).

Social License to Operate

Local communities have lived alongside geothermal power plants for decades, benefiting from power and heat for nearby residential and industrial facilities. The sector has also created direct and indirect employment opportunities, contributing positively to domestic and regional economies. According to the International Renewable Energy Agency (IRENA), the geothermal industry provided approximately 196 thousand direct and indirect employees worldwide by year-end 2021 (IRENA 2022).

Figure 9. Emissions of selected electricity supply technologies.



Source: Intergovernmental Panel on Climate Change (2011).[9]

However, geothermal development has faced challenges in some countries. In Japan, for example, restrictions on drilling in certain areas, including those near communities or national parks, have led to periods of stagnation. Strong opposition from local communities fearing impacts on traditional hot spring temperatures has hindered progress.

Public and political perceptions of geothermal energy vary widely. Concerns about induced seismicity, often associated with hydraulic fracking[10] and other stimulation techniques, have led to delays or halts in some developments. However, these effects are typically short lived and can be managed with proper planning and communication. Engaging communities early in the development process and investing in education and outreach programs can help overcome opposition and ensure project success.

Text Box 1. Social licensing for geothermal energy in Saudi Arabia

In Saudi Arabia, social licensing may not pose a major challenge for upcoming greenfield development projects. The O&G industry is deeply tethered to the Saudi economic and social fabric. O&G exploration and drilling activities across the country are welcomed by communities because they promote investments in the infrastructure and contribute to employment. The O&G sector complies with high standards for safety and environmental stewardship. Similarly, this sector is highly unlikely to face opposition from local communities.

Regulatory Barriers to Geothermal Energy Projects

Geothermal energy is not distinctly categorized as either a mineral- or water-based resource. This ambiguity in classification often creates overlapping jurisdictions, which can lead to potential conflicts, thereby hampering the development of geothermal resources. On the one hand, geothermal energy can be considered similar to hydrocarbon exploitation, given that it involves extracting heat from beneath the Earth's crust, much like mining operations for coal, oil, gas, or other mineral resources. On the other hand, this energy can also be viewed as a type of water resource since it often involves the extraction of hot water or steam from underground reservoirs. Apart from the U.S. and some jurisdictions in a few countries, the ownership of pore space belongs to the state, and different government bodies often oversee and regulate water, hydrocarbons and mineral resources. Brines may be governed by one government body (e.g., agriculture authorities), but heat, an energy source, is administered by another body (e.g., authorities in charge of minerals, energy, or both).

Licensing, permitting, and environmental considerations are essential to ensure that geothermal projects meet national standards and environmental regulations, preventing adverse impacts on reservoirs, the environment, and nearby communities. However, lengthy processing times for permits and authorizations lead to project delays and significant costs for developers, particularly in countries such as Japan, with a limited number of qualified contractors and strict regulations.

Regulatory complexity arises from the unfamiliarity of geothermal energy in many regions, resulting in time-consuming processes, with agencies lacking a sufficient understanding of geothermal energy development (Robins et al. 2021). The lack of coherent legislation further hinders proliferation.

To address these barriers, countries need updated policies and regulations to accommodate new technologies and distinguish geothermal energy from mining and hydrocarbon extraction, as in the case of Indonesia. Many countries are increasingly implementing regulations with a specific focus on geothermal energy. These regulations govern the use, taxation, and extraction of geothermal energy and its byproducts, such as hydrogen, and value added minerals, such as lithium. Such laws and regulations are transparent, and the processes to facilitate the deployment of new geothermal projects should be straightforward. The harmonization of regulatory procedures is essential for streamlining processes and promoting growth in the geothermal market. Competent bodies must collaborate to propose coherent regulatory frameworks that simplify procedures and ensure transparency.

Text Box 2. Saudi regulations on geothermal energy

At present, Saudi Arabia has no laws defining geothermal energy, distinguishing it as an energy source, or governing its extraction and usage. The absence of such legislation and regulations poses risks to the geothermal sector, including inefficiency, lack of quality control, and potential environmental impacts. This legal ambiguity creates uncertainties for prospective investors and developers in geothermal projects. The introduction of relevant policies and regulations can help ensure that the sector develops in a sustainable, safe, and efficient manner within legal parameters. Policies can mitigate the perils in the geothermal development process, thus appealing to prospective investors and developers. The topic of geothermal risk is discussed further in the subsequent section.

Geothermal Project Stages and Risk Regime

High-level initial investment and long timelines to revenue have historically prevented energy firms from entering the geothermal energy sector. According to the Climate Policy Initiative, the development of a geothermal power plant typically takes nearly 5.5 years, approximately 1.5 years longer than that of wind projects. The exploration and development phase, averaging 2 to 3 years, varies depending on resource conditions and regulatory hurdles (Micale, Oliver, and Messent 2014).

Geothermal projects undergo several stages, starting with preliminary surveys, followed by geoscientific studies, exploration drilling, reservoir studies, field development, construction, and commissioning, all of which depend on the degree of uncertainty throughout the project's lifespan. Greenfield projects face higher levels of risk initially due to sunk costs in identifying and testing resources. However, the degree of uncertainty decreases as projects progress (Figure 10). The key advantage of geothermal energy over other types of energy is its low and predictable operating costs since it provides continuous baseload power with very high-capacity factors exceeding intermittent energy sources, as described earlier.

Scattered and inadequate data and models encapsulating geoscientific and heat flow distributions have been obstacles for many developers. The level of geological risk can be significantly minimized by gathering and integrating subsurface data, particularly those based on Geographic Information Systems (GISs), and making them accessible. O&G companies have amassed extensive well records and characterizations of geological formations, temperature gradients, and other reservoir properties. These data can be highly beneficial once they are made publicly available, aiding in the creation of a geothermal resource atlas. This approach can, in turn, establish a competitive environment for newcomers in the geothermal industry. Numerous national agencies, such as the Dutch Oil and Gas Portal (NLOG), the Slovak Renewable Energy Agency, the Japan Oil, Gas, Metals National Cooperation, and the Australian Renewable Energy Agency, have created and shared their subsurface data (Aguilera et al. 2024).

Text Box 3. Geothermal database for geothermal energy in Saudi Arabia

The Saudi Ministry of Energy can build a centralized repository of subsurface data for geothermal reservoirs alone or in partnership with other agencies, such as the Saudi Geological Survey. A comprehensive database can help decision-makers and prospective developers understand the potential of geothermal energy; select sites for the exploration and deployment of geothermal projects; and assist in creating suitable regulations, incentives, and market models catering to the development of the geothermal energy sector.

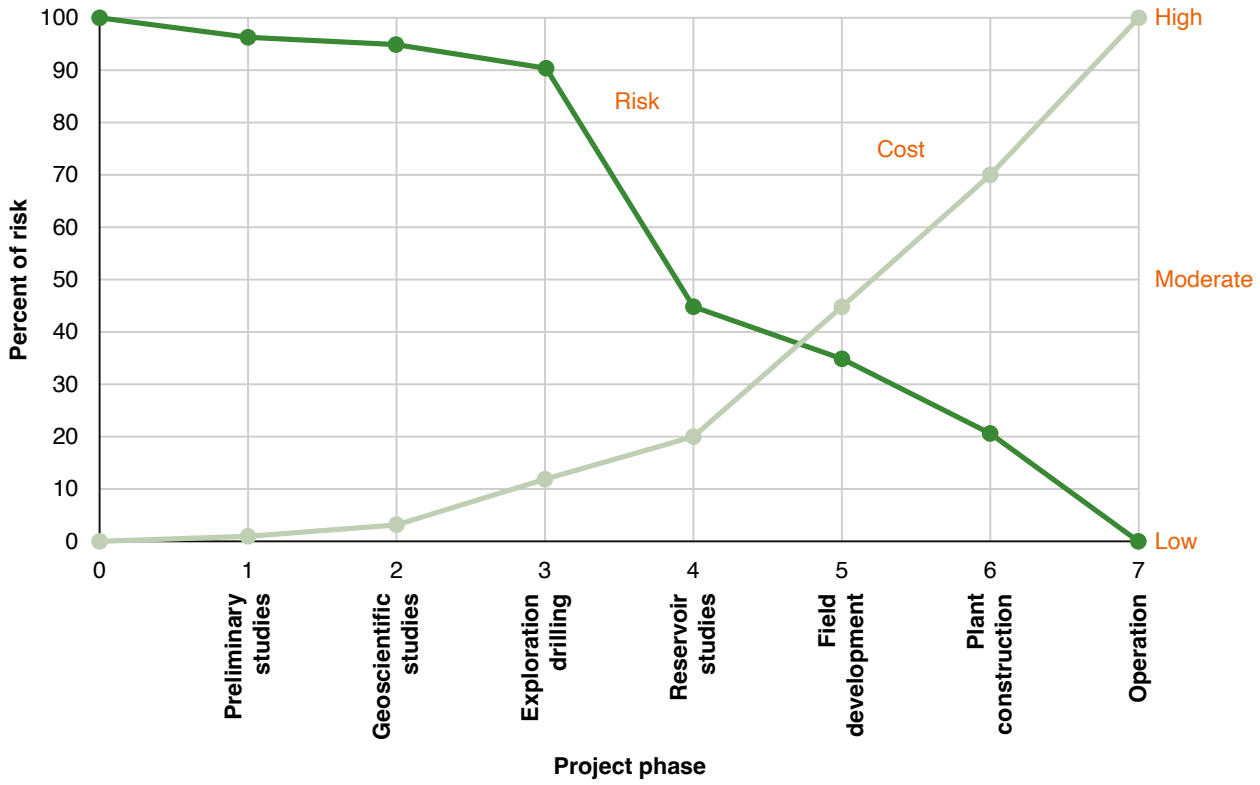
Countries such as the U.S., Kenya, Türkiye, and Indonesia have made significant strides in geothermal electricity generation in the past decade. More countries are showing interest in exploiting geothermal energy, with growth linked to policy choices and risk mitigation strategies. Currently, 27 countries harness electricity from geothermal reservoirs according to the International Geothermal Association.

Risk mitigation instruments such as risk insurance, capital grants, cost-sharing programs for the use of innovative drilling technologies, and loan guarantees allow geothermal developers to transfer geological risk, either fully or partially, to public and private entities. Public, private, and private–public partnership (PPP) schemes are the three categories of risk mitigation schemes. A public scheme usually has a legal foundation, such as an act, an ordinance, or a decree. In PPPs, the government or energy agencies regularly require public banks or insurance corporations to provide low-interest loans or loan guarantees, often in partnership with commercial private companies (Karytsas et al. 2022).

The level of maturity and competitiveness in the geothermal market determines the type of risk scheme employed. In countries and jurisdictions with more competitive geothermal markets, developers usually assume responsibility for a private, insurance-based risk mitigation scheme. However, in countries that are new to geothermal energy, developers tend to prefer public or PPP risk mitigation schemes for greenfield geothermal projects. While this is generally the case, it should be noted that this is a prevalent market trend rather than a hard and fast rule.

A significant proportion, over 30%, of geothermal project costs, are attributed to geothermal wells, with approximately 22% of the wells considered unsuccessful. Complex subsurface geology in volcanic formations contributes to this phenomenon. Adopting advanced

Figure 10. Geothermal cost profiles at various development phases.



Source: Modified from Gehringer and Loksha (2012).

technologies and best practices from the O&G industry can improve success rates and reduce costs, which is a topic discussed further in this paper.

The primary cost in geothermal projects lies in the plants themselves, encompassing equipment procurement, such as flash separators, heat exchangers, turbines, and fluid disposal systems (Rystad Energy 2023). To manage risk, the industry often secures long-term PPAs or feed-in tariffs with utilities or off-takers, typically spanning 15-25 years, to facilitate financing during the development phase.

However, financing remains a significant barrier for new private entrants. While governments and major O&G companies increasingly support geothermal development through public debt or equity, the private sector remains hesitant due to resource risk and long lead times.

The landscape is evolving, with medium to large-sized O&G companies and service providers investing in geothermal projects and technologies. Companies such as Chevron and BP have acquired stakes in Eavor, a closed-loop technology developer, whereas state-owned entities such as India's Oil and Natural Gas Corporation and the China National Offshore Oil Corporation are commissioning GPPs (Zhou and Goldie-Scot 2022). Major O&G companies, which are well capitalized and familiar with subsurface risks, can absorb sunk costs and help reduce the degree of risk in the exploration and development phases, potentially overcoming investment shortages and fostering geothermal energy growth.

3. Complementarities between the O&G and Geothermal Energy Markets

The O&G industry has historically shown limited interest in geothermal energy due to technical risks, long lead times, and high exploration costs (Brenhouse 2010) (Micale, Oliver, and Messent 2014). Many O&G companies, such as Chevron, have divested their geothermal operations due to lower returns, especially during oil price downturns (Chevron 2017; 2022). However, since 2016, with the emergence of the Paris Agreement and the UN's Sustainable Development Goals, there has been a shift in focus toward low-carbon investments, including geothermal energy (Rystad Energy 2023). O&G firms, leveraging their technological expertise, are now exploring opportunities in the geothermal market to diversify their portfolios and hedge against O&G supply and demand shocks (Al Suwailem and Henni 2022).

The O&G industry has been increasingly drawn toward geothermal energy since 2016, following its recovery from a recession. This shift coincided with the enforcement of the Paris Agreement and the UN's Sustainable Development Goals. Consequently, O&G companies have been intensifying their geothermal energy activities, and numerous countries are more strategically incorporating this type of energy into their energy portfolios. Several major integrated oil companies (IOCs), including ExxonMobil, Equinor, Eni, TotalEnergies, Petrobras, Chevron, and BP, are actively engaging in internal innovation, research and development (R&D), and industry joint ventures (JVs) related to geothermal energy. Historically, oilfield service companies have supplied equipment and services for the exploration and exploitation of geothermal assets. However, since the geothermal energy market has been relatively nonsignificant compared with the O&G sector, leading service companies such as Schlumberger, Baker Hughes, and Halliburton have shown little interest in expanding heavily into the geothermal energy sector. However, recently, the service industry has capitalized on this shift toward renewable energy and has rebranded itself as an energy service provider (see Figure 11) (Bansal et al. 2022).

Geothermal industry innovation has historically been slow due to budget constraints and risk aversion (Trembath 2011). However, with increased interest from O&G firms and increased R&D funding, there is potential for accelerated innovation in terms of geothermal technologies (Al Suwailem et al. 2023). Despite promising

Figure 11. Service companies and major IOC ventures in the geothermal space.

	Investor	Geothermal innovator companies	Description of venture
Integrated oil companies	Chevron	Eavor	Drilling closed-loop technologies
	bp	Eavor	Drilling closed-loop technologies
	equinor		Internal innovation, R&D, and industry JVs
	TotalEnergies		Internal innovation, R&D, and industry JVs
	Petrobras		Internal innovation, R&D, and industry JVs
	Tecpetrol	Luminescent, Eden, QUISE	TechEnergy venture (CVC) investments
Service companies	Baker Hughes	GreenFire	Closed-loop, AGS called the "green loop"
	NABORS	HEPHAE, GA Drilling, QUISE, GEOX	Large portfolio in geothermal drilling
	NOV	Particle	Drilling bit technologies for hard rock
	slb	CELSIUS	Low-carbon heating/cooling to buildings
	HALLIBURTON	Cache	Industrial heat and long-duration energy storage
	PATTERSON-UTI	CRITERION	Drilling geothermal wells
	HP	GreenFire, Eden, Eavor	Large geothermal portfolio

Source: Authors' analysis based on press releases and media reports.

prospects, the geothermal energy market remains relatively concentrated, with few players overseeing all aspects of development, transportation, and distribution (Rystad Energy 2023). To foster growth and competitiveness, the geothermal energy business model needs revamping, and a larger number of entrants are needed in the sector (see Figure 12).

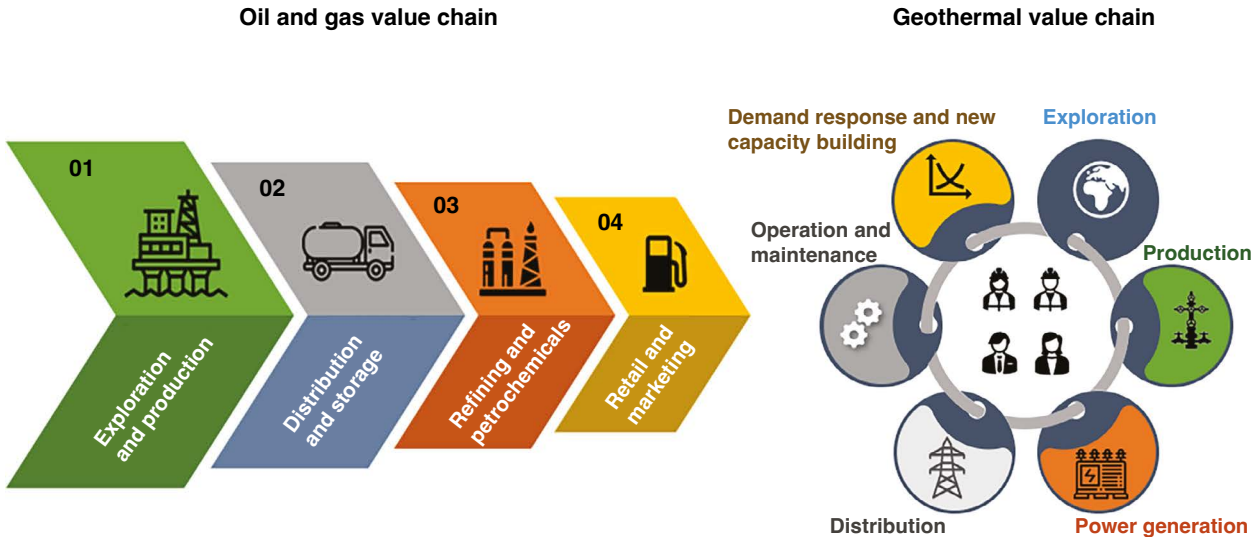
The geothermal market is currently fragmented, with small developers operating in limited geographic areas, unlike the global footprint of major O&G companies (Kazmi 2023). To increase efficiency and mitigate risks, the geothermal business model can benefit from compartmentalization overseen by various operators, fostering partnerships between O&G and specialized geothermal firms to leverage economies of scale.

O&G firms can significantly advance geothermal energy, especially in sedimentary basins with existing well records and infrastructure. Many depleted reservoirs offer high temperatures and a high degree of permeability, coupled with preexisting infrastructure, making them ideal for geothermal development.

While geothermal energy projects share risk profiles with O&G ventures, they offer more stable, predictable cash flows shielded from commodity price volatility, as in the case of O&G. However, unlike O&G, heat cannot be stored in the long term, and geothermal trade relies on energy units rather than on barrels.

O&G firms entering the geothermal market must engage with stakeholders across the value chain and adapt their expertise to meet the unique demands of geothermal projects. These firms can inject capital and deploy advanced technologies to optimize heat extraction and mitigate project risks. The increasing level of involvement of O&G companies in the geothermal energy sector is seen as a positive development. In addition to financial support and technological expertise, these firms can bring lobbying power to advance geothermal energy (Lee 2023). By leveraging their resources and influence,

Figure 12. O&G and geothermal market comparison.



Source: Authors' analysis.

O&G firms can help promote policies that are favorable to geothermal energy development and contribute to climate discussions.

Cross-Industry Technology Synergies Between Geothermal and Other Sectors

Cross-industry collaboration can significantly bolster the growth of geothermal energy, most notably by synergizing technologies such as carbon capture and storage, critical mineral extraction, and green hydrogen production. The cross-industry technology synergies include the following:

- **Carbon Capture and Storage and Mineralization**

  Carbon capture and storage and mineralization[11] are technologies that have a natural affinity with geothermal energy production. Carbon-free energy can be used to power direct air capture (DAC) plants, and industries can not only reduce their need for hydrocarbons as inputs (particularly for thermal applications) but also store captured CO_2 as part of the reinjection stream depending on the application. Hydrothermal (aquifer-based) systems can store CO_2 directly, and other applications where there is direct contact with minerals such as basalt can chemically bind the carbon to the rock. Iceland, a country with a significant amount of geothermal resources, has an operational sequestration pilot that stores carbon through this mechanism. As an additional benefit, deeper engineered systems for heat transfer are less likely to leak to the surface, which is often a concern in naturally occurring aquifer systems. Some challenges that adding CO_2 to the system may create are increased corrosivity and, consequently, increased material costs. However, there are also opportunities for additional revenue for geothermal operators if sequestration is offered as a service.

  DAC is indeed a promising technology for mitigating negative emissions, but its high costs and strict energy requirements present significant challenges for its large-scale deployment. Geothermal energy can play a crucial role in addressing these challenges and scaling up DAC technology. DAC processes require significant energy inputs, primarily for powering fans and compressors and for the regeneration of sorbent materials. Geothermal energy can provide a

sustainable and reliable source of electricity and heat, which can significantly lower the operational costs of DAC facilities.

Colocating DAC facilities with geothermal plants can increase the efficiency and economic viability of both systems. Close proximity reduces the energy losses associated with transportation and allows for the direct use of geothermal heat and electricity. Possible locations in which to implement DAC using geothermal energy in Saudi Arabia are Jazan and Wadi Al-Lith, as both are promising geothermal prospects given their high levels of enthalpy.

- **Critical Mineral Extraction**

The energy transition has placed the largest purchase order for critical minerals required for electrification since the Paris Agreement came into force in late 2016. The demand for lithium and critical minerals, key components for wind turbines, solar panels, and electric vehicles, has been on a steep ascent as countries are increasingly greening their power systems and transportation fleets.

Unlike hydrocarbons, which are found in more than 100 countries around the globe, conventional lithium resources are concentrated in only 10 countries. A few market players, such as China, also control critical minerals' supply chains. There are concerns mainly in the Western Hemisphere over China's dominance of midstream/downstream critical metal and mineral supply chains, which are critical for the generation and transportation of renewable energy.

According to McKinsey & Co., the global demand for lithium increased from 500,000 metric tons of lithium carbonate equivalent in 2021 to nearly 4 million metric tons in 2023, and demand currently exceeds the supply and is causing prices to soar; however, this gap can be bridged by additional conventional supply from new mines or expansion to existing mines, and most importantly, it can be offset by extracting lithium from geothermal and oilfield brines (Azevedo et al. 2022).

Lithium is likely to be vulnerable to EGS-linked investment criteria. Lithium extraction from salt brines will come under increasing scrutiny from government and investment firms in the coming years. Each ton of lithium requires 2 million liters of water to evaporate, resulting in enormous quantities of water being lost yearly and putting underground freshwater reserves in danger of salinization through contact with brine. Furthermore, this extraction process causes vast quantities of securely stored carbon to be released into the atmosphere (Wetlands International 2023), in addition to health risks caused by toxic chemical leaks for miners and communities living within the vicinity of these mines. Hydrothermal fluids can dissolve lithium and minerals from underground rock formations, but their concentrations tend to be very low. Geothermal brines with grades of 100 to 200 parts per million[12] (ppm) may contain sufficient lithium deposits (Azevedo et al. 2022). With high volumes of hydrothermal fluids dissolved in the fluids and captured at the surface, lithium and other minerals can become economically feasible to extract and help decrease the cost of electricity generation, shortening the time needed to increase net profits.

In the Salton Sea geothermal field, the proven reserves of lithium, manganese, and zinc that can be extracted from its brines are 2 million metric kilotons, 5 million metric kilotons, and 15 million metric kilotons, respectively (McKibben, Elders, and Raju 2021). It is even argued that the revenues generated from mineral extraction in this project exceed those of geothermal power generation. Once lithium is extracted from geothermal brines, the water is recycled back into the reservoirs to replenish them. There are no open-cut mining or evaporation ponds ascribed to mineral extraction from geothermal brines. The land footprint for such projects is minimal compared with that of lithium mines. Conversely, lithium extraction from geothermal brines faces many economic and technical issues. Brine chemistry is notoriously difficult to work with and requires cutting-edge ion exchange technologies to separate lithium from fluids.

4. Geothermal Technology Ecosystem

Geothermal extraction technologies are systems used to harness or store heat for electricity generation and direct-use applications. These systems offer diverse solutions tailored to various reservoir conditions (i.e., temperatures and depths) and their intended uses. Most of these systems have been borrowed from the O&G industry and range from heat pumps that harness consistent temperatures at shallow depths, enhancing the efficiency of homes and buildings, to advanced high-temperature applications (> 400°C), such as supercritical geothermal systems, designed for large-scale power generation. Each of these systems addresses unique challenges, ranging from the technological complexities of accessing deep geothermal reservoirs to the economic and environmental considerations of implementing large-scale geothermal infrastructure (see Figure 13).

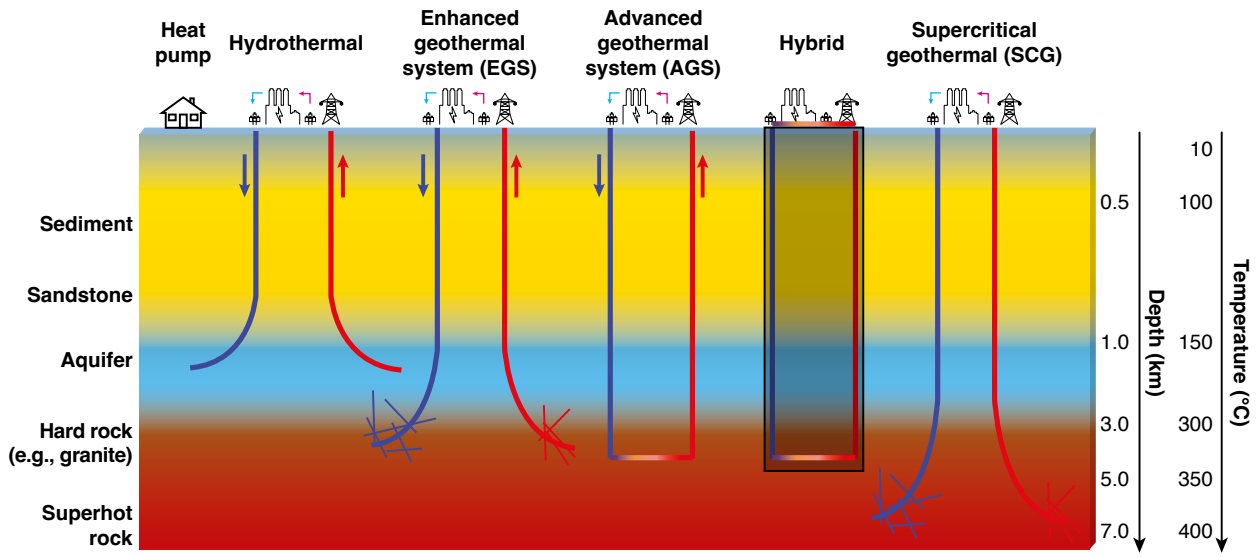
While heat pumps offer simplicity and widespread applicability, deeper hydrothermal systems provide a more traditional approach to exploiting geothermal energy. Enhanced and advanced geothermal systems push the boundaries of engineering to extract energy from less permeable rock formations or (recharge) geothermal reservoirs with water to ensure sustainable heat supplies. Hybrid systems integrate the strengths of different technologies to maximize efficiency, and supercritical geothermal systems represent the cutting edge, aiming to unlock enormous energy potential from extreme subsurface conditions (see Table 1).

Since 2016, notable progress has been made in technology development and deployment driven by the increased entry of O&G firms in the geothermal arena. As discussed, oilfield service companies are increasingly modifying and retrofitting tools and equipment that can endure extreme temperatures and hard/heterogeneous rocks for heat extraction.

The technical feasibility of mining heat from high-temperature, water-poor rocks has been demonstrated; however, the costs of doing so are not yet economically competitive. The longest operating EGS project currently generating power is in France. Most EGS developments remain in the demonstration phase. The most notable project is the Frontier Observatory for Research in Geothermal Energy (FORGE), funded mainly by the U.S. DOE, which comprises three phases. Six pilot wells have been spudded and stimulated and are monitored to evaluate their productivity levels and temperatures.

Various government agencies, research institutions, and industry players are playing a key role in accelerating the technological readiness levels of many geothermal

Figure 13. Key underground heat extraction and utilization systems.



Source: Hoxha et al. (2023).

technologies. Such technologies include geotechnical assistant status reports, thermal heat transfer models, and other specialized geothermal software. These technologies represent the forefront of geothermal technology, where new concepts are being formulated.

Together, these codependent technologies illustrate a dynamic and multifaceted approach to advancing the geothermal energy sector, highlighting a blend of innovation, adaptation, cross-industry collaboration, and groundbreaking developments (See Appendices 2 and 3).

Table 1. Description of underground heat extraction and utilization systems.

System	Description
Heat pumps	Utilizes the low temperature of shallow ground or surface water to heat and cool buildings.
Hydrothermal	Capitalizes on naturally occurring reservoirs of hot water within the Earth. It typically involves drilling wells into these reservoirs to bring the hot water or steam to the surface for electricity generation or direct-use applications.
EGS (open-loop system)	Accesses the heat of the Earth's crust by creating a subsurface reservoir through the injection of fluids at high pressure levels, enhancing or creating rock permeability. Heat is extracted by circulating water through a humanmade reservoir to generate electricity.
AGS (closed-loop system)	Fluids are not introduced to or extracted from the Earth's subsurface. Instead, a "working fluid" circulates underground inside pipes, absorbing heat via conduction from the surrounding rocks.
Hybrid	Combines the features of different geothermal technologies, for example, hydrothermal and EGS approaches in a closed-loop system with a hybrid power plant* to utilize both natural and enhanced permeability to maximize efficiency.
Supercritical geothermal systems (SCG)	Aims to exploit the supercritical state of water at extremely high temperatures and pressures found deep below the Earth's surface. SCG systems can produce a significantly higher power output compared to conventional geothermal systems by tapping into this superhot rock layer.

Notes:

** A hybrid power plant is a power generating system that combines two or more different generating methods to produce electricity. These different methods often involve various types of renewable energy sources such as solar, wind, and hydropower, as well as traditional sources like fossil fuels or nuclear power.*

5. Geothermal Energy Resource Regime in Saudi Arabia

Most geothermal prospects in the Arabian Peninsula are believed to be found in the Gulf of Aden Rift, Red Sea Rift, and Arabian Shield, which have medium and high levels of enthalpy potential. The Kingdom of Saudi Arabia (KSA) exhibits prominent geological characteristics that suggest the presence of geothermal resources, especially in the western parts of the country (see Figure 14). This area includes the Red Sea Rift and the Arabian Shield, which are associated with tectonic features and volcanic flows. The last volcanic eruption was recorded in 1256 AD near the holy city of Medina.

Geothermal resources in Saudi Arabia are characterized predominantly by low-to-medium heat flows and temperature gradients, except for the Red Sea Rift in the western part of the Kingdom and the Wadi Al-Lith and Jizan areas in the southwestern parts of the Kingdom, where temperature gradients are appreciably higher than 38°C per kilometer. These areas are considered promising geothermal prospects on the basis of the analysis of available satellite images, geoindicators, and 2D electric geophysical surveys conducted on hot springs. Overall, 11 volcanic terrains, known as "Harrats," are scattered across the western region, containing more than 2,500 dormant volcanoes and craters and a few hot springs (see Figure 14). The surface water temperatures recorded in some of these hot springs, on average, are below 80°C, with seasonally varying flow rates. However, their hydrothermal systems and related heat sources do not appear deeply rooted, as the water circulates within shallower layers.

Reservoir temperatures ranging from 100°C to 150°C may also be found in deep sedimentary basins near the coasts of the Arabian Gulf and the Red Sea. These basins have significant potential for exploiting geothermal energy for large-scale water desalination plants. Saudi Arabia is largely desert and has very few lakes, which leads to a scarcity of freshwater. Over 30 water desalination plants are strategically positioned on both coasts, supplying freshwater for drinking, agricultural, and other uses.

The eastern part of the country is home to sedimentary basins containing Saudi Arabia's O&G reserves. O&G wells, especially those depleted and abandoned, have the requisite temperature for geothermal applications and can synergize with other energy transition technologies, such as hydrogen production and carbon capture and storage.

As previously discussed, heat may be harnessed from active O&G wells with high water levels. However, considering the low levels of associated water production in Saudi Arabia, coproduction may have a limited number of applications. Nevertheless, it may be worth conducting a comprehensive study in the future to determine its feasibility and potential applicability for meeting localized energy needs in oilfields or enhanced oil recovery via steam flooding[13] (see Appendix 2).

A few publications – generally from academia and small-scale projects – provide circumstantial evidence

Figure 14. Geothermal areas in Saudi Arabia (red polygons: volcanic fields; red triangles: hot springs).



Source: Modified from Lashin et al. (2020).

of the peninsula's geothermal energy potential. Thus, a robust assessment of its geothermal resources and the development of rigorous heat flow maps and associated drilling prognoses are not possible with the available public data. To date, there are no publicly available heat flow maps for Saudi Arabia that can aid in assessing resource regime potential and informing new entrants (Aguilera et al. 2024).

The initial geological and geophysical exploration for the northern part of Harrat Rahat and surrounding areas of Medina, conducted by the Saudi Geological Survey, has hinted at potential "sweet spots" for geothermal energy production. These sweet spots have been followed by a series of exploration wells drilled further to assess the resource potential, distribution, and depth. The second observatory well was spudded on KAUST campus in February of this year as part of a pilot development in partnership with TAQA Geothermal, a Saudi-based energy company, to harvest geothermal heat and demonstrate its direct use for various applications, including district cooling (e.g., via absorption chilling) and water desalination. Furthermore, this project aims to assess the potential of lithium extraction and CO_2 or flue gas sequestration. Following the success of this exploration project and other assessments, a series of production and injection wells are to be drilled to target temperatures (150°C-175°C) to evaluate and demonstrate advanced geothermal energy systems[14] (Aguilera et al. 2024). Concurrently, other pilot projects are under investigation by Saudi Aramco and NEOM to explore and utilize geothermal energy.

6. Desirable Interventions and Technology Roadmaps for Saudi Arabia

Saudi Arabia is taking a multidimensional approach to diversifying its energy mix and reducing GHG emissions. In 2020, the KSA established a goal to displace 1 million barrels per day of liquid fuels in the power sector and to generate 50% of its power from renewables, with the remainder being supplied by natural gas, by 2030. Concurrently, in its updated NDCs, the country pledged to reduce GHG emissions by 278 million tons by 2030, enabled by initiatives and projects under the Circular Carbon Economy Program[15].

These targets will be achieved through the utilization of several low-carbon energy generation technologies, including solar, wind, hydrogen, and nuclear, as well as carbon capture, utilization, and storage. Furthermore, negative emission technologies such as DAC will be needed to offset the residual emissions from hard-to-abate sectors by 2060 as part of the net-zero journey. Over 20 solar, wind, and green hydrogen megaprojects across the Kingdom are either completed or currently under development. However, the intermittency and diluteness of solar and wind energy can pose challenges to grid stability, issues that can be solved with backups or alternative technologies such as geothermal methods. As a cornerstone technology, geothermal energy provides sustainable baseload electricity, reduces the level of dependence on hydrocarbons, complements ongoing efforts to decarbonize the power system (thus freeing more barrels for alternative uses, including refined products and chemicals), and aids in decarbonizing the power system, especially the water desalination and cooling sectors.

Saudi Arabia, which has a predominantly desert climate, frequently experiences extremely hot days, with temperatures often exceeding 40°C. A significant portion of the energy demand in buildings is attributable to cooling. Research suggests that the electricity utilized for cooling represents 101 TWh in residences and 70 TWh in commercial establishments. This consumption equates to approximately 50% of the total yearly electricity usage in

buildings, increasing to as much as 70% during periods of peak cooling demand. Consequently, in its strategic planning, the government has earmarked district cooling and urban planning as two important topics (Al Suwailem, Aldubayan, and Al-Momen 2024). Cooling via ground-source heat pumps, as described earlier, is likely to yield greater energy efficiency by providing cooling for both residential districts and large-scale districts.

As a desert country with minimal freshwater resources, Saudi Arabia is one of the largest producers of desalinated water in the world. The principal method employed for freshwater production is reverse osmosis, a technology notable for its carbon-intensive nature and reliance on O&G-fired facilities. The prospect of transitioning to geothermal energy for powering certain desalination plants could present Saudi Arabia with a more environmentally friendly and cost-effective approach to freshwater production. Geothermal energy for desalination is being tested as part of KAUST's abovementioned campaign. As the KSA considers the integration of geothermal energy into its extensive energy portfolio, it encounters a landscape where challenges and opportunities are deeply intertwined. The dual-edged nature of this venture is deftly captured in Table 2, which maps the associated challenges and opportunities.

Establishing national geothermal energy targets for a specific year for both power generation and cooling via geothermal energy can substantially aid in capitalizing on these opportunities and surmounting the related challenges, which can be executed through diverse strategies such as legislative and policy formulation, technology advancement, capacity building, planning, and investments. These targets can boost investor confidence by illustrating the government's dedication to geothermal energy development. Such guarantees can highlight potential returns on investment and subsequently diminish perceived investment risk levels.

Table 2. Challenges of and opportunities for geothermal extraction and utilization in Saudi Arabia.

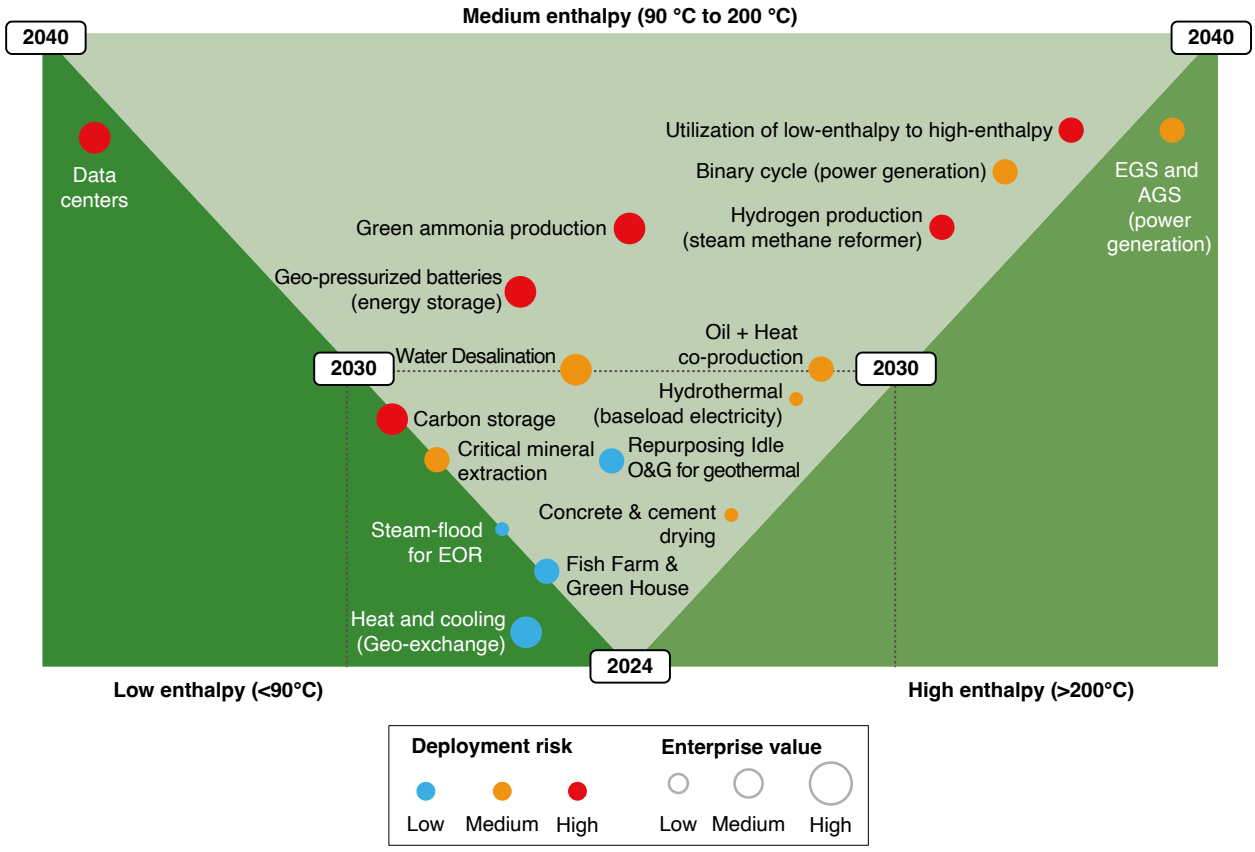
Variables	Challenges	Opportunities
Financial	• High upfront capital costs and risk • Long revenue gestation periods	• Utilization of the existing energy portfolio • Decentralized geothermal model in the market promoting competitiveness and lower overall LCOE of electricity
Technical	• Lack of exploration to identify and develop undiscovered geothermal sources • Limited reservoir/geoscience mapping • Lack of access to transmission infrastructure	• Synergies – technology, infrastructure, and expertise adopted from O&G companies • Retrofit O&G wells or repurpose idle/abandoned wells
Policy	• Infant policy regulations • No cross-function government-public-corporate sector agencies or institutes	• Adopt existing, successful geothermal programs in emerging markets, such as those in Indonesia, Kenya, and Türkiye
Market	• Cannibal effect if geothermal energy production competes with hydrocarbons (unlikely but possible) • Energy procurement hurdle (existing utility procurement practices do not value all benefits of geothermal power)	• Possibility of recovering critical minerals from brine (e.g., lithium and vanadium) • Complement water desalination plants to provide electricity and heat
Ecological	• Location selection	• Reduced carbon footprint

Figure 15 illustrates a strategic technology roadmap and impact radar for Saudi Arabia, delineating the phased adoption of geothermal energy within targeted timeframes. The chart highlights immediate actions and long-term plans, spanning current applications, such as heat and cooling solutions, to the future integration of advanced technologies for mass energy production and critical mineral mining. This roadmap highlights the Kingdom's commitment to capitalizing on geothermal energy, aligning with its 2030 vision to create a sustainable and diversified energy sector (see Appendix 2 for more information on certain technologies).

The deployment of these technologies (illustrated in Figure 15) will require a collaborative approach from different sectors, including the government, private sectors, and academia. Research institutions and universities can spearhead the development of efficient, customized technologies. In conjunction, the Research, Development, and Innovation Authority, alongside others, can play an instrumental role in incubating and financially incentivizing innovative technologies.

With decades of experience in O&G exploration and development, Saudi Arabia is uniquely positioned to exploit geothermal energy. The vested interests of Saudi Aramco present an opportunity to shape the development of geothermal energy as a viable alternative. As previously discussed, the business model for geothermal energy development is distinct from that of the O&G industry because of the fundamental differences in resources and their utilization. Leveraging Saudi Aramco's ability to upscale geothermal energy in the country is a promising strategy. Additionally, embracing a decentralized geothermal model with multiple market players can further enhance competitiveness and reduce

Figure 15. Technology roadmap and direct actionable use cases for Saudi Arabia.



Source: Authors' analysis.

the overall LCOE from geothermal sources, fostering a more dynamic and affordable energy landscape.

Overall, geothermal projects require robust legal regulations for a fair playing field. These regulations should cover aspects such as resource endowment, land access, permitting, social and environmental impact assessments, and tax incentives. A successful illustration of this approach is the 2020 Saudi Mining Investment Law, which transformed the mining landscape by eliminating barriers to entry and mitigating sector risks. This legislation established a mining fund to support geological surveys, exploration programs, mining-area infrastructure projects, and mining research and studies. This legislation also provides clear rules and support measures for investors, promoting transparency and fair competition. Furthermore, this law outlines specific mining licensing rules, terms, and fees (Bureau of Experts at the Council of Ministers 2020). Drawing lessons from these recent advancements in Saudi mining legislation can also help create an enabling environment for geothermal energy exploration, investment, and research and accelerate the pace of geothermal deployment at scale.

Endnotes

[1] Zetta = 10^{21} or 1,000,000,000,000,000,000,000.

[2] Earth's outer shell is divided into 15 large slabs of solid rock, called plates, that glide over Earth's mantle, the rocky inner layer above Earth's core. Earthquakes are the result of sudden movement along these boundaries (British Geological Survey 2024).

[3] Geothermal enthalpy refers to the amount of heat energy contained within geothermal fluids, such as hot water or steam, that can be extracted from Earth's crust.

[4] A conventional geothermal system is a method of harnessing Earth's natural heat for energy production. This system relies primarily on naturally occurring permeable reservoirs of hot water or steam. When one of these key components is lacking, such as adequate permeability or sufficient fluids, advanced technologies like enhanced geothermal systems are employed to overcome these challenges. Enhanced geothermal system techniques involve stimulating the rock to increase permeability and injecting water to replenish the reservoir, ensuring a sustainable and efficient geothermal energy source.

[5] LCOE is a figure used to measure the lifetime cost of energy production. It is a simple and well-known metric used by energy and utility firms. However, this term does not account for attributes in each technology that contribute to the safe and stable functioning of the electric system. Examples include dispatch flexibility, regulation capabilities, environmental attributes, and reduced transmission congestion and demands (Robins et al. 2021).

[6] Lazard estimates are based primarily on the capital and operational expenditures and subsidy estimates from U.S. projects. They are for indicative purposes only in this publication.

[7] The capacity factor is the amount of energy produced over a given time.

[8] A PPA is a long-term electricity supply agreement between two parties (usually between a renewable energy supplier and a utility company) with power generated purchased by the off-taker at predetermined and agreed-upon prices.

[9] These include direct GHG emissions and indirect emissions from the infrastructure and supply chains.

[10] Hydraulic fracturing or "fracking" is a process that involves injecting water, sand, and chemicals under high pressure into O&G bearing formations or geothermal reservoirs to create new fractures in the rock that enable the extraction of trapped hydrocarbons or hydrothermal fluids.

[11] Carbon mineralization is the process by which CO_2 becomes a solid mineral, such as carbonate. It is a chemical reaction that happens when certain rocks are exposed to CO_2 (Alturki et al. 2024).

[12] Ppm describes the concentration of a mineral in water. One ppm is equivalent to 1 milligram of the particular mineral per liter of water.

[13] Steamflooding is an enhanced oil recovery method that is used to extract heavy crude oil and viscous oil from oil reservoirs. The process involves injecting steam into a well at high temperatures and pressure levels. The heat from the steam reduces the viscosity of the oil, making it easier to pump to the surface. The injected steam also increases the pressure in the reservoir, pushing the oil toward production wells. This method better improves the recovery of the oil from a reservoir compared to traditional extraction methods.

[14] This is a heat extraction system where fluid is contained and circulated to harvest heat from subsurface rocks. This often looks like a series of horizontal laterals in hot, dry rocks. Fluids are circulated in sealed pipelines and boreholes, picking up the heat by conduction and carrying it to the surface, where it can be used to cogenerate heat and electricity.

[15] The circular carbon economy framework provides a holistic, pragmatic, and cost-effective framework for assessing climate change mitigation options and pathways at a global, national, or organizational level. It is a closed loop system involving reducing, reusing, recycling, and removing (4Rs) as mitigation options (Alturki et al. 2024).

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Appendix I

Supercritical Geothermal Systems

Geothermal developers are vigorously exploring novel technologies, such as enhanced geothermal systems, to derisk geothermal development and exploit economies of scale. These technologies will help harness a portion of the heat capacity in the subsurface. Some developers push the envelope by exploring drilling deeper, hotter dry rock systems (>400°C). A superhot geothermal well is envisaged to deliver 5 to 10 times the capacity of conventional geothermal wells. Unlike EGS and AGS, such wells are unlikely to disrupt the geothermal landscape in the near future because their applications are confined to volcanically and tectonically active regions and require the use of high-end, expensive materials to withstand such conditions.

According to the Clean Air Task Force (2024), the superhot rock energy capacity in the Middle East is estimated to be 5,257 GWe, which could generate up to 44,000 TWh of electricity and potentially export an excess of 34,000 TWh to other countries or use it to incentivize other hard-to-decarbonize and energy-intensive industries. At present, superhot rock energy pilots currently taking place include the Japan Supercritical Project, the Geothermal: Next Generation project in New Zealand, the Iceland Deep Drilling Project, and the Newberry Deep Drilling Project in the U.S., among others (Aguilera et al. 2024).

Appendix 2

Cogeneration and Conversion of O&G Wells for Geothermal Energy

Harnessing heat from current and future O&G wells can be achieved by two means. One way is to retrofit wells for exclusive geothermal production (conversion). Another way is via coproduction, where wells continue to produce hydrocarbons, and heat is harvested from hot brines. Both applications are increasingly gaining impetus among O&G experts, and many projects are underway to exploit these opportunities.

- **Repurposing idle O&G wells for geothermal production**

  To mitigate the inherently high costs of drilling new wells, abandoned wells that are no longer in use can be deepened or upcycled as geothermal wells, thus decreasing drilling risks and costs. There are more than 29 million abandoned wells worldwide (Groom 2020). Most of these wells have ceased to flow and have been decommissioned.

  These stranded assets can be repurposed for other applications, including carbon capture and storage, biogas, hydrogen, helium, and geothermal energy production. Many of these idle wells have the requisite temperatures for geothermal exploitation, and it is possible that many of them have large diameters and can be reconfigured as closed- or open-loop systems. The benefits from converting these assets to geothermal wells include cost savings, risk mitigation, and environmental protection.

  Another substantial benefit, still unrealized, is methane mitigation. Research shows that an unplugged abandoned well leaks approximately 0.13 tons of methane per year. Methane leaks can be prevented by repairing and repurposing these wells for geothermal production. Essentially, these wells can be transformed into a sort of carbon sink, leading to negative emissions. In regions with carbon trading schemes, these credits can be traded by operators, creating an additional revenue stream or leading to potential profits from carbon tax breaks. Typically, O&G wells have a lifespan of 20 to 30 years, after which they are decommissioned when they dry out or cease to produce at economical rates. However, research indicates that a repurposed geothermal well can remain active for 30 years or more, representing a considerable opportunity to prolong the life span of these stranded assets. Over the past decade, over 20 projects have aimed to convert idle O&G wells into geothermal generation assets, with most yielding promising results (Ashena 2022).

- **Repurposing O&G wells for geothermal energy storage**

  Geopressured reservoirs can be used as “energy storage/batteries” by combining high pressure and high temperatures with dissolved methane in brine. These reservoirs can provide a dual benefit of storing energy and extracting geothermal energy simultaneously. Recent studies have focused on the feasibility and optimization of using these reservoirs for energy storage, leveraging their high pressure and temperature conditions to enhance efficiency. Geopressured batteries have the potential to play a significant role in integrating renewable energy sources into the grid. By providing grid-scale energy storage capabilities, these batteries can help address the intermittent issues associated with renewables like

wind and solar power, thus contributing to grid stability and reliability. Two current deployments worth noting are as follows:

- Brunei Shell is repurposing wells instead of abandoning them to store energy or generate electricity using geopressured formations (Salehabadi et al. 2023).
- Hunt Energy Network (HEN), in partnership with Quidnet Energy, is trying to scale up its geopressured energy storage prototype and create 300 MW of geomechanical energy storage across Texas (Jacobs 2024).

- **Harnessing heat from current O&G wells**

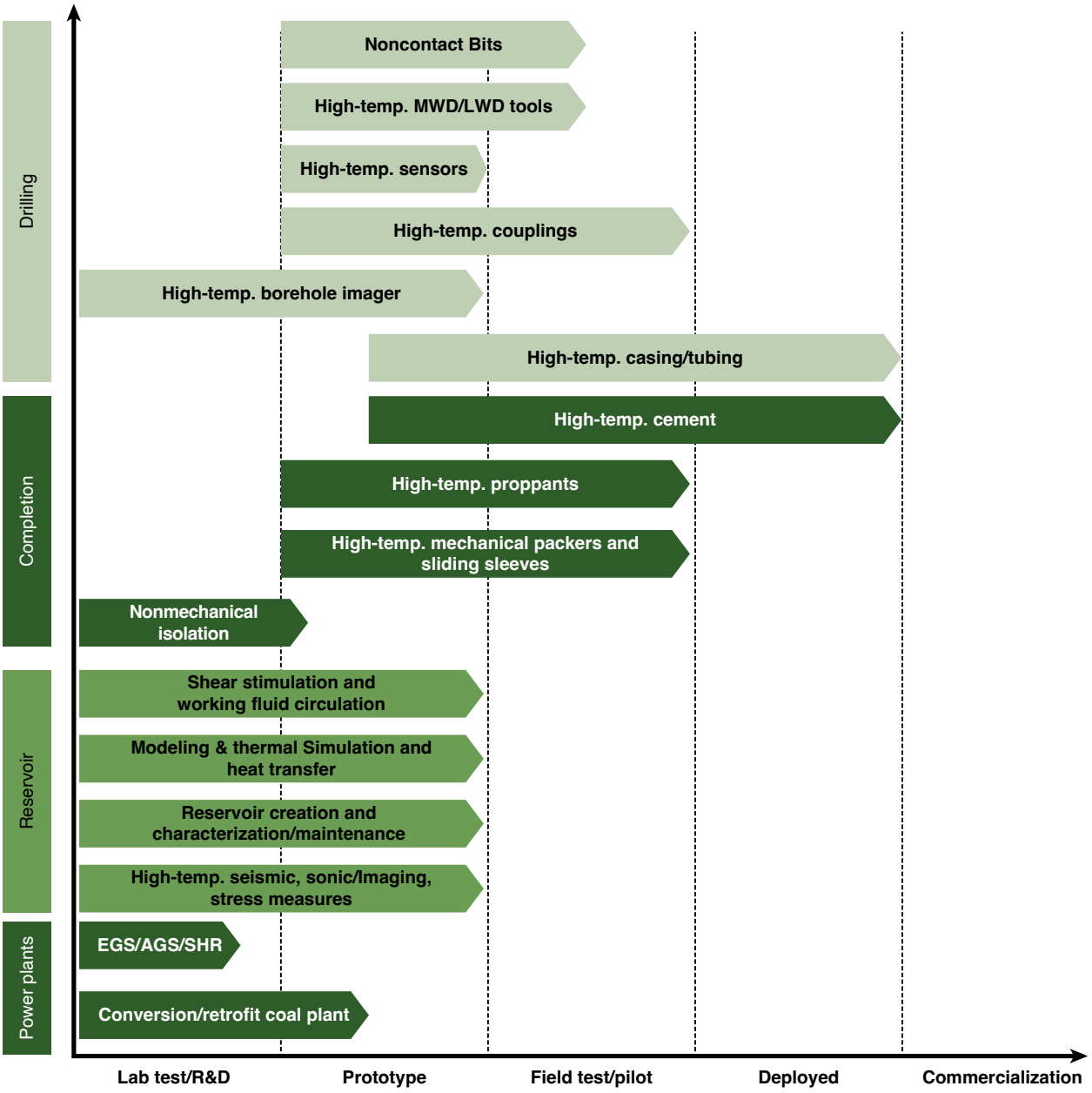
  Warm and hot water are often produced during O&G production at different reservoirs and volume levels. The ratio of produced water to O&G typically increases over time. Increased water production levels usually correlate with a decline in O&G production since water tends to be denser. When it infiltrates the wellbores, water can dominate production, resulting in operational challenges for operators. The need to separate this water from hydrocarbons and treat and recycle it underground places a significant operational expenditure on O&G companies. Globally, for every barrel of oil produced, three to five barrels of water are also produced. In mature regions, this figure can reach as high as 10 to 14. From a volume perspective, the O&G industry produces more water than it does any other fluid (Nazbar and Duplan 2011).

  This water, although challenging, represents potential opportunities. For example, high water-to-oil or water-to-gas ratio wells that have substantial enthalpy but are no longer economical could be reconfigured for exclusive geothermal production (conversion), similar to idle wells. Furthermore, when O&G can be produced economically from wells, the heat from the associated water can be harnessed on the surface in a process known as coproduction. These solutions can prove economically viable by avoiding the need for drilling new wells and saving on decommissioning costs. These solutions can also enhance social acceptance, which is often a barrier to geothermal proliferation due to concerns over safety, health, and the environment (Robins et al. 2021). This approach has been successfully implemented in U.S. oilfields. Many O&G producers worldwide are evaluating the economic feasibility of coproduction from their active and idle wells, especially those with high water-to-oil ratios. Most coproduction applications are aimed at direct use for district heating. Existing geothermal wells can greatly benefit from O&G technologies. The O&G industry has experience in revitalizing nonproductive wells through economical rigless interventions. Many geothermal wells have been stimulated to enhance their productivity, and many have electrical pumps installed to bring hydrothermal fluids to the surface when geothermal reservoir pressures are inadequate.

Appendix 3

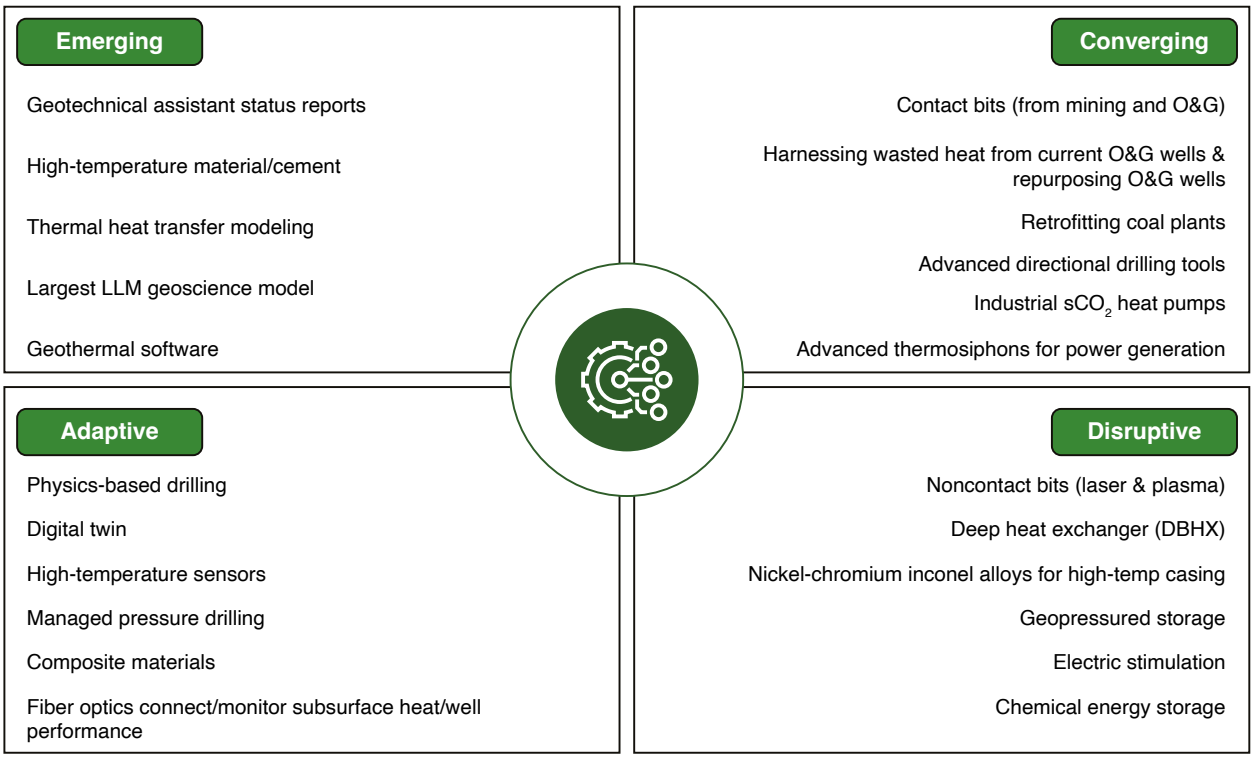
Figures 16 and 17 provide a strategic overview of geothermal technology progression and maturity, which highlights the technological landscape in geothermal energy development, charting the progression of various high-temperature tools and methodologies across different stages of maturity – from laboratory testing and R&D through prototyping and field testing to full commercial deployment. This landscape encapsulates a spectrum of innovations across drilling, completion, reservoir, and power plant domains, emphasizing the gradual transition of geothermal technologies from conceptual frameworks to tangible, industry-standard applications. This visualization underscores the comprehensive approach necessary for advancing geothermal energy systems, highlighting the critical pathways that must be navigated to enhance the efficacy and economic viability of geothermal energy extraction and utilization.

Figure 16. Technology progression and maturity for advanced systems.



Sources: Hoxha et al. (2023) and Clean Air Task Force (2024).

Figure 17. Emerging technologies in the geothermal industry.



Sources: Hoxha et al. (2023) and Clean Air Task Force (2024).

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About the Project

Saudi Arabia has initiated a renewable energy strategy with the primary aims of reducing dependence on hydrocarbons, cutting GHG emissions, and fostering economic and social progress. A critical strategy toward achieving these goals is the effective exploitation of geothermal potential. This KAPSARC project seeks to guide national energy policies and initiatives, advocating further advancements in geothermal development, while also delving into the significant trends in technological innovation, market dynamics, and policies and regulations influencing the overarching geothermal market.



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