The Future of Geothermal in India

POWERING ECONOMIC GROWTH AND PROSPERITY WITH ABUNDANT DOMESTIC ENERGY

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Powering Economic Growth and Prosperity with Abundant Domestic Energy

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Figures

Definitions

Advanced geothermal system (AGS): Occasionally referred to as closed-loop geothermal systems, a geothermal technology (with many configurations) that allows the circulation of fluid in the subsurface without fluid leaving the wellbore. Fluid is pumped from the surface, picks up heat from the surrounding formation (primarily through conduction), and flows back to the surface, where the heat is harvested for direct-use or power applications. AGS can be deployed in various rock types, can use engineered fluids such as supercritical carbon dioxide (sCO2) to improve efficiency, and is considered scalable.

Brittle-ductile transition zone: The zone of the Earth's crust that marks the transition from the upper, more brittle (fractured) crust to the lower, more ductile (plastically flowing) crust.

Caldera: A large volcanic depression, generally circular in form, with a diameter many times greater than that of a crater. A caldera forms when a volcano's magma chamber empties during an eruption, causing the ground above to collapse.

Conventional geothermal: A geothermal extraction method that requires a hydrothermal system and does not use hydraulic fracturing to artificially engineer a subsurface reservoir. Horizontal drilling may be used, but only to improve access to otherwise naturally occurring reservoirs and naturally occurring fluid.

Conventional hydrothermal system (CHS): Also known as a traditional geothermal system or hydrothermal geothermal system, a geothermal resource that is often accessible close to the surface and at times has surface manifestations, such as hot springs, volcanic rock formations, geysers, or steam vents, among others. A CHS has a combination of sufficient permeability in the subsurface, sufficient heat transfer into the system, and the natural presence of circulating water, which produces an exploitable geothermal resource. Heat flow is convection dominant (that is, conduction and advection contribute to the movement of heat). Most of the world's developed geothermal capacity is currently produced from CHS resources.

Direct-use geothermal system: Instead of using geothermal heat to generate electricity, uses the heat contained in geothermal fluids to enable various heating and cooling applications. This system can be shallow or deep.

- Shallow direct-use applications typically use a ground source heat pump to harvest the constant temperature of the shallow subsurface for a variety of low-temperature applications, including heating and cooling buildings.
- With deep direct-use applications, wells are drilled to reach higher subsurface temperatures that can be used for various applications, including industrial and commercial direct heating or numerous industrial and manufacturing processes. Deep direct-use applications may still use heat pumps but do so at much higher temperatures. Wells can target deep aquifers or human-made places filled with water, like mines.

Engineered/enhanced geothermal system (EGS): A geothermal technology that uses hydraulic fracturing to engineer a subsurface reservoir by creating or enhancing existing fractures in rock. Fluids are then circulated through the fracture network, where they heat up and are then brought to the surface for generating electricity or for direct use. This system can be deployed in various rock types and is considered scalable.

- **Traditional engineered geothermal system:** A system that uses hydraulic fracturing to engineer or enhance a subsurface reservoir to produce geothermal heat or electricity but does not use advanced directional drilling or multi-stage fracturing techniques. This system is typically developed by drilling vertical or deviated wells

and can be deployed in various rock types, but the development of the system has historically focused on basement rock formations.

- **Next-generation engineered geothermal system:** Not to be confused with the umbrella "next-generation geothermal" concept, a sub-type of EGS that still uses hydraulic fracturing to engineer or enhance a subsurface reservoir while also incorporating advanced drilling and/or hydraulic fracturing techniques, including but not limited to horizontal drilling and multi-stage fracturing. This system can be deployed in a variety of rock types.

Geophysics: The study of the Earth's physical properties and processes, combining knowledge from geology, physics, mathematics, and other sciences. In geothermal exploration, geophysical methods are used to map the Earth's subsurface, including the distribution of rock types, geological structures, temperatures, magnetic and gravity fields, occurrence of groundwater, and other features.

Geothermal gradient: The rate at which temperature increases with depth in the Earth.

Geothermal system: A system involving the transfer of heat from the Earth's interior to the surface.

Granite: A coarse-grained, light-colored intrusive igneous rock composed mainly of quartz, feldspar, and mica minerals. It often contains relatively high concentrations of radioactive elements such as uranium, thorium, and potassium, which release radiogenic heat as they decay, contributing to the Earth's internal heat.

Ground source (Geothermal) heat pump (GSHP): Pump that harvests the ambient temperature in the top 1 metres to 2 metres of the subsurface, where the ground remains at a relatively constant temperature of 13°C. GSHPs have traditionally been used to heat and cool buildings, but these pumps are increasingly used in higher-temperature industrial and commercial applications.

Hydraulic fracturing: The application of pressure exceeding that of the subsurface to create or expand cracks in the rock underground, which has been used to produce oil and gas but can also increase the efficiency of geothermal energy production.

Hydrothermal: Relating to hot water, especially in processes involving heated fluids within a geothermal system.

Magma: Molten or semi-molten natural material located beneath or within the Earth's crust that forms igneous rocks as it cools and solidifies. Magma temperatures generally range from 700°C to 1,300°C but can exceed 1,800°C.

Manifestation: Surface features where geothermal fluids are discharged (for instance, hot springs, hot lakes/pools, and fumaroles) and those formed by hot fluid-rock interactions and hydrothermal mineral deposition at the ground surface.

Mohorovičić (Moho) discontinuity: The boundary between Earth's crust and the underlying mantle. It is typically found at depths of between 5 kilometres and 10 kilometres beneath the ocean floor and between 30 kilometres and 40 kilometres beneath the continents.

Next-generation geothermal: An umbrella term for any geothermal extraction technology that harvests subsurface energy outside the geography of a conventional hydrothermal system. In most cases, next-generation geothermal technologies rely on advances from the oil and gas industry and expand the geographic potential of geothermal.

Pluton: A massive body of igneous rock that forms below the Earth's surface by the slow cooling and solidification of magma.

Radiogenic: Related to radioactivity. Radiogenic heat is thermal energy released by the radioactive decay of elements in the Earth's crust and mantle, contributing to geothermal heat.

Rock types

- **Igneous rock:** A rock formed by the solidification of molten rock material (magma) generated deep within the Earth.
- **Sedimentary rock:** A rock formed from the accumulation and cementation of sediments, which may include fragments of other rocks, minerals, or biological materials. These rocks typically form in sedimentary basins and are heated by conductive heat from the Earth's interior and by radiogenic heat from decaying elements.
- **Metamorphic rock:** A rock created when existing rocks (igneous, sedimentary, or metamorphic) are gradually transformed by heat and pressure without melting. This transformation alters the rock's mineralogy and texture and can generate residual heat that may be extracted.

Sedimentary geothermal system: A type of conduction-dominated geothermal resource found in sedimentary rock formations (with some convection cells in complex settings). These sedimentary rocks—including sandstone, shale, and limestone—often contain water within their pores that can be harvested for geothermal energy production. Most sedimentary basins are closed systems, unless they have experienced uplift, in which case surface springs may highlight geothermal potential.

Supercritical: Refers to a state above the critical temperature and pressure at which a substance becomes a supercritical fluid. Such fluids exhibit properties of both gases and liquids, making them highly efficient for heat extraction in geothermal systems.

Superhot rock (SHR): A term given to geothermal technologies that aim to exploit hot-rock resources above approximately 373°C, the supercritical point of water. In volcanic regions of the world, SHR may be encountered relatively close to the surface; in other regions, SHR may require drilling to as deep as 10 kilometres or more, so SHR is sometimes referred to as *deep geothermal*.

Tectonic plates: Massive slabs of the Earth's lithosphere (crust and upper mantle) that move slowly across the planet's surface. There are two main types: oceanic and continental plates. Their movement drives many geological processes, including earthquakes, volcanism, and mountain formation.

Abbreviations

This list defines the report's frequently used abbreviations.

ADFB: Aravalli Delhi Fold Belt

AGS: advanced geothermal system

AI: artificial intelligence

ASHP: air source heat pump

ATES: aquifer thermal energy storage

AUTL: Administration of Union Territory of Ladakh

BCCL: Bharat Coking Coal Limited

BEE: Bureau of Energy Efficiency

BTES: borehole thermal energy storage

CAPEX: capital expenditure

CCGT: combined-cycle gas turbine

CEEW: Council on Energy, Environment and Water

CEGE: Center of Excellence for Geothermal Energy

CIL: Coal India Limited

CO_2: carbon dioxide

CO_2e: carbon dioxide equivalent

CPWD: Central Public Works Department

°C: Celsius

dBA: A-weighted decibels

DCN: district cooling network

DHCN: district heating and cooling network

EGMB: Eastern Ghats Mobile Belt

EGS: engineered or enhanced geothermal system

EPC: Engineering, Procurement, and Construction

FRA: Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act

GAIL: Gas Authority of India Limited

GDP: gross domestic product

GES: geothermal energy storage

GIFT City: Gujarat International Finance Tec-City

GSHC: ground source heating and cooling

GSHP: ground source heat pump

GSI: Geological Survey of India

GW: gigawatts

GWh: gigawatt-hours

GWHC: groundwater heating and cooling

GWHP: ground water heat pump

HDR: hot dry rock

HiP: heat-in-place

HSA: hot sedimentary aquifer

HVAC: heating, ventilation, and air-conditioning

ICAP: India Cooling Action Plan

IDW: inverse distance weighting

IEA: International Energy Agency

IIT: Indian Institute of Technology

ISB: Indian School of Business

LAHDC: Ladakh Autonomous Hill Development Council

LCA: life cycle assessment

LCOE: levelised cost of electricity

MGES: minewater geothermal energy schemes

MMDR: Mines and Minerals (Development and Regulation)

MNRE: Ministry of New and Renewable Energy

MSMEs: micro, small, and medium enterprises

MW: megawatts

MWh: megawatt-hours

NCG: non-condensable gas

NDR: National Data Repository

O&M: operations and maintenance

OECT: Oil and Natural Gas Corporation Limited Energy Centre Trust

OIL: Oil India Limited

ONGC: Oil and Natural Gas Corporation Limited

OPEX: operating expenditures

ORC: Organic Rankine Cycle

ORDA: Oilfields (Regulation and Development) Act

PAT: Perform, Achieve, and Trade

PESA: Panchayats (Extension to Scheduled Areas) Act

PLI: Production Linked Incentive

PM-KUSUM: Prime Minister's Farmer Energy Security and Upliftment Mission

RBI: Reserve Bank of India

RE-RTD: Renewable Energy Research and Technology Development

SAMEEEKSHA: Small and Medium Enterprises Energy Efficiency Knowledge Sharing

SECI: Solar Energy Corporation of India

SHR: superhot rock

SMB: Satpura Mobile Belt

SONATA: Son-Narmada-Tapti

TCO: thermal consumption obligation

TEN: thermal energy network

TJ: terajoules

TWh: terrawatt-hours

UTES: underground thermal energy storage

VOC: volatile organic compound

Methodology for Calculating India's Geothermal Potential

The Heat-in-Place (HiP) method utilises the calculations from Pocasangre and Fujimitsu,[1] as described in their 2018 paper, computing the thermal energy stored in each grid cell as a function of depth, temperature, rock and fluid properties, and recovery efficiency. The assessment divides the subsurface into 500 metre depth slices (from 500 metres to 5,000 metres; current technology for electricity generation) or 7,000 metres (future potential electricity generation) and 3,500 metres for heat applications (current technology) and 5,000 metres (future potential).

For each grid cell at each depth slice, the calculation proceeds as follows:

1. Temperature estimation: T(z) is computed using the domain-specific temperature-depth curves, incorporating the local geothermal gradient, surface temperature, and nonlinear corrections for sedimentary compaction and advective heat transport.

2. Porosity calculation: Porosity is modeled using Athy's compaction law, $\varphi(z) = \varphi_0 \cdot \exp(-c \cdot z)$, calibrated to Ehrenberg and Nadeau[2] using more than 40,000 global reservoir measurements.

3. Thermal energy: The heat stored per unit volume is calculated as:

$$Q_{rock} = V \times \rho_r \times C_r \times (1 - \varphi) \times \Delta T$$

$$Q_{water} = V \times \rho_w \times C_w \times \varphi \times \Delta T$$

4. Recoverable energy: The electrical potential is computed as:

$$GWe = Q \cdot R\_f \cdot \eta(T) / (plant\_life \cdot seconds\_per\_year)$$

where R_f is the recovery factor (20%), η(T) is the temperature-dependent conversion efficiency used in the electricity model, and plant_life is 30 years.

The deterministic calculation is augmented by a 2,000 iteration Monte Carlo simulation that perturbs key input parameters within their empirically calibrated uncertainty ranges. This produces probability distributions (P2, P10, P50, P90) of the geothermal potential for each grid cell and country.

The following parameters are perturbed in each Monte Carlo iteration:

- **Geothermal gradient:** Gaussian perturbation with category-specific standard deviations.
- **Surface temperature:** Triangular distribution with bounds (–3, 0, +3) °C.
- **Temperature at depth:** Depth-dependent sigma values calibrated from well P10–P90 spreads, ranging from ±8°C–11°C at 0.5 kilometres to ±24°C–35°C at 5 kilometres, depending on geological domain.
- **Rock density (ρ_r):** Gaussian perturbation around 2,500 kilograms per cubic metre with ρ_r–C_r correlation of –0.2.
- **Recovery factor (R_f):** Perturbation around 20% with R_f–C_e correlation of 0.1.
- **Porosity:** Depth-dependent sigma from Ehrenberg & Nadeau's analysis.

Marginal sigma scaling is applied to ensure that uncertainty decreases with proximity to well control points, providing spatially varying confidence levels. The Monte Carlo results converge well at 2,000 iterations, with coefficient-of-variation for global totals below 1%.

METHODOLOGY SPECIFIC TO CHAPTER 4, "GEOTHERMAL COOLING OPPORTUNITIES"

Project InnerSpace overlaid India's regional-level heat risk, as assessed by the Council on Energy, Environment and Water, with geothermal resource estimates from the Project InnerSpace Heat-in-Place model to

identify priority areas that are suitable for aquifer-based geothermal district cooling. (This temperature represents the minimum threshold typically required for efficient operation of the geothermal-driven absorption chillers used in district cooling.) This approach ensures that cooling is targeted to sites with both the greatest need and opportunity. It also provides a replicable, data-driven framework for evaluating which of India's vulnerable regions would most benefit from this infrastructure investment.

This study used the Project InnerSpace HiP model to screen aquifers to a depth of 3,500 metres so we could identify the ones that would be most effective. Because the absorption chillers used in geothermal cooling typically require inlet temperatures near 90°C to operate efficiently and reliably, only aquifers at or above this temperature were selected to ensure consistent output, particularly during peak summer demand. This cutoff guarantees that selected aquifers can deliver scalable, grid-independent cooling in areas where high heat risk overlaps with critical cooling needs. Resource estimates were generated for each high-risk district and expressed in gigawatts—a metric that can be linked to the district's cooling demand and energy planning.

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Executive Summary

The Geothermal Opportunity in India

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Geothermal energy can become a cornerstone of India's future energy supply for industrial heat, building cooling, and some electricity generation—enhancing energy security, reducing emissions, and supporting regional equity. And India can position itself at the forefront of the global geothermal boom, creating hundreds of thousands of jobs and ensuring a reliable, domestic, affordable, and clean energy future for generations to come.

From the Himalayas to the Deccan Traps, India's subsurface holds extensive geothermal resources—including some sites with temperatures hot enough to produce electricity and many locations where geothermal could supply cooling for buildings and heat for industrial processes. Perhaps most exciting is that by deploying these abundant direct-use geothermal resources, India could displace coal, oil, and diesel; improve urban air quality; and ease pressure on the grid.

As one of the world's fastest-growing major economies, India faces a dual challenge: sustaining rapid economic development while meeting its commitments to energy security and decarbonization. The government of India has set ambitious goals to achieve energy independence by 2047 and net-zero emissions by 2070 while also ensuring reliable and affordable energy for its population. To accomplish these goals, India needs to diversify its clean energy mix beyond solar, wind, and hydropower and accelerate the adoption of firm, clean energy sources that can provide round-the-clock reliability. The country's geothermal potential can play a key role.

According to the India Climate and Energy Dashboard, industry accounts for roughly 40% of the nation's energy use and households for about 24%.[1] Given the country's rapidly growing cooling demand—and the continued dominance of coal and oil in overall energy use—geothermal offers a major opportunity to meet a good portion of India's energy needs. Many areas facing

GEOTHERMAL APPLICATION POTENTIAL ACROSS INDIA, CLASSIFIED BY APPLICATION TYPE

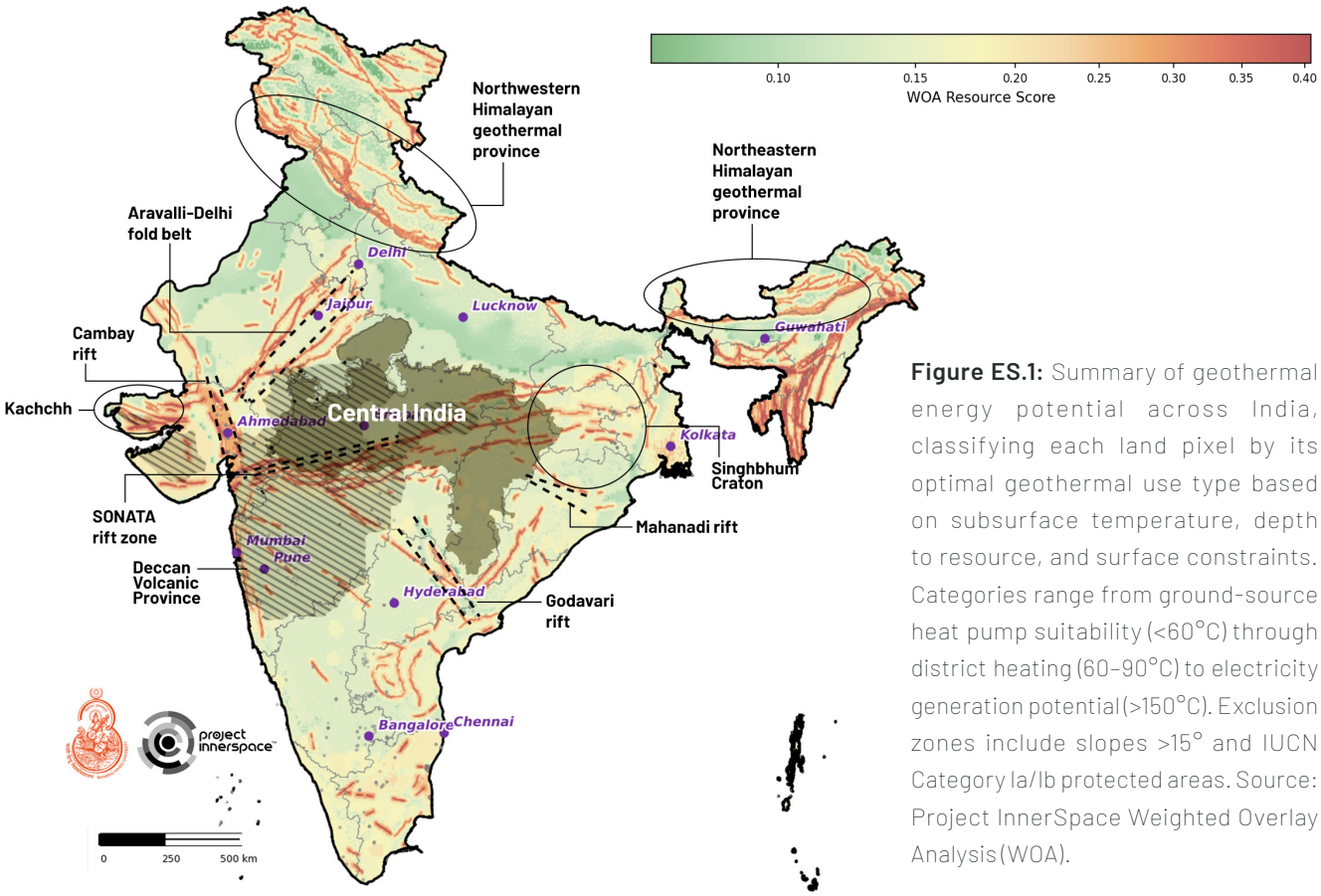


Figure ES.1: Summary of geothermal energy potential across India, classifying each land pixel by its optimal geothermal use type based on subsurface temperature, depth to resource, and surface constraints. Categories range from ground-source heat pump suitability (<60°C) through district heating (60–90°C) to electricity generation potential (>150°C). Exclusion zones include slopes >15° and IUCN Category Ia/Ib protected areas. Source: Project InnerSpace Weighted Overlay Analysis (WOA).

heat stress in India sit on top of geology that is well suited for geothermal cooling.

India's geothermal potential is vast and widely distributed. Project InnerSpace analysis estimates the country has more than 11,000 gigawatts of direct-use industrial heat potential (with a 100°C cut-off temperature down to 3,500 metres) and more than 1,500 gigawatts of geothermal cooling potential. Additionally, India has technical potential for roughly 450 gigawatts of electricity generation (down to 5 kilometres) today and more than 8,000 gigawatts of electricity (down to 7 kilometres) as technology improves. (For more on how these estimates were developed, see Chapters 2, 3, and 4.) This potential means every state could deploy this energy source through electricity, industrial heat, or cooling.

The government has recently published the National Policy on Geothermal Energy, which sets a framework for geothermal exploration, permitting, and pilots. This policy is an important step, but more can be done to move from opportunity to projects. This report identifies areas where geothermal heat, cooling, and electricity can scale first; outlines policy pathways to tap this potential; and highlights environmental, workforce, and legal issues that need to be addressed for the country to ensure that successful and secure projects are built this decade.

Going big on all geothermal applications in India could improve air quality, reduce fuel imports, and—via upskilling and training—create hundreds of thousands of jobs that build on the country's strengths in drilling, geoscience, and engineering. It would also expand access to cooling—a public health and productivity priority—without proportionally increasing electricity demand. As a result, India would strengthen resilience and equity as dangerous heat events become more frequent.

IN SHORT: GEOTHERMAL'S ADVANTAGES AND BENEFITS FOR INDIA

- **Energy security:** As a domestic resource, geothermal reduces dependence on imported fuels, enhances energy independence, and supports critical applications such as data centers.
- **Resilience, reliability, and regional equity:** Geothermal provides continuous, round-the-clock energy and can withstand extreme weather, grid stress, and supply disruptions. Geothermal cooling systems also require less energy, can operate during grid challenges, and can be deployed across much of the country.
- **Local economic and workforce benefits:** Geothermal could create between 350,000 and 700,000 jobs while also increasing economic development in the agricultural industry.
- **Long-term competitiveness:** Direct-use applications reduce fuel consumption by as much as 80%. Technological innovations and competitive levelized costs make geothermal increasingly cost-attractive for industrial heat and baseload electricity.[2,3]
- **Small footprint:** Geothermal facilities require far less space and infrastructure than most other energy sources, including less transmission build-out.
- **Lower emissions and cleaner air:** Geothermal displaces coal, diesel, and furnace oil for power, heat, and cooling, slashing greenhouse gases while sharply reducing sulfur dioxide, nitrogen oxides, and fine particulate matter. As a result, the country could make meaningful progress toward climate targets and immediate air quality and public health gains in cities and industrial corridors.

TODAY'S INDIAN ENERGY LANDSCAPE

Over the past decade, India's electricity sector has changed dramatically. As of September 2025, about 51% of total capacity (more than 255 gigawatts)[4] comes from non-fossil sources—most of it solar and wind.[5] India is decarbonising its electricity system rapidly—yet most industrial heat and process-energy demand (needed to power cooling, industrial drying, and agricultural processing) remains fuel-based,[6] meaning thermal energy continues to be a critical missing piece of the country's clean energy transition. Coal alone contributes more than 91% of the total fossil fuel energy used in India.[7] Geothermal energy is a strong solution for India because it provides clean, reliable, always-available heat in the exact temperature range needed for many industrial, agricultural, and cooling applications. Unlike solar or wind, geothermal delivers steady, 24/7 thermal energy without storage, making it a practical and cost-effective alternative to coal.

At the same time, the demand for energy in India is rising quickly: Peak electricity demand in some regions is growing at between 8% and 10% each year as industrialisation, urbanisation, and cooling loads increase.[8] During severe heat waves in 2024, electricity demand rose by 10.4% compared with the previous year.[9]

SOURCES OF ELECTRICITY IN INDIA AS OF SEPT. 2025

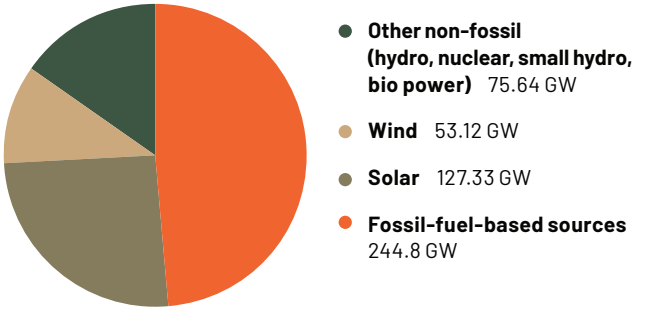
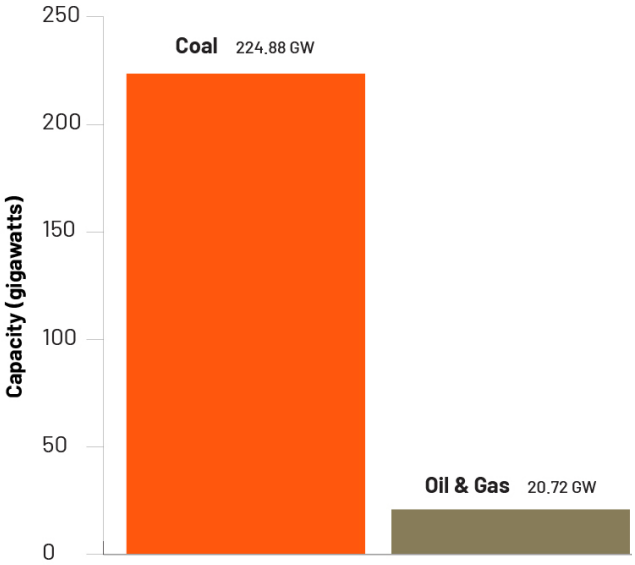


Figure ES.2: As of September 30, 2025, India's total installed power capacity had reached 500 gigawatts (GW), led by non-fossil sources, including just more than 127 gigawatts of solar and 53 gigawatts of wind power, making up 51% of the total, and almost 245 gigawatts of fossil fuel–based sources (about 49%). This marks a strong shift toward renewable energy and energy security. Source: Ministry of Power. (2025, October 29). *India achieved historic milestone in power sector: Surpasses 500 GW and renewable energy generation exceeds 50% of demand* [Press release]. Government of India.

Air-conditioning alone accounted for nearly one-third of that increase. This combination of higher demand and the continued reliance on thermal generation sources to

INSTALLED FOSSIL FUEL ENERGY CAPACITY IN INDIA AS OF OCT. 2025



ES.3: India's thermal energy needs—the heat needed to power cooling, industrial drying, and agricultural processing—remain heavily dependent on fossil fuel, largely coal. Source: INITI Aayog. (2025). *India climate and energy dashboard*.

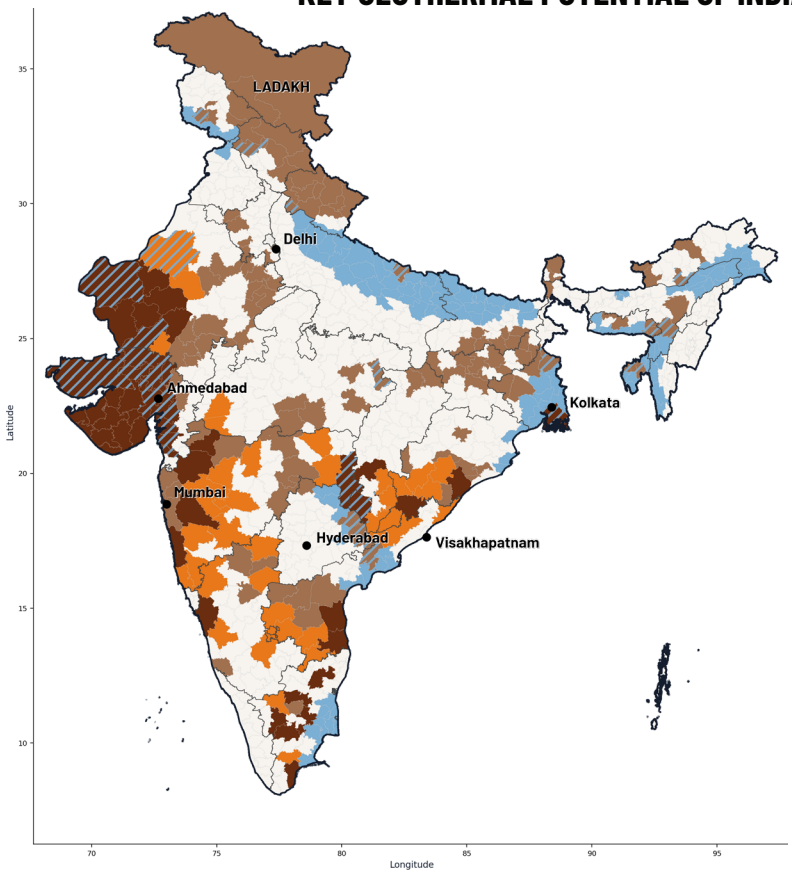
cater to peak energy demand underscores the urgency for policy, regulatory, and financing innovation. Without taking action now, meeting this projected cooling demand would require an additional 180 gigawatts of conventional generation capacity by 2035, and by 2037, it would generate roughly 810 million tonnes of carbon dioxide equivalent (CO_2e) annually.[10,11]

INDIA'S GEOTHERMAL RESOURCES

India started looking into geothermal energy in the 1970s. When the Geological Survey of India began exploring thermal anomalies, it found 381 geothermal fields with an estimated potential of 10.6 gigawatts of energy, then developed the first *Geothermal Atlas of India*.[12] Despite this resource base, geothermal deployment in India has lagged far behind solar and wind power.[13,14]

To date, India has only piloted direct-use projects and small-scale demonstration plants rather than commercial-scale geothermal electricity generation. As explained in detail in Chapter 2, "Where Is the Heat? Exploring India's

KEY GEOTHERMAL POTENTIAL OF INDIA BY DISTRICT



Electricity
Industrial process heat
Cooling
Electricity and cooling
Observed electricity potential based on thermal springs
Thermal springs electricity and cooling potential

Figure ES.4: Key geothermal potential of India by district. This map classifies India's districts by their geothermal potential and primary application based on the Project InnerSpace Heat in Place (HIP) volumetric model and the Global Advection Database. Observed electricity potential is derived from thermal springs information and is not modelled. Source: Project InnerSpace HIP analysis and advection database, 2026.

Subsurface Geology," India's geothermal resources are predominantly low- to medium-heat, with a small proportion containing high-temperature geothermal resources suitable for electricity generation. With recent advances in technology, the potential areas where India can deploy its geothermal resources are expanding from a few hot spots to broad regions suitable for a range of geothermal applications, as illustrated in **Figure ES.4**.

GEOTHERMAL APPLICATIONS FOR INDIA

Cooling and Heating in Buildings

To tackle the rising demand for air-conditioning, developers should look to geothermal cooling systems. These heating and cooling systems are far more efficient than conventional systems—up to 70% more efficient than a standard heating, ventilation, and air-conditioning (HVAC) system. Ground source heat pump (GSHP) systems harness the Earth's relatively stable shallow subsurface temperature—generally between 20°C and 30°C at depths of between 8 metres and 20 metres across much of India—to serve as a heat sink for cooling via electrically driven heat pumps. And they can be deployed in most regions across India. Geothermal systems can also cut generation and transmission costs and ease peak surges. Paired with solar and batteries, geothermal heating and cooling systems can also operate off-grid during periods of grid stress. Studies in Indian metropolitan areas indicate that GSHPs can reduce electricity use for cooling by between 30% and 40% because they efficiently leverage stable subsurface temperatures.[15] This finding is critical for cities in hot climates such as Delhi, Ahmedabad, Hyderabad, and Chennai, where cooling drives peak electricity demand.

Additionally, geothermal district cooling—systems that function much like utilities that are built to distribute cooling across an area with multiple buildings(see Chapter 1,

GEOTHERMAL COOLING AND HEATING NETWORK

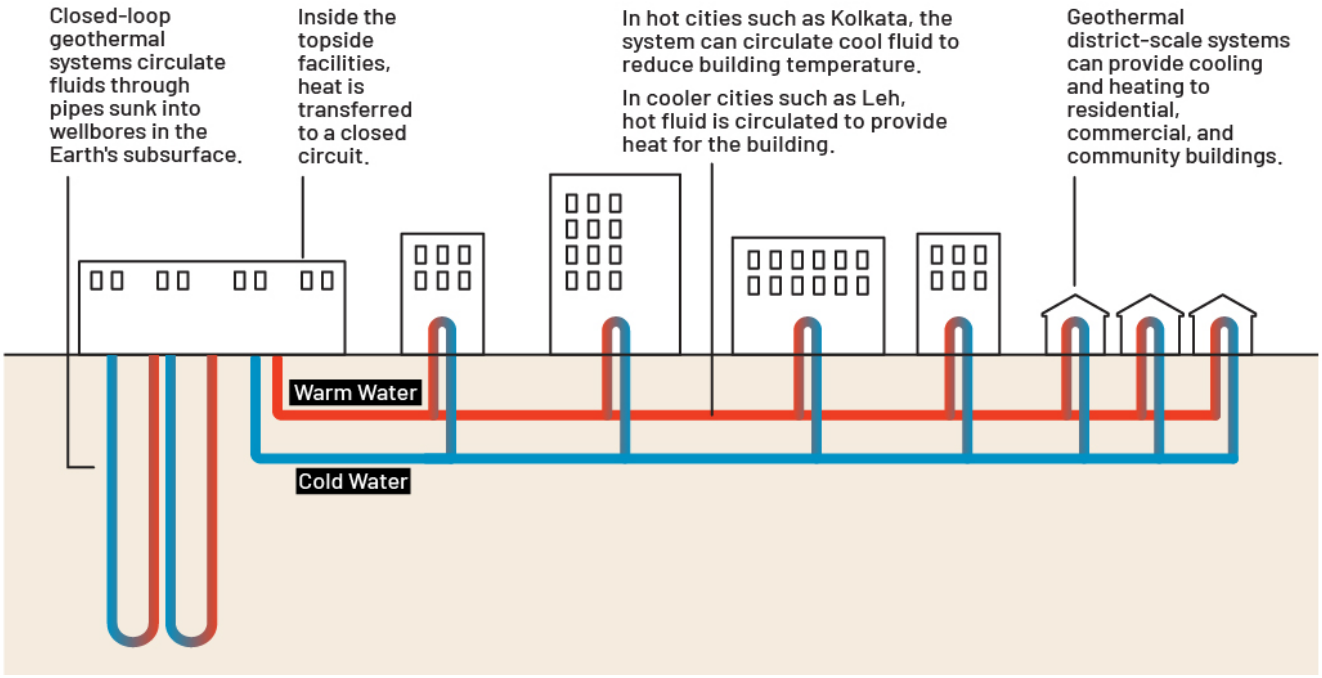


Figure ES.5: In a district cooling system, fluid is typically brought to the surface at a target temperature of around 21°C. That fluid is then passed through a heat pump to provide cold water in the summer for cooling and hot water in the winter for heating. This style of cooling and heating can be more than twice as efficient as traditional HVAC systems as the thermal load is shared between buildings. Source: Adapted from U.S. Department of Energy. *Geothermal district heating & cooling.*

DISTRICTS WITH ALIGNMENT OF AQUIFER COOLING POTENTIAL AND HIGH DEMAND DUE TO EXTREME HEAT

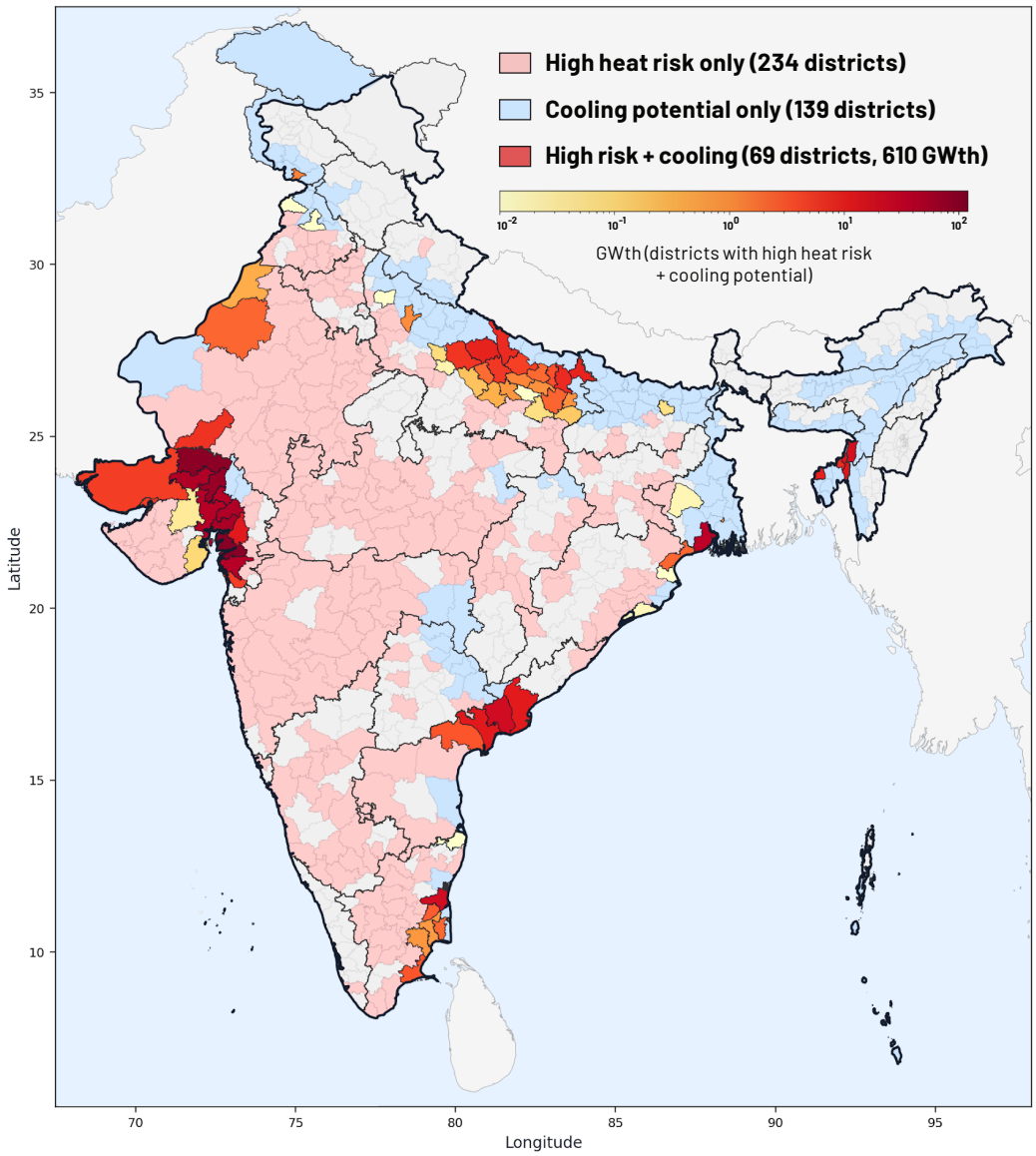


Figure ES.6: The highlighted districts represent areas identified as having both (a) significant geothermal energy potential (in gigawatts [GWth] per pixel ~ 10 square kilometers) in sedimentary aquifers and (b) high or very high heat risk according to the Council on Energy, Environment and Water Composite Heat Risk Index. These zones present optimal conditions for sustainable cooling interventions, offering a strategic opportunity for geothermal-based thermal resilience infrastructure. Source: Project InnerSpace analysis, 2025.

"Geothermal 101: Overview of Actions and Technologies")—is particularly well suited to India's sediment-rich basins, where high-permeability aquifers lie beneath densely populated urban areas experiencing acute heat stress. Chapter 4, "Geothermal Cooling Opportunities," identifies the key areas in India where geothermal aquifer cooling can provide critical relief in the face of extreme heat, with the states of Gujarat, Uttar Pradesh, Tamil Nadu, West Bengal, Tripura, and Meghalaya potentially benefiting the most from district-scale geothermal cooling infrastructure. (See **Figure ES.6**.)

Geothermal district cooling offers a powerful low-carbon alternative that can help India meet its growing and urgent cooling needs—with an estimated 610 gigawatts of total cooling potential in areas at high risk for heat events and a

AARTI INDUSTRIES FACILITY IN JHAGADIA

Figure ES.7: A feasibility study done for the Aarti Industries facility in Jhagadia, Gujarat, illustrates how geothermal could serve as a cost-effective alternative to coal. Source: Aarti Industries.

total capacity of about 1,500 gigawatts across the country. Geothermal cooling can also help increase regional equity by not only increasing access to cooling but also creating jobs in areas that deploy these technologies.

Industrial Process Heat

As mentioned, the industrial sector dominates energy demand in India. Many processes—such as drying, bleaching, pasteurisation, washing, and more—require temperatures between 60°C and 200°C. Geothermal fluids are perfect for processes in that temperature range.[16] Plenty of industrial corridors are located near provinces with strong geothermal resources, including the following:

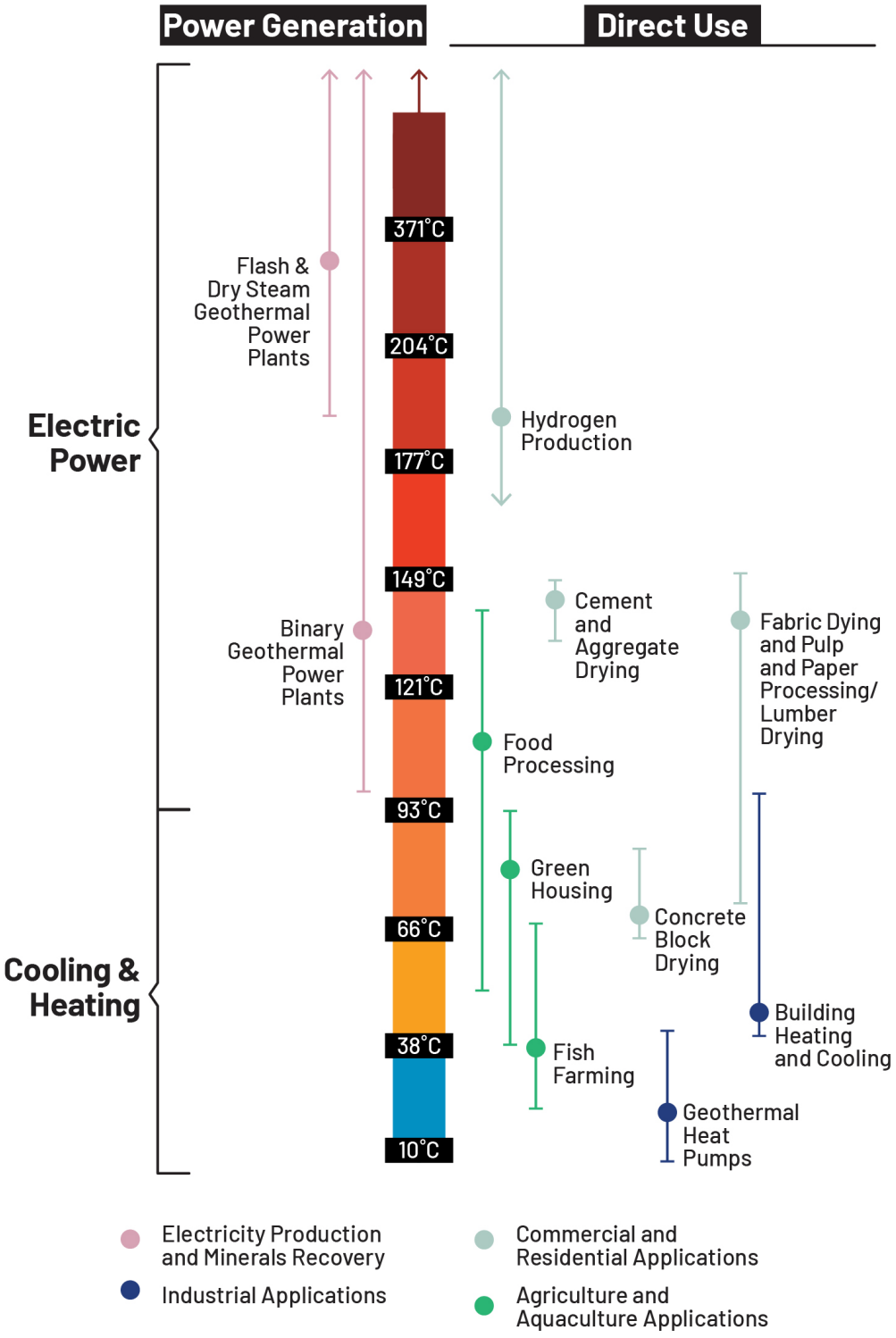
- Textile and chemical industries near Ahmedabad and Ankleshwar, on the Cambay graben in Gujarat.
- Agro-processing and paper mills near Chhattisgarh and Jharkhand, above the Son-Narmada-Tapti (SONATA) lineament zone.
- Food processing and pharmaceuticals in Maharashtra, West Coast Province.

Deploying geothermal heat in these clusters could replace the need for furnace oil, coal, and liquified petroleum gas, reducing both operational costs and carbon emissions. The use of geothermal would generate other significant benefits, such as reduced air pollution, a decrease in carbon dioxide emissions, and more local jobs. A recent feasibility study conducted by Project InnerSpace and Aarti Industries found that geothermal could fully replace high-grade process steam using only 0.8 hectares (approximately 2 acres) of land and a three-well system delivering approximately 200 kilograms per second of 250°C fluid. At between $30 and $35 per megawatt thermal, geothermal steam becomes cost-competitive with coal while offering long-term energy security and savings of millions of tonnes of carbon dioxide. (See Chapter 3, "Direct-Use Geothermal for Manufacturing and Industrial Processes.")

Heat for Agriculture Processes and Cold Chains

Geothermal energy can strengthen India's agricultural industry via greenhouse heating, aquaculture, and crop drying. For example, the geothermal heat below the low-

GEOTHERMAL APPLICATIONS AND TEMPERATURE REQUIREMENTS



ES.8: Geothermal energy can be used for generating electricity, heating and cooling homes and offices, and manufacturing. There are also new and emerging applications such as geothermal energy storage, where the subsurface serves as an earthen battery, and geothermal critical minerals extraction, for rare elements such as lithium. Adapted from Porse, S. (2021). *Geothermal energy overview and opportunities for collaboration*. Energy Exchange.

TAPRI GEOTHERMAL COLD STORAGE PROJECT

Figure ES.9: The Tapri Geothermal Cold Storage Project, an InnerSpace GeoFund portfolio project. Source: Geotropy.

enthalpy fields in Himachal Pradesh, Bihar, and Jharkhand could extend growing seasons, support horticulture, and power cold-storage facilities.[17] Deployment would support India's growing focus on reducing food loss and modernising cold chains. (In Chapter 3, "Direct-Use Geothermal for Manufacturing and Industrial Processes," the author explains how geothermal direct use at the Tapri Geothermal Cold Storage Project facility in Himachal Pradesh can relieve farmers from the challenges of seasonal variability and improve resilience for farming communities. See **Figure ES.9**.)

Electricity Generation

While most of India has low- to medium-temperature resources, a few areas with high temperatures hold promise for electricity generation. (See Chapter 2, "Where Is the Heat? Exploring India's Subsurface Geology.") The Puga Valley in Ladakh has reservoir temperatures of between 220°C and 270°C,[18] which means it could support binary and flash power plants as well as next-generation technologies. Chhattisgarh, Himachal Pradesh, Uttarakhand, Rajasthan, Gujarat, Maharashtra, Madhya Pradesh, Sikkim, Arunachal Pradesh, and Meghalaya also have high-temperature geothermal fields that could support power generation.

Direct Use First: Priorities to Maximise India's Geothermal Resources

The best near-term roles for geothermal in India lie in *thermal applications*—industrial and residential heat, industrial and residential cooling, district energy, and agriculture— with benefits such as the following:

- **Load management for cooling:** GSHPs and district cooling systems can lower peak electricity demand in densely populated cities, easing grid integration challenges. This approach offers a cost-effective alternative to expanding transmission, distribution, and infrastructure in rapidly growing urban areas.
- **Industrial decarbonisation:** Direct geothermal heat can replace fossil fuels for businesses, helping India achieve its net-zero goals. Focusing on micro, small, and medium enterprise clusters located where there are strong geothermal resources would be an effective first step.
- **Improved agriculture resilience**: Geothermal can be used for many agricultural purposes, including extending growing seasons, reducing food loss, and creating economic opportunities in rural areas.

LOWERING GEOTHERMAL COSTS IN INDIA: POLICY AND EMERGING TECHNOLOGY PATHWAYS

Unlocking India's geothermal potential for industrial heat, cooling, and electricity generation will require new policies. Recognizing this need, India recently adopted a National Policy on Geothermal Energy; Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," outlines a set of five policy recommendations aimed at accelerating geothermal deployment through rapid implementation of the National Policy on Geothermal Energy and proposes additional ideas for pilot projects, clear government signals, and targeted financial incentives.

Near-term policy priorities could include the following:

1. Establishing national goals and launch a national geothermal cooling mission inside India's Cooling Action Plan—targeting 10 gigawatts of cooling, 50 gigawatts of industrial direct use, and 10 gigawatts of electricity by 2050.
2. Implementing the 2025 National Policy on Geothermal Energy through clear rules, timelines, and transparent permitting.
3. De-risking investment via financial incentives, such as covering about 50% of exploration costs and around 30% of development costs.

POLICY RECOMMENDATIONS TO CATALYSE GEOTHERMAL DEVELOPMENT IN INDIA

Near Term (1–3 Years)

1 — Establish national goals and a national geothermal cooling mission.

India could set national geothermal targets for electricity, industrial heat, and cooling:

- **Electricity:** 200–400 MW of geothermal electricity by 2035, 1 GW by 2040, and 10 GW by 2050.
- **Industrial:** 10 GW of geothermal process heat by 2035, 20 GW by 2040, and 50 GW by 2050.
- **Cooling:** 800–1,000 MW of geothermal cooling by 2035, 3–4 GW by 2040, and 10 GW by 2050, supported by a national geothermal cooling mission under the India Cooling Action Plan.

2 — Implement the 2025 National Policy on Geothermal Energy.

The Ministry of New and Renewable Energy could rapidly operationalise the new policy by:

- directing states to form geothermal nodal agencies;
- launching a single-window clearance system; and
- piloting projects in high-potential regions such as the Himalayas, Cambay Graben, and the Godavari Rift Valley.

3 — De-risk investment through financial incentives.

Introduce exploration and development subsidies (50% and 30%, respectively), tender-based procurement for power and heat, and Production Linked Incentive–style manufacturing incentives for geothermal equipment. Budgetary support of between ₹500 and ₹1,000 could fund R&D and early demonstration projects.

Medium Term (3–5 Years)

4 — Enact a geothermal energy act within the National Renewable Energy Act.

A geothermal energy act would define resource ownership, clarify permitting processes, and establish environmental and safety standards. It would also provide legal certainty for investors and streamline coordination between central and state agencies. While not a prerequisite for progress, such legislation would accelerate deployment and reduce friction across jurisdictions.

5 — Create market demand and awareness.

Governments could introduce thermal consumption obligations that require industries to adopt renewable heat; integrate geothermal into public procurement; and expand capacity-building programs for micro, small, and medium enterprise clusters and state energy departments.

Figure ES.10: Policy recommendations to catalyse geothermal development in India. Source: the authors.

Longer-term measures could include the following:

4. Enact a geothermal energy act within the National Renewable Energy Act.
5. Create market demand and awareness.

Geothermal development is capital-intensive. Exploration and drilling often account for between 40% and 60% of a project's costs—and returns are uncertain until wells are proven. This issue is one of the main reasons why India's geothermal installations are still in the pilot phase, despite all of the nation's subsurface resources. The policy recommendations in this report are intended to move pilots to projects.

Alongside policy reforms, technological progress and an increase in domestic project data will be critical to lowering costs. India's few geothermal deployments are currently concentrated in remote sites that are geologically difficult when it comes to electricity generation. As a result, historical costs are not representative and should not be used as proxies for large-scale planning across all geothermal applications.

However, insights from more advanced geothermal markets show what is achievable. Emerging technologies—largely from the oil and gas sector—such as improved reservoir stimulation, modern well completion methods, and advanced thermal resource management are already reducing costs around the world.[19,20,21, 22] Recent results from Fervo Energy in the United States demonstrate significant cost improvements. Between 2022 and 2024, the costs for a well dropped by nearly half, and the time it took to drill a well fell by almost 70%.[23,24]

Advances in directional drilling, artificial intelligence (AI)-assisted site characterisation, and improved drilling fluids are similarly shortening timelines and reducing risk in the United States and Europe. These results provide a strong indication of how India can bridge its technology gaps and improve performance, especially for medium-temperature resources. More domestic deployment builds expertise and reduces costs.

The policies outlined in this report are designed to help reinforce one another and to catalyse projects, thereby reducing costs quickly. Taken together, the five recommendations in the report can support India's pursuit of energy independence, economic competitiveness, and climate resilience, helping the country meet its growing energy needs while contributing to its commitment to achieve net-zero status by 2070.

OTHER CONSIDERATIONS FOR GEOTHERMAL DEPLOYMENT IN INDIA

Building a Skilled Workforce

With each megawatt of installed capacity in geothermal, between 5 and 10 employees are needed along the value chain.[25] Thus, reaching the geothermal goals laid out in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," could create between 350,000 and 700,000 jobs. India already has a strong oil and gas industry; fortuitously, many of the skills those workers possess are applicable to geothermal. But while many existing engineering skills can be transferred to geothermal projects, to meet the goals outlined in this report, Indian workers will still need to develop some specialised knowledge in areas of geothermal exploration, drilling, and resource management. Not having enough engineering expertise may be the biggest bottleneck that could prevent India from achieving its geothermal potential. Vocational institutes and academic programmes can bridge these gaps by updating curricula, developing new training programs, collaborating with other academic institutions, and supporting industry-led initiatives, as noted in Chapter 5, "Leveraging Oil, Gas, and Mining Technologies and Workforce to Advance Geothermal in India." Seventy-five percent of oil and gas industry respondents surveyed for Chapter 5 said they expect geothermal development to increase employment in technical fields such as drilling, maintenance, plant operations, exploration, reservoir engineering, construction, equipment manufacturing, environmental monitoring, power plant operation, maintenance, and more.

TRANSFERABLE SKILL SETS FROM THE OIL AND GAS INDUSTRY

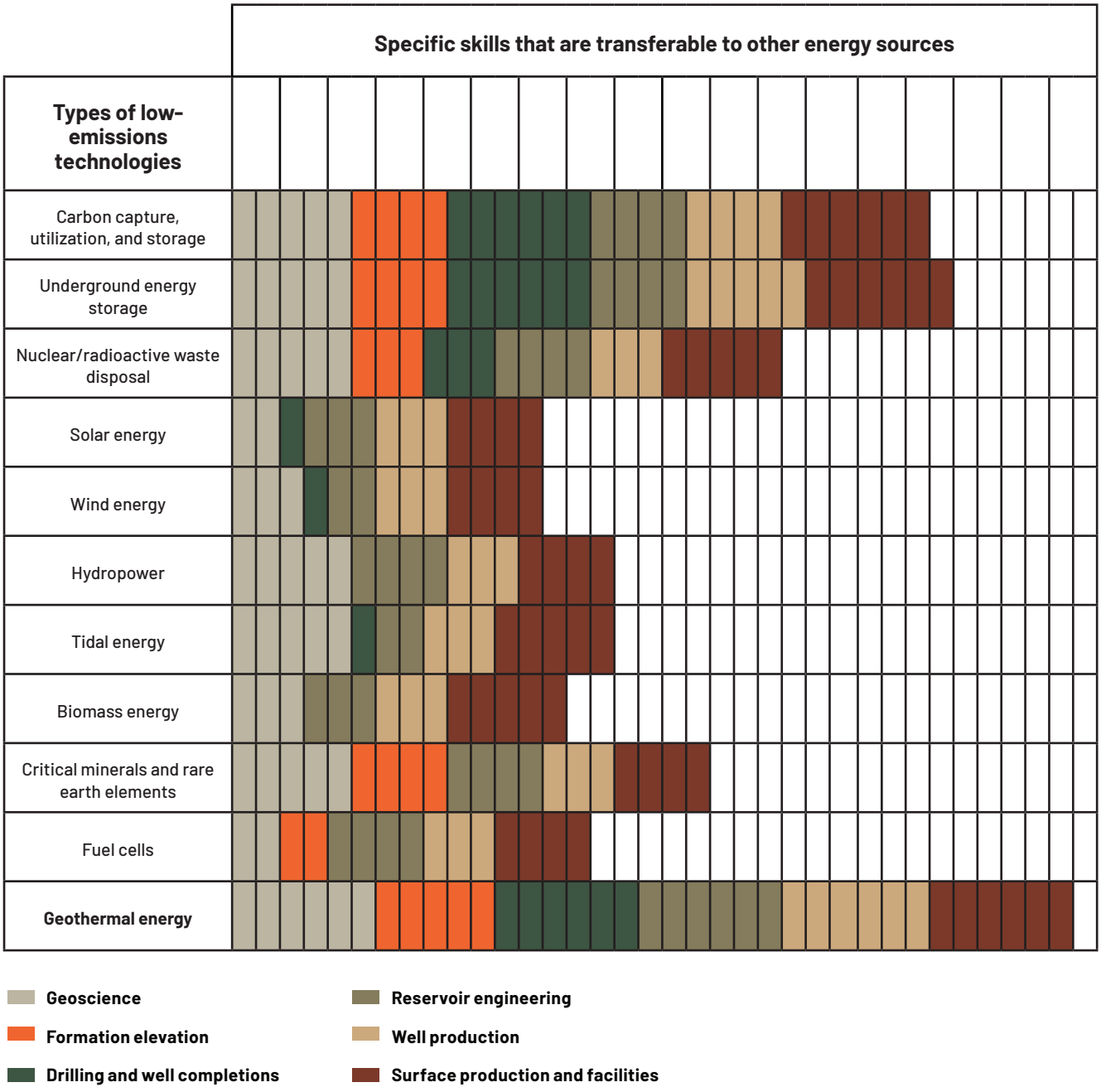


Figure ES.11: As shown, geothermal ranks highest when considering the potential impact of transferring oil and gas skills into other energy transition and low-carbon technologies. Source: Tayyib, D., Ekeoma, P. I., Offor, C. P., Adetula, O., Okoroafor, J., Egbe, T. I., & Okoroafor, E. R. (2023). *Oil and gas skills for low-carbon energy technologies*. Society of Petroleum Engineers Annual Technical Conference and Exhibition. San Antonio, TX, United States.

COMPANIES OPERATING IN INDIA'S OIL, GAS, AND MINING SECTORS

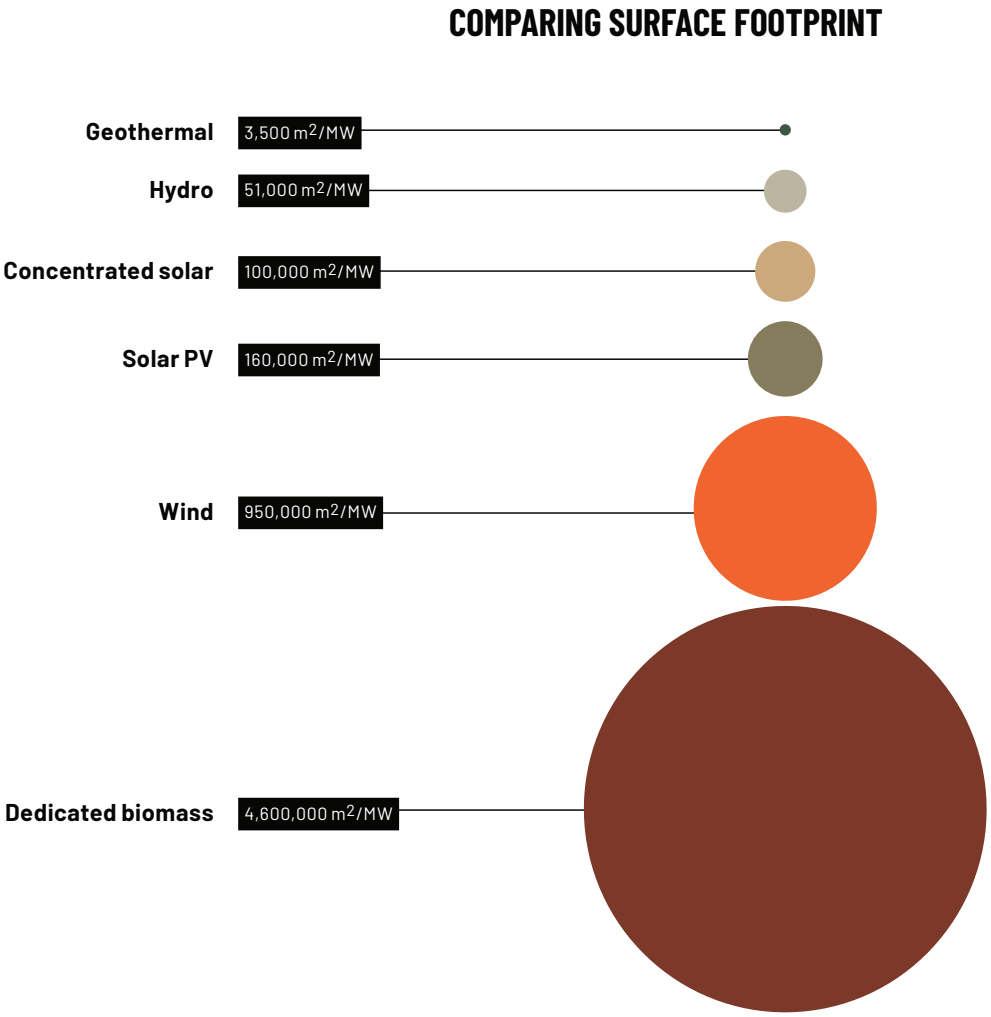
Operator Companies	Service Companies
Oil and Natural Gas Corporation Limited (ONGC)	Schlumberger (SLB)
Oil India Limited (OIL)	Baker Hughes
Coal India Limited (CIL)	Halliburton
GAIL (India) Limited	Seros
Bharat Coking Coal Limited (BCCL)	Revata Engineering
Indian Oil Corporation Limited (IOCL)	Global Drilling Fluids and Chemicals Limited
Bharat Petroleum Corporation Limited (BPCL)	Catalyst Drilling Fluids
Hindustan Petroleum Corporation Limited (HPCL)	Lotus Tricone Drill Bits
Cairn Oil & Gas (Vedanta Limited)	Gpak Offshore Services Private Limited
Reliance Industries Limited	Bergzest Energy Private Limited
Essar Oil and Gas Exploration and Production Limited	Interface Gas Consultants Private Limited
Shell	Stratom Energy Solutions
ExxonMobil	Encode Net Ventures Private Limited
Chevron	Petrosh Energia
BP	SAZ Oil

Figure ES.12: Operator and oil field service companies in India's oil, gas, and mining sectors. Source: Raj Kirana, Subsurface Energy and Storage Systems Lab, Department of Petroleum Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad.

Environmental Benefits and Management

Geothermal energy offers substantial environmental benefits. It produces little to no carbon dioxide, methane, or other pollutants. It is a powerful tool for reducing India's harmful emissions and air pollution. Compared with coal-fired power plants of similar size, geothermal plants can cut sulfur emissions by up to 97% and carbon dioxide emissions by up to 99%.[26] Geothermal facilities also have a smaller land footprint than any other renewable energy source, which helps protect natural landscapes and wildlife habitats. These facilities also use significantly less water than oil, gas, or coal—an important advantage in water-stressed regions of India.

At the same time, geothermal development requires careful environmental management. Risks include the potential for induced seismicity (earthquakes) from deep drilling and the improper discharge of drilling-related contaminants into water sources. These concerns are especially important in ecologically sensitive areas such as the Himalayas. Chapter 9, "Environmental Benefits and Considerations in India: Balancing Renewable Expansion and Ecological Stewardship in the Geothermal Sector," outlines recommendations for responsible and ethical geothermal development tailored to India's unique environments. Overall, with appropriate safeguards, expanding geothermal energy in India represents a major net environmental benefit.



Geothermal has the smallest footprint of any renewable energy source

Figure ES.13: The project surface footprint, acre for acre for 1 gigawatt of generating capacity, is smallest for geothermal compared with other renewables and coal. PV = photovoltaic. Source: Lovering, J., Swain, M., Blomqvist, L., & Hernandez, R. R. (2022). Land-use intensity of electricity production and tomorrow's energy landscape. *PLOS ONE*, *17*(7), e0270155; National Renewable Energy Laboratory (NREL). (2022). *Land use by system technology.*

CONCLUSION: SEIZING INDIA'S GEOTHERMAL OPPORTUNITY

As this report highlights, India sits on a vast and diverse geothermal resource base—from the high-temperature fields of the Himalayas to low- and medium-temperature systems across central and western India. These resources can support a wide range of valuable geothermal applications, from industrial heat, district heating and cooling, and agricultural processing to electricity generation in select high-temperature zones. By leveraging this potential, India can address both non-electric energy needs and firm renewable power requirements, complementing its solar- and wind-heavy energy system.

India's renewable energy targets include achieving 500 gigawatts of non-fossil fuel capacity by 2030—and energy independence by 2047.[27] To meet these goals, India can and should bring additional resources to the energy mix. Adding geothermal—with its continuous, low-carbon baseload power source—can make all the difference.

India can turn its geothermal potential into real projects. Policymakers, researchers, industry, and communities can align to advance exploration, modern drilling, a trained workforce, and clear and efficient rules. With that coordination, costs will fall, risks will shrink, and deployment can accelerate at the scale India needs.

By embracing this opportunity, India can make geothermal energy a cornerstone of its clean energy transition—enhancing energy security, reducing industrial emissions, and supporting regional equity. And the country can position itself at the forefront of the global geothermal transition, ensuring a reliable, domestic, affordable, and low-carbon energy future for generations to come.

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Part I

The Basics of Geothermal

Chapter 1

Geothermal 101: An Overview of New Geothermal Technologies and Applications

Project InnerSpace

Because it is hot everywhere underground, and thanks to technological developments from the oil and gas industry, we can access underground heat in many more locations than was historically possible. The potential for geothermal development across a variety of applications and use cases is now truly global.

Geothermal is a naturally occurring, ubiquitous, and clean energy source. About 6,400 kilometres from the planet's crust, the core of the Earth is roughly as hot as the surface of the sun—approximately 6,000°C (see **Figure 1.1**). Geothermal heat is present across the entire planet—on dry land and on the ocean floor—and offers enough potential energy to power the whole world thousands of times over.

Humans have tapped these heat resources for centuries: In the 19th century, people started using heat from the Earth for industrial processes like heating and cooling buildings and generating electricity. The first documented instance of geothermal electricity generation was in Larderello, Italy, in 1904.[1]

But throughout history, these conventional hydrothermal systems have been geographically limited. They require specific subsurface conditions—sufficient heat, water, and rock permeability—which are typically found in tectonically active regions such as Indonesia, Iceland, and the western United States.[2] Only when all three of these factors overlapped was there an exploitable geothermal resource. Even then, finding such a resource typically required a fourth natural phenomenon: an obvious surface manifestation, such as a geyser or hot spring.[3] The need for these specific conditions severely restricted geothermal's broader global use, as few locations met these natural requirements. India has identified 381 hot spring sites,[4] but these have not yet been translated into active electricity-generation projects—largely because most lack the full

TEMPERATURE OF THE EARTH'S INTERIOR

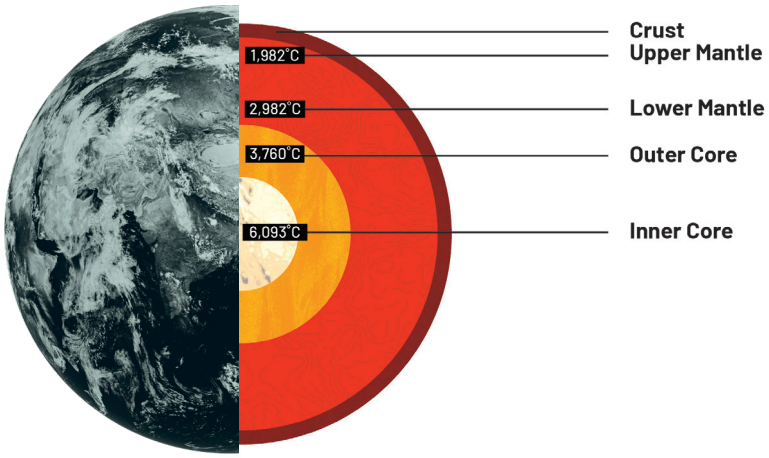


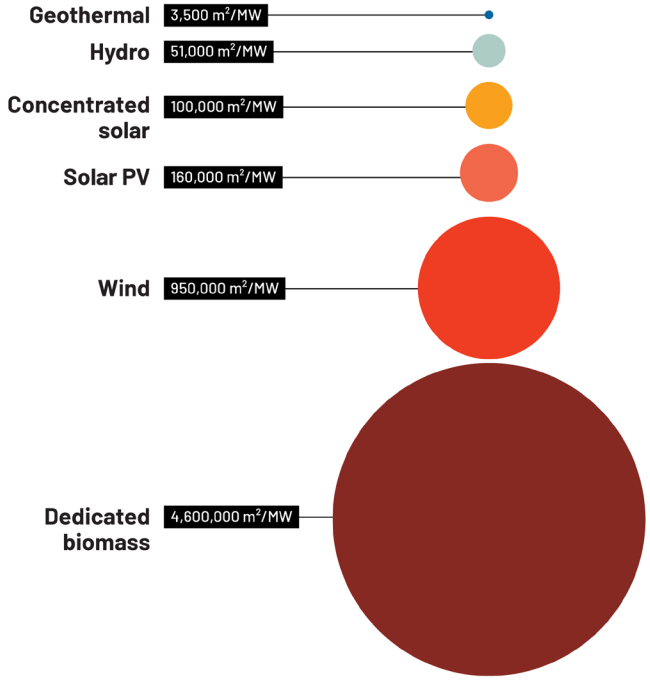
Figure 1.1: The temperature of the core of the Earth exceeds the temperature of the surface of the sun. Because the crust of Earth is an excellent insulator, enough heat is trapped beneath us to power the world hundreds of times over. Source: Project InnerSpace.

combination of natural heat, fluid, and permeability at the depth needed for traditional geothermal development.[5]

But now, adoption of geothermal for various uses can be higher in many locations as well. How? Because it is hot everywhere, and thanks to technological developments from the oil and gas sector and a new generation of geothermal entrepreneurs, we can access that heat in regions outside the limited volcanic zones—regions without traditional surface characteristics, or even without natural steam at all.

These areas include countries such as India where geothermal potential was previously thought to be low. Geothermal projects that use these new technologies are generally called *next-generation geothermal*. These new approaches—such as advanced geothermal systems and geothermal for cooling—are expanding the future of geothermal energy beyond all of the previous geographical limitations. (See "The Evolution of Geothermal: From Constraints to Possibilities" later in this chapter.)

COMPARING SURFACE FOOTPRINT



Geothermal has the smallest footprint of any renewable energy source

Figure 1.2: The project surface footprint, acre for acre for 1 gigawatt of generating capacity, is smallest for geothermal compared with other renewables. PV = photovoltaic. Source: Lovering, J., Swain, M., Blomqvist, L., & Hernandez, R. R. (2022). Land-use intensity of electricity production and tomorrow's energy landscape. *PLoS ONE*, *17*(7), e0270155; National Renewable Energy Laboratory (NREL). (2022). *Land use by system technology.*

These newer technologies—directional drilling, deeper drilling, hydraulic fracturing techniques that create additional pore space for fluid flow, more efficient drill bits, or the introduction of fluids into subsurface areas where they may not naturally be present—can be very effective for electricity generation. They can enable us to create an artificial heat reservoir.

Geothermal has the advantage of being a 24/7/365 clean baseload energy source. Unlike wind and solar, it is always on. Unlike natural gas and coal, it has no emissions or fuel costs. And unlike nuclear power, there is no need to dispose of radioactive material. Add to that, it has the smallest footprint of any power source.

GEOTHERMAL ELECTRICITY GENERATION

With these new technologies, in general, the hotter the geothermal resource, the more efficient a geothermal power plant will be at producing electricity. The more efficient the production, the lower the cost. As shown in **Figure 1.4**, geothermal electricity generation is possible with fluid temperatures as low as 93°C using "binary" cycle power plants (in other words, two fluid cycles).[6,7] In these binary plants, hot water extracted from the reservoir passes through a heat exchanger to boil a separate low-boiling-point liquid; the vapor from this liquid spins a turbine to make electricity, while the geothermal water never enters the turbine.[8] Both fluids circulate in closed loops—the working fluid is cooled and reused, and the geothermal water is reinjected—keeping emissions to a minimum while enabling power generation from low to moderate temperatures. Flash steam and dry steam electric turbines (see **Figure 1.5**) can be used when the fluid temperature rises above 180°C.[9] And some higher-temperature installations have started using novel binary-type configurations.

A report published in 2024 by the International Energy Agency (IEA) says that "the potential for geothermal is now truly global" and next-generation geothermal systems have the technical potential "to meet global electricity demand 140-times over."[10] That analysis also notes that by 2035, geothermal could be highly competitive with solar photovoltaics and wind when paired with battery storage.

Globally, heat energy makes up about half of all energy consumption and contributes to about 40% of energy-related emissions.[11] To put it another way: Clean geothermal can address almost half of the world's energy demand. Until recently, this opportunity has been almost entirely overlooked.

COMPARING CAPACITY FACTOR

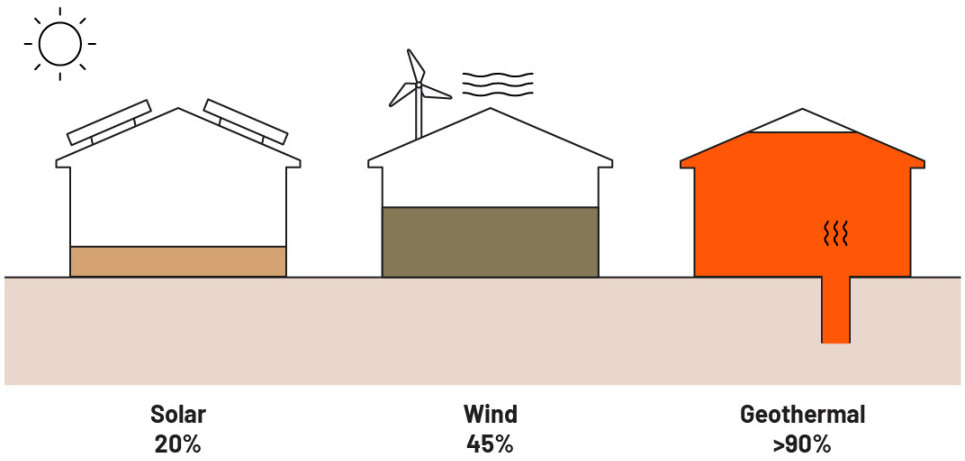


Figure 1.3: Capacity factor is the percentage of time that a power plant is generating electricity in a given day. Source: Adapted from International Energy Agency (IEA). (2024). *The future of geothermal energy*. IEA.

GEOTHERMAL APPLICATIONS AND TEMPERATURE REQUIREMENTS

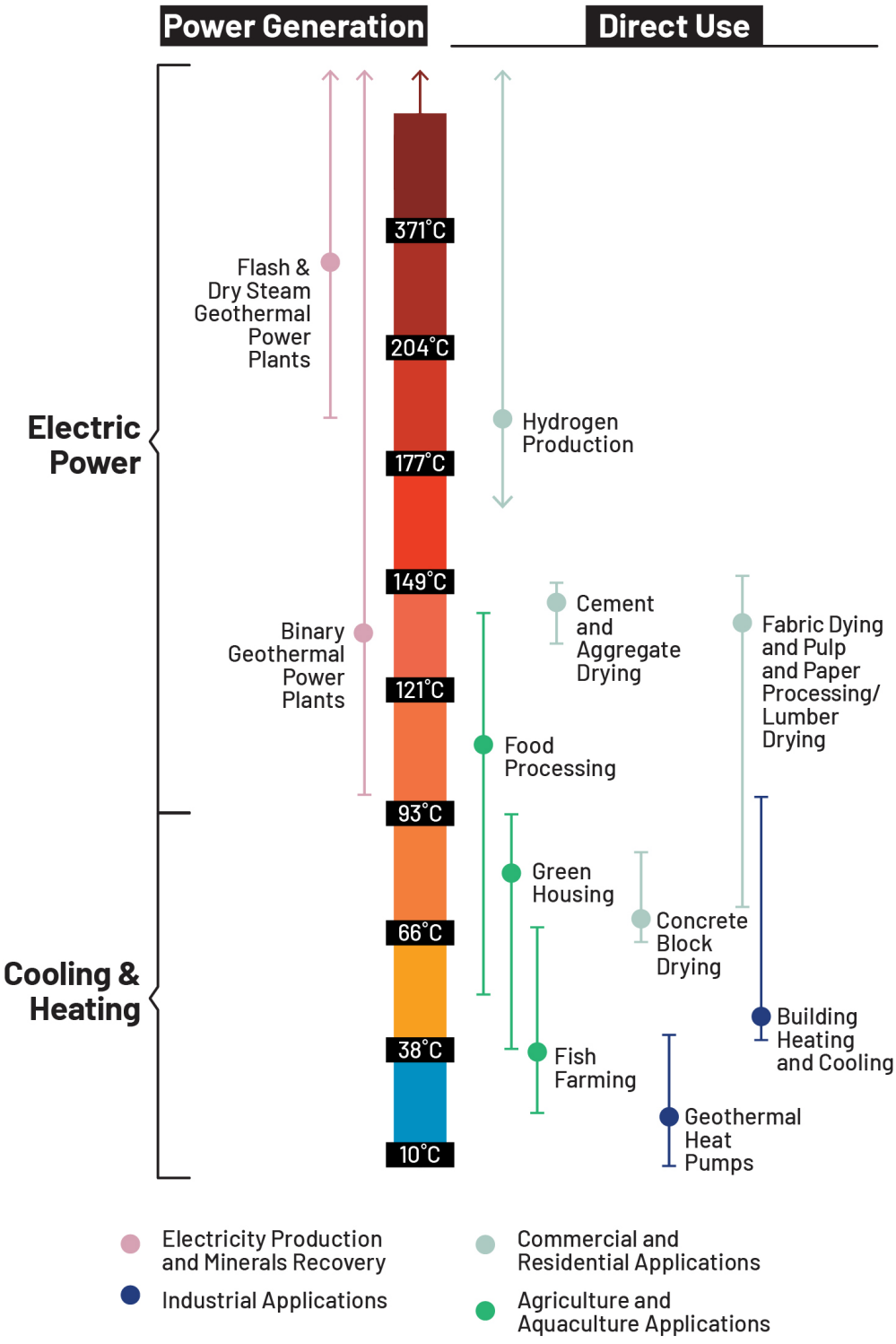


Figure 1.4: Geothermal energy can be used for generating electricity, heating and cooling homes, and manufacturing processes. There are also new and emerging applications such as geothermal energy storage, where the subsurface serves as an earthen battery, and geothermal critical minerals extraction for rare elements such as lithium. Adapted from Porse, S. (2021). *Geothermal energy overview and opportunities for collaboration.* Energy Exchange.

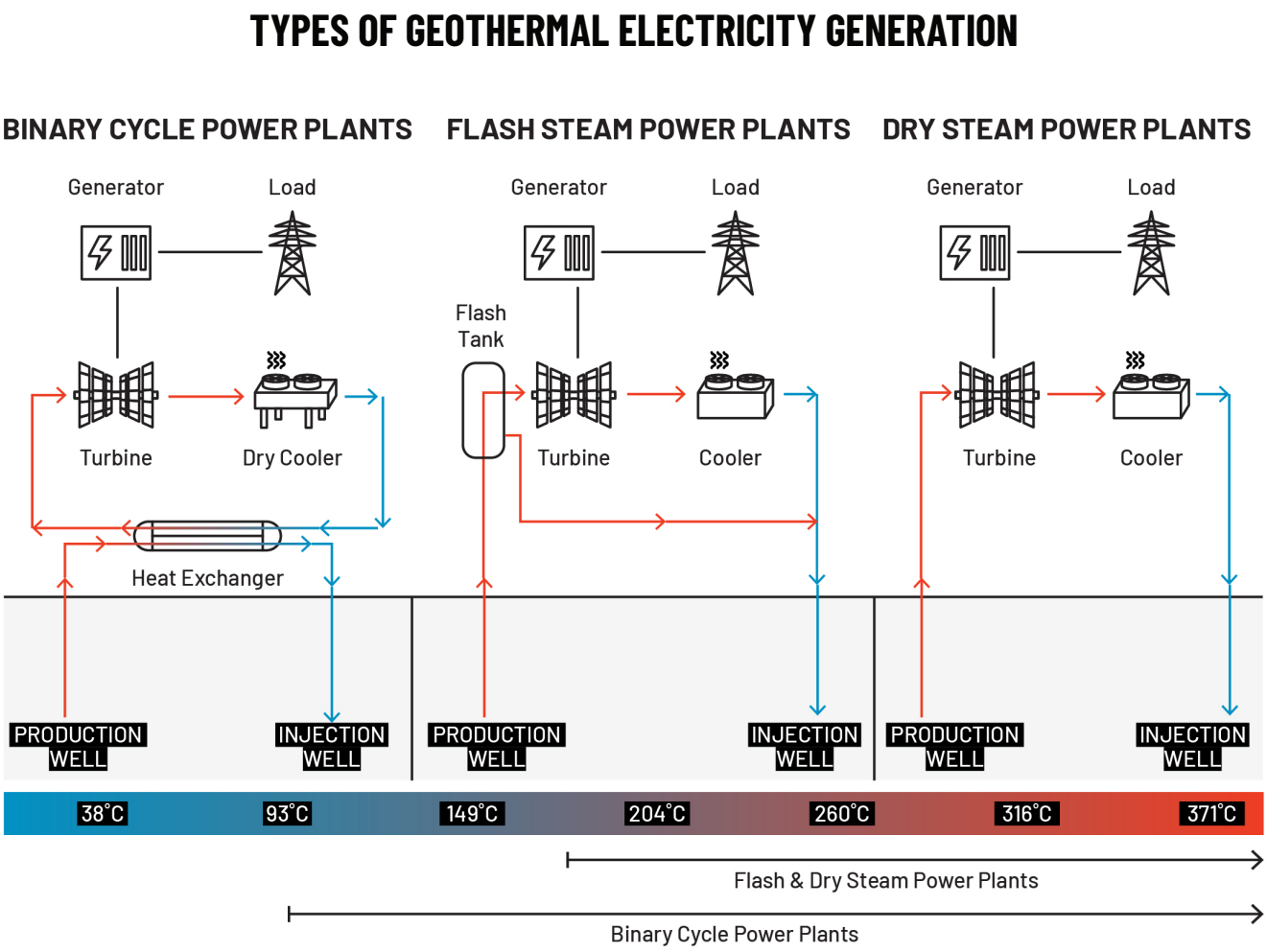


Figure 1.5: There are three primary configurations for generating electricity using geothermal: binary, flash steam, or dry steam. In general with these new technologies, the hotter the underground geothermal resource—whether conventional hydrothermal or next-generation geothermal—the more efficient the surface equipment will be at producing electricity. Binary geothermal electricity generation is possible with fluid temperatures as low as 95°C. Flash and dry steam geothermal electric turbines can be used when fluid temperature rises above ~182°C. Source: Beard, J. C., & Jones, B. A. (Eds.). (2023). *The future of geothermal in Texas: The coming century of growth and prosperity in the Lone Star State*. Energy Institute, University of Texas at Austin.

DIRECT USE: GEOTHERMAL HEATING, COOLING, AND INDUSTRIAL PROCESS HEAT

Approximately three-quarters of all heat used by humans—from building heating and cooling to industrial processes—is produced by directly burning oil, gas, and coal.[12] The rest is produced from other sources, like burning biomass, or via the electrification of heat—meaning electricity that is produced using solar, wind, or other fuels and then converted back into heat (for instance, electric strip heaters).

In India, space cooling is a fast-growing driver of energy demand. Air-conditioning accounts for 40% to 60% of peak power consumption during summer in major cities such as New Delhi and Mumbai.[13] This use of air-conditioning creates enormous strain on the electricity grid.

The good news is that geothermal technologies that can help meet this demand already exist: ground source heat pumps (geothermal heat pumps; see **Figure 1.6**), geothermal district cooling (large-scale connected heat pumps that are also known as thermal energy networks, or TENS), and absorption chillers (see the

GEOTHERMAL COOLING AND HEATING NETWORK

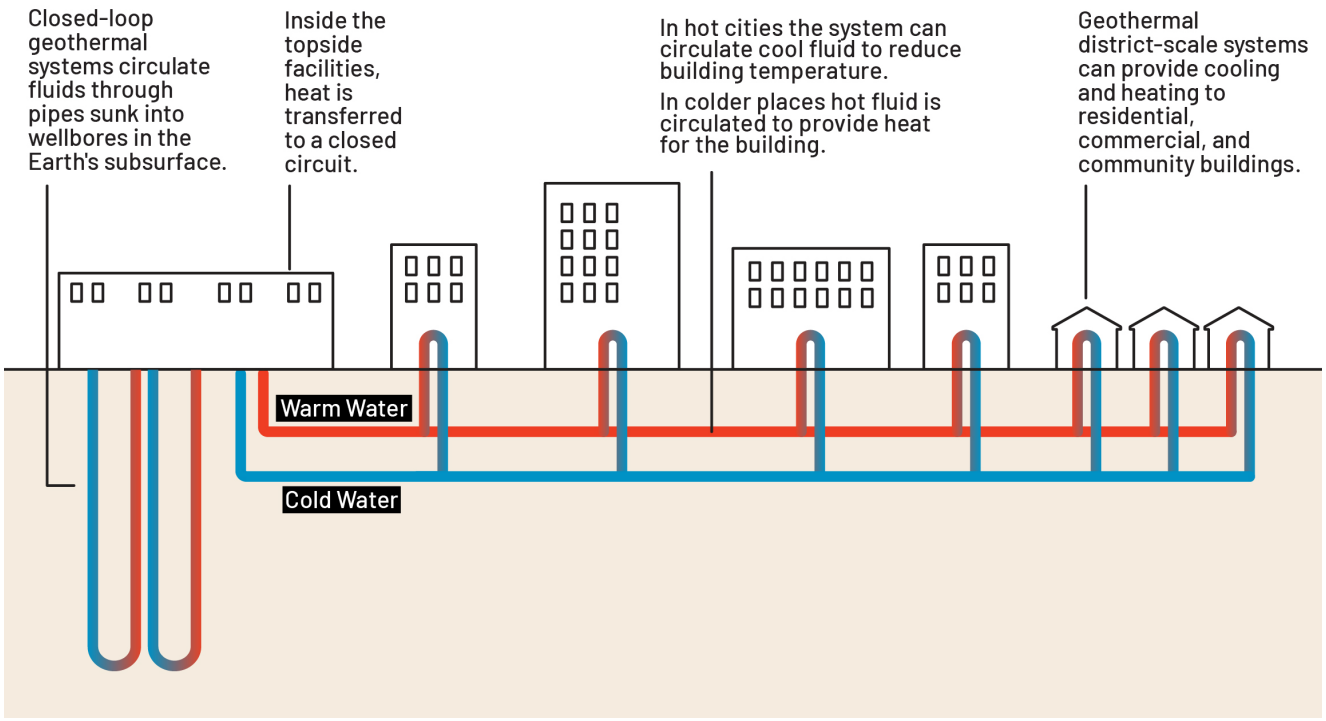


Figure 1.6: District heating system fluid is typically brought to the surface at a target temperature of around 21°C. That fluid is then passed through a heat pump to provide hot water in the winter for heating and cold water in the summer for cooling. This style of heating and cooling can be more than twice as efficient as traditional HVAC systems because the thermal load is shared between buildings. Source: Adapted from U.S. Department of Energy. *Geothermal district heating & cooling*.

chapter on direct-use geothermal in this report for more information). Implementing these solutions in India's dense urban centres could dramatically improve cooling efficiency and reduce peak load stress, given the country's high population density in cities (see more in Chapter 4, "Geothermal Cooling Opportunities").

Industrial process heat is used to make everything from pens to paper, pasteurised milk to pharmaceuticals. Four of the most critical materials in the modern world—fertiliser, cement, steel, and plastics—all require significant amounts of heat to produce. In the industrial sector, thermal consumes more than half of total energy use and contributes the majority of the sector's emissions.[14]

In India, industrial heat demand is enormous: The country is the world's second-largest producer of crude steel and cement,[15] and these industries rely heavily on coal and other fossil fuels for high-temperature heat. Geothermal heat could offer a cleaner alternative for some of these processes, helping to decarbonise India's industrial sector.

All building cooling and heating (heating, ventilating, and air-conditioning; HVAC) and 30% of heat used for manufacturing processes worldwide use temperatures below 150°C.[16] In many parts of the world, geothermally derived heat at this temperature is currently comparable in cost with coal, biomass, solar, and wind. The IEA report estimates that next-generation geothermal could economically satisfy 35% of all global industrial thermal demand for processes requiring temperatures below 200°C. The use of next-generation geothermal could thus save about 750 megatons of carbon dioxide (CO_2) emissions—equivalent to the annual emissions of Canada, the world's 12th-largest emitter.[17] **Figure 1.7** illustrates the range of sectors

INDUSTRIAL PROCESS TEMPERATURES AND HEAT PUMP TECHNOLOGIES

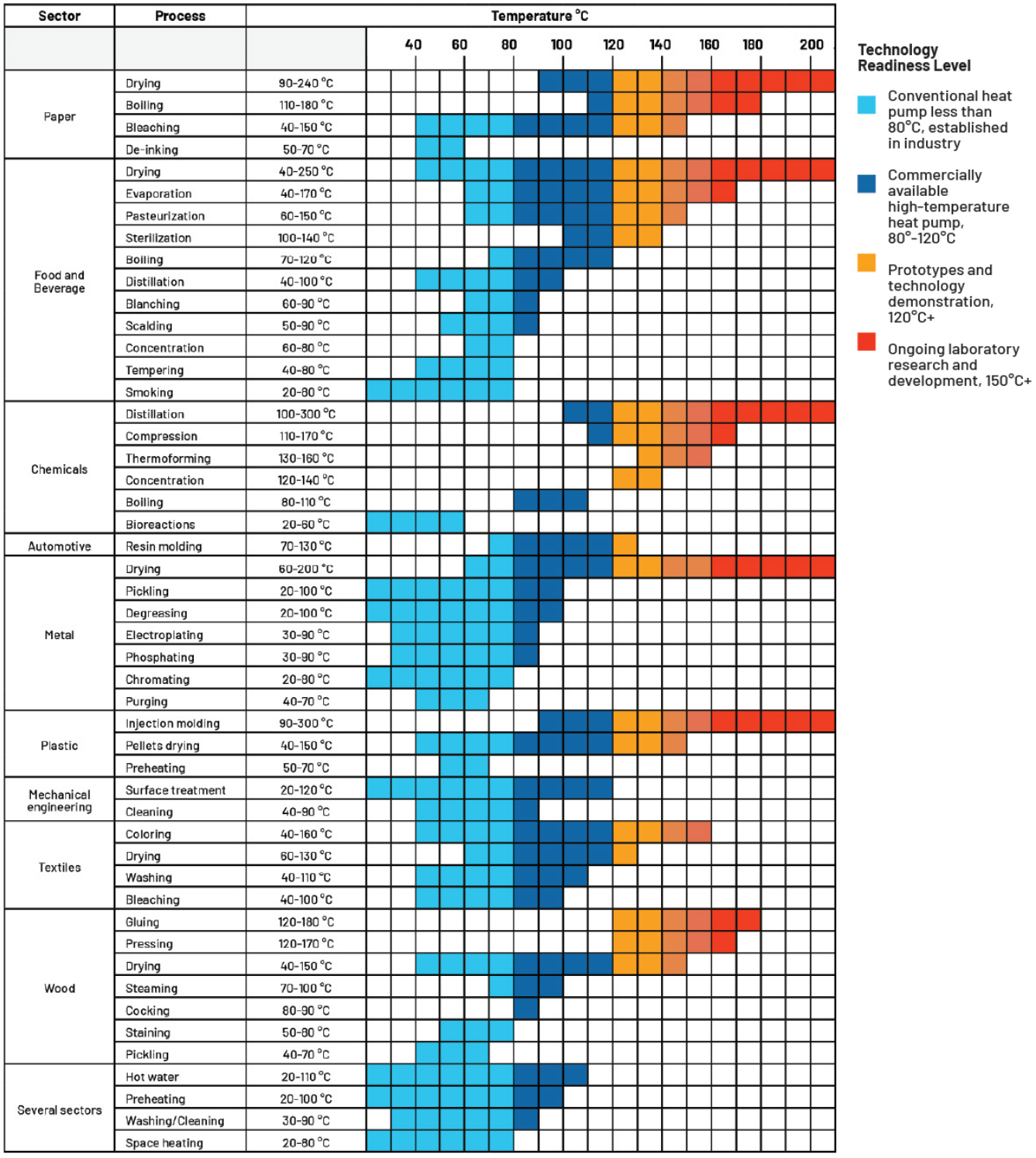


Figure 1.7: Rough technology readiness levels of high-temperature heat pumps as of July 2023. Geothermal can enable industrial processes without heat pumps; however, combining the two technologies may prove even more useful. High-temperature industrial heat pumps above 100°C have seen significant advances in recent years. Source: Arpagus, C., et al. (2023). *Industrial heat pumps: Technology readiness, economic conditions, and sustainable refrigerants*. American Council for an Energy-Efficient Economy (ACEEE).

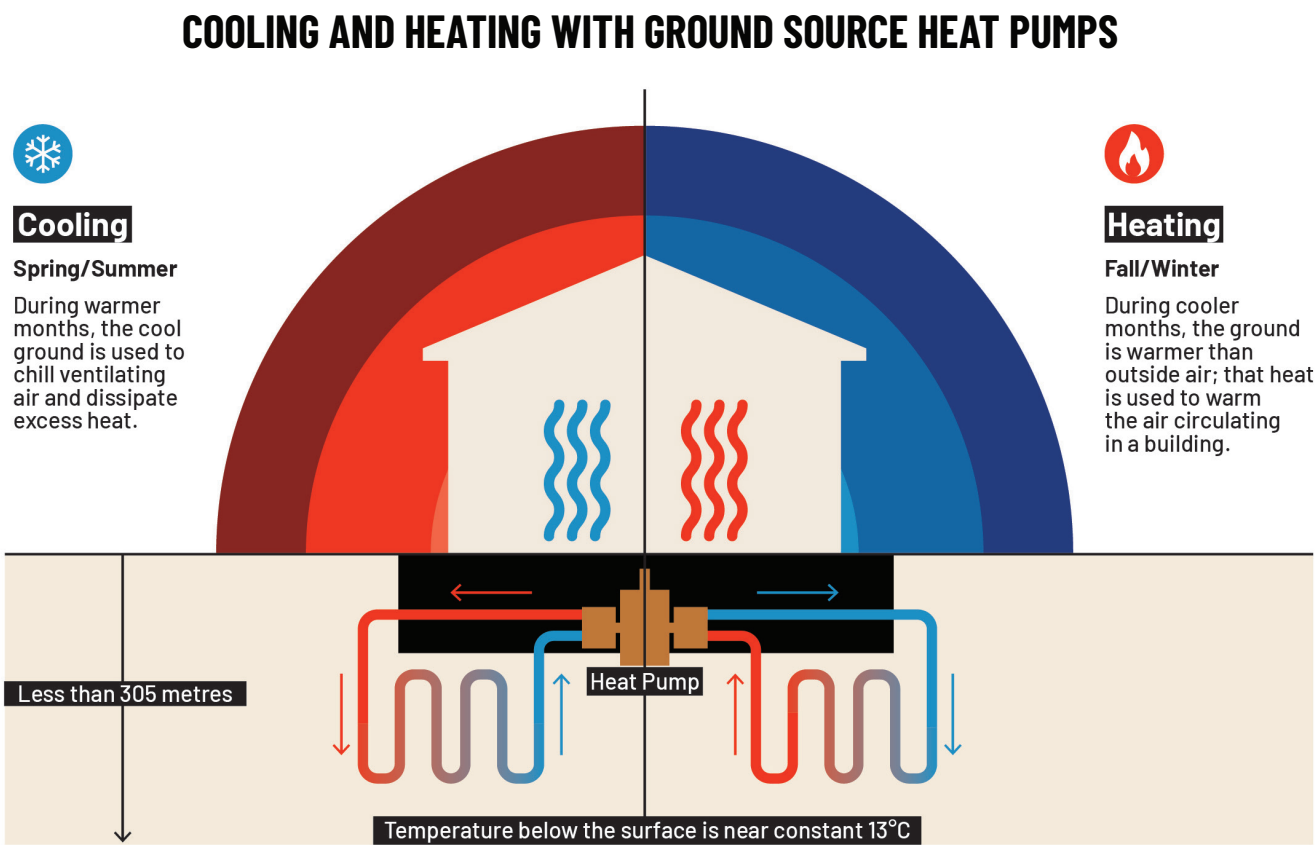


Figure 1.8: The constant temperature of the ground helps improve the efficiency of ground source heat pumps relative to other HVAC methods. Source: Beard, J. C., & Jones, B. A. (Eds.). (2023). *The future of geothermal in Texas: The coming century of growth and prosperity in the Lone Star State.* Energy Institute, University of Texas at Austin.

and processes that could use geothermal heat, with or without heat pumps, depending on whether a facility can reach the necessary heat at a reasonable subsurface depth.

Beyond space conditioning, geothermal energy can be used for refrigeration and commercial cooling operations, via a technology known as an absorption chiller. Absorption chillers are cooling systems that mainly use heat instead of electricity to drive refrigeration.

As illustrated in **Figure 1.9**, low-pressure liquid ammonia draws heat out of a cold storage or air-conditioned space, turning the ammonia into low-pressure vapor. This vapor is then absorbed by water, creating an ammonia solution, which is then pumped to a generator. There, geothermal heat can be used to boil the pressurised ammonia solution into high-pressure ammonia vapor, which will reject the heat into a cooling tower and turn it into low-pressure liquid ammonia to repeat the cooling cycle again.

By harnessing the Earth's heat in this way, absorption chillers provide cooling without the need for conventional electric compressors or burning fossil fuels. For India, where cooling already constitutes between 40% and 60% of peak electricity demand in major cities,[18] geothermal absorption chillers offer a sustainable solution to meet the nation's refrigeration and air-conditioning needs while easing the power grid burden and reducing greenhouse gas emissions.

GEOTHERMAL ENERGY STORAGE

The modern electricity grid is a delicate, vital system requiring constant monitoring to balance electricity production against electricity demands. With more

HOW ABSORPTION CHILLERS WORKS

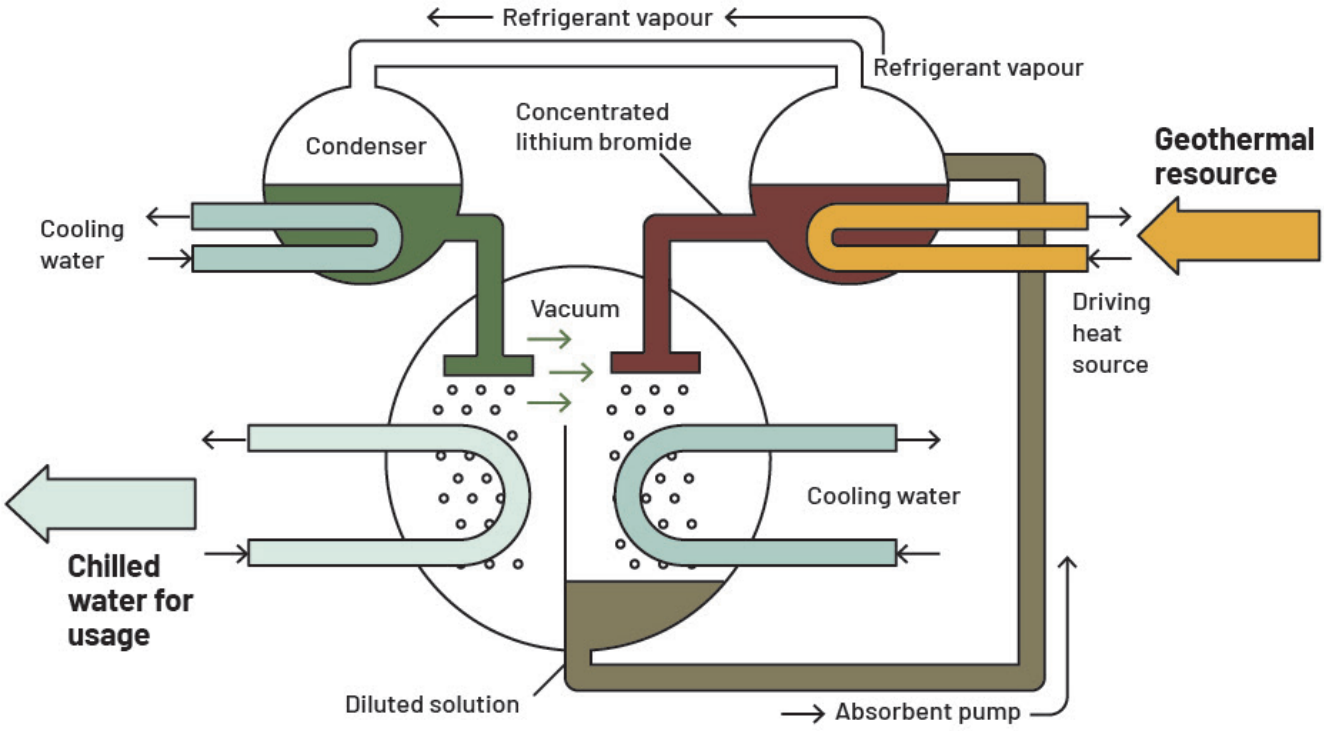


Figure 1.9: Absorption chillers use heat (like hot water or steam) instead of electricity to drive a cooling cycle, using a pair of fluids that work together to create refrigeration. Instead of using an electric compressor, they rely on a salt solution—commonly lithium bromide (LiBr)—that absorbs and releases water vapour, enabling the cycle to run using heat. The hot water provides the energy to keep this process going, which makes a refrigerant evaporate and pull heat out of water—creating a chilled water stream for cooling. Source: Project InnerSpace.

electrons flowing onto the grid from intermittent energy sources such as wind and solar—which are only available when the sun shines or the wind blows—concerns about having power when needed have highlighted the need for energy storage.[19] Today, pumped hydroelectric storage provides most global energy storage capacity,[20] and recent years have seen a significant expansion in the deployment of batteries for energy storage. A new approach, underground thermal energy storage, also known as *geothermal energy storage* (GES), may offer an additional option.

GES systems capture and store waste heat or excess electricity by pumping fluids into natural and artificial subsurface storage spaces (aquifers, boreholes, mines). GES can be primarily mechanical, with hydraulic fracturing techniques storing pressurised fluid in subsurface reservoirs. Or it can be mechanical and thermal, with pressure and heat combined to return more energy than was required to pump the fluid underground.

CRITICAL MINERALS EXTRACTION

Fluids, or brines, are often produced from geothermal systems. These brines are rich in dissolved minerals, including lithium, which can be harvested to meet the growing demand for lithium-ion batteries in electric vehicles and electric-grid storage solutions. This dual-purpose approach—providing clean energy and a domestic lithium source—could reduce lithium extraction's environmental impact compared with traditional mining and improve the economics of a geothermal project.

TRANSFERABLE SKILL SETS FROM THE OIL AND GAS INDUSTRY

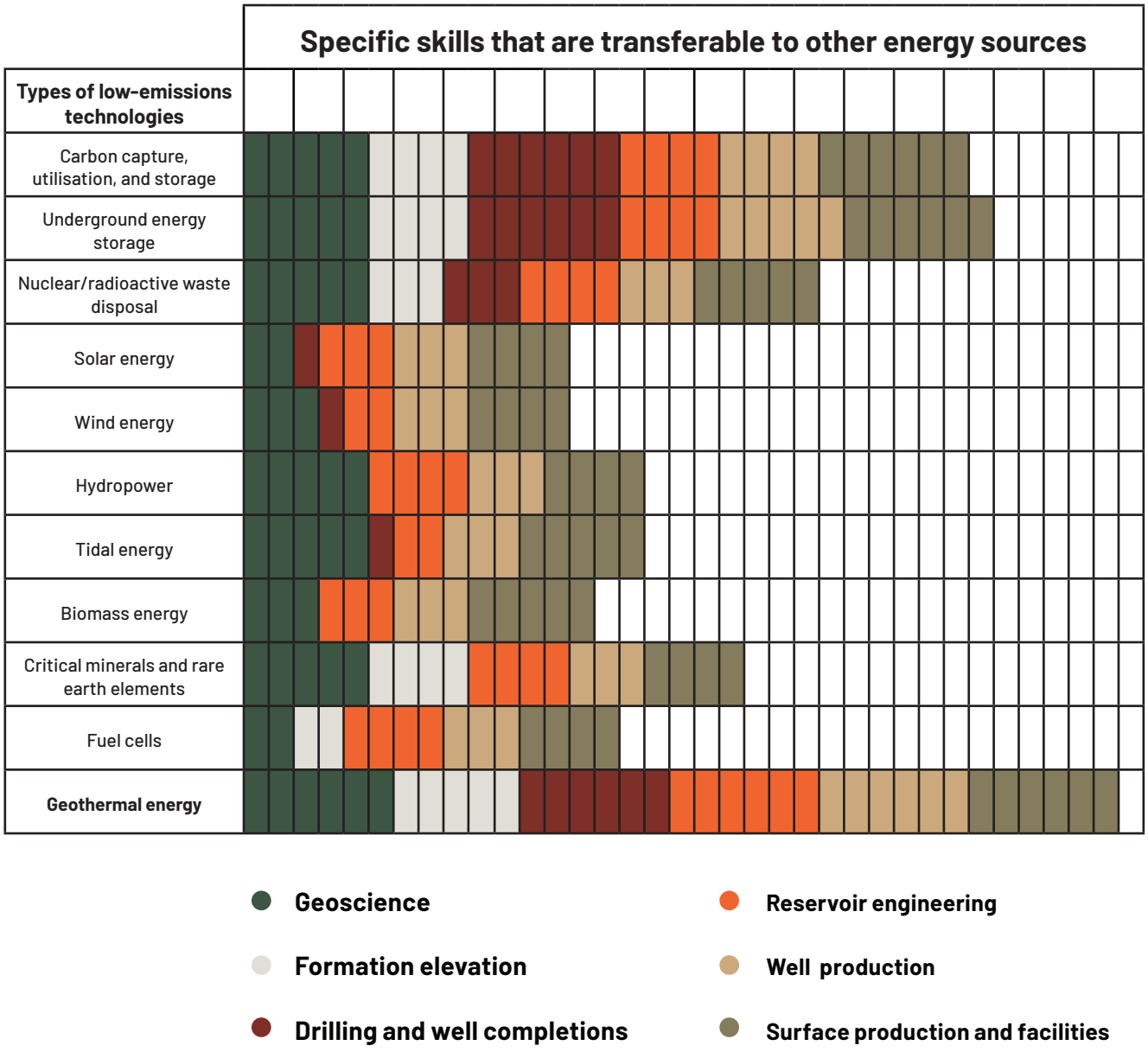


Figure 1.10: As shown, geothermal ranks highest when considering the potential impact of transferring oil and gas skills into other energy transition and low-carbon technologies. Source: Tayyib, D., Ekeoma, P. I., Offor, C. P., Adetula, O., Okoroafor, J., Egbe, T. I., & Okoroafor, E. R. (2023). *Oil and gas skills for low-carbon energy technologies*. Society of Petroleum Engineers Annual Technical Conference and Exhibition.

Globally, some geothermal fields are beginning to explore lithium co-production. At California's Salton Sea geothermal field, for example, studies indicate that co-production could support extremely large lithium output, with one analysis suggesting up to 600,000 tonnes of lithium per year could eventually be produced from brines there.[21] This kind of effort, also being piloted in places such as Indonesia and Germany,[22,23] shows that geothermal brines can be transformed from a nuisance (by causing mineral scaling in pipes) into a valuable resource. For India, which currently imports most of its lithium for batteries, future geothermal projects could integrate direct lithium extraction to provide a domestic supply of this critical mineral.

THE EVOLUTION OF GEOTHERMAL: FROM CONSTRAINTS TO POSSIBILITIES

As shown in **Figure 1.11**, the Earth's crust contains more potential thermal energy than is present in all fossil fuels and natural nuclear fissile material combined. The challenge, then, is how to identify the areas and technologies that can tap into that potential energy most efficiently and economically.

Figure 1.13 summarises the latest geothermal extraction technologies. The following sections describe these technologies in greater detail.

Advanced geothermal system (AGS): Like an engineered geothermal system (EGS), AGS eliminates the need for permeable subsurface rock. Instead, AGS creates and uses sealed networks of pipes and wellbores closed off from the subsurface, with fluids circulating entirely within the system in a "closed loop."

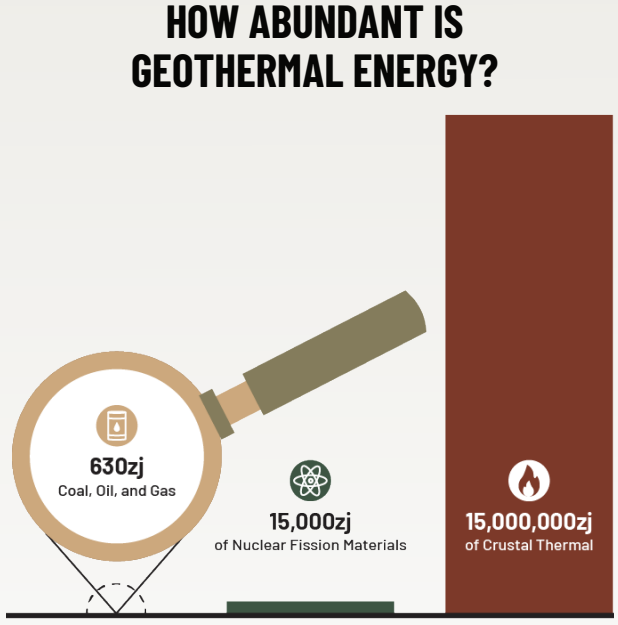


Figure 1.11: Total heat energy in Earth's crust, compared to that contained in fossil fuels and naturally occurring fissile materials. Note that total fossil fuels, when compared with crustal thermal energy, is the equivalent of less than one pixel at the bottom of the graphic, shown magnified to illustrate scale. Measurements in zettajoules ("zj"). Source: Beard, J. C., & Jones, B. A. (Eds.). (2023). *The future of geothermal in Texas: The coming century of growth and prosperity in the Lone Star State*. Energy Institute, University of Texas at Austin. Adapted from Dourado, E. (2021). *The state of next-generation geothermal energy.*

Today, many AGS geothermal well designs are in development, including single well, U-shaped well "doublets" with injection and production wells, and subsurface radiator designs. All of these designs use only their own drilled pathways; none require a conventional hydrothermal resource or hydraulic fracturing to create fluid pathways.

All geothermal energy extraction relies on conduction, the heat transfer from hot rock to fluid (see "Geothermal Geology and Heat Flow" for more details). Thus, unlike EGS, which benefits from the substantial surface area created by hydraulic fracturing, AGS has only the walls of its wells to conduct heat. As such, AGS must drill deeper, hotter, or longer well systems than EGS to conduct similar amounts of heat energy. Because AGS does not exchange fluids with the subsurface, it can more easily use engineered, nonwater working fluids, such as supercritical CO_2. Along with advances in technology, AGS is also being scaled for use in industrial-size projects. XGS Energy and Meta recently partnered to construct a first-of-its-kind 150 megawatt AGS power plant in the United States that will target approximately 250°C hot rock to deliver power for data center projects in New Mexico.[24]

AGS can be developed in virtually any geological condition with sufficient subsurface heat. While AGS guarantees a more definitive pathway for fluid flow in the subsurface relative to fracked EGS wells, drilling sufficiently long and deep AGS wells can be challenging and expensive.

Engineered geothermal system (EGS): This kind of system uses both directional drilling and hydraulic fracturing to create artificial permeability, allowing for the use of geothermal energy far beyond the regions with naturally occurring hydrothermal. EGS extracts heat by introducing fluids into the subsurface, breaking open fissures in relatively impermeable rock, and circulating fluid between one or more wells. The more fractures there are, the greater the surface area for the flowing fluid to conduct heat from rock.

Although the EGS was conceived as early as the 1970s,[25] its scalability has only been possible because of cost reductions and technological advances in drilling and fracturing techniques commercialised by the oil and gas industry over the past few decades. However, unlike

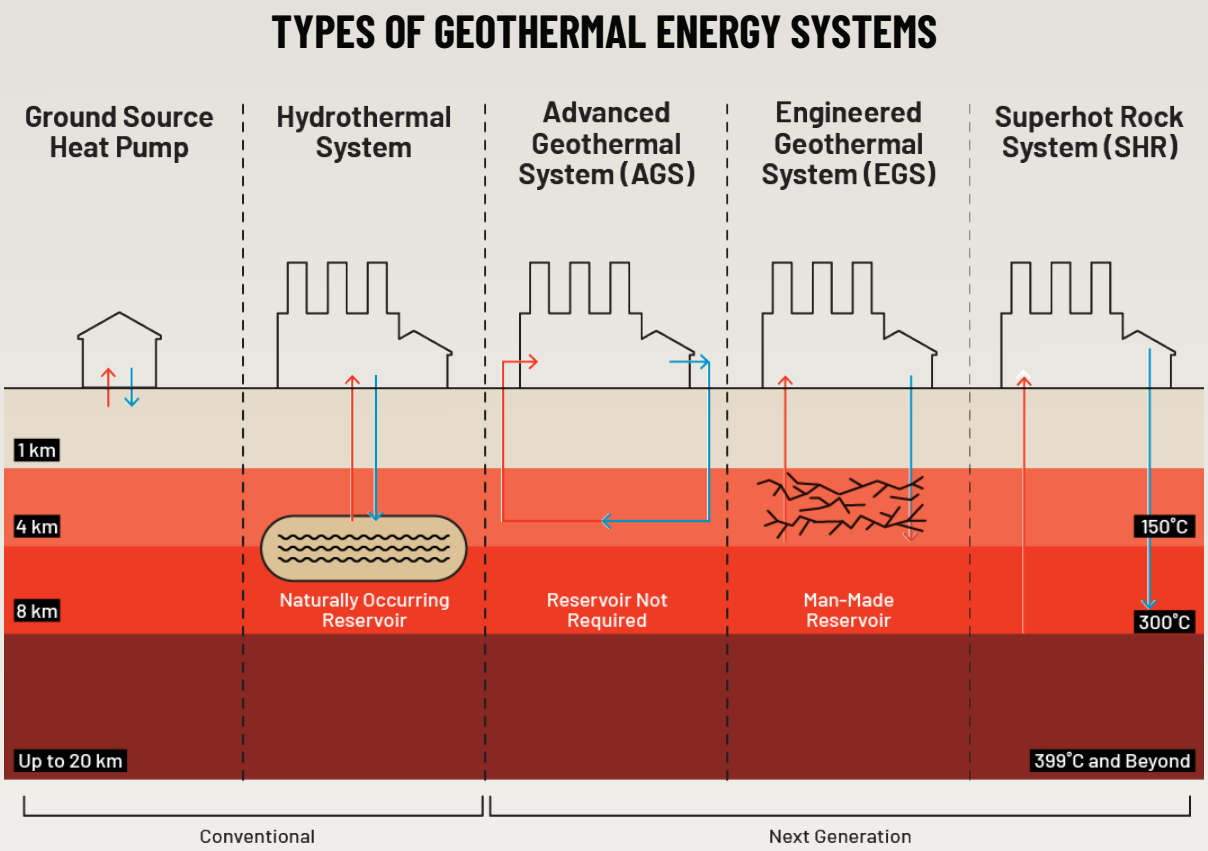


Figure 1.12: Comparison of key geothermal power generation technologies illustrating variations in resource type and heat extraction method for electricity production and industrial direct use. Ground source heat pumps (GSHPs) are also shown, illustrating a building heating scenario. In the GSHP scenario, fluid flow can be reversed to provide cooling. Source: Adapted from D'avack, F., & Omar, M. (2024). *Infographic: Next-generation technologies set the scene for accelerated geothermal growth*. S&P Global.

hydraulically fractured oil and gas wells—which are only intended for one-way extraction of oil and gas—EGS is designed to reuse fluids, so the same liquid flows continuously through hot rock in a convective loop.

EGS generally targets shallow hot-rock formations with few natural fractures and limited natural permeability to minimise uncontrolled fluid loss. Well depths can vary depending on where sufficient temperatures and appropriate stress conditions are found.[26]

Fracturing methods are subject to some uncertainty; even the most accurate engineering model cannot perfectly predict how a subsurface rock will crack or how fluids will flow. Because most of India is not located on active volcanic rift zones and lacks abundant naturally permeable high-enthalpy reservoirs, EGS and other engineered approaches could be key long-term strategies for tapping the country's geothermal energy. While India's few known hydrothermal sites can be developed conventionally, much of the nation's geothermal potential lies in "conduction-dominated" resources that would need EGS or AGS technologies to exploit. See Chapter 2, "Where Is the Heat? Exploring India's Subsurface Geology," for more information.

Superhot rock (SHR): SHR is a type of next-generation geothermal that targets extremely deep, high-pressure rocks above approximately 373°C, the temperature at which water goes supercritical. SHR has the potential to revolutionise power production globally with superheated, supercritical geothermal steam capable of highly efficient heat transfer from the subsurface. Theoretically, SHR can employ either EGS or AGS well technologies, but no commercial SHR geothermal project has yet been developed because advances are needed in drilling technologies, rates, and costs to enable the economically competitive development of this next-generation concept.[27]

GEOTHERMAL GEOLOGY AND HEAT FLOW

The movement of heat from Earth's hot interior to the surface—what geologists call *heat flow*—is controlled by the geology of the planet. Heat from the core and mantle, as well as the decay of naturally occurring radioactive deposits in the Earth's crust, combine and emanate toward the surface of the planet.

Conduction, Advection, Convection, and Radiation

Heat flow in the Earth results from physical processes that contribute, to varying degrees, to the available heat in a geothermal resource.

- **Conduction:** The transfer of energy between objects in physical contact through molecular vibrations without the movement of matter. Conduction is efficient in some materials, like metals, and inefficient in others. Rock is a relatively poor conductor, but conduction is nonetheless considerable in the interior of the Earth.
- **Advection:** The transfer of heat due to the movement of liquids from one location to another. In geology, advection occurs in the movement of magma and groundwater, where the fluid carries heat as it moves through cracks, fractures, and porous rock formations. Advection is different from conductive heat transfer, which relies solely on direct contact between particles to transfer heat.
- **Convection:** A cycle of heat transfer involving conduction and advection that occurs when matter is heated, becomes less dense, rises, cools, increases in density, and sinks. Convection typically creates circulating loops of rising and sinking material. The Earth's mantle is almost entirely solid but behaves as a highly viscous fluid, thus allowing for convective heat transfer. The mantle's movement is extremely slow relative to human life but becomes significant over geologic periods.
- **Radiation:** Energy that moves from one place to another as waves or particles. Certain areas in the Earth's crust have higher concentrations of elements with natural radiation, such as uranium-238, uranium-235, thorium-232, and potassium-40.

Geology and Energy Extraction

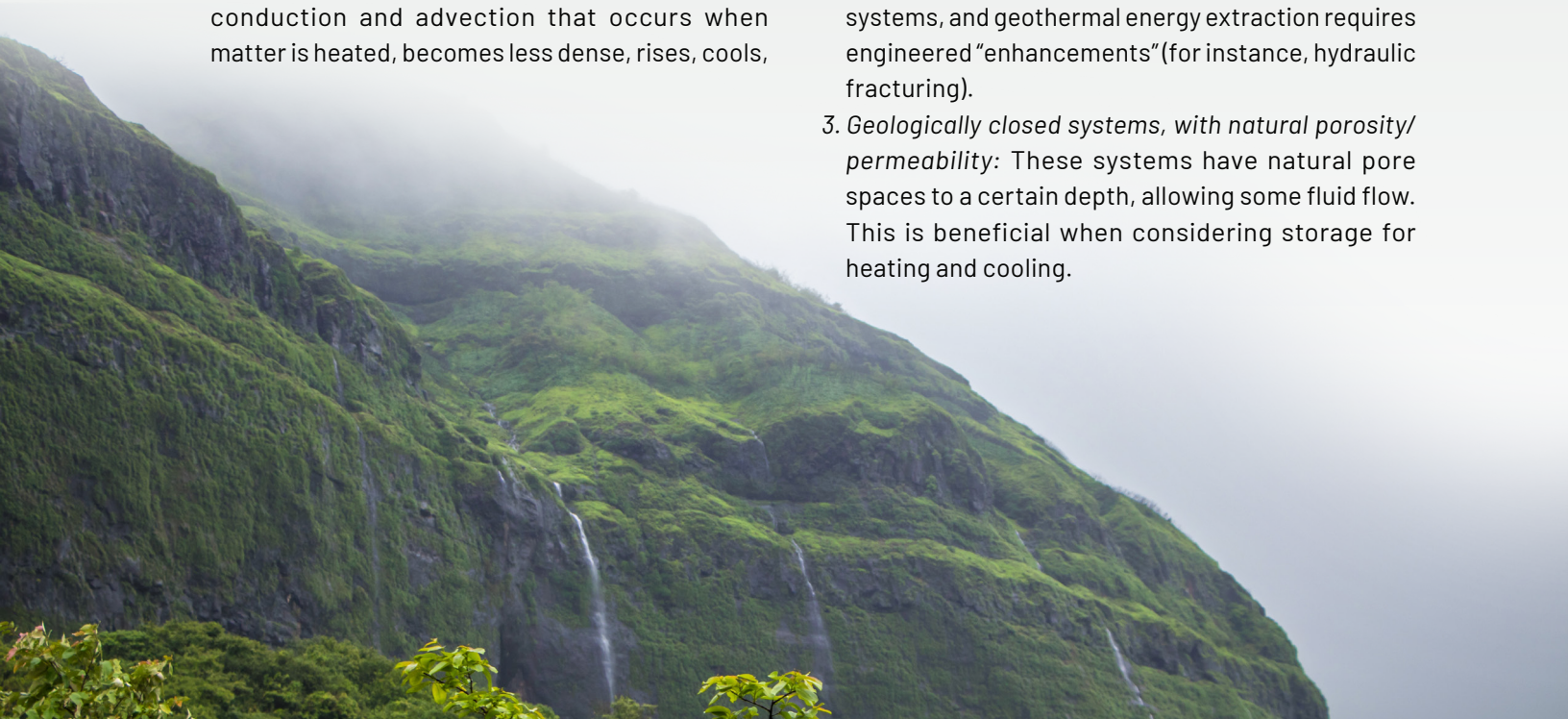
The geological processes described previously interact to contribute to geothermal energy extraction under three common geological settings:

Convection-Dominated

1. *Geologically open geothermal systems:* In these systems, water circulates freely (such as in the Great Basin in the United States). These systems are typically targeted for power generation and open-loop heat.

Conduction-Dominated

2. *Geologically closed systems, with limited porosity/permeability:* Water does not flow naturally in these systems, and geothermal energy extraction requires engineered "enhancements" (for instance, hydraulic fracturing).
3. *Geologically closed systems, with natural porosity/permeability:* These systems have natural pore spaces to a certain depth, allowing some fluid flow. This is beneficial when considering storage for heating and cooling.



COMPARISON OF EXISTING AND EMERGING GEOTHERMAL TECHNOLOGIES AND CONCEPTS

Existing Geographies, Applications, and Technologies			
	Conventional Hydrothermal Geothermal	District Heating	Ground Source Heat Pumps
Basic Concept	Relies on natural hydrothermal systems with hot water and porous rock	Provides heating through interconnected building networks, using centralised geothermal systems	Uses shallow ground temperature stability to heat and cool buildings
Working Fluid	Naturally occurring fluids	Water or steam circulated through centralised pipes to buildings	Typically, water or antifreeze or refrigerant in a closed-loop system
Reservoir Type	Open to natural hydrothermal reservoir	Central reservoir supplying district buildings with hot water or steam	Closed-loop system buried at shallow depth
Geological Requirements	Natural hot aquifers in porous rock formations	Typically, sedimentary aquifers but can be used near conventional geothermal systems such as Iceland	No special geology; suitable for almost any location
Temperature Range	150°C - 350°C	Generally, around 80°C-100°C	All ranges
Drilling Depth	Shallow or deep, depending on hydrothermal location	Shallow to medium depth, depending on temperature requirements	Very shallow, typically between 3 metres and 152 metres for residential to deeper for industrial heat pumps
Scalability	Limited to those few regions with natural hydrothermal conditions	Scalable anywhere concentrated clusters of buildings can share interconnected hot water or steam	Highly scalable; can be installed almost anywhere
Environmental Impact	Lower impact but dependent on natural resource conditions	Low impact; minimal drilling required and low emissions	Minimal impact; closed system without subsurface interaction
Examples of Use	Traditional geothermal power plants, direct-use heating in regions with hydrothermal conditions	Geothermal district heating in Iceland, Paris, and some U.S. cities	Commonly used for residential and commercial building heating and cooling but increasing in use for industrial heat when combined with industrial heat pumps
Primary Advantages	Established technology in areas with existing hydrothermal resources	Efficient and cost-effective heating for multiple buildings in urban or suburban networks	Proven, simple, reliable system for year-round building climate control and a key technology for data center cooling
Challenges	Limited to specific geographical areas with natural conditions	High initial setup cost, complex infrastructure needed to connect multiple buildings	Higher upfront cost relative to conventional HVAC

Figure 1.13: Existing and new geographies, applications, and technologies.

New Geographies, Applications, and Technologies			
	Superhot Rock	Sedimentary Geothermal System	Engineered Geothermal System
Basic Concept	Exploits extremely high temperatures at great depths	Utilises sedimentary rock formations that may contain hot water in pores; can involve low-porosity rocks	Uses hydraulic fracturing to create artificial permeability for heat extraction
Working Fluid	Water, potentially reaching supercritical state	Typically, water from aquifers in sedimentary rocks; may require pumped circulation	Recirculates same fluid (water or otherwise) through fractures in hot rock
Reservoir Type	Open, targeting superhot rock	Open, with naturally porous and permeable rock acting as the reservoir for fluid flow	Open to reservoir with engineered fractures
Geological Requirements	High temperatures (above 373°C)	Sedimentary rock formations with some porosity and permeability for water flow	Requires heat and engineered permeability; benefits from high rock surface area for heat transfer
Temperature Range	373°C + (targeting supercritical steam)	Can vary (from low ~ 20°C to >200°C)	Typically, 50°C -300°C
Drilling Depth	Significant depth (potentially 10+ kilometres)	Variable depth range, from 500 metres to 8,000 metres	Typically < 3,000 metres, as high pressure and high drilling would incur additional costs
Scalability	Potentially scalable with improved deep-drilling technology	Scalable; 73% of continental land mass contains sedimentary basins	Scalable with advances in hydraulic fracturing and drilling but potentially limited to areas where hot dry rock is < 3,000 metres and does not contain natural fractures that will increase uncertainty and potential fluid losses
Environmental Impact	High-impact drilling; needs tech improvements for feasibility	Typically low	Possible induced seismicity, depending on geology; significant water use despite reuse of working fluid
Examples of Use	Experimental; no large-scale deployment yet	Residential and industrial heat applications: Southampton, United Kingdom; Paris	U.S. Department of Energy's FORGE project, Fervo's Project Red in Utah
Primary Advantages	High efficiency in power generation due to superheated steam	Cost-effective and scalable, particularly in well-explored basins. Stacked aquifer systems mean these basins could supply tiered geothermal, ranging from low-temp direct use to higher-temp electricity generation—and geothermal energy storage.	Unlocks geothermal potential in non-ideal rock formations with artificial permeability
Challenges	High-cost drilling; significant research and development required	Limited to areas with sufficient sedimentary rock in basins with moderate temperatures	Subsurface unpredictability in fracturing; possible seismic risks; high initial costs; high water use

New Geographies, Applications, and Technologies			
	Advanced Geothermal System	Geothermal Cooling	Thermal Storage
Basic Concept	Closed-loop system with no fluid exchange with subsurface	Uses ground or subsurface temperatures to provide cooling in buildings or industrial processes	Stores thermal energy in subsurface reservoirs for later use in heating, cooling, or power generation
Working Fluid	Circulates fluid (water, supercritical CO_2, or otherwise) entirely within sealed, engineered system	Water or refrigerant circulated to transfer cool temperatures to buildings	Water or other heat-transfer fluid for thermal storage; optimal recovery in pressurised reservoirs
Reservoir Type	Closed to reservoir; uses sealed pipes and engineered pathways	Closed or open loop with pipes in shallow ground, utilising ground cooling	Closed underground reservoirs or aquifers for energy storage, utilising natural or engineered pathways
Geological Requirements	No permeability needed; functions anywhere with heat availability	Generally, no special requirements; suitable for most shallow grounds with stable temperatures	Requires subsurface space with adequate pressure retention for heat and energy storage
Temperature Range	Variable; typically requires hotter rock (> 100°C) to achieve competitive heat extraction	Utilises both the shallow natural ground temperature (~13°C) for cooling purposes and the deep ground temperature with absorption cooling technology	Flexible; can be adapted for seasonal thermal storage or for high-temperature dispatch
Drilling Depth	Potentially deeper to access high heat, as system is inherently limited in the surface area available for conductive heat transfer	Both shallow, typically between 3 metres and 152 metres, as cooling requires lower temperatures, and deeper >100°C with absorption cooling technology	Depth varies; can be shallow for seasonal storage or deep for high-temperature storage
Scalability	Scalable, as system is independent of subsurface permeability	Scalable for residential, commercial, and industrial applications	Scalable; suitable for integration with renewable sources for energy balancing
Environmental Impact	Low impact; closed system with no interaction with surrounding rock fluids	Minimal impact; closed-loop systems ensure no ground contamination	Low impact; relies on pressure management for safe thermal storage
Examples of Use	Various closed-loop designs in development, technologies such as Eavor-Loop and GreenFire Energy's GreenLoop	ADNOC, in collaboration with the National Central Cooling Company PJSC (Tabreed), has initiated operations at G2COOL in Masdar City, Abu Dhabi.	Underground thermal energy storage, borehole thermal energy storage, and aquifer thermal energy storage
Primary Advantages	No fluid exchange with subsurface; suitable for areas lacking natural aquifers	Cost-effective cooling in regions with high air conditioning demand; reduces HVAC costs; could be used to optimise data center cooling	Provides energy storage to balance renewable power and support grid stability
Challenges	Expensive drilling costs; reduced heat transfer area compared with EGS; requires wells to touch more rock for heat exchange	Installation and initial costs; suitable ground area needed for installation	Requires specific geological settings for pressure control; drilling costs can be high

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Part II

Geothermal Resources and Applications in India

Chapter 2

Where Is the Heat? Exploring India's Subsurface Geology

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More than one-quarter of India's extraordinary and diverse topography could be used for either geothermal power or direct-use heat. This chapter pinpoints the regions across the nation with the most promising geothermal resources, including the high-potential Himalayan fields, western rift systems, and eastern-central fault-controlled basins.

India's diverse terrain is well suited to geothermal energy development, but the resource remains largely untapped. India has more than 11,000 gigawatts of direct-use industrial heat potential (with a 100°C cutoff temperature down to 3,500 metres) and more than 1,500 gigawatts of geothermal cooling potential. It also has technical potential for roughly 450 gigawatts of electricity generation (down to 5 kilometres) today and more than 8,000 gigawatts of electricity (down to 7 kilometres) as technology improves.[1]

Despite this potential, efforts to develop large-scale geothermal projects have faltered due to high costs of exploratory drilling and detailed geophysical investigations. To address these issues, we assessed India's geothermal resources using a weighted overlay analysis of geological data sets. This approach focuses time, effort, and expenditures on areas with the most potential, enabling more efficient planning and decision-making, while drilling and on-site investigations remain essential for confirming resource viability.[2,3] Our method integrates multiple geological, geophysical, and tectonic data sets—including data covering proximity to thermal springs, fault systems, seismicity, lithology, heat flow, Moho depth (the boundary between Earth's crust and its mantle), and shear wave velocities—to identify favourable zones for geothermal energy production. The analysis classifies geothermal potential by application type, identifying areas suitable for high-temperature power generation, potential power generation, direct use and direct heating, low-temperature industrial heating and cooling, and geothermal heating and cooling.

Of these areas, northern, western, and northeastern India all demonstrate potential for geothermal electricity, with promising prospects in the states of Ladakh, Himachal Pradesh, Uttarakhand, Rajasthan, Gujarat, Maharashtra, Madhya Pradesh, Sikkim, Arunachal Pradesh, and Meghalaya. All of these regions exhibit favourable subsurface thermal regimes and geotectonic conditions that make them excellent candidates for geothermal exploitation.

Strikingly, more than one-quarter of India's land area shows potential for geothermal electricity generation, direct use, and direct heating, with significant moderate-temperature resources, while a smaller proportion contains high-temperature geothermal resources suitable for power generation.

This analysis confirms that geothermal energy is a crucial pillar in India's future renewable energy mix and provides a scientifically grounded way to prioritise target areas. It also underscores just how much geothermal can accelerate India's development of a resilient, renewable, and non-polluting energy system, ultimately improving both national energy security and grid stability.

This chapter provides a comprehensive assessment of India's geothermal potential. A weighted overlay analysis integrating eight geological and geophysical parameters was used to generate information about application potential across India (**Figure 2.1**). The analysis and resulting categorisation were then cross-checked against real-world observations, including thermal springs, to confirm the model's validity. The resulting map shows geothermal potential by application type, identifying areas suitable for high-temperature power generation, potential power generation, direct use and direct heating, low-temperature industrial heating and cooling, and geothermal heating and cooling.

GEOTHERMAL APPLICATION POTENTIAL ACROSS INDIA, CLASSIFIED BY APPLICATION TYPE

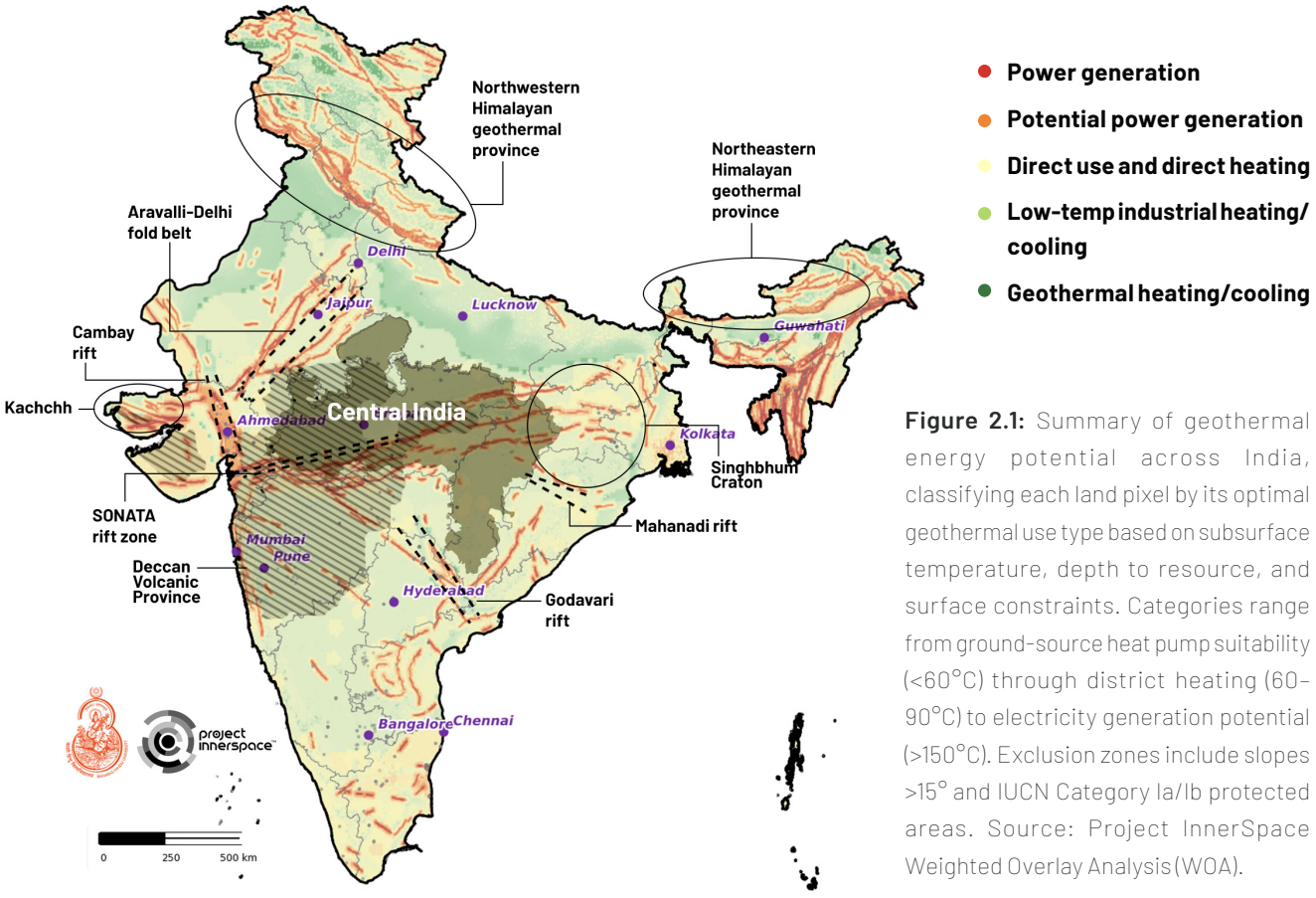


Figure 2.1: Summary of geothermal energy potential across India, classifying each land pixel by its optimal geothermal use type based on subsurface temperature, depth to resource, and surface constraints. Categories range from ground-source heat pump suitability (<60°C) through district heating (60–90°C) to electricity generation potential (>150°C). Exclusion zones include slopes >15° and IUCN Category Ia/Ib protected areas. Source: Project InnerSpace Weighted Overlay Analysis (WOA).

Regions with the highest potential for electricity generation include the Himalayan geothermal province (both the northwestern and northeastern segments), the Aravalli Delhi Fold Belt, the Kachchh and Cambay rifts, the SONATA rift zone, select zones of the Deccan Volcanic Province, the Singhbhum Craton, central India, and segments along the western coast, as well as the Mahanadi and Godavari rift systems (**Figure 2.1**). All of these areas display physical and thermal characteristics that make them excellent prospects for generating geothermal electricity.

GEOLOGY OF INDIA

The Indian subcontinent has a long and complex geodynamical evolution spanning billions of years and characterised by the association of stable Archean cratonic blocks, Proterozoic mobile belts, intracratonic sedimentary basins, and extensive Phanerozoic volcanic provinces (**Figure 2.2**). Architecturally, these cratons are underlain by thick, refractory, and buoyant lithospheric keels that extend into the subcontinental mantle lithosphere, giving it significant thermomechanical stability. These lithospheric roots serve as tectonic anchors, rendering the cratonic interiors less susceptible to subsequent deformation.[4] During the Proterozoic era, the Indian continental crust experienced multiple inter-cratonic collisions, giving rise to prominent suture and mobile belts such as the Aravalli Delhi Fold Belt (ADFB), the Eastern Ghats Mobile Belt (EGMB), and the Satpura Mobile Belt (SMB; **Figure 2.2**).[5,6] These mobile belts are tectonic imprints of Proterozoic orogenesis and serve as fundamental structural discontinuities.

As a result of this complex geotectonic history, the Indian subcontinent has developed a substantial number of thermal springs—more than 300—that serve as surface manifestations of deeper hydrothermal geothermal systems (**Figure 2.3**). These thermal springs are largely concentrated along the Proterozoic mobile belts, rift zones, and major suture zones that define the lithospheric architecture of the Indian subcontinent (**Figure 2.2**). Similarly, geothermal provinces such as the Himalayan geothermal belt, the Sohana and Cambay grabens, the Godavari and Mahanadi rifts, the West Coast region, and the SONATA lineament zone are aligned along structurally weak zones and tectonic discontinuities, as expected (**Figure 2.2**).

Past initiatives by the Geological Survey of India (GSI) have helped characterise these zones through heat flow mapping, fluid geochemistry, and reservoir temperature estimations. Detailed geophysical and geochemical investigations have also revealed high geothermal gradients and subsurface thermal anomalies, particularly in regions such as Puga-Chumthang (Himalayas), Tatapani (Chhattisgarh), and Unai (Gujarat), indicating the presence of significant hydrothermal geothermal reservoirs.

Today, these hydrothermal geothermal systems embedded within ancient cratons, mobile belts, and active collision zones hold immense promise for sustainable energy development, and they should be a high priority for advanced structural, thermal, and geophysical modelling.

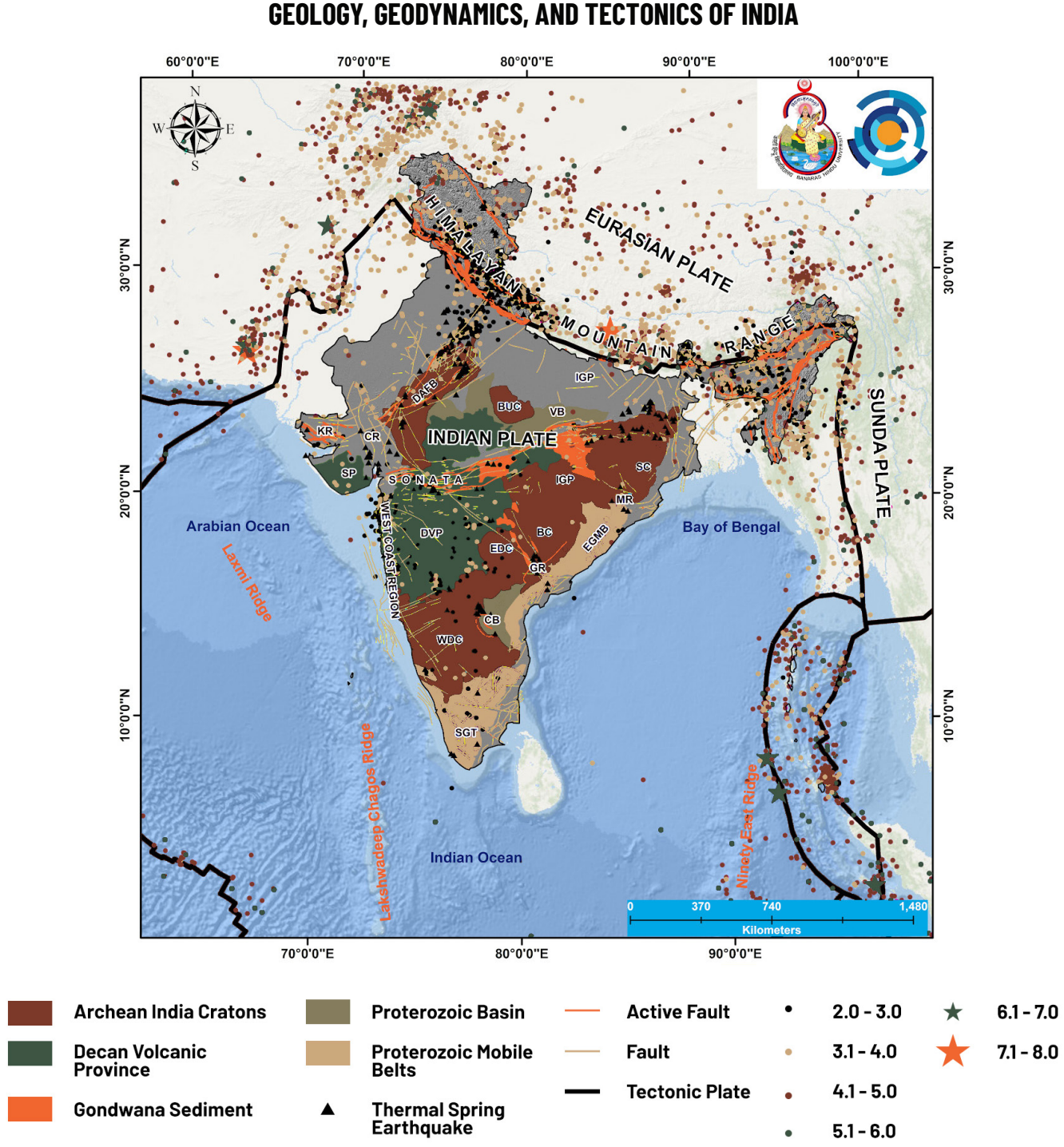


Figure 2.2: This figure shows the geological and tectonic framework of India, highlighting the Precambrian cratons, volcanic regions, the Proterozoic basins, and the nearby Cenozoic basins. Shallow earthquakes (at depths of less than 10 kilometres) in India and its neighbouring regions are shown. ADFB = Aravalli Delhi Fold Belt; BC = Bastar Craton; BUC = Bundelkhand Craton; CB = Cuddapah basin; CR = Cambay rift; CTB = Chhattisgarh Basin; DVP = Deccan Volcanic Province; EDC = Eastern Dharwar Craton; EGMB = Eastern Ghats Mobile Belt; GR = Godavari rift; IGP = Indo-Gangetic Plain; KR = Kachchh rift; MR = Mahanadi rift; SC = Singhbhum Craton; SGT = Southern Granulite Terrain; SHP = Shillong Plateau; SP = Saurashtra peninsula; VB = Vindhyan Basin; WDC = Western Dharwar Craton. Sources: Hasterok, D., Halpin, J. A., Hand, M., Collins, A. S., Kreemer, C., Gard, M. G., & Glorie, S. (2022). *New maps of global geologic provinces and tectonic plates* [Preprint]. *Earth Science Reviews*. EarthArXiv; National Center for Seismology. (2023). *Data portal*. Ministry of Earth Sciences, Government of India.

AN OVERVIEW OF THE MAP LAYERS

This section provides details of each map layer's variation and suitability score classification.

Proximity to Thermal Springs

Thermal springs represent the most direct and observable surface expression of underlying geothermal systems, as they reflect the accessibility of deep-seated heat to the surface through permeable geological structures. Productive geothermal systems are closely associated with these springs so long as the two are in close proximity. Empirical studies conducted in northern Japan indicate that approximately 97% of geothermal wells are located within a 4 kilometre radius of thermal springs.[7] Similar geothermal assessments across Iran and Africa have likewise found that areas within 5 kilometres of thermal springs have the highest geothermal potential. In this study, proximity to thermal springs was reclassified into six suitability classes, with locations within 2 kilometres receiving the highest score (5) to indicate that they were the most suitable for geothermal and those beyond 6 kilometres classified as the least suitable (score = 0; see also **Figures 2.3** and **A.3**).

Proximity to Active Faults

Active faults play a critical role in geothermal systems by acting as high-permeability conduits for the migration of heat and hydrothermal fluids from deeper crustal levels to the surface.[8,9] Their presence significantly enhances a region's geothermal potential, particularly where recent

GEOTHERMAL SUITABILITY BASED ON PROXIMITY TO THERMAL SPRINGS

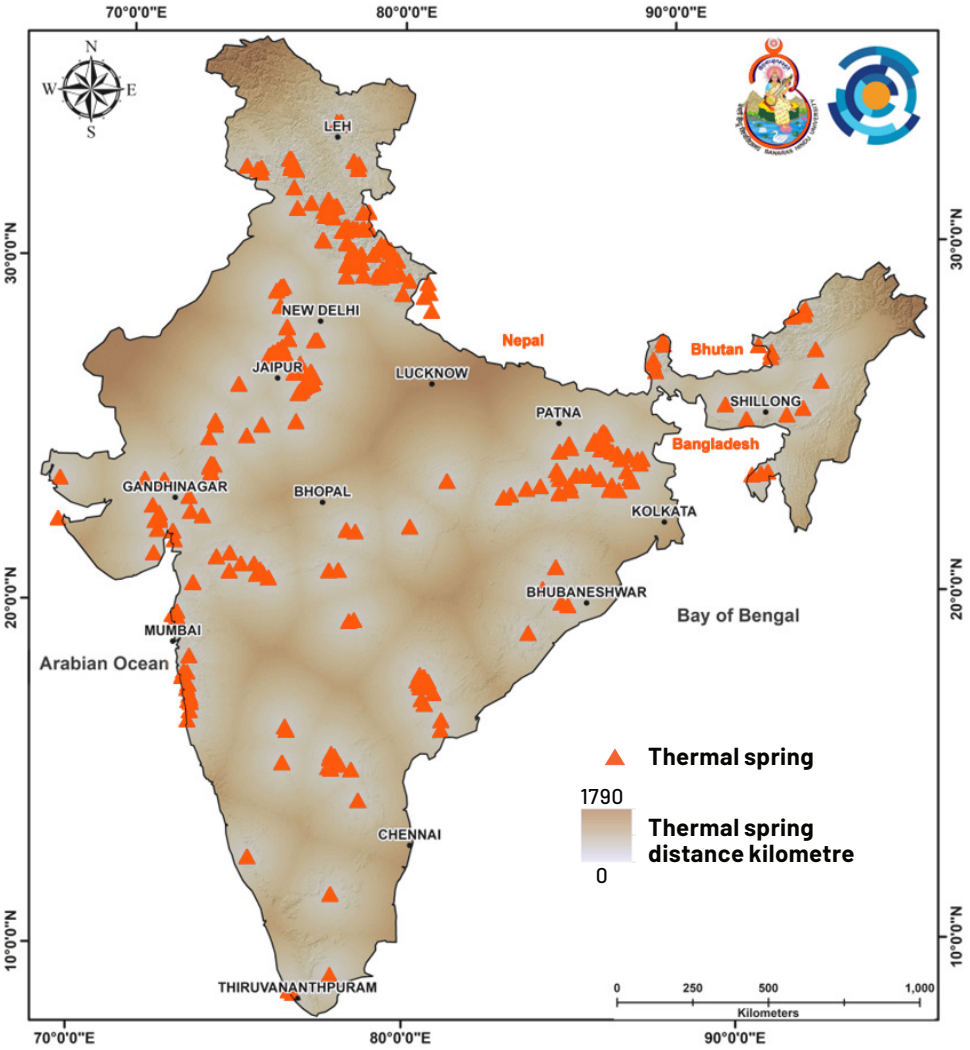


Figure 2.3: Proximity to geothermal springs. Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace; Tamburello et al., 2022; Craig et al., 2013; Das et al., 2022; Sinha, 1980; Dhirendra et al., 1992; Bajpai & Narayan, 2005; Singh et al., 2014; Gurav et al., 2015; Dutta et al., 2023; Pandey & Raymahashay, 1981. (See full source information in the conclusion to this chapter.)

tectonic activity maintains fracture connectivity and fluid circulation.[10,11,12] Areas in close proximity to active faults are therefore prioritised in geothermal suitability mapping, as they facilitate enhanced convective heat transfer. Empirical studies have also consistently shown that geothermal manifestations such as thermal springs and fumaroles are frequently aligned with active fault traces due to their structural permeability.[13] India exhibits a good distribution of active faults along the Himalayan arc, in northeast India, and in isolated segments across the central (along SONATA), western (along the Kachchh rift and ADFB), and southern regions—areas that coincide with higher geothermal gradients and thermal spring occurrences (**Figure 2.4**). In this study, zones within 2 kilometres of active faults were assigned the highest suitability score (5), while regions located beyond 10 kilometres received the lowest score (0), reflecting their diminished influence on geothermal fluid migration (**Figures 2.4** and **A.3**).

Proximity to Major Fault Lines

The circulation of water from atmospheric precipitation (such as rain) through fault and fracture networks is a fundamental mechanism that influences the formation and sustainability of geothermal reservoirs.[14,15,16] These structural discontinuities act as high-permeability channels that allow deep-seated geothermal fluids to ascend and accumulate, thereby playing a pivotal role in heat and mass transport within the crust.[17,18] In geothermal provinces, the spatial association between thermal manifestations and major fault zones is well documented, highlighting the importance of fault proximity

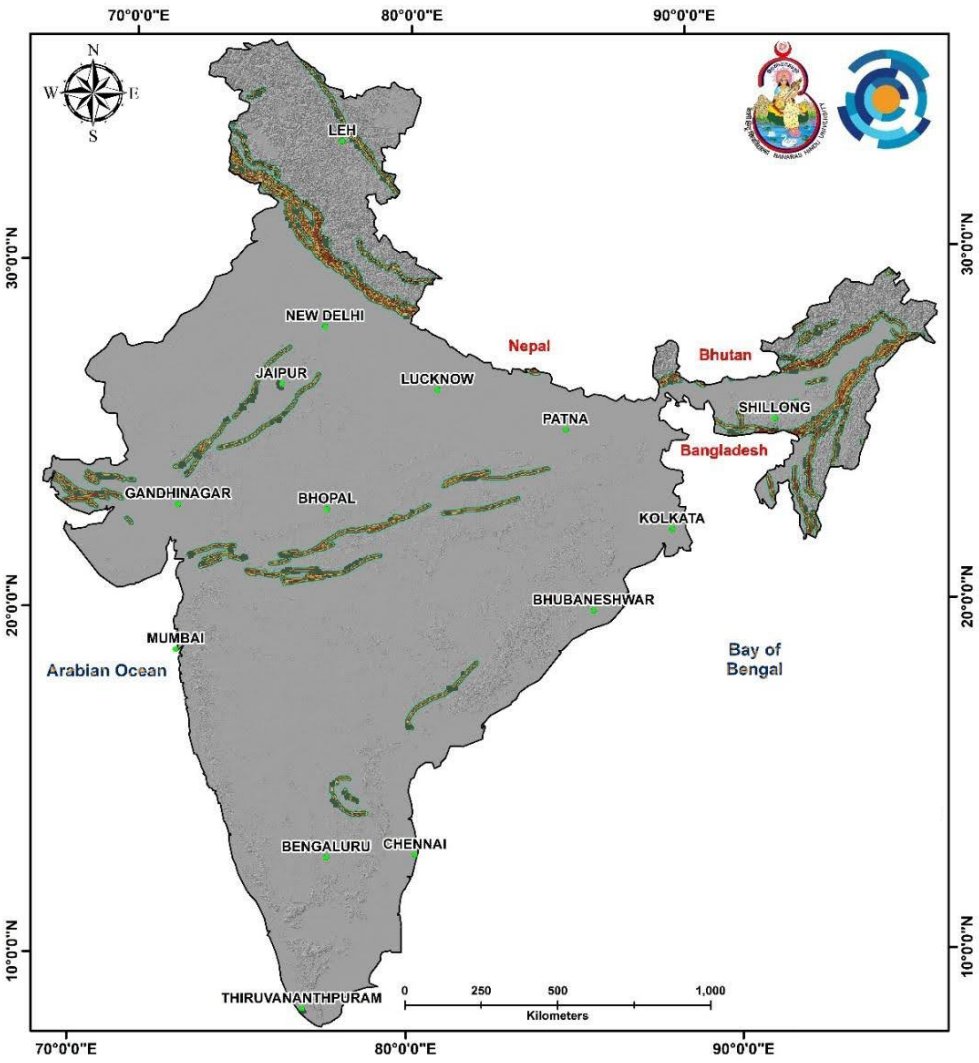


Figure 2.4: Proximity to active faults classified from 0 (least favourable for geothermal) to 5 (most favourable for geothermal). Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

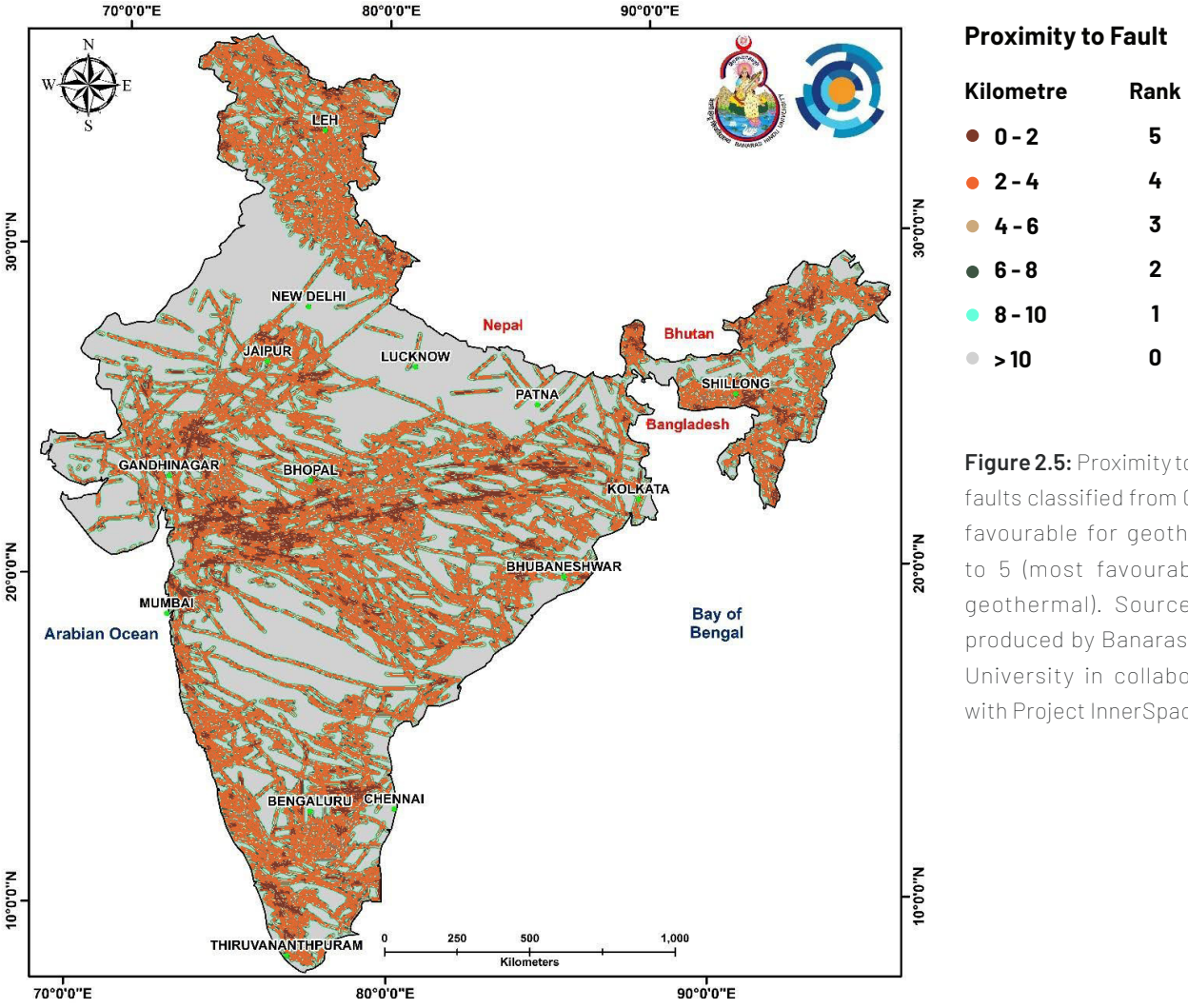


Figure 2.5: Proximity to major faults classified from 0 (least favourable for geothermal) to 5 (most favourable for geothermal). Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

as a key criterion in geothermal potential assessment.[19] Observations from this study confirm that a significant number of thermal springs are situated near fault structures (**Figure 2.5**), indicating a strong structural control of fluid migration pathways. Previous research, particularly in tectonically active regions such as Japan, has demonstrated that more than 95% of geothermal wells are located within 6 kilometres of major fault traces.[20] Based on this empirical evidence, fault proximity was integrated into the weighted overlay model as a critical factor. Distances of less than 2 kilometres from major faults were assigned the highest suitability score (5), recognizing their enhanced permeability and geothermal favourability, while regions situated beyond 10 kilometres were considered the least favourable, with a suitability score of 0 (**Figure 2.5**).

Proximity to Shallow Seismicity

Geothermal resources are frequently discovered in areas where earthquakes occur within fault zones. In this study, we have integrated the National Centre for Seismology earthquake catalogue covering 1900 to 2022 to identify high-density seismic zones such as the Himalayas, the ADFB, the Kachchh and Cambay rifts, northeastern India, and western coastal areas that are likely to have increased geothermal potential and tectonic activity (**Figure 2.6**). A previous study by Elbarbary and colleagues used earthquakes with depths of less than 10 kilometres for the geothermal potential zonation of Africa.[21] Following this study, we have used only earthquakes with less than 10 kilometres of focal depth and have taken a similar approach to faults in seismicity. Shallow earthquakes (depths of

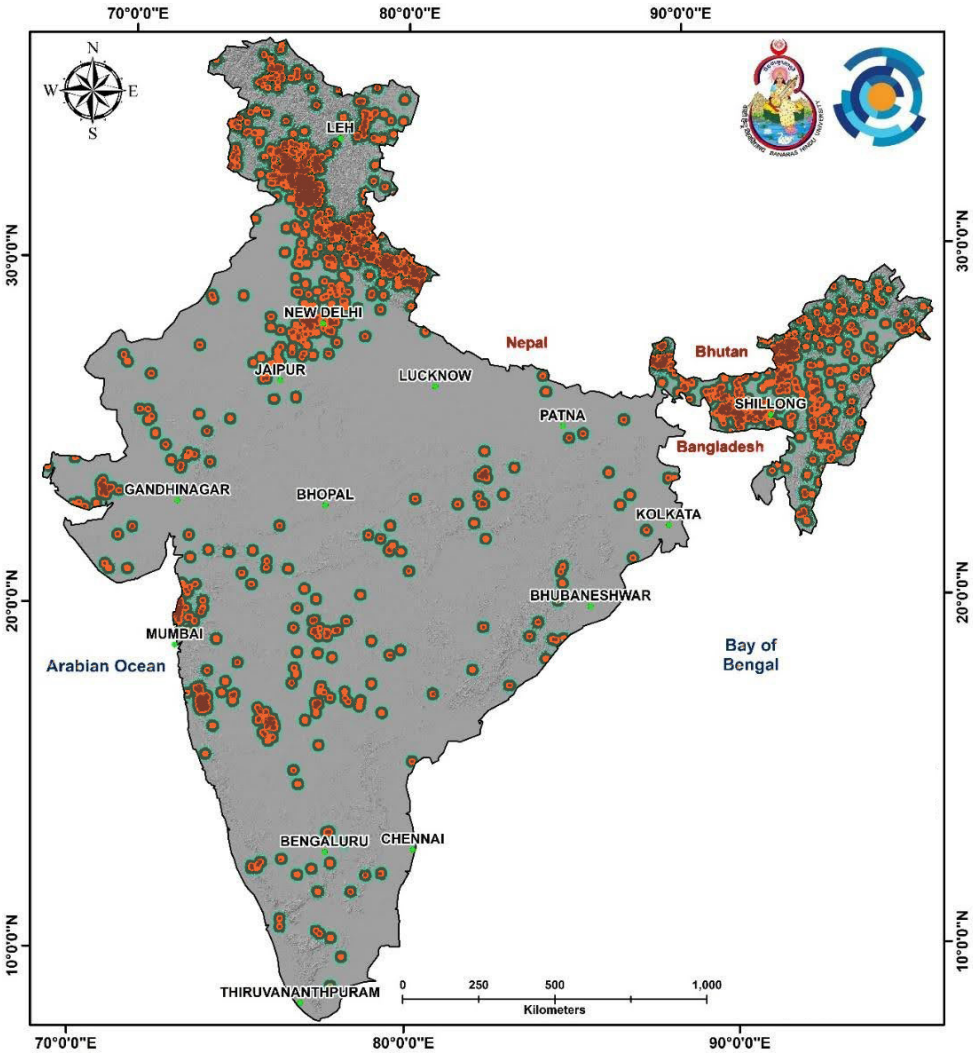


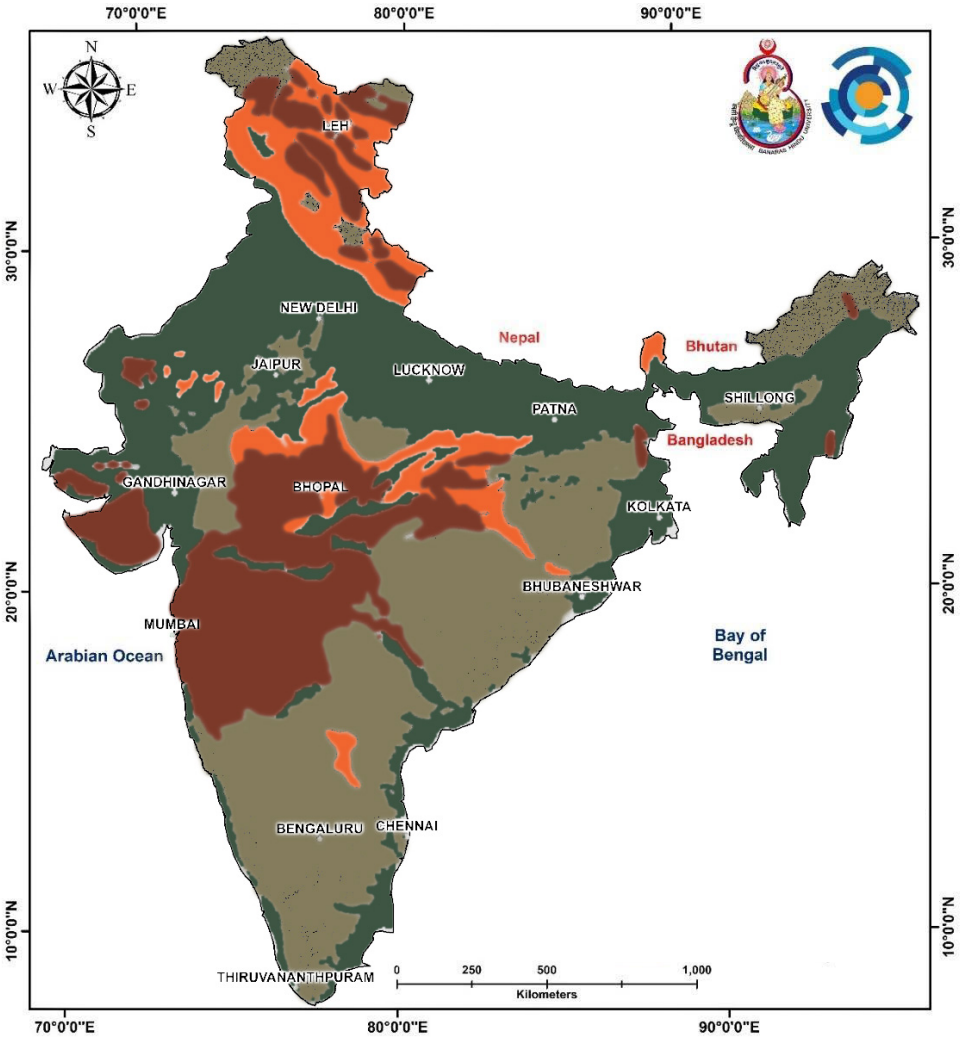
Figure 2.6: Proximity to shallow seismic events, classified from 0 (least favourable to geothermal) to 5 (most favourable to geothermal). Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace. Data from National Center for Seismology. (n.d.). *Data portal*. Ministry of Earth Sciences, Government of India.

less than 10 kilometres) suggest the presence of active crustal deformation and enhanced permeability, both of which support geothermal activity. As a result, locations within 5 kilometres of such events are scored highest (5), while those beyond 25 kilometres are considered the least favourable for geothermal (score 0; **Figures 2.6** and **A.3**).[22]

Geological Framework

India's geological framework is a complex assemblage of rocks dating from the Precambrian to the Cenozoic eras (**Figure 2.7**). The northern region is dominated by the tectonically active Himalayan orogen, which emerged from the ongoing convergence between the Indian and Eurasian plates.[23,24] This region hosts several major active fault systems, such as the Karakoram and Kishtwar faults, and accounts for nearly 50% of India's thermal springs, highlighting its geodynamic significance.[25,26] South of the Himalayas, the Indo-Gangetic plains are underlain by thick Cenozoic sedimentary sequences, with basin fill thickness reaching up to 8 kilometres, predominantly derived from Himalayan orogenic processes.[27] The central and southern regions of the Indian subcontinent are composed mainly of Precambrian and Mesozoic formations, where key cratonic blocks (the Aravalli-Bundelkhand, Bastar, Chhotanagpur-Singhbhum, and Dharwar) are bounded by mobile belts and interspersed with rift systems including the SONATA, Godavari, Mahanadi, Cambay, and Kachchh (**Figure 2.7**). These tectonic and lithological features play a critical role in influencing geothermal gradients, heat flow, and reservoir characteristics.

DISTRIBUTION OF MAJOR GEOLOGICAL FORMATIONS BY ERA



Geology

Age	Rank
Cenozoic	1
Mesozoic	5
Paleozoic-Mesozoic	4
Precambrian	3

Figure 2.7: Distribution of major geological formations by era: Cenozoic, Mesozoic, Palaeozoic-Mesozoic, and Precambrian. Classified from 0 (least favourable to geothermal) to 5 (most favourable to geothermal). Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

Mesozoic terrain—which is often associated with volcanic activity, high heat-retaining capacity, and a large number of thermal springs—has the highest geothermal suitability score (5). Paleozoic-Mesozoic terrain has the second-highest score (4), followed by Precambrian (3), and finally the less favourable Cenozoic sequences (1; **Figures 2.7** and **A.3**).

Proximity to Heat Flow

Heat flow is a critical geophysical parameter for identifying zones of high geothermal potential, as it directly reflects the subsurface thermal regime and indicates the presence of anomalously high temperatures at shallow depths.[28] Heat flow data provide insights into the conductive and convective heat transfer mechanisms within the Earth's crust, which can help geothermal developers identify regions with a sustained thermal energy source—an essential condition for viable geothermal systems.[29] In our study, heat flow is assigned the highest weight (20%) among all input layers due to its crucial role in determining geothermal resource viability. High heat flow values have been observed in the northwestern Himalayan zone, the Cambay rift, and the Saurashtra peninsula, all of which are favourable zones for geothermal potential (**Figure 2.8**).[30] Areas that exhibit heat flow values exceeding 100 milliwatts per square metre are considered the most favourable for geothermal and are assigned the maximum suitability score (5). Conversely, regions with heat flow below 30 milliwatts per square metre are deemed the least suitable for geothermal, receiving a

score of 0. Intermediate heat flow ranges are classified into graduated suitability classes, which indicates a continuum of geothermal favourability in the weighted overlay framework (**Figures 2.8** and **A.3**).

Moho Depth Variation

Crustal thickness plays a pivotal role in modulating heat flow, as it directly influences the efficiency of heat conduction from the underlying mantle to the Earth's surface.[31] Globally, crustal thickness—also known as Moho depth, or the boundary between Earth's crust and its mantle—varies significantly across different tectonic domains, averaging 35 kilometres in stable continental interiors, thinning to 7 kilometres in oceanic settings, and exceeding 70 kilometres in active orogenic regions such as the Himalayas. In the context of geothermal potential zonation, Moho depth is a critical geophysical parameter. Shallower Moho depths are typically associated with higher heat flow due to reduced lithospheric thickness and enhanced mantle heat flux.[32] These regions promote vertical heat transport, which makes them more likely to form geothermal reservoirs. Accordingly, areas with Moho depths shallower than 30 kilometres are classified as highly favourable to geothermal and assigned the maximum suitability score (5), while zones with Moho depths greater than 50 kilometres—reflecting thicker, more thermally resistive crust—are considered the least suitable for geothermal exploitation and are scored the lowest (0; **Figures 2.9** and **A.3**).

GEOTHERMAL SUITABILITY BASED ON HEAT FLOW DISTRIBUTION

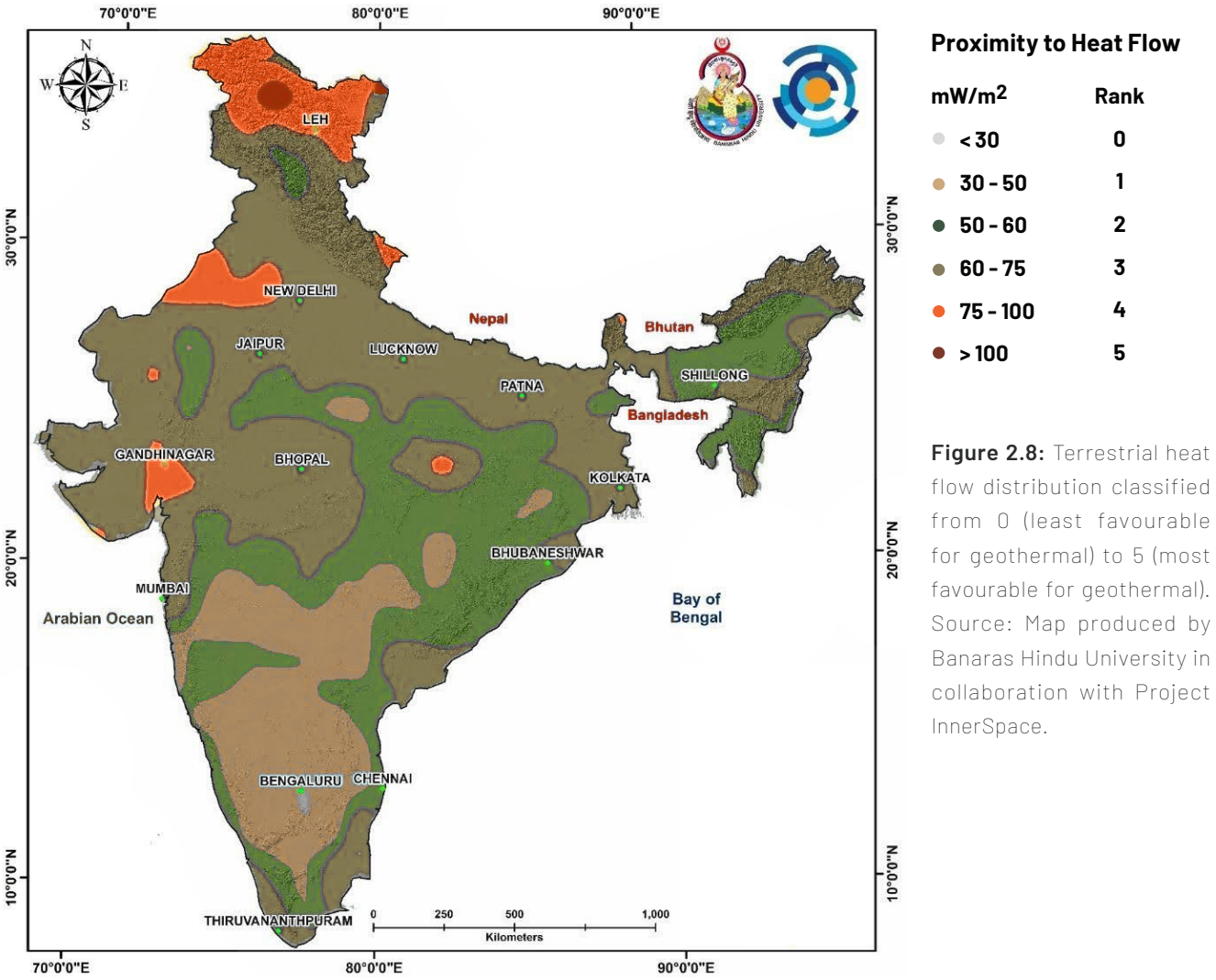
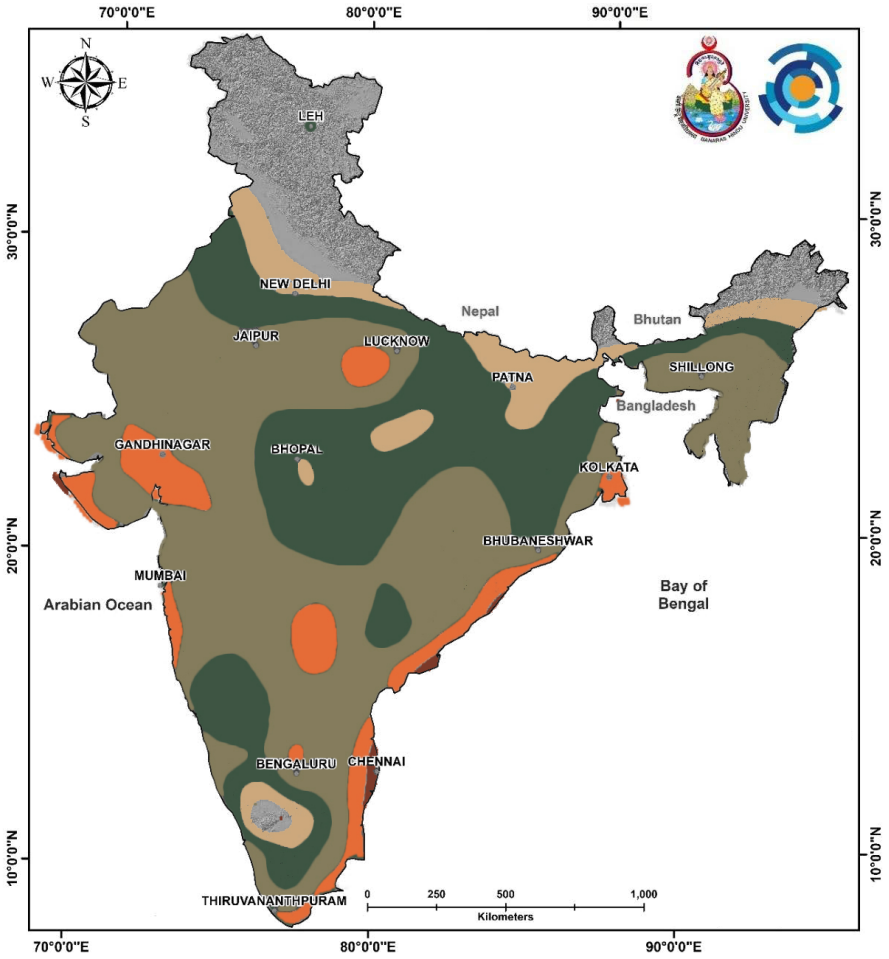


Figure 2.8: Terrestrial heat flow distribution classified from 0 (least favourable for geothermal) to 5 (most favourable for geothermal). Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

GEOTHERMAL FAVOURABILITY BASED ON MOHO DEPTHS



Proximity to Moho Depth

Kilometre	Rank
< 30	5
30 - 35	4
35 - 40	3
40 - 45	2
45 - 50	1
> 50	0

Figure 2.9: Moho depth distribution classified from 0 (least favourable for geothermal) to 5 (most favourable for geothermal). Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

Average Shear Wave Velocity Variation

When assessing geothermal potential, average shear wave velocity within the upper mantle (specifically between 110 kilometres and 150 kilometres deep) serves as a critical proxy for subsurface thermal conditions.[33] Lower shear wave velocities typically correspond to elevated temperatures, partial melting, or the presence of fluids, all of which are conducive to geothermal activity.[34] Regions exhibiting velocities below 4.1078 kilometres per second are classified as highly favourable to geothermal and assigned the maximum suitability score (3). Conversely, velocities exceeding 4.4189 kilometres per second suggest colder, more rigid mantle conditions and are considered the least suitable (assigned a score of 1). Intermediate velocity ranges are progressively scored to reflect decreasing geothermal favourability, thereby allowing for refined integration into the weighted overlay framework (**Figures 2.10** and **A.3**).

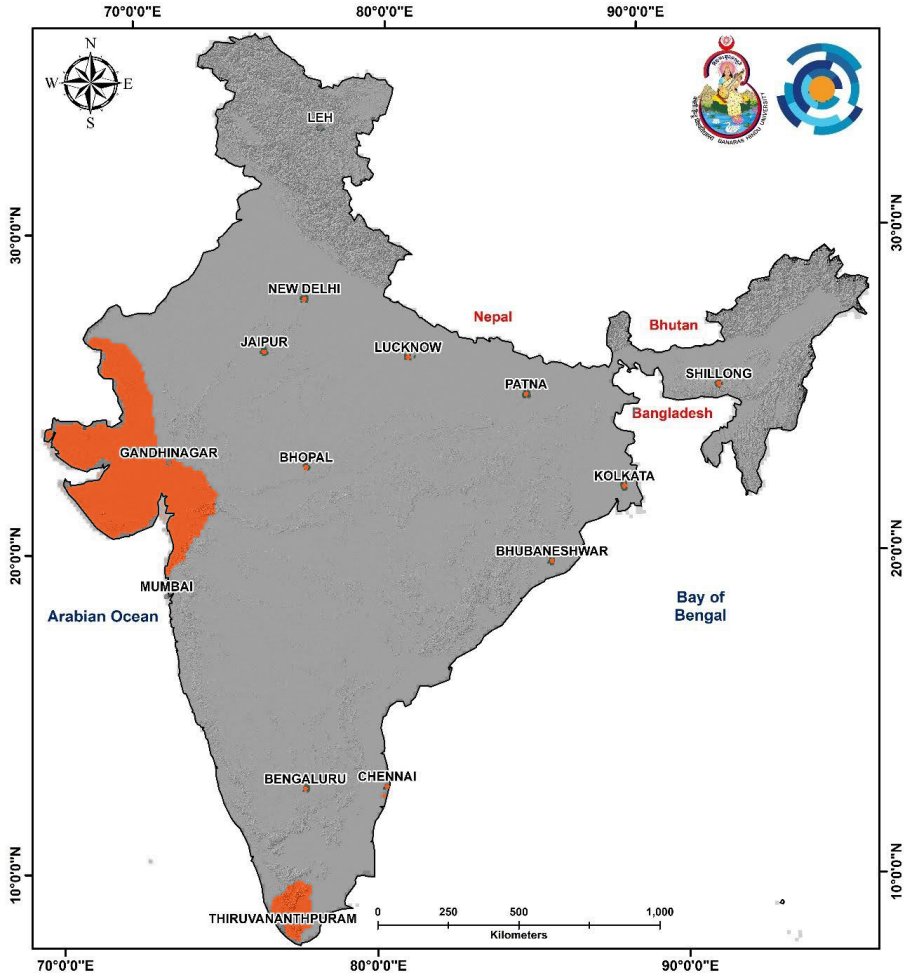
REGIONAL AND STATE ANALYSIS OF GEOTHERMAL POTENTIAL

India has technical potential for roughly 450 gigawatts of electricity generation (down to 5 kilometres) today and more than 8,000 gigawatts of electricity (down to 7 kilometres) as technology improves.[36] These geothermal regions occupy three main tectonic domains:

- The Himalayan collision zone associated with active continental convergence.
- The Aravalli Delhi Fold Belt (ADFB).
- Stable peninsular India, particularly near the Cambay, Kachchh, and SONATA rift systems; the Gondwana sedimentary basins; and the thermally active belts along the eastern and western coasts.

For the purpose of regional analysis, we divided the Indian geothermal landscape into five zones corresponding to

GEOTHERMAL FAVOURABILITY BASED ON SHEAR WAVE VELOCITY



Shear Wave Velocity

m/sec	Rank
4.2633 - 4.3411	2
4.3411 - 4.4189	1
> 4.4189	0

Figure 2.10: Average shear wave velocity between 100 kilometres and 150 kilometres. Regions exhibiting velocities below 4.1078 kilometres per second are classified as highly favourable to geothermal and assigned the maximum suitability score (3). Conversely, velocities exceeding 4.4189 kilometres per second suggest colder, more rigid mantle conditions and are considered least suitable (assigned a score of 1). Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

ROBUSTNESS AND LIMITATIONS OF THE ANALYSIS

The study integrates eight geoscientific data sets (shown earlier; see the appendix for details). To ensure the robustness of this analysis of geothermal potential, the results were cross-validated against existing geoscientific literature and previously identified geothermal provinces. This approach confirmed that our assessment was accurate in its findings that high-potential zones could be found in the northwestern Himalayas, eastern and western India, and northeastern provinces—findings that correspond closely with previous studies.[35]

That said, geothermal potential mapping is subject to inherent uncertainties, primarily due to limitations in the availability and resolution of input data sets. One significant constraint is the sparse and uneven nature of heat flow measurements across India, which may affect the spatial accuracy of potential zones. Likewise, seismic data sets generally span the past two centuries, so earlier seismicity remains partially undocumented. Thick sedimentary covers, particularly in the Indo-Gangetic Basin and other alluvial regions, can also make it challenging to accurately identify structural features such as active and major faults. This issue introduces additional uncertainty, especially in rifted domains where geothermal activity is structurally controlled. Finally, there are several discrepancies among global data sets such as Moho depth and shear wave velocity, which creates additional uncertainty. As more high-resolution geophysical, geological, and geochemical data become available—particularly heat flow measurements, detailed seismicity catalogues, and refined fault maps—this new information can be integrated to further enhance the map's inputs and resulting precision.

administrative divisions: northwestern, northeastern, western, eastern, and southern Indian states.

Northwestern Indian States

The northwestern Himalayas, located within the Trans-Himalayan tectonic belt, are rich in seismic faults and possess nearly half of India's thermal springs (more than 100; **Figures 2.3**, **2.4**, and **2.5**). The geothermal reservoirs are primarily located in post-Tertiary gneissic, granitic, and schistose formations, overlain by a thick layer of sedimentary deposits.[37,38] These granitoid intrusions act as significant heat sources, with high reservoir temperatures (above 250°C), anomalously high geothermal gradients (greater than 100°C per kilometre), and surface heat flow exceeding between 150 and 200 megawatts per square metre (**Figure 2.8**).[39,40] Magnetotelluric surveys in the Puga geothermal field have revealed low-resistivity zones corresponding to high-temperature fluid circulation at depth and the existence of an active magmatic system at a depth of between 5 kilometres and 7 kilometres.[41,42,43] Together, these measurements confirm there is considerable geothermal energy potential within the Ladakh region, with Puga, Chumthang, and the Nubra Valley emerging as key target zones for future development. Recent drilling operations undertaken by the Oil and Natural Gas Corporation provide empirical validation of the region's geothermal exploration potential, underscoring the strategic importance of this region for this exploration. **Figure 2.11** shows that northwestern India—particularly Ladakh, Jammu and Kashmir, Himachal Pradesh, and Uttarakhand—has extensive zones with high-temperature geothermal potential for power generation, along with broader areas of moderate potential.

In Himachal Pradesh and Uttarakhand, the most prospective zones fall within the Central and Lesser Himalayan domains, where several thermal springs exhibit

GEOTHERMAL POTENTIAL ZONES IN THE NORTHWESTERN INDIAN STATES

Geothermal Potential by Application Type

- **Power generation**
- **Potential power generation**
- **Direct use and direct heating**
- **Low-temp industrial heating/cooling**
- **Geothermal heating/cooling**

Figure 2.11: Geothermal resource potential across northwestern Indian states, classified by application type. Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

very high temperatures. Notably, the Manikaran hot spring in Himachal Pradesh reaches a discharge temperature of 97°C, with inferred reservoir temperatures of between 80°C and 110°C.[44,45] In Uttarakhand, the Badrinath and Tapoban springs record even higher subsurface temperatures of between 122°C and 142°C.[46] The combination of high surface and reservoir temperatures with high geothermal potential indices makes these systems among the most promising for future energy development in the Indian Himalayas.

By contrast, parts of eastern and southern Jammu and Kashmir within the Central Himalayan zone also host geothermal springs, but with lower surface (42°C–53°C[47]) and subsurface (41°C–85°C[48]) temperatures, making them more suitable for direct-use heating and cooling rather than power generation.

From a population perspective, many of these high-potential zones lie in sparsely populated mountainous areas, which limits immediate large-scale grid integration but offers strong opportunities for localised power and heat supply to tourism hubs, remote communities, and strategic installations. Moderate-potential zones in more accessible valleys and foothills are closer to population centres, providing attractive targets for direct-use applications and smaller-scale geothermal projects.

Northeastern Indian States

The map shows that northeastern India—particularly Arunachal Pradesh, Sikkim, Meghalaya, Assam, and parts of Manipur, Mizoram, Nagaland, and Tripura—hosts extensive zones with high and moderate geothermal potential (**Figure 2.12**). In Sikkim, five documented thermal springs have surface temperatures ranging between 38°C and 59°C,[49] with our model indicating higher prospectivity in the surrounding zones. The western part of Arunachal Pradesh has particularly strong geothermal signatures, with more than 30 thermal springs and reservoir temperatures estimated to reach up to 200°C,[50,51] highlighting this region as a priority for future

GEOTHERMAL POTENTIAL ZONES IN THE NORTHEASTERN INDIAN STATES

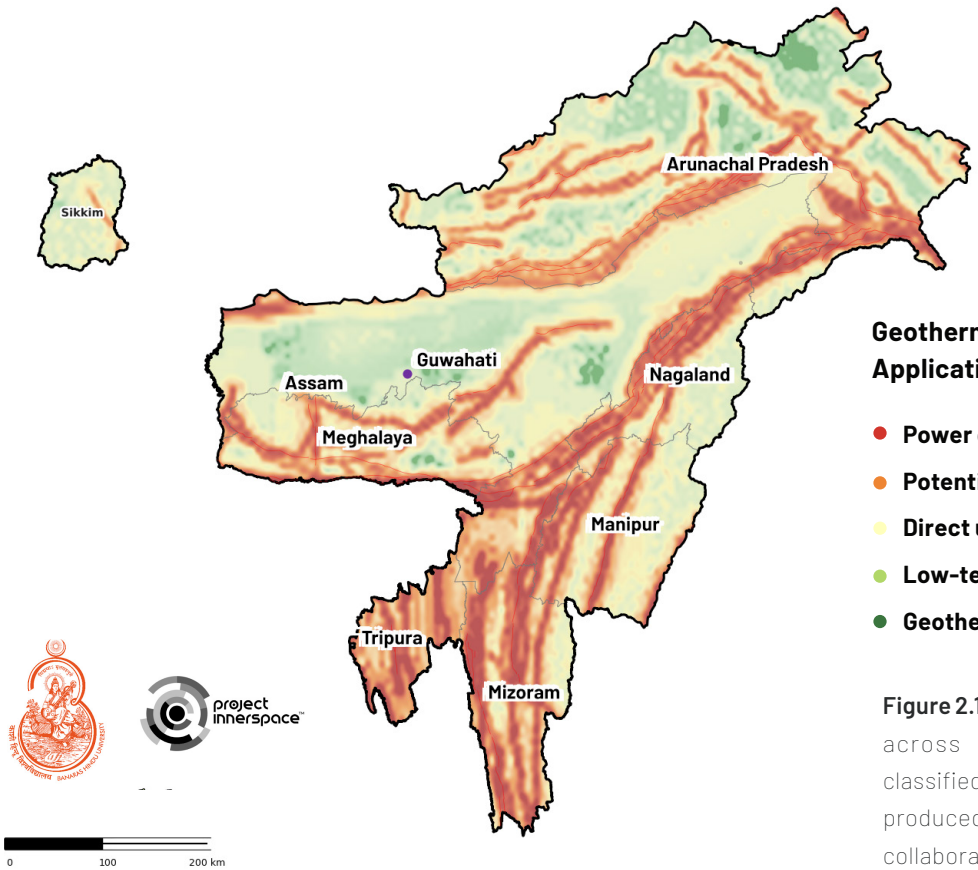


Figure 2.12: Geothermal resource potential across northeastern Indian states, classified by application type. Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

geothermal development. In 2023, the Arunachal Pradesh government formalised a memorandum of understanding with GSI, the Government of India, and the Norwegian Geotechnical Institute to conduct a comprehensive geoscientific assessment aimed at evaluating the feasibility of geothermal energy exploitation from the state's thermally active hydrothermal systems.

In Meghalaya, the East Garo Hills host between 10 and 20 thermal springs (**Figure 2.3**), and investigations by the Bhabha Atomic Research Centre in India's Department of Atomic Energy have reported surface temperatures between 28°C and 48°C and reservoir temperatures as high as 300°C.[52,53] This high heat flow is linked to uraninite-bearing granitoid intrusions of the Archean Shillong Plateau that exhibit enhanced natural radioactivity.[54] Despite relatively modest surface temperatures, the deep thermal regime reflects significant geothermal potential.

Assam, Manipur, Nagaland, Mizoram, and Tripura also display geothermal prospectivity, though with fewer documented thermal springs (**Figure 2.3**). In the Upper Assam Basin, well log data from 17 boreholes reveal five wells with significantly elevated heat flow, highlighting promising sites for geothermal energy applications.[55]

From a population perspective, many of the zones with the greatest potential—particularly in Arunachal Pradesh, Mizoram, and Nagaland—are in remote, sparsely populated terrain, favouring decentralised off-grid systems for local communities, tourism hubs, and strategic installations. In contrast, prospects in Assam and Meghalaya are closer to major population centres and industrial corridors, making them more suitable for grid-connected power generation and direct-use heating and cooling.

Overall, the combination of high estimated reservoir temperatures, heat flow anomalies, and favourable tectono-magmatic settings confirms that northeastern India is a strategically important frontier for geothermal energy exploration.

Western Indian States

In the western states, high geothermal potential exists in Rajasthan and Haryana along the ADFB (**Figure 2.13**), which hosts several low- to moderate-temperature thermal springs, with discharge temperatures between 35°C and 47°C and estimated reservoir temperatures of between 60°C and 80°C.[56] This zone is structurally controlled by northeast-southwest trending strike-slip faults, which have been active since the Precambrian era and serve as primary conduits for the ascent of deep-circulating geothermal fluids.[57] Thermal anomalies in this region are likely driven by heat-producing alkaline intrusions and high-thermal-conductivity silicic lithologies, which enhance the subsurface geothermal regime.[58] Thermal fluid discharge in the Sohana area is linked to groundwater percolation through a structurally induced depression formed by the downward displacement of a central crustal block flanked by two uplifted ridges of the Delhi Mobile Belt.[59] This tectonic configuration facilitates gravity-driven infiltration of meteoric water along fractures and faults, where it is subsequently heated during deep circulation.

The Kachchh rift, Cambay rift, and Saurashtra peninsula regions of Gujarat are all characterised by high geothermal potential. Among these areas, the Cambay rift stands out as the most promising area for geothermal exploration. A majority of the thermal springs are spatially associated along the boundary fault of the Cambay rift, and surface temperatures of thermal springs in this region are generally moderate to high (40°C–93°C), from the Dholera spring (40°C–45°C) up to the Tuwa (93°C).[60,61] In the Unai geothermal system, surface and reservoir temperatures are reported at approximately 50°C to 55°C and 120°C, respectively (**Figure 2.13**).[62] Reservoir temperature estimations also suggest high geothermal gradients, with inferred subsurface temperatures of 150°C on the eastern margin of the rift and between 70°C and 90°C on the western margin.[63] Magnetotelluric investigations at the Chabsar hot springs also indicate high fluid saturation along the western boundary fault, which likely serves as a conduit for ascending geothermal fluids.[64]

Along with the aforementioned regions, the central segment of the seismically active Kachchh rift also holds considerable geothermal potential, although it hosts only a single known thermal spring (**Figure 2.13**). Geophysical investigations—including gravity, magnetotelluric, and seismic studies—have revealed the presence of intrusive bodies in the upper crust and a partially molten magma chamber at mid- to lower-crustal depths.[65] These subsurface features indicate a viable heat source and suggest that the Kachchh rift may support geothermal energy development, contingent on further exploratory efforts.

The SONATA megatectonic lineament, extending across southern Gujarat, northern Maharashtra, and central Madhya Pradesh, reveals the presence of a structurally significant corridor with considerable geothermal exploration potential. The Salbardi and Anhoni thermal springs (in the northern region of Maharashtra and the southern region of Madhya Pradesh, respectively) are spatially aligned with the western segment of this major tectonic feature (**Figure 2.13**). Surface discharge temperatures at the Salbardi thermal springs range between 44°C and 47°C, while subsurface reservoir temperatures have been estimated at approximately 150°C.[66,67] In the Anhoni geothermal zone, the surface temperature is around 45°C, with reservoir temperatures estimated at nearly 100°C.[68,69] The high heat flow in this region is thought to result from the presence of partial melts and associated fluids at mid- to lower-crustal depths. Geophysical and petrological evidence further suggests the existence of high-density mafic intrusions and magmatic underplating at the base of the crust, which may serve as significant heat sources driving hydrothermal circulation.[70]

Our analysis also found high geothermal potential along the coastal tract of Maharashtra (**Figure 2.13**), where abundant thermal springs (**Figure 2.3**) show surface temperatures ranging from 47°C to 72°C.[71,72] These thermal manifestations are primarily governed by deep-seated tectonic structures like the West Coast Fault and are associated with fluid migration through the Deccan Traps.[73] The Rajapur hot spring is particularly significant, as its thermal waters circulate through granitic basement rocks underlying the basalt cover, suggesting a complex hydrothermal system with both volcanic and plutonic contributions.

Given their favourable tectonic setting, elevated geothermal gradients, and robust surface and reservoir

GEOTHERMAL POTENTIAL ZONES IN THE WESTERN INDIAN STATES

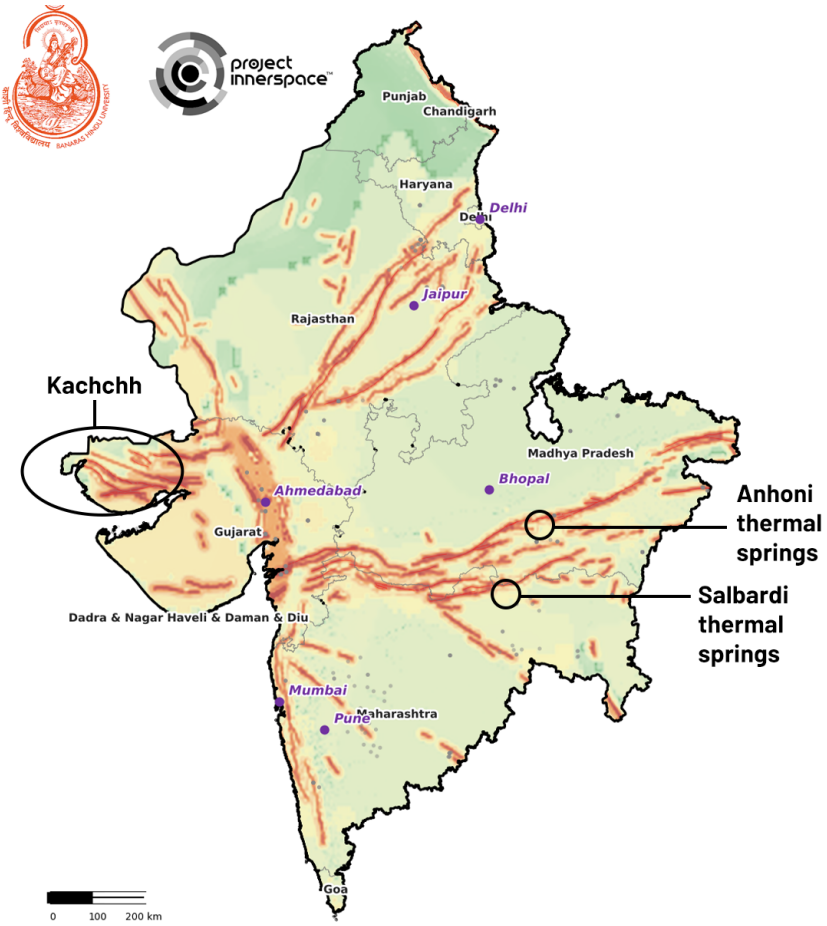


Figure 2.13: Geothermal resource potential across western Indian states, classified by application type. Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

temperature profiles, the Cambay rift and the SONATA lineament zones collectively should be high-priority targets for geothermal resource development in western India.

Eastern Indian States

The eastern region of India is geologically diverse, featuring major tectonic and crustal units such as the Indo-Gangetic Plain, Singhbhum Craton, Mahanadi rift, and Bastar Craton (**Figure 2.2**). Within this tectonic framework, our analysis shows high geothermal potential in the Rajgir geothermal province of Bihar (**Figure 2.14**). This zone is spatially associated with the Munger-Saharsa Ridge fault system, a prominent tectonic feature that facilitates deep fluid circulation. Several thermal springs have been documented within this structurally controlled corridor, exhibiting surface discharge temperatures ranging from 30°C to 65°C. Reservoir temperature estimates suggest subsurface values reaching up to 100°C.[74,75] These temperatures position the Bihar state as a promising candidate for low- to medium-enthalpy geothermal resource development in eastern India.

Multiple thermal spring occurrences have been identified in the western part of West Bengal and the adjoining eastern region of Jharkhand (**Figure 2.14**). Previous investigations by Ravi Shanker and colleagues have documented anomalously high geothermal gradients in this region, reaching up to 90°C per kilometre.[76] High geothermal gradient values are thought to result from deep-seated geodynamic processes, including possible mantle upwelling and mafic intrusions, particularly in the Bakreswar and Tantloi areas, as supported by regional gravity anomaly data.[77] Furthermore, the thermal regime is influenced by the occurrence of vein-type uranium-bearing mineralization (brannerite and uraninite) hosted in Paleoproterozoic quartz-chlorite schist within the tectonically active Singhbhum Shear Zone.[78,79] (In other words, the radioactive decay produces heat.) As a result, these states should be designated as a high-priority target for further geothermal exploration and resource development.

GEOTHERMAL POTENTIAL ZONES IN THE EASTERN INDIAN STATES

Geothermal Potential by Application Type

- **Power generation**
- **Potential power generation**
- **Direct use and direct heating**
- **Low-temp industrial heating/cooling**
- **Geothermal heating/cooling**

Figure 2.14: Geothermal resource potential across eastern Indian states, classified by application type. Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

In northern Chhattisgarh, the Tatapani geothermal system is structurally situated between two prominent east-west-trending fault zones, spatially associated with the SONATA megatectonic lineament to the north and the Tapi lineament to the south. This fault-bounded configuration plays a crucial role in facilitating subsurface fluid migration. Previous investigations by Chandrashekharam and Antu and by Minissale and colleagues have reported surface discharge and reservoir temperatures ranging from 60°C to 80°C and 205°C to 217°C.[80,81] Studies attributed the geothermal anomalies in the region to deep fluid circulation along these fault-controlled conduits, enabling efficient heat transport from mid- to lower-crustal levels.[82] The high geothermal potential identified in this zone, in conjunction with the state's favourable geological framework and thermal regime, reaffirm Chhattisgarh as a strategically significant zone for advanced geothermal resource exploration, assessment, and sustainable exploitation.

The state of Odisha (**Figure 2.14**) exhibits a broad spatial distribution of thermal springs (**Figure 2.3**), with surface discharge temperatures ranging from 32°C to 67°C and inferred subsurface reservoir temperatures estimated between 90°C and 130°C.[83] These thermal characteristics are indicative of low-enthalpy geothermal systems, underscoring the region's potential for moderate-temperature geothermal resource development.

Southern Indian States

Compared with the rest of the country, the southern Indian states show comparatively lower geothermal potential (**Figure 2.15**). Very localised geothermal prospective zones have been identified in the southern part of Karnataka, with geo-structural and lithological conditions similar to those seen in the coastal Maharashtra region, particularly with regard to thermal regime and fault-controlled hydrothermal fluid migration. The Godavari rift zone, extending across the northern and eastern regions of Telangana and Andhra Pradesh, represents a prominent exception, exhibiting high geothermal prospectivity. Within this tectonically active northwest-southeast trending graben structure, more than 15 thermal springs have been documented (**Figure 2.3**), with

GEOTHERMAL POTENTIAL ZONES IN THE SOUTHERN INDIAN STATES

Geothermal Potential by Application Type

- **Power generation**
- **Potential power generation**
- **Direct use and direct heating**
- **Low-temp industrial heating/cooling**
- **Geothermal heating/cooling**

Figure 2.15: Geothermal resource potential across southern Indian states, classified by application type. Source: Map produced by Banaras Hindu University in collaboration with Project InnerSpace.

surface discharge temperatures ranging from 36°C to 62°C and reservoir temperatures inferred to be between 80°C and 120°C.[84,85,86] The bounding fault systems of the rift act as conduits, facilitating the ascent of thermally altered fluids from deeper crustal levels to the surface.

CONCLUSION

India's diverse topography—ranging from high mountain ranges to extensive river basins and coastal plains—contains a wealth of geothermal resources. The Himalayan region, with its rugged terrain and high-altitude geothermal springs, presents logistical challenges but offers immense potential for energy generation. In contrast, the western and central parts of India have more accessible geothermal reservoirs due to their relatively stable geological settings.

Our integrated and systematic assessment offers vital insights into the geological, geophysical, and thermal characteristics that underpin India's geothermal resources and highlights a number of extremely promising areas for exploration across a diverse set of tectonic and lithological settings.

In eastern and central India—including the Rajgir geothermal group in Bihar, the Jharkhand-West Bengal corridor, and the Mahanadi Rift Basin in Odisha—there are extensive geothermal resources thanks to heat-producing lithologies and structurally controlled spring systems. In particular, the Tatapani geothermal field in northern Chhattisgarh is one of India's most promising reservoirs, with temperatures exceeding 200°C and deep fluid circulation along major fault alignments.

The Godavari rift system in Telangana and Andhra Pradesh, as well as isolated zones in Karnataka, are also strong geothermal targets thanks to a combination of rift tectonics, magmatic intrusions, and thermal fluid pathways. In the northwestern Himalayan corridor, the Ladakh region's Puga, Chumthang, and Nubra valleys collectively possess significant subsurface heat reservoirs. Likewise, the geothermal systems in Jammu and Kashmir, Himachal Pradesh, and Uttarakhand—exemplified by sites like Manikaran, Tapoban, and Badrinath—show high reservoir temperatures and strong hydrothermal circulation linked to deep-seated fault systems and granite-hosted radiogenic heat sources, making all of them excellent candidates for geothermal energy production.

In western India, the geothermal provinces of Haryana (Sohana region), Rajasthan (ADFB), Gujarat (Cambay and Kachchh rifts), and coastal Maharashtra are good candidates for both low- and medium-enthalpy geothermal systems, with fault-mediated hydrothermal pathways facilitating deep fluid migration.

In the northeastern Himalayan, provinces such as Sikkim, Arunachal Pradesh, and Meghalaya remain underexplored but exhibit surface thermal anomalies and spring systems that merit targeted geoscientific investigations.

Going forward, we recommend additional high-resolution subsurface investigations—using magnetotelluric imaging, seismic tomography, heat flow measurements, isotopic hydrochemistry, and 3D geothermal modelling—to produce an even deeper understanding of subsurface characteristics and thermohydraulic regimes, with an eye toward identifying extractable energy potential. These studies will make geothermal resource assessments more accurate and will contribute to the design of both exploration strategies and pilot-scale projects.

This work is crucial to allowing India to take advantage of its exceptional geothermal resources. With its minimal land footprint and significant baseload generation capacity, geothermal energy can help India meet both its urgent national energy security needs and multiple United Nations Sustainable Development Goals. Our investigation provides a foundational scientific basis for future exploration, development, and policy planning.

The electricity generation potential and industrial heat potential numbers were calculated using methodology that expresses electricity estimates in gigawatts-electric down to 5,000 metres and all heat applications for industrial use (with a 100°C cutoff) down to 3,500 metres in gigawatts-thermal per square kilometre.

Additional Figure Source Information

Figure 2.3: Tamburello, G., Chiodini, G., Ciotoli, G., Procesi, M., Rouwet, D., Sandri, L., Carbonara, N., & Masciantonio, C. (2022). Global thermal spring distribution and relationship to endogenous and exogenous factors. *Nature Communications, 13*, 6378; Craig, J., Absar, A., Ghat, G., Cadel, G., Hafiz, M., Hakhoo, N., Kashkari, R., Moore, J., Ricchiuto, T. E., Thurow, J., & Thusu, B. (2013). Hot springs and the geothermal energy potential of Jammu & Kashmir State, N.W. Himalaya, India. *Earth-Science Reviews, 126*, 156–177; Das, P., Maya, K., & Padmalal, D. (2022). Hydrogeochemistry of the Indian thermal springs: Current status. *Earth-Science Reviews, 224*, 103890; Sinha, R. K. (1980). Some thermal springs in Kameng District, Arunachal Pradesh. *Journal of the Geological Society of India, 21*(9), 464–467; Dhirendra, K., Bajpai, R. K., & Sengupta, B. (1992). Geochemistry and geothermometry of the thermal springs of Resubelpara, East Garo hills, Meghalaya, India, and their bearing on uranium exploration. *EARFAM, 5*, 53–62; Bajpai, R., & Narayan, P. K. (2005). Natural analogue study of Resubelpara Group of thermal springs at Garo Hills, Meghalaya for demonstration of safe geological disposal of nuclear waste. *Current Science, 88*(6), 986–989; Singh, H. K., Garg, G. C., Chandrasekharam, D., Trupti, G., & Singh, B. (2014). Physicochemical evolution of the thermal springs over the Siwana Ring Complex, western Rajasthan. *Journal of the Geological Society of India, 84*, 668–674; Gurav, T., Singh, H. K., & Chandrasekharam, D. (2015). Major and trace element concentrations in the geothermal springs along the west coast of Maharashtra, India. *Arabian Journal of Geosciences, 9*, 44; Dutta, A., Thapliyal, A. P., Singh, P. K., Rohilla, S., & Gupta, R. K. (2023). Geological setup and physicochemical characteristics of Munger Groups of thermal springs along Munger–Saharsa Ridge Fault, Bihar, India: A conceptual hydrogeochemical model. *Journal of Earth System Science, 132*, 12; Pandey, G. C., & Raymahashay, B. C. (1981). Studies on some low-temperature East Indian hot springs. *Chemical Geology, 34*(1–2), 113–129.

APPENDIX: DATA AND METHODOLOGY

Data

The data sets employed in this study are derived from a range of authoritative sources, including peer-reviewed scientific literature, government agencies, and publicly available geoscientific databases. The spatial distribution and attributes of thermal springs were obtained from the Geological Survey of India, conducted by the Government of India. Geological frameworks, including major and active fault systems and crustal heat flow data, were sourced from Project InnerSpace's GeoMap.[87,88,89,90,91] The earthquake catalogue, comprising seismic events with focal depths shallower than 10 kilometres between 1900 and 2023, was acquired from the National Centre for Seismology within the Government of India. A detailed summary of all data sets used is presented in **Figure A.1**.

Using QGIS-based spatial analysis, continuous variables were standardised, reclassified, and combined through a weighted overlay analysis informed by expert-derived significance scores. The resulting composite geothermal potential index identifies priority zones across India with the highest favourability for future geothermal exploration and development.

Tools Used for Thematic Map Preparation

All thematic layers in this study were generated and processed within QGIS using its advanced spatial analysis capabilities. The proximity analyses—including distances to thermal springs, fault lines, and shallow earthquake epicentres—have been computed using the "Proximity (Raster Distance)" tool in the QGIS Processing Toolbox. This tool calculates the distance from each raster cell to the nearest vector feature, producing continuous distance raster where lower values indicate spatial closeness to the geologic features of interest, which are considered critical in geothermal prospecting.[92]

For the heat flow distribution, interpolation was conducted using the inverse distance weighting (IDW) method, available through the QGIS interpolation tool set (**Figure A.2**). IDW is a deterministic spatial interpolation technique that estimates unsampled values based on the proximity-weighted average of known data points. The power coefficient in the IDW function modulates the influence of nearby points, ensuring that interpolated values remain bounded within the range of observed heat flow measurements and reflect spatial continuity.

SUMMARY OF DATA SETS USED FOR THE STUDY

S. No.	Data	Source	Other Details
1	Thermal springs	Geological Survey of India, Government of India	340 Thermal springs
2	Active fault	Project InnerSpace database	Scale: n/a
3	Major fault	Project InnerSpace database; Geological Survey of India, Government of India	Scale: n/a
4	Shallow seismicity (<10 kilometres)	National Centre for Seismology, Government of India	Duration: 1900–2023 AD
5	Geology	Project InnerSpace database	Scale: n/a
6	Heat flow	Project InnerSpace database	Resolution: n/a
7	Moho depth	Mooney et al.	Resolution: 1° x 1°
8	Average shear wave velocity between 110 kilometres and 150 kilometres	Schaeffer & Lebedev	Resolution: 0.5° x 0.5°

Figure 2.A.1: Summary of the data (source, scale, resolution, and number of points) used in this study. Sources: Geological Survey of India, 1991; Geological Survey of India, 2025; National Center for Seismology, n.d.; Mooney et al., 2023; Schaeffer & Lebedev, 2013; Markwick et al., in preparation; Fuchs et al., 2023; Dou et al., 2024; Smithsonian Institution, n.d., *Holocene Volcano List*; Smithsonian Institution, n.d., *Pleistocene Volcano List*. (See full source information at the end of this appendix.)

METHODOLOGY FOR MAPPING GEOTHERMAL POTENTIAL ZONES

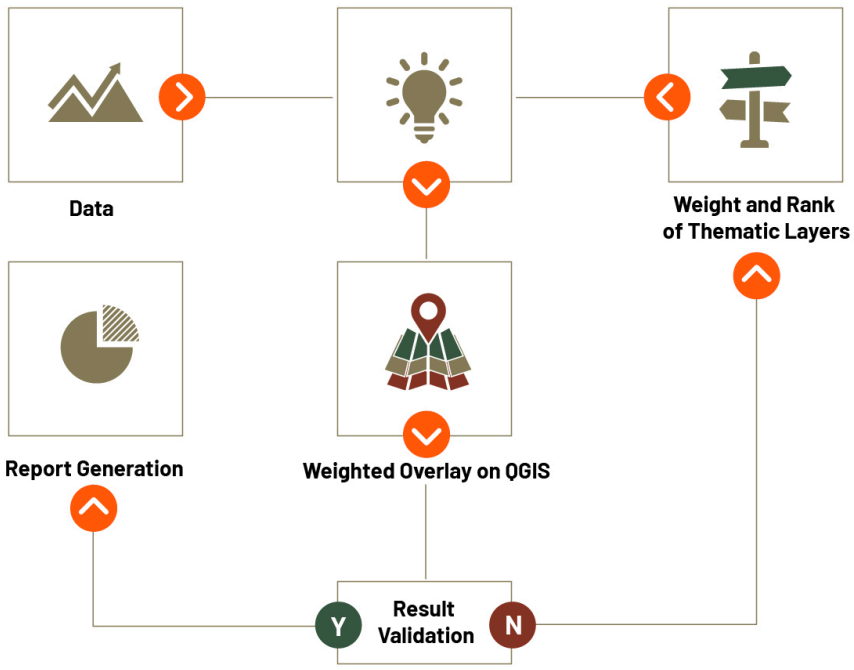


Figure 2.A.2: Flow chart of the methodology used for mapping of geothermal potential zones in India. Source: Chouhan, A. K., Kumar, R., & Mishra, A. K. (2024). Assessment of the geothermal potential zone of India utilizing GIS-based multi-criteria decision analysis technique. *Renewable Energy, 227*, 120552.

WEIGHTED OVERLAY ANALYSIS SCORES

S. No.	Layers	Unit	Weights	Suitability Score					
				0	1	2	3	4	5
1	Proximity to thermal springs	km	20	> 6	5–6	4–5	3–4	2–3	< 2
2	Proximity to active fault	km	10	> 10	8–10	6–8	4–6	2–4	< 2
3	Proximity to major fault	km	10	> 10	8–10	6–8	4–6	2–4	< 2
4	Proximity to shallow seismicity	km	10	> 25	25–20	20–15	15–10	10–5	< 5
5	Geology	Era	10	n/a	Cenozoic	n/a	Precambrian	Palaeozoic	Mesozoic
6	Heat flow	(mW/m^2)	20	< 30	30–50	50–60	60–75	75–100	> 100
7	Moho depth	km	10	> 50	50–45	45–40	40–35	35–30	< 30
8	Average shear wave velocity between 110 and 150 km	(km/sec)	10	> 4.4189	4.3411–4.4189	4.2633–4.3411	4.1856–4.2633	4.1078–4.1856	< 4.1078

Figure 2.A.3: Weights and suitability scores of the thematic layers for the mapping of geothermal potential zones of India. Source: the authors.

Reclassification of continuous raster layers—such as proximity to thermal features, fault zones, seismic activity, and interpolated heat flow—was carried out using the "Reclassify by Table" tool. This process involved discretising the continuous data into ordinal suitability classes based on thresholds informed by geoscientific domain knowledge and relevant published literature. Each class represents the degree of favourability with respect to geothermal potential (**Figure A.3**).

Subsequently, a weighted overlay analysis was performed to integrate the standardised thematic layers and derive a composite geothermal potential index. Each layer was assigned a relative weight, reflecting its significance in geothermal resource localisation, as determined through expert consensus and prior studies. The integration was operationalised using the QGIS "Raster Calculator" tool, where each reclassified raster was multiplied by its respective weight, and the resulting layers were aggregated to produce a final geothermal potential map. This composite output represents a continuous spatial surface depicting relative geothermal favourability across the study area, thereby enabling the identification of priority zones for detailed geothermal exploration and potential development.

Weights for the Layers

To delineate geothermal potential zones, eight layers have been analysed based on their geoscientific significance and relevance to geothermal processes. Each layer is mapped and ranked from 0 to 5, where 5 represents the most favourable geothermal conditions and 0 the least favourable for that respective layer (**Figure A.3**). Each layer is then weighted (ranging from 0% to 100%) in accordance with its relative influence on geothermal potential (details have been provided in this appendix). The combined weighted layers provide a single, summary weighted overlay analysis, which provides a robust assessment of overall subsurface geothermal favourability.

Additional Figure Source Information

Figure A.1: Geological Survey of India. (1991). *Geothermal atlas of India*. Government of India; Geological Survey of India. (2025). *BHUKOSH*. Government of India; National Center for Seismology. (2023). *Data portal.* Ministry of Earth Sciences, Government of India; Mooney, W. D., Barrera-Lopez, C., Suárez, M. G., & Castelblanco, M. A. (2023). Earth Crustal Model 1 (ECM1): A 1° x 1° global seismic and density model. *Earth-Science Reviews*, 243, 10449; Schaeffer, A. J., & Lebedev, S. (2013). Global shear speed structure of the upper mantle and transition zone. *Geophysical Journal International, 194*(1), 417–449; Markwick, P. J., Paton, D. A., & Mortimer, E. J. (in prep). An update for the North American continent based on the previous work of Markwick, P. J., Paton, D. A., & Mortimer, E. J. (2021). *Reclus,* a new database for investigating the tectonics of the Earth: An example from the East African margin and hinterland. *Geochemistry, Geophysics, Geosystems, 22*(11), e2021GC009897; Fuchs, S., Norden, B., Neumann, F., Kaul, N., Tanaka, A., Kukkonen, I. T., Pascal, C., Christiansen, R., Gola, G., Šafanda, J., Espinoza-Ojeda, O. M., Marzan, I., Rybach, L., Balkan-Pazvantoğlu, E., Ramalho, E. C., Dědeček, P., Negrete-Aranda, R., Balling, N., Poort, J., ... Verdoya, M. (2023). Quality-assurance of heat-flow data: The new structure and evaluation scheme of the IHFC Global Heat Flow Database. *Tectonophysics, 863;* Dou, H., Xu, Y., Lebedev, S., Chagas de Melo, B., van der Hilst, R. D., Wang, B., & Wang, W. (2024). The upper mantle beneath Asia from seismic tomography, with inferences for the mechanisms of tectonics, seismicity, and magmatism. *Earth-Science Reviews, 255*, 104841; Smithsonian Institution. (n.d.). *Holocene Volcano List* [Database]. Global Volcanism Program; Smithsonian Institution. (n.d.). *Pleistocene Volcano List* [Database]. Global Volcanism Program.

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Chapter 3

Direct-Use Geothermal for Manufacturing and Industrial Processes

Namrata Bist, Pandit Deendayal Energy University

Industry drives India's economy—and its pollution and emissions. India's geothermal resources include approximately 11,000 gigawatts of direct-use industrial technical potential, and its resources are particularly well suited for food processing and chemical, pharmaceutical, pulp, paper, and textile manufacturing. Unlocking its geothermal resources can enable India to increase competitiveness, reduce expenditures, improve air quality (and public health), and create jobs.

Heat makes up nearly half of all global energy consumption. In India, heat runs boilers and process equipment used for many industries, including chemical, cement, textile, and paper manufacturing and food processing. It is also used for low- to medium-temperature processes for agriculture, aquaculture, and community needs.[1] And much of this heat is still produced by burning coal and other fossil fuels.

Delivering useful heat is more difficult than moving electrons: Heat must arrive at the right temperature exactly where the process needs it. That's where direct-use geothermal heat stands out, as it supplies steady, on-site thermal energy without the need to convert to electricity and back or to have major grid build-outs. On an already constrained grid, the use of geothermal to provide heat improves reliability, lowers operating risks, and helps control energy costs.

India's economy is growing rapidly, with demand for energy surging across the industrial and residential sectors. The nation relies heavily on coal, which accounts for roughly 1,500 terawatt-hours of India's energy usage (doubled from 2012).[2]

From high-enthalpy heat in Himalayan provinces to low- and medium-temperature systems in Gujarat, Maharashtra, and the Northeast, India has vast untapped geothermal potential. Taken together, these regions contain 11,000 gigawatts of technical potential for geothermal industrial direct-use heat (with a 100°C cutoff temperature down to 3,500 metres). By using these resources, India can

From high-enthalpy heat in Himalayan provinces to low- and medium-temperature systems in Gujarat, Maharashtra, and the Northeast, India has vast untapped geothermal potential. Taken together, these regions contain 11,000 gigawatts of technical potential for geothermal industrial direct-use heat.

improve air quality, create skilled local jobs that leverage drilling and engineering capabilities, strengthen resilience with 24/7 local energy, and position itself as a global leader in geothermal services and standards—all while supporting national development objectives.

As outlined in this chapter and Chapter 4, "Geothermal Cooling Opportunities," direct-use heat, industrial steam, and cooling are among the biggest near-term opportunities for the nation to use its geothermal resources. This chapter focuses on heat use for industry and agriculture, while Chapter 4 focuses on geothermal applications for building cooling.

Process steam generation accounts for about 38% of India's total industrial energy consumption— comparable to the energy consumption of India's transportation sector.[3] In addition, key Indian industries such as food processing and chemicals and textile manufacturing run on steam generated by process boilers, producing 1.26 billion tonnes of steam each year. This process releases 182 million tonnes of carbon dioxide emissions, more than one-quarter of all industrial greenhouse gas emissions.[4] The decarbonisation of steam and high-temperature heat is critical to reducing India's industrial energy use and emissions.

Geothermal can deliver the same steam quality—pressure and temperature—that plants use today, slotting into existing networks while eliminating fuel purchases, reducing price volatility, and removing stack emissions. These advantages, coupled with the nation's significant subsurface potential, means India could achieve a goal of producing 10 gigawatts of geothermal process heat by 2035, 20 gigawatts by 2040, and 50 gigawatts by 2050, as suggested in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India."

How Direct-Use Geothermal Heat Systems Work

- Hot geothermal fluids from a subsurface reservoir pass through a boiler, a device that transfers heat from one fluid to another without the two fluids mixing. (The fluids are kept separate by solid walls—usually metal tubes, plates, or coils—that conduct heat efficiently.) The geothermal fluid is hotter and gives up its heat; the other fluid is water, which transforms into steam when it absorbs the heat.
- Steam is delivered via a network of pipelines to different facilities or customers.
- The high-grade heat produced can then be used as process steam for industrial purposes. The residual heat can be routed to drying, cold storage, or other processes to cascade the heat.
- After the heat dissipates from the geothermal fluids, the liquid is reinjected into the reservoir to close the loop and sustain the reservoir.

Benefits of Direct-Use Geothermal Heat to Industry and Community

- Cuts fuel costs and reduces reliance on coal or gas-powered boilers, minimising emissions.
- Improves air quality in locations with industrial clusters.
- Creates skilled local jobs in drilling, construction, and operations and maintenance while building Indian geothermal supply chains.
- Makes industry and residential heating more efficient when combined with thermal networks for residential areas.
- Unlocks cascading value by using the same geothermal resource at multiple temperature levels (for example, high-temperature steam for industrial processes, followed by lower-temperature heat for food drying, and finally absorption cooling for cold storage).
- Diversifies the energy mix with a reliable, domestic resource.

How Geothermal Compares with Other Clean Heat Options

When comparing geothermal to other clean heat options, it's important to consider project needs. Solar thermal is attractive in locations where land is available and process temperature is modest and needed during the day. Biomass can work in situations where sustainable feedstock is available but air quality and logistics constraints present potential barriers. Electric heat pumps excel at low- to mid-range temperatures when secure, affordable electricity and capacity are available.

Geothermal heat is most competitive when thermal energy is needed 24/7 year-round, land is constrained, necessary temperatures are between 150°C and 250°C, and fuel price or availability is risky. In these conditions, geothermal can provide the lowest life cycle cost, highest reliability, and largest air-quality gains.

ADVANCING DIRECT-USE HEAT IN INDIA

Thanks to India's geothermal resources,[5] direct-use systems are already at work today (**Figure 3.1**). But development remains limited because of policy gaps, high up-front costs, and a lack of technical capacity.[6] Advancing geothermal heat in the nation requires coordinated investment, resource mapping, and cross-sector collaboration.

Existing and Expandable Direct-Use Geothermal Heat Applications in India

Industrial Processes

Industrial steam offers an immediate opportunity for direct-use geothermal in India. It requires the lowest operational change while reducing fuel costs, particularly for sectors such as food processing and chemical, pharmaceutical, pulp and paper, and textile manufacturing in which most on-site fuel goes into boilers that make steam at defined pressures and temperatures. Geothermal heat can be transferred via

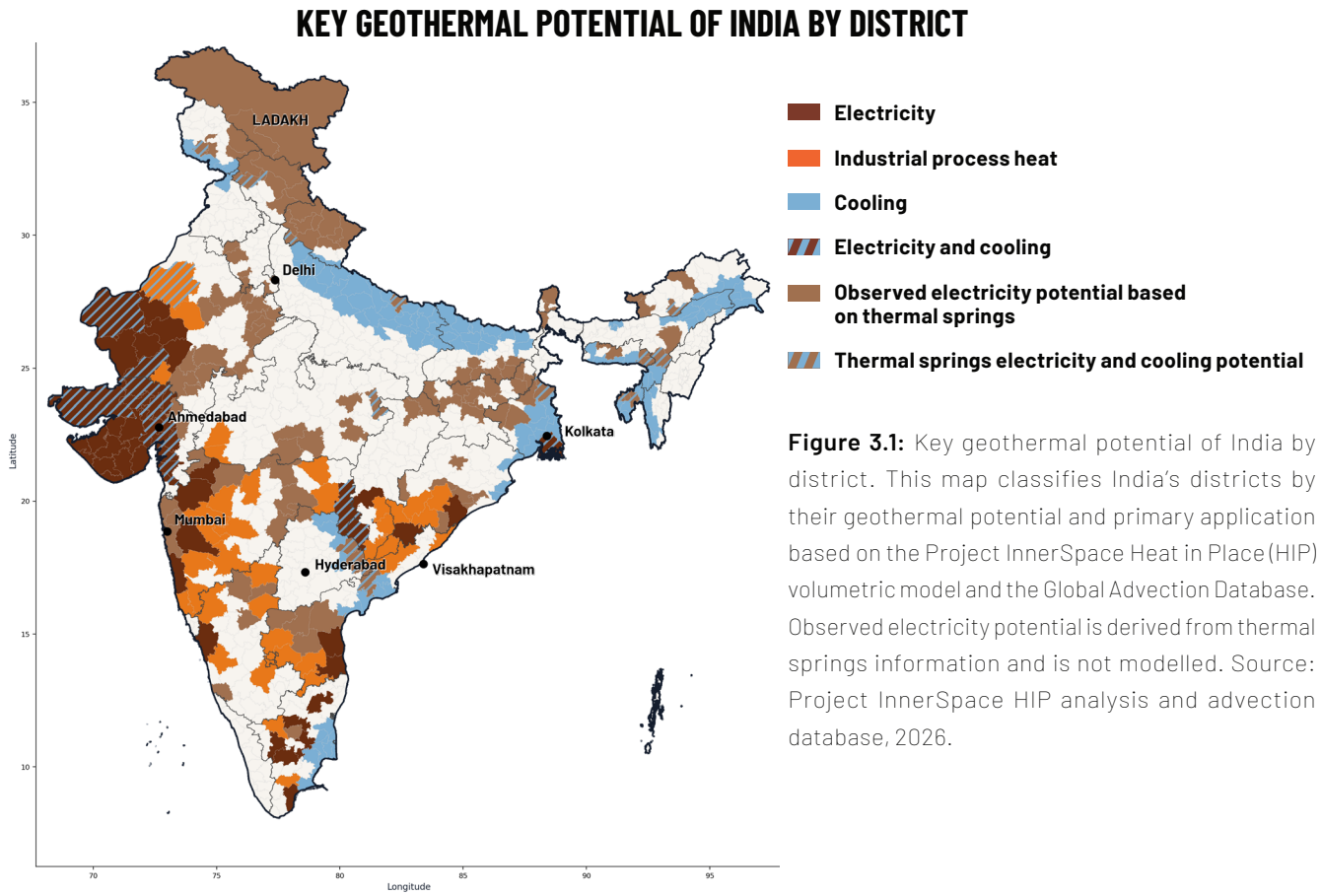

Figure 3.1: Key geothermal potential of India by district. This map classifies India's districts by their geothermal potential and primary application based on the Project InnerSpace Heat in Place (HIP) volumetric model and the Global Advection Database. Observed electricity potential is derived from thermal springs information and is not modelled. Source: Project InnerSpace HIP analysis and advection database, 2026.

GEOTHERMAL APPLICATIONS AND TEMPERATURE REQUIREMENTS

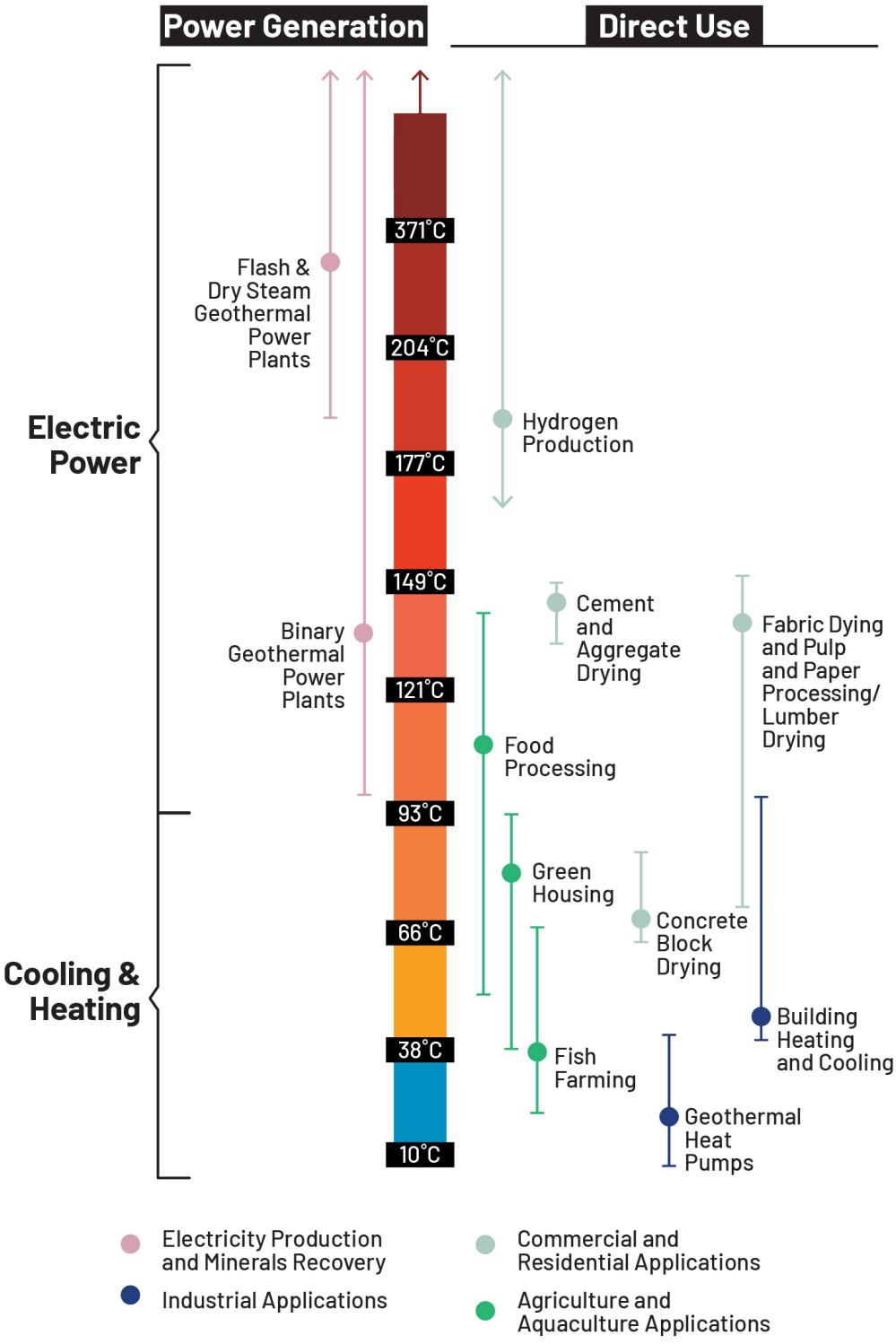

Figure 3.2: This Lindal diagram shows potential applications based on variation of temperature range. Source: Adapted from Porse, S. (2021). *Geothermal energy overview and opportunities for collaboration*. Energy Exchange.

Thanks to India's geothermal resources, direct-use systems are already at work today. But development remains limited because of policy gaps, high up-front costs, and a lack of technical capacity. Advancing geothermal heat in the nation requires coordinated investment, resource mapping, and cross-sector collaboration.

closed heat exchangers to generate matched-quality steam (in other words, steam at the same specs the plant uses today), slotting into existing steam networks with minimal retrofit needed. What's more, because geothermal delivers 24/7 heat without fuel purchases, it cuts operating costs, eliminates stack emissions, and stabilises production against fuel-price shocks.

For example, in Kenya, a cement manufacturer has partnered with a geothermal development company to use geothermal steam rather than fossil fuels for drying pozzolanic ash.[7] Implementing similar geothermal drying processes in India's construction industry could enhance energy efficiency and sustainability.

Geothermal will fit best in sites that require year-round demand; sites that use heat at temperatures between 150°C and 250°C; regions that experience fuel-price volatility; places that aren't meeting air-quality standards; and sites with the potential to cascade residual heat to drying, cold storage, and district cooling.

Industrial steam offers an immediate opportunity for direct-use geothermal in India. It requires the lowest operational change while reducing fuel costs, particularly for sectors such as food processing and chemical, pharmaceutical, pulp and paper, and textile manufacturing.

UNLOCKING INDIA'S INDUSTRIAL DECARBONISATION

Project InnerSpace conducted a case study on Aarti Industries' plant in Jhagadia, Gujarat, to determine how a geothermal industrial heat project would work in the region.

By Dani Merino-Garcia, Project InnerSpace

In India, a significant amount of fossil fuels are used to create steam for chemical, steel, and cement manufacturing; food processing; pharmaceuticals; and paper factories. Replacing fossil-fuel-fired steam with low-carbon energy is critical for both emissions reduction and long-term energy security. Project InnerSpace has studied India's geothermal potential using GeoMap, the organisation's open-access prospecting tool, and has found that Gujarat is a prime candidate for direct-use geothermal networks.

In partnership with Aarti Industries, a leading Indian chemical manufacturing company (**Figure 3.4**), Project InnerSpace conducted a feasibility study for Aarti's industrial site in Jhagadia, Gujarat, to evaluate whether coal use could be replaced in a cost-effective way with direct-use steam generation. The region has rich geothermal resources and is currently heavily dependent on coal-fired power for industry. The analysis considered a cascade process in which the residual heat from Aarti would be sent to three additional nearby facilities to produce mid- and low-pressure steam at different temperature grades (see **Figure 3.5**).

Gujarat's industrial facilities sit in a geothermal zone with a temperature gradient of more than 50°C per kilometre—twice the global average, which indicates excellent geothermal potential. To provide the high-grade steam needed in these facilities (250°C), engineers need to drill to 4 kilometres depth. At that

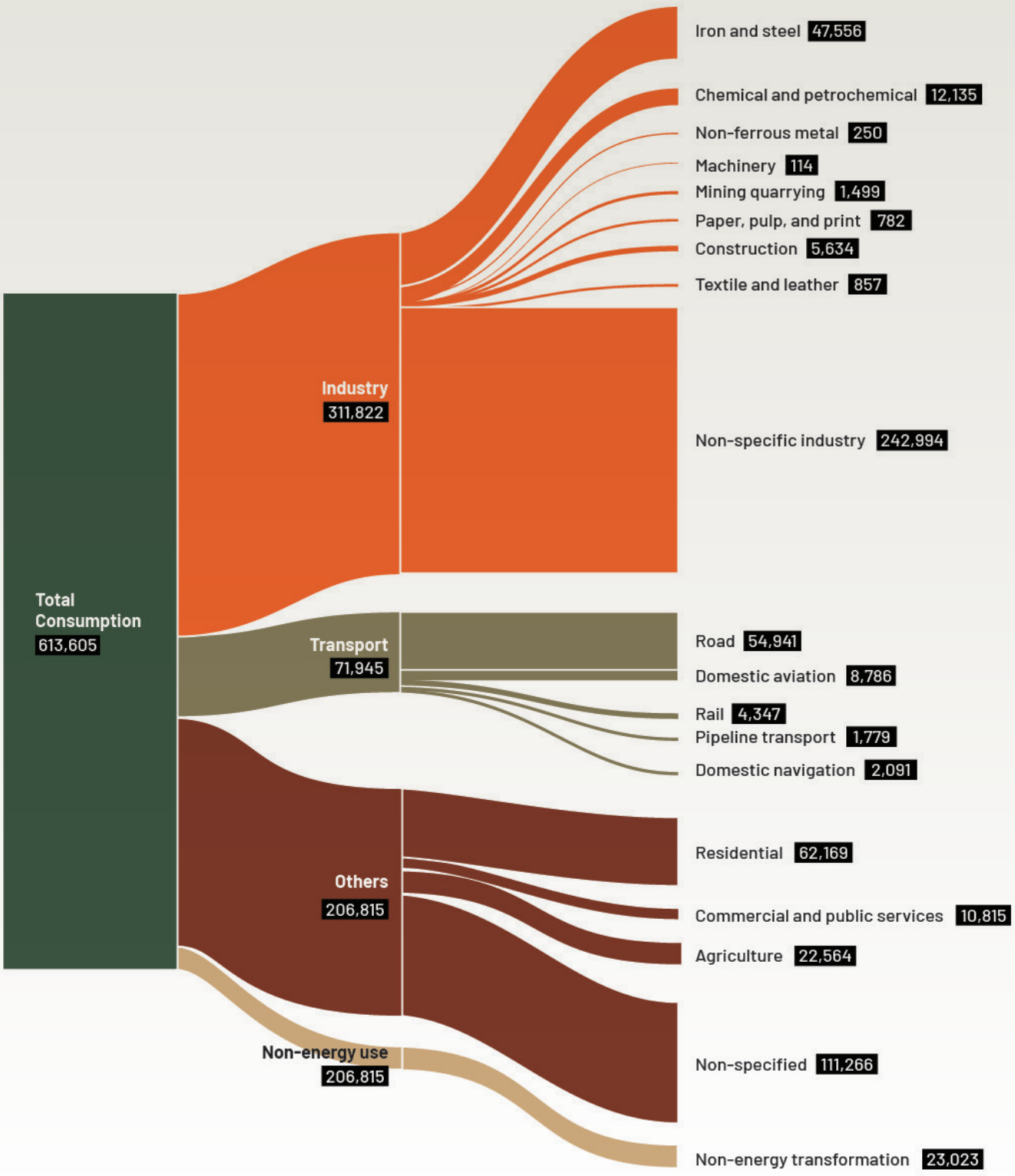

Figure 3.3: Sankey diagram of India energy use in 2024 (kilotonnes of oil equivalent). Source: Ministry of Statistics and Programme Implementation, National Statistics Office. (2025). *Energy statistics India 2025*. Government of India.

AARTI INDUSTRIES INDUSTRIAL FACILITY

Figure 3.4: Aarti Industries industrial facility in Jhagadia, Gujarat. Source: Aarti Industries.

DIRECT-USE GEOTHERMAL FOR INDUSTRIAL STEAM PROCESSES

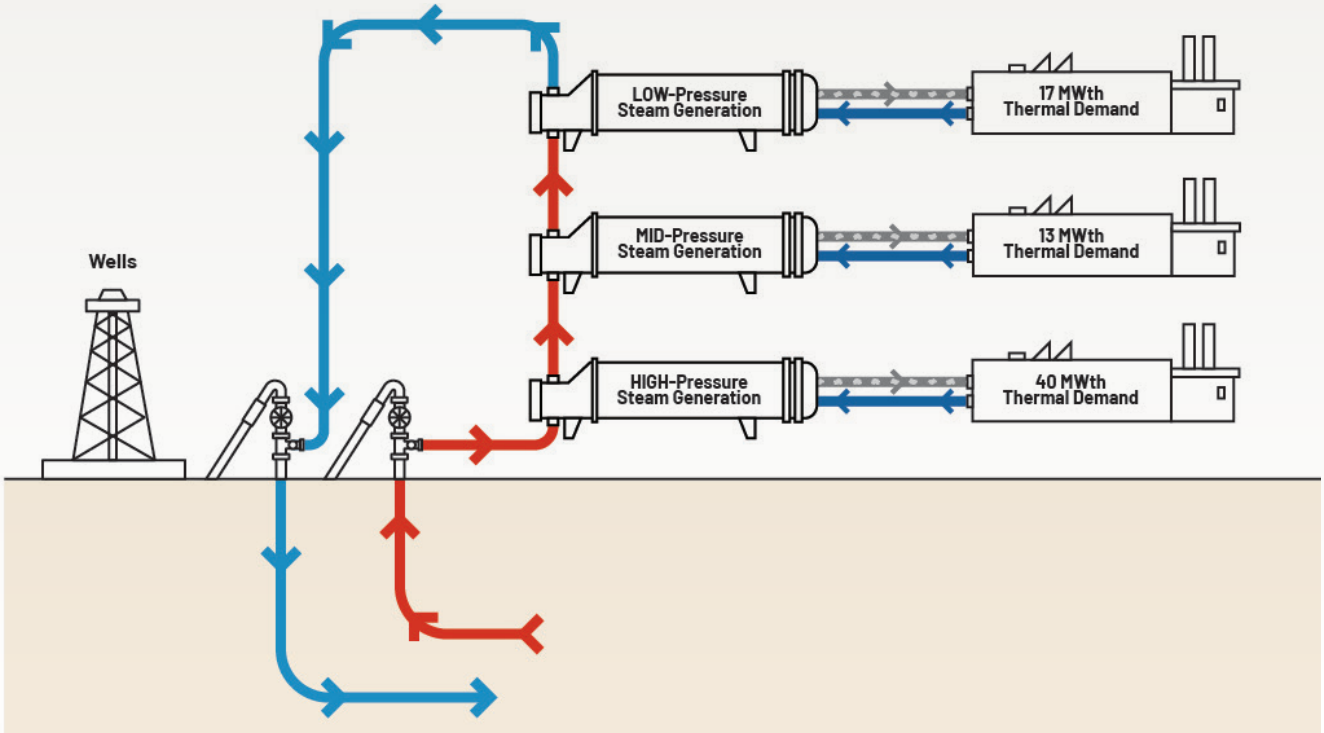

Figure 3.5: Direct use of geothermal energy to provide steam of different qualities to three facilities. MWth = megawatts-thermal. Source: Project InnerSpace.

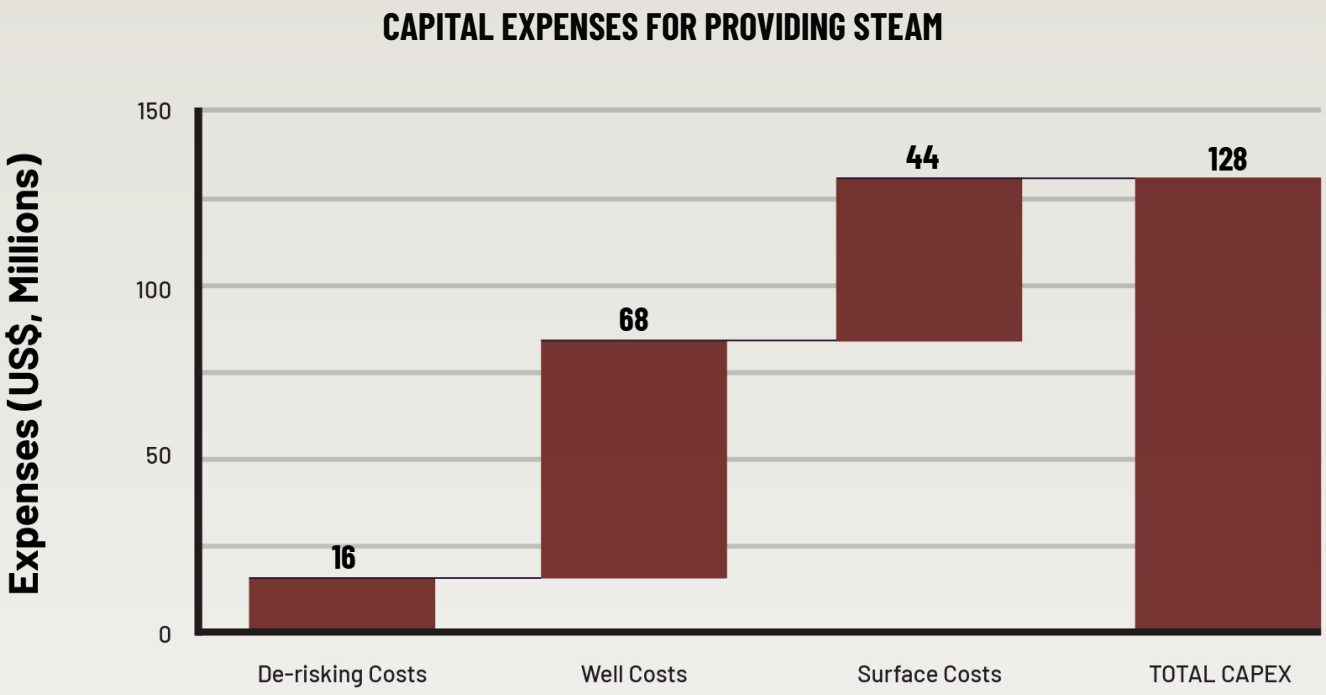

Figure 3.6: Capital expenses (CAPEX) split (US$, millions) in Gujarat case study to provide steam to four facilities. Source: Project InnerSpace.

point, the subsurface is expected to be made of fractured basement formations.

To meet all of the steam demand, the Gujarat facilities need about 200 kilograms per second of geothermal fluid at 250°C. A typical geothermal well is expected to deliver between 60 kilograms and 100 kilograms per second. Therefore, provided sufficient fracture connectivity, the study suggests drilling three production wells to sustain this output for more than 30 years.

To reduce corrosion risks and minimise operating costs in the industrial cluster, the companies prefer to work with steam and liquid water. Because geothermal fluids are prone to solid formation and tend to be corrosive, companies also want to eliminate exposure and locate boilers as close to the geothermal wells as possible so that the corrosive geothermal fluids stay out of the facilities.

Industrial processes tend to have well-optimised steam networks in which multiple processes share a steam supply. To keep costs low and make sure the system fits smoothly into existing facilities, the geothermal fluid is used to generate the same steam quality as the current boilers that use coal. This way, the facilities only receive the same clean, high-quality steam they are already accustomed to using.

In this scenario, steam production at four facilities has a potential break-even cost of between US$30 and US$35 per megawatt-thermal-hour, making it competitive with the cost of steam with coal (US$35–US$40 per megawatt-thermal-hour). These figures take into consideration the cost of a de-risking phase to unlock a project's full investment potential by properly characterising the resource via geophysics work and drilling exploration wells, the cost of drilling of three producers and three injector wells, and the cost of the fluid circulation pipeline network and the boilers for heat exchange. This cost comparison does not include any climate and air pollution benefits in switching from coal to carbon-free geothermal.

India's recently published National Policy on Geothermal Energy may further improve the economics of such a project. The policy highlights various financial support mechanisms to offset capital costs to geothermal

development, including concessional loans, viability gap funding, tax incentives, and import duty exemptions. (For more on the National Policy on Geothermal Energy and recommendations for expanding a geothermal industry in India, see Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India.")

The following steps are necessary for building an industrial direct-use system:

1. Carry out a feasibility study (as has been done for the cluster detailed above industrial buildings).
2. Conduct studies that can de-risk projects, including a geophysics campaign and the drilling of exploratory wells to characterise the resource.
3. Drill the production wells for the heat.
4. Install the equipment to transport fluid from the wells to the industrial buildings (the end users).
5. Develop an asset management system to optimise heat distribution among facilities in a cluster with variable loads and heat demands.

The Way Forward

The Gujarat industrial cluster is a microcosm of India's broader boiler-driven process heat economy—a system heavily reliant on coal, which is expensive, emission-intensive, and increasingly unsustainable. A geothermal direct-use network offers a low-carbon, reliable, and cost-effective substitute, delivering steam without fuel combustion.

Geothermal systems also offer long-term cost savings by replacing fossil fuels—with their operational expenditures and emissions—with a stable, renewable heat source. They also cut a "fuel purchase" line from a company's budget, as once a system is in place, there's no need to purchase more fuel (which is often subject to price volatility). In other words, a direct-use system improves a company's or industrial centre's global competitiveness—especially in energy-intensive sectors. Local geothermal projects also create skilled jobs in drilling, engineering, and system maintenance, contributing to regional economic development. (See Chapter 5, "Leveraging Oil, Gas and Mining Technologies and Workforce to Advance Geothermal in India.")

These are important projects to explore: Over a 30-year period, there is potential to reduce carbon dioxide by up to 7 million metric tonnes when compared to coal for this one project. A direct-use system can also reduce local air pollutants such as particulate matter and nitrogen oxides. These benefits are particularly relevant in industrial zones such as Gujarat, where air quality is affected by combustion-related emissions. At a national level, geothermal deployment would support India's climate goals by cutting industrial greenhouse gas emissions, a key step for achieving its net-zero target by 2070.

What's more, according to Project InnerSpace analysis, the footprint for such a geothermal system would be only 0.8 hectares, or 2 acres. Additionally, after steam is generated for an industrial plant, the residual energy above 90°C can be used for direct thermal applications in a residential district heating or cooling network. When integrated into thermal networks, geothermal systems enhance energy efficiency across entire clusters.

Together, these economic and environmental advantages make geothermal direct-use applications a compelling tool for industrial decarbonisation and sustainable growth.

With supportive policies—including licencing reform, fiscal incentives, and capacity building, as outlined in Chapter 7, "Who Owns the Heat? Navigating Subsurface Rights in Indian Law"—India could accelerate industrial decarbonisation, positioning geothermal heat as a strategic lever in its clean energy transition.

GEOTHERMAL WATER-BASED FOOD DRYER

Figure 3.7: Outlet of India's first-ever geothermal water-based food dryer developed by the Centre of Excellence for Geothermal Energy. Source: Bist, N., Yadav, K., & Sircar, A. (2023). Water for food drying: Geothermal energy-based food dryer. In S. Saxena, S. Shukla, & P. K. S. Mural (Eds.), *Emerging materials and technologies in water remediation and sensing: Proceedings of ICWT 2022*. Springer.

Agricultural Drying Processes

Geothermal energy is a highly promising and viable solution for food drying in India given its strong agricultural base, diverse crop production, and significant post-harvest losses. India is a leading producer of perishable crops such as mangoes, bananas, chilies, turmeric, paddy, and tea—many of which require efficient and hygienic drying processes to retain quality and reduce spoilage. Traditional sun-drying methods are often unreliable and weather-dependent, leading to microbial contamination and value loss.

Today, geothermal provides agricultural facilities with the capability to dry fruits and vegetables in various regions across India. Using geothermal energy for food drying can reduce food waste, lower energy costs, and provide a sustainable solution for rural communities. India's first geothermal-based food drying unit—at the Centre of Excellence for Geothermal Energy at Pandit Deendayal Energy University in Gandhinagar, Gujarat (see **Figure 3.7**)—harnesses geothermal heat from wells in Gujarat to power a hot air generator, which dries apples, turmeric, and other local produce.[8]

Low-enthalpy geothermal resources found in regions like Gujarat and Himachal Pradesh are ideal for direct-use applications, offering a resilient, efficient alternative to diesel or electric dryers. In the Dholera region of Gujarat, a geothermal energy–based food dryer has been developed to dry Tulsi leaves, an herb used in many Indian and Thai dishes. This drying method preserves the leaves' phytochemical properties.

Such applications can be extended to other crops, enhancing shelf life and reducing post-harvest losses. Globally, successful examples such as the geothermal fruit drying plant in Alasehir, Turkey, and the industrial-grade food dehydrator in Nayarit, Mexico, demonstrate how geothermal systems can reduce operational costs, improve product shelf life, and support sustainable agro-processing.[9,10] In India, integrating such systems in agricultural zones can enhance farmer incomes, reduce post-harvest losses, and promote energy access in rural areas.

HARNESSING EARTH'S HEAT FOR SUSTAINABLE AGRICULTURE: GEOTHERMAL COLD STORAGE IN HIMACHAL PRADESH

By Smita Satiani, Project InnerSpace

Around the world, many croplands are near untapped geothermal resources, which presents an opportunity to leverage the Earth's heat for sustainable agriculture. In Himachal Pradesh, a new project funded by Project InnerSpace aims to use that resource to enhance food security, boost rural incomes, and cut environmental footprints.

Nestled in the scenic Kinnaur district of Himachal Pradesh, Tapri is a high-altitude village known for its premium apple orchards and other produce. The region's cool climate and fertile slopes make it ideal for fruit cultivation. But the absence of reliable cold storage for these goods forces farmers to sell during peak harvest periods, when prices can be at their lowest.

Tapri, however, is also home to a naturally occurring hot spring. In other words, near these orchards is a valuable geothermal resource that has the potential to power sustainable infrastructure. This unique combination of

APPLE ORCHARDS IN KINNAUR, HIMACHAL PRADESH, INDIA

Figure 3.8: Apple orchards in Kinnaur, Himachal Pradesh, India, the location of the GeoFund pilot project. Source: Shutterstock.

GEOTHERMAL DRILLING IN HIMACHAL PRADESH

Figure 3.9: Geothermal drilling in Himachal Pradesh. Source: Geotropy.

agricultural abundance and geothermal energy makes Tapri the perfect location for a pioneering secure cold storage and crop-drying project.

Built by the company Geotropy, a geothermal project developer and consultancy, the Tapri Geothermal Cold Storage Project is designed to be a model for agricultural infrastructure in India's mountainous regions. When completed in 2026, the facility will feature a 500 tonne controlled atmosphere storage system to preserve apples and other produce for extended periods and a geothermal system for drying fruits and vegetables to minimise losses, with a capacity up to 2 tonnes per day. At the heart of the facility is a vapor refrigeration system powered by geothermal water from an existing borewell. Hot water pumped through the well from 100 metres below the surface—at approximately 96°C— will drive the absorption chiller (a heat-powered cooler that produces chilled water) to maintain optimal storage temperatures, while the residual heat will be recovered through a heat exchanger to operate the drying unit. This system maximises energy efficiency, reduces operational costs, and operates entirely on a secure and renewable heat source.

The Tapri Geothermal Cold Storage Project is also tailored to Tapri's steep terrain. The wellbore and pump housing will be located along National Highway 5; the storage building will sit on the river side of the road. The three-story structure will have equipment space; storage chambers; and areas for loading, unloading, and pre-grading activities such as inspection and cleaning. Farmers will be able to store produce for up to eight months, which lets them avoid distress sales during peak harvest periods and earn better prices.

Geothermal direct-use projects like this facility address one of India's most pressing agricultural challenges: post-harvest losses due to lack of proper storage. At the same time, they reduce reliance on diesel-powered cold chains (such as transportation and storage warehouses) that drive up costs and emissions. In horticulture-dependent regions such as Himachal Pradesh, the year-round stability of geothermal energy

FRUIT AND VEGETABLES DEHYDRATED USING GEOTHERMAL HEAT

Figure 3.10: Fruit and vegetables dehydrated using geothermal heat. Source: Geotropy.

ensures uninterrupted operation. In other words, it can relieve farmers from seasonal variability and improve the resilience of farming communities. India's cold chain and refrigerated logistics market—valued at roughly US$4 billion to US$5 billion in 2024—is projected to nearly triple to around US$12 billion by 2030.[11] This rapid expansion reflects both chronic underinvestment in storage infrastructure and rising demand for temperature-controlled supply chains. As the country scales its cold storage capacity over the next decade, the key question is not whether growth will occur, but how it will be powered.

Direct-use agriculture applications are considered the "low-hanging fruit" of geothermal development in India because they operate efficiently with moderate-temperature resources, require lower capital investment, and deliver immediate economic benefits.

Furthermore, as India seeks to scale its cold storage, geothermal offers an excellent opportunity to do so with minimal impact. Cold storage could be undertaken using methods such as those implemented in Tapri or through ground source heat pumps (described in more detail in Chapter 4, "Geothermal Cooling Opportunities").

The Tapri model is both scalable and replicable. Other geothermal-rich areas in India—such as parts of the Himalayas, Western Ghats, and Northeast—can adopt similar systems. Matching cropland to low- to moderate-temperature geothermal resources offers opportunities to deploy low-carbon cold storage solutions while also limiting post-harvest losses for nutrient-dense crops. Today, approximately 14% of food is lost between harvest and retail worldwide, contributing to between roughly 8% and 10% of global greenhouse gas emissions. Local geothermal cold storage projects such as the Tapri facility can help improve food security, stabilise rural incomes, and reduce environmental footprints.

The Tapri project is designed for community impact. It will prioritise training and hiring local workers to build community expertise, offer equitable access to storage for all village households, and extend services to nearby villages if capacity allows. Operations will follow transparent rental-based pricing, and revenues will be reinvested in the upkeep of the facilities. By uniting secure energy, efficient post-harvest handling, and local participation, Tapri's geothermal project offers a blueprint for sustainable rural transformation.

GEOTROPY TEAM MEMBERS

Figure 3.11: Vijay Chauhan with the Geotropy team. Source: Geotropy.

Vijay Chauhan: Bringing Geothermal Innovation Home

For Vijay Chauhan, the CEO of Geotropy, the journey with geothermal energy is as much personal as it is professional. A native son of an apple-growing community, he sees in the Earth's heat not only power but also a way to give back to the land that raised him. Chauhan earned his doctorate in mechanical engineering at Háskólinn í Reykjavík and worked in the geothermal fields in Iceland. At the Iceland Deep Drilling Project, he researched the frontier of superheated steam, devising new techniques for its use in power generation.

Today, Vijay straddles the worlds of innovation and education as an adjunct faculty member at Reykjavik University. Through his leadership at Geotropy, he comes full circle—channeling the lessons of Iceland into sustainable energy solutions for his own community in Himachal Pradesh.[12]

Greenhouse Cultivation

Geothermal greenhouse farming is a viable direct-use application in India, enabling year-round cultivation of fruits and vegetables in cold or arid regions such as Ladakh, Himachal Pradesh, and parts of Gujarat, where traditional farming is limited. By using geothermal heat for temperature control, crops such as tomatoes and leafy greens can thrive, improving food security and farmer income.

There are some global examples of this use: In Türkiye, the Sultan Sera facility in Aydın uses geothermal energy for soil-less tomato farming on once-unusable land, while Sandıklı exports geothermal-grown tomatoes to Europe, proving its commercial success.[13,14]

India's pioneering efforts in geothermal greenhouse cultivation, led by Kunzes Dolma (the author of Chapter 6 in this report, "India's Stakeholders: Opportunities and Implications for Geothermal Growth and Development"), have taken root in the high-altitude region of Chumathang, Ladakh, where a pilot greenhouse project has successfully demonstrated the use of geothermal heat for year-round vegetable farming.[15] Using training in Iceland, the

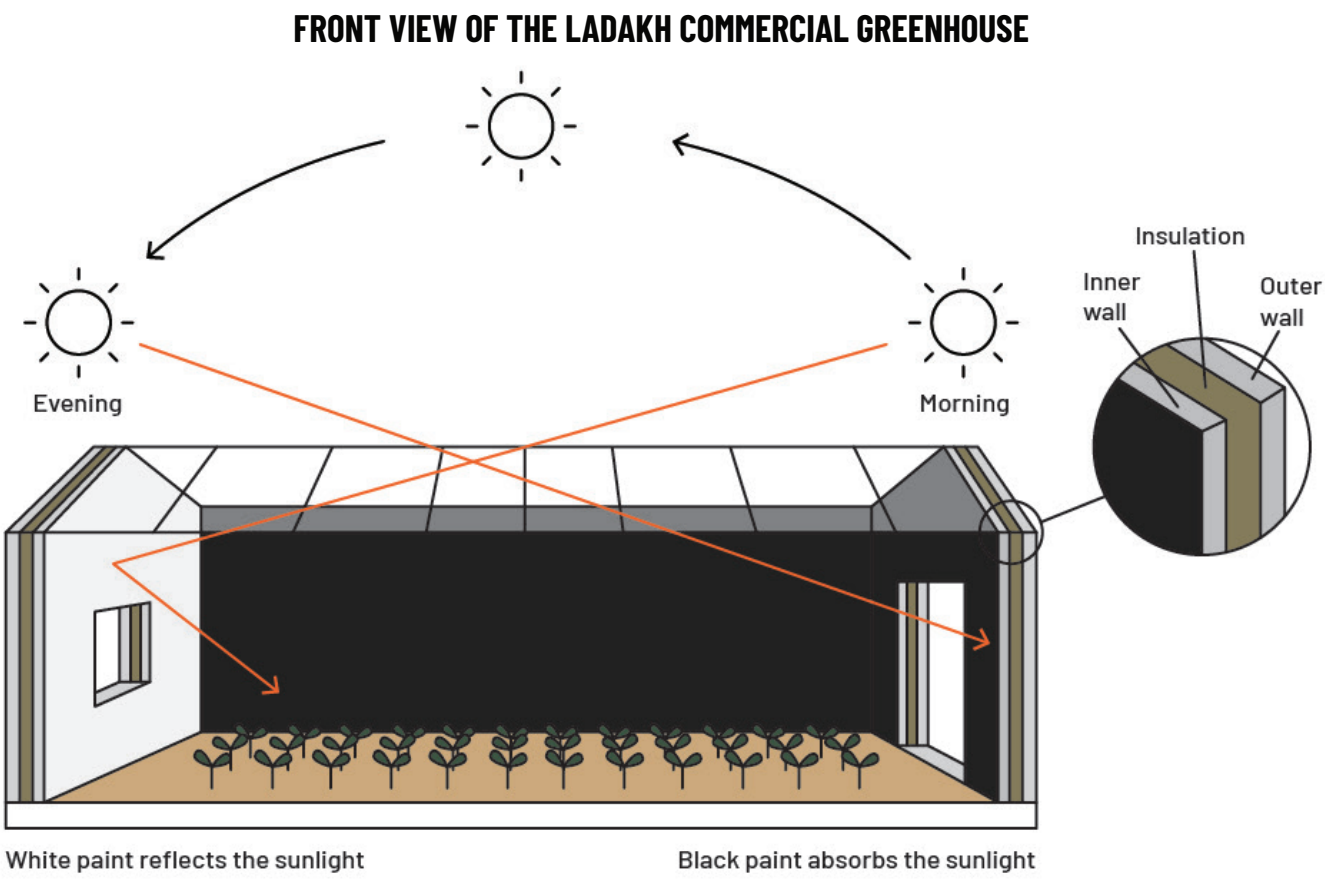

Figure 3.12: Schematic of a front view of the Ladakh commercial greenhouse. Source: Dolma, K. (2020). *Energy and food security using geothermal energy: A case study of Chumathang, Union Territory of Ladakh, India*. Master of science thesis, GRÓ Geothermal Training Programme. Re-created by Project InnerSpace.

project brought a sustainable solution to the harsh winter conditions of Ladakh, where temperatures often plummet below -20°C. The greenhouse taps into naturally heated groundwater, maintaining optimal growing temperatures without the need for fossil fuels. (See **Figure 3.12**.) This innovative approach has significantly improved local food security, reduced dependence on imported vegetables, and empowered rural women through active participation in agricultural operations.

Aquaculture

Geothermal energy offers a sustainable solution for aquaculture, especially in maintaining optimal water temperatures. In the Philippines, for instance, geothermal resources are used to heat aquaculture ponds, enhancing the growth rates of species such as tilapia and shrimp. This use reduces fuel costs by up to 80% and minimises the need for antibiotics due to the presence of beneficial minerals in geothermal water. In India, the Directorate of Coldwater Fisheries Research has developed polyculture techniques for exotic carp species in mid-altitude regions, which could benefit from geothermal heating to maintain optimal growth temperatures. In India, regions with geothermal potential, such as parts of Gujarat and Andhra Pradesh, can leverage this energy source to boost aquaculture, particularly for species like carp, which thrive in warmer waters.

Honey Processing

The Centre of Excellence for Geothermal Energy has also pioneered the direct use of geothermal energy for honey processing. The centre developed an integrated system at Dholera, where geothermal water between the temperatures of 45°C and 75°C is used for honey pasteurisation and

enzyme deactivation, reducing energy consumption.[16] The system includes plate-type heat exchangers and supports other applications such as milk pasteurisation, space heating, and food drying, making a significant step towards sustainable agro-processing in India.

Thermal Baths

India's geothermal hot springs are an important part of the nation's history and culture. They include prominent sites in Gujarat, such as Tuwa, Unai Dholera, Lasundra, and Tulsishyam, where thermal waters are rich in sulphur and other minerals. These springs have surface temperatures ranging from 60°C to 90°C and are known for their anti-inflammatory and antimicrobial properties that makes them effective for the treatment of arthritis, skin disorders (psoriasis and eczema), and muscular pain.[17]

In Manikaran and Tattapani (Himachal Pradesh), Surajkund (Jharkhand), and Puga Valley (Ladakh), people frequent thermal baths for religious and medicinal purposes. In Uttarakhand, the Badrinath hot springs near the Alaknanda River are famous for postpilgrimage rejuvenation. Ganeshpuri and Akaloli (Maharashtra) are major sulphur spring sites near Mumbai. Across India's more than 400 geothermal spring locations, the natural presence of sulphur compounds has made these sites essential for traditional healing, naturopathy, and wellness tourism. (See **Figure 3.13**.)

Traditional hot springs in Manikaran, Tattapani, and Bakreshwar show the potential for India to develop more hot springs for bathing purposes. Iceland's Blue Lagoon serves as a model for boosting tourism through luxury spa and medical facilities.[18]

Cloth Drying

Geothermal energy holds significant potential for India's textile industry, particularly in cloth drying, an energy-

GEOTHERMAL HOT SPRING NEAR MANIKARAN TEMPLE

Figure 3.13: Geothermal hot spring near the Manikaran temple in Himachal Pradesh, India. Source: Shutterstock.

intensive process. Although currently underutilised in India, geothermal heat is being used for drying in the Wayang Windu geothermal field in Indonesia. Hot geothermal fluids are piped to heat exchangers and create the hot air used in tea-drying units.[19] This approach replaces conventional fossil fuels, reducing both energy costs and emissions. In India, textile hubs such as Gujarat and West Bengal could benefit by leveraging nearby geothermal sources, such as those in Unai or Bakreshwar, for fabric drying. Implementing such systems would require feasibility studies, pilot projects, and supportive policy frameworks to promote resilient and efficient industrial practices.

Direct geothermal applications should be prioritised in regions with low- to moderate-temperature uses that align with the socioeconomic conditions of rural and semi-urban areas. Applications such as food drying, community bathing, and greenhouse farming should be high on the list because of resource availability and daily applicability. These uses appeal to large populations whose access to a resilient and stable source of energy is limited. Emphasis should also be placed on decentralised, low-cost solutions that improve quality of life and reduce fuel dependency. Development should balance economic aspects with social impact—in favour of inclusive and sustainable development.

DELAYED, ABANDONED, OR STALLED GEOTHERMAL PROJECTS AND ASSOCIATED CHALLENGES

Despite the many successful projects, a number of geothermal projects in India have been delayed, abandoned, or underdeveloped. Understanding why projects experienced setbacks can help inform future projects. Common challenges include environmental and permitting risks, insufficient subsurface data, design and equipment shortfalls, financing gaps, lack of an offtaker, and higher-than-expected costs (all of which are discussed in more detail in the following sections).

Dholera Geothermal Project, Gujarat

A small-scale geothermal plant was installed in the Dholera region in Gujarat, via the Centre of Excellence for Geothermal Energy, for heating and cooling. Future plans for the plant included electricity generation through Organic Rankine Cycle technology. Project installation was successful, yet it faced financial challenges. The project started at ₹1 crore, but operating expenses were between 20% and 25% higher than typical conventional methods.[20] Based on the author's assessment, indications for cost recovery in three years failed to overcome the initial investment barriers, which slowed widescale duplication.

Understanding why projects experienced setbacks can help inform future projects. Common challenges include environmental and permitting risks, insufficient subsurface data, design and equipment shortfalls, financing gaps, lack of an offtaker, and higher-than-expected costs

Tapovan Geothermal Prospect, Uttarakhand

In Tapovan, Uttarakhand, the Wadia Institute of Himalayan Geology identified hot springs with surface temperatures between 89°C and 93°C, suitable for low-enthalpy applications. A memorandum of understanding was signed with Jaydevm Energies Private Limited to develop a 5 megawatt geothermal power plant at the site.[21] However, scientists have raised concerns about the environmental sensitivity of the area, particularly due to the proximity of the subsidence-prone town of Joshimath. Potential issues include noise and vibrations from drilling activities, which could exacerbate land instability. As a result, while geothermal potential exists, the project faces environmental and logistical challenges that have delayed its implementation.[22]

Bakreswar Geothermal Area, West Bengal

Medium-enthalpy geothermal systems exist in the Bakreswar region of West Bengal, which has significant potential. An analysis of magnetotelluric studies exposed conductive areas below the surface that indicate the presence of geothermal reservoirs. But development in the area remains slow because there is not enough investment or quality local infrastructure and advanced geophysical methods are not used.

SCALING DIRECT-USE GEOTHERMAL

In India, scaling direct-use geothermal will hinge on a few essentials: building talent and research and development capacity; streamlining permitting and land access with early community engagement; and taking the risk out of capital. As mentioned, Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," provides specific, actionable recommendations for expanding direct-use geothermal in India. Hitting these marks would deliver enormous benefits: lower energy costs and import dependence; cleaner air in industrial corridors; stronger grid resilience through 24/7 local heat; globally competitive manufacturing; and the potential creation of between 350,000 and 700,000 skilled jobs across drilling, fabrication, and operations and maintenance.

To integrate direct-use geothermal into India's industrial and commercial heating infrastructure, a structured plan is essential. The roadmap starts at pilot deployments, then moves to broader market scale-up and finally, as costs fall, to district-wide systems. This map is complementary to the policy solutions outlined in Chapter 8.

The roadmap has three steps:

1. **2025–2030:** Pilot direct-use projects in industrial clusters, funding exploration, wells, and heat-exchange equipment.
2. **2030–2040:** Scale projects to commercial and residential markets with standards, technician training, and tighter operating cost management.
3. **2040–2050:** Deploy district networks and grid-integrated systems at scale as technology matures, targeting payback timelines of six to eight years.

POTENTIAL ROADMAP FOR DIRECT-USE IMPLEMENTATION

Phase 1: Pilot Demonstration (2025–2030)

- Target industrial clusters (e.g., food processing, textiles).
- Focus on direct-use systems for thermal applications.
- High CAPEX: drilling, exploration, reservoir evaluation.
- Deploy in high-enthalpy zones.
- Require R&D support, risk-sharing, public-private partnerships.
- Objective: Technology validation and localised success models.

Phase 2: Expansion and Standardisation (2030–2040)

- Scale to commercial and residential sectors.
- Develop standard building codes and safety guidelines.
- Roll out training and workforce development programs.
- Focus on OPEX management: heat pumps, system monitoring.
- Policy integration and urban utility planning.
- Objective: Mainstream adoption and regulatory framework.

Phase 3: Full Deployment and Grid Integration

- Establish direct heating networks.
- Optimize OPEX with automation and predictive maintenance.
- Encourage private sector investment through policy certainty.
- Aim for carbon offset benefits and long-term energy cost savings.
- Objective: Sustainable, large-scale geothermal heating transition.

Figure 3.14: Roadmap for implementing direct-use geothermal in India based on capital and operating expenditures (CAPEX and OPEX, respectively). Source: Adapted from author by Project InnerSpace.

CONCLUSION

India has substantial resources for geothermal energy, particularly for direct-use heat. Using geothermal energy for industrial steam boilers, food and crop drying, food processing, greenhouse cultivation, balneotherapy, and other direct-use processes has proven successful and can be an important part of India's economy going forward. The programs carried out at Indian School of Business Mohali, the Centre of Excellence for Geothermal Energy project in Gujarat, and the Geotropy project in Himachal Pradesh saw energy use fall by 55%, making them beneficial to local communities. Still, the lack of a national policy, insufficient technical experience, and lengthy approval processes for environmentally important areas such as Puga Valley and Tapovan represent ongoing challenges to direct-use geothermal heat.

The case studies and experiences outlined in this chapter provide a roadmap for how to achieve the suggested geothermal goals for industrial direct-use heat: 10 gigawatts by 2035, 20 or more gigawatts by 2040, and 50 or more by 2050. A successful scaling of geothermal requires exploring ideas at the pilot level and getting support from policymakers, standardising geothermal's industrial use from 2030 to 2040, and increasing use in industrial clusters with heat cascaded to agricultural drying and cold storage between 2040 and 2050. In rural areas, food drying and greenhouse farming should be prioritised, as geothermal energy can prevent food spoilage and increase sufficiency of food resources. Using viability gap funding, forming public-private groups, and working with countries such as Iceland can help reduce risks and boost the adoption of these solutions. By building expertise, creating a streamlined approach to development, and engaging the community, India can use geothermal energy as a vital part of sustainable and responsible growth. Prioritising industrial steam first—while expanding high-impact uses like drying and greenhouses—will deliver cleaner air, stronger energy security, competitive industry, and skilled jobs at scale.

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Chapter 4

Geothermal Cooling Opportunities

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Geothermal cooling from ground source heat pumps and sedimentary aquifers is a powerful low-carbon option that can help meet India's growing and urgent cooling needs. The nation has an estimated 610 gigawatts of aquifer cooling potential in areas with high heat risk—and more than 1,500 gigawatts of total potential for aquifer cooling across the country.

As the most populous country in the world, India is at the forefront of a changing climate. In recent years, the nation has seen an increase in the frequency, intensity, and duration of extreme heat events, with daytime temperatures exceeding 45°C for extended periods of time in certain parts of the country.[1] This escalation in heat—compounded by urbanisation, humidity, and prolonged warm nights—is not only a climate hazard but also a multidimensional problem that affects human health and productivity, water availability, agriculture, and energy infrastructure.

According to the Council on Energy, Environment and Water (CEEW), more than one billion people across 57% of India's districts live in zones with high to very high heat risk.[2] The health risks of such heat can be severe if people do not have access to cooling, though space conditioning has been shown to significantly enhance health, quality of life, and productivity. This growing heat burden threatens to reduce India's gross domestic product (GDP) by more than 5% by 2030—and in absolute terms is expected to cause the loss of the equivalent of 34 million full-time jobs.[3]

Using traditional air-conditioning to meet this challenge would require an enormous amount of energy, roughly 40% more than India currently produces.[4] This level of energy use would, in turn, produce an additional 810 million tonnes of carbon dioxide equivalent (CO_2e) emissions annually by 2037.[5] To put it another way, the projected energy increase for cooling alone in India would be in the top 10 of global CO_2 emissions unless the country takes action to use more efficient cooling approaches.

BY THE NUMBERS

- **323 million** people in India are at high risk due to heat.[6]
- Only **7%** of households in India have access to air conditioners.[7]
- **2024** was recognised as the hottest year globally since records were first kept.[8]
- Many states in India faced daytime temperatures above 40°C for an entire month in 2024, leading to more than **44,000** cases of heatstroke.[9]

These alarming figures underscore the need for a solution. By leveraging the thermal stability of the Earth's subsurface in India, geothermal can provide powerful and efficient cooling to buildings via ground source heat pumps (GSHPs) and district cooling networks. (See "GSHP and District Cooling Network Installation in India" in this chapter and Chapter 1, "Geothermal 101: Overview of Geothermal Technologies and Applications.") Both solutions offer a renewable and round-the-clock alternative that reduces electricity use and peak load on the grid. Geothermal district cooling is especially suited to India's sediment-rich basins, where high-permeability aquifers are often found in the subsurface of densely populated urban zones under acute heat stress.

In 2019, to address the sustainability of the nation's growing need for cooling, the Ministry of Environment, Forest and Climate Change launched the India Cooling Action Plan (ICAP), a national campaign to reduce cooling demand by between 20% and 25% by 2038.[10] ICAP does not directly address ground source heat pumps or geothermal cooling, but it does note the importance of district cooling and the increased use of efficient cooling options. More recently, India launched the 2025 National Policy on Geothermal Energy, which authorises the Ministry of New and Renewable Energy (MNRE) to support direct-use cooling applications through pilot projects and other policy mechanisms.[11]

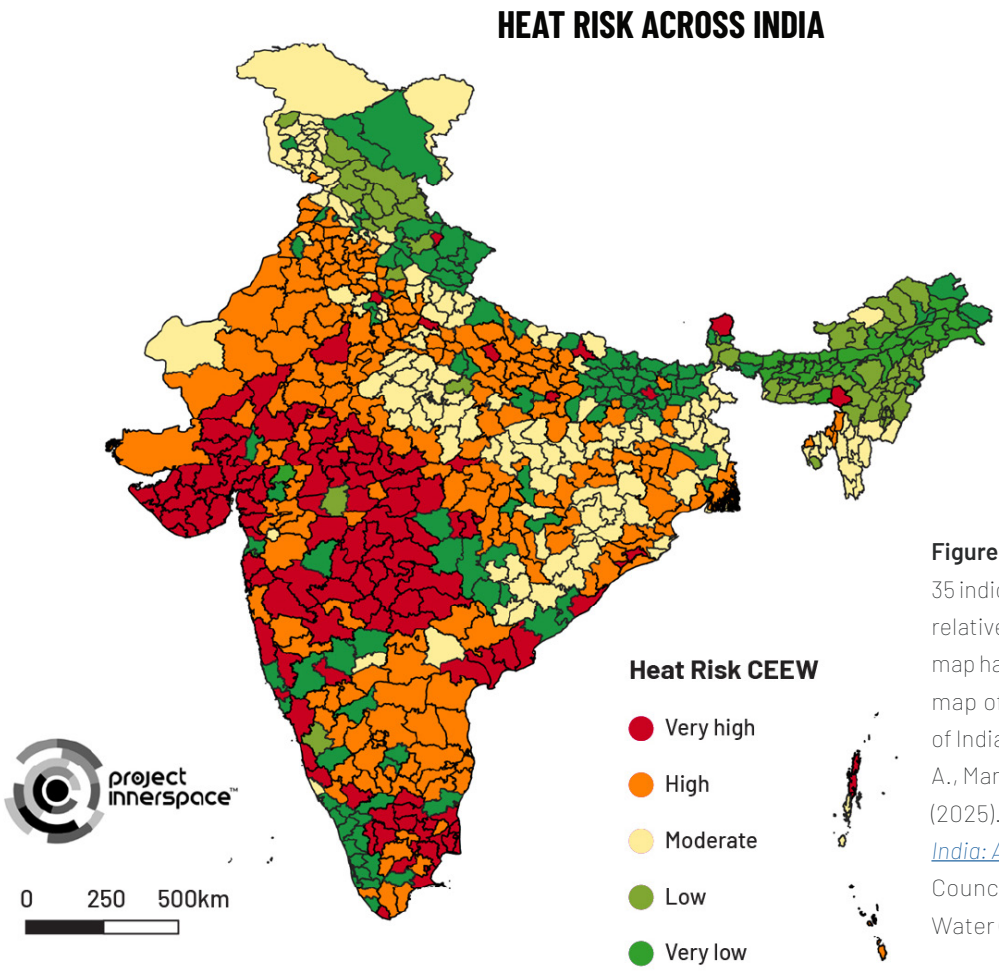


Figure 4.1: The data for this map include 35 indicators, including nighttime heat, relative humidity, and vulnerability. The map has been modified from the CEEW map of heat risk across 734 districts of India. Source: Prabhu, S., Suresh, K. A., Mandal, S., Sharma, D., & Chitale, V. (2025). *How extreme heat is impacting India: Assessing district-level heat risk.* Council on Energy, Environment and Water (CEEW).

However, given the staggering impacts of rising temperatures and the unsustainability of traditional air-conditioning, geothermal should be part of the Indian cooling solution going forward, either through district cooling or ground source heat pumps (GSHPs). The country has more than 1,500 gigawatts of potential geothermal cooling capacity—and much more when including GSHPs. Gujarat, Gandhinagar, Anand, Mahesana, and Kheda offer the most promise for district cooling solutions. Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," notes how important it can be for India to develop a national geothermal cooling mission that can launch these more efficient (and potentially lifesaving) technologies—and take advantage of this significant untapped cooling potential.

ELECTRICITY DEMAND FOR COOLING

As the world's seventh-largest country by land area, India encompasses a wide range of climatic zones. Most of its citizens live in hot climates. The National Building Code of India recognises five zones for heating, ventilation, and air-conditioning (HVAC) and building design.[12] (See **Figure 4.7**.) One study covering 60 cities across India found that there were 171,974 total cooling degree days, compared with only 6,088 heating degree days.[13] Another study analysed data from 14,500 weather stations across 219 countries and ranked India as first worldwide in total cooling degree days exposure (a product of the population and annual cooling degree days).[14]

For many years, air-conditioning was mostly confined to hospitals, cinemas, commercial spaces, and high-end residences. As of 2017, only 8% of India's households had air-conditioning units, which amounted to about 40 million homes.[15] That figure is now projected to grow threefold, to 170 million by 2027 (**Figure 4.2**).[16,17,18]

Currently, the most common types of air-conditioning are fans, air coolers, room air-conditioning, packaged direct expansion systems, variable refrigerant flow systems, and chillers. Fans are widely used because they are simple and inexpensive and generally have low power requirements. Commercial buildings and large luxury residences primarily use large systems such as packaged direct expansion systems, variable refrigerant flow systems, and chillers.

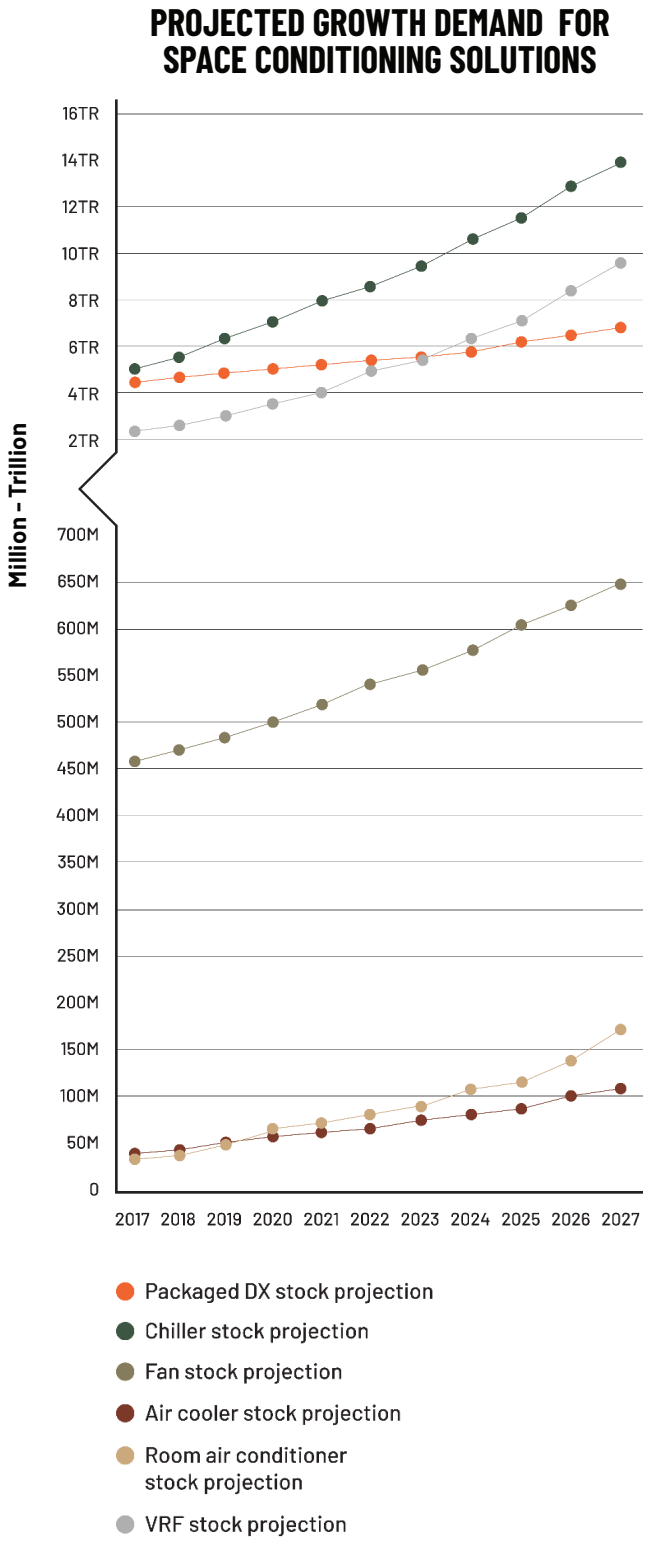


Figure 4.2: Projected growth in the demand for various space conditioning solutions in India. DX = packaged direct expansion system; TR = tonnes of refrigeration; VRF = variant refrigerant flow system. Source: Kumar, S., Sachar, S., Kachhawa, S., Goenka, A., Kasamsetty, S., & George, G. (2018). *Demand analysis of cooling by sector in India in 2027*. Alliance for an Energy Efficient Economy.

The total electricity generation in India for 2023–24 was about 1,734 terawatt-hours.[19] Out of this amount, close to 200 terawatt-hours—or around 10% of the total—are estimated to have been used for space cooling needs.[20]

In 2024, approximately 73% of the fuel used for electricity power generation in India was coal-based (**Figure 4.3**). In other words, a meaningful amount of India's total air pollution and climate emissions stems from demand for cooling.

Out of this amount, close to 200 terawatt-hours—or around 10% of the total—are estimated to have been used for space cooling needs.

This growing demand is already placing enormous strain on India's power grid—and the situation will only get worse. Even if it were possible to install traditional HVAC across the country, the energy and emissions costs would be enormous, requiring 180 gigawatts of additional power[21] and generating an additional 810 million tonnes of CO_2e emissions annually by 2037,[22] which would put India's energy demand for cooling alone in the top 10 causes of CO_2 emissions globally.[23] This level of demand underscores the urgent need for sustainable cooling solutions that can operate at scale without exacerbating emissions.

ELECTRICITY GENERATION BY SOURCES, 2024-2025

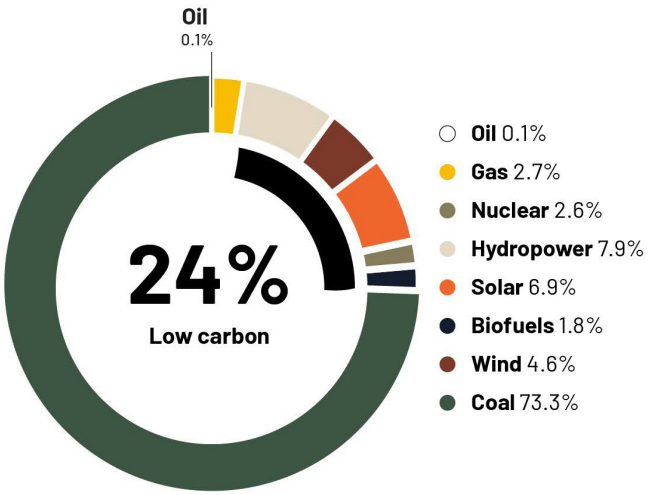


Figure 4.3: Electricity generation by source in India from September 2024 to August 2025. Source: Low Carbon Power. (n.d.). *Electricity in India in 2024/2025*.

Even though India has the fifth-largest coal reserve in the world, it still has to import coal to meet its power generation requirements.[24] Adopting district cooling systems and GSHPs across the nation can help India meet its rising energy demands with a clean, homegrown energy source that reduces dependence on fossil fuels.

CO_2 EMISSIONS FROM COOLING TECHNOLOGIES

	2017		2037 (Projected)	
Type of System	**Energy Consumption (TWh)**	**CO_2 Emissions (million tonnes)**	**Energy Consumption (TWh)**	**CO_2 Emissions (million tonnes)**
Room air conditioner	56.7	40.4	304.2	216.9
Chiller system	12.2	8.7	64.4	45.9
Variable refrigerant flow system	4.1	2.9	52.7	37.5
Packaged direct expansion system	10.8	7.7	23.4	16.7
Fan	40.5	28.9	64.4	45.9
Air cooler	10.8	7.7	76.1	54.2
Total	**135.0**	**96.3**	**585.0**	**417.1**

Figure 4.4: Projected carbon dioxide (CO_2) emissions from cooling technologies between 2017 and 2037. TWh = terawatt-hours. Source: Adapted from data in Ozone Cell, Ministry of Environment, Forest and Climate Change. (2019). *India Cooling Action Plan*. Government of India; combined with data from Our World in Data. (2025). *Carbon intensity of electricity generation, 2000 to 2024*.

EQUITABLE OPTIONS: GSHPS AND DISTRICT COOLING

In many parts of India, access to cooling technologies remains deeply inequitable. Air-conditioning is still scarce outside of urban high-income areas, but India's rising income levels are accelerating the adoption of air-conditioning well beyond the wealthy elite.

Although electric fans are still the primary space-conditioning tool for much of the country, more Indians are adding room air conditioners to their homes as they become more affordable. The share of space cooling in India's peak electricity load is projected to rise from around 10% in 2018 to nearly 45% by 2050.[25]

Meeting this rapidly growing demand affordably and sustainably is complicated. While solar power will account for roughly one-third of cooling-related generation additions,[26] solar's daily generation pattern does not always align with evening cooling needs, forcing the grid to maintain costly peak capacity. GSHP technology—with or without deeper district cooling—is emerging as a promising solution.

GSHPs are particularly useful for urban environments, institutional campuses, and army bases. These systems harness the Earth's relatively stable shallow subsurface temperature so they can serve as a heat sink for cooling via electrically driven heat pumps. Because GSHPs use these stable temperatures, they can be twice as efficient as air source heat pumps and can be up to 70% more efficient than traditional HVAC solutions.[27] They can also deliver between three and five units of cooling per unit of electricity.[28] The more extreme the outside air temperature is, the more efficient GSHPs are, making them particularly well suited for India's climate.[29] Additionally, by using electricity only for compression, GSHPs significantly reduce cooling-related electricity demand and emissions compared with traditional HVAC

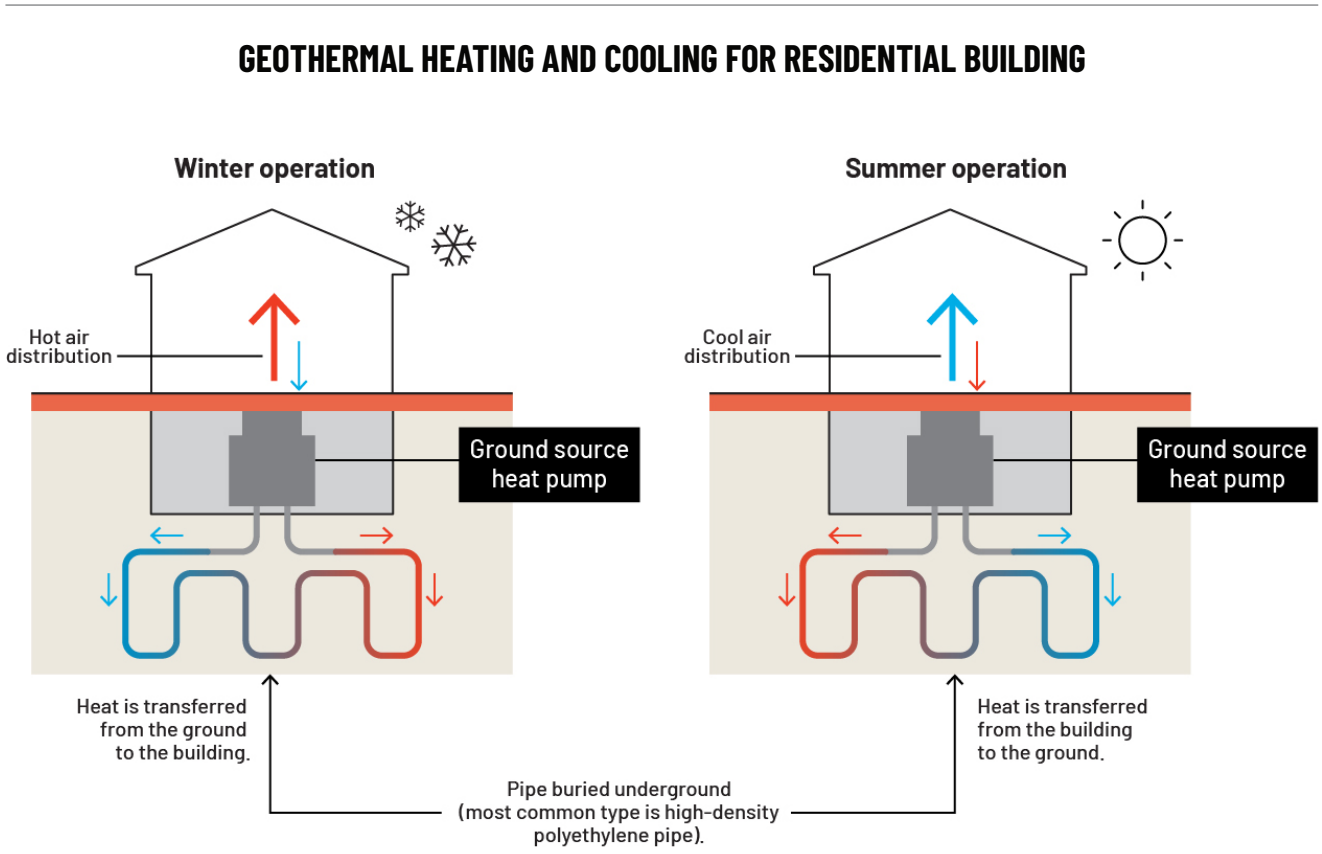


Figure 4.5: Geothermal heating and cooling for residential buildings. Source: Adapted from Lund, J. W. (2025). *Geothermal energy*. Encyclopedia Britannica.

systems. The electricity used by these systems can come from the grid, or the systems can be set up to run on solar and storage, ensuring the cooling system remains operational even if the grid is stressed.

The Indian Army's Net Zero Energy Building in Jhansi, commissioned in 2025, provides a compelling demonstration of GSHP technology. The facility uses 10 vertical boreholes that are 120 metres deep and connected to a closed-loop GSHP system, maintaining indoor temperatures at 22°C when outdoor extremes reach 43°C. Supported by rooftop solar photovoltaics, the building functions as an off-grid geothermal-cooled system and serves as a replicable model for cantonment and institutional infrastructure across India.[30]

GSHP systems are broadly configured as follows:

- **Open-loop groundwater systems:** These systems extract and reinject aquifer water via heat exchangers and are viable where groundwater and regulatory clearances permit.
- **Horizontal closed-loop systems:** These systems involve shallow pipe loops buried between 1.5 metres and 2 metres underground and are effective for low-density developments with land availability.
- **Vertical closed-loop systems or borehole heat exchangers:** These systems drill to depths of between 60 metres and 150 metres and are ideal for buildings in densely populated areas due to their small surface footprint and high efficiency.

ADDED BENEFITS: DISTRICT COOLING NETWORKS

GSHP systems are highly compatible with next-generation district cooling networks (DCNs), which make it possible to distribute cooling power across multiple buildings.

In fourth-generation DCNs, a centralised energy station integrates GSHP arrays with either open-loop aquifer doublets or buried closed-loop collectors. Cooled water is distributed via insulated pipes to selected buildings, which extract cooling using heat interface units. This setup is suitable for smart city districts, government estates, and commercial precincts with coordinated infrastructure (see **Figure 4.6**).[35]

GSHP Cooling Deployment Across India's Various Climates

Regional studies include those by Chedwal and colleagues and Shahare and Harinarayana, which evaluated GSHP applications in Rajasthan and Gujarat, respectively.[31,32] Roy and colleagues conducted detailed simulations across 10 cities, including five Indian locations—New Delhi, Jodhpur, Chennai, Bengaluru, and Srinagar—each representing distinct climate zones and soil characteristics. Their findings indicate that except for Srinagar, the deployment of GSHPs in Indian cities would require hybrid systems and custom designs to ensure economic viability.[33] Aggarwal and colleagues echoed these thoughts, emphasising that geothermal space conditioning in India remains in its nascent stages.[34] They highlight the country's predominantly hot and humid climate, suggesting that building designs must account for high cooling demand and peak load mitigation through an in-depth understanding of building physics. Optimisation of GSHP systems must be building specific, taking into consideration local climate, seasonal variation, soil properties, and both space cooling and hot water requirements.

More advanced fifth-generation DCNs distribute ambient-temperature heat-transfer fluids through a shared-loop connected to borehole fields or aquifers (see **Figure 4.6**). Each connected building has its own small heat pump that extracts or rejects thermal energy as needed.[36] These ambient networks require no insulation, reduce operational losses, and decentralise power use—making them ideal for integrating with solar photovoltaics. Clients are responsible for their own electricity use, which simplifies financial models and allows for demand balancing across residential, institutional, and commercial cooling loads.

GEOTHERMAL COOLING AND HEATING NETWORK

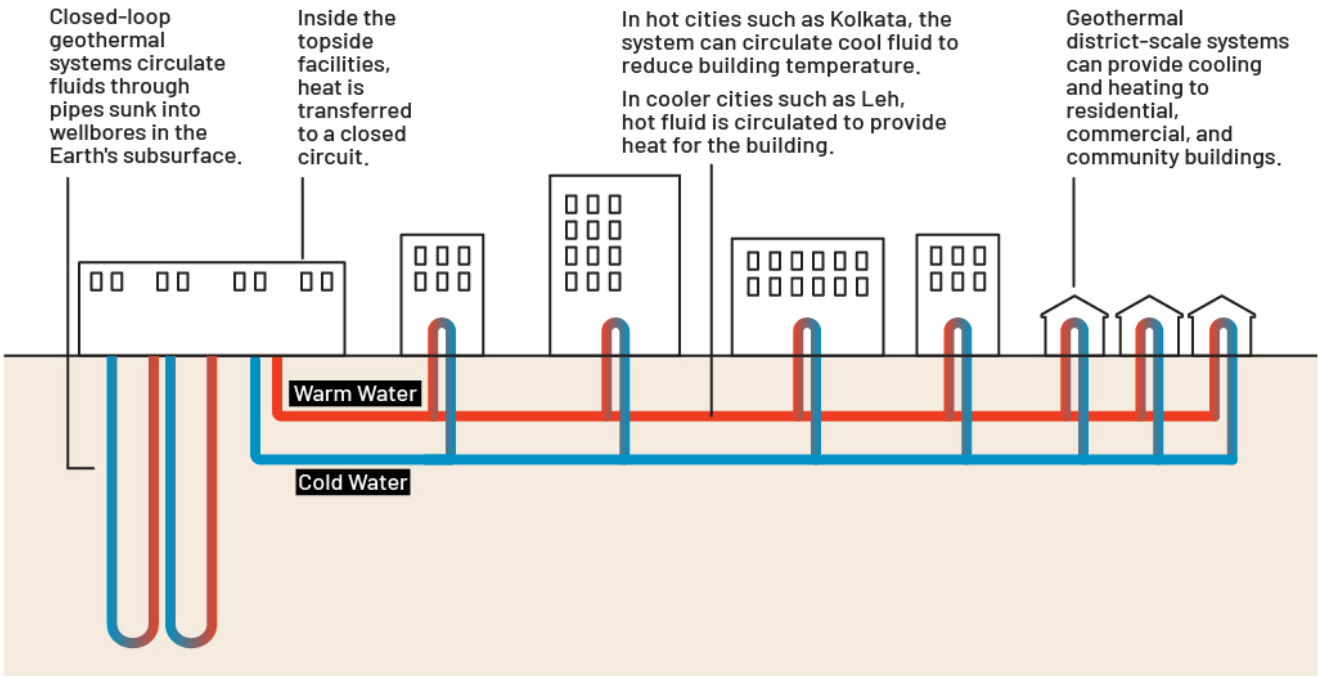
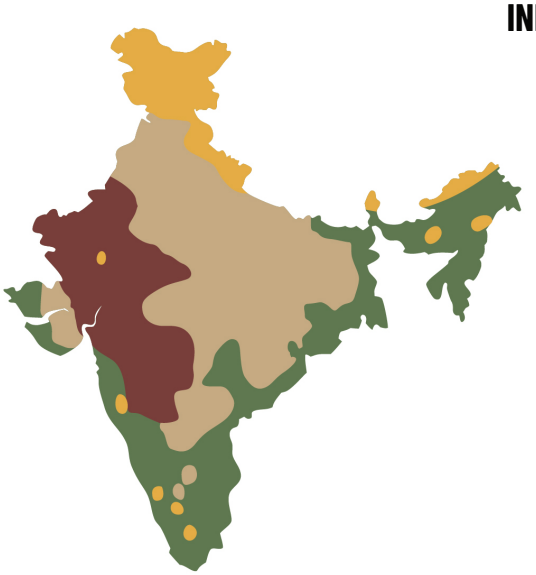


Figure 4.6: District heating system fluid is typically brought to the surface at a target temperature of around 21°C. That fluid is then passed through a heat pump to provide hot water in the winter for heating and cold water in the summer for cooling. This style of heating and cooling can be more than twice as efficient as traditional HVAC systems as the thermal load is shared between buildings. Source: Adapted from U.S. Department of Energy. *Geothermal district heating and cooling.*

INDIA'S CLIMATE ZONES



Climate type	Summer temperature	Winter temperature	Relative humidity
Hot and dry	20°C–45°C	0°C–25°C	55%
Warm and humid	25°C–35°C	20°C–30°C	70%–90%
Composite	27°C–43°C	4°C–25°C	20%–25% (dry) 55%–95% (wet)
Temperate	17°C–34°C	16°C–33°C	<75%
Cold	17°C–30°C	-3°C– -8°C	70%–80%

Figure 4.7: Map and table showing the different climate zones in India. Source: Adapted from Bureau of Indian Standards (BIS). (2005). *National Building Code of India 2005*. Government of India; Ozone Cell, Ministry of Environment, Forest and Climate Change. (2019). *India Cooling Action Plan*. Government of India; Ashok. P. (2025). Evaluation of policy options and recommendation of a phased policy strategy to promote adoption of geothermal ground source heat pumps (GSHP) in India. In *Proceedings of the 2nd Global Conference on Decarbonizing India*. Kerala, India.

REGIONS IN THE BEST POSITION TO LEAD A LARGE-SCALE GEOTHERMAL AQUIFER COOLING REVOLUTION

Project InnerSpace

India's wealth of sedimentary aquifers with subsurface temperatures above 90°C provides a rare opportunity for large-scale cooling across entire regions. So, which parts of India are best suited for this kind of geothermal cooling—and which areas need it the most?

Project InnerSpace overlaid India's regional-level heat risk, as assessed by CEEW, with geothermal resource estimates from the Project InnerSpace Heat in Place model to identify priority areas that are suitable for aquifer-based geothermal district cooling. (This temperature represents the minimum threshold typically required for efficient operation of the geothermal-driven absorption chillers used in district cooling.) This approach ensures that cooling is targeted to sites with both the greatest need and opportunity. It also provides a replicable, data-driven framework for evaluating which of India's vulnerable regions would most benefit from this infrastructure.

The good news is that high aquifer cooling potential aligns with extreme heat risk in a number of important areas across India. Some districts—such as Gandhinagar (28.3 gigawatts), Anand (27.7 gigawatts), Pilibhit (19.1 gigawatts), and Kolkata (17.2 gigawatts)—stand out as strategic hot spots that are vital to target. About 100 other regions also show great potential, making them strong candidates for geothermal cooling technology.

The success of the Indian Army's Net Zero Energy Building in Jhansi—coupled with the urgent need to decarbonise India's cooling infrastructure—means geothermal cooling networks offer an excellent opportunity for cooling that could be implemented soon. Although district cooling leverages centralised chilled-water systems to serve multiple buildings, areas with deep sedimentary aquifers have an added advantage. Deep sedimentary aquifers are present in many major Indian basins (e.g., Cambay, Krishna-Godavari, Cauvery) and can function as powerful heat sinks, taking advantage of the naturally cool subsurface temperatures to distribute chilled water via underground networks—a technique known as *aquifer thermal energy storage*. These networks are widely deployed in Europe for heating and could easily be deployed in India for cooling.

This study used the Project InnerSpace Heat in Place model to screen aquifers to a depth of 3,500 metres so we could identify the ones that would be most effective. Because the absorption chillers used in geothermal cooling typically require inlet temperatures near 90°C to operate efficiently and reliably,[37] only aquifers at or above this temperature were selected to ensure consistent output, particularly during peak summer demand. This cutoff guarantees that selected aquifers can deliver scalable, grid-independent cooling in areas where high heat risk overlaps with critical cooling needs.[38] Resource estimates were generated for each high-risk district and expressed in gigawatts—a metric that can be linked to the district's cooling demand and energy planning.

RESULTS

Heat-Risk Distribution

The Composite Heat Risk Index calculated by CEEW classifies 417 areas—representing 76% of India's population—as either high risk or very high risk. These districts are concentrated in the following areas (see **Figure 4.1**):

- **Western India:** Gujarat and Rajasthan experience frequent heat waves, expanding urban heat islands, and significant humidity rise inland.
- **Southern Peninsular states:** Andhra Pradesh, Tamil Nadu, and Karnataka have seen a rise in both daytime and nighttime temperatures, particularly in midsize cities (typically defined as having populations between 100,000 and 1 million people).
- **Central and Northern Plains:** States such as Maharashtra, Madhya Pradesh, Bihar, and Uttar Pradesh experience the dual burden of heat and socioeconomic vulnerability, particularly in agrarian or rural communities where adaptive capacity remains limited.

The study confirms that urbanising districts with high population density and built-up area growth—such as Ahmedabad, Delhi, Nagpur, and Guntur—are at the greatest risk due to compounding heat hazards and infrastructure constraints.[39]

Geothermal Potential from Sedimentary Aquifers

India's aquifer cooling potential varies widely across states and is closely linked to the distribution of major sedimentary basins. Overall, we estimate a total potential capacity of more than 1,500 gigawatts of cooling using a spacial resolution of 10 square kilometres or per pixel. The Cambay Basin in Gujarat (542 gigawatts) shows the highest aquifer cooling potential in the country due to basin size and sediment thickness. Leading districts include Bharuch (101 gigawatts), Banas Kantha (92 gigawatts), Mahesana (72 gigawatts), Anand (52 gigawatts), Kheda (47 gigawatts), Patan (46 gigawatts), Ahmadabad (43 gigawatts), and Surat (41 gigawatts). These regions have thick quaternary and tertiary sediments, which can support both seasonal and continuous cooling applications in urban and industrial zones.

The Bengal Basin, covering West Bengal (260 gigawatts), shows the second-highest potential nationally. Key districts include South Twenty Four Parganas (100 gigawatts), North Twenty Four Parganas (43 gigawatts), Purba Medinipur (36 gigawatts), Nadia (31 gigawatts), and Hugli (25 gigawatts). These areas are well suited for urban cooling systems, cold chain infrastructure, and climate-adaptive urban planning, especially around Kolkata and the broader Bengal delta. The Ganges Basin—beneath Uttar Pradesh (142 gigawatts) and Bihar (76 gigawatts)—shows substantial aquifer cooling potential due to basin extent and sediment thickness.

Parts of Tripura (117 gigawatts) and Assam (110 gigawatts) also have significant potential. Key districts include Dhalai (22 gigawatts) and Gomati (18 gigawatts) in Tripura, and Karimganj (18 gigawatts) and Cachar (15 gigawatts) in Assam. Telangana (76 gigawatts), not previously identified in the analysis, emerges as a significant contributor. Districts such as Mulugu (24 gigawatts), Bhadradri (23 gigawatts), and Jayashankar (13 gigawatts) show notable aquifer cooling potential linked to the Pranhita–Godavari Basin.

Rajasthan (85 gigawatts) shows substantially higher potential than previously estimated (was 5 gigawatts), driven primarily by Jaisalmer (73 gigawatts) in the Barmer-Jaisalmer Basin.

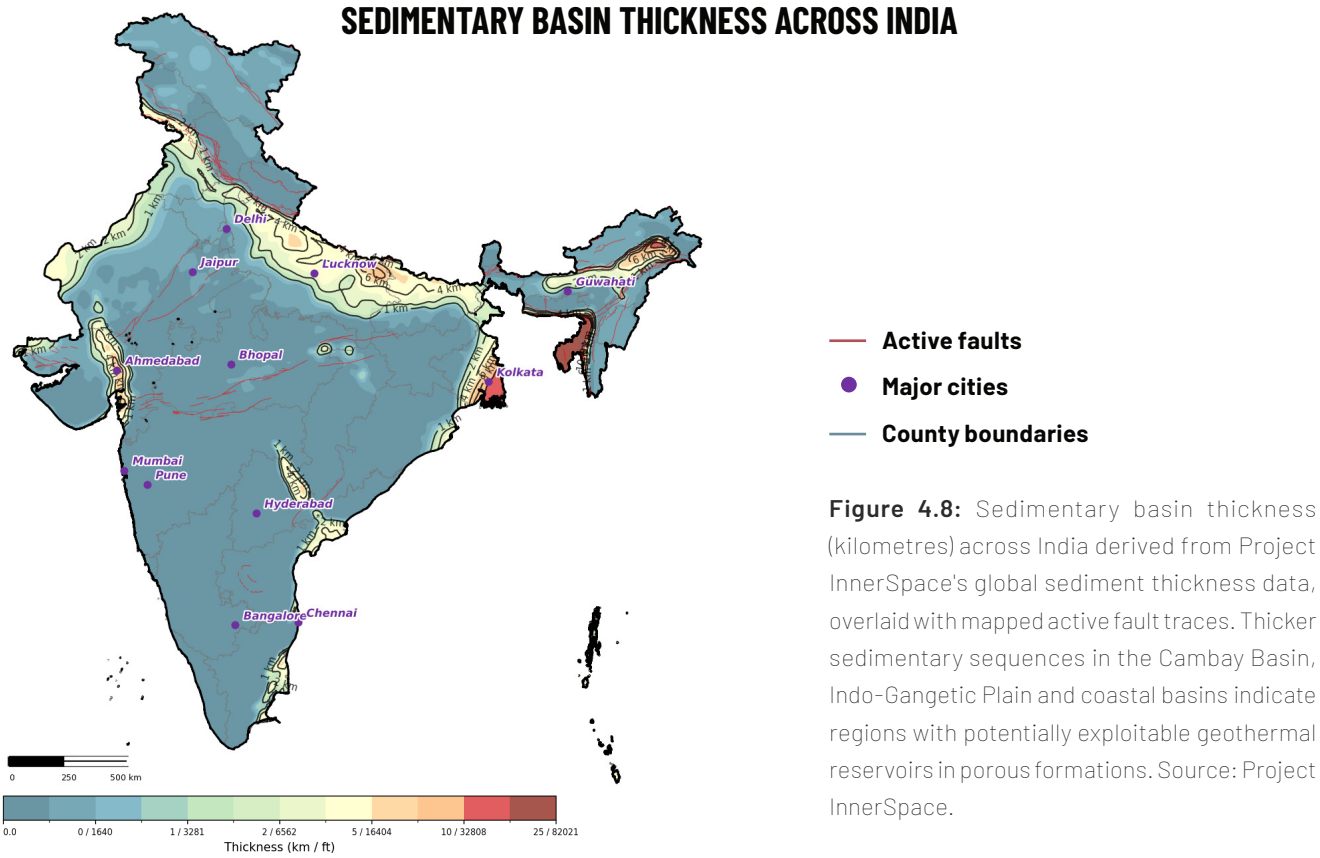


Figure 4.8: Sedimentary basin thickness (kilometres) across India derived from Project InnerSpace's global sediment thickness data, overlaid with mapped active fault traces. Thicker sedimentary sequences in the Cambay Basin, Indo-Gangetic Plain and coastal basins indicate regions with potentially exploitable geothermal reservoirs in porous formations. Source: Project InnerSpace.

In Tamil Nadu (39 gigawatts), high aquifer cooling potential is concentrated in the Cauvery Basin, with Cuddalore (21 gigawatts) as the leading district. Andhra Pradesh (46 gigawatts) contributes through the Krishna-Godavari Basin, with West Godavari (21 gigawatts) and Krishna (12 gigawatts) as leading districts. Jammu and Kashmir (19 gigawatts), partially underlain by the Indus Basin, supports local aquifer cooling.

Low-Potential States and Target Areas

In contrast, states with limited sedimentary cover or predominant hard rock geology—such as Chhattisgarh (2.0 gigawatts), Himachal Pradesh (0.78 gigawatts), and Madhya Pradesh (1.4 gigawatts)—show modest to low cooling potential. These regions may support small-scale or pilot projects. Similarly, coastal and island regions such as the Andaman and Nicobar Islands (0.06 gigawatts) and Haryana (0.19 gigawatts) present negligible potential due to limited aquifer extent.

For this reason, development should focus on deep sedimentary basins—especially the Cambay, Bengal, Ganges, Pranhita-Godavari, and Cauvery basins—where aquifer cooling can be integrated into urban resilience strategies, energy-efficient infrastructure, and sustainable groundwater management.

Target Areas: Where Heat Risk and Cooling Potential Align

By combining the findings shared earlier, we have identified the key areas in India where geothermal aquifer cooling can provide critical relief in the face of extreme heat. Of these areas, Gujarat clearly emerges as the area that would benefit the most, with districts such as Bharuch (101 gigawatts), Mahesana (72 gigawatts), Anand (52 gigawatts), Kheda (47 gigawatts), Patan (46 gigawatts), Ahmadabad (43 gigawatts), and Surat (41 gigawatts) showing particular promise.

In the Ganges Basin, districts in Uttar Pradesh—Sitapur (9.5 gigawatts), Kushinagar (9.4 gigawatts), and Bahraich (7.9 gigawatts)—also exhibit both aquifer potential and extreme heat exposure.

In the coastal and deltaic regions, Tamil Nadu's Cauvery Basin (Cuddalore [21 gigawatts] and Ramanathapuram [3.2 gigawatts] and West Bengal's Bengal Basin (Kolkata [0.91 gigawatts), Bankura [0.02 gigawatts], and Puruliya [0.00 GW]) have promise.

Overall, this study establishes a replicable framework for district-scale geothermal cooling assessments. Future work should focus on enhancing the hydrogeological characterisation of promising districts

ESTIMATED AQUIFER COOLING POTENTIAL ACROSS INDIA AT 3,500 METRES DEPTH

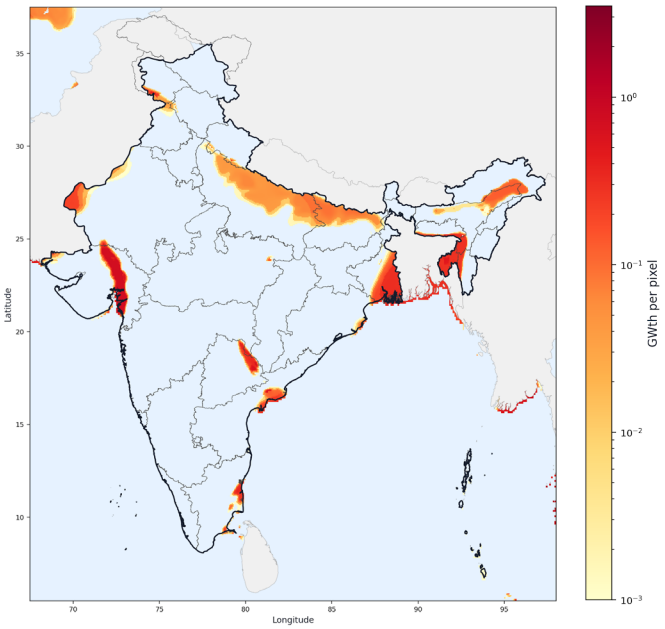


Figure 4.9: This map illustrates the theoretical aquifer-based cooling potential (in gigawatts [GWth] per pixel ~10 km^2]) across India to a depth of 3,500 metres, based on subsurface properties. Zones with higher cooling potential (shown in red) are concentrated in regions such as Gujarat, West Bengal, parts of Uttar Pradesh, and coastal Tamil Nadu. The spatial analysis highlights areas with significant opportunity for aquifer systems for sustainable cooling applications. Source: Project InnerSpace analysis, 2025.

TOTAL AQUIFER COOLING POTENTIAL BY INDIAN STATE IN GIGAWATTS

Thermal energy potential (GWth) in sedimentary basins at 0-3.5 km depth. MC P50 values.

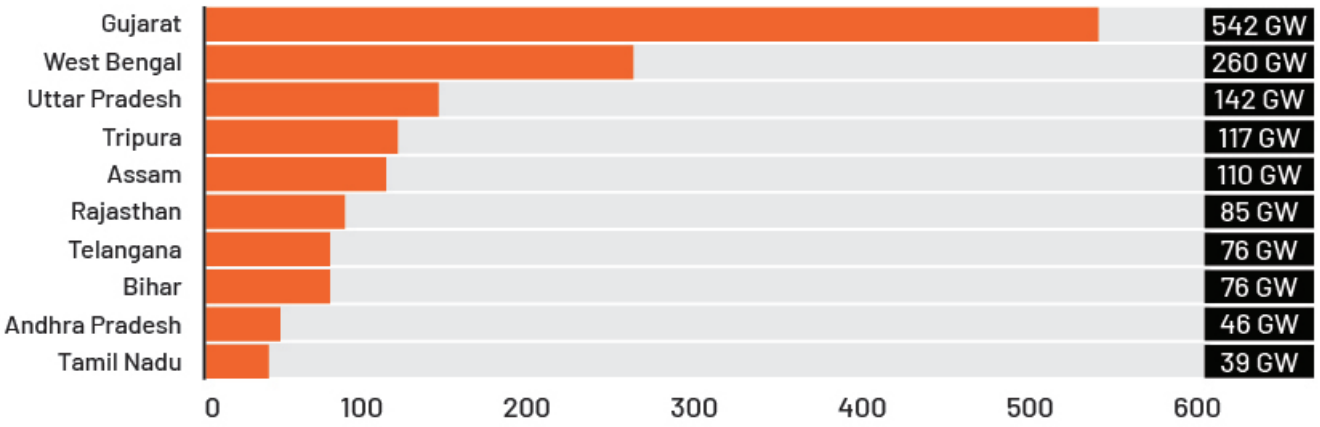


Figure 4.10: This bar chart quantifies the cumulative aquifer cooling potential by state in India to a modeled depth of 3,500 metres. Uttar Pradesh, Gujarat, Bihar, and West Bengal emerge as the leading states, each with more than 100 gigawatts (GWth [per pixel ~ 10 km^2]) of estimated thermal energy storage potential. These high-potential regions align closely with the spatial hot spots shown on the corresponding aquifer cooling potential map (**Figure 4.9**). This analysis supports strategic planning for large-scale deployment of aquifer cooling systems across India. Source: Project InnerSpace analysis, 2025.

(for instance, from national geophysical surveys and borehole data), integrating local feasibility studies and drilling logistics, building capacity for local governments, and conducting pilot demonstration projects in high-priority urban zones.

The findings of this study demonstrate that geothermal cooling—particularly from sedimentary aquifers in high heat-risk districts—offers a viable, scalable, and powerful low-carbon alternative that can help meet India's growing needs with an estimated 610 gigawatts of total cooling potential in high-risk areas—and more than 1,500 gigawatts everywhere. Results show that several dozen high-risk districts across western, southern, and central India possess significant geothermal reserves, with leading areas such as Ahmedabad, Guntur, and Tirunelveli offering energy-rich opportunities for district-scale or institutional geothermal deployment.

GEOTHERMAL COOLING POTENTIAL PER DISTRICT AT 3,500 METRES DEPTH

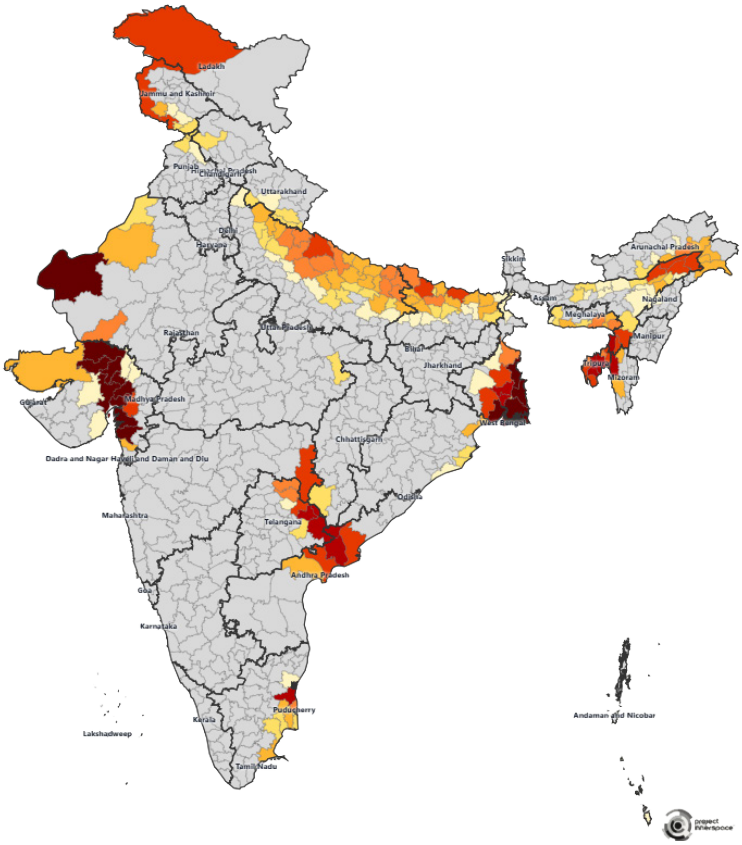
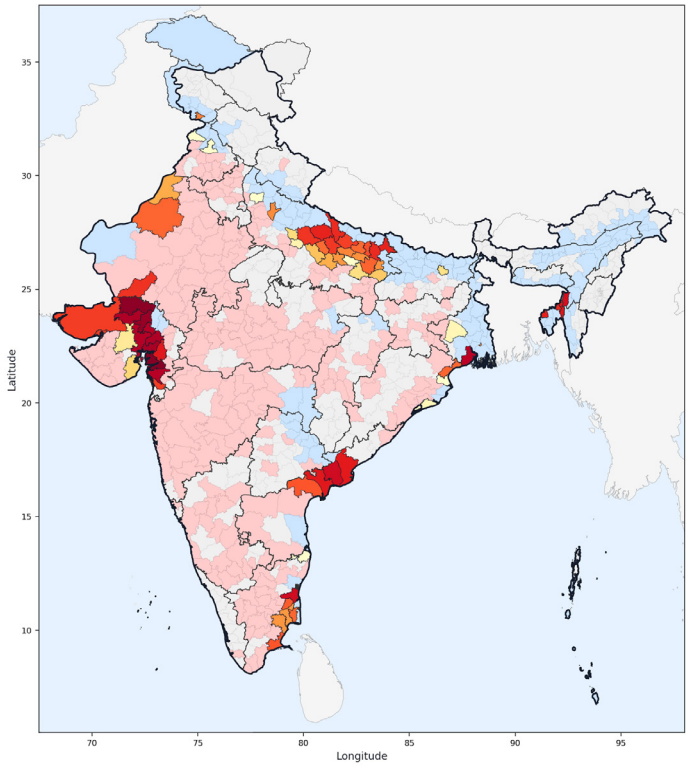


Figure 4.11: This map shows the geothermal potential in gigawatts (GW) for each district, with the highest resource zones aligned with the sedimentary basins such as the Cambay of Gujarat and peninsular Andhra Pradesh. The grey areas lack sedimentary basins and therefore have no district cooling potential. Source: Project InnerSpace analysis 2025.

DISTRICTS WITH ALIGNMENT OF AQUIFER COOLING POTENTIAL AND HIGH DEMAND DUE TO EXTREME HEAT



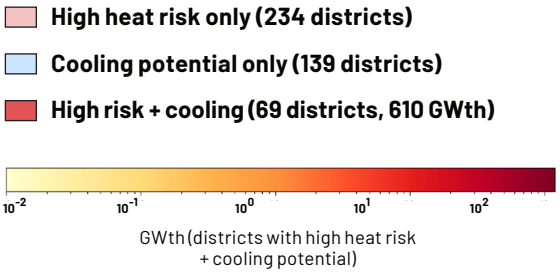


Figure 4.12: The highlighted districts represent areas identified as having both (a) significant geothermal energy potential in gigawatts (GWth) per pixel ~ 10 square kilometres in sedimentary aquifers and (b) high or very high heat risk according to the Council on Energy, Environment and Water's Composite Heat Risk Index. These zones present optimal conditions for sustainable cooling interventions, offering a strategic opportunity for geothermal-based thermal resilience infrastructure. Source: Project InnerSpace analysis 2025.

BENEFITS OF GEOTHERMAL COOLING

Geothermal represents a major opportunity to help India meet the goals outlined in the India Cooling Action Plan and produce additional important benefits. Developing a national geothermal cooling mission and cooling goals will help unlock the following benefits:

- **Increased climate resiliency:** Geothermal cooling options deliver efficient and round-the-clock cooling, reduced strain on local grids, and the ability to operate off-grid when paired with solar and storage—ensuring cooling remains operational even if the grid is under stress.
- **Enhanced equity:** Geothermal cooling expands access to safe, affordable cooling, ensuring benefits to people across India.
- **Prioritisation of high-heat-risk areas:** Sedimentary aquifers in basins such as Cambay, Cauvery, Bengal, and Indus align with extreme heat districts, enabling deployment where need and resource overlap.
- **Cleaner air and demand relief:** Geothermal cooling replaces conventional air-conditioning with high-efficiency, low-carbon systems that slash cooling-related electricity use and pollution, avoiding close to 810 metric tonnes of CO_2e annually by 2037. It also shifts energy loads to the subsurface, which cuts peak-hour demand, eases blackout risk, and limits the need for new transmission infrastructure and costly power plants that provide electricity only during periods of high demand.
- **Urban-fit and scalable:** Borehole and aquifer systems have modest footprints, can integrate with dense districts and campuses, and can scale from single buildings to ambient-loop networks.

SPACE HEATING AND COOLING LAYOUT OF INDIRA PARYAVARAN BHAWAN

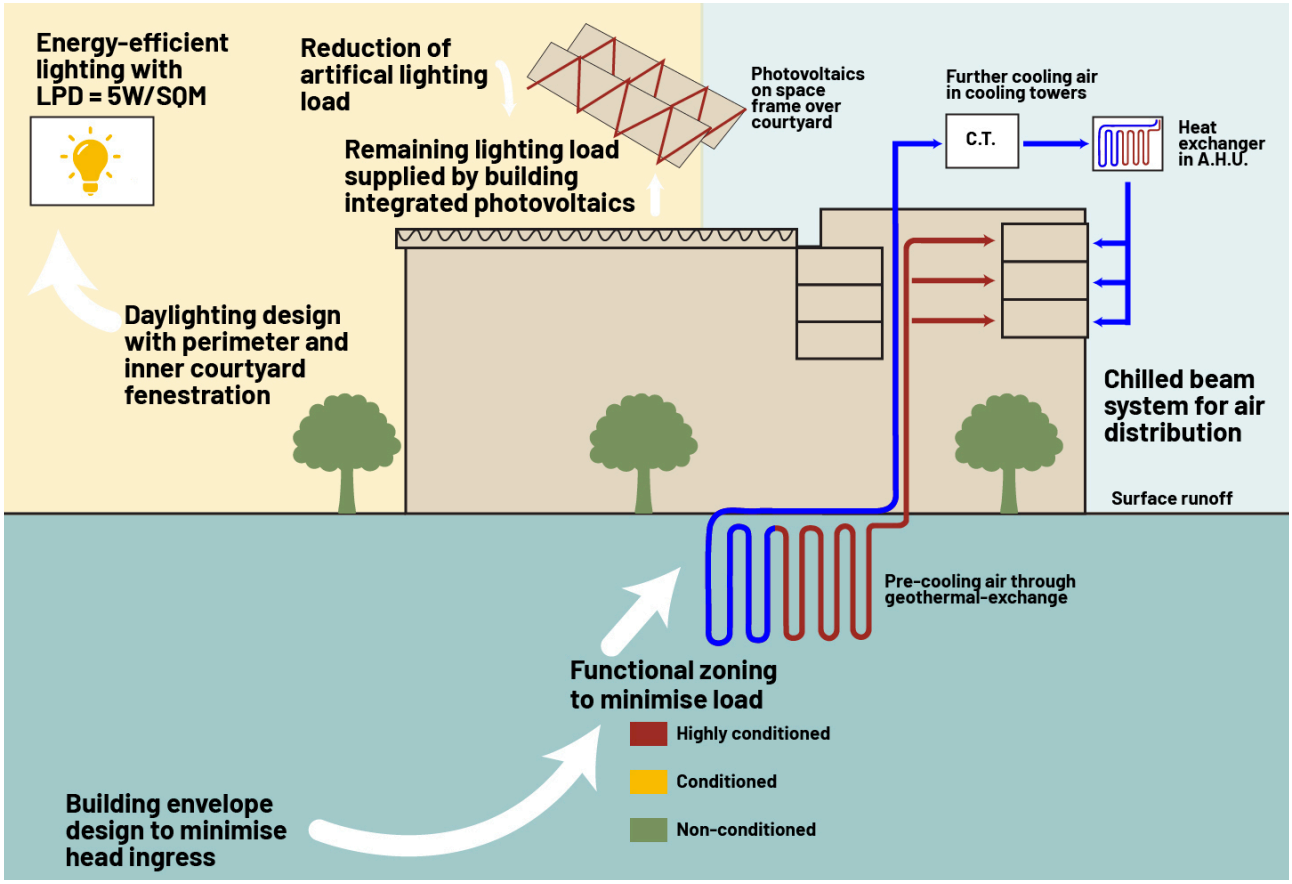


Figure 4.13: Space heating and cooling layout of Indira Paryavaran Bhawan. Source: Khandelwal, R., Jain, R. K., & Gupta, M. K. (2020). Case study: India's first net-zero energy building-Indira Paryavaran Bhavan. *International Journal of Scientific & Technology Research*, *9*(11), 353-357.

GSHP AND DISTRICT COOLING NETWORK INSTALLATION IN INDIA

GSHPs are a mature technology that has been deployed across the globe. In recent years, GSHPs have been installed in some limited locations in India. Policies and regulatory support for how to reduce up-front costs and expand this technology in India (such as financial incentives, research and development funding, and vocational programs) are detailed in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India."

The following examples illustrate shallow geothermal cooling systems currently operating in India. These differ from the deep aquifer cooling approaches described in the previous section, which rely on sedimentary aquifers at depth. In contrast, these shallow systems use relatively short boreholes or groundwater loops to exchange heat with the near-surface subsurface. They do not depend on specific aquifer conditions or deep geological structures. Instead, they draw on the naturally stable temperatures found at modest depths to deliver efficient, low-energy cooling for buildings. The case studies in this section show how such shallow geothermal systems are already being deployed across India.

Indira Paryavaran Bhawan, New Delhi

This building—which houses the Ministry of Environment, Forest and Climate Change—is India's first on-site net-zero energy building (see **Figure 4.13**). It employs a vertical closed-loop geothermal heat exchange system made up of 180 boreholes, each 80 metres deep and spaced 3 metres apart. Each borehole was also built to reduce reliance on traditional cooling towers. This system contributes to a 40% reduction in electricity consumption and a 55% decrease in water use compared with conventional designs.[40]

SPACE CONDITIONING USING GEOTHERMAL ENERGY AT ISB MOHALI

1. At the ISB's new campus in Mohali (one of the buildings pictured here), cold water from a 'chiller plant' circulates through the building, absorbs heat, reaches high temperature
2. The heated water passing again through the chiller plant, reaches the heat exchanger
3. The geothermal exchanger cools the water as it flows through an underground network of pipes
4. Cooled water goes back into the building

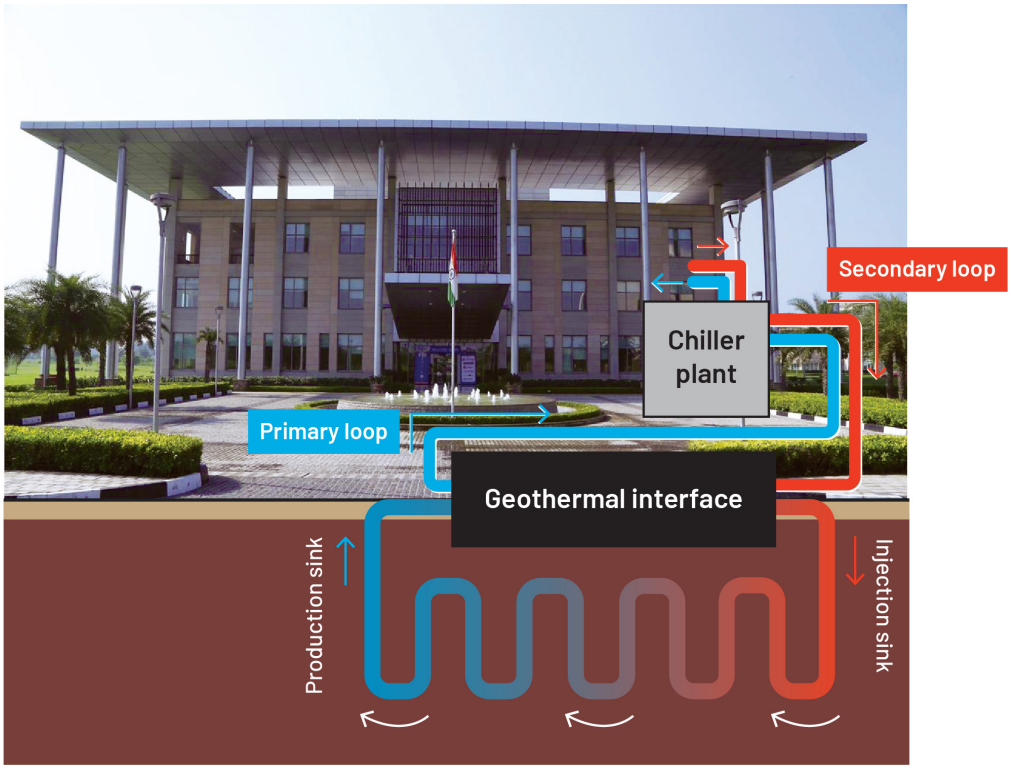


Figure 4.14: Space conditioning using geothermal energy at ISB Mohali. Source: TCBU Editorial. (2020, April 2). *ISB Mohali inducted as India's most energy efficient building*. Thermal Control Business Update.

Indian School of Business (ISB), Mohali, Punjab

ISB Mohali has implemented a closed-loop geothermal HVAC system with zero water discharge covering its 70-acre campus, as shown in **Figure 4.14**. This system leads to a 30% reduction in electricity use and conserves approximately 13 million litres of water annually. The campus also features white rooftops to minimize the heat island effect, and it has received multiple accolades, including the Smartest Educational Building in India and the Best Green Campus Award.[41]

ACC Hostel Facility, Thane, Maharashtra

This facility uses an open-loop geothermal heat pump system that leverages groundwater at 28°C for air-conditioning purposes. This approach significantly reduces the electrical load required for cooling, showcasing an effective application of geothermal energy in a tropical climate.[42]

CHALLENGES TO GROUND SOURCE HEAT PUMP ADOPTION IN INDIA

Despite the many benefits of GSHPs, they face some hurdles to adoption in India: The drilling and piping requirements for ground-loop installation mean initial costs can be high; while these systems are suitable for all climates, the return on investment timeline will depend on climate and soil conditions; there have not yet been enough installations to make the case to would-be investors that this technology is financially viable. The installation of these systems can also be complex by requiring understanding of geology, and it can take longer than traditional HVAC systems. In the United States and Europe, however, many companies are working to address these barriers.

Another significant barrier in India is the shortage of technical expertise required for the design and implementation of GSHP systems; only a few companies are currently capable of delivering such solutions. Chapter 5, "Leveraging Oil, Gas, and Mining Technologies and Workforce to Advance Geothermal in India," addresses how to overcome barriers to the limited workforce. Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," discusses solutions to reduce up-front costs.

DIRECT USE FOR SPACE HEATING

Given India's climate, the majority of this chapter focuses on geothermal as a cooling solution. However, the same technologies can be deployed for heating. (See Chapter 1, "Geothermal 101: Overview of Geothermal Technologies and Applications.")

In high-altitude regions such as Ladakh, where temperatures can plummet below -20°C, the Indian Army currently relies heavily on diesel generators for heating, leading to substantial logistical challenges and environmental concerns. Implementing geothermal-based space heating systems in these areas can offer a sustainable alternative, reducing diesel consumption and associated emissions.

Developed by the Defence Research and Development Organisation, the Snow and Avalanche Study Establishment near Manali, Himachal Pradesh, marks India's first significant closed-loop geothermal space heating system. The system comprises 27 boreholes with a total length exceeding 2,500 metres, connected to a reverse cycle water-to-water heat pump. Operating at an output load capacity of about 115 kilowatts, it maintains indoor temperatures between 30°C and 32°C in winter and between 18°C and 19°C in summer, with a ground entry temperature between 13°C and 19°C. The system achieves an annual carbon emission reduction of 14.2 tonnes and has a payback period of approximately five to six years.[43]

India's largest geothermal space conditioning system is already in development at Ladakh's Leh Airport, using 457 boreholes for year-round temperature control.[44] A pilot geothermal heating project is also being implemented in the hospitals of Kargil, a city in Ladakh.[45] Globally, projects such as Beijing's Linked Hybrid complex (which uses 655 geothermal wells for 70% of its heating and cooling[46,47]) and Iceland's widespread geothermal district heating systems showcase the scalability and sustainability of geothermal heating systems.

Adopting similar systems in India's cold regions can enhance energy security and operational efficiency for military installations.

THE INDIA COOLING ACTION PLAN AND POLICY FRAMEWORK

As mentioned, the Ministry of Environment, Forest and Climate Change has put together the ICAP to address India's cooling needs through active engagement with multiple stakeholders.[48] Some of the goals identified in the plan for achievement by 2038 include reducing the overall need for cooling by between 20% and 25%, reducing the amount of energy needed for cooling by between 25% and 40%, and reducing refrigerant demand by between 25% and 30%.

To meet these goals, the ICAP recommends various intervention strategies; as of 2024, India has made measurable progress toward achieving these goals. The Bureau of Energy Efficiency issued an advisory to set the minimum air-conditioner temperature at 24°C and implemented Minimum Energy Performance Standards, along with a star rating and labelling program. New efficiency standards were introduced for room air conditioners, and e-market initiatives encouraged the production of efficient models. Together, these measures helped reduce energy consumption by about 10 terawatt-hours (to 188 terawatt-hours in 2022–23).

While the ICAP has not yet mentioned employing direct-use geothermal technologies to meet cooling demand, India's geothermal resources have the potential to be transformative in the nation's strategy. To better advance direct-use applications, India could also adopt several policies that translate the technical potential mapped in this chapter into steel-in-the-ground projects. Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," recommends that India adopt a national geothermal cooling mission as part of the ICAP to jump-start geothermal cooling across the country. Potential targets include between 800 megawatts and 1 gigawatt (thermal) for cooling by 2035, between 3 gigawatts and 4 gigawatts by 2040, and more than 10 gigawatts by 2050. The mission should also prioritise locating district cooling networks in districts such as Cambay, Cauvery, Bengal, and Indus basin cities that have overlapping heat risk and sedimentary basin potential. These targets could be formally nested under the ICAP, which could ensure that geothermal district cooling and GSHPs count toward the ICAP's demand- and energy-reduction goals.

Potential targets include between 800 megawatts and 1 gigawatt (thermal) for cooling by 2035, between 3 gigawatts and 4 gigawatts by 2040, and more than 10 gigawatts by 2050. The mission should also prioritise locating district cooling networks in districts such as Cambay, Cauvery, Bengal, and Indus basin cities that have overlapping heat risk and sedimentary basin potential.

Chapter 8 also notes the importance of key parts of India's new geothermal framework, such as advancing pilot projects. Given the importance of cooling in India, it seems logical for some pilots to focus on cooling. Additionally, India could establish a national institute of geothermal energy to lead research on GSHP adaptation across India's diverse climatic zones and soil types. This research—combined with cooling pilot projects and other related recommendations outlined in Chapter 8—could enable the widespread adoption of geothermal cooling, ensuring equitable access and optimised system performance across different regions.

CONCLUSION

As India confronts the intensifying impacts of extreme heat—now a chronic climate hazard affecting more than 400 districts and three-quarters of the country's population—the country has a pressing need to expand beyond conventional, energy-intensive cooling technologies. By undertaking such expansion, India could emerge as a leader in climate resilience. With rising temperatures, the severe risks to human health, agriculture, and the national GDP are growing sharply. At the same time, conventional strategies for cooling are failing.

Fortunately, India's geography offers a sustainable alternative. Thanks to the country's sediment-rich basins, geothermal cooling is not merely a technical possibility—it is an urgent adaptation imperative.

Heat from the Earth is a renewable, domestic energy source, and extracting that energy not only helps reduce carbon emissions but also can address India's growing energy needs and shortage in fuel supply. Investing in research and development, focusing on each region's unique needs, and subsidising the development of geothermal are all essential to the country's future. In the long run, these efforts will help bring costs down, promote a home-grown supply chain, and develop a workforce with the necessary knowledge about the technology. Nonprofits and philanthropic organisations have greatly assisted with the development and monitoring of a cooling plan, and their support can be critical for the widespread adoption and deployment of geothermal-based cooling solutions in India.

By harnessing the transformational power and potential of geothermal cooling in key regions, India can create a long-term, sustainable strategy for cooling at a time when solutions are desperately needed.

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Supplement

Powering India's Data Centre Growth with Geothermal Energy and Cooling

Investors have committed tens of billions of dollars to build new AI-driven data processing centres in India. Fortunately, the nation has significant geothermal resources that can be deployed to safely and securely meet the incoming demand for data centre power and cooling—and alleviate the intense pressure these centres will put on the national grid.

India's data centre sector is growing exponentially as cloud adoption, 5G expansion, streaming, e-commerce, and hyperscale artificial intelligence (AI) workloads drive demand for intensive data processing. In late 2025, a number of U.S. technology giants announced major investments in data centres and AI infrastructure in India, including Amazon (US$ 35 billion[1]), Microsoft (US$ 17 billion[2]), and Google (US$15 billion).[3] These investments are in addition to those made by major Indian companies such as Reliance (US$ 110 billion) and the Adani Group (US$ 100 billion).[4] India has clearly moved from being a fast-growing digital market to a global-scale platform.

These trends may accelerate given that India mandates certain categories of information such as payment-system data are stored locally. The country also requires localisation and sovereign-access requirements across financial services, telecommunication networks, government cloud infrastructure, cybersecurity logging, and more.[5] Beyond policy, physics matters: AI and high-volume services are sensitive to latency, and delays of even milliseconds can compound. Until recently, much of India's data was stored on servers abroad, increasing both latency and dependence on technology out of the nation's control. All of these factors intensified India's need and drive for local servers.

HOW TO POWER AND COOL THE COMING DATA CENTRES

A 2024 analysis estimated that India would add roughly 464 megawatts of new co-location capacity per

CURRENT DATA CENTRES AND GEOTHERMAL ELECTRICITY-GENERATION POTENTIAL

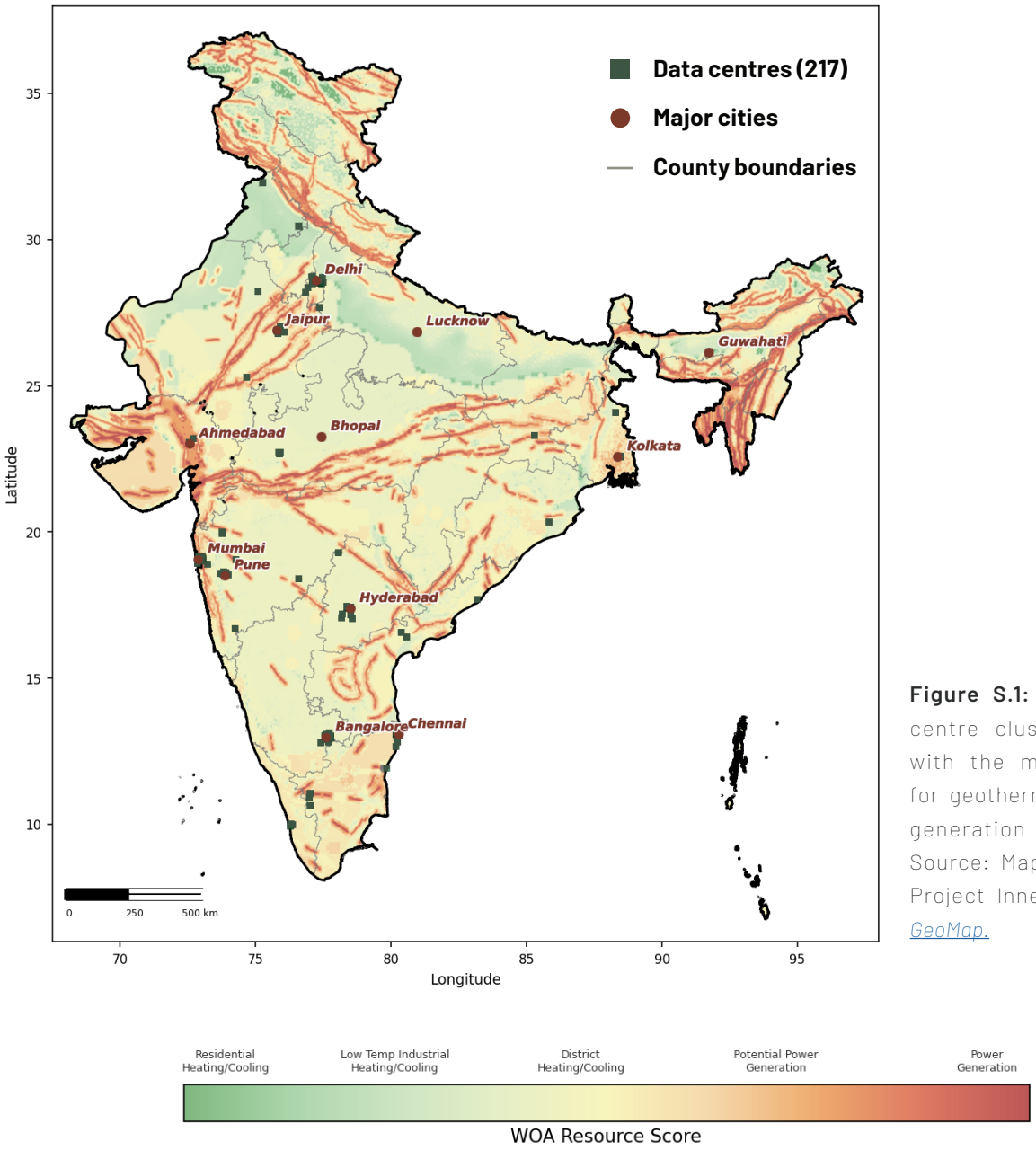

Figure S.1: Current data centre clusters in India with the most potential for geothermal electricity generation and cooling. Source: Map produced by Project InnerSpace (n.d.). *GeoMap.*

year until 2028—and that the installed co-location information technology (IT) load was 977 megawatts.[6] That estimate shows there will be a large near-term concentration in the main hubs, most notably Mumbai (about 301 megawatts under construction and about 916 megawatts planned), Chennai (about 182 megawatts under construction and close to 152 megawatts planned), Delhi National Capital Region (109 megawatts under construction and approximately 139 megawatts planned), and Hyderabad (an estimated 36 megawatts under construction and 55 megawatts planned).[7]

The key question is, How will these data centres be powered and cooled in a way that does not compound peak grid demand? Geothermal offers two complementary pathways: (i) behind-the-meter geothermal power, which offers firm and secure electricity at the source; and (ii) geothermal direct-use cooling, which lowers the cooling penalty.

Behind-the-Meter Geothermal Power

Co-locating new data centres with geothermal resources can provide dependable baseload power without relying exclusively on grid availability or the carbon intensity of marginal generation. This model is particularly compelling where there are high-temperature resources or where next-generation systems can economically access subsurface heat. While a project's economics will vary by location and drilling cost, reservoir productivity, and local tariffs, the value is consistent: Geothermal can deliver 24/7 power for the 24/7 demand of a data-processing centre. Behind-the-meter geothermal serves as the primary power source, while grid connection through distribution companies provides the N+1 or N+2 redundancy (that is, one or two additional backup power sources beyond operational needs) that data centre reliability standards require.

Data centres do not draw power at a flat rate; they experience significant spikes throughout operation as workloads shift. Geothermal's firm baseload output is therefore most effective when paired with complementary flexible resources, including energy storage systems, grid interconnection, and demand-shaping algorithms that smooth consumption peaks. This pairing allows geothermal to anchor a data centre's power supply while flexible resources absorb variability.

Geothermal lead times are falling fast—and are already shorter than nuclear and, in some cases, gas. Fervo Energy drilled a well to 4,800 metres (15,765 feet) in just 16 days in 2025 as part of its 500 megawatt Cape Station project, a 79% reduction from the U.S. Department of Energy's baseline for ultra-deep geothermal wells.[8]

What's more, the latest hyperscale investments make geothermal even more valuable. As data centres scale to need hundreds of megawatts (and gigawatts),[9] the cost of instability rises—both for operators and for the grid. In places where governments and utilities can offer large, dedicated blocks of "industrial-scale" electricity (hundreds of megawatts of firm capacity, with the grid connections and reliability guarantees to match), operators have a strong incentive to lock in long-term contracts for power that is dependable and aligned with decarbonisation goals.

Geothermal Direct-Use Cooling

Geothermal is not only a source for electricity generation. Subsurface temperatures and groundwater systems such as aquifers can also support cooling for large sites, either by acting as a stable place to sink heat or by developing thermal storage systems that help reduce demand at peak load.

Data centres devote a significant share of their total energy use to keep servers cool—in other words, rejecting heat. That need will rise as AI processing demands climb. As a result, when it comes to choosing locations for new data centres, cooling infrastructure may become a decisive factor, especially in hot climates, dense cities, and regions with stressed grids.

In many situations, direct-use cooling can offset a substantial portion of a facility's energy consumption that would otherwise be dedicated to powering chillers, pumps, and heat rejection equipment—reducing the draw on the grid and improving resilience during extreme heat or when there are supply constraints.[10]

Take, for example, the Iron Mountain Data Center in Boyers, Pennsylvania, in the United States. The owners installed a geothermal cooling system that resulted in the facility using about 34% less energy for cooling infrastructure processes.[11,12] In other words, less power is spent moving heat out of the building and more is available for servers, allowing a data centre to deliver more computing power with the same grid connection. That efficiency gain is especially valuable when power is constrained, which helps operators maximise limited capacity and eases pressure created by long wait times for new generation and grid upgrades.

In addition to large data centre cooling, India's edge data centre network—smaller, distributed facilities located closer to end users to reduce latency and support local data processing—offers a strong use-case for geothermal cooling solutions such as ground source heat pumps. Highly distributed across more than 60 cities—with facilities strategically located in major metropolitan areas such as Mumbai, Chennai, and Bengaluru, as well as a wide range of smaller cities such as Jaipur and Guwahati—these edge data centres support 5G and low-latency services close to end users. These smaller, telecom-linked facilities typically rely on municipal water and conventional air- or water-cooled systems, creating sustainability challenges

in water-stressed regions. Closed-loop borehole heat-exchange systems offer a promising alternative, particularly for small- to mid-scale edge sites (that need anywhere from hundreds of kilowatts to a few megawatts). These systems provide stable, water-free cooling and align well with the distributed nature of edge infrastructure. In India's hotter climates and dense urban environments, they are most viable as part of hybrid systems—combined with dry coolers or heat pumps—rather than as stand-alone solutions, with up-front costs and limited local geothermal supply chains remaining key barriers to adoption.

INDIA'S ADVANTAGE: THOUSANDS OF GIGAWATTS OF TECHNICAL GEOTHERMAL POTENTIAL

India is unusually well positioned to use geothermal for digital infrastructure because its resources are broad and geologically diverse, yet those resources are still largely untapped. As explained in Chapter 2, "Where Is the Heat? Exploring India's Subsurface Geology," researchers estimate that India has the technical potential for roughly 450 gigawatts of electricity generation (down to 5 kilometres) today and technical potential for more than 8,000 gigawatts of electricity (down to 7 kilometres) as technology improves in the future. Additionally, the country has more than 1,500 gigawatts of geothermal cooling potential. More than 300 thermal springs show evidence of deeper hydrothermal systems, concentrated along mobile belts, rift zones, and major suture zones—exactly the kinds of structural settings that allow for permeability and the transfer of heat.

Chapter 2 also classifies India's geothermal potential by application type, separating zones suitable for (i) high-temperature electricity generation, (ii) potential electricity generation, (iii) direct use and direct heating, (iv) low-temperature industrial heating and cooling, and (v) geothermal heating and cooling. This classification matters for data centres because the sector can benefit from both electricity and direct cooling.

The result is striking: More than one-quarter of India shows potential for a mix of geothermal electricity, direct-use, and cooling applications. Importantly, analysis shows that there is significant potential for geothermally powered data centres in Mumbai and New Delhi (**Figure S.3**). Geothermal offers India a rare two-for-one advantage: always-on power and direct-use geothermal cooling (**Figure S.4**) that can materially reduce electricity draw.

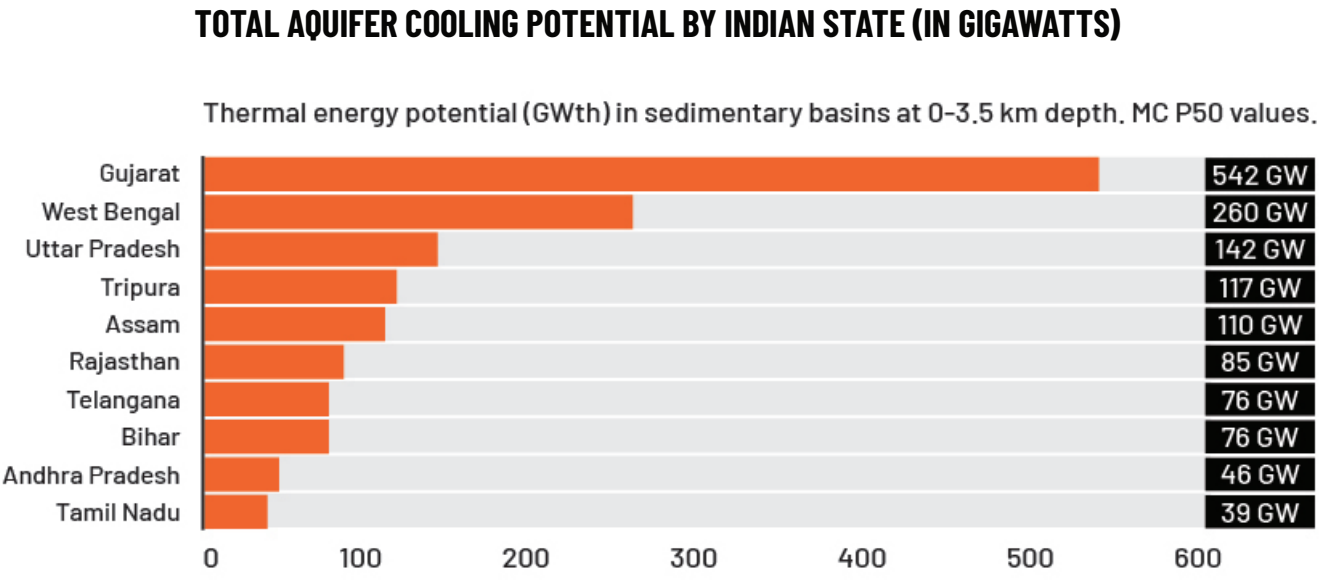

Figure S.2: Total aquifer cooling potential by Indian state in gigawatts (3,500 metres depth). Gujarat, West Bengal, Uttar Pradesh, and Tripura emerge as the leading states. Error bars show P10–P90 range. Source: Project InnerSpace analysis, 2025.

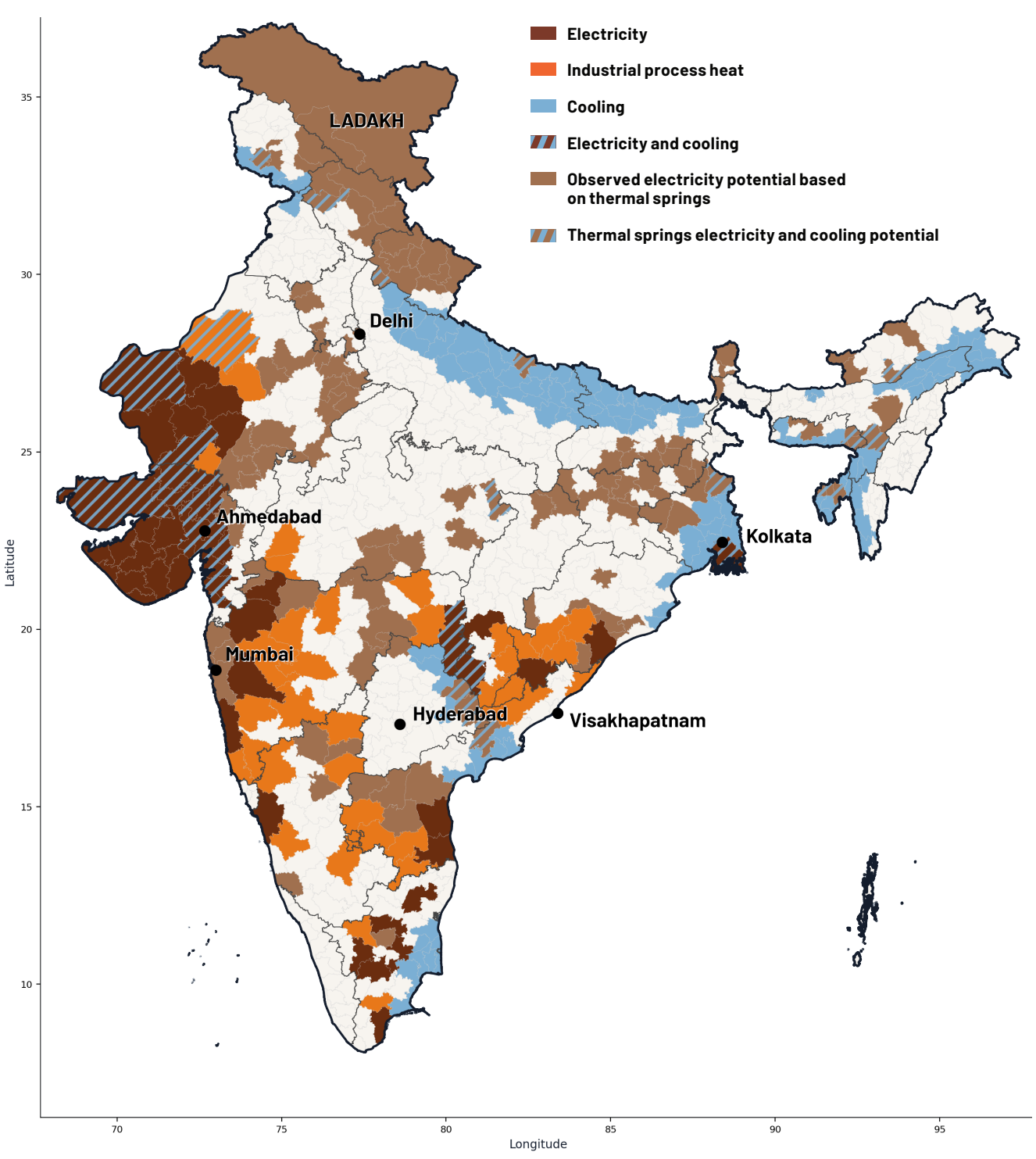

Figure S.3: Key geothermal potential of India by district. This map classifies India's districts by their geothermal potential and primary application based on the Project InnerSpace Heat in Place (HIP) volumetric model and the Global Advection Database. Observed electricity potential is derived from thermal springs information and is not modelled. Source: Project InnerSpace HIP analysis and advection database, 2026.

GEOTHERMAL COOLING GIGAWATT POTENTIAL PER DISTRICT AT 3,500 METRES DEPTH

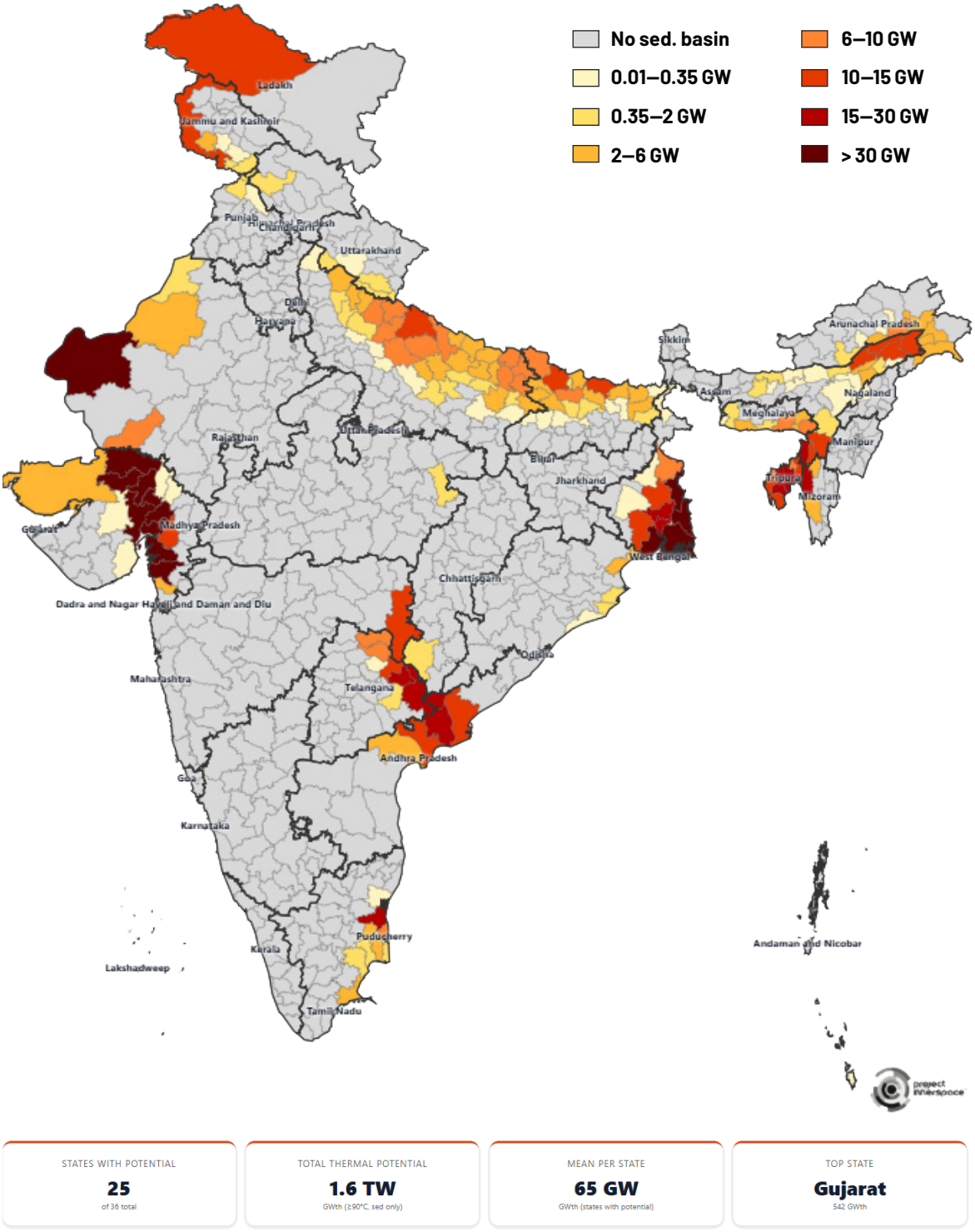

Figure S.4: Geothermal cooling and storage potential in gigawatts (GW) per district at 3,500 metres depth. This map shows the GW potential per pixel at approximately 10 square kilometres per district, with the highest resource zones aligned with the semi-arid basins of Gujarat, West Bengal, Tripura, parts of Uttar Pradesh, Bihar, Telangana, and peninsular Andhra Pradesh. Source: Project InnerSpace analysis, 2026.

DIGGING DEEPER: MATCHING GEOTHERMAL RESOURCES WITH DIGITAL CORRIDORS

India's geothermal resources are distributed across several states and territories. For data centre power, the key is matching the best geothermal resources with today's digital infrastructure clusters—and those of the future.

Near-Term Opportunities

The Mumbai–Maharashtra corridor presents the most compelling immediate opportunity for integrating geothermal energy into India's data centre infrastructure. This region, which hosts the country's largest concentration of data centre facilities, coincides with a substantial zone of moderate to high geothermal potential within the Cambay Basin, extending inland from the coast. The presence of thermal springs throughout the greater Gujarat and Maharashtra areas further validates the subsurface potential in this area. Given that Mumbai accounts for more than 40% of India's operational data centre capacity and has more than 1,000 megawatts of planned expansion, the potential to leverage geothermal energy for baseload power or direct cooling applications represents a significant opportunity for sustainable infrastructure development.[13]

Similarly, the Hyderabad region and extended Telangana within the Godavari rift demonstrates notable overlap between emerging data centre development and geothermal resources that could support the region's projected 44% compound annual growth in data centre capacity through 2030.[14]

Untapped Potential: High-Resource Zones Without Data Centre Development

Central India: Son-Narmada Fault Zone

The Son-Narmada-Tapi (SONATA) lineament belt in central India, including the Tattapani Geothermal Field, represents another zone of high geothermal potential with limited current data centre presence.

Himalayan Region

India's first utility-scale geothermal project is currently in development in the Puga Valley, Ladakh. While the Himalayan region's remoteness limits near-term data centre development, the project will provide crucial operational experience and demonstrate the technical viability of geothermal electricity generation in India—knowledge that can be applied to more accessible locations as drilling technology improves.

Gujarat

The Kachchh rift, Cambay rift, and Saurashtra peninsula regions of Gujarat are all characterised as having high geothermal electricity-generation potential.

Andhra Pradesh

The Godavari rift system, which extends across Telangana and Andhra Pradesh, is characterised as having high geothermal potential. Combined with the state's subsea fiber optic cable landing infrastructure, Andhra Pradesh is a compelling candidate for early geothermal-powered data centre development beyond the established Mumbai and Delhi corridors.

GEOTHERMAL-READY INDIA: POLICY STEPS TO POWER AND COOL THE NEXT WAVE OF DATA CENTRES

Today, India's geothermal mapping makes it possible to move from "resource awareness" to bankable projects, but success will require policies that can enable the development and use of geothermal (see Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India"). Particularly important will be rapid implementation of the Ministry of New and Renewable Energy's (MNRE's) 2025 National Policy on Geothermal Energy, which focuses on taking the risk out of early projects and establishing measures that create durable offtake (also known as demand-pull) for both electricity generation and cooling.

The immediate question is not whether India has enough subsurface resources for powering data centres with geothermal, but whether its policy and market architecture can convert those resources into deliverable, economically viable capacity at the pace needed for today's rapid data centre expansion. The following five steps translate the recommendations outlined in Chapter 8 into a practical, geothermal-

ready checklist for data centre developers, state governments, and MNRE.

1. Prioritise pilot projects in high-alignment zones such as Gujarat–Maharashtra, Delhi–Haryana, the Godavari rift, and select hubs that pair data centre planning with early subsurface validation. These pilots should be treated as proof-of-concept deployments under MNRE's 2025 National Policy on Geothermal Energy—structured to build investor confidence, generate replicable technical templates, and populate state-level project pipelines.
2. Build on India's existing framework for behind-the-meter generation and private-wire supply. The Electricity Act, 2003, already permits consumers to lay dedicated lines without a licence, and having 9 gigawatts of behind-the-meter solar demonstrates that the model works at scale, which enables data centres to procure secure geothermal power directly where feasible. Regulatory frameworks should additionally enable revenue stacking alongside geothermal assets to manage load spikes. Procurement models should be evaluated against system-wide objectives, including reduced emissions, lower costs, improved reliability, and an equity principle that ensures dedicated industrial supply does not disadvantage other consumers, with a one-to-many configuration preferred where market conditions allow. This makes it simpler for large buyers such as hyperscale operators and co-location providers to procure secure, firm power via open access, whether through third-party or captive routes.
3. Establish resource rights and permit pathways for geothermal direct-use cooling, which often faces different regulatory questions than electricity generation. Geothermal sits between existing oil and gas, mining, land, and water statutes; without clear treatment of subsurface heat and streamlined permissions—including groundwater protection and reinjection norms—direct-use cooling will remain hard to finance even where it is technically attractive.
4. Invest and strengthen the availability of higher-resolution subsurface data, particularly from abandoned and existing oil wells for geothermal development (including heat flow measurements, magnetotelluric imaging, seismic tomography, and hydrochemistry) to reduce exploration risk and financing costs. This step is the practical backbone of the "de-risk investment" agenda detailed in Chapter 8: Having better data reduces uncertainty, enables bankable project reports, and makes incentives and tenders more effective by improving project selection and performance.
5. Treat water and cooling as co-equal constraints in siting policy. Hyperscale investment is inclined towards locations that can guarantee inputs at scale, so policy should evaluate geothermal cooling not only for energy savings but also for how it reduces peak stress and improves operational resilience in water- and heat-constrained regions. This area is also where a national geothermal cooling mission becomes directly relevant to digital infrastructure. If permitting, standards, and public sector pilots are designed to validate it at meaningful scale, geothermal can provide more than decarbonisation—it can enable resilience and a wider choice of building location.

CONCLUSION

India's data centre boom is being supercharged by the hyperscale deployment of AI. As a result, data centres face increased requirements and a practical need to keep latency low by storing and processing data closer to users. This combination means the demand for "always-on" electricity and cooling is being rapidly concentrated in a handful of corridors in India, particularly Mumbai, Delhi, Hyderabad, and Chennai. But this demand is happening just as grid stability, water stress, and heat resilience are becoming decisive constraints for where to locate a data centre.

Geothermal offers India firm, resilient power that matches the 24/7 need for data processing, as well as direct-use cooling that can materially reduce the cooling energy demand for data centres. If India deploys MNRE's framework, takes the risk out of early geothermal projects, and creates durable demand-pull for both electricity generation and cooling, geothermal could move from an underused resource to a productive and valuable piece of the country's digital infrastructure strategy. If implemented well, geothermal becomes more than a decarbonisation option: It helps India build more data processing power without compounding peak stress on the national electricity grid and builds a secure, more resilient foundation for the next wave of data-driven growth.

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Part III

Workforce, Stakeholder, Legal, Policy, and Environmental Considerations

Chapter 5

Leveraging India's Oil and Gas and Mining Industries to Advance Geothermal

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Anugrah Singh, Department of Petroleum Engineering, Indian Institute of Technology, Guwahati

India has significant geothermal potential, and tapping into it will require new jobs and skills. Fortunately, India's large oil and gas and mining sectors have both enthusiasm for geothermal's prospects and many skills that are transferable to the emerging geothermal field. By reaching goals suggested in this report, India could create between 350,000 and 700,000 jobs.

In a country where the energy landscape is still dominated by coal and supplemented by solar and wind, geothermal can provide much needed diversification, particularly in industrial and cooling applications.[1,2,3,4]

To help tap into its geothermal potential, India can look to its oil, gas, and mining sectors. Technology and infrastructure—such as drilling rigs, seismic data systems, and heat-resistant pipelines from oil and gas operations—can be adapted for geothermal use. Inactive oil wells and mining assets can be converted into geothermal production sites, and the associated subsurface data can be very helpful for mapping out geothermal projects. By taking such steps, the nation can help lower project costs and de-risk early-stage development.[5,6]

This transition from legacy energy to geothermal also offers a powerful way to create jobs while capitalising on the country's existing oil and gas workforce. As the number of geothermal projects expands, India will face a growing demand for skilled professionals, including drilling engineers; heating, ventilation, and air-conditioning (HVAC) technicians; geoscientists; and plant operators. Many of these roles already exist in the oil, gas, and mining industries, creating a natural pathway for workers to stay employed while also developing new skills.[7]

Following a survey of professionals across various energy sectors, this chapter identifies key trends, challenges, and opportunities for geothermal energy

adoption. It also highlights ways to unlock the potential of geothermal energy by leveraging India's existing oil, gas, and mining industries. If supported with appropriate incentives, infrastructure, and increased workforce development and skills training, these industries can play a transformative role in positioning India as a global leader in geothermal innovation while creating new jobs. If the goals suggested in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," are adopted, the country could create between 350,000 and 700,000 jobs across its various geothermal applications.

The country could create between 350,000 and 700,000 jobs across its various geothermal applications.

SURVEY METHODOLOGY

For this chapter, the survey targeted professionals with expertise in energy production, policy formulation, research, and investment. The survey group included people employed in the executive, senior management, and general parts of the workforce, as well as professionals in oil and gas, mining, and related companies (e.g., Oil and Natural Gas Corporation Limited [ONGC], Oil India Limited [OIL], Cairn Oil and Gas, Essar Oil and Gas Exploration and Production Limited, Reliance, Gas Authority of India Limited [GAIL], Coal India Limited [CIL], Bharat Coking Coal Limited [BCCL], SLB, and GE Baker Hughes. Participants were asked about their experience, awareness of geothermal projects, economic outlook, and suggestions for government and academia.

The survey covered the major themes, including industry experience and role, current involvement in geothermal energy, perceived economic impact, workforce development and skill gaps, policy and regulatory challenges, and investment and market potential. It asked about geothermal energy engagement, company interest, pilot projects, research and development initiatives, collaboration, training needs, employment opportunities, and understanding of the current government policies impacting geothermal industry growth. The survey produced 76 complete responses.

Survey Respondents

The respondents were mainly from oil and gas sectors and mining sectors, as shown in **Figure 5.1**.

INDUSTRY EXPERIENCE OF SURVEY PARTICIPANTS

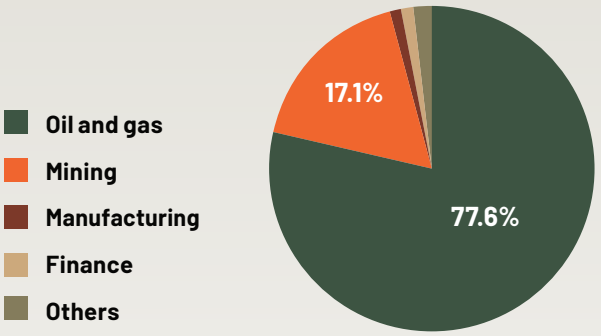

Figure 5.1: Industry experience of the survey participants. The remaining values total to less than 5%. Source: authors.

Figure 5.2 breaks down the participants' experience levels. Overall, participants mostly came from the oil and gas professions, and the number of respondents from each age category is balanced.

EXPERIENCE LEVEL OF RESPONDENTS

Experience Level	Percentage (%)
15+ years	22.4
10-15 years	28.9
5-10 years	22.4
<5 years	26.3

Figure 5.2 breaks down the participants' experience levels. Overall, participants mostly came from the oil and gas professions, and the number of respondents from each age category is balanced.

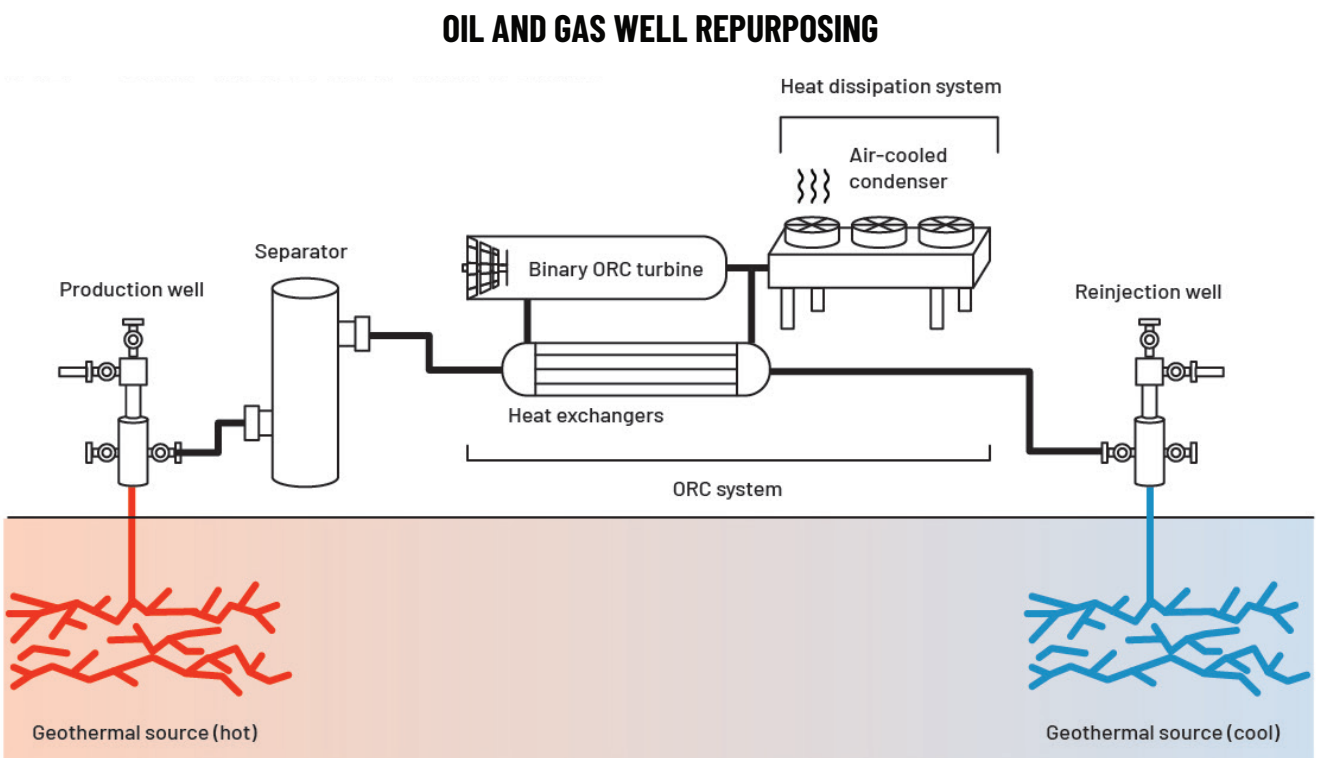

Figure 5.3: Typical geothermal setup for oil and gas repurposing. Source: Project InnerSpace.

OIL, GAS, AND MINING IN INDIA

India has a long and complex history of oil, gas, and mineral resource development. Mining activities in India date back thousands of years, with ancient civilisations extracting gold, copper, and iron for tools and trade. Modern mining took shape under British rule, particularly in coal-rich regions like Jharkhand, West Bengal, and Odisha, which supplied fuel for colonial railways and industries. The discovery of oil in Assam in 1889 marked the beginning of India's petroleum industry, with the Digboi oil field as the site of Asia's first commercial oil well.

After gaining independence, India nationalised much of its oil, gas, and mining industry to secure energy sovereignty and industrial growth through the establishment of such major public sector institutions as ONGC and CIL. In the 1990s, economic liberalisation opened the energy sector to private and foreign investment, leading to technological upgrades and increased production, particularly in offshore oil and gas blocks. Today, India remains one of the world's largest producers of coal and continues to invest in domestic oil and gas exploration, even as the country begins transitioning toward cleaner energy alternatives.

Existing Subsurface Assets and Geothermal Potential

As India charts a path to a low-carbon future, the legacy infrastructure and knowledge base of its oil and gas industry—particularly in mature energy-producing states—provide a valuable foundation for geothermal development.The greatest advantage of India's energy-producing states lies not only in their physical infrastructure but also in the extensive subsurface data and deep geological understanding that decades of hydrocarbon exploration have generated.

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The Cambay basin of Gujarat, for instance, is one of India's most studied sedimentary basins, with rich geological,

thermal, and structural data from oil and gas operations that can inform geothermal resource assessment. Such data offer an unparalleled head start for identifying viable geothermal sites with reduced exploration uncertainty.[8]

Other states—including Maharashtra, Andhra Pradesh, Madhya Pradesh, Rajasthan, Chhattisgarh, Jharkhand, Telangana, and Odisha—similarly possess both subsurface data and technical expertise stemming from decades of oil, gas, and mining activity. These regions could use existing geological surveys and drilling records to assess geothermal potential and target development zones, but current NDR rules restrict data to oil and gas. As noted in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," allowing geothermal access would reduce risk and speed deployment.[9,10]

Globally, several pilot projects have shown how existing subsurface knowledge from oil and gas fields can accelerate geothermal development, including initiatives by GreenFire Energy in the United States (2020), MS Energy Solutions in Hungary (2021), and CeraPhi in the United Kingdom (2023).[11] While some of these projects also involved repurposing wells, success hinged on leveraging preexisting geological understanding and operational data.

India's oil and gas sector also brings essential technical capabilities such as directional drilling, well logging, and reservoir modelling that can enhance the precision and efficiency of geothermal projects. Advanced monitoring tools—including fiber optic temperature sensing and subsurface imaging, already used in India's mature basins—can be directly applied to geothermal resource assessment and management.

By capitalising on this wealth of subsurface knowledge and expertise, India can de-risk early-stage geothermal exploration and accelerate deployment, particularly in industrial regions where geological data and technical capacity are already concentrated.

Sharing Technology Across Industries

Over the past two decades, technological advancements in oil and gas, particularly in unconventional drilling, have opened up new frontiers with strong relevance to geothermal development in India. Techniques such as directional drilling, advanced casing, use of polycrystalline diamond compact bits, and reservoir stimulation—widely used in shale plays like the Permian Basin in the United States—can be adapted for India's deeper and more complex geothermal reservoirs, especially in regions such as Ladakh, Himachal Pradesh, and Gujarat. Recent engineered geothermal system pilot projects globally (including in Utah, in the United States) have demonstrated how hydraulic stimulation and real-time monitoring tools like seismometers, distributed acoustic sensing, and tracer diagnostics can help map subsurface heat flows and optimise well performance. Leveraging these capabilities through cross-sector collaboration can reduce exploration risk, lower costs, and speed up the commercialisation of geothermal energy in India, especially in industrial zones where heat demand is high and existing energy infrastructure can be repurposed.

One thing to note is that oil and gas firms have a higher level of direct engagement in geothermal energy than the mining industry. However, there is no significant difference in exploratory or collaborative efforts between the two sectors. Increased knowledge-sharing initiatives between both sectors may accelerate geothermal adoption.

Existing Workforce and Skills

India's oil, gas, and mining industries represent a significant portion of the national workforce. The oil and gas sector alone employs more than 2.5 million people directly and indirectly—including those working for both Indian and international companies operating in the country—while the mining sector accounts for more than 1.2 million direct jobs and supports several million more through related industries and services. Many of these roles—such as drilling crews; transport workers; Engineering, Procurement, and Construction (EPC) contractors; and maintenance technicians—possess skill sets that align closely with the needs of the geothermal sector.

However, even with this significant overlap, there are still knowledge gaps between these established industries and geothermal. While technical expertise from these sectors can be transferred to geothermal projects, workers will need to develop specialised knowledge in geothermal exploration, drilling, and resource management. Vocational institutes and academic programs can bridge these gaps by updating curricula, developing new training programs,

TRANSFERABLE SKILL SETS FROM THE OIL AND GAS INDUSTRY

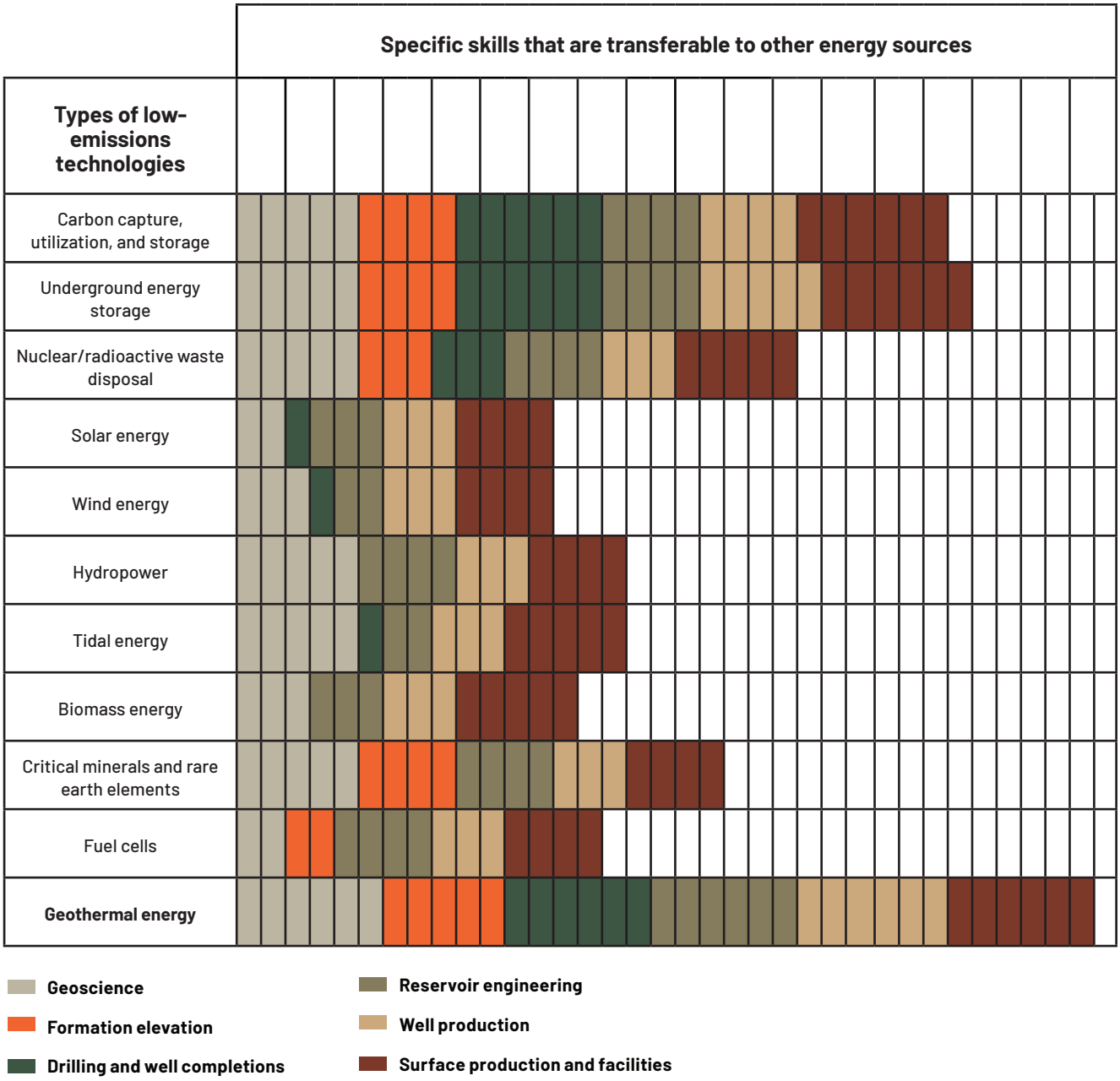

Figure 5.4: Geothermal ranks highest when considering the potential impact of transferring oil and gas skills into other energy transition and low-carbon technologies. Source: Tayyib, D., Ekeoma, P. I., Offor, C. P., Adetula, O., Okoroafor, J., Egbe, T. I., & Okoroafor, E. R. (2023). *Oil and gas skills for low-carbon energy technologies.* Society of Petroleum Engineers Annual Technical Conference and Exhibition.

collaborating with other academic institutions, and supporting industry-led initiatives. Since such efforts will require funding, government support and financial incentives can jump-start efforts while also stimulating investment. (See Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India.") Successful geothermal markets such as Indonesia and Kenya demonstrate that strong public–private partnerships and favourable regulatory environments are critical for attracting additional investment. Adopting similar strategies would put India in a position to unlock the full potential of its geothermal resources.

WORKFORCE AND JOB CREATION BENEFITS OF GEOTHERMAL

India's oil and gas sector can be organized into five verticals that are relevant to the geothermal industry: exploration and production, refining, marketing, pipelines, and research and development. Companies across these verticals employ workers in executive, supervisory, clerical, and general roles. According to the Ministry of Petroleum and Natural Gas database, there are an estimated 86,000 employees at Indian companies (e.g., ONGC, OIL, GAIL, Indian Oil Corporation Limited, Bharat Petroleum Corporation Limited, and Hindustan Petroleum Corporation Limited; see **Figure 5.5**).[12,13] Contracts with auxiliary companies allow these companies to fill an additional 430,000 manufacturing and service roles, among others.

Seventy-five percent of respondents surveyed in the oil and gas industry said that they expect geothermal development to increase employment in technical fields such as drilling, maintenance, plant operations, exploration, reservoir engineering, construction, equipment manufacturing, environmental monitoring, power plant operation and maintenance, and more.

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COMPANIES OPERATING IN INDIA'S OIL, GAS, AND MINING SECTORS

Operator Companies	Service Companies
Oil and Natural Gas Corporation Limited (ONGC)	Schlumberger (SLB)
Oil India Limited (OIL)	Baker Hughes
Coal India Limited (CIL)	Halliburton
GAIL (India) Limited	Seros
Bharat Coking Coal Limited (BCCL)	Revata Engineering
Indian Oil Corporation Limited (IOCL)	Global Drilling Fluids and Chemicals Limited
Bharat Petroleum Corporation Limited (BPCL)	Catalyst Drilling Fluids
Hindustan Petroleum Corporation Limited (HPCL)	Lotus Tricone Drill Bits
Cairn Oil & Gas (Vedanta Limited)	Gpak Offshore Services Private Limited
Reliance Industries Limited	Bergzest Energy Private Limited
Essar Oil and Gas Exploration and Production Limited	Interface Gas Consultants Private Limited
Shell	Stratom Energy Solutions
ExxonMobil	Encode Net Ventures Private Limited
Chevron	Petrosh Energia
BP	SAZ Oil

Figure 5.5: Operator and oil field service companies in India's oil, gas, and mining sectors. Source: Raj Kiran, Subsurface Energy and Storage Systems Lab, Department of Petroleum Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad.

maintenance, and more. The increase in geothermal direct-use applications for residential and industrial cooling is also expected to benefit the HVAC and maintenance workforce.

According to multiple studies, for each megawatt of installed capacity in geothermal, at least 5 to 10 employees are needed along the entire value chain from research and development, education and training, administration and authorities, production of surface and underground technology, plant construction, and pipeline construction to operation and maintenance and services.[14]

As mentioned in the executive summary and other chapters, India could create 10 gigawatts of power, 10 gigawatts of cooling, and 50 gigawatts of industrial direct-use geothermal by 2050.

Creating these 70 megawatts could, in turn, generate between 350,000 and 700,000 jobs across various geothermal applications.

The recent growth of solar power in the energy sector provides a useful analog for comparison. In 2024, the Ministry of New and Renewable Energy reported that 9.7 gigawatts of grid-connected solar photovoltaic were installed in 2023. These efforts created 17,000 jobs related to both solar heating and cooling. Geothermal heating and cooling are similarly manpower-intensive.

Wages

Sixty percent of survey respondents said they anticipate wage increases in skilled geothermal professions, owing to the demand for specialised knowledge in geothermal engineering and resource management. Eighty-five percent agree that geothermal energy will contribute to regional economic growth by providing stable, renewable energy sources and reducing reliance on fossil fuels.

As mentioned in the executive summary and other chapters, India could create 10 gigawatts of power, 10 gigawatts of cooling, and 50 gigawatts of industrial direct-use geothermal by 2050.

Creating these 70 megawatts could, in turn, generate between 350,000 and 700,000 jobs across various geothermal applications.

EXPECTED ECONOMIC AND WORKFORCE IMPACT

Impact area	Positive response
Job creation	75%
Wage growth	60%
Economic Boost	85%

Figure 5.6: Survey results on expected economic and workforce impacts. Source: authors.

According to AmbitionBox,[15] a career advisory company in India, average annual salaries in the energy sectors are as follows:

1. Oil and gas
   a. Executive salaries for roles such as chief general manager and other high-level positions range from INR 24.0 lakhs to 97.8 lakhs.
   b. Supervisory staff and engineering salaries range from INR 3.2 lakhs to 27.5 lakhs.

2. Coal mining
   a. Executive salaries range from INR 38.1 lakhs to 54 lakhs.
   b. Managerial salaries (such as deputy general managers and management trainees) range from INR 9.0 lakhs to 17.9 lakhs.

Given the close technical and operational similarities between these industries and geothermal energy, these ranges provide a useful benchmark for the emerging geothermal sector. Geothermal jobs in India could aim to align with comparable compensation levels to attract and retain skilled professionals transitioning from other energy sectors.

While geothermal energy is still an emerging field in India, the significant skill overlap with oil and gas suggests that employees who transition into geothermal roles could expect competitive wages. The survey conducted for this report also supports this expectation.

Roughly 50% of respondents noted their companies are planning to leverage existing infrastructure to develop geothermal, suggesting a clear pathway to scale this sector in India.

IMPACTS AND PLANS

When respondents from companies with a geothermal focus (see **Figure 5.7**) were asked about both current impacts and future plans, their answers reflected optimism about geothermal energy's economic potential and industry outlook. Their responses, however, also reveal lackluster sentiments about the lack of ongoing activities and the participants' involvement in the geothermal projects. Most of the respondents with less enthusiastic responses work at companies with no ongoing geothermal activities.

Roughly 50% of respondents noted their companies are planning to leverage existing infrastructure to develop geothermal, suggesting a clear pathway to scale this sector in India.

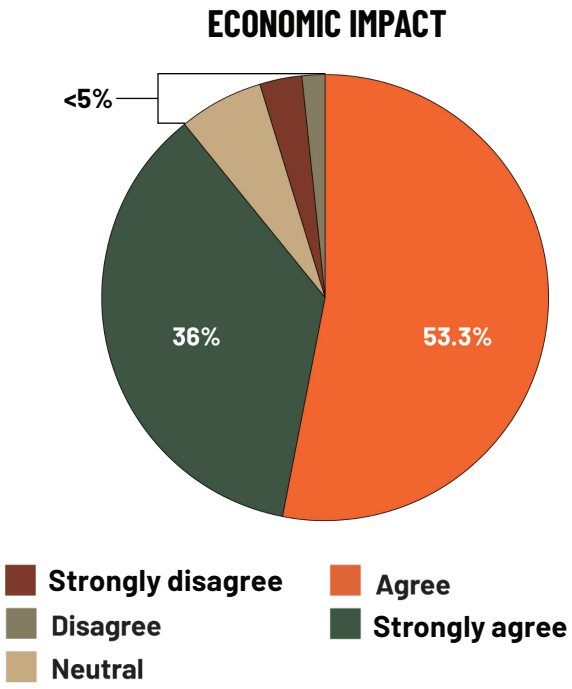

Figure 5.8: Percentage of respondents with each response to the question "Will there be a positive impact on the Indian economy due to increased geothermal activity?" Source: authors.

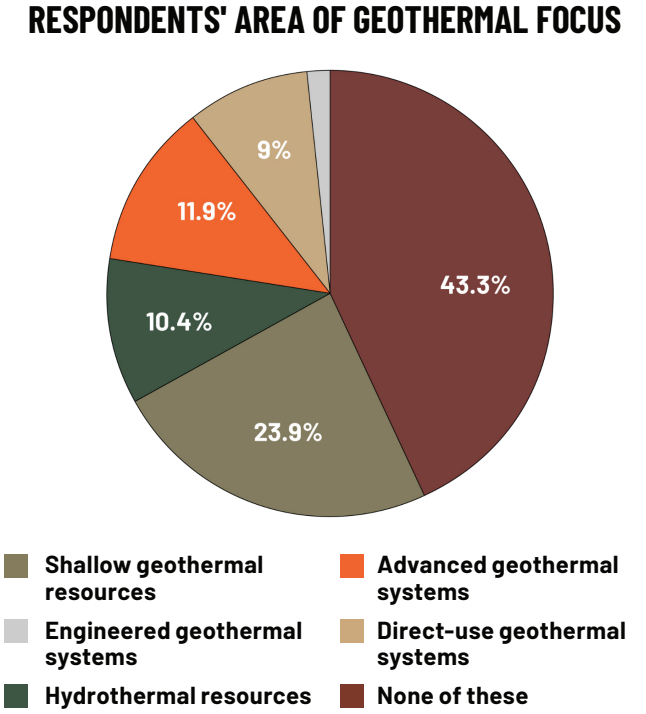

Figure 5.7: Respondents' areas of geothermal focus. Source: authors.

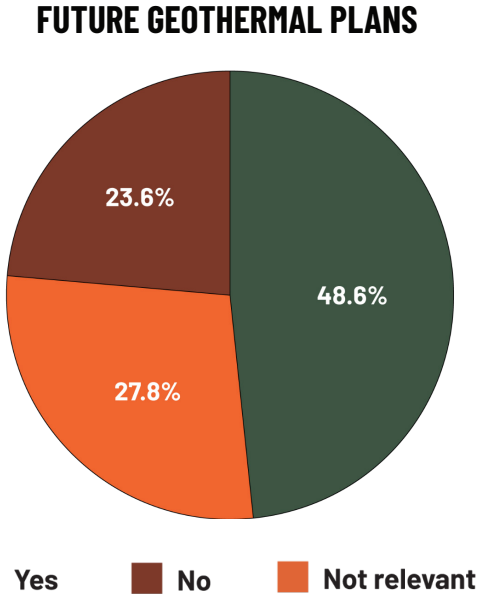

Figure 5.9: Percentage of respondents with each response to the question "Is your company planning to leverage existing infrastructure to develop geothermal resources?" Source: authors.

OVERALL FINDINGS

The statistical results of the survey undertaken to assess the oil and gas industry and perceptions of geothermal highlight a positive and consistent perception of geothermal energy's potential impact, competitiveness in wages, and industry interest. Eight-five percent of respondents agree that geothermal energy will contribute to regional economic growth by providing stable, renewable energy sources and reducing reliance on fossil fuels. Such findings are encouraging for policymakers and investors, as they suggest a readiness within related energy sectors to support geothermal development and workforce integration.

Eight-five percent of respondents agree that geothermal energy will contribute to regional economic growth by providing stable, renewable energy sources and reducing reliance on fossil fuels.

Overall, the responses were largely neutral to positive when it comes to the economic benefits of enhanced geothermal activities. The industry professionals are optimistic about the geothermal opportunities in India, though some participants expressed concerns regarding the trajectory of geothermal sector developments. Pilot projects in potential areas could enhance the participation of various stakeholders and demonstrate the viability of geothermal energy in India.

The survey results indicate that while geothermal energy is gaining recognition, direct involvement remains limited. About 70% of respondents reported that they had not previously worked on geothermal projects, though 80% belonged to companies operating in oil, gas, or mining. These findings suggest that while technical expertise exists, its application to geothermal energy is still in a nascent stage. The response pool consisted of a large number of managers, indicating that most participants have strategic decision-making capabilities in their respective organizations. A small portion of professionals were actively engaged in exploration and drilling operations, which are key areas for geothermal project execution.

Respondents also expressed concerns over regulatory hurdles and financial viability. While 75% expected geothermal development to create jobs, 60% worried about the existing workforce's skill gap. Overall, while industry experience in geothermal projects is currently limited, there is a growing interest in leveraging existing technical skills for geothermal energy expansion. With the right policies (as outlined in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India"), training, and investments, geothermal energy has the potential to become a significant contributor to India's renewable energy mix.

CONCLUSION AND FUTURE RECOMMENDATIONS

Interest in geothermal energy is gaining traction among academics, policymakers, and industry professionals across India, as evident with the release of the Ministry of New and Renewable Energy's 2025 National Policy on Geothermal Energy.

The development of a skilled workforce is essential for unlocking the full potential of geothermal energy in India, and the country has a big head start on the path to achieving this potential with its experienced oil and gas industry. For India to become a leader in geothermal power, the country should consider taking the following steps:

- Leverage expertise from the oil, gas, and mining sectors to support geothermal exploration and drilling advancements.
- Make strategic investments in education, training, and specialised courses to accelerate workforce development and bridge the workforce skills gap.
- Form collaborations between private enterprises and government entities to bolster research and infrastructure development.
- Encourage companies to undertake small-scale geothermal pilot projects to help establish feasibility and build confidence in long-term investment.
- Expanding NDR rules to allow for geothermal use of oil and gas data will reduce exploration risk and accelerate geothermal's development.

Taking such actions will allow India to create a robust geothermal workforce—one that will increase employment and wages while helping the country achieve a more resilient and sustainable energy industry.

APPENDIX: DATA COLLECTION, SAMPLING, AND METHODOLOGY

Oil and gas industry data were collated from various sources, including Ministry of Petroleum and Natural Gas and the annual reports of different companies available in the public domain.

We used a combination of random and stratified sampling methods to ensure a balanced representation of industry stakeholders. The survey remained open for responses for eight weeks, during which we sent reminders to maximise participation. We collected data anonymously to ensure confidentiality and encourage honest responses.

We conducted the study based on data analysis that included general patterns, exploratory data analysis, statistical analysis, and sentiment analysis. The survey questionnaire contained Likert-scale questions on various industry aspects, such as geothermal job impact, wage comparisons, and company interests. To perform statistical tests, we converted text-based Likert-scale responses into numerical values:

- Strongly disagree = 1
- Disagree = 2
- Neutral = 3
- Agree = 4
- Strongly agree = 5

For categorical variables, we applied appropriate numerical encoding based on the number of categories present. We either removed or imputed missing values to maintain data integrity. First, we employed principal component analysis (PCA) to identify the most influential factors in the survey responses.[16] The PCA included four steps: (i) standardisation of data sets to ensure equal weights for all variables, (ii) eigenvalues and eigenvector computation to determine the principal components, (iii) selection of components to explain the majority of variance, and (iv) a scree plot to visualise the importance of each component.

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Chapter 6

India's Stakeholders: Opportunities and Implications for Geothermal Growth and Development

Kunzes Dolma, Reykjavik University and Sustainable Development Forum of Ladakh
Sunetro Ghosal, Stawa and Sustainable Development Forum of Ladakh

India's geothermal sector will touch a range of stakeholders and industries—indigenous communities, farmers, hospitals, universities, security forces, environmental groups, and more. Its success depends on effectively engaging these stakeholders. Early community consultation, robust environmental and social safeguards, and strategic pilot projects and partnerships can help the nation realize its geothermal potential—and reduce energy costs, strengthen resilience, create jobs, and ensure local benefits.

India is home to more than 1.4 billion people who represent a rich mosaic of languages, ethnicities, and communities—many with deep historical ties to the land they inhabit. As the geothermal sector in India grows, it will increasingly intersect with and bring benefits to a diverse set of stakeholders: central and state government agencies, public sector energy enterprises, private developers, universities and research institutions, industrial users, and agricultural interests.

Crucially, this growth will also touch rural communities, farmers, and landholders whose livelihoods may be affected by project siting and resource use. In ecologically sensitive regions—such as parts of the Himalayas or tribal territories—early and meaningful engagement with local governing bodies, village councils (*panchayats*), and indigenous leadership will be essential. Such collaboration can help address concerns related to environmental impacts, water use, and land rights while building trust and ensuring that geothermal development proceeds in a socially responsible and inclusive manner.

As reflected in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," setting national targets for geothermal power generation, industrial heat, and cooling—together with the proposed national cooling mission—offers an opportunity to connect local priorities with national ambitions.

Achieving these goals will depend on early engagement and cooperation between communities, local governments, and developers to ensure the benefits of geothermal energy are widely shared.

This chapter examines the range of constituencies relevant to India's geothermal future and explores the opportunities and challenges for each group. By fostering inclusive dialogue and transparent decision-making, India can lay the groundwork for a geothermal sector that delivers economic, environmental, and social benefits while respecting the diverse interests of its people.

RELEVANT STAKEHOLDERS

Indigenous Communities

Some of the most important stakeholders with regard to geothermal energy are indigenous groups (also known as *Adivasis*, or *original inhabitants* or *first dwellers*). Although these groups have some benefits in terms of access to educational facilities, government jobs, and other programmes, they generally live in marginal ecologies. Many of these locations, however, are rich in various resources, including geothermal resources.[1] Since many of these areas are relatively remote, geothermal energy can be the ideal resource to tap to provide basic amenities such as electricity, heating, and cooling. Many indigenous groups already use geothermal resources as part of their indigenous medical system. For instance, in the Sowa Rigpa medicine system, practiced on the Tibetan plateau, hot springs are an important form of treatment for a number of ailments.[2]

New geothermal development should ensure it does not undermine indigenous groups, and all geothermal planning should include local indigenous groups. This inclusion could be via increased investment in the welfare of these groups through monetary benefits, resource allocation, meaningful skills training and education, and sustainable development. These efforts could help shift the conversation around resource extraction from indigenous lands in India, which have often been associated with challenges such as displacement, marginalisation, and environmental degradation.[3]

KEY INDIAN STAKEHOLDERS

- **Indigenous and local communities**
- **Environmental and civil society groups**
- **Agricultural and industrial sectors**
- **Universities and research institutions**
- **Defence, public health, public education, and public infrastructure agencies**
- **State and central governments**

Environmentalists

It is also important to engage with environmental groups that focus on the ecological impacts of human activities, such as air pollution, greenhouse gas emissions, deforestation, and biodiversity loss. Renewable and clean energy sources such as geothermal can offer practical solutions to many of these challenges. However, geothermal development may also present environmental risks that could diminish its perceived benefits if the risks are not managed responsibly—particularly while the sector is still emerging. Environmental and civil society organisations working across areas such as environmental protection, social justice, and rights-based development can play a constructive role as partners to help ensure geothermal projects are implemented equitably and sustainably. Poorly managed projects risk both harming local communities and undermining broader public support for geothermal energy in India. (Chapter 9, "Environmental Benefits and Considerations in India: Balancing Renewable Expansion and Ecological Stewardship in the Geothermal Sector," outlines in more detail the benefits, potential risks, and solutions to these issues.)

Agriculture and Allied Sectors

Agriculture and related sectors can also play an important role in promoting the use of geothermal resources. Agriculture sectors are among the biggest contributors to the Indian economy; together, they represent more than 16% of the gross domestic product (GDP) and support more than 44% of the population.[4] Any change in this sector therefore has far-reaching impacts.

To reduce the energy consumption and greenhouse gas emissions from farming, geothermal energy could be used to manage temperature and humidity in greenhouses and to dry crops and other produce. (For a more detailed case study on geothermal use for sustainable agriculture, see Chapter 3's "Case Study: Harnessing Earth's Heat for Sustainable Agriculture: Geothermal Cold Storage in Himachal Pradesh.")

Hospitals and Health Care

India has a large health care sector that includes public and private agencies, as well as many pharmaceutical manufacturers. While private health care establishments tend to be concentrated in urban areas, public sector health care centres are spread across the country. Each centre requires dependable energy and connectivity to provide consistent services to patients. And in more remote areas, geothermal can provide a more reliable, cheaper, and cleaner source of cooling (or heating) and—where possible—electricity. The national cooling mission discussed in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," would go towards ensuring locations such as these health centres have efficient and affordable cooling for essential public services and can provide cooling even when the grid is under stress.

Universities and Educational Institutions

The Center of Excellence for Geothermal Energy (CEGE) in Gujarat is an institutional pioneer for exploring geothermal resources in India. Founded in 2013 as part of the Pandit Deendayal Energy University, its sole intention is to explore geothermal energy in India. Along with the CEGE, India has premier technology universities spread across the country via the Indian Institute of Technology (IIT) network. Institutions that are part of the IIT network have both the resources and the intellectual capacity to develop affordable technologies, which can then be transferred to the energy sector in due course. Additionally, companies from the energy sector can form partnerships with IIT universities to develop relevant and clean technology that can harness geothermal energy.

Beyond research and technology collaborations, educational institutions could benefit greatly from the use of geothermal energy, particularly for cooling. Geothermal cooling uses the stable temperatures underground to regulate building climates efficiently, reducing reliance on electricity-intensive air-conditioning systems. For schools—from nurseries and primary schools to universities—this cooling can mean more comfortable classrooms, lecture halls, and dormitories throughout the year, even during India's hottest months.

In addition to providing comfort, geothermal cooling can significantly reduce energy costs for educational institutions, allowing funds to be redirected towards learning resources and student programmes. It also contributes to a smaller carbon footprint, which can help schools meet sustainability goals and serve as living laboratories for students to learn about clean energy technologies. Across India's diverse climate zones, geothermal systems offer a reliable, low-maintenance solution that can operate consistently, even in remote or rural areas where grid electricity may be limited or expensive.

India's Security Forces

Indian security forces (including the Indian Army and paramilitary forces) have bases and forward posts in a wide range of areas, including the Indian Himalayan region, the Thar Desert, and other parts of the country. Because many of these locations are remote and not connected to the electrical grid, they must rely on diesel-powered generators and coal-based systems for space heating and cooling—an unsustainable practice because the fuel has to be transported to each location.

Fortunately, many of these regions are rich in geothermal resources, which can be harnessed to provide heating, cooling, and—in some locations—electricity. One example is the use of space heating in areas with severe winters, all while reducing both operational costs and the greenhouse gas emissions associated with maintaining these facilities.

Indian security forces have already been experimenting with various renewable energy technologies to meet their energy needs, especially solar, wind, and micro-hydroelectric projects. However, geothermal energy could offer a better way to meet the military's energy needs, especially since many bases are located in areas with hot geysers, making them especially well suited to hydrothermal or conventional geothermal development.

As discussed in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," the Indian Army's Net Zero Energy Building in Jhansi, commissioned in 2025, provides a compelling demonstration of geothermal energy. The facility uses 10 vertical boreholes, each 120 metres deep,[5] that are connected to a closed-loop ground source heat pump system, which maintains indoor temperatures at 22°C even when outdoor extremes reach 43°C.[6] Supported by rooftop solar photovoltaics, the building functions as an off-grid geothermal-cooled system and serves as a replicable model for cantonment and institutional infrastructure across India.

The Defence Research and Development Organisation under the Ministry of Defence and the Indian Army Corps of Engineers are two important sub-agencies that can shepherd the adoption of these technologies at various scales for use by Indian security forces.

As noted in Chapter 8, public procurement can provide a structured and centralised pathway for testing, scaling, and standardising new geothermal technologies. This controlled environment can also reduce early-stage risks, accelerate learning, and establish benchmarks for performance—giving an important boost to the adoption of geothermal energy in India more broadly. Over time, the technologies proven in these public projects can then be adapted and deployed for broader civilian and commercial use.

Airports

India has one of the fastest-growing aviation sectors in the world.[7] In addition to several privately owned airline companies, India's government has also launched various plans—such as the Regional Connectivity Scheme (Ude Desh ka Aam Naagrik) and the National Master Plan for Multi-Modal Connectivity (PM Gati Shakti)—that aim to improve regional and intermodal connectivity. Airports are managed by the Airports Authority of India and require a secure, reliable source of electricity, as well as energy for space cooling and heating facilities. Geothermal energy is an ideal resource that can provide a round-the-clock, reliable source of energy while also reducing environmental impact.

INSIGHTS FROM CURRENT GEOTHERMAL PROJECTS

As mentioned in Chapter 2, "Where Is the Heat? Exploring India's Subsurface Geology," geothermal resources in India have been identified in northern, western, and northeastern India, with promising prospects in the states of Ladakh, Himachal Pradesh, Uttarakhand, Rajasthan, Gujarat, Maharashtra, Madhya Pradesh, Sikkim, Arunachal Pradesh, and Meghalaya. While preliminary studies have been carried out in some of these areas, the country has only a handful of active geothermal projects, including one in Dholera in Gujarat and two in Ladakh in the Puga Valley in the northwest Himalayan region (one is in testing at Leh Airport and the other at the University of Ladakh). These projects, which are in various stages, provide deeper insight into the dynamics of landownership, stakeholder impacts, and opportunities for the sector's development in India.

Puga Valley Project

Puga Valley, in the Changthang region of Ladakh in northern India, contains extensive zones of high-temperature geothermal potential for electricity generation. The valley—at 4,000 metres above sea level—lies southwest of the Indus Suture Zone and features mud pools, borax hot springs, rangelands, and sulphur deposits across 15 square kilometres.[8]

Ladakh is a remote, high-altitude region separated from mainland India by the Himalayas. It experiences extremes of temperature—from below -30°C in winter to above 30°C in summer—and relies mainly on groundwater for water supply. While the region was connected to the national grid in 2019, transmission lines do not extend to Puga Valley, where many communities still depend on solar technologies.

Geothermal research in Puga dates back to the 1970s, but progress remained limited until 2020, when Prime Minister Narendra Modi announced Ladakh's inclusion in India's carbon-neutral development plan.[9,10] In 2021, the Administration of Union Territory of Ladakh (AUTL), the Ladakh Autonomous Hill Development Council (LAHDC,

NATURAL GEYSERS IN PUGA VALLEY

Figure 6.1: The natural geysers dotting the Puga valley, 170 kilometres east of Ladakh's capital, Leh. Source: Shutterstock

Leh), and Oil and Natural Gas Corporation Limited (ONGC) Energy Centre Trust (OECT) signed a memorandum of understanding to develop a geothermal power plant. LAHDC, Leh, agreed to provide land—preferably public—and AUTL would secure all necessary permits and clearances. A joint venture between AUTL, LAHDC, and OECT has later phases planned, with potential grid-connected power providing much-needed local income.

A key feature of the project is its financing: AUTL is not liable for the high up-front costs, making the model replicable for other sites such as Chumathang, which is between about 30 kilometres and 40 kilometres west of Puga. LAHDC's participation provides a degree of democratic representation, though affected communities remain underrepresented in decision-making.[11,12]

Puga Valley lies partly within the Changthang Wildlife Sanctuary and has long been used by nomadic pastoralists and Amchi healers who practise Sowa Rigpa, the Tibetan system of medicine. These practitioners have traditionally used the valley's hot springs for healing, but drilling and restricted access have disrupted their work and displaced some local people without compensation. While verbal promises have been made to ensure communities benefit from this work, these agreements have not been formalised, and most project jobs require skills that locals currently lack. In addition, the project has encountered some setbacks during implementation due to higher-than-expected fluid pressures, which resulted in concerns around water pollution and local wildlife impact. Drilling has since resumed after upgrading drilling equipment, with an initial target of generating 1 megawatt of electricity.

The absence of a clear regulatory framework for geothermal development compounds many environmental and stakeholder challenges. Without an Environmental Impact Assessment—because many renewable projects are exempt[13]—the country does not have any mechanism to address the social and ecological impacts that have emerged. Introducing proper environmental and social safeguards could prevent similar issues in future projects.

The Puga Valley project, India's first geothermal electricity initiative, represents both a learning opportunity and a test case. OECT has partnered with ÍSOR, Iceland's national geothermal agency, to bring global expertise to the project. If managed transparently and inclusively, Puga could demonstrate how geothermal energy can advance India's national clean energy goals while delivering tangible local benefits. Success will depend on capacity building, job creation, and equitable participation for the people of Ladakh.

Kushok Bakula Rinpoche Airport in Leh

There is a small geothermal project in development at Kushok Bakula Rinpoche Airport in Leh, the main airport in Ladakh. The scope and details of the project are not clear, but various stakeholders have said the project is meant for heating, with the possibility of generating 2,500 kilowatts of electricity.[14] The Airports Authority of India has control of the airport premises, as the airport is a high-security zone. Presumably, this project is in line with the national government's stated vision to make Ladakh a carbon-neutral region and to meet India's global targets in cutting greenhouse gas emissions.

This project is handled by the Central Public Works Department (CPWD), which hired an Indian consulting firm, S.A.P. Automation, to provide expertise to execute this project. The project will benefit local communities, security forces, and tourists. CPWD will also gain knowledge about executing geothermal projects and hopefully will be able to execute more in the future.

University of Ladakh

CPWD also works with S.A.P. Automation on campus at the government's University of Ladakh. The project is for a ground source heat pump at a dormitory to generate 850 kilowatts of electricity.[15] The project will benefit students and faculty and spread awareness about geothermal technologies. In addition, it should help CPWD build capacity to design and execute small geothermal projects for other stakeholder groups. Similar projects are reported to be underway at two government-owned facilities: Sonam Norboo Memorial Hospital in Leh and a site in Kargil.

Dholera, Gujarat, Western India

Dholera is located 60 kilometres north of Bhavnagar city in the Ahmedabad district of Gujarat. Due to its location along the Western Marginal Fault in Cambay

Basin, Dholera had a number of thermal springs.[16,17] The Dholera site is regarded as the first site in India where geothermal resources have been used for building heating—and to generate 20 kilowatts of electricity to demonstrate its potential.[18] The project is located on the state-run campus, Pandit Deendayal Energy University, and was developed by CEGE in the Dholera Special Investment Region (DSIR). DSIR is a collaboration between Gujarat state and the government of India in which the state supplies the land (this time at the university) and the national government invests funds to develop infrastructure and promote industrial development in the region.[19]

The primary beneficiaries of the geothermal project should be the industries that invest and establish infrastructure in the region. The consultant on the Dholera project was Seros Energy, a privately held Indian oil field services company that specialises in drilling operations. Once again, this partnership should expand the knowledge of geothermal and the new technologies advancing the industry.

CONCLUSION

India's geothermal development must move forward in partnership with the communities and institutions it will affect the most. The country's diverse stakeholders—from indigenous groups to research institutions and industrial users—will determine whether or not geothermal becomes a trusted, inclusive, and transformative energy source. The experience of early projects such as Puga Valley underscores that success depends not only on technology and investment but also on dialogue, transparency, and equitable participation.

To build a strong foundation for geothermal growth, we recommend taking action with the following stakeholders:

1. **Indigenous and local communities:** Ensure early consultation and genuine participation through frameworks that protect land rights and cultural heritage. Establish benefit-sharing mechanisms and community training programmes so geothermal projects deliver tangible improvements in livelihoods.
2. **Environmental and civil society groups:** Engage environmental advocates as partners in project planning and oversight, and ensure they are aware of geothermal's many benefits. Integrate environmental and social safeguards, including mandatory Environmental Impact Assessments, to strengthen public trust and minimise ecological risks.
3. **Agricultural and industrial sectors:** Promote direct-use geothermal applications—such as greenhouse heating, crop drying, and process heat—to reduce energy costs and emissions. Encourage pilot projects that demonstrate economic gains for rural industries.
4. **Universities and research institutions:** Expand partnerships between government, academia, and industry to accelerate geothermal research and innovation. Support field-based training and technology transfer programmes to build the technical workforce needed for large-scale deployment.
5. **Defence, public health, public education, and public infrastructure agencies:** Prioritise geothermal heating and cooling at military bases, health centres, hospitals, schools, airports, and public buildings in remote and high-demand regions. Use public procurement to test and standardise new technologies that can later be adapted for civilian use.
6. **State and central governments:** Expand on the current National Policy on Geothermal Energy to further clarify permitting, ensure transparent revenue sharing, and align fiscal incentives with energy security and decarbonisation outcomes. (See Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," for more information.)

Growing India's geothermal heating, cooling, and electricity capacity presents a tremendous opportunity for the country. Realising this potential will require many more projects and deeper engagement with stakeholders across sectors and regions. Taken together, these efforts can turn India's geothermal resources into a shared national asset that supports communities, industries, and institutions alike. Done well, geothermal development can strengthen energy resilience, create skilled jobs, and ensure that the benefits of clean energy are distributed equitably across India's diverse landscape.

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Chapter 7

Who Owns the Heat? Navigating Subsurface Rights via Indian Law

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There is a compelling case for India to revise legal frameworks to recognise geothermal heat as a public resource held in trust—subject not to unfettered private appropriation but to public stewardship. Making such a change would help reduce the risks and uncertainties of investment in geothermal development.

Over the past decade or so, the oil and gas industry has developed technology that can now be used to access geothermal resources that have been historically considered unreachable. As this report makes clear, there are abundant geothermal resources across India that could be deployed for clean, always-on, and secure electricity generation and direct-use industrial heat and building cooling. To build out a strong geothermal industry, however, it is important to have a clear legal framework governing the resources. India has laws and precedents it can build on to establish such a framework, but decisions have to be made.

The issues at hand for a geothermal industry in India are as follows:

- Establish the roles of the central and state governments with respect to geothermal energy.
- Distinguish between regulatory power (including the power to decide how the resource can be developed), who gets to develop a resource, and who owns a resource.
- Get clarity on the question of ownership of the surface land and subsurface resources, the laws governing the use of underground resources, and how laws or regulations classify geothermal resources.

In a perfect world, the details of these issues would be clear so that public and private entities could access and use subsurface resources without confusion. India's National Policy on Geothermal Energy recognises

geothermal energy can be used as an energy source and for heat processes; the policy has also been formulated for the exploration and development of geothermal resources in India.[1] However, it lacks clarity on who has the authority to legislate issues related to geothermal resources and how such resources should be regulated. (India follows a federal structure in which legislative powers are divided between the centre and the states. The constitution of India's Seventh Schedule contains three lists—Union List, State List, and Concurrent List—that enumerate the subjects on which each level of government can legislate.)

This chapter examines how Indian law can accommodate geothermal resources by situating them within established legal categories. We employ four lenses: (i) the classification of geothermal as a public resource; (ii) its potential treatment as a unique natural resource; (iii) whether geothermal should or could be included under current mineral law; and (iv) a comparison of geothermal with established groundwater jurisprudence. The chapter also addresses the intersection of statutory property rights with community and customary claims to subsurface thermal resources. Discussion on how these findings impact policy can be found in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India," which outlines ideas for how to revise India's legal frameworks to better facilitate geothermal growth.

THE POTENTIAL CLASSIFICATION OF GEOTHERMAL AS A PUBLIC RESOURCE

It is important to look at the history of property law in India as a foundation for answering the question of whether geothermal should be held in private or considered a public resource. The primary legislation that governs ownership of property in India is the Transfer of Property Act, 1882. Although the word *property* is not defined in any legislation in India, from judicial analysis it is commonly understood as a "bundle of rights," and in the case of tangible property, it would include the "right of possession, the right to enjoy, the right to retain, the right to alienate, and the right to destroy."[2]

The term *property* includes corporeal and incorporeal property. Corporeal property refers to the right of ownership in material things, whereas incorporeal property concerns any other proprietary right made against or affecting a thing (for example, patent rights and rights of way). Corporeal property is always visible and tangible, while incorporeal property is not.

Property can be movable and immovable. Movable property is understood as property not fixed to the Earth.[3] Immovable property includes land; benefits coming from the land; and things attached to the Earth,[4] such as buildings, hereditary allowances, lights, ferries, and fisheries. Immovable property also includes all things permanently fastened to anything attached to the Earth.[5] (On the other hand, standing timbre, growing crops, and grass are not considered immovable property.[6])

The right to property was originally guaranteed as a fundamental right under the Constitution of India in the 1950s. Following the 44th Constitutional Amendment, 1978, the right to property was reclassified as a constitutional right under Article 300A[7] and is governed by various statues. Although they are no longer fundamental rights, property rights are legally enforceable, meaning that a person can approach civil courts for protection or restitution of their property. However, these rights are not absolute and are subject to state regulation, zoning laws, environmental regulations, and customary rights. The state retains the power of eminent domain and can acquire private property for public purposes.[8]

There is also a social and cultural aspect of property rights in India. Customary and community-based property rights are recognised under laws such as Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006, and Panchayats (Extension to Scheduled Areas) Act, 1996, reflecting India's pluralistic and inclusive approach to property regimes. Many customary claims are recognised in Indian legal systems, but a vast number of claims remain undocumented. For this reason, and to minimise social and ecological impacts, all land-based projects should account for social and economic impacts in a more holistic sense to include land-dependent communities.

In common law systems, land ownership has historically extended vertically upwards and downwards, a concept captured by the *ad coelum* doctrine: "He who owns the land owns up to the sky and down to the centre of the earth."[9] In India, however, this principle is significantly restricted by statute. Over time, several laws have

Natural resources are public goods in India, and the state is the legal owner of the natural resources as a trustee of the people. Legal jurisprudence has made it clear that the ambit of public resources is not restricted to traditional common resources like air, water, and forests but extends to intangibles such as subterranean resources (for example, minerals).

carved out exceptions to private subsurface ownership, vesting certain underground resources in the state or union government.

So ultimately the question is, where should the ownership of geothermal resources—which are not clearly addressed in any Indian statute—fall under Indian law?

IS GEOTHERMAL ENERGY A PUBLIC RESOURCE?

Natural resources are public goods in India,[10] and the state is the legal owner of the natural resources as a trustee of the people. Legal jurisprudence has made it clear that the ambit of public resources is not restricted to traditional common resources like air, water, and forests but extends to intangibles such as subterranean resources (for example, minerals).[11] In this context, geothermal resources—subterranean and potentially strategic energy resources—could reasonably be classified as a public resource. If so, it would, by legal extension, fall within the ambit of the public trust doctrine. The public trust doctrine requires the state—as the trustee of natural resources—to preserve them for public use and enjoyment. These resources cannot be converted into private ownership.[12] Although this doctrine originates from Roman law, it has been firmly entrenched in Indian law through landmark judgments such as *M. C. Mehta v. Kamal Nath*,[13] where the Supreme Court stated the following: "The State is the trustee of all natural resources which are by nature meant for public use and enjoyment. The public at large is beneficiary of the sea-shore, running waters, airs, forests and ecologically fragile lands. The State as a trustee is under a legal duty to protect the natural resources. These resources meant for public use cannot be converted into private ownership."

Similarly, in *Fomento Resorts & Hotels Ltd. v. Minguel Martins*,[14] the court reiterated this principle, holding that both renewable and non-renewable resources fall within the public trust doctrine: "[R]esources, associated uses, ecological values or objects in which the public has a special interest (i.e. public lands, waters, etc.) are held subject to the duty of the State not to impair such resources ... even if private interests are involved."

The doctrine imposes a fiduciary duty on the state to protect, preserve, and manage such resources for the benefit of present and future generations. Its application has expanded to cover even groundwater,[15] notably reinforcing the doctrine's applicability to subterranean resources. Therefore, geothermal energy could very well be subsumed under this jurisprudence, which would make it consistent with the evolving global understanding of geothermal governance in places such as Iceland,[16] New Zealand,[17] and Kenya,[18] where geothermal is owned by the state and treated as a public resource. There is a compelling legal rationale for recognising geothermal as a public resource held in trust—subject not to unfettered private appropriation but to public stewardship, as it would allow the state to establish a stable regulatory framework and might help reduce the risks and uncertainties of investment in geothermal development.

The public trust doctrine requires the state—as the trustee of natural resources—to preserve them for public use and enjoyment. These resources cannot be converted into private ownership.

Treatment as a Sui Generis Natural Resource

Another alternative is to treat geothermal as a unique natural resource—distinct from conventional categories such as minerals, groundwater, or hydrocarbons and thus requiring a tailored legal and regulatory framework.

In *Centre for Public Interest Litigation v. Union of India*,[19] the Supreme Court observed the following: "[E]ven though there is no universally accepted definition of natural resources, they are generally understood as

elements having intrinsic utility to mankind. ... Natural resources belong to the people but the State legally owns them on behalf of its people and from that point of view natural resources are considered as national assets."

This expansive conception enables the recognition of unclassified or emerging resources—such as geothermal—as national assets, particularly where they hold strategic environmental and economic value. A compelling parallel can be found in the treatment of natural gas. In *Reliance Natural Resources Ltd. v. Reliance Industries Ltd.*,[20] the Supreme Court recognised natural gas as a resource of national importance governed under a special statutory regime—the Petroleum and Natural Gas Rules, 1959. The court stated that "national assets belong to the people. The Government holds such natural resources in trust. ... The Government owns the gas till it reaches its ultimate consumer."

Geothermal shares several defining characteristics with hydrocarbons: It is subterranean and technically inaccessible without intervention; it possesses significant public utility as a low-carbon energy source; and its extraction requires caution to avoid depletion and ecological harm. However, unlike oil and gas, there is not yet specific legislation for geothermal resources. India's legislative history offers multiple precedents for creating sui generis legal regimes to govern complex or strategically sensitive resources. The Atomic Energy Act, 1962[21] (for nuclear energy), and the Offshore Areas Mineral (Development and Regulation) Act, 2002[22] (for offshore minerals), were designed to address jurisdictional and strategic sensitivities. Similarly, the Protection of Plant Varieties and Farmers' Rights Act, 2001,[23] represents a deliberate attempt to create a distinct legal architecture for plant genetic material that acknowledges its socio-economic and ecological uniqueness.

It is important to remember that sui generis legislation typically governs the use of extracted resources rather than the extraction process itself. For example, while uranium extraction is regulated under the Mines and Minerals (Development and Regulation) Act, 1957 (MMDR Act), its use for nuclear energy falls under the Atomic Energy Act, pursuant to Entry 6 of the Union List. Similarly, offshore mineral resources require stand-alone legislation due to the explicit constitutional mandate under Article 297.

In the case of geothermal resources, a more constitutionally coherent and administratively efficient approach may be to amend the MMDR Act to explicitly cover geothermal resource extraction and immediate management—such as defining geothermal wells and regulating drilling processes—within the existing mineral development framework. Stand-alone sui generis legislation may only become necessary at a later stage to govern the specific applications of geothermal energy (for example, electricity generation or direct heat use), much like the Atomic Energy Act complements the MMDR Act in the nuclear sector. Thus, while downstream use may warrant distinct treatment, the extraction phase is more appropriately addressed through amendments to the MMDR Act.

In the case of geothermal resources, a more constitutionally coherent and administratively efficient approach may be to amend the MMDR Act to explicitly cover geothermal resource extraction and immediate management—such as defining geothermal wells and regulating drilling processes—within the existing mineral development framework.

Inclusion Under Mineral Law

Should Geothermal Energy Be Treated Akin to a Mineral Oil?

In India, minerals are governed by the MMDR Act. Notably, the act does not define the term *mineral* in a general sense, but instead it operates through a list of major and minor minerals that are listed in schedules to the act. The central government is empowered to add additional minerals to this list by notification.[24] The only explicit statutory position is that *mineral* excludes mineral oil,[25] which includes petroleum and natural gas—placing hydrocarbons outside the scope of the MMDR Act and instead under the Petroleum and Natural Gas Rules, 1959.

A Broad Definition of *Mineral*

A broader definition of *mineral* appears in the Mines Act, 1952. Section 2(jj) of the Mines Act defines *minerals* as "all substances which can be obtained from the earth by

Geothermal energy currently lies outside the regulatory scope of the MMDR Act and cannot be subjected to its extraction, leasing, or royalty provisions unless there is specific legislative or administrative action to bring it within the framework.

mining, digging, drilling, dredging, hydraulicing, quarrying or by any other operation and includes mineral oils (which in turn include natural gas and petroleum)."[26]

From this definition, it can be argued that because geothermal energy is obtained by drilling into the Earth's crust to access naturally occurring thermal energy, this method would align with the modalities listed in Section 2(jj), particularly "drilling" and "any other operation." Therefore, geothermal arguably satisfies the threshold of being "a substance obtained from the Earth" through the processes addressed in the Mines Act. However, it is critical to note that inclusion under the Mines Act does not imply legal recognition as a mineral under the MMDR Act. The Mines Act is primarily concerned with regulating mine safety, labour conditions, and the physical processes of extraction. By contrast, the MMDR Act determines ownership, commercial rights, leasing, and royalties. In other words, if geothermal activity is subject to the operational regulatory framework of the Mines Act, this does not automatically subject it to the governance, revenue, or licensing provisions of the MMDR regime.

In *Bharat Coking Coal Ltd. v. State of Bihar*,[27] the Supreme Court addressed whether coal slurry deposited on riverbeds constituted a mineral and observed the following: "[T]he slurry flows into the river and is deposited on the river bed, which is later on collected and used as fuel after it is formed into briquettes. The deposit which is collected from the river bed continues to be carbonaceous in character having all the elements of coal. Thus, the slurry is coal in liquid form. ... In our opinion the slurry coal deposited in the river bed or land, in substance as well as in its character, continues to be coal."

Therefore, the term *mineral* connotes a tangible, naturally occurring substance—typically solid or liquid—that is physically extracted from the Earth for economic use. This definition does not automatically extend to geothermal, which is an intangible form of thermal energy rather than a material substance. It is worthwhile to mention that the MMDR Act does not envision geothermal energy, nor has it been notified under the statute as of yet.[28] As a result, geothermal energy currently lies outside the regulatory scope of the MMDR Act and cannot be subjected to its extraction, leasing, or royalty provisions unless there is specific legislative or administrative action to bring it within the framework.

Policymakers could explore amending the MMDR Act to explicitly classify geothermal resources under a new Part E of Schedule I, recognising their unique nature as a combination of subsurface heat and potentially extractable minerals within geothermal fluids. They could also amend Section 2(i) of the Mines Act to define a geothermal well as a type of mine, akin to the existing classification of an oil well. These changes would enable Parliament to either introduce a new section—similar to Section 8A added by the 2015 Amendment—or expand the scope of the existing Section 8A to cover geothermal energy. This section could be useful because it would provide a clear statutory basis for central regulation of geothermal extraction sites.

By-Product Extraction

An additional dimension of geothermal exploration is the extraction of mineral by-products (from the subsurface fluid) such as silica, borax, cesium, lithium, and other alkali minerals. This "incidental activity" is recognised in the National Policy on Geothermal Energy, which specifies that the extraction of such minerals will be subject to the rules and royalty payments under the MMDR Act.[29]

Defining *Mineral Oil*

Before considering whether geothermal energy could be treated akin to a "mineral oil," it is necessary to note how that term is defined under the Oilfields (Regulation and Development) Act, 1948 (ORDA). Prior to its amendment, mineral oils were understood to include only petroleum and natural gas. However, the Oilfields (Regulation and Development) Amendment Act, 2025,[30] substituted this definition to mean "any naturally occurring

while its extraction involves similar well-based drilling and fluid-handling operations, geothermal energy does not fall within the statutory meaning of mineral oils under ORDA and cannot be governed by that regime without legislative amendment.

hydrocarbon, whether in the form of natural gas or in a liquid, viscous or solid form, or a mixture thereof," and expressly includes crude oil, natural gas, condensate, coal-bed methane, shale oil and gas, tight oil and gas, and gas hydrates, while excluding coal, lignite, and helium. The common element across both versions is the hydrocarbon character of the resource. Geothermal, by contrast, is the manifestation of subsurface thermal energy, not a hydrocarbon substance. Accordingly, while its extraction involves similar well-based drilling and fluid-handling operations, geothermal energy does not fall within the statutory meaning of *mineral oils* under ORDA and cannot be governed by that regime without legislative amendment.

The National Policy on Geothermal Energy provides for geothermal energy development by prioritising the retrofitting of inactive or unproductive oil and gas wells. The conversion of such abandoned wells into geothermal plants is a principal focus area for the Ministry of New and Renewable Energy (the nodal agency for the exploration, development, and production of new and renewable energy sources in India), through collaborative ventures involving the Ministry of Petroleum and Natural Gas, the Directorate General of Hydrocarbons, and oil companies.[31]

The policy also mentions that ORDA and its amendments will apply depending on the location of the project. While the geothermal policy's reference to ORDA indicates a degree of regulatory alignment with the union's hydrocarbon framework, this does not automatically extend the ownership regime of mineral oils to geothermal. The naming of ORDA appears to ensure the continuity of technical, safety, and operational standards in projects where geothermal energy is extracted from retrofitted oil and gas wells. In such cases, the wells themselves remain under the administrative jurisdiction of the Ministry of Petroleum and Natural Gas and the Directorate General of Hydrocarbons, which justifies applying ORDA's procedural controls. However, the underlying geothermal resource accessed through these wells is not legally vested in the union under the present statutory framework. Its proprietary status therefore remains indeterminate, pending explicit legislative clarification on whether geothermal energy will be treated as a union or state resource.

The lack of clarity raises the possibility of developing a dedicated regulatory framework for geothermal resources, one that draws upon the operational principles of the Petroleum and Natural Gas Rules, 1959, while accounting for the distinct character of geothermal energy. Such a framework would also clarify institutional roles and could influence which ministry—Ministry of New and Renewable Energy, Ministry of Petroleum and Natural Gas, or the Ministry of Mines—ultimately oversees resource allocation, licensing, and revenue-sharing mechanisms, as foreshadowed in the geothermal policy itself.[32]

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IS GEOTHERMAL ANALOGOUS TO GROUNDWATER?

One approach to classifying geothermal resources under Indian law is to examine whether a resource is functionally analogous to groundwater. Both resources are subsurface, fluid-based, and accessed through boreholes or wells. Moreover, like groundwater, geothermal is often embedded in hydrothermal reservoirs that may span multiple land parcels and could potentially be vulnerable to temporary depletion.[33] However, this analogy must be carefully assessed in light of the legal, hydrological, and thermodynamic differences between the two. The extent to which geothermal parallels groundwater in Indian law—and whether groundwater jurisprudence can offer regulatory guidance—remains an important line of inquiry.

The main statutory mention of groundwater rights in India is found in Section 7 of the Indian Easements Act, 1882, which implies a right to extract water as an incident of land ownership. This statutory mention is limited, however, and does not define groundwater rights comprehensively. Scholars and policymakers often refer to this legislation when discussing groundwater rights, even though "the right in groundwater can by no means be defined as an easement."[34] The foundational legal principles governing groundwater allocation were shaped by English common law, especially in the context of land use for mining and industry.

In *Chasemore v. Richards*,[35] groundwater was distinguished from surface water by holding that water "percolating through underground strata, which has no certain course, no defined limits, but which oozes through the soil in every direction in which the rain penetrates," is not governed by the same rules as flowing water. This finding established the principle that percolating groundwater is legally distinct from defined surface water.

Similarly, in *Acton v. Blundell*,[36] the court articulated the dominant rule as follows: "The person who owns the surface may dig therein, and apply all that is there found to his own purposes at his free will and pleasure; and that if, in the exercise of such right, he intercepts or drains off the water collected from underground springs in his neighbour's well, this inconvenience to his neighbour falls within the description of *damnum absque injuria*, which cannot become the ground of an action."

This precedent established that landowners have virtually unrestricted rights to groundwater beneath their property, with no duty owed to neighbours affected by extraction. Over time, courts have increasingly recognised that unregulated extraction can deplete shared aquifers, harm ecosystems, and infringe on community rights, so the state bears an obligation to regulate use in the public interest.[37] This principle may be particularly instructive for geothermal governance. Like groundwater, geothermal reservoirs can span multiple landholdings. The extraction of geothermal resources can induce significant externalities, including land subsidence, reservoir cooling, and

seismicity. Moreover, excessive withdrawal may render the resource thermally or economically unrecoverable over time.

Despite these similarities, geothermal is not merely a hydrological resource; it is a thermodynamic one. Unlike groundwater, which is part of the hydrological cycle and recharges relatively predictably, geothermal systems—especially enhanced or dry rock geothermal—may not replenish within meaningful time frames. Moreover, geothermal development often requires complex infrastructure, including reinjection systems and pressure management, and poses distinct environmental risks.

In light of this fact, the analogy between geothermal resources and groundwater offers a useful starting point for legal classification, particularly in recognising the shared risks of unregulated extraction and the value of collective stewardship. However, geothermal energy's scientific distinctiveness, slower replenishment, and technical risks justify the development of a tailored legal framework drawing from, but not duplicating, groundwater law.

COMMUNITY AND CUSTOMARY CLAIMS TO SUBSURFACE ENERGY

India's geothermal landscape is deeply intertwined with its sacred geography. Many geothermal springs such as Tapt Kund in Badrinath (Uttarakhand), Manikaran (Himachal Pradesh), Bakreshwar (West Bengal), and Unapdev (Maharashtra) are not merely geological features but revered religious sites as well. Historically associated with ritual purification, healing, and pilgrimage, these hot springs raise an important legal question: Who owns and governs the subsurface energy in these sacred geothermal sites?

Temple Trusts and Religious Endowments

Many geothermal sites in India are situated adjacent to or within temple precincts and are managed by religious trusts. These sites are regulated by specific legal regimes applicable to religious properties. This point becomes particularly pertinent in the event that geothermal is treated as property owned by a religious institution or entity. Under Indian law, temple trusts are legal entities empowered to hold immovable property, including land and natural appurtenances, for religious purposes. In *Deoki Nandan v. Murlidhar*,[38] the Supreme Court elucidated the nature of temple endowments: "Though under Hindu law an idol is a juristic person capable of holding property, and the properties endowed for the temple vest in it, it can have no beneficial interest in the endowment, and the true beneficiaries are the worshippers, as the real purpose of a gift of properties to an idol is not to confer any benefit on God, but the acquisition of spiritual benefit by providing opportunities and facilities for those who desire to worship."

This principle implies that any use of temple property, including subsurface resources such as geothermal, must align with the religious objectives of the trust and benefit the worshippers.

Furthermore, in *Tilkayat Shri Govindlalji Maharaj v. State of Rajasthan*,[39] the court emphasised the custodial role of temple managers: "The Tilkayat Maharaj for the time being is merely a Custodian, Manager and Trustee of the said property for the shrine of Shri Nathji and that the Udaipur Darbar has absolute right to supervise that the property dedicated to the shrine is used for legitimate purpose of the shrine."

Therefore, it is indicative that temple managers cannot exploit temple properties, including geothermal resources, for purposes that are inconsistent with the trust's religious objectives. In light of the findings in these cases, where geothermal sites are located on temple trust lands (or any other equivalent religious sites in India), the energy beneath may fall within the trust's custodianship. Moreover, such custodianship is not absolute: It is constrained by the religious purposes of the trust, subject to applicable religious law. A holistic geothermal governance framework must navigate this additional cultural dimension of the ownership question.

Tribal Governance and Customary Claims in Scheduled Areas

Many geothermal zones also intersect with Scheduled Areas as defined under the Fifth Schedule of the Constitution. In these areas, tribal communities may have customary and cultural claims to geothermal sites, particularly where such features are treated as sacred. The legal framework governing tribal rights in such areas includes the Panchayats (Extension to Scheduled Areas) Act, 1996 (PESA),[40] and the Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 (FRA).[41]

In *Samatha v. State of Andhra Pradesh*,[42] the Supreme Court—while opining on leasing tribal lands in Scheduled Areas to non-tribal entities for mining purposes—ruled that leasing these lands went against the tribes' fundamental rights enshrined in the constitution. The case established a clear precedent that tribal communities possess inherent rights over their traditional lands and resources and any development on these lands requires their prior informed consent and adherence to environmental regulations.

Similarly, in *Orissa Mining Corporation v. Ministry of Environment and Forests*,[43] the court upheld the right of Gram Sabhas to withhold consent for mining projects in sacred forests of the Dongria Kondh tribe, affirming the binding nature of customary and religious claims over land and resources.

Where geothermal sites are located within community forest lands or sacred tribal sites, tribal communities may assert community forest resource rights under the FRA and prior informed consent requirements under PESA and jurisprudence. These customary claims are not merely economic or administrative—they are cultural, spiritual, and constitutional. Any policy governing geothermal in Scheduled Areas must account for these plural legal orders and proceed with informed consent, cultural sensitivity, and constitutional compliance.

CONCLUSION

This chapter has covered the legal complexities surrounding the ownership and classification of geothermal resources in India, an essential foundation for their future governance and development. While the analysis has explored multiple legal characterisations that could apply to geothermal under the existing Indian legal framework, it does not—and cannot—claim to offer a definitive placement within current law. A clear tension that runs through this inquiry is whether geothermal energy should be treated as a private property right connected with the ownership of land or as a public resource. Additionally, policymakers may prefer to subsume geothermal resources under existing legal regimes to avoid lengthy parliamentary processes and to expedite development. On the other hand, experts may argue that geothermal energy's use warrants sui generis treatment to ensure it is effectively regulated and sustainably managed. There is a third perspective, a contextual one: Where geothermal resources are found—on a petroleum site, on a religious site, or in tribal areas—imbues the ownership question with a specific contextual legal regime, rights, and a governance framework. Ultimately, because the legal characterisation of geothermal intersects with multiple regimes and institutional mandates, it is a matter of policy that the government must decisively address.

RECOMMENDATIONS

- **Recognise subsurface geothermal energy as a national resource rather than as private property**, even if surface rights remain privately or communally held. Doing so will remove the present legal ambiguity around this question.
- **Conduct a comparative legal analysis** of integrating geothermal resources into existing regimes (such as the MMDR Act, the Mines Act, and the Petroleum Act) rather than adopting a sui generis legal framework, assessing the administrative, economic, and legal trade-offs of each.
- **Evaluate contextual dimensions** of where geothermal resources are located to determine applicable legal regimes, governance frameworks, and benefit-sharing mechanisms.

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Chapter 8

Policy and Regulatory Pathways to Catalyse Geothermal in India

Shayak Sengupta, with contributions from Karthik Ganesan, Council on Energy, Environment and Water, and Project InnerSpace

Deploying next-generation geothermal across industrial heat, building cooling, and electricity generation can help India meet soaring energy demand while cutting pollution, strengthening resilience, and creating jobs. India just announced a national geothermal policy framework; this chapter lays out five near- and medium-term actions to implement and expand it. Taken together, these five steps can convert India's large potential into projects while making India less reliant on imported energy.

Like many other parts of the world, India has long used geothermal hot springs for bathing and religious practices, yet its vast geothermal potential remains largely untapped. With energy demands expected to nearly double by 2050 and building stock projected to grow by close to 70% between now and 2047, the country faces soaring heating, ventilation, and air-conditioning (HVAC) needs.[1,2]

The good news is that India has more than 11,000 gigawatts of direct-use technical potential (with a 100°C cut-off temperature down to 3,500 metres) and more than 1,500 gigawatts of geothermal cooling potential. Additionally, India has the technical potential for roughly 450 gigawatts of electricity generation (down to 5 kilometres) today and technical potential for more than 8,000 gigawatts of electricity (down to 7 kilometres) as technology improves in the future. In fact, in 2024, the International Energy Agency issued a report stating that India has some of the highest potential for geothermal globally: "India is the third-largest market for next-generation geothermal power capacity by 2050. … Deploying next-generation geothermal technologies would help India meet growing electricity demand while avoiding the need for additional coal-fired power plants, and it may be a more affordable option that could … eliminate the need for some solar PV capacity and batteries, creating a more diverse clean energy mix."[3]

Recognising this potential, India recently adopted a national geothermal policy framework. Now, the country needs rapid implementation, bankable incentives, and

proof-of-concept pilots, as well as clear signals from the government on next steps. This chapter outlines a set of five policy recommendations aimed at exponential acceleration of geothermal energy development in India. These recommendations are grouped by implementation timeline: near term (between one and three years) and medium term (between three and five years). Recommendations touch on the core legal and regulatory foundations for geothermal energy in India, efforts to reduce the high up-front costs and incentivise the supply of geothermal energy, and ways to dramatically scale up customer demand as India continues to urbanise and industrialise.

Together, these recommendations can support India's pursuit of energy independence, economic competitiveness, and climate resilience, helping the country meet its growing energy needs while contributing to its commitment to being net zero by 2070.

Many of the ideas build on India's current successful renewable energy programmes or draw lessons from international geothermal policies adapted for India's unique context. Taking advantage of these opportunities will require close coordination among central and state agencies, industry partners, and local communities.

POLICY RECOMMENDATIONS

Near Term (1–3 Years)

1. The central government could set national geothermal goals in electricity, industrial heat, and building cooling and establish a national geothermal cooling mission.
2. Rapidly operationalise the 2025 National Policy on Geothermal Energy.
3. The Ministry of New and Renewable Energy (MNRE) could advance pilot projects and financial incentives envisioned in the National Policy on Geothermal Energy.

Medium Term (3–5 Years)

4. Central and state governments could adopt demand-pull market-activating reforms.
5. The central government could pass a dedicated geothermal act within the National Renewable Energy Act or as a stand-alone framework for geothermal.

GEOTHERMAL REGULATION AND POLICY IN INDIA

Geothermal regulation and policy in India are in their early and formative stages. In September 2025, MNRE published, for the first time ever, the National Policy on Geothermal Energy to set a framework for geothermal development. We have incorporated many pieces of the geothermal policy into our recommendations. We also developed additional policy refinements and recommendations after reviewing the challenges faced during the development of Indian oil gas and other subsurface resources, as well as incentive structures for other renewable energy sources. The policy recommendations in this chapter aim to help developers of geothermal energy avoid similar obstacles and scale projects significantly faster in order to meet India's national priorities.

India's Current Legal and Regulatory Geothermal Policy Regime

The term *geothermal* seldom appears in Indian statutory law. In fact, it only occurs twice (that we are aware of) in *The Gazette of India*.[4] The first instance was late in November 1999, when the term *geothermal energy* was formally recognised through the Allocation of Business rules as 10th in a list of subjects for which MNRE has administrative responsibilities.[5] In the years since, MNRE has taken some steps to develop geothermal, including by drafting a proposed National Policy for Geothermal Energy in 2016.

Allocation of Business

By allocating geothermal resources to MNRE management, the president of India, as directed by the prime minister and cabinet, tasked MNRE with coordinating, developing, and promoting geothermal energy, as well as crafting and administering geothermal programmes. With this authority, MNRE can draft policies, set goals, and establish guidelines and best practices. Consequently, project developers must receive MNRE's consent to undertake projects.

The second official reference to geothermal appeared in a December 2022 amendment to regulations for the Electricity Rules, 2005. In that instance, geothermal was recognised as a possible source of "renewable energy" for electricity generation.[6] As a result, if India were to develop a geothermal electricity project, the project and resulting electricity would be subject to the updated provisions of the Electricity Act, 2003, and Electricity Rules, 2005.[7]

Outside of MNRE programme requirements, there is no central regulation governing geothermal development. Drilling and subsurface rights are subject to existing oil, gas, mining, and environmental laws and their accompanying regulations in India. As funded by Parliament in the annual budget, MNRE can administer grants and subsidies, fund pilots or demonstrations, and develop plans. MNRE's policy proposals will broadly guide clearances given by other authorities until the central government stipulates specific regulations. Because the central government governs many of these areas in tandem with state governments, regulations may also vary from state to state.[8]

As such, there is still significant uncertainty as to how any developer can proceed without adopting guidance from MNRE directly or how this guidance would directly affect other general state-level permissions (such as land clearance and groundwater use) and environmental approval.

MNRE's National Policy on Geothermal Energy

Although MNRE was given its geothermal authority in 1999, no major actions were taken until 2016, when, in an aspirational effort to help spur geothermal development, MNRE drafted its first proposed regulatory roadmap.

The 2025 policy outlines some of the foundational regulatory concepts that MNRE would use to administer a geothermal programme, including the definition of a geothermal resource and the outlining of various processes, such as leasing, exploration approval, and project development. (See **Figure 8.1** for more details on the new policy.) The roadmap does not address every legislative or regulatory policy necessary to scale geothermal exponentially. This chapter suggests specific items within the new policy that can be moved forward quickly, as well as additional actions India can take to scale geothermal.

HIGHLIGHTS FROM THE 2025 NATIONAL POLICY ON GEOTHERMAL ENERGY

1. Defines *geothermal resources* and establishes processes for leasing, exploration, approvals, and project development.
2. Establishes a single-window clearance system, with states required to designate nodal agencies for permitting and monitoring.
3. Authorises MNRE to support geothermal power and direct-use pilot projects.
4. Acknowledges high up-front costs and risks and calls for policy mechanisms including incentives, subsidies, and risk-mitigation tools to attract public and private investment.
5. Empowers MNRE and state governments to issue additional guidelines and incentives to make geothermal development sustainable and bankable.
6. Highlights priority areas for development, including high-heat-flow regions such as the Himalayan geothermal belt, Cambay Graben, and the Godavari Rift Valley; industrial clusters such as steel, cement, and food-processing zones; and repurposing opportunities in oil and gas basins such as Cambay and Krishna-Godavari.
7. Promotes diverse applications across electricity generation, industrial process heat, district cooling, agriculture, and ground source heat pumps.
8. Leverages oil and gas drilling expertise, equipment sharing mechanisms, and Directorate General of Hydrocarbons (DGH) data on abandoned and existing oil wells for geothermal development.
9. Advances public–private partnerships and pilot demonstrations to build investor confidence and technical capacity.
10. Aligns geothermal development with India's 2070 net-zero goal and a broader transition to clean energy.

Figure 8.1: Highlights from the 2025 National Policy on Geothermal Energy. Source: the authors.

OPPORTUNITIES FOR STRENGTHENING INDIA'S GEOTHERMAL POLICY	
While the 2025 National Policy on Geothermal Energy is a critical step forward, there are several additional opportunities to further de-risk early projects, diversify the innovation ecosystem, and ensure India's geothermal development is ready for the future.	
Start-up and university innovation	The policy supports research and development broadly but does not establish direct funding lines or incubation mechanisms for start-ups and universities, missing a chance to catalyse early innovation.
Detailed project reports (DPRs)	Funding or co-developing DPRs with states could accelerate state-level project pipelines.
Geothermal site listing	Although the policy includes engineered geothermal systems, advanced geothermal systems, and data-sharing provisions, the final policy retains a static list of 381 hot spring sites—which risks keeping the focus on traditional geothermal sources instead of tapping into the vast distributed resource base that could help cater to large population centres as well.
Strengthening NDR data access to enable geothermal development	India's National Data Repository (NDR) has been designed primarily to support petroleum operations, which limits access for geotwhermal developers. The 2025 National Policy on Geothermal Energy recognises the potential for DGH-managed oil and gas data to be used for geothermal prospective analysis, subject to existing NDR procedures and guidelines. Broadening NDR provisions to include geothermal—and to provide mechanisms for guaranteed access—would support the accelerated development of India's geothermal sector.

Figure 8.2: Four opportunities to strengthen India's current geothermal policy. Source: the authors.

A BRIEF HISTORY OF INDIAN OIL, GAS, AND MINING REGULATION: A BIT OF A JUMBLE

Some existing laws and regulations in India are likely to influence geothermal governance—particularly those governing oil and gas production and non-coal minerals. Some of these rules date back to British colonial rule. Both fossil fuels and non-coal minerals saw increasing nationalisation of industry in the decades immediately after independence in 1947, followed by growing liberalisation and openness to private sector participation.

Since its enactment in 1950 and in subsequent amendments, the Indian Constitution has explicitly outlined the roles of the central and state governments in regulating oil, gas, minerals, and most energy and natural resource–related ancillary topics. In detailed lists, the constitution enumerates (1) powers of the central government, (2) powers of state governments, and (3) subjects where regulation is concurrently shared by both the central and state governments. Powers not explicitly enumerated to either the central or state governments are retained by the central government.[9] Geothermal is not explicitly enumerated and, therefore, falls to the central government by default.

Per the nation's constitution, the regulation of petroleum in India is the responsibility of the central government.[10] In practice, for oil and gas exploration and production, the central government has adopted regulations that cede authority over land use and oil and gas leases to state governments, particularly for onshore production—but these are also subject to central government approval.[11,12]

The Indian constitution also outlines that state governments own their non-oil-and-gas mineral resources; however, mining regulation of these minerals is subject to central government approval.[13] Parliament has asserted extensive central legislative control over these regulations, especially royalties.[14] As for other properties (e.g., land and water), the constitution largely tilts towards regulation by state governments. That said, it also outlines joint central–state jurisdiction over electricity and forests. Environment and pollution, which are not explicitly mentioned, fall under central purview, but in practice, state and central governments share responsibilities.[15,16] Legal, ownership, and royalty considerations are unpacked in Chapter 7, "Who Owns the Heat?"

GEOTHERMAL HEAT: A NATIONAL RESOURCE?

India's legal treatment of subsurface resources is fragmented across petroleum, mining, land, and water statutes. Geothermal sits between these frameworks: It is neither a hydrocarbon nor a hard mineral, yet it requires drilling, reservoir management, and long-lived stewardship. To unlock investment while protecting communities and ecosystems, India should recognise subsurface geothermal heat as a national resource held in the public interest, separate from surface ownership. Surface rights, private or communal, would remain intact; what changes is clarity that title to the heat itself does not vest with the surface owner. This idea is included in Recommendation 4, but it could also move forward as part of implementation of the current geothermal framework.

Access would occur through transparent, time-bound licenses or leases with clear duties; environmental safeguards and reinjection; groundwater protection and monitoring; data-sharing and public reporting; restoration and decommissioning; and fair compensation for access corridors and easements. This approach removes present ambiguity; harmonises central and state government roles; and provides a coherent basis for royalties and fees, auctions, or administered pricing. It also aligns geothermal with India's tradition of stewarding strategic subsurface resources for long-term public benefit—while giving developers the certainty they need to finance exploration, industrial heat projects, district cooling, and next-generation systems at scale.

INDIAN ELECTRICITY MARKETS AND REGULATION

In addition to potential impacts from geothermal-specific laws and regulations, the increasing deployment of geothermal energy in India will be influenced by Indian electricity markets and regulations, particularly since the current MNRE roadmaps envision electricity generation geothermal projects.

India's Electricity Market Structure

India's electricity market is among the world's largest systems. The sector and operations are coordinated between the central and state governments. The current structure of the electricity sector in India stems from reforms in the 2003 Electricity Act that spurred private sector participation and the unbundling of generation, transmission, and distribution assets.[17,18] Power plants are owned by either the central or a state government or the private sector. Distribution companies—or *discoms*—are load-serving entities that purchase the generated power and deliver it to consumers. Most discoms are owned by state governments, but a small number are privately owned.

Long-term contracts between discoms and developers that tender for generating capacity—rather than short-term scheduling and operations—are more likely to influence the uptake of geothermal electricity and capture its clean, firm attributes. (For example, there have been tenders for solar and energy storage projects as well as hybrid solar-wind projects to procure firm renewable power.[19,20]) For geothermal electricity to be deployed, a project developer must secure a contract for its capacity at a sufficiently attractive price for a discom or large (corporate or industrial) buyer. Moreover, these contracts would likely need to be modelled on India's conventional fossil fuel electricity contract or round-the-clock renewable energy contracts to accurately capture the clean, firm attributes of geothermal energy.[21] These contracts have various pricing structures (e.g., fixed and variable components or peak and off-peak tariffs) to incentivise uptake.

Regulatory Efforts to Address Weak Distribution Companies

Distribution companies are the key buyers of wholesale electricity in India. However, companies have historically been the weakest link in India's electricity system due to their poor financial health, often characterised by liquidity issues stemming from revenue and cost pressures. On the cost side, many discoms are obligated to pay higher capacity charges for older coal power purchase agreements, as well as for obligations to use renewable energy as "must run" sources. On the revenue side, state government–owned discoms often struggle to collect revenue from consumers because of technical losses,

power theft, and low regulated tariffs that do not cover the actual cost of power (a politically contentious issue). With such poor financial health and offtake risk, discoms continue to hinder investment by renewable energy project developers and their financiers.[22] This issue will also apply to geothermal energy.

Given the risk from state discoms, the central government has instituted several instruments and policies to encourage the expansion of renewable energy in India, including offtake guarantees, green open-access policies, and captive power for larger consumers.

The main offtake guarantee in India is provided through central government–owned companies—such as the Solar Energy Corporation of India (SECI) and NTPC Limited (formerly the National Thermal Power Corporation)—with assets in fossil, hydro, nuclear, and renewable electricity generation. These companies act as intermediaries between private sector renewable energy developers and state government–owned distribution companies. SECI and NTPC enter into power purchase agreements with project developers through competitive tendering and bidding, after signing power sale agreements with the discoms. Through dedicated funds and contracts, these intermediaries reduce the risk of non-payment by discoms to developers. One tool available to these intermediaries is a tripartite agreement between India's central bank, the Reserve Bank of India (RBI); the central government; and state governments. As a last resort,

POLICY RECOMMENDATIONS TO CATALYSE GEOTHERMAL DEVELOPMENT IN INDIA

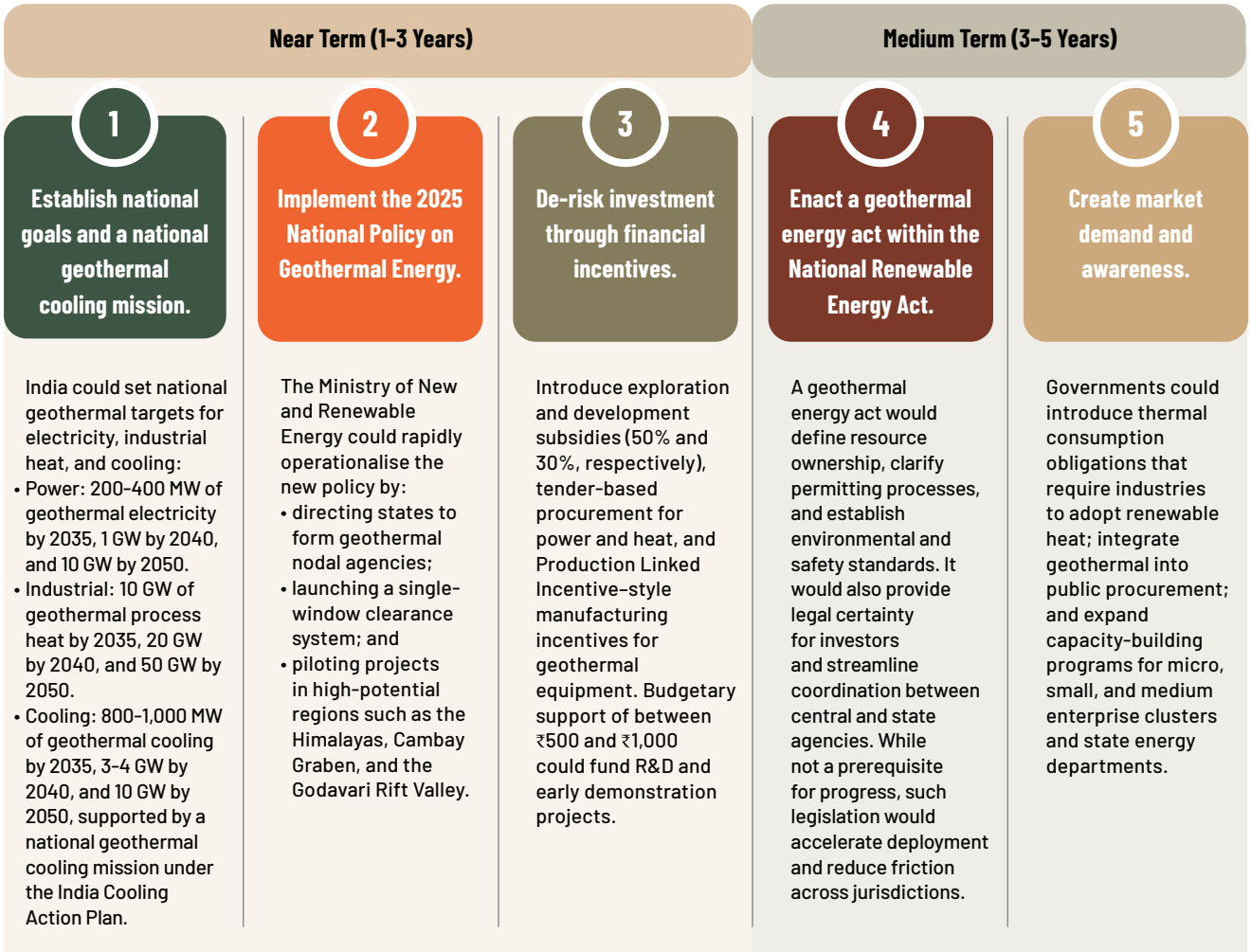

Figure 8.3: Policy recommendations to catalyse geothermal development in India. GW = gigawatts; MW = megawatts. Source: the authors.

the central government may ask RBI to deduct money from a state government's account in case of default or payment delays by the state's discom.[23]

Two other instruments to promote renewable energy in India are green open-access and captive power, which enable large power consumers to bypass the need to purchase power from a discom. In open-access power, large power consumers can contract with renewable power producers directly and use the existing power grid to transmit that electricity (and pay fees to the transmission and distribution companies to cover their network costs and cross-subsidies). Likewise, in captive power, a large consumer can also set up their own renewable energy project as a single user or with a group of consumers.[24] In both instruments, large commercial and industrial customers may get cheaper, cleaner power depending on project economics and regulated state and central government charges.[25] These procedures are governed by the Electricity (Promoting Renewable Energy Through Green Energy Open Access) Rules, 2022. (Some states have been unsupportive of these policies, as they take away large revenue-generating customers for their discoms, further exacerbating discom financial woes.)

POLICY RECOMMENDATIONS

The remainder of this chapter delves into each of the enumerated policy recommendations, some of which go beyond the 2025 policy and some of which help implement it to ensure continued momentum. As noted earlier, existing laws and regulations governing oil, gas, mining, and electricity will also shape the geothermal sector's regulatory landscape. Related recommendations explore the implications of these existing laws on accelerated geothermal development.

1. Establish national goals and a national geothermal cooling mission.

India's geothermal potential spans power generation, industrial heating, and cooling—three interconnected areas that together can reshape how the country meets its growing energy demand. Expanding geothermal power reduces reliance on fossil fuels and provides clean, steady electricity; using geothermal heat directly in industry cuts costs and emissions from manufacturing; and deploying geothermal cooling can supply cooling to many more people without needing to add significant new electricity generation while also increasing resiliency, particularly during periods of peak demand. While progress in any one of these areas is valuable, their combined impact is far greater. Setting coordinated goals across each of these sectors allows each to grow and complement the others. Doing so can improve air quality, strengthen grid stability, enhance energy resiliency, and fortify India's long-term energy independence.

Electricity

Geothermal energy could play a role in India's next phase (post-2030) of clean electricity development to help meet growing power demand. India's energy needs are accelerating, and some projections suggest that the country may need to more than triple its current installed capacity of 468 gigawatts by 2040[26]—roughly equivalent to adding a grid the size of the European Union's.[27] Project InnerSpace analysis suggests that bringing between 200 megawatts and 400 megawatts of geothermal electricity online by 2035 and reaching 1 gigawatt by 2040 and 10 gigawatts by 2050 could significantly contribute to a more diversified and resilient energy mix for India. While ambitious, these levels of deployment could support the development of a stable, low-carbon energy sector. They would also be broadly in line with initiatives pursued in other countries, including Kenya and the United States.[28,29]

Chapter 2, "Where Is the Heat? Exploring India's Subsurface Geology," highlights that India has total technical potential for roughly 450 gigawatts of electricity generation (down to 5 kilometres) today and technical potential for more than 8,000 gigawatts of electricity (down to 7 kilometres) as technology improves in the future. This finding indicates that, in principle, there is substantial scope for geothermal power to contribute to India's clean energy transition if exploration and development are pursued.

Industrial Direct Use

Geothermal energy could be a promising source of heat for India's industries, all of which are expected to see substantial growth in energy demand and currently lack adequate, credible alternatives to fossil fuels or traditional biomass. For example, the International Energy Agency projects that by 2040, industry will be the single largest source of India's energy consumption.[30]

In particular, India's low- and medium-enthalpy geothermal resources could be suited for the heat needs of small and medium industries such as textile manufacturing, food processing, pulp and paper production, and pharmaceutical production—all processes that require thermal energy at temperatures between 80°C and 250°C. Geothermal energy could displace the mix of coal, biomass, and (increasingly) natural gas that these industries use for their heat needs.[31,32,33] As noted at the start of this chapter, the total technical potential for industrial direct-use heating is more than 11,000 gigawatts (with a 100°C cut-off temperature down to 3,500 metres).

With this industrial direct-use energy, the government could aim to bring 10 gigawatts of geothermal process heat online by 2035, more than 20 gigawatts by 2040, and more than 50 gigawatts by 2050.

Building Cooling and a National Geothermal Cooling Mission

In addition to industrial demand, India's building stock will also see growth in energy demand to be the second-largest source by 2040.[34] Geothermal energy could help meet the cooling needs of these buildings through district cooling and more efficient ground source heat pumps (GSHPs).

India's cooling energy demand is expected to be the largest source of demand growth in buildings. In 2040, projected increases in electricity consumption just for cooling in India could rival all of Germany's current power consumption. Air-conditioners and space cooling will primarily drive this growth.[35] Consequently, the need for more efficient space cooling could mean a greater role for geothermal energy. Chapter 3 notes that India has more than 1,500 gigawatts of total technical cooling potential in India, and 610 gigawatts of this cooling potential can be found in high heat-risk areas that have significant aquifer cooling potential. GSHPs, which can cool buildings by using the ground as a heat sink, are more energy-efficient than conventional air-conditioners, yet they also have higher up-front costs, requiring concerted policy support such as dedicated targets, financing, and building codes.[36] For example, the 2024 Energy Conservation and Sustainable Building Code for commercial buildings mentions the use of GSHPs, but this updated code needs to be adopted and enforced by individual states.[37]

Likewise, establishing district cooling networks paired with geothermal sinks could increase the availability of efficient cooling in buildings and reduce additional loads for the electricity system. District cooling systems pump cold water from a centralised station to multiple buildings for their cooling needs. This station could then use large GSHPs to cool these buildings.[38] India's first district cooling network at Gujarat International Finance Tec-City (GIFT City) provides a pilot for similar systems to expand the country but should be coupled with geothermal sinks.[39] As outlined in Chapter 4, "Geothermal Cooling Opportunities," India has significant potential for this type of cooling, particularly in regions that are—and will continue to be—impacted by extreme heat events. States ranking in the top 10 for cooling potential include Uttar Pradesh, Gujarat, Tamil Nadu, and Andhra Pradesh.

To that end, India could set a goal of between 800 megawatts and 1,000 megawatts of geothermal heating and cooling by 2035 (thermal output), between 3 gigawatts and 4 gigawatts by 2040, and more than 10 gigawatts by 2050. This goal is crucial: India is projected to nearly double its building stock over the coming decades, adding between 700 million and 900 million square metres in new floor space every year through 2040, with demand for a new air-conditioner every 15 seconds.[40]

These targets are not just a matter of energy efficiency but climate resilience and public health as well. Between 2001 and 2019, India experienced almost 20,000 heat wave–related deaths.[41] By 2036, heat waves and erratic rainfall are expected to affect more than 80% of India's population, with dangerous heat events projected to increase in frequency and severity.[42] Already, these events are straining power grids, health systems, and vulnerable communities.

In this context, geothermal cooling systems can serve as a form of distributed climate adaptation. In line with these targets, the Government of India could initiate a national geothermal cooling mission as part of the India Cooling Action Plan outlined in 2019. The India Cooling Action Plan envisions significant increases in cooling demand, and the plan's intention to promote non-in-kind cooling technologies aligns with this geothermal cooling mission. A national geothermal cooling mission would incorporate these targets as well as promote district cooling pilot projects in schools, public hospitals, government buildings,

and community centres. Given the limited implementation of the India Cooling Action Plan, there is ample scope to incorporate geothermal energy as a cooling solution.[43,44]

The Indian Army's Net Zero Energy Building in Jhansi, commissioned in 2025, provides a compelling demonstration of this technology. The facility uses 10 vertical boreholes (120 metres deep) connected to a closed-loop GSHP system, maintaining indoor temperatures at 22°C when outdoor extremes reach 43°C. Supported by rooftop solar photovoltaics, the building functions as an off-grid geothermal-cooled system and serves as a replicable model for cantonment and institutional infrastructure across India.[45]

These targets—for electricity, industrial direct use, and geothermal cooling—are achievable with industrial process heat clusters, a few city-wide thermal energy networks (TENs), and GSHPs in thousands of public and commercial buildings. As discussed in more detail in Policy Recommendation 3, if the central government implements a Production Linked Incentive (PLI) plan for GSHP or TEN equipment, India can significantly ramp up its domestic production of equipment used for geothermal cooling.

2. Implement the 2025 National Policy on Geothermal Energy.

India's geothermal sector has waited decades for a clear framework. While not a substitute for statutory legislation, MNRE's National Policy on Geothermal Energy offers a foundational framework for the development of all types of geothermal, including for power, cooling, and direct-use heat. With this policy now in place, MNRE can move quickly to turn it into practice by prioritizing governance and administration. The policy establishes a single-window clearance system, defines geothermal resources, and empowers MNRE and state governments to issue additional guidelines. These elements are important, as they give clarity to developers, investors, and state authorities—and therefore help organise a credible market. To ensure early success and credibility, MNRE could take the following steps:

- Direct states to establish geothermal nodal agencies within 6 to 12 months to serve as one-stop shops for land, water, forest, and environmental permits. MNRE can issue model structures and staffing guidance to ensure consistency nationwide.
- Publish national clearance guidelines with firm timelines (e.g., 90 days for exploration permits, 120 days for development approvals) to reduce uncertainty and provide predictability for investors.
- Launch a national digital clearance portal integrated with existing resource data repositories to allow developers to track applications and reduce duplicative processes.

Additionally, MNRE could prioritise early rollouts in high-potential regions such as the Himalayan geothermal belt, Cambay Graben, and Godavari Rift Valley. Demonstrating proof-of-concept in these areas will build confidence among developers and investors and provide a replicable model for nationwide adoption.

It is also important to note that this report finds far more geothermal potential in the country than was identified in the policy. As mentioned, India has the technical potential for roughly 450 gigawatts of electricity generation (down to 5 kilometres) today and technical potential for more than 8,000 gigawatts of electricity (down to 7 kilometres) as technology improves in the future; more than 1,500 gigawatts of geothermal technical potential for cooling; and more than 11,000 gigawatts of potential for direct-use heat for industrial processes. The size of this opportunity should be an incentive for MNRE to move more quickly to tap into it.

3. De-risk investment through financial incentives.

The adoption of MNRE's policy was critical and authorised the ministry to support geothermal power and direct-use pilot projects and create policy mechanisms (including incentives, subsidies, and risk-mitigation tools) to address high up-front costs. To further support geothermal growth, MNRE might explore measures such as the following:

- **Establish a 50% exploration subsidy and 30% development subsidy, aligning geothermal with international best practices and India's proven solar support model.** Covering approximately 50% of exploration costs follows international

best practices—such as exploration risk-mitigation facilities in Indonesia,[46] Turkey,[47] and Kenya[48]—by reducing early-stage financial risk and addressing the highest-uncertainty phase where investors are most reluctant.[49]

A subsidy of around 30% of plant development costs would mirror the level of support that India already extends to solar projects under schemes such as Central Financial Assistance. Applying this proven model to geothermal will level the playing field for a resource that has higher up-front costs but delivers always-on, firm power and heat once operational. Together, these subsidies would not only reduce the financial burden on early projects but also attract private capital, accelerate pilot deployments, and signal the government's commitment to making geothermal a mainstream part of India's energy transition. MNRE could also empower state nodal agencies to issue additional guidelines and incentives that reflect local conditions while maintaining alignment with central policy.

- **Launch tenders for direct-use geothermal applications.** MNRE could launch a pilot tender to showcase an example of direct-use geothermal. The organisation could also seek, from Parliament, full funding in the budget for a dedicated tender no later than 2027. These competitive solicitations would offer long-term offtake agreements or viability gap funding. MNRE has used similar mechanisms to support early-stage deployment of emerging technologies such as floating solar, biomass gasification, offshore wind, and, most recently, green hydrogen.[50,51,52,53]

  These efforts were often launched before statutory mandates or large budget lines existed, leveraging modest funding under R&D, technology innovation, or public–private partnership programs. A similar approach can be applied to geothermal—especially for electricity generation in high-potential areas, industrial process heat in key clusters, and district cooling–scale or public GSHP systems in urban buildings.

  Industrial process heat, district energy systems, and GSHPs would benefit from capital subsidies modelled on existing MNRE programmes such as PM-KUSUM (Prime Minister's Farmer Energy Security and Upliftment Mission) for agricultural solar[54] or PM Muft Bijli Yojana (Prime Minister's Free Electricity Scheme) for rooftop solar. These could be targeted toward public infrastructure, industrial clusters, and commercial building retrofits in high-density areas. Because many of these systems reduce demand on the grid and avoid fossil fuel use, they already qualify under Bureau of Energy Efficiency (BEE)–administered building efficiency programmes and the Energy Conservation Building Code.[55]

  As noted in Chapters 3 and 4, pilot projects could include industrial heat in Cambay's manufacturing clusters and district cooling systems in heat-stressed cities near the deep sedimentary basins—especially the Indus, West Bengal, Cambay, and Cauvery basins—where aquifer cooling potential is high and can be integrated into urban resilience strategies, energy-efficient infrastructure, and sustainable groundwater management These visible, replicable pilots would demonstrate geothermal's versatility beyond power generation.

- **Promote technology localisation and supply chain development.** MNRE could adapt India's successful PLI-style model to support domestic manufacturing of geothermal components (e.g., drilling rigs, heat exchangers, GSHP units), lowering costs while building industrial capacity.

- **Fully fund the government's Renewable Energy Research and Technology Development (RE-RTD) Programme.** This programme is critical to de-risking exploration, identifying viable zones, and supporting demonstration-scale drilling.

It is also vital that Parliament pair policy approval for a geothermal plan with a dedicated line item in MNRE's annual budget. A capital allocation of between ₹500 and ₹1,000[56] (US$60 million–$120 million) over five years could support early-stage resource mapping, public–private demonstrations, risk-sharing instruments, and institutional capacity building, which would in turn activate geothermal's long-dormant mandate and position it alongside wind, solar, and hydrogen in India's renewable strategy.

OTHER RENEWABLE ENERGY POLICY TEMPLATES

Several other policies and programmes specific to incentivising clean energy in India are worth highlighting, as they could serve as models for how to stimulate growth for geothermal power through financial incentives, specifically the following:

- Solar parks and ultra mega projects that receive land, transmission, and permitting support from MNRE.[57]
- National Wind Solar Hybrid Policy, which promotes co-located wind and solar to improve grid stability.[58]
- Waived inter-state transmission charges for wind and solar projects commissioned by specific deadlines, therefore reducing the costs of that energy (though this incentive is expected to end soon).
- Generation-based incentives that are paid per kilowatt-hour generated for projects feeding into the grid.[59]

Finally, while it requires parliamentary action, MNRE could recommend geothermal be incorporated into India's tax and market incentive structures. Accelerated depreciation provisions helped catalyse early wind and solar growth.[60] The same could apply to geothermal heat systems and power plants, particularly in sectors with heavy thermal energy demand.

MNRE has a proven playbook for nurturing early-stage energy technologies. By adapting existing instruments to geothermal's distinct technical and market profile, India can accelerate deployment of this underutilised resource while staying consistent with financial and institutional models that have successfully scaled other renewables.

4. Enact a geothermal energy act within the National Renewable Energy Act.

While India currently defines and regulates renewable energy, including geothermal energy, through the Electricity Act, 2003, and amendments to the Electricity Rules, 2005, additional legislation and statutory authorities are helpful to scale geothermal in the country. This legislation could be incorporated into a Renewable Energy Act, or it could be stand-alone legislation focused just on geothermal. No matter what form this act takes, the reasons for why this is needed and the language and provisions are detailed in this section.

Geothermal more closely resembles oil, gas, and mining than it does solar or wind. Geothermal development must navigate risks such as subsurface drilling with its attendant safety and environmental issues, resource management and conservation, and intricate land and mineral rights issues.

Consequently, the nascent geothermal energy sector in India will greatly benefit from robust legal infrastructure to ensure safe and sustainable development and transparent scaling. A well-structured geothermal act in India might borrow elements from India's Oilfields Act for drilling and subsurface rights; the Electricity Act for generation, transmission, and grid integration; the Environment Act for environmental safeguards and permitting; and possibly the Mines and Minerals Act for land access and royalties regulations.

5. Create market demand and awareness.

While MNRE-led tenders, grants, and subsidies will help increase supply by pushing pilot projects into the market, these are not enough to drive widespread commercial deployment. In parallel, the central government could create demand-pull incentives for geothermal energy, which could include (a) mandating clean thermal consumption obligations for large energy-intensive industries; (b) raising awareness of geothermal technologies among energy efficiency measures for micro, small, and medium enterprises (MSMEs); and (c) public procurement of geothermal technologies.

a. Mandate clean thermal consumption obligations for large industries.

BEE could mandate large energy-intensive, heat-consuming industries to procure some thermal energy from clean, renewable sources. These TCOs could be an expanded or modified version of renewable consumption obligations (RCOs) that BEE has notified as of August 2025 for designated consumers: electricity distribution companies (discoms), open

access, and captive power users.[61] However, TCOs would differ from RCO regulations by first mandating use of clean heat as opposed to only electricity, which would capture industrial energy derived from direct fuel combustion. Moreover, the TCOs would expand the list of designated consumers to large industrial energy users. BEE can issue TCO regulations for a wider set of industries through the ordinary rulemaking process since the 2022 Energy Conservation Act Amendments explicitly give the central government broad authority to regulate and mandate fossil and non-fossil energy use by industries.[62] While the TCOs could start modestly, they have the potential to cover approximately 80% of industrial energy use in India that comes from direct combustion of coal, gas, oil, and biomass.[63]

Topics to Cover in a Geothermal Act

Regardless of whether a geothermal act is issued on its own or as part of the Renewable Energy Act, it would benefit from covering these topics:

- **Resource classification:** a durable, technology-agnostic definition of geothermal resources.
- **Institutional authority:** clearly empowering licensing and regulatory bodies, with appellate procedures for geothermal. This could be MNRE or the Ministry of Petroleum and Natural Gas for well drilling and development and the Central Electricity Regulatory Commission and state electricity regulatory commissions for electricity development.
- **Inter-ministerial coordination:** requirement of coordination covering new and renewable energy, mines, environment, petroleum and natural gas, and others to ensure consistent and cohesive governance.
- **Permitting timelines:** mandate for time-bound approvals (with clear standards and procedures); single-window systems; and streamlined clearances across land, water, power, and environment.
- **Coordination with states:** clear delineation of union vs. state roles, especially where land and groundwater are state subjects under the constitution
- **Incentives:** building on MNRE's programmatic incentives, creation of clear provisions allowing central and state governments to promote geothermal with statutory financial incentives.
- **Licensing and exploration:** a framework for issuing exploration and production licenses and leases, including who has authority to grant them and how public vs. private enterprises will participate.
- **R&D:** a sandbox approach to support R&D and early-stage projects, allowing innovative technologies and methods to be tested under controlled, flexible regulatory conditions.
- **Drilling and well safety:** technical standards for drilling, well integrity, and reservoir management (akin to the Oilfields Act).
- **Grid integration:** rights and responsibilities of geothermal plants under the Electricity Act (e.g., deemed open access, tariff mechanisms).
- **Direct-use rights:** legal support for industrial heating and cooling, district energy, GSHPs—especially in urban and industrial clusters.
- **Environmental compliance:** specific environmental assessment norms such as tailored assessment triggers; thermal discharge limits; continuous seismic monitoring; promotion of safe fluid and waste management, life cycle assessments, land restoration plans, and noise barriers; protection of sensitive areas; and strategies to to minimise risks (see Chapter 9).
- **Dispute resolution:** mechanisms to resolve conflicts over access to heat, which also consider existing mechanisms for water rights and land.
- **Data and transparency:** requirements for resource data reporting, drilling logs, production rates, possibly modelled on requirements for oil and gas.
- **Guarantee National Data Repository (NDR) rules to include geothermal data use:** updates to NDR rules to guarantee geothermal developers use oil and gas seismic and well data, accelerating project development.
- **Subsurface access:** property rights regime for accessing land and ownership of subsurface heat on private, central, state, or tribal lands, including recognising subsurface heat as a national resource and developing a national policy that defines geothermal energy's legal status and sets out clear regulatory and licensing guidelines, as noted in Chapter 7.
- **Local and community stakeholder rights:** enabling of inclusive regulation and benefit-sharing mechanisms, particularly in "scheduled areas" and around religious or sacred geothermal sites.

Aligning TCOs with Existing Energy Efficiency and Emissions Regulations

Thermal consumption obligations (TCOs) could align with India's energy efficiency cap-and-trade programme for the industrial sector Perform, Achieve, and Trade (PAT) scheme. This programme aims to promote increased energy efficiency in designated large, energy-intensive sectors such as steel, cement, and chemicals. Facilities must comply with stipulated energy-intensity targets by either making necessary investments or trading energy-saving certificates.[64,65] Notably, the scheme incentivises renewable energy by not counting its use against a facility's required energy intensity target. While PAT increased energy efficiency awareness and established an energy auditing and compliance infrastructure across large industrial units, the scheme lacked effectiveness due to insufficiently stringent targets, an abundance of energy-saving certificates, and lax enforcement.[66,67] There are plans to extend the programme to include greenhouse gas emissions through the Indian Carbon Credit Trading Scheme.[68,69,70] Consequently, energy and emissions intensity targets should account for any decreases from adopting TCOs for large industries.

b. Integrate geothermal technologies into MSMEs' energy efficiency efforts.

BEE could spread geothermal technology awareness in its knowledge-sharing and pilot project efforts for MSMEs. While TCOs would cover large industries to increase the uptake of geothermal energy, existing energy efficiency regulations do not cover MSME industries due to their size, heterogeneity, and economic informality. MSME industries face a number of challenges in adopting energy efficiency and renewable energy, including lack of awareness, access to finance, technical expertise, and energy data.[71,72] Nonetheless, given India's low- and medium-enthalpy geothermal resource base, MSMEs could benefit from geothermal energy. For example, SAMEEEKSHA (Small and Medium Enterprises Energy Efficiency Knowledge Sharing) is a central repository for BEE to share knowledge about various energy efficiency technologies, yet it lacks any information on geothermal technologies.

c. Leverage public procurement to de-risk adoption.

The central government could procure geothermal energy through its own contracts, buildings, and construction. As previously mentioned in this chapter, the Indian Army recently inaugurated its first geothermal-powered building in Jhansi, Uttar Pradesh.[73,74] This project delivers space cooling with 120 metre deep geothermal systems. Innovative projects like this one show that the central government has the ability to invest in demand generation for geothermal technologies. By doing so in construction of office buildings, hospitals, and other public areas, learnings from adoption can be applied to other sectors, which can also reduce risk for the private sector.

CONCLUSION

India stands at a critical inflexion point in its energy journey. With one of the world's fastest-growing populations and economies, the nation is facing an unprecedented surge in energy demand across electricity, industrial heating, and cooling. Meeting this demand sustainably, affordably, and reliably will require tapping into every viable domestic energy resource. Geothermal energy, long underutilised in India, is uniquely positioned to play a transformative role in helping India achieve its national goals.

The policies outlined in this chapter are designed to turn that vision into reality. By implementing the five recommendations outlined, India can establish a robust foundation for geothermal market growth. These reforms will enable the development of new projects across the country, helping meet growing energy demand while uplifting communities.

In short, geothermal energy is not just a technical opportunity—it is a nation-building one as well. With the right policies in place, India can become a global leader in geothermal innovation, delivering clean heat and power to its people while driving long-term economic and environmental gains. The path is ready. The time is now.

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Chapter 9

Environmental Benefits and Considerations in India: Balancing Renewable Expansion and Ecological Stewardship in the Geothermal Sector

Ayush Kumar Jha, Noel Jackson Therattil, and Aryama Singh Parihar, Council for Energy, Environment and Water (CEEW), and Arkaja Singh, Centre for Policy Research, with contributions from Smita Satiani, Project InnerSpace

Geothermal has one of the lowest land-use requirements of any energy type and can play a key role in reducing India's air pollution and greenhouse gas emissions. However, careful environmental oversight remains essential in geothermal development, with support from technical expertise, regular monitoring, data transparency, and safeguards to protect the country's precious resources.

With its vast and varied landscapes—from the Himalayas to the Thar Desert, the dense forests of the Western Ghats to the mangroves of the Sundarbans—India is home to extraordinary biodiversity. More than 100,000 documented species of animals, plants, and other organisms thrive in its ecosystems.[1] Safeguarding these landscapes and the ecosystems they support is one of the country's defining challenges.

As India seeks to meet its growing energy needs while decreasing its reliance on fossil fuels and improving air quality, geothermal energy offers resilient, always-on energy that also has the smallest surface footprint of any renewable energy source.

Given India's size and geological diversity, environmental factors will vary, as will surrounding communities' land and water needs. This chapter examines the environmental benefits and impacts—and some closely connected social and cultural factors—of geothermal development in India across all technology types (conventional, enhanced, and advanced geothermal systems) and stages of development. Key issues include wastewater handling, water use, induced seismicity, land changes, community disruption, and air quality.

The chapter also addresses best practices for geothermal development. When properly planned and managed, geothermal projects can be integrated into local

landscapes with minimal disruption—offering a pathway to sustainable growth that supports both economic development and environmental protection.

ENVIRONMENTAL BENEFITS OF GEOTHERMAL ENERGY

Reduced Carbon Dioxide Emissions

One of the most obvious environmental benefits of increasing geothermal energy for any nation is the significant decrease in carbon dioxide emissions. India's continued dependence on coal, oil, and gas for energy and heating needs and the industrial sector's heavy use of coal and oil and gas are major causes of emissions. In fact, about 25% of India's total greenhouse gas emissions comes from burning coal for power.[2] Chapter 4, "Geothermal Cooling Opportunities," shows that without action, cooling alone would produce an additional 810 million tonnes of carbon dioxide equivalent emissions annually by 2037, an increase so large that, on its own, it would place India among the world's top 10 emitting countries, comparable to the total annual emissions of major emitters such as Canada or Saudi Arabia.

In September 2025, India's government published a first-ever National Policy on Geothermal Energy, establishing a framework for geothermal development in the country. The policy noted that geothermal energy offers a significant additional renewable energy resource to help India's ambitious climate targets and the commitment to achieve net-zero emissions by 2070.[3] These goals include achieving "50% cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030" and reaching the country's "long-term goal of reaching net-zero by 2070."[4] Chapter 8 of this report, "Policy and Regulatory Pathways to Catalyse Geothermal in India," outlines suggested geothermal development goals to help the Indian government achieve these targets.

In 2023 in the United Kingdom, scientists developed a meta-analysis of hundreds of studies comparing the climate change impacts of electricity-generating technologies.[5] The results showed how developing geothermal energy can help countries reach their carbon emissions reduction goals. The analysis found that nuclear systems and wind are the technology with the lowest emissions, followed closely by geothermal, hydroelectric, photovoltaics, and concentrated solar power. Geothermal performs almost identically to photovoltaics—and it can have a much smaller surface footprint. The International Energy Agency's recent report *The Future of Geothermal Energy* shared similar results, showing that geothermal has more potential than any other secure energy source except solar. The report also noted that there is enough geothermal energy potential to power the world 140 times over and that India has significant geothermal potential.[6]

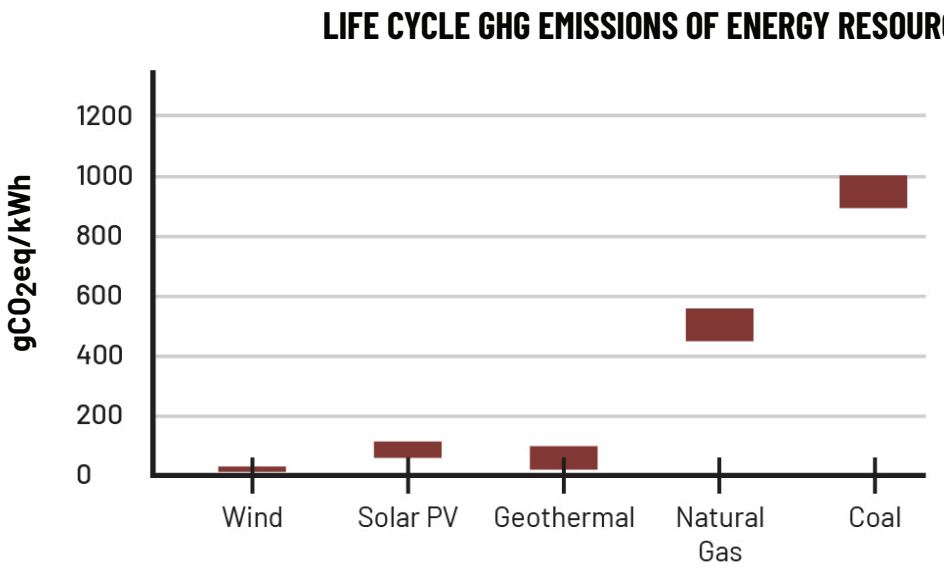


Figure 9.1: Life cycle greenhouse gas (GHG) emissions of different energy sources. gCO_2eq/kWh = grammes of carbon dioxide equivalent per kilowatt-hour; PV = photo voltaic. Source: Evans, A., Strezov, V., & Evans, T. J. (2009). Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Reviews*, *13*(5), 1082–88.

A 2010 life cycle assessment of conventional geothermal energy systems,[7] which focused on the total greenhouse gas emissions generated across all phases of a geothermal project, found that geothermal still ranks among the lowest-emission technologies on a life cycle basis, especially when effective reinjection and gas-abatement systems are in place (**Figure 9.1**).[8] This benefit is even higher for next-generation geothermal projects.

Though conventional geothermal power plants have slightly higher carbon dioxide emissions than solar and wind facilities, they offer a critical advantage: Geothermal plants have a much higher capacity factor. Conventional geothermal plants operate almost continuously, with capacity factors ranging from 70% to 90%, and next-generation geothermal is likely to have even greater capacity factors.[9] Wind and solar power plants generate electricity only when the wind blows or the sun shines, so a 100 megawatt geothermal plant will deliver far more electricity over the course of a year than a wind or solar facility of the same size. Because this power is available at all times, its contribution to decarbonisation is more valuable. As next-generation geothermal technologies continue to mature, improvements in drilling, reinjection, and plant design are likely, which will further reduce life cycle greenhouse gas emissions and increase geothermal's capacity factor, making it more favorable than wind and solar.

Reduced Air Pollutants

Expanding geothermal deployment in India would also cut emissions of fine particulates, sulfur dioxide, and nitrogen oxides that are by-products of fossil fuel combustion and major contributors to air pollution in the nation. A recent study found that one in eight deaths in India could be attributed to air pollution.[10] Coal combustion, in particular, is identified as the largest anthropogenic source of air pollution–related health impacts in India.[11]

Switching to geothermal, which emits virtually no on-site air pollutants, would significantly reduce local and regional pollution exposure and yield measurable public health benefits.

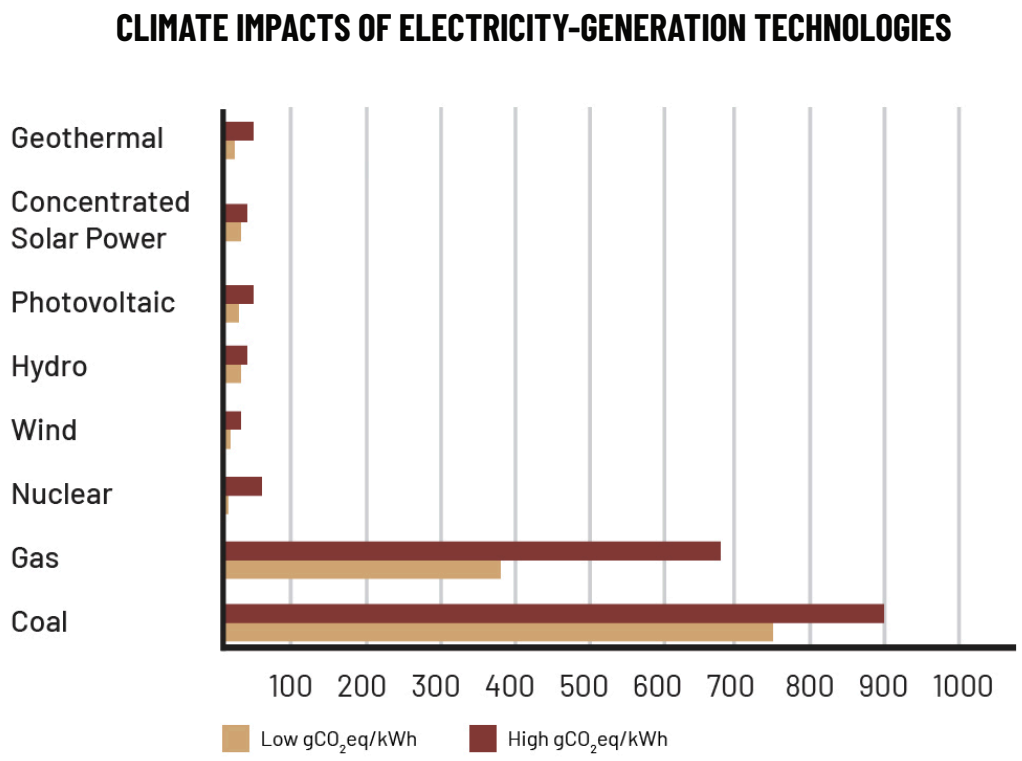


Figure 9.2: Climate impacts of various electricity-generation technologies. gCO_2eq/kWh = grammes of carbon dioxide equivalent per kilowatt-hour. Source: Graph created using figures from Guidi, G., Violante, A. C., & De Iuliis, S. (2023). Environmental impact of electricity generation technologies: A comparison between conventional, nuclear, and renewable technologies. *Energies*, *16*(23), 7847.

In the industrial sector, a large share of the combustion heat used for manufacturing and other processes is produced by burning coal or gas.[12] Replacing that share with direct geothermal heat would similarly slash emissions, especially in industrial clusters. With air pollutants often concentrated in industrial corridors, geothermal adoption would reduce localised pollution hot spots, mitigating exposure disparities.

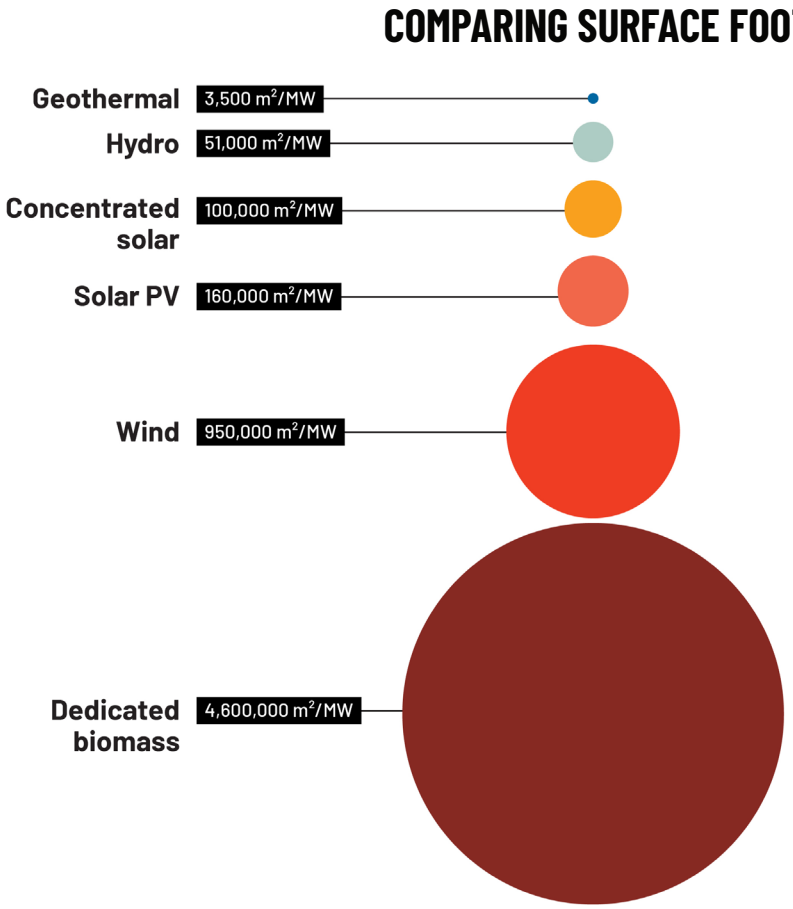
Reducing coal-related emissions would improve air quality across India. One recent study showed that nitrogen oxide emissions from coal-fired plants depress crop yields by as much as 10% in nearby agricultural regions.[13] Over time, the combined reductions in particulate and gaseous emissions would help India meet its ambient air-quality objectives more rapidly and reduce the costs of health care related to pollution.

Limited Land Use

One of geothermal energy's major advantages over other energy sources is that it typically uses the smallest land area of any renewable energy source. Geothermal electricity plants typically use only 2.25% of the land that solar requires, 0.38% of the land needed for onshore wind, and 0.078% of the land needed by electricity plants that burn biomass for fuel (see **Figure 9.3**).[14,15]

A typical geothermal energy power plant occupies just 3,500 square metres per megawatt (0.37 acres per megawatt), compared with 40,000 square metres per megawatt (9.9 acres per megawatt) for a coal-fired power plant.[16,17] Novel next-generation geothermal designs may use multi-bench well configurations that could occupy even less space for future energy production.

When compared with solar and wind, geothermal power plants occupy between about 1 hectare and 2 hectares per megawatt of installed capacity.[18] In contrast, solar photovoltaic facilities typically require between 4 hectares and 8 hectares per megawatt. Wind farms—although they have a smaller direct footprint (0.25 hectares to 0.5 hectares per megawatt at turbine



Geothermal has the smallest footprint of any renewable energy source

Figure 9.3: The project surface footprint, acre for acre for 1 gigawatt of generating capacity, is smallest for geothermal compared with other renewables. PV = photovoltaic. Source: Lovering, J., Swain, M., Blomqvist, L., & Hernandez, R. R. (2022). Land-use intensity of electricity production and tomorrow's energy landscape. *PLOS ONE*, *17*(7), e0270155; National Renewable Energy Laboratory (NREL). (2022). *Land use by system technology*. U.S. Department of Energy.

bases)—demand anywhere from 30 hectares to 50 hectares per megawatt when accounting for the total spread of the farm.[19,20]

What's more, deep geothermal heat-only projects for industrial or institutional use are even more land efficient and can be retrofitted into urban areas. Many complexes that are large enough to warrant deep geothermal heating already have access to the land area needed for development and drilling.

Importantly for India, however, is that most geothermal land-use estimates are derived from high-enthalpy regions such as Iceland or the western United States, where energy density is high and wells can be spaced more closely. In India, geothermal resources are largely low to medium enthalpy, which means they may require wider well spacing (or more land requirements), particularly for some next-generation geothermal such as engineered geothermal systems.[21]

Multi-Use Efficiency: Process Heat, District Cooling, Agro-Industrial Clusters, and More

In some cases around the world (for example, places with low- to medium-enthalpy resources in the Paris Basin, or in Klamath Falls, Oregon), a single geothermal resource has offered benefits for a number of applications. Because geothermal water remains warm even after its highest-temperature energy is extracted, it can be used sequentially—for electricity generation, industrial process heat, district heating or cooling, agriculture, and thermal storage. These cascading uses maximise energy recovery from each well, improve overall system efficiency, lower costs, and increase the economic and social value generated per unit of land.[22] Geothermal systems can provide reliable, fuel-free thermal energy for industrial process heat, district cooling, and agro-industrial applications (see more in Chapter 3, "Direct-Use Geothermal for Manufacturing and Industrial Processes").

While international experience demonstrates the viability of cascading geothermal systems, this model remains at an early stage in India, and additional pilot and demonstration projects will be necessary to validate their technical and economic feasibility under local conditions.

Reduced Ecosystem Pressure

Compared with large hydropower and biomass expansion, geothermal energy imposes significantly less pressure on ecosystems. In addition to having a small surface footprint, geothermal deployment mostly avoids the need to divert rivers. It also helps projects avert impacts such as displacement, sedimentation, and harm to biodiversity that are often associated with large hydropower projects. This benefit is particularly relevant in ecologically sensitive Himalayan and forested regions. Unlike biomass, geothermal energy does not compete for agricultural land, creates less strain on water resources, and is less likely to contribute to deforestation and air pollution from combustion.

As this chapter makes clear, the potential benefits of geothermal energy are plentiful. But scaling geothermal across India will also present environmental and community concerns. Next, we consider some of the potential challenges.

ENVIRONMENTAL CONSIDERATIONS

Impacts of Geothermal Technologies

Geothermal electricity generation falls into three main technological categories: conventional geothermal systems, engineered geothermal systems (EGS), and advanced geothermal systems (AGS). (See Chapter 1, "Geothermal 101.") Each type can have different environmental footprints throughout the development cycle.

India's potential for geothermal energy, however, extends well beyond electricity generation. Industries such as food processing, textiles, ceramics, and agriculture can directly tap into geothermal for low-cost, zero-emissions process heat (see more in Chapter 3, "Direct-Use Geothermal for Manufacturing and Industrial Processes"). Moreover, geothermal-based cooling systems can help reduce electricity use for air-conditioning in India's rapidly growing cities (see more in Chapter 4, "Geothermal Cooling Opportunities"). Together, these applications offer a practical path to secure growth, industrial competitiveness, and climate resilience. These industrial heat and urban cooling projects may use any of the approaches outlined in the following sections.

Advanced Geothermal Systems (AGS)

Closed-loop systems are designed to maintain complete separation between the working fluid and natural geothermal reservoirs. Because no direct contact occurs between the fluid and subsurface formations, AGS significantly reduce the risk of groundwater contamination and chemical discharge.[23,24] Because AGS have a small surface footprint, they can be deployed under buildings or within urban areas. Overall, AGS represent the least environmentally intrusive geothermal technology, with the smallest impact. Most geothermal heating and cooling systems are also closed-loop systems and have similar benefits to AGS.

Enhanced Geothermal Systems

The vast majority of geothermal projects in India will use low- to medium-enthalpy resources—ground source heat pumps, or closed-loop geothermal installations—for direct heating and cooling applications. These resources don't require hydraulic fracturing (also known as *fracking*). However, in select areas, and for a small number of electricity-generation projects that extract heat from hard granite, water-based hydraulic fracturing may be used to open microfractures in the rock. This technology has some environmental concerns that should be managed. The most prominent risk is induced seismicity, which results from fluid injection and fault activation.

While most induced seismic events are too minor to be felt (magnitudes less than 2.0), there have been exceptions. A well-known case occurred in Pohang, South Korea, in 2017, where an EGS project was linked to a 5.4 magnitude earthquake, causing injuries, damage to buildings, and long-term public opposition to geothermal energy.[25]

Much next-generational geothermal development in India is still in the exploratory or pre-commercial stages, yet caution is warranted. India's Himalayan geothermal provinces (such as those in Uttarakhand, Himachal Pradesh, and Ladakh) lie in tectonically active zones with known fault lines and should be drilled carefully and continuously monitored to mitigate seismic risks (**Figure 9.4**). Land subsidence in Joshimath, Uttarakhand, is an important example of how construction and industrial activity in fragile ecosystems can significantly exacerbate the severity of geohazards.[26]

Water consumption is another potential challenge, as EGS operations require substantial volumes for both drilling and circulation.[27] EGS can also mobilise trace elements from deep rock layers, leading to potential chemical contamination if reinjection is not managed effectively. Nonetheless, with appropriate controls, reinjection systems, transparent community engagement, communication of safety measures, and continuous monitoring of microseismic events, all of these impacts can be significantly mitigated. The effectiveness of these strategies will depend on proper state and national regulatory oversight and institutional capacity.

Additionally, because both AGS and EGS technologies only need hot rock, rather than hot water, there are more areas across India in which those projects can be developed. This feature is important because it doesn't just mean more opportunities for geothermal; it also means that projects in environmentally sensitive areas where only conventional geothermal would work can be avoided.

Conventional Geothermal Systems

While conventional systems have a smaller surface footprint than other renewable energy sources such as solar and wind, they often disturb surface manifestations such as geysers and hot springs that may be ecologically or culturally sensitive. Emissions of gases such as carbon dioxide, hydrogen sulfide, and trace elements can occur, though advanced gas-abatement technologies (including scrubbers and condensers) are capable of reducing these emissions by more than 95%.[28] Reinjection of used fluids is now a standard practice, not only to minimise surface discharge pollution but also to maintain reservoir pressure and ensure long-term sustainability.[29] While conventional systems present moderate environmental risks, as with EGS, those risks are manageable when best practices are implemented.

India's Geothermal Landscape: Geological and Environmental Features

Geothermal opportunities in India are found in a diverse range of geological formations and ecological zones, each with its own history, ecosystem, and sociocultural context.

EXAMPLE OF CONTINUOUS SEISMIC MONITORING SYSTEM

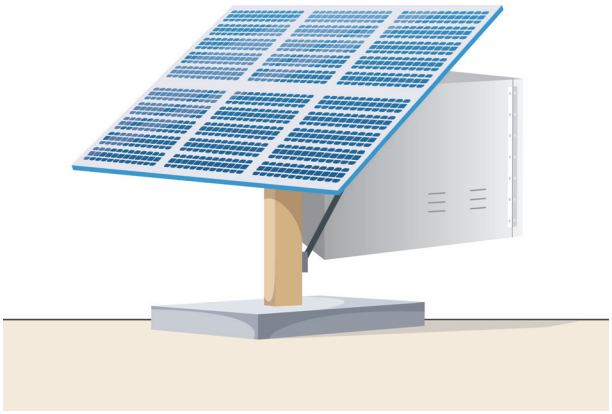


Figure 9.4: Example of a continuous seismic monitoring system. Source: Project InnerSpace.

Himalayan Provinces

These regions stand out due to their ecological fragility, cultural significance, and tectonic sensitivity. Stretching over 1,500 kilometres from Ladakh to Assam, the Himalayan geothermal belt is home to key sites such as Puga Valley, Chumathang (Ladakh), and Manikaran (Himachal Pradesh). This region offers significant opportunities for geothermal development, provided certain factors are carefully considered and addressed:

- **Ecological fragility:** The sites fall within or near protected areas with rich biodiversity and fragile alpine ecosystems. Environmental clearances for geothermal projects in this belt must account for the impacts on flora, fauna, and hydrology.
- **Cultural significance:** Some of these locations, such as Manikaran, are considered sacred by local communities and attract large numbers of pilgrims. Development in such areas requires engagement with religious stakeholders and culturally sensitive planning.
- **Seismic vulnerability:** The Himalayas lie within Seismic Zones IV and V, the most seismically active zones in India.[30] Incorrect deep drilling and subsurface fluid injection, particularly in EGS, carry the risk of induced seismicity in these tectonically active zones.[31]

Cambay Graben, Gujarat, Western India

This region presents a different scenario. With a moderate geothermal gradient and a well-developed oil infrastructure, the basin has potential as a site for binary-cycle geothermal power generation using retrofitted oil wells.[32] While the area overlaps with agricultural land, careful site selection, advanced drilling techniques, and closed-loop heat exchange systems can help minimise land acquisition needs and prevent groundwater contamination. Seismically, the region lies in Zone III,[33] indicating moderate seismic risk, but caution remains necessary given the induced seismicity observed in oil and gas operations in similar basins globally. A combination of strong resource potential and proactive environmental safeguards offers a pathway for sustainable geothermal expansion in the region.

Tattapani Field, Chhattisgarh, Eastern India

This geothermal field, along the Son-Narmada Lineament, lies in a mixed landscape of forest patches, agriculture, and rural settlements. The Tattapani site does not fall within a high seismic-risk zone, but the surrounding terrain may still require careful hydrological and ecological assessment to avoid unintended impacts on local water resources and habitats. While this area is not as culturally sensitive as the Himalayan sites, any energy development here must engage with rural communities to address land rights and livelihood concerns.

Regardless of the location, where land is ecologically fragile, densely populated, and often socially contested, it is critical to assess how geothermal development can alter land-use dynamics. A careful balance of energy extraction and environmental oversight will be required as these sites are developed—a balance that can be achieved with a combination of technical expertise, regular monitoring, data sharing, and transparency.

CULTURAL AND SOCIAL IMPACT

Geothermal development can contribute positively to regional energy security, job creation, and economic upliftment. However, these benefits often come with social and cultural trade-offs, particularly for local communities. In India, many geothermal provinces—

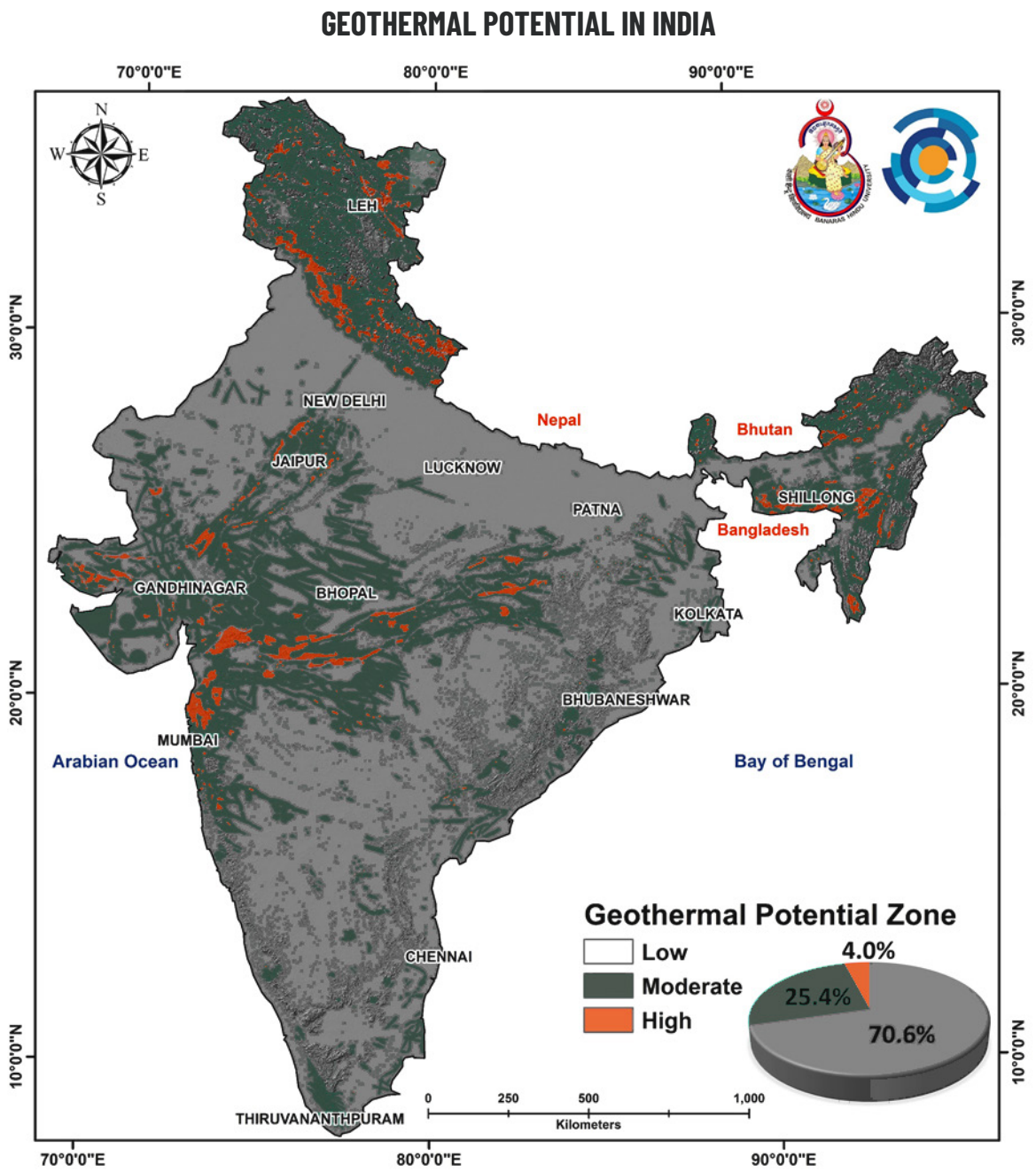


Figure 9.5: Map showing geothermal potential in India (without the Andaman and Nicobar islands and Lakshwadeep). Source: Project InnerSpace; Satya Prakash Maurya & Avinash Chouhan.

such as Puga (Ladakh), Tattapani (Chhattisgarh), Manikaran (Himachal Pradesh), and Bakreshwar (West Bengal)—are not only rich in geothermal potential but also deeply embedded in religious and cultural traditions. These sites host sacred hot springs, pilgrimage routes, and temples that are integral to local identity and spiritual practices.

The development of infrastructure such as roads, pipelines, and drilling facilities near these culturally sensitive areas can lead to land acquisition disputes, displacement, or the desecration of sacred landscapes. In some instances, geothermal surface manifestations themselves (for instance, steaming vents or hot water pools) are considered holy and worshipped by communities. Disrupting these features without due consideration can

erode community trust and lead to project opposition, as seen in past infrastructure projects in culturally significant zones. (For more information and details about solutions to community and stakeholder engagement, see Chapter 6, "India's Stakeholders: Opportunities and Implications for Geothermal Growth and Development.")

ENVIRONMENTAL IMPACT OF PROJECT PHASES

Geothermal development has three main phases: exploration, resource development, and operations and decommissioning. Of these phases, exploration and resource development are the most complex, while the operations and decommissioning phase has fewer environmental implications.

Exploration

Many geothermal exploration techniques are largely non-invasive and observational. For example, sampling methods occasionally involve the need to access sensitive areas, but environmental impacts from these activities are largely minimal. Some exploration methods, however, do have a larger effect.[34] Most exploration surveys use existing road and infrastructure networks to save costs, resulting in little habitat loss or vegetation removal. When there is a need to create new infrastructure, care must be taken to minimise environmental impacts.

During the exploration phase, seismic exploration involves generating seismic waves at the surface through rapid ground displacement. Active seismic surveys often compress soil or rock at the surface with an air gun or a seismic vibrator.[35] Though this method creates noise and disturbs soil and wildlife, it is temporary and usually doesn't require excavation or result in any lasting impacts.

Exploration boreholes require drilling small-diameter holes, much like those used in exploration drilling typical of mining projects. In deep geothermal projects, these holes can range from hundreds of metres to a few thousand metres and are used to measure subsurface temperatures and collect rock cores. Land disturbance is confined to a drill site (or pad) of a few hundred square metres, a space in which vegetation may be cleared and temporary access tracks constructed. As with development drilling, the process generates rock fragments and mud (on a smaller scale than with project drilling) that are managed on-site or removed per environmental regulations. Although noise, vehicle traffic, and soil displacement occur during drilling, the level of sound generated is small and the duration short-lived, and sites can be reinstated once the borehole is complete.

Overall, the exploration phase has minimal impact on the environment.

Project Drilling and Construction

Most of the environmental impact of developing a geothermal plant in a region occurs during the drilling and construction phases, so it is vital to understand mitigation strategies for each potential hazard.

Surface Modifications

Although geothermal systems occupy less area in absolute terms, the associated infrastructure (drilling pads, pipelines, cooling towers, and access roads) requires earthworks and surface modification. These impacts, though concentrated, are ecologically significant in mountainous and high-altitude regions such as Puga Valley (Ladakh) or Tattapani (Chhattisgarh), where terrain instability, fragile ecosystems, and biodiversity sensitivity amplify the risks.

Water and Fluid Management

Drilling geothermal wells uses methods similar to those employed by the oil and gas industry, such as mud rotary-drilling techniques with water and additives rich with bentonite (an absorbent swelling clay consisting mostly of montmorillonite and used in drilling mud) to help carry rock cuttings to the surface. For these projects to be environmentally sound, developers first need to consider the impact of water use, as securing an adequate water source in remote or water-scarce regions such as Ladakh or parts of the Deccan Plateau can present logistical and ethical challenges.[36,37] As a result, water extracted for drilling must be carefully managed to prevent the depletion of local sources that are vital to residents' livelihoods, public health, agriculture, and ecosystems.

The wastewater generated by this process must also be carefully managed because it may be contaminated with heavy metals and other naturally occurring chemicals.

(The wastewater might also be so hot that direct disposal could damage the environment.) Mishandling, or a lack of adequate regulations, can cause these metals and chemicals to seep into the soil or leach into groundwater, threatening both environmental and human health.

In the Puga Valley geothermal project in Ladakh, an unexpected release of geothermal fluid into a local stream raised environmental concerns and led to significant project delays. Work on the site resumed in 2024 after changes in operational and drilling teams occurred. Multiple reports in the media point to this issue,[38,39] though there doesn't seem to be a publicly available scientific report on the incident. For projects to succeed, developers should ensure that disposal strategies account for how to contain, treat, and manage wastewater. This can be challenging, as pollution levels can vary depending on complicated factors such as the underground flow of groundwater and the permeability of different barriers. Wetlands are especially vulnerable because groundwater and surface water interact, making spread of contamination more likely.[40] Broken pipes,[41] casing failure and leakage,[42] and leaks from both wastewater storage reservoirs and solid waste sites should be closely monitored.

Surface Emission

During drilling and initial well testing, geothermal reservoirs may release gases such as carbon dioxide, hydrogen sulfide, methane, and other trace compounds. These emissions are deeply tied to the geological nature of the resource.

For example, India's Himalayan geothermal zones, such as those in the Garhwal and Ladakh regions, exhibit natural carbon dioxide emissions from hot springs.[43] Although these emissions are often low compared with coal-fired plants, certain geothermal fields globally have shown carbon dioxide emission levels exceeding 500 grammes of carbon dioxide per kilowatt-hour, underscoring the need for proper site assessments and emission controls.[44] Moreover, hydrogen sulfide, even in small amounts, is toxic and must be monitored closely due to its pungent odor and potential health hazards.

Noise

During drilling and plant construction, noise from drill rigs, generators, and construction vehicles can push sound levels up to 120 decibels.[45] For workers, residents, and wildlife, such levels can be distressing, particularly in tranquil rural areas or protected natural habitats. Moreover, conventional geothermal sites might be situated near communities and tourist locations (such as the hot springs of Manikaran or Tattapani) where noise pollution can disrupt daily life and diminish the area's spiritual or recreational value. While the noise is largely temporary, its effects on migratory birds, sensitive species, and local residents need mitigation through noise barriers, timing restrictions, and community coordination, so addressing the noise is important. The good news is that from 900 metres away, the noise produced by drilling and construction decreases to match ambient noise levels in urban areas (71 dBA–83 dBA). And during normal operations, noise levels drop to between 15 dBA and 28 dBA, which matches the average background noise in wilderness areas (20 dBA–30 dBA).[46]

Many geothermal operations employ muffling techniques such as noise shields, exhaust mufflers, and acoustic insulation to reduce noise by up to 40%.[47]

Impact on Biodiversity

The intensity and nature of risk to biodiversity from geothermal activity is generally lower than what are associated with oil and gas exploration and other resilient energy sources—thanks to the absence of hydrocarbons, a lower chemical load, and more stable flow patterns and smaller surface footprints—yet it is important to recognise that geothermal can still have a damaging effect if development is not managed carefully.[48,49]

Biodiversity, which is often fragile in geothermal-rich ecosystems, can be at risk during development phases. The initial stages of geothermal projects (such as site clearance for access roads, drilling rigs, and heavy equipment) can lead to habitat fragmentation and species displacement.[50] These disruptions can be critical in ecologically sensitive or protected areas, where intrusions can cascade into broader ecosystem imbalances. Another major threat is the discharge of untreated geothermal fluids, which can contain toxic elements such as arsenic, boron, mercury, and lithium. This practice is carefully regulated and prohibited in most jurisdictions where geothermal development is more advanced, and India should ensure this global best practice is implemented.

If released into adjacent streams or wetlands, these pollutants may alter water chemistry and become catastrophic for aquatic and soil-dependent life forms.[51] These fluids may significantly exceed safe levels for drinking water or ecological thresholds, depending on site-specific geology and fluid chemistry.

Figure 9.6 illustrates the concentration of naturally occurring major contaminants that have been found in conventional geothermal fluids from various global geothermal fields. These values are presented alongside average freshwater concentrations and regulatory thresholds established by the World Health Organization and the U.S. Environmental Protection Agency.[52,53] The figure underscores that although geothermal energy is a secure energy source, development carries non-trivial risks to water quality and aquatic ecosystems that need to be addressed through updated case-specific waste-management protocols.

That said, these embedded chemicals are less likely to be an issue for shallow geothermal systems such as ground source heat pumps and next-generation geothermal systems, which are more often designed as closed-loop or contained systems that circulate a working fluid through sealed pipes rather than producing formation fluids.

The Puga Valley in Ladakh exemplifies the biodiversity challenges in geothermal zones. Puga Valley is not only one of India's most promising high-temperature geothermal fields but also a designated wetland ecosystem and seasonal habitat for migratory birds such

CONCENTRATION OF MAJOR CONTAMINANTS IN FLUIDS IN CONVENTIONAL GEOTHERMAL POWER PLANTS

Contaminant	Concentration in Geothermal Fluids	Geothermal Fields	Avg. Freshwater Concentration	WHO Threshold	U.S. EPA Maximum Concentration Limit (MCL)	India's General Standard for Discharge into Inland Surface Water*
Arsenic (AS)	Up to 2.6 mg/L	West Java, Indonesia	0.001 mg/L	0.01 mg/L	0.01 mg/L	0.2 mg/L
Boron (B)	Up to 25 mg/L	El Salvador	0.01 mg/L	2.4 mg/L	NA	NA
Mercury (Hg)	Up to 6.5 µg/L	West Java, Indonesia	0.00004 mg/L	0.006 mg/L	0.02 mg/L	0.01 mg/L
Hydrogen Sulfide (H_2S)	Approximately 130 mg/L	Krafla, Iceland	<0.001 mg/L	NA	NA	NA
Ammonia (NH_3)	Up to 30 mg/L	Iceland, El Slavador and others	0.04 mg/L	NA	NA	5.0 mg/L

Figure 9.6: Naturally occurring contaminants that have been found in conventional geothermal fluids from various global geothermal fields. * = as provided in Schedule VI of The Environment (Protection) Rules 1986. EPA = Environmental Protection Agency; g = grammes; L = litre; mg = milligrams; WHO = World Health Organization. Source: World Health Organization (WHO). (2017). *Guidelines for drinking-water quality, fourth edition: Incorporating the first addendum*; U.S. Environmental Protection Agency (EPA). (2025, December 1). *National primary drinking water regulations*; Central Pollution Control Board (CPCB). (1986). *General standards for discharge of environmental pollutants*; Stefánsson, A., Arnórsson, S., Gunnarsson, I., Kaasalainen, H., & Gunnlaugsson. (2011). The geochemistry and sequestration of H_2S into the geothermal system at Hellisheidi, Iceland. *Journal of Volcanology and Geothermal Research, 202*(3–4), 179–88; Irnawati, I., et al. (2021). Assessment of arsenic levels in water, sediment, and human hair around *Ie Seu'um* geothermal manifestation area, Aceh, Indonesia. *Water, 13*(17), 2343; Herdianita, N. R., & Priadi, B. (2008). Arsenic and mercury concentrations at several geothermal systems in West Java, Indonesia. *ITB Journal of Science, 40*(1), 1–14; Stefánsson, A. (2017). Gas chemistry of Icelandic thermal fluids. *Journal of Volcanology and Geothermal Research, 346*, 81–94.

as bar-headed geese and ruddy shelducks. In such high-altitude ecosystems, noise from drilling operations, alterations in groundwater regimes, and increased human activity may disturb wildlife, particularly endemic and sensitive species. Aquatic habitats, which rely on stable thermal and chemical conditions, are especially vulnerable to potential changes caused by accidental geothermal discharges or leaks.

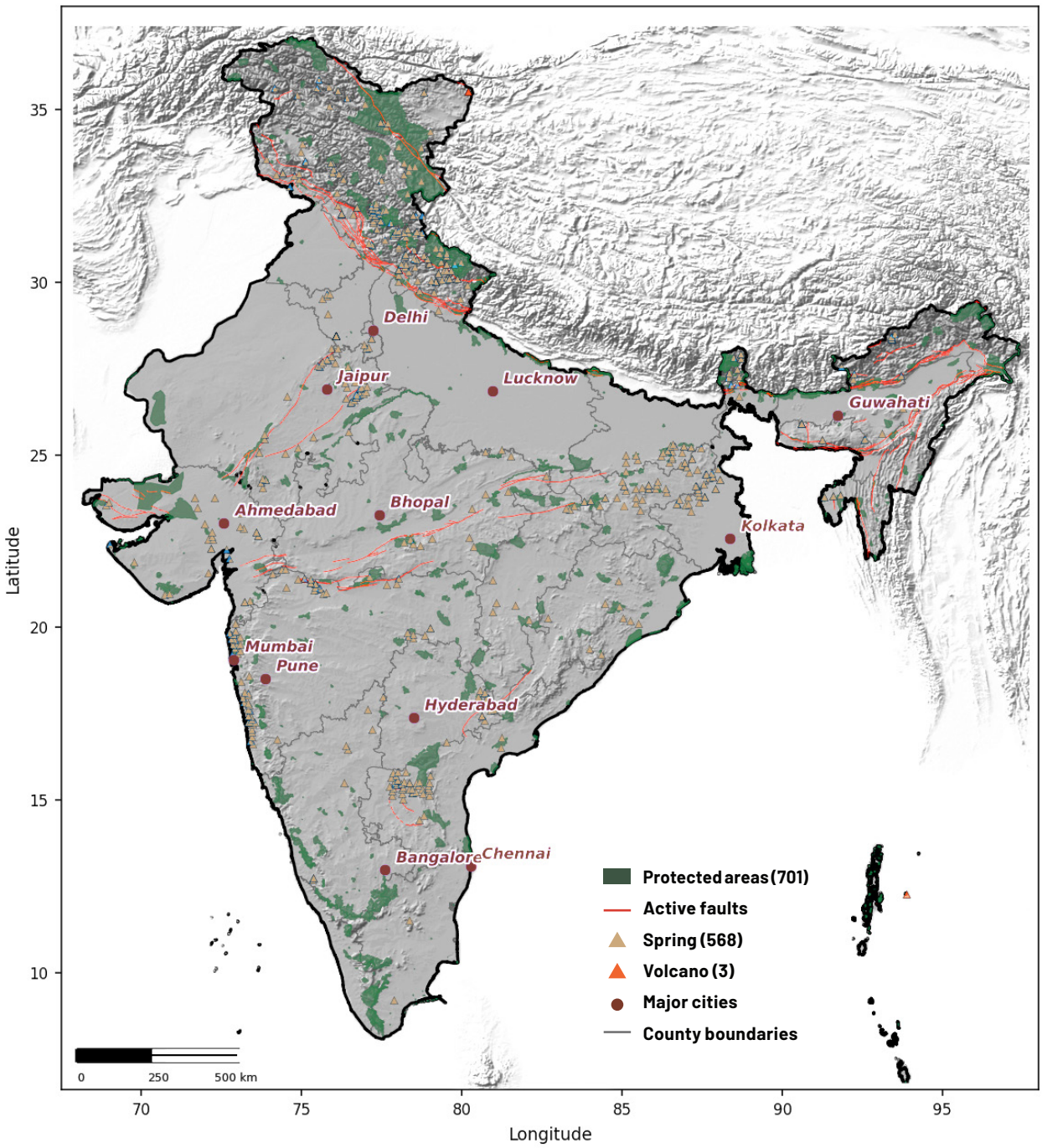


Figure 9.7: Geothermal potential overlaid with environmentally protected areas: Source: Project InnerSpace. (n.d.). *GeoMap*.

To address biodiversity risks, Environmental Impact Assessments for geothermal projects should include a baseline biodiversity inventory, particularly in ecologically sensitive zones such as the Himalayas and northeast India. The inclusion of a project-specific biodiversity impact table that details species presence, conservation status, seasonal patterns, and potential impact pathways can be invaluable for regulatory decision-making and long-term monitoring.

To mitigate these impacts, early and meaningful community engagement is crucial. This engagement includes recognising customary land rights, involving local leaders and religious authorities in project planning, and developing a shared social and economic benefit framework. Preservation of religious structures and features must be prioritised not only as an act of compliance but also as a sign of respect for local traditions and an investment in long-term project viability. Read more about these strategies in Chapter 6, "India's Stakeholders: Opportunities and Implications for Geothermal Growth and Development."

Project Operations and Decommissioning

Once a project becomes operational, environmental impacts stabilise and remain relatively low, particularly compared with other fossil fuel–based or even some renewable energy systems. Advanced gas-abatement systems reduce emissions by as much as 95%.[54] Abandoned boreholes and wells can be decommissioned, capped, or repurposed for monitoring throughout the lifespan of the project so there is minimal lasting impact on land use. The land surrounding a project can be repurposed for community benefits such as eco-tourism, educational facilities, or small-scale manufacturing units powered by resilient energy.

Land Subsidence

Extracting geothermal fluids from underground reservoirs alters the pressure and mechanical balance within subsurface rock formations. Over time, this pressure change can lead to land subsidence (the gradual sinking or compaction of the Earth's surface).

Enhancing Biodiversity Through Geothermal Development: A Case Study from the Eden Project in the UK

In some areas, geothermal power plants have created additional habitats for wildlife. At the Eden Project in Cornwall in the United Kingdom, for example, project managers made improvements in species-rich grassland and wildflowers, as trenches there were sowed with a diverse seed mix. Ducks, geese, house martins, willow warblers, and grey wagtails all nest there, and foxes and deer are often present at the site. Staff also protected a woodland area in the centre of the drilling site with oak trees and willow carr and retained hedge lines to support biodiversity. Topsoil trenches were also reinstated and seeded with wildflower mix and topsoil bunds to be suitable habitats for insects and burrowing bees. Natural stone gabions—rather than concrete pillars—were used to support the above-ground sections of pipe. (During drilling, the site was monitored for noise, and the loudest sound recorded was the dawn chorus of birds in the hedge.[55,56])

Wildflower mix planted over the heat main at Eden Geothermal. Image provided by Eden Geothermal 2023.

Though often subtle at first, this phenomenon can accumulate to cause significant structural damage to geothermal wells, pipelines, roads, and surrounding infrastructure. In severe cases, subsidence may even disrupt the hydrology of an area by altering surface and subsurface drainage patterns.

A cautionary example comes from Mehsana, Gujarat, where extensive oil extraction combined with groundwater withdrawal led to observable subsidence that damaged buildings, pipelines, and roads over time.[58] Though the subsidence in this case was caused by fossil fuel development, the underlying mechanisms are similar to those used in geothermal operations,

REGULATORY SIMILARITIES BETWEEN OIL AND GAS AND GEOTHERMAL ENERGY SECTORS

As noted in Chapter 5, "Leveraging Oil, Gas, and Mining Technologies and Workforce to Advance Geothermal in India," oil, gas and mining industry expertise, supply chains, and data sets can support geothermal development. Enhanced geothermal system (EGS) technologies in particular have been adapted from the oil and gas industry.[57] The development process for new geothermal projects involves several phases that mirror upstream petroleum activities such as comprehensive subsurface assessment, computational modelling, specialised drilling operations, and surface facility management. Consequently, the environmental considerations stemming from both sectors have some overlap.

From a regulatory perspective, a perusal of oil and gas sector regulations highlights the extent to which these can be applied to the geothermal sector. In some cases, these can be applied in pari materia, while others could be used to guide the development of geothermal specific regulations for India.

Laws Applicable to the Geothermal Sector and the Oil and Gas Sector
Environment (Protection) Act, 1986, and rules and regulations under this act
Wildlife (Protection) Act, 1972; Forest (Conservation) Act, 1980
Mines and Minerals (Development and Regulation) Act, 1957; Mines Act, 1952
Water (Prevention and Control of Pollution) Act, 1974; Water (Prevention and Control of Pollution) Cess Act, 1977; relevant states groundwater acts, such as the Karnataka Ground Water (Regulation for Protection of Sources of Drinking Water) Act, 1999, and Maharashtra Ground Water (Regulation for Drinking Water Purposes) Act, 1993
Air (Prevention and Control of Pollution) Act, 1981
Public Liability Insurance Act, 1991

Analogous Regulations
Petroleum and Natural Gas Rules, 1959
Oilfields (Regulation and Development) Act, 1948
Petroleum and Minerals Pipelines (Acquisition of Right of User in Land) Act, 1962
Petroleum & Mineral Pipelines (Acquisition of Right of User in Land) Rules, 1963
Oil Industry Safety Directorate standards

Figure 9.8: Laws that are applicable to the geothermal and oil and gas sectors and analogous regulations. Source: Oil Industry Safety Directorate (OISD). (n.d.). *OISD standards list*. Ministry of Petroleum and Natural Gas, Government of India.

where fluid withdrawal without adequate pressure management can result in ground compaction and structural instability. The risk of this happening with geothermal, however, is much smaller: Conventional geothermal reinjects most fluids, and next-generation geothermal does not depend on local water.

One of the most effective mitigation strategies for geothermal-induced subsidence is the reinjection of spent geothermal fluids back into the reservoir. Reinjection serves multiple purposes: It helps maintain reservoir pressure, supports thermal recovery, and minimises the risk of ground deformation. Global experience shows that systematic reinjection, which has been implemented in fields such as Wairakei (New Zealand) and The Geysers (United States), can significantly reduce or stabilise subsidence rates.[59] As India expands next-generation geothermal development, especially in sensitive regions such as Puga Valley, project design must include early reinjection planning and regular geotechnical monitoring to prevent long-term damage.

Emissions

As mentioned, operational conventional geothermal plants emit significantly less carbon dioxide than fossil fuel–based power plants. On average, conventional geothermal plants release between 40 grammes and 120 grammes of carbon dioxide per kilowatt-hour, depending on the reservoir and technology used. (In some rare cases, particularly when development happens in high gas fields, carbon dioxide emissions can reach up to 500 grammes of carbon dioxide per kilowatt-

CONSIDERATIONS TO ENSURE RESPONSIBLE, ETHICAL GEOTHERMAL DEVELOPMENT IN INDIA

1	**Mitigate induced seismicity through continuous monitoring.** Implement real-time seismic monitoring systems around geothermal project sites, particularly in tectonically sensitive zones. Monitoring pressure changes and microseismic events can help operators adjust fluid injection rates and prevent larger fault reactivations. Advanced monitoring can include deploying Advanced Traffic Light Systems (ATLS), as developed by the GEISER (Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs) consortium, to monitor and manage induced seismicity risks.
2	**Ensure safe fluid and waste management.** Promote reinjection as a mandatory procedure to prevent groundwater and surface contamination through used fluids. Ensure proper treatment and disposal of spent fluids and drilling muds containing toxic elements such as arsenic, mercury, and boron.
3	**Promote low-emission technologies and life cycle planning.** Encourage deployment of binary and advanced closed-loop systems, which minimise greenhouse gas emissions and surface disturbance. Projects should include life cycle assessments from the outset, with clear decommissioning and land restoration plans in place.
4	**Implement noise control approaches.** Install temporary noise barriers during drilling in ecologically sensitive areas. Use equipment with silencers, mufflers, and acoustic shielding to limit operational noise impacts on local communities and wildlife.
5	**Apply reinjection strategies.** Maintain balanced water extraction and reinjection rates to minimise subsidence risks. Differences and delays between water extraction and reinjection can cause land subsidence and hinder sustainable use of geothermal resources. Although these risks primarily pertain to EGS and conventional geothermal systems, they underscore the need for careful reservoir management practices across all geothermal developments.
6	**Protect culturally and ecologically sensitive areas.** Many geothermal zones in India overlap with sacred hot springs or ecologically fragile habitats. Prioritising Environmental Impact Assessments, buffer zones, and community engagement can reduce conflict and help preserve biodiversity and cultural heritage.
7	**Design risk-mitigation strategies for early-stage development.** The relatively higher risks and uncertainties of early-stage development could be mitigated to some extent through collaborations that bring expertise from countries and regions with more experience of geothermal development, including through scientific institutes, regional and national agencies, and international institutions.

Figure 9.9: Considerations for ensuring responsible and ethical development of geothermal in India. Source: authors.

hour, approaching coal plant levels.) While hydrogen sulfide emissions are more significant, due to toxicity and odour, these are highly site specific (typically 0.1 grammes to 10 grammes per kilowatt-hour) and can also be managed with advanced gas-abatement systems such as scrubbers and condensers. Together, these tools can reduce emissions by 99%, making the plant much cleaner during the operational phase.[60]

Noise and Vibrations

Turbine generators and associated machinery generate operational noise ranging from 60 dBA to 90 dBA at close range. While these numbers are lower than construction phase levels, continuous noise may still impact nearby communities or wildlife if not mitigated with acoustic enclosures and vegetative buffers.

Thermal and Chemical Discharge

If geothermal brine is not reinjected, it can contaminate surface waters with heavy metals and salts. This concern is particularly relevant in conventional geothermal systems and EGS, in which large volumes of fluid are extracted from and reintroduced into deep reservoirs. Common constituents include arsenic (up to 2 milligrams per litre), boron (up to 10 milligrams per litre), mercury (trace to 0.1 milligrams per litre), and lithium, depending on reservoir chemistry. However, reinjection techniques, now standard practice, drastically reduce these risks by returning spent fluids underground to maintain reservoir balance and avoid surface pollution.[61]

CONCLUSION AND RECOMMENDATIONS

Geothermal energy offers India significant environmental benefits by cutting air pollution, greenhouse gas emissions, and associated health impacts and minimising surface impacts given its small footprint. Although risks such as induced seismicity, water use, and subsurface contamination exist, they are well understood, readily managed through established best practices, and much less impactful than the environmental and social risks posed by fossil fuels or even large-scale hydropower.

As with all technologies, geothermal's success hinges on creating robust environmental safeguards and meaningful community engagement. Enforcement, mitigation, and consensus should be key in proliferating geothermal energy in India. Establishing a regulatory framework that can accommodate different types of risks and mitigation strategies—by geography and context and by stage of project and types of technology deployed—is also essential.These steps could be fostered through scientific and technical collaborations with other countries where geothermal energy is more advanced.

Some key elements for this framework are set out in **Figure 9.9**, some of which are explored in more detail in Chapter 8, "Policy and Regulatory Pathways to Catalyse Geothermal in India." With careful planning and management, nearly all of the potential challenges—including water resource use, groundwater protection during drilling, induced seismicity, and land subsidence—can be effectively mitigated, allowing for sustainable and responsible development.

Geothermal represents one of the few always-on, renewable energy options available to India. Its success, however, will depend as much on strong governance, robust environmental oversight, transparent data, and meaningful community engagement as on drilling technology itself.

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India has the potential to become a global leader in geothermal energy, with a vast and diverse resource base for cooling, industrial use, and electricity. Every state has some opportunity to harness this reliable, domestic, and clean energy source. Geothermal can become a defining pillar of India's secure, affordable, and low-carbon energy future—powering prosperity for generations to come.

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