Chapter 8

# Keeping Geothermal Green: Safeguarding Nature and Communities in a New Era of Growth

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***Geothermal energy combines low life cycle greenhouse gas emissions, round-the-clock reliability, and the smallest surface footprint of any renewable or fossil source. Many issues tied to conventional hydrothermal are minimized with next-generation, district cooling, and heat projects. Smart siting, real-time monitoring, transparent data, and community partnerships can minimize these risks so leaders can scale geothermal while safeguarding forests, waters, wildlife, and public health.***

When geothermal energy is used instead of coal, diesel, or heavy fuel oil, air quality improvements are immediate: Nitrogen oxide, sulfur dioxide, fine particulate matter, and carbon dioxide levels fall sharply, improving public health in urban and industrial corridors. Modern geothermal energy designs such as closed-loop systems (advanced geothermal system, or AGS) and reinjection programs (engineered geothermal system, or EGS) circulate water rather than consuming it, therefore mitigating water stress. Add to that, brines and non-condensable gases are contained and treated, and well pads, pipeline corridors, and compact plants can be built on brownfields or within existing industrial estates, which limits the disturbance of natural areas and habitats.

For Indonesia, geothermal's multi-use profile is especially powerful. As Chapter 4, "Beyond Electricity: Indonesia's Thermal Energy Demand and Geothermal Direct Use Potential," describes in more detail, the same subsurface know-how that enabled world-leading conventional geothermal power can also build geothermal district cooling for heat-stressed cities; geothermal networks for hospitals and campuses; and direct-use geothermal heat for food processing, textiles, pulp and paper, and pharmaceuticals. These facilities are much smaller than utility-scale power plants and therefore not as intensive to build. Drilling time is shorter, and the facilities use less fluid, resulting in less impact and more local environmental gains, including cleaner air, steady-state operations, minimal visual impact, and less noise.

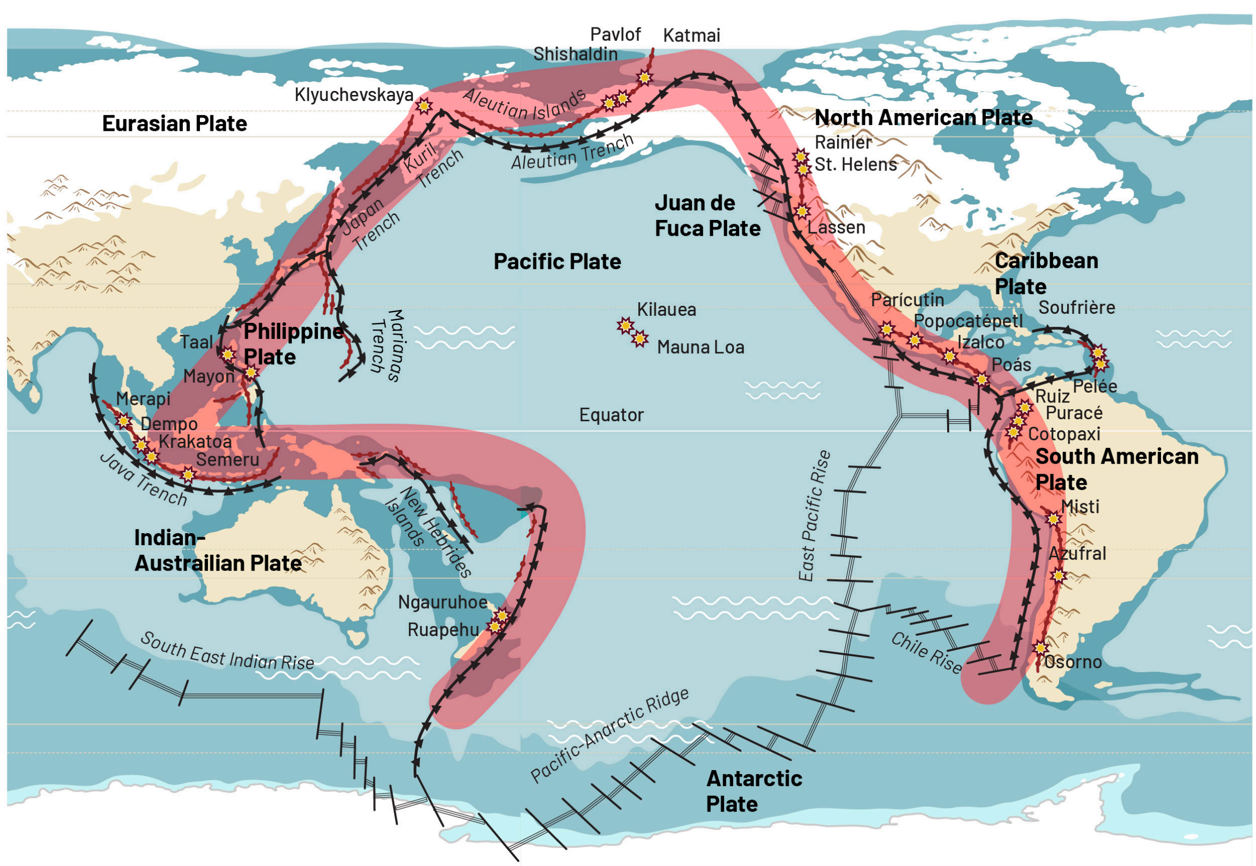
As with every other type of energy generation, however, geothermal presents environmental risks that need to be addressed. The risks for geothermal vary depending on the location and the type of geothermal system being installed. Risks can range from groundwater contamination and land subsidence to loss of biodiversity and damage to conservation lands. Historically, building geothermal has been tricky in Indonesia, particularly for conventional hydrothermal systems. Today, however, new technology helps minimize impact, and mitigation strategies have improved.

Countries around the world offer examples worth emulating. Costa Rica, the United States, and Germany have developed geothermal projects while protecting the environment and engaging local communities. There are also plenty of examples of next-generation geothermal and cooling-focused projects (with short construction times) that have eliminated most hydrogen sulfide pathways, enabling geothermal production outside of conventional fields.

With clear technical guidelines, transparent monitoring, reinjection and well integrity standards, and biodiversity safeguards, Indonesia can expand geothermal while protecting forests, wildlife, and ecosystem services.

By pairing its world-class geothermal expertise with these best practices, Indonesia can extend its geothermal leadership to create more benefits and fewer impacts. This chapter details potential environmental effects in the Indonesian context and lays out strategies and standards to minimize them.

## PACIFIC RING OF FIRE



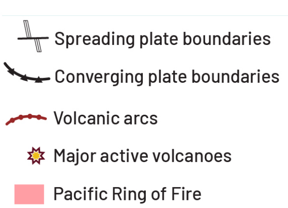




**Figure 8.1:** Countries located in the Pacific Ring of Fire, with relevant tectonic and volcanic features. Source: Encyclopaedia Britannica. (2025). Ring of fire; Roque, P. J. C., Violanda, R. R., Bernido, C. C., & Soria, J. L. A. (2024). Earthquake occurrences in the Pacific Ring of Fire exhibit a collective stochastic memory for magnitudes, depths, and relative distances of events. *Physica A: Statistical Mechanics and Its Applications, 637*, 129569.

## AN OVERVIEW OF INDONESIA'S UNIQUE ENVIRONMENTAL CONDITIONS

### Geographic and Volcanic Activity

Indonesia stands among the most volcanically active regions in the world because it sits directly on the Pacific Ring of Fire, a roughly 40,000 kilometer zone that hooks around the Pacific Ocean like a horseshoe (**Figure 8.1**). This belt marks the meeting point of several major lithospheric plates, including the Indo-Australian, Pacific, and Eurasian Plates, causing tectonic activity such as earthquakes and volcanic eruptions to frequently shift the landscape. About 90% of the world's earthquakes happen in the Ring of Fire, including most of the large ones.[1] These same unique subsurface attributes also give Indonesia an abundance of geothermal resources and present unique challenges for developing and managing energy infrastructure, including geothermal systems.

Most of Indonesia's islands lie near the equator and receive between about 2,000 millimeters and 4,000 millimeters of rainfall each year.[2] Many conventional geothermal resources, including hot springs, are also located along steep, unstable, high-relief stratovolcano slopes. The combination of heavy rainfall and unstable terrain creates a high risk of geohazards, such as collapses, landslides, and flash floods.[3] Landslides are a particular concern because they can be triggered by several factors, namely intense rainfall, seismic activity, land use changes, and overloading of slopes.[4] At least four significant landslides have been documented at conventional Indonesian geothermal fields: Wayang Windu (2015), Sungai Penuh (2013), Hululais (2016), and Lembata Island (1979). A few of the slides were tied to geothermal-related factors, including natural hydrothermal manifestations that weakened slopes and project-related activities such as vibrations from heavy equipment. These findings underscore the importance of managing landslide risks in hydrothermal development.[5]

**ILLUSTRATION OF FLASH FLOOD RELATED TO GEOTHERMAL AREA**

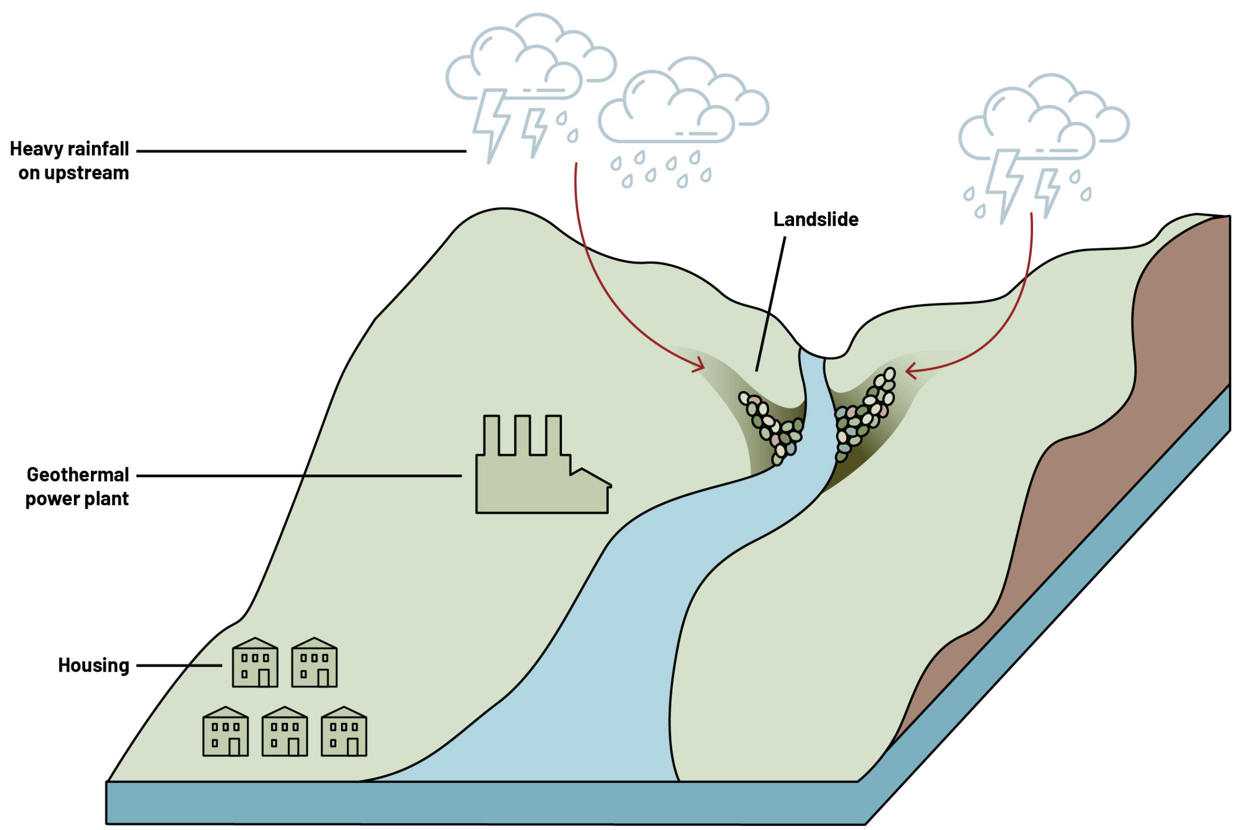



**Figure 8.2:** Illustration of a flash flood related to geothermal area. Source: Chandra, V. R., Purba, D. P., Nayoan, A. G. P., Fadhillah, F. R., Ramadhan, R. F., &. Anggara, R. (2021). [Identifying and assessing geohazards in Indonesia geothermal area: How difficult is it?]() In *Proceedings of the 46th Workshop on Geothermal Reservoir Engineering.* Stanford, CA, United States.

Flash floods—in which rainfall in upstream areas generates water volumes beyond a stream's capacity—are also a particular hazard in certain terrain and need to be considered. If a landslide blocks a stream and forms a temporary dam, water will accumulate behind it. The eventual breach of such a blockage can send a sudden torrent downstream (**Figure 8.2**).

Volcanic eruptions are, of course, a risk as well. Indonesia has 128 active volcanoes (around 13% of the world's total),[6] and nearly all of the country's conventional geothermal fields are in volcanic zones, making eruption hazards a major concern. An eruption at Mount Tangkuban Perahu in August 2019, for example, temporarily closed a nearby hydrothermal field. The incident prompted calls for closer cooperation between geothermal developers and volcanology agencies to better mitigate such risks.[7,8]

## BIODIVERSITY AND ECOSYSTEMS

According to Conservation International, Indonesia is one of the world's 17 mega-diverse countries,[9] a classification denoting nations with exceptionally high levels of species richness and endemism. With rainforests, peatlands, mangroves, and coral reefs on more than 17,000 islands, the country contains about 17% of the world's bird species, 12% of mammals, and 10% of flowering plant species.[10,11] These ecosystems deliver vital services—regulating floods; storing vast amounts of carbon; and supplying food, clean water, and raw materials—yet deforestation, habitat fragmentation, and overexploitation threaten this biodiversity. Between 2001 and 2022, the country lost roughly 9.75 million hectares of tree cover, much of it in biologically rich areas such as Kalimantan and Sumatra.[12] Indonesia's conservation framework—through the Indonesian Biodiversity Strategy and Action Plan (IBSAP) and a pledge to expand protected areas to 32.5 million hectares by 2030—seeks to address these challenges. The IBSAP mentions the role of biodiversity in supporting environmental services, including those relevant to geothermal development.

Because many high-potential geothermal resources lie within or near conservation forests, expanding this renewable energy source must balance climate benefits with the imperative to protect biodiversity. Geothermal has a very small footprint—the smallest of any renewable power source (see **Figure 8.3**). Still, about 28,600 hectares of deforestation—less than half of one percent of the total—can be directly attributed to existing geothermal development projects.[13]

At the same time, according to a study conducted by Profor and the World Bank, around 8,000 megawatts of conventional geothermal power potential lie outside forest areas,[14] representing an opportunity to prioritize development in these lower-risk zones (see **Figure 8.4**). However, when adding next-generation geothermal resources, that number jumps to 2,160 gigawatts of potential outside of protected areas. (See **Figure 8.8** and the Chapter 3 supplement, "Expanding the Scope: Next-Generation Geothermal Opportunities," for more information.)

### COMPARING SURFACE FOOTPRINT

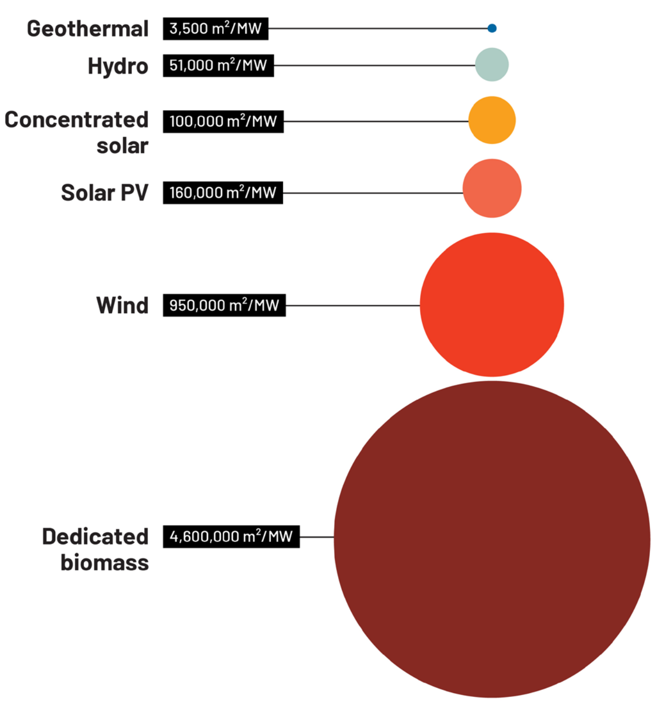



**Figure 8.3:** The project surface footprint, acre for acre for 1 gigawatt of generating capacity, is smallest for geothermal compared with other renewables and coal. $m^2$/MW = square meters per megawatt; PV = photovoltaic. Source: Lovering, J., Swain, M., Blomqvist, L., & Hernandez, R. R. (2022). 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*.

## CONVENTIONAL GEOTHERMAL SITES AND CAPACITY BASED ON LAND USE STATUS IN INDONESIA

| Land Use Status | Number of Geothermal Potential Points | Potential Capacity (MW) |
|---|---|---|
| Conservation areas | 48 | 4,873 |
| Protection forest | 54 | 5,736 |
| Production forest | 46 | 2,416 |
| Non-forest use | 182 | 8,056 |
| **Total** | **330** | **21,081** |

**Figure 8.4:** Conventional geothermal sites and potential capacity based on land use status in Indonesia. MW = megawatts. Source: Meijaard, E., Dennis, R. A., Saputra, B. K., Draugelis, G. J., Qadir, M. C. A., & Garnier, S. (2019). *Rapid environmental and social assessment of geothermal power development in conservation forest areas of Indonesia*. PROFOR & World Bank.

In other countries, geothermal projects have actually helped create ecosystems for plants and species. In the United Kingdom, managers of the Eden Project have sown trenches with diverse seed mixes, creating new, lush habitat for an array of birds and pollinators. They also protected a stand of oak trees, a field of willow carr, and long lines of hedge to retain existing biodiversity.

***Emerging next-generation geothermal technologies require even less space, such as a single, shallow groundwater circulation well for direct use or a geothermal doublet well for electricity production.***

***Even better to note is that as Indonesia expands the development of its abundant geothermal resources, next-generation technologies will allow developers to focus on regions that have fewer of the major risks inherent with flooding and unstable earth that are commonly found in Ring of Fire regions.***

## POTENTIAL ENVIRONMENTAL IMPACTS OF GEOTHERMAL DEVELOPMENT

As mentioned, one of geothermal energy's major advantages over other energy sources is that it uses the smallest land area. Geothermal electricity plants require one-fifth as much land as solar and one-tenth the amount as onshore wind—and a miniscule amount (1/70th) compared with electricity plants that burn biomass for fuel. Facilities generally require far less infrastructure than other energy sources, with a typical geothermal energy power plant occupying just 1,500 square meters per megawatt-hour (0.37 acres per megawatt-hour) compared with 40,000 square meters per megawatt-hour (9.9 acres megawatt-hour) for a coal-fired power plant.[15]

Deep geothermal heat-only projects for industrial or institutional use are even more efficient and can be retrofitted for use in urban areas. Many complexes large enough to warrant deep geothermal heating already have access to the land needed for development and drilling. This is one clear benefit of the technology compared with other energy sources: It disrupts less land and disturbs less habitat.

## TYPES OF GEOTHERMAL SYSTEMS

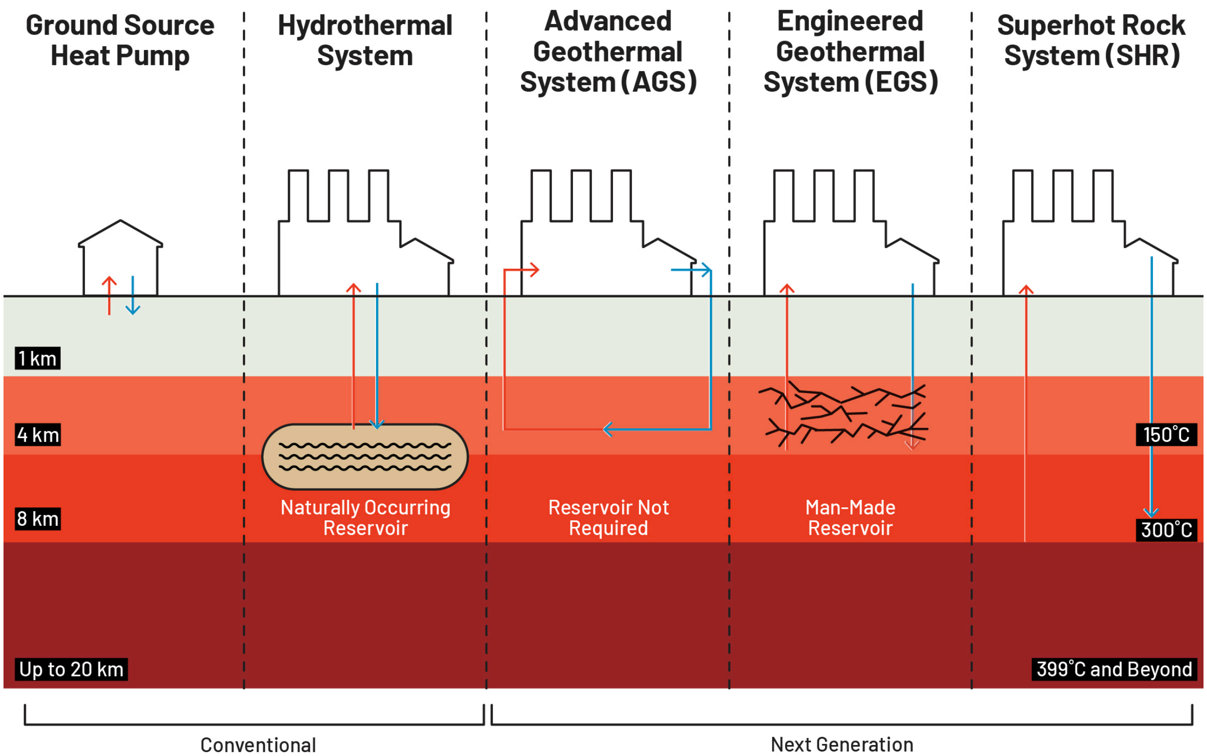



**Figure 8.5:** Comparison of key geothermal power generation technologies illustrating variations in resource type and heat extraction method for electricity production and industrial direct use. Ground source heat pumps (GSHP) are also shown, illustrating a building heating scenario. In the GSHP scenario, 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.

## A COMMERCIAL-SCALE GEOTHERMAL HEAT PUMP PROJECT IN SWITZERLAND

**Figure 8.6:** Well services teams prepare to drill a series of shallow geothermal boreholes to provide commercial-scale heating and cooling in the urban area of Lausanne, Switzerland. Photo courtesy of Groupe Grisoni.

As explained in Chapter 4, "Beyond Electricity: Indonesia's Thermal Energy Demand and Geothermal Direct Use Potential," Indonesia has significant potential to deploy geothermal for urban cooling, as is already done in Europe on a fairly widespread basis. Many cities either deploy geothermal district heating or use geothermal to heat and cool individual buildings. In a geothermal installation in Lausanne, Switzerland, a total of 150 boreholes—each plunging 300 meters deep and fitted with high-efficiency double-U probes—now power the site's heating and cooling systems. Urban drilling, a common practice, has a small footprint. When done, the system provides secure heat and cooling for the lifetime of the building.[16]

## GLOBAL GHG EMISSIONS BY POWER SOURCE

| Technology | Typical Life Cycle GHG Emission Range ($gCO_2/kWh$) | Notes |
|---|---|---|
| Conventional Geothermal (hydrothermal, flash/binary) | 10–120 | Highly site-dependent due to non-condensable gas (NCG) content; Indonesian fields like Dieng (higher, ~100+) vs. Lahendong (lower, <50). Reinjection lowers emissions. |
| Engineered Geothermal Systems (EGS) | 5–40 | Still pilot-scale; most emissions from drilling and construction. No NCG release since reservoirs are engineered. |
| Advanced Geothermal Systems (AGS, closed-loop) | <5–15 | Projected values (no commercial-scale yet); emissions only from materials and construction. |
| Coal (subcritical to supercritical, no CCS) | 820–1050 | Among the highest; Indonesia's coal-dominated grid averages ~900. |
| Natural Gas (CCGT) | 400–500 | Lower than coal, but methane leakage can push higher. |
| Solar PV | 20–60 | Most emissions from panel manufacturing. |
| Onshore Wind | 8–20 | Very low; mostly from steel and concrete in turbines. |
| Hydropower (large reservoir) | 1–250 | Wide range; tropical reservoirs (like Indonesia) can emit more methane. |

**Figure 8.7:** Global greenhouse gas (GHG) emissions by power source. CCS = carbon capture and storage; CCGT = combined-cycle gas turbine; $gCO_2/kWh$ = grams of carbon dioxide per kilowatt-hour. Source: Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate change 2021: The physical science basis*. Cambridge University Press; International Energy Agency (IEA). (2022). *Renewables 2022*; International Energy Agency (IEA). (2023). *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*; O'Sullivan, M., Gravatt, M., Popineau, J., O'Sullivan, J., Mannington, W., & McDowell, J. (2021). Carbon dioxide emissions from geothermal power plants. *Renewable Energy, 175*, 990–1000; Geothermal Technologies Office. (2019). *GeoVision: Harnessing the heat beneath our feet*. U.S. Department of Energy.

That said, care must be taken at each stage of development and during plant operations to mitigate any environmental hazards. Broadly, geothermal projects have three stages: site exploration, drilling and construction of a plant, and ongoing operations. The following sections explain the environmental considerations at each stage.

## IMPACTS OF EXPLORATION AND CONSTRUCTION

### Exploration

Most geothermal exploration techniques are largely non-invasive and observational. For example, sampling methods occasionally involve the need to access sensitive areas, but these activities largely have minimal environmental impacts. Certain exploration methods, however, do have a larger effect. Some surveys need to build roads and some infrastructure networks, resulting in some habitat loss or vegetation removal. When there is a need to create new infrastructure, developers must take care to minimize environmental impacts.

The case of Baturraden in Central Java highlights these concerns. During the 2016–17 exploration phase, the clear waters of the Prukut River, which runs from the slopes of Mount Slamet, turned brown. Monitoring confirmed that geothermal developer PT Sejahtera Alam Energi was responsible. Local reports also mentioned people had a harder time accessing clean water.

Some projects also require exploration boreholes to confirm the subsurface properties of a proposed geothermal project. Exploration boreholes require the drilling of small-diameter holes, much like those used in exploration drilling that is typical for mining projects. For boreholes, land disturbance is confined to a drill site (or pad) of a few hundred square meters, a space in which vegetation may be cleared and temporary access tracks constructed. 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. Any abandoned boreholes should be safely capped.

The government of Indonesia takes environmental concerns related to project development seriously. For every project, the Ministry of Environment and Forestry requires a mandatory Environmental Impact Assessment (EIA). The EIA is a regulatory requirement for both conventional and unconventional geothermal developments; it ensures that potential environmental and social impacts are thoroughly assessed and that public consultations are conducted before project approval and permitting. (See Chapter 6, "Common Ground: Building Trust and Transparency in Indonesia's Energy Transition," for more information.)

### Construction

The plant construction phase is the most impactful phase, as well as the one with the most risks. Plants can require extensive surface infrastructure, such as drilling pads, production and injection wells, pipelines, and the power plants themselves. While geothermal plants have the smallest surface footprint of any power source (see **Figure 8.3**),[17] the dispersed nature of wells means that large tracts of land can still be affected in some instances. In Indonesia, many high-potential conventional geothermal sites overlap with conservation forest areas, creating risks of deforestation, habitat fragmentation, and ecosystem disruption.[18] These concerns are particularly acute in biodiversity-rich montane forests where ecological integrity is already under pressure.

As mentioned, though, next-generation technologies such as an EGS and an AGS may reduce surface damage even more (see Chapter 1, **"**Geothermal 101: Overview of Technologies and Applications"). The smaller footprints of AGS and EGS installations minimize disturbance to topsoil and allow development away from high-value farmland and protected volcanoes, further minimizing soil-degradation risks and damage to culturally sensitive lands. In Indonesia, several lands hold sacred or cultural value to local communities; these lands require a specific protocol for development beyond just ecological protection.

According to Project InnerSpace's GeoMap analysis, Indonesia holds immense untapped geothermal potential even when protected areas are excluded. Within just the first 5 kilometers of subsurface depth, the country could harness an estimated 2,160 gigawatts of geothermal electricity—equivalent to more than 21 times its total installed power capacity in 2024 (see the Chapter 3 supplement, "Expanding the Scope: Next-Generation Geothermal Opportunities"). This analysis shows that major expansion is possible outside protected lands and that with today's improved drilling and plant design practices, next-generation geothermal development can be carried out with far less environmental impact than the conventional projects of past decades (see **Figure 8.8**).

## TOTAL GEOTHERMAL HEAT-IN-PLACE FOR INDONESIA'S PROTECTED AREAS

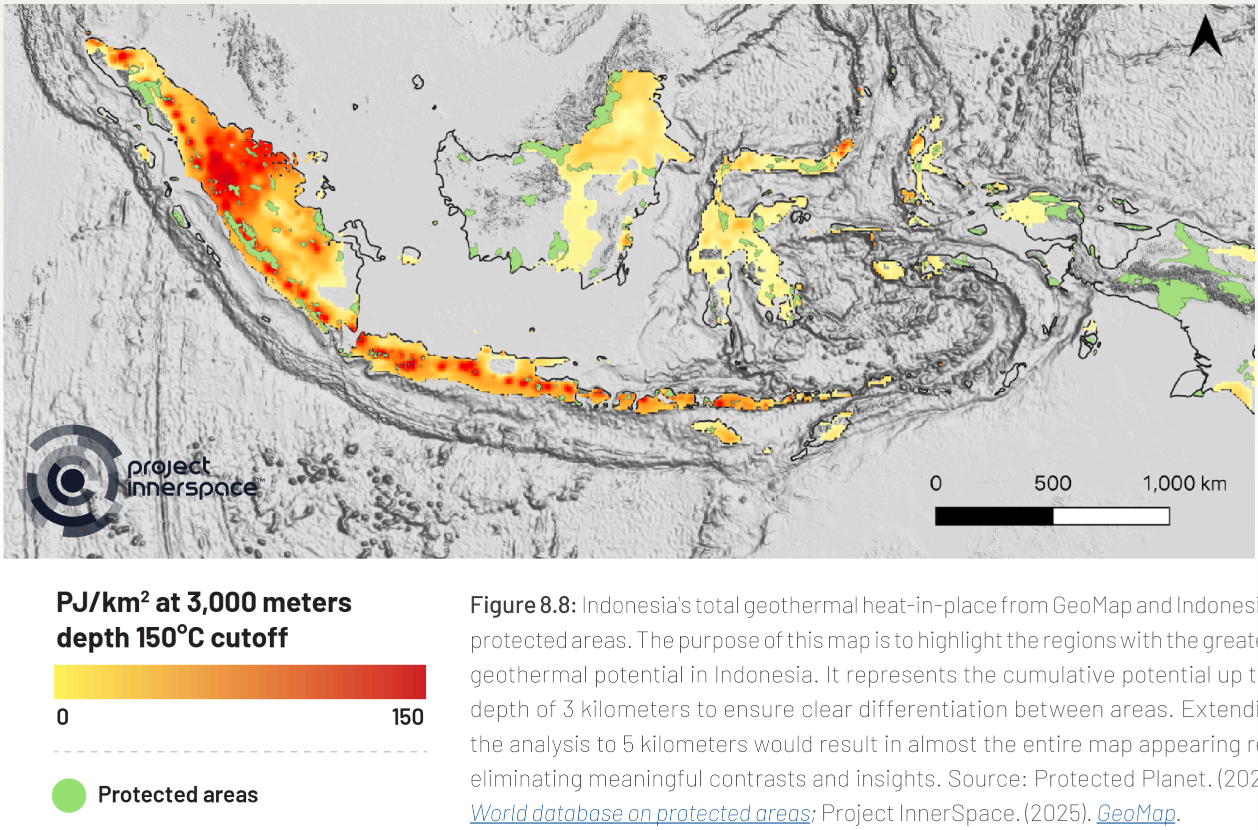



Figure 8.8: Indonesia's total geothermal heat-in-place from GeoMap and Indonesia's protected areas. The purpose of this map is to highlight the regions with the greatest geothermal potential in Indonesia. It represents the cumulative potential up to a depth of 3 kilometers to ensure clear differentiation between areas. Extending the analysis to 5 kilometers would result in almost the entire map appearing red, eliminating meaningful contrasts and insights. Source: Protected Planet. (2025). *World database on protected areas*; Project InnerSpace. (2025). *GeoMap*.

## LESSONS LEARNED

During development of the Gunung Salak conventional geothermal plant in Mount Halimun Salak National Park in West Java, plant construction created forest clearance and habitat loss, soil erosion, alterations in stream water quality, elevated hydrogen sulphide levels in ambient air, and traffic congestion and accidents on narrow roads. Developers implemented several mitigation measures, including reforestation and efforts to avoid forest fragmentation.[19]

Moreover, surface infrastructure in volcanic and hilly terrain may disrupt watershed functions, reduce soil stability, and increase erosion and sedimentation in rivers. With hydrothermal development, care must also be taken to avoid degrading surface features such as fumaroles and hot springs, which are often seen as ecologically and culturally significant landmarks.[20]

***Costa Rica provides important lessons on how to mitigate these impacts. Its geothermal projects—Las Pailas I and II power plants and the planned Borinquen plant—sit on volcanic flanks outside national park boundaries to avoid damaging critical ecosystems.[21]***

***The country uses directional drilling and multi-well pads to reduce surface disturbances, and compact designs link each production pad directly to separation and reinjection units, limiting the spread of roads and pipelines. Reinjection practices help stabilize reservoirs, reducing the need for new drilling areas, and repowering existing plants extends operational lifespans without creating a need to develop more land.[22]***

These best practices are relevant for Indonesia, where leaders can reduce the ecological footprint of geothermal development by mandating clustered well pads, directional drilling from outside conservation zones, and compact field layouts.

### Greenhouse Gas Emissions

Geothermal is widely recognized as a low-emission renewable energy source, which is particularly attractive for countries like Indonesia that have abundant geothermal potential.[23,24] However, geothermal systems are not entirely free of greenhouse gas emissions, particularly during the construction phase.[25,26,27] When building a geothermal operation, 95% of the emissions generally come during construction. The drilling process can release gases into the atmosphere, including carbon dioxide, methane, and hydrogen sulfide, among others.

Where possible, grid electricity can be used to power drilling, which reduces sulfur dioxide and volatile organic compound (VOC) impacts to negligible levels, or hydrogenated vegetable oil can be used in place of diesel to run the generators, greatly reducing the impacts of

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## NON-CONDENSABLE GAS (NCG) COMPOSITION AND HARM THRESHOLDS IN GEOTHERMAL SYSTEMS

| Gas | Typical Share of NCGs | Key Concerns | Harmful Levels |
|---|---|---|---|
| Carbon dioxide | 90%–99% | Main GHG, asphyxiant in confined spaces, vegetation die-off near vents | >0.5% (5,000 ppm, OSHA 8-hr limit), >4% harmful to humans |
| Hydrogen sulfide | 0.1%–3% | Acute human toxicity, corrosive, toxic to flora and aquatic life | >10 ppm irritation, >100 ppm dangerous, >500 ppm fatal |
| Methane | 0.1%–1% | Potent GHG (GWP ~28–34), explosive hazard | 5%–15% explosive in air |
| Ammonia | <0.1% | Irritant to humans (lungs/eyes), toxic to plants | >25 ppm harmful (OSHA limit) |
| Others (Nitrogen, Hydrogen, Radon) | Trace | Mostly inert, except radon (radioactive risk) | Varies |

**Figure 8.9:** Non-condensable gas (NCG) composition and harm thresholds in geothermal systems. GHG = greenhouse gas; GWP = global warming potential; OSHA = Occupational Safety and Health Administration. Source: DiPippo, R. (2012). *Geothermal power plants: Principles, applications, case studies and environmental impact* (3rd ed.). Elsevier; Fridriksson, T., Mateos, A., Audinet, P., & Orucu, Y. (2016). Greenhouse gases from geothermal power production. World Bank; Intergovernmental Panel on Climate Change (IPCC). (2022). AR6 climate change 2022: Mitigation of climate change. IPCC; OSHA. (2006). Occupational safety and health standards-Air contaminants. U.S. Department of Labor.

carbon dioxide by up to 90%; nearly eliminating sulfur dioxide; and greatly reducing nitrogen oxide, particulate matter, and VOC emissions.

The main emissions from geothermal energy production come from non-condensable gases (NCGs) that are naturally present in geothermal reservoirs, particularly carbon dioxide and, to a lesser extent, hydrogen sulfide, methane, and other trace gases (see **Figure 8.9**).[28,29] These gases are released into the atmosphere during drilling and well testing.[30,31]

## Water Consumption, Fluid Management, and Soil Disturbance

Geothermal development is water-intensive, particularly during well drilling. Depending on geological conditions and drilling technology, a single well may require between 1,000 cubic meters and 3,000 cubic meters of water.[32,33] In Indonesia, these projects are often located in volcanic highland regions that overlap with conservation forests and watersheds, areas that are critical for biodiversity and water catchment.[34,35] Early in development, improper management of drilling muds and geothermal fluids may contaminate nearby surface and groundwater sources.[36]

Globally, several mitigation strategies have been applied to balance geothermal development with water and environmental security, including reinjecting geothermal fluids to prevent contamination, sourcing drilling water from reservoirs specifically designated for industrial use, and adopting advanced waste treatment before disposal.[37,38] Next-generation geothermal technologies, such as AGS closed-loop systems and EGS, offer alternative approaches that reduce water and contamination risks even further. Advances in water recycling and the use of non-potable water have also helped mitigate impacts.[39]

For Indonesia, given the country's highly volcanic setting, EGS may not be a practical option, but AGS could shape the future of geothermal development nationally, particularly in areas where water availability or environmental sensitivities limit conventional hydrothermal projects.

In agricultural regions, geothermal development can also undermine soil fertility by introducing contaminants such as heavy metals and boron into irrigation waters and soils, leading to crop toxicity and reduced yields. In some areas of Indonesia, geothermal expansion has also reportedly led to water contamination, soil destabilization, and declining crop performance. These findings highlight that unmanaged solid waste not only threatens soil fertility but also directly affects food security in surrounding communities.

The waste disposal regulations in Indonesia, particularly Waste Management Law No. 18 of 2008,[40] emphasize the importance of reducing reliance on landfills and safeguarding the environment, highlighting the necessity for a strong and flexible waste management framework. By incorporating advanced waste management practices and leveraging AGS technology, geothermal developers can minimize solid waste impacts, protect soil quality, and ensure that geothermal energy remains a sustainable resource.

## Induced Seismicity

An EGS, which often requires hydraulic fracturing, can reactivate existing fault lines, reducing rock cohesion and leading to seismic events. The seismic events are usually relatively minor, but sometimes injection can generate migrating swarms. In tectonically active regions, this result can raise concerns that repeated small quakes could trigger a larger slip on nearby faults.[41,42,43]

Indonesia's Geothermal Law No. 21 of 2014 enables the government to supervise every project phase to ensure compliance with safety, environmental, and operational standards.[44] Recent global practice emphasizes a modular risk management framework.[45] This approach integrates (i) pre-screening of sites for geological suitability and fault stability; (ii) hazard and risk assessment using geomechanical and seismic models; (iii) adaptive traffic-light systems linked to operational thresholds; (iv) deployment of dense, real-time seismic monitoring networks; and (v) transparent communication with regulators and local communities. Several geothermal projects worldwide have successfully applied these measures.

For example, at Soultz-sous-Forêts in France, pressure-controlled stimulation protocols kept seismic events below damaging levels.[46] In Helsinki, Finland, the St1 Deep Heat project used near-real-time seismic monitoring to adjust injection rates and avoid escalation to highermagnitude events.[47] And in the United States, the Blue Mountain plant in Nevada combined pre-operational risk modelling with a responsive traffic-light system to maintain low seismicity,[48,49] while the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) research site has demonstrated that comprehensive site screening and staged injection can limit seismic hazards, even in complex tectonic settings.[50]

***These cases show that with proactive learning, adaptive operational controls, and continuous monitoring, geothermal projects can significantly reduce the likelihood and impact of induced seismicity while maintaining safe and reliable operations.***

For Indonesia, adopting these lessons will require real-time seismic monitoring, enforcement of traffic-light systems as part of project permits, the establishment of a centralized seismicity database, and stronger site-approval procedures.

### Noise Pollution

The construction of a geothermal plant can cause a lot of noise that may disturb local communities and wildlife. Most noise pollution is ignored during environmental assessments, but in many situations it can have strong effects on human health and animal behaviors—the latter of which is particularly concerning because geothermal plants are usually built in remote, ecologically sensitive areas. Noise pollution in these environments can disrupt the feeding, mating, and migration patterns of wildlife. Research on geothermal noise impacts on wildlife remains limited.

Take, for example, the Wae Sano project on Flores (West Manggarai, East Nusa Tenggara), a World Bank–supported Geothermal Energy Upstream Development Program project to establish a plant that could initially produce between 10 megawatts and 32 megawatts. In this rural setting, heavy machinery, well pad construction, and drilling generate constant sounds that stand out against the low background noise levels (daytime = 44 dBA–49 dBA, nighttime = 39 dBA–44 dBA). Modeled construction noise is about 65 dBA at approximately 100 meters and about 43 dBA at around 500 meters; around the nearest residence (approximately 80 meters), daytime maximums can reach around 70 dBA, exceeding the residential limit of 55 dBA if the noise is unmitigated (see **Figure 8.10**).[51] Short well-testing phases can briefly produce levels up to approximately 110 dBA at the source, though these events are episodic and usually mitigated with silencers, mufflers, and temporary barriers.

The good news is that almost all of this noise goes away when construction is finished and plant operations begin.

## OPERATIONAL PHASE

The lifespan of a geothermal plant is often long, which is good news. Once a plant is up and running, there are fewer issues to monitor. The following issues should be monitored once a plant is in operation.

### Surface Emissions

The emissions of conventional geothermal plants in Indonesia are a fraction of the amount created from burning coal. If Indonesia can transition from coal to geothermal power, the country could cut its carbon dioxide emissions by more than 90% and also reduce local air pollutants such as sulfur dioxide, nitrogen oxides, and total suspended particulates. That said, conventional geothermal plants in Indonesia have some emissions, typically through steam containing NCGs, primarily carbon dioxide and hydrogen sulfide.

For example, the 230.5 megawatt Wayang Windu hydrothermal field emits about 65.9 grams of carbon dioxide equivalent per kilowatt-hour and roughly 2,067 tons of hydrogen sulfide per year.[52] Other gases, such as methane and ammonia, and trace elements such as mercury, arsenic, and radon are present in minor concentrations and generally reinjected into the reservoir as per national environmental regulations.[53]

The primary environmental and health concern is hydrogen sulfide, which has a characteristic "rotten egg" smell and can be harmful at high concentrations. Chronic exposure limits are low, with the World Health Organization recommending no more than 150 micrograms per cubic meter over a 24-hour period. Acute danger occurs only at very high concentrations (approximately 500 ppm–

## NOISE LEVELS ACROSS GEOTHERMAL DEVELOPMENT PHASES COMPARED TO ANTHROPOGENIC SOURCES

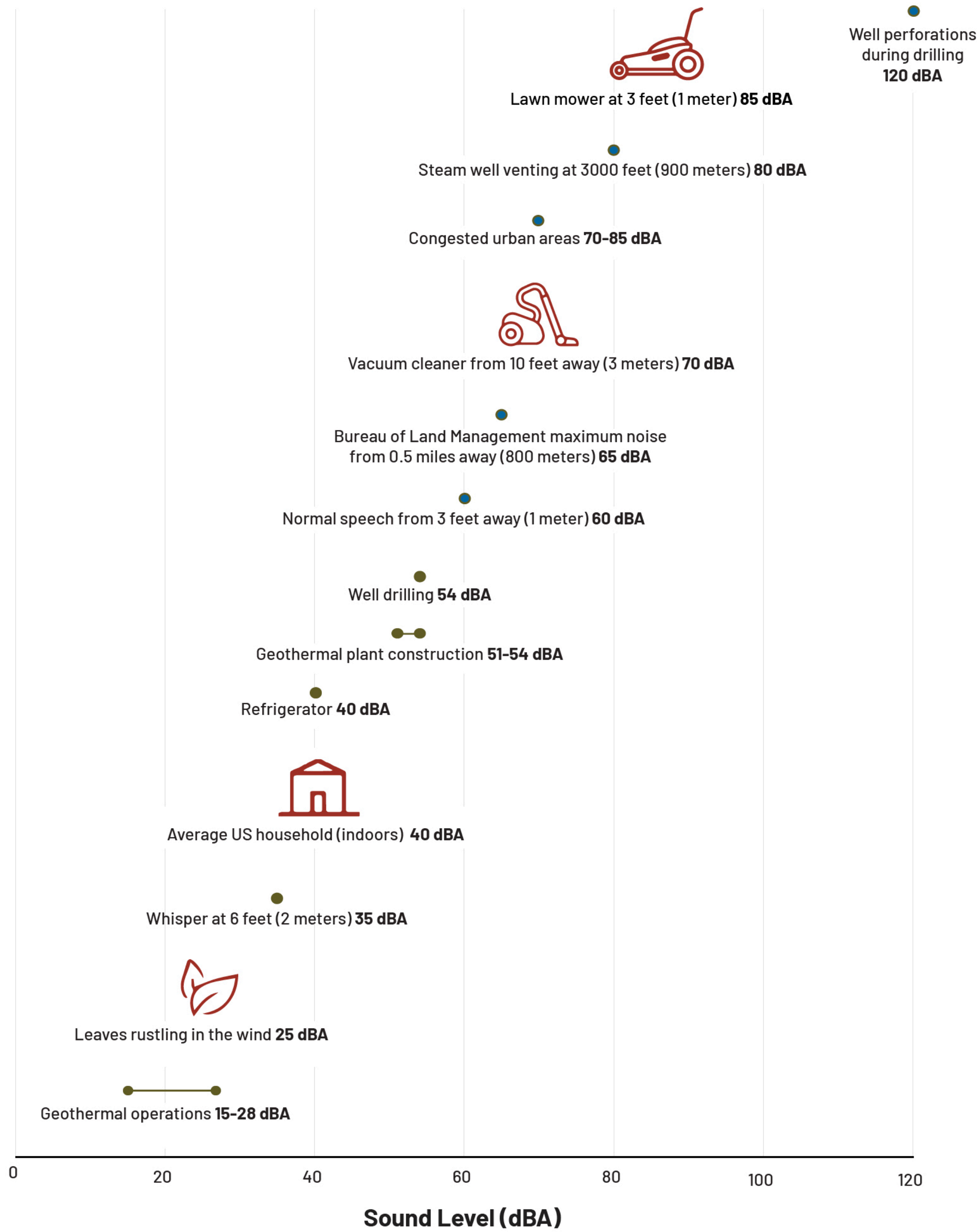


**Figure 8.10:** Noise levels across geothermal development phases compared with anthropogenic sources. Sources: Kagel, A., Bates, D., & Gawell, K. (2005). *A guide to geothermal energy and the environment*. Geothermal Energy Association; Massachusetts Institute of Technology (MIT). (2006). Environmental impacts, attributes, and feasibility criteria. In MIT (Ed.), *The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century* (pp. 8-1–8-20). MIT; Bryant, M., Starkey, A. H., & Dick-Peddie, W. A. (1980). *Environmental overview for the development of geothermal resources in the State of New Mexico*. New Mexico Department of Energy; Birkle, P., & Merkel, B. (2000). Environmental impact by spill of geothermal fluids at the geothermal field of Los Azufres, Michoacán, Mexico. *Water, Air, and Soil Pollution, 124*, 371–410.

700 ppm) and can be lethal within an hour. Field monitoring, such as at the Lumut Balai geothermal site, has recorded maximum hydrogen sulfide levels at around 0.54 ppm—well below acute toxicity thresholds.[54]

In one case, modeling at the Dieng geothermal field showed that bleeding NCGs through a hydrogen sulfide abatement tank would cut near-source hydrogen sulfide from between around 2 ppm and 5 ppm down to between around 0.4 ppm and 1.0 ppm, safely under the 5 ppm threshold.[55] While this modeling demonstrates a viable mitigation pathway, it is not universally required for all geothermal power plants. Fields with low hydrogen sulfide reservoirs, such as Sarulla, have been reported to exhibit minimal surface emissions, with measured concentrations typically fewer than 0.1 ppm, suggesting that continuous abatement may be unnecessary.[56] However, for "sour" fields such as Dieng and Lahendong—where elevated hydrogen sulfide levels are common and surrounding communities are directly exposed—abatement technologies should be considered standard practice.[57,58] This aligns with Indonesian air quality regulations,[59] which set ambient hydrogen sulfide limits at 30 micrograms per cubic meter (24-hour average) and occupational thresholds at 5 ppm.[60]

In the longer term, next-generation technologies (see Chapter 1, "Geothermal 101: Overview of Technologies and Applications") represent a strategic solution to address surface emission risks and strengthen the environmental performance of Indonesia's geothermal sector. Studies completed on next-generation pilot projects have reported surface emissions at 32 grams of $CO_2$-equivalent per kilowatt-hour for EGS facilities[61] and 11.6 grams of $CO_2$-equivalent per kilowatt-hour for AGS.[62]

## Greenhouse Gas Emissions

Plants tend to release much lower volumes of NCGs during operation than during exploration or construction. In Indonesia, carbon dioxide emissions from current conventional geothermal plants range between 42 grams and 73 grams of carbon dioxide-equivalent per kilowatt-hour, with an average of 63 grams of carbon dioxide-equivalent per kilowatt-hour (see **Figure 8.11**).[63]

Next-generation systems such as a closed-loop AGS offer a pathway to fewer operational emissions. Most potential reservoir-derived gases remain dissolved or

### GHG EMISSIONS OF GEOTHERMAL PROJECTS IN INDONESIA

| Project Name | Location | Installed Capacity (MW) | Technology Type | Estimated GHG Emissions ($gCO_2e/kWh$) | Developer / Operator |
|---|---|---|---|---|---|
| Wayang Windu | West Java | 227 | Flash steam | 73 | Star Energy Geothermal |
| Sarulla | North Sumatra | 330 | Binary cycle & flash steam | 100 | Medco Power, Itochu, Ormat, INPEX |
| Lahendong | North Sulawesi | 120 | Flash steam | 60–80 | PT Pertamina Geothermal Energy |
| Ulubelu | Lampung, Sumatra | 220 | Flash steam | 63 | PT Pertamina Geothermal Energy |
| Kamojang | West Java | 235 | Flash steam | 73 | PT Pertamina Geothermal Energy |
| Dieng & Patuha | Central & West Java | 120 | Flash steam | 65-75 | Geo Dipa Energi |

**Figure 8.11:** Greenhouse gas (GHG) emissions of geothermal projects in Indonesia. $gCO_2e/kWh$ = grams of carbon dioxide-equivalent per kilowatt-hour; MW = megawatts. Source: Ea Energy Analyses. (2024). *Technology data for the Indonesian power sector: Catalogue for generation and storage of electricity*.

trapped in the closed circuit of an AGS, and under normal operations, they do not vent to the surface.

### Solid Waste

Geothermal development creates drill cuttings, spent drilling mud, silica sludge, materials from maintenance activities, and other solid waste (**Figure 8.12**) that threaten soil, water, and agricultural health if not properly managed, particularly in the rural and ecologically sensitive areas of Indonesia.[64,65,66]

At the same time, if managed well, geothermal solid waste presents opportunities for reuse. Silica sludge can be used as a supplementary cementitious material in concrete, improving strength and reducing reliance on raw materials.[67,68] Drill cuttings may serve as aggregates for road base construction or landfill cover, and bentonite-based drilling mud has potential as a soil amendment if contaminants are controlled.[69]

Emerging technologies also enable the recovery of commercial-grade silica and other valuable minerals from geothermal waste streams, linking geothermal development with circular economy strategies.[70] To support this aspect, common waste management practices such as composting organic waste, recycling non-hazardous materials, and implementing secure disposal of hazardous waste remain essential to Indonesian geothermal operations.[71]

## SUMMARY OF THE SOURCE AND THE TYPE OF GEOTHERMAL FIELD SOLID WASTE

| No. | Activity | Source | Type of Solid Waste |
|---|---|---|---|
| 1 | Exploration and production | Drilling | Drill cutting |
| | | Steam field | Silica |
| | | Condensation | Scale<br>Sludge |
| | | Office | Paper<br>Paper box<br>Plastics<br>Woods<br>Battery<br>Food waste<br>Mixed waste<br>Used fluorescent lamp<br>Used PPE (personal protective equipment) |
| 2 | Maintenance | Washing | Scale |
| | | Spare parts replacement and workshop activity | Used spare parts<br>Scrap metal<br>Used paint cans<br>Used toner<br>Used lubricants can |
| | | Gardening | Leaves<br>Grass |
| 3 | Laboratory analysis | Water treatment | Sludge |
| | | Analysis using chemical | Contaminated rag<br>Expired chemical substances<br>Biocyte cans |
| 4 | Power generation | Cooling tower | Scale |

**Figure 8.12:** Summary of the source and type of geothermal field solid waste. Source: Utami, A., Aji, N., Fadyah, A., Ghifari, A., Anam, M. B., Ramadhani, S., Rasyid, F. H., & Maulana, R. R. (2020). Geothermal energy solid waste management: Source, type of waste, and the management. *AIP Conference Proceedings*, *2245*(1), 060001.

Looking forward, next-generation technologies offer pathways to mitigate many of these risks. Because an AGS uses closed-loop systems that circulate working fluids through sealed wells (see Chapter 1, "Geothermal 101: Overview of Technologies and Applications"), these systems do not need the large volumes of drilling mud required for conventional hydrothermal plants. An AGS also creates less contaminated sludge.

### Land Subsidence

In Indonesia, with its high tectonic activity, geothermal energy extraction raises serious concerns about land subsidence, especially when fluid-removal rates are higher than reinjection rates, as in conventional geothermal.[72,73] Excessive overdrawing can consolidate subsurface reservoirs so much that the surface above visibly sinks. Subsidence can diminish the efficiency and sustainability of geothermal systems because it reduces pore spaces and fracture pathways, impairing fluid storage and movement.[74] The type of geothermal technology matters here. Conventional systems, which involve large-scale fluid extraction and reinjection, are more likely to cause the ground to sink. But newer technologies, such as AGS closed-loop systems, are designed to maintain reservoir pressure, reducing or eliminating the risk of subsidence.

Several geothermal fields in Indonesia have experienced notable subsidence because of surface loading, geological faults, altered rock compaction, and other factors.[75] Land in Muara Laboh, for instance, sinks up to 30 millimeters per year,[76] and Ulubelu averages 3.3 millimeters per year.

To mitigate land subsidence caused by geothermal development, countries around the world inject geothermal fluids back into the reservoir to maintain underground pressure and prevent compaction, a method proven effective in stabilizing fields such as Wairakei in New Zealand and areas within California's Basin and Range region.[77,78] Regulators and developers can also deploy comprehensive monitoring programs using techniques such as levelling and gravity surveys to measure ground deformation and remote-sensing technologies to detect subtle surface movements across large areas. These combined practices help prevent or minimize subsidence impacts while ensuring long-term reservoir sustainability.[79,80]

### Water Consumption and Fluid Management

The types of plant and technology used determine how much water is needed during operations. An EGS requires the most water to maintain reservoir pressure and keep fractures open, whereas an AGS requires the least. An AGS eliminates the need for direct interaction with subsurface fluids by circulating a working fluid through sealed wells, and this design greatly reduces the risk of groundwater contamination and minimizes water consumption. Pilot projects in Germany by Eavor Technologies and in New Mexico by XGS Energy show that an AGS can operate with near-zero water withdrawal, addressing one of the key concerns in water-scarce regions and water-sensitive geologies.

### Noise Pollution

In the operation phase, geothermal plants continue to produce noise from steam flow, turbines, and cooling systems, though at lower and more stable levels than construction. The Wae Sano project, for example, creates noises of only 55 dBA that cannot be heard beyond 500 meters. Plants can mitigate operational noise by deploying measures such as acoustic enclosures, low-noise fans, vegetation buffers, and earth berms.[81]

Geothermal noise is usually fairly moderate, but long-term exposure can still bother nearby communities.[82] To minimize risks, projects should apply noise-reduction technologies across both phases and comply with Indonesia's ambient noise limits (55 dBA for housing; 70 dBA for industrial zones).[83] Such measures are also important for protecting sensitive ecosystems where wildlife may be vulnerable to prolonged disturbance.

## ONGOING CONCERNS

Injecting or extracting fluids from geothermal reservoirs can cause earthquakes, and Indonesia's location on the Pacific Ring of Fire makes it especially vulnerable. Earthquakes have been documented in active zones such as the Muara Laboh geothermal field in Sumatra, where minor induced seismic events range from moment magnitudes of −0.5 to 2.0.[84] Similar concerns have been reported near the Gunung Salak and Dieng geothermal plants. Residents living close to Gunung Salak have reported frequent tremors since operations began, despite limited scientific evidence confirming a direct link. In Kepakisan, near the Dieng plant, communities have also associated increased earthquake activity with geothermal drilling, citing instances of property damage.[85]

AGS and superhot rock (SHR) systems are more suitable options for Indonesia considering the country's high volcanic activity and frequent eruptions. Unlike conventional hydrothermal systems, an AGS—which operates through a closed-loop design and does not rely on underground reservoirs or fluid permeability—allows geothermal heat extraction in non-volcanic or seismically safer zones.[86] And SHR systems, which harness heat from extremely deep, supercritical rock formations, offer the potential for significantly higher energy output per well. Given Indonesia's abundant volcanic heat sources and delicate geology, these next-generation technologies provide a safer and more flexible alternative for expanding geothermal energy across a broader and more stable range of locations.[87] To further mitigate the risks of seismic events, developers should conduct comprehensive geological and fault mapping studies before starting exploration, prioritize low-risk sites, carefully manage fluid injection pressures, and set up ongoing seismic monitoring.

## CONCLUSION AND RECOMMENDATIONS

The geothermal energy sector in Indonesia holds significant promise for achieving the nation's resilient energy and carbon reduction targets, particularly with the advancement of new geothermal technologies. Realizing its full potential, however, requires a careful approach to environmental hazards. Environmental impacts such as groundwater contamination, greenhouse gas emissions, biodiversity loss, induced seismicity, and land subsidence can be concerns, depending on location, and must be managed carefully. These risks can be amplified in Indonesia if development is pursued within conservation forests, protected ecosystems, and volcanic zones.

To guard against these hazards, policymakers and developers should prioritize smart resource siting, strong regulation, and resilient technologies. (For more on this topic, see Recommendation #9 in Chapter 7, "Turning Potential into Power: A Policy Blueprint for Indonesia's Geothermal Transformation.") By implementing careful strategies and proper safeguards, developers can scale up geothermal energy without sacrificing the forests, waters, and communities that make Indonesia unique. The following ideas—some of which are explored in more detail in Chapter 7—highlight ways to mitigate potential geothermal risks:

- Promote the adoption of next-generation geothermal systems for additional power generation as well as for cooling and industrial uses. Next-generation geothermal could be of particular value in opening up areas with limited permeability outside of High Conservation Value Areas to reduce surface disruption, water use, and subsurface and ecological risks.
- Prioritize geothermal development in lower-risk zones outside forest areas, where more than 2,160 gigawatts of potential have been identified (see the Chapter 3 supplement, "Expanding the Scope: Next-Generation Geothermal Opportunities"), while strengthening land use regulations to enforce strict "no-go" protections for high-biodiversity and conservation forests. Next-generation geothermal could significantly expand the potential for geothermal in Indonesia.
- All geothermal development should include requirements for post-operation land rehabilitation, including reforestation, slope stabilization, and ecological restoration, especially in forested or mountainous areas.
- Developers should be required to install real-time monitoring systems at all sites to track seismic activity, subsidence, emissions, and groundwater quality, with transparent public reporting.
- A circular approach to geothermal waste should be implemented by encouraging the reuse of silica sludge, drilling muds, and other byproducts in construction, agriculture, or industrial applications.
- Develop a national geothermal environmental database that is accessible to developers, investors, and communities for tracking land use, emissions, seismicity, and biodiversity impacts.
- Clear guidelines should be developed for inclusive community engagement, ensuring that local residents and Indigenous groups are consulted meaningfully and that environmental data are made publicly accessible.

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