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Global Collaboration Toward Standardizing Geothermal Gas Emissions Reporting: The International Energy Agency (IEA) Geothermal Gas Management Task

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Geothermal energy is a renewable resource. The extraction of geothermal fluids nonetheless mobilizes naturally occurring gases of deep geological origin. Emission intensities vary substantially between fields depending on geological setting, reservoir characteristics and plant design. Current guidelines of the Intergovernmental Panel on Climate Change (IPCC) classify geothermal carbon dioxide (CO_2) and methane (CH_4) as fugitive emissions, but national reporting practices remain inconsistent. To address this, an International Energy Agency (IEA) Geothermal Gas Management Task was established in 2024. Drawing on country case studies, the Task has compiled the first Global Catalogue of Geothermal Gas Emissions (IEA-GCE), bringing together plant-level emissions, natural surface fluxes, and isotopic source contributions. In this paper, we summarize differences in national inventory practice, compare plant emissions with natural surface fluxes, and present initial findings. Across reviewed fields, plant emissions are often comparable to or lower than natural degassing fluxes from the same systems, supporting the interpretation that production largely redistributes pre-existing geological CO_2 release rather than introducing entirely new flux. Mitigation measures, particularly reinjection, can substantially reduce net specific emissions but are not currently visible in formal national reporting. By situating emissions within their natural crustal context and comparing with conceptual analogues from other managed systems, such as hydropower reservoirs and biochar, the Task is developing a harmonized reporting methodology for geothermal gases within existing IPCC categories. This work aims to support clearer, more comparable national inventory practices that reflect geological settings, mitigation measures, and long-term emission trajectories, providing a foundation for accurate climate accounting and the credible integration of geothermal energy low-carbon transitions.

1 INTRODUCTION

Earth's crust continuously releases gases to the atmosphere through fractures, hydrothermal systems, and volcanic regions, including CO_2, H_2S, CH_4, H_2, and other volatile species that underpin the planet's natural geochemical cycles. Together, these gases constitute a continuous exchange between the Earth's interior and the atmosphere that has occurred throughout Earth's geological history (Fischer, 2008). Fumaroles, hot springs, and diffuse soil degassing mark its surface expression (Chiodini et al., 1998). Crucially, this flux is dynamic, varying from short-term fluctuations to geological timescales in response to changes in pressure, temperature, and processes acting throughout the crust (Ármannsson et al., 1989). Geothermal energy utilization taps into pre-existing subsurface fluid pathways, accelerating the release of gases that would otherwise degas more slowly through natural processes.

The IPCC 2006 Guidelines for National Greenhouse Gas Inventories (2006) categorize geothermal activities under 1B3: Other Emissions from Energy Production. This classification underscores the geological origin of geothermal gases as distinct from combustion or industrial activity, while recognizing that their release to the atmosphere is operationally controlled. With appropriate practices, such as gas reinjection and targeted utilization, geothermal operations can further reduce their atmospheric impact and, in cases of effective reinjection, achieve net surface flux below pre-development background levels.

Despite these classifications, the boundaries between natural geological emissions and those considered anthropogenic are not always consistently defined, leading to differing interpretations across countries. This inconsistency creates uncertainty in national greenhouse gas inventories and complicates how geological

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emissions are treated in policy and regulatory development. As mitigation technologies mature and reporting expectations evolve, the need for accurate and harmonized reporting becomes more relevant.

To address these challenges, the IEA Geothermal Gas Management Task was established. By situating geothermal emissions within their natural crustal context and recognizing their dynamic variability, this initiative aims to provide a more rigorous basis for evaluating the climate performance of geothermal energy and geothermal energy's role in the global transition.

2 IEA GEOTHERMAL GAS MANAGEMENT TASK

The IEA's Geothermal Technology Collaboration Programme (IEA Geothermal TCP) established the Geothermal Gas Management Task in 2024 in recognition of the need for consistent and scientifically robust methodology for reporting of geothermal gas emissions. The Task is the first international platform dedicated specifically to this subject, bridging geoscience, engineering, and policy.

2.1 Formation and Objectives

The Task was formally initiated in response to increasing requests from member countries for guidance on the assessment of geothermal gas emissions within international climate reporting frameworks. It's objectives are threefold: (1) develop international guidelines for reporting geothermal gas emissions in alignment with IPCC methodologies; (2) compile and maintain the IEA-GCE database, covering both natural surface fluxes and emissions associated with utilization; and (3) facilitate knowledge exchange and innovation by documenting best practices, mitigation strategies, and opportunities for industrial utilization of geothermal gases. Three publications have thus far been associated with the Task, including this contribution (Stefánsdóttir et al., 2025; 2026).

2.2 Participating Countries and Organizations

Participation in the Task is open to member countries of the IEA Geothermal TCP and affiliated organizations, with additional stakeholders welcomed by invitation. To date, contributions have been made by France, Iceland, Italy, Japan, New Zealand, Portugal, and the United States, with interest by additional geothermal nations. National contributors include public and private geothermal operators, research institutions, and energy companies, reflecting the Task's broad stakeholder base and the importance of public–private collaboration.

2.3 Scope and Strategic Vision

The Task's scope extends from scientific understanding of gas origins and variability to practical methodologies for measurement and management, integrating (1) geological context, recognizing that emissions depend strongly on geological settings; (2) technical practices and challenges, including closed-loop systems for binary and flash and utilization pathways; (3) policy frameworks, ensuring reporting and regulatory clarity in line with IPCC standards; and (4) collaboration and transparency, fostering an open platform for sharing data, methods, and experiences.

The strategic vision is to demonstrate that geothermal CO_2 emissions are ultimately governed by deep geological inputs and that, with appropriate management, particularly with reinjection, emission trajectories can decline toward natural pre-development levels over the operational life of a field. While these emissions reflect natural subsurface processes, they can be managed, reduced, or repurposed through appropriate technologies. By standardizing reporting and fostering innovation, the Task aims to support the role of geothermal in the global energy transition to underpin responsible management of geothermal resources within international climate frameworks.

2.4 Policy and regulatory frameworks

The governance of geothermal gas emissions is shaped by international accounting rules, regional climate policies, and national regulatory systems. Together, these frameworks determine how geothermal gases are categorized, reported, and managed, and they influence how geothermal energy is perceived within sustainable energy development. The Task engages with these frameworks both to ensure compliance and to support targeted improvements where current rules inadequately reflect the geochemical reality of geothermal emissions.

3 NATIONAL INVENTORY REPORTS AND NATURE OF GEOTHERMAL SETTINGS

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Volume 2, Energy; Chapter 4, Fugitive Emissions) state in Table 4.2.1 that "emissions from geothermal energy production and other energy production

not included in 1B1 or 1B2" should be reported under category 1B3: Other Emissions from Energy Production. Beyond this short statement, no dedicated methodological guidance is provided. In practice, however, most reviewed countries, including Iceland, Italy, Japan, and New Zealand report geothermal emissions under category IB2d as fugitive emissions. Estimates are typically derived from measured or default CO_2 content of geothermal fluids accounting for the fraction vented to the atmosphere versus that reinjected or abated.

This reporting placement reflects the geological origin of geothermal gases, which arise from natural crustal processes rather than combustion or industrial inputs. The IPCC approach thus recognizes geothermal emissions as a mobilization of natural crustal fluxes rather than wholly anthropogenic sources, an important distinction for developing consistent reporting standards. From the perspective of inventory account, however, regulators are primarily concerned with greenhouse gas (GHG) emissions contributing to near-term global warming, rather than cumulative geological releases over geological timescales. The Task therefore seeks to reconcile the geochemical reality of crustal degassing with the policy-driven accounting framework. This reconciliation has direct stakes: participating countries have quantified 2030 commitments under the Paris Agreement, referenced to national totals reported in their National Inventory Reports (NIRs). As a result, the choice of accounting methodology for geothermal gases can materially influence Paris Agreement compliance.

The CO_2 released from geothermal systems originates from geological sources, including magmatic degassing and the thermal decomposition of carbonate-bearing rocks and sediments. These sources are typically traced by the carbon isotopic composition ($\delta^{13}C$) in CO_2, sometimes supplemented by helium isotopes as conservative tracers of deep degassing. Magmatic CO_2 typically exhibits $\delta^{13}C$ values between –2 and –7 ‰ depending on magma source, metamorphic decarbonation yields around –2 to –5 ‰, and biogenic or thermogenic sources are usually more depleted (< –10 ‰) (Sano and Marty, 1995; Stefánsson et al., 2017).

Natural CO_2 emissions from geothermal fields occur primarily through soil degassing, fumaroles, hot springs, and dissolutions into groundwater (Chiodini et al., 1998; Stefánsson et al., 2016). Geothermal utilization can temporarily enhance CO_2 emissions through active extraction and decompression of deep geothermal fluids enriched in magmatic and crustal carbon, analogous to rapid degassing of a carbonated beverage upon opening. Operational data from geothermal fields, supported by numerical modelling, indicate that CO_2 emissions commonly decline over months to years or a few decades as stored reservoir carbon is released faster than it can be replenished by deep inputs (Fridriksson et al., 2017; Akin et al., 2020; O'Sullivan et al., 2021). In some systems, longer response times have been modelled, highlighting strong field-specific variability. Depending on reservoir characteristics and fluid residence times, often indicated by tritium activity and sulfur species equilibrium, emissions may decline toward pre-development levels within timescales relevant to Paris Agreement targets (2030–2050), while longer-term behavior remains important for sector-level sustainability assessments. Natural variability related to volcanic and tectonic processes further complicates assessment of net geothermal CO_2 impacts (Ármannsson et al., 1989).

The following sections provide an overview of CO_2 emissions from geothermal fields as reported in official National Inventory Reports (NIRs) and associated Common Reporting Tables (CRTs), which are publicly accessible in the United Nations Framework Convention on Climate Change (UNFCCC) website. In addition, the IEA Geothermal Management Task has compiled data on natural surface emissions and power plant emissions across participating countries to create the first IEA-GCE database. For each participating nation, the first paragraph summarizes geothermal gas emissions reported in the respective NIR and CRT; the second paragraph reviews information obtained directly from national participants, partner institutions, or published sources, now included in the IEA-GCE database; and the final paragraph compares these two sources.

3.1 France

The NIR of France (UNFCCC, 2025a) does not mention geothermal, and it is not reported in the CRT, except under chapter 2F in cooling for geothermal heat pumps. This reflects the country's limited geothermal electrical generation capacity, restricted to small plants in Guadeloupe and Alsace. France relies more heavily on low-temperature geothermal for district heating, particularly in Paris. These systems are not addressed in the NIR or CRT, as they are not considered to release geothermal gases.

In the IEA-GCE database for France, the Bouillante geothermal field in Guadeloupe, an overseas department of France, is registered as operating around 245 °C and is associated with active arc volcanism. $\delta^{13}C$ values of ~about -3.5 ‰ indicate a magmatic CO_2 source like other island-arc systems (Moretti et al., 2021). Natural CO_2 emissions are estimated at 4.6 kt yr^{-1} (Klein et al., 2024). Power plant emissions are similar at 4.2 kt yr^{-1}, corresponding to 32 g kWh^{-1} (Ministère de la Transition Écologique et de la Cohésion des Territoires, 2024).

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The NIR is therefore not consistent with the information established by the IEA Task.

3.2 Iceland

In Iceland's 2025 NIR, geothermal emissions are classified under 1B2d (Icelandic Environment and Energy Agency, 2025). The inventory covers all high-temperature geothermal plants, including electricity-only facilities, combined heat and power stations, and one heat-only plant. Emissions from low-temperature systems, widely used for direct heating, are excluded as negligible. The NIR cites Baldvinsson et al. (2011), which summarizes and compares the methodologies used by power companies and provides an overview of geothermal gas emissions from 1970 to 2011. The National Energy Authority (Orkustofnun) publishes annually from its data repository (Orkustofnun, 2024). Iceland relies heavily on geothermal energy, providing ~97% of household heating (37 PJ of heat use) and about 30% of electricity (174 PJ primary energy use). Operators measure gas concentrations at wellheads and separators, and emissions are calculated from steam flow and chemical composition; during plant commissioning, estimates were derived from test wells venting directly to the atmosphere. The time series shows strong fluctuations linked to operational and geological dynamics, with notable spikes in 1998 and 2006 coinciding with the commissioning of the Nesjavellir, Hellisheiði, and Reykjanes plants. In 2023, geothermal electricity generation reached ~6,000 GWh, associated with emissions of ~172 kt CO_2, ~4.5 kt CH_4, and ~34 kt SO_2 (H_2S reported as SO_2 equivalent). Mitigation measures are underway: At Hellisheiði and Nesjavellir Carbfix operates pioneering carbon reinjection and mineralization projects where CO_2 is dissolved in water and reinjected into basaltic rock, rapidly forming stable carbonates. H_2S is reinjected, as part of the same process, achieving permanent mineral fixation. Additionally, a methanol plant at Svartsengi additionally recycled CO_2 into synthetic fuel; however, long-term deployment of such CO_2-to-fuel pathways remains constrained by the EU regulatory treatment of geothermal CO_2 as a green fuel feedstock. Geothermal CO_2 at concentrated wellhead sources represents one of the most cost-effective opportunities globally, although the realization of larger-scale carbon capture and utilization (CCU) projects depend partly on regulatory clarification of permitting regulations of the resulting product as renewable.

The IEA-GCE database, Icelandic plant emissions ranging from about 1 to 56 kt yr^{-1}, corresponding to 13–158 g kWh^{-1} excluding heat sales. At Hellisheiði and Nesjavellir, active CO_2 reinjection further reduces specific emissions to ~15 g kWh^{-1} (Orkustofnun, 2024). The isotope composition of CO_2 indicates a deep and mantle-magmatic source with $\delta^{13}C$ values of –4.2 to –2.1 ‰ (Stefánsson et al., 2017). Natural surface emissions range from <5 to 165 kt yr^{-1} and often exceed power plant emissions.

The NIR for Iceland are consistent with the information reported through participants in the IEA Task.

3.3 Italy

According to Italy's 2025 NIR, geothermal fluids contain varying proportions of CO_2, CH_4, and minor gases such as H_2S, H_2, ammonia (NH_3), and nitrogen (N_2) reported under 1b2 (UNFCCC, 2025b). In their NIR, it is stated that "geothermal energy is a renewable source it is considered carbon neutral so while the CO_2 emissions are not accounted the emissions of CH_4 are evaluated". In Italy, geothermal electricity generation occurs exclusively in Tuscany, amounting to 5.9 TWh, with considerable direct uses estimated at around 10 PJ. Methane emissions are estimated for the full time series using monitoring data from the Agenzia Regionale per la Protezione Ambientale della Toscana (ARPAT), the regional environmental agency of Tuscany. ARPAT issues annual reports that provide CH_4 flux measurements (kg/h) from selected plants. Since operating hours are only available as averages across all geothermal plants, flux data are combined with these averages to estimate annual emissions. To avoid sampling bias, such as years when only high-flux plants were measured, the method incorporates a three-year average for non-sampled plants, extending the dataset and reducing distortion. The final estimates are normalized by plant capacity and scaled to the total installed geothermal power in Tuscany.

In the IEA-GCE database for Italy, the following information is listed. For the Amiata geothermal area (Bagnore and Piancastagnaio fields), the natural CO_2 emissions are elevated, 331–705 kt yr^{-1} and powerplant emissions are also significant but lower or 216–267 kt yr^{-1}, corresponding to 404–494 g CO_2 kWh^{-1} excluding heat sales (ENEL, 2025). The isotope composition with $\delta^{13}C$ values of –6.5 ‰ is consistent with a dominantly magmatic origin of CO_2 with minor crustal carbonate input (Frondini et al., 2009). Recent studies indicate depletion effects in which natural emissions offset power plant emissions (Sbrana et al., 2021).

The NIR for Italy reports CH_4 emissions from geothermal but excludes CO_2, whereas the IEA-GCE includes both.

3.4 Japan

Japan's 2025 CRTs list geothermal emissions under 1B2d (UNFCCC, 2025c). For 2023, geothermal activity is associated with 191.9 kt CO_2 and 0.38 kt CO_2e of CH_4, while nitrous oxide (N_2O) is reported as not occurring. The reporting follows IPCC conventions, placing geothermal under fugitive emissions rather than combustion categories. While the NIR does not provide methodologies or discuss mitigation, the figures are constant across the full time series, demonstrating continuity and transparency in reporting. Japan thus systematically quantifies geothermal emissions even though they represent only a minor component of its overall energy-sector profile (Greenhouse Gas Inventory Office of Japan, 2019).

In the IEA-GCE database the following information is registered. Powerplant emissions are very variable, <0.1–313 kt yr^{-1}, corresponding to 7.2–1324 g kWh^{-1} (Japan Organization for Metals and Energy Security, 2025). Natural CO_2 emissions from individual geothermal fields are not available at present. The $\delta^{13}C$ values range from –27.4 to -2.3 ‰, indicating variable sources of CO_2 including magmatic inputs, marine carbonates, and organic sediments with most values between -7.0 and -3.9 ‰ (Ono et al., 1993).

The NIR of Japan reports a national total for CO_2, but the IEA Task Force was unable to register individual plants due to lack of data.

3.5 New Zealand

New Zealand's 2025 NIR and associated CRTs report geothermal emissions under 1B2d, with a continuous time series from 1990–2023 (UNFCCC, 2025d). Geothermal energy is an important contributor to the national electricity supply, and the CRTs capture CO_2 and CH_4 emissions from this source. For 2023, geothermal primary energy use was ~200 PJ with direct uses around 10 PJ, associated with 376 kt CO_2 and 3.6 kt CO_2e of CH_4; N_2O was reported as not occurring. Emissions vary over time with field development, reflecting expansions of generating capacity, geological differences between reservoirs, and changes in reservoir CO_2 content over time. The NIR does not formally report mitigation projects. The continuous time series provides a transparent record of how geothermal emissions evolve alongside resource development.

In the IEA-GCE database, the following information is listed for New Zealand. The country's geothermal fields exhibit a broad $\delta^{13}C$ range from –9.7 to -4.9 ‰, indicating mixed magmatic–metamorphic and sedimentary CO_2 sources (Giggenbach, 1995). Estimated natural CO_2 emissions vary widely, from 13 to 143 kt yr^{-1} (McLean et al., 2024). Powerplant emissions are 24–141 kt yr^{-1}, corresponding to specific emissions of 30–345 g CO_2 kWh^{-1} excluding heat sales (Yang et al., 2024). At Ngatamariki, Ngawha, and Te Huka power stations, a substantial portion, and in some cases all, of the CO_2 is reinjected back into the reservoir. Overall, New Zealand's geothermal industry has moderate to low CO_2 emission intensities.

The NIR includes CO_2 emissions from geothermal. The data fits the average of the database.

3.6 Portugal

In Portugal's 2024 CRTs, geothermal emissions are reported under 1B2d, primarily from power generation in the Azores (UNFCCC, 2025e). Geothermal use in Portugal is small in scale and geographically restricted. For 2022, activity data show ~620 TJ of geothermal energy, with reported CO_2 emissions of 34.4 kt. CH_4 and N_2O are recorded as not occurring. No detailed methodological description is provided in the NIR, but the CRTs systematically report sources, even if relatively minor emissions.

In the IEA-GCE database, the following is reported. Despite relatively small installed capacities of 23 MW in Ribeira Grande, and 4 MW in Pico Alto, surface degassing is high, reaching 94.5 kt yr^{-1} at Ribeira Grande, and 0.9 kt yr^{-1} at Pico Alto, indicating substantial background volcanic CO_2 fluxes independent of production (Viveiros et al., 2020). Power plant emissions are 11 kt yr^{-1} at Pico Alto and 31 kt yr^{-1} at Ribeira Grande, corresponding to 603 and 182g CO_2 kWh^{-1}, respectively (UNFCCC, 2025a–e). These fields emphasize that small-scale volcanic geothermal systems can have relatively high CO_2 emissions, reflecting the strong CO_2 magmatic input characteristics of arc volcanic systems. Both systems exhibit $\delta^{13}C$ values of about –4.5 ‰, suggesting a predominantly magmatic origin with possible mantle-derived contributions.

The NIR for Portugal includes CO_2 emissions, and comparison with the gathered information shows that the reported values fall within a similar production range.

3.7 United States

The U.S. Inventory of Greenhouse Gas Emissions and Sinks (2024) does not report any geothermal emissions under 1B2d across the entire time series (UNFCCC, 2024). However, in the state of California, GHG emissions

are reported to federal agencies based on state regulations. The United States hosts over 90 geothermal plants with a combined capacity of ~3.9 GW, generating 16 TWh/a of electricity and about 152 PJ of direct use. This reflects both the geographically constrained deployment of geothermal resources in the western U.S. and its treatment as negligible within national totals (Robertson-Tait et al., 2023). The U.S. geothermal market continues to evolve, with the California Public Utilities Commission (CPUC) mandating 2 GW of new geothermal capacity by 2028. Since 2000, nearly 90% of new geothermal projects have adopted binary-cycle technology, operationally considered non-emitting, replacing older flash systems. The CPUC Transmission Planning Process model incorporates this transition as a strategic shift toward more sustainable, lower-GHG, and lower-temperature resources (U.S. Department of Energy, 2019). The total estimated power plant CO_2 emissions for 2023 were ~810 kt/yr, with California data derived from the California Ari Resources Board (CARB) (2025).

In the IEA-GCE database the following information is listed for USA. The fields display the widest $\delta^{13}C$ range globally, from –13.4 to –1.5 ‰, reflecting diverse geological settings spanning from subduction-related systems, extensional terrains, and sedimentary basins. The Geysers (–13.4 ‰) shows highly depleted CO_2, consistent with organic or thermogenic sources from metamorphosed sediments along deep, high-heat-flow fault zones with minimal magmatic input. Despite its large power outputs (~700–800 MW), CO_2 emissions are modest at 271 kt yr^{-1}, corresponding to 20 g kWh^{-1} (Bergfeld et al., 2001b). At the other end of the spectrum, the Salton Sea field (–2.9 ‰) reflects magmatic–metamorphic CO_2 associated with high-temperature basinal brines and magmatic fluids originating from oblique rifting. It emits 158 kt yr^{-1} or 39 g kWh^{-1}, moderate relative to its scale (Mazzini et al., 2011). Fields like Coso (–5.1 ‰) and Dixie Valley (–4.8 ‰) are intermediate and associated with extensional rifting, with emissions ranging from 21 to 299 kt yr^{-1} or 33 to 113 g kWh^{-1} (e.g. Bergfeld et al., 2001a; Buck, 2020). Overall, geothermal CO_2 emission intensities in the United States span a broad range of 3–720 g kWh^{-1}, with most fields between ~20–100 g kWh^{-1}. This variability reflects the country's great geological diversity and the range of carbon sources involved. Estimated CO_2 production emissions for 2023 vary between 0 and 299 kt/yr (CARB, 2025).

The NIR for the USA excludes CO_2 emissions from geothermal sources. However, several states officially report geothermal gas emissions, contradicting the federal values which are registered in the IEA-GCE database.

4 WORLD SUMMARY

Official figures from the UNFCCC database, as presented in each country's NIR and CRTs, align well with the IEA-GCE database for Iceland, New Zealand, and Portugal, where national reporting is broadly consistent with field-scale measurements within available uncertainty. In contrast, for France, Italy, and the United States, the absence of geothermal-specific data in NIRs and CTRs prevents reliable comparison with the IEA-GCE database. This gap is notable given the contrasting emission profiles observed across geothermal fields: France (Bouillante) and many Japanese fields display the low to moderate emissions typical of andesitic volcanic systems, Italian fields shows the highest natural fluxes linked to carbonate-bearing lithologies; and U.S. fields span the widest range of geological settings, from very low-emitting volcanic systems to high-output sedimentary and magmatic reservoirs in metasedimentary hosts. Without corresponding national reporting, this field-level variability remains unrepresented in the UNFCCC inventories.

Across countries, $\delta^{13}C$ values highlight clear controls on CO_2 origin that broadly track geodynamic setting and host-rock interaction. Divergent plate boundaries with mantle plume influence, such as Iceland and the Azores (Portugal), yield isotopically heavy values (–2 to –4‰) consistent with mantle-derived magmatic CO_2. Volcanic-arc systems like Japan, Italy and New Zealand, have variable signatures of mixed magmatic–metamorphic inputs (–4 to –7‰). Magmatic systems hosted in metasedimentary rocks like The Geysers are isotopically lightest (–9 to –13‰), while extensional and transtensional systems in the Western U.S., such as Salton Sea (–2.9‰), Coso (–5.1‰), and Dixie Valley (–4.8‰), have heavier $\delta^{13}C$ values that cluster in the magmatic range.

Power plant CO_2 emissions from geothermal systems vary by over four orders of magnitude from <0.1 to >300 kt yr^{-1}, reflecting string geological and reservoir-specific controls on reservoir gas content. In many cases, the plant emissions are comparable to or lower than the natural degassing flux from the same field, suggesting that production largely redistributes and accelerates pre-existing geological CO_2 release rather than creating an entirely new flux. Noting this, plant emissions are operationally anthropogenic and are appropriately reported within the Energy sector (IPCC categories 1B2d/1B3). When normalized to electricity generation using reported power plant-level CO_2 data, emissions typically center around an indicative, generation-weighted global average of ~75 g CO_2 kWh^{-1}, with interquartile values of ~30–170 g CO_2 kWh^{-1} and an overall reported range of ~3–1324 g CO_2 kWh^{-1} as shown in Figure 1. This value is intended as an order-of-magnitude synthesis rather than a compliance metric, considering measurement bases, data completeness, and treatment of high-emission systems vary across reporting streams. Given this variability, and the difficulty of separating anthropogenic and

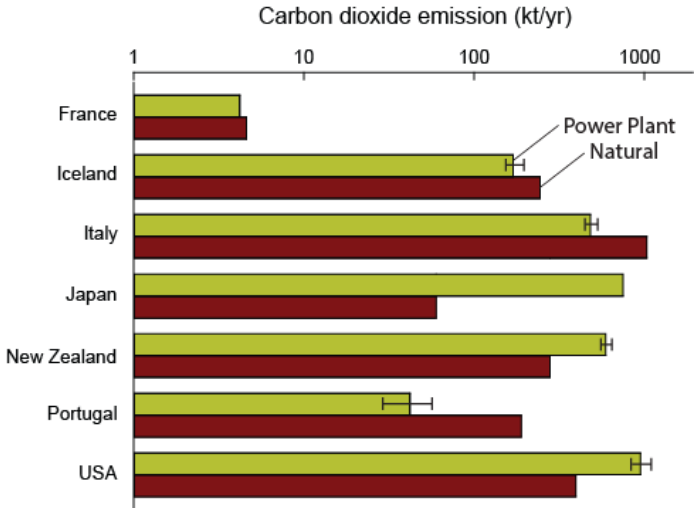


Figure 1. Registered CO_2 emissions reported in the IEA-GCE database from geothermal fields, grouped by country. Bars show reported natural surface CO_2 emissions (red) and CO_2 emissions associated with geothermal power plant operations (yellow). Values compile heterogeneous data sources, including measured field-level data where available and literature-based country-level estimates. Reported values are indicative and subject to methodological differences, data gaps, and source-specific uncertainties, which are documented in the underlying IEA-GCE database.

natural contributions, improved reporting transparency is essential. Structured annexes in NIRs documenting emission factors, baselines, system characteristics, and methodologies would substantially improve policy of geothermal inventory data that are prerequisites for alignment with sustainability frameworks and Paris Agreement obligations.

Based on the synthesis of information compiled in the IEA-GCE database, the Geothermal Gas Management Task observes that geothermal CO_2 emissions exhibit substantial variability across systems and over time, driven primarily by geological setting, reservoir characteristics, and operational history. In several of the geothermal systems reviewed here, natural surface CO_2 fluxed and emissions associated with electricity generation are of similar order of magnitude. Combined with isotopic evidence linking plant CO_2 to the same sources that feed natural degassing, this suggests that production commonly accelerates and redistributes pre-existing degassing pathways, rather than introducing entirely new carbon sources.

Operational experiences and historical data indicate that geothermal utilization commonly produces an initial increase in measured emissions due to decompression-driven degassing, followed by stabilization and, in some cases, a gradual decline as reservoir conditions evolve and stored CO_2 becomes depleted. In some systems, emissions have approached pre-development background levels over time, while in others natural and operational fluxes remain comparable. Low-temperature systems employing binary technologies generally exhibit minimal direct emissions.

Overall, the available evidence suggests that geothermal CO_2 emissions are highly system-specific and dynamic, underscoring the importance of long-term monitoring, transparent reporting, and responsible reservoir management. These findings highlight the potential for emission trajectories to stabilize or decline over the operational life of geothermal projects, while recognizing that outcomes vary across fields and must be assessed within their broader geological context (Ketilsson et al., 2026).

5 INVENTORY REPORTING - TOWARDS A HARMONIZED APPROACH

Across the world, countries with geothermal resources face a shared reporting challenge: geothermal gases originate largely from deep geological processes, yet national greenhouse gas inventories are designed to quantify anthropogenic emissions. As reviewed in the country case studies above, current practice is fragmented, some nations report only vented plant emissions, others include background natural fluxes, and few explicitly account for mitigation or geological variability. This reduces comparability and can obscure the true climate performance of geothermal systems.

Under existing IPCC guidance, geothermal gases are reported within the Energy sector (1B2d/1B3). While this ensures completeness, it does not fully capture the hybrid nature of geothermal fields situated in volcanically and tectonically active settings, where background fluxes are uncertain, emissions vary over time, and short-

lived natural disturbances (e.g., volcanic unrest, tectonic swarms) can temporarily enhance degassing independently of utilization. These dynamics complicate attribution when inventories rely solely on vented plant emissions.

A useful point of reference exists in hydropower, where reservoirs are reported under the LULUCF sector as managed wetlands, acknowledging that human intervention modifies natural carbon cycling. Although geothermal systems differ, this example shows that inventory frameworks can accommodate systems in which natural and human-influenced fluxes interact. Geothermal could similarly benefit from the addition of structured explanatory context, without changing its sectoral classification, to clarify how development modifies existing natural fluxes and to improve transparency in national reporting.

Two existing reporting traditions offer partial analogues. Hydropower reservoir emissions, addressed under LULUCF, demonstrate how managed systems interacting with natural carbon fluxes can be accommodated within inventories. Biochar methodologies, such as Verra's VM0044 Biochar Utilisation in Soil and Non-soil Application, offer more directly transferable concepts: baseline-relative attribution, uncertainty treatment, monitoring requirements, and durability and reversal-risk considerations. Going beyond this, the GHG Protocol Land Sector and Removals Standard also reinforces some of these principles for corporate reporting. While geothermal systems differ fundamentally, together these examples illustrate how inventory frameworks can be adapted to managed systems with natural carbon fluxes.

Within existing IPCC categories, the IEA Geothermal Gas Management Task proposes a harmonized reporting framework that encourages: (i) explicit characterization of the geological setting and baseline natural CO_2 flux with quantified uncertainty; (ii) transparent reporting of mitigation outcomes (e.g., reinjection, mineralization technologies); (iii) documentation of emission trajectories over the operational life of the field; (iv) clear identification and separate reporting of natural disturbance events using defined evidence thresholds (to be developed); and (v) supplementary narrative annexes in NIRs documenting assumptions, methodological choices, and field-level data.

6 CONCLUSION

In many geothermal systems, natural surface fluxes of CO_2 equal or even exceed those associated with the electricity generation, indicating that development largely redistributes existing pathways. It has also been observed in some fields that emissions ultimately approach background levels where utilization has resulted in a steady decline in reservoir pressure. Gas emissions commonly show an initial increase during early stages of geothermal utilization, as decompression drives enhanced degassing, followed by a steady decline as the reservoir evolves, ultimately approaching natural background levels. With mitigation measures such as reinjection and mineralization, the emission intensity of geothermal power generation can be substantially reduced over the operational life of a plant.

Geothermal energy occupies a unique position among renewable technologies: it draws on deep geological systems that naturally release gases to the atmosphere, meaning that development typically redistributes existing crustal CO_2 rather than generating new emissions. Although this distinction is reflected in current IPCC guidance, national inventory practices still vary widely in how geothermal gases are treated. As geothermal deployment expands and as reinjection, mineral carbonation, and utilization technologies mature, the need for a clearer and more consistent reporting framework has become increasingly apparent.

The work of the IEA Geothermal Gas Management Task demonstrates that international collaboration can help bridge the gap in geothermal emissions reporting. By compiling data from participating countries and establishing the IEA-GCE database, the Task has documented the scale of natural variability, the strong influence of geological setting, and the long-term emission trajectories observed across many geothermal reservoirs. These insights confirm that geothermal emissions can only be interpreted correctly when considered alongside geological baselines, operational history and mitigation measures.

A practical near-term approach is to retain geothermal reporting within the Energy sector (1B2d/1B3) while improving transparency through a structured annex in National Inventory Reports. Such an annex could separately document utilization-related emissions, mitigation activities, and extraordinary volcanic or tectonic events that temporarily alter degassing. This approach is conceptually consistent with practices elsewhere, including the EMEP/EEA Air Pollution Emission Inventory Guidebook, in which natural geological emissions are reported separately from industrial activities. This allows improved clarity without premature reclassification or quantified attribution, which requires further methodological development. EMEP is the Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe, a special

programme under the United Nations Economic Commission for Europe (UNECE). EEA is the European Environment Agency.

Geothermal gas management is ultimately a challenge for both science and policy, requiring integration of geoscience, engineering, and emissions accounting. By developing a harmonized methodology grounded in geological reality, the IEA Task aims to support more accurate, comparable, and methodologically robust inventory practices. Thereby, allowing geothermal energy to more clearly demonstrate its role in the low-carbon transition—not only as a renewable heat and power source, but as a technology that can manage and reduce its emissions footprint over time.

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