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How the Type of Geothermal Power Plant Affects Disposition of Non-Condensable Gases

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ABSTRACT

Sustainable geothermal energy utilization requires a deep understanding of all aspects of the production process, particularly regarding associated gas emissions from geothermal power plants and reservoirs. All geothermal fluids contain species that are gases at ambient temperatures and pressures. Such species, called non-condensable gas (NCG) may include carbon dioxide (CO_2), hydrogen sulfide (H_2S), hydrogen (H_2), nitrogen (N_2), ammonia (NH_3), and methane (CH_4) along with other trace gas species. Some types of geothermal power plants do not allow NCGs to evolve as a separate gas phase, thus do not vent or otherwise deal with NCG. Other types of plants have NCGs that are in a gas phase. In these geothermal plants, NCG may be collected for use or other disposition. This paper explains differences between types of geothermal power plants (e.g. condensing flash plants; back-pressure flash plants; single and two-phase binary plants), including their rough relative efficiencies, the situations under which each is typically used, and approximate relative costs. Then, the paper discusses how the type of plant affects disposition of the NCG. For example, collecting NCG for use (or to eliminate venting) requires different considerations for each type of geothermal power plant. The paper also reviews potential dispositions for NCG. For example, NCG could be re-injected back underground for sustainable operations. Alternately, species (e.g. CO_2, H_2S, perhaps H_2) could be separated prior to venting the remaining NCG or sending the remainder elsewhere. The content should be useful for plant operators as well as those considering future geothermal developments and policies. This paper is meant to contribute know-how from the IEA Geothermal Gas Management Task to enhance global research and geothermal development.

1 INTRODUCTION

Utilization of geothermal resources for energy production is considered environmentally sustainable (Goldstein, 2011). Sustainable utilization of geothermal resources is increasingly being tied to environmental performance (National Renewable Energy Laboratory (NREL), 2017). The utilization has some environmental impacts, although they are significantly lower than energy production originating from fossil fuels. The geothermal gases of focus in this paper are CO_2 and H_2S, which are recognized as some of the main gases regarding the environment, health and safety in geothermal utilization. These gases originate naturally within the geothermal reservoir, where they are dissolved in the circulating geothermal fluid prior to extraction, rather than being generated during energy production. Among the key environmental challenges is the handling of NCGs, particularly CO_2 and H_2S. The choice of power plant type directly affects both greenhouse gas (GHG) emissions and compliance with regulatory frameworks for emission reductions. Geothermal reinjection of NCG reduces the impact that geothermal utilization has on the environment by returning more of what was extracted, not only the liquid part of the geothermal fluid but also the dissolved constituents (NCG) within the fluid.

This paper examines the relationship between geothermal power plant design and NCG disposition. We compare flash-type and binary geothermal power plant designs and discuss how their operating conditions influence NCG composition due to air ingress, possible gas removal processes, and options for reinjection, utilization and venting into the atmosphere. This paper is meant to contribute know-how from the IEA Geothermal Gas Management Task to enhance global research and geothermal development, with practical implications for plant operators and policymakers.

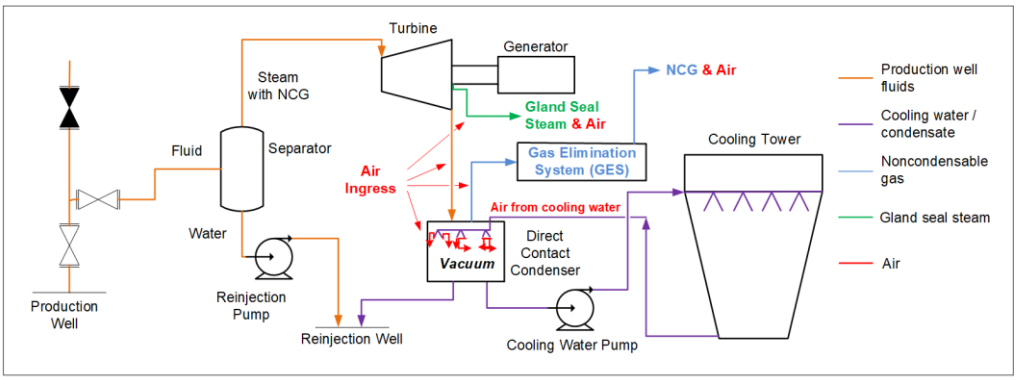
2 KEY DIFFERENCES BETWEEN POWER PLANT TYPES

The selection of a geothermal power plant type is primarily determined by the temperature and phase state of the geothermal resource, the chemical composition of the geothermal fluid, and the economic trade-off between efficiency and capital cost. High-enthalpy reservoirs that naturally produce steam are best suited for flash or dry-steam plants, while moderate-enthalpy, liquid-dominated resources typically require binary

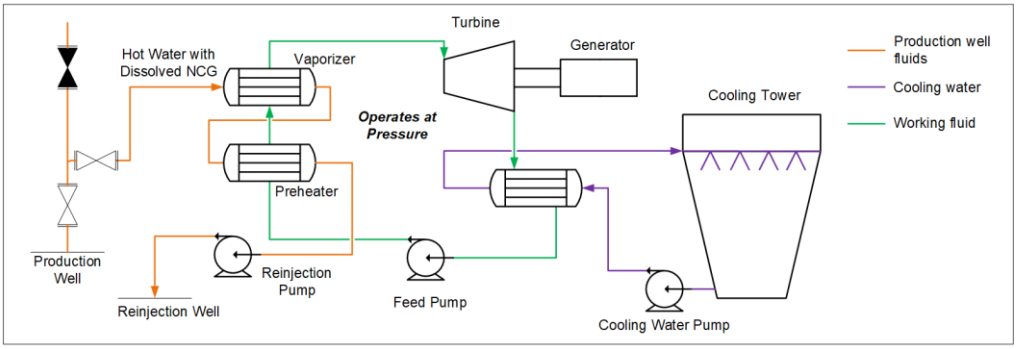
technology. Back-pressure units are often used in smaller or early-stage developments due to their simplicity in both construction and operation but have significantly lower efficiency, limiting their economic relevance.

Historically, flash and dry-steam plants have dominated global installed capacity, reflecting their ability to deliver higher efficiency and power output where suitable resources exist (Gutiérrez-Negrin, 2024). However, in recent decades, binary plants have gained greater prominence, especially in regions with moderate-temperature reservoirs, enabling utilization of resources once considered uneconomic. Today, binary technology is the fastest-growing type of geothermal power plants for electricity generation worldwide, though flash plants remain the most common for large, high-enthalpy geothermal fields. Figure 1 shows simplified schematics of flash and binary geothermal power plants. One key difference of importance in the operation of flash vs binary plants is the pressure at which the power plants are operated. Flash plants operate with a vacuum in the main condenser to maximize the turbine efficiency, whereas binary plants allow for the selection of a working fluid and operating conditions without the need for operating the turbine under vacuum. This difference is one of the key reasons why separation and disposition of NCG from all geothermal power plants are not equal due to air ingress in plants that operate under vacuum.

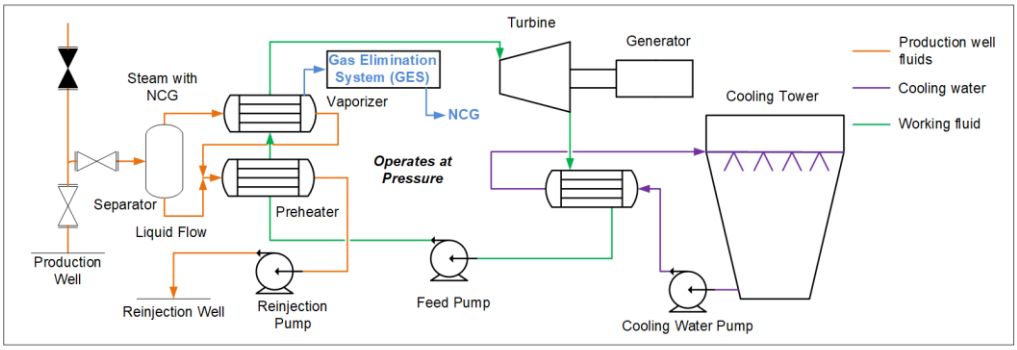
The following subsections explore the key differences between flash and binary power plants, with respect to their production processes and impact on NCG disposition, with a summary table at the end of the section.



Simplified Example Sketch of Flash Power Plant with Direct Contact Condenser



Simplified Example Sketch of Single-Phase (Liquid) Binary Power Plant



Simplified Example Sketch of Two-Phase (Vapor/Liquid) Binary Power Plant

Figure 1. Schematics of simplified flash and binary geothermal power plants.

2.1 Flash-type Power Plants

Flash plants are the conventional choice for high-enthalpy geothermal systems where the geothermal fluid naturally exists as a two-phase mixture of steam and liquid water. High-enthalpy resources are typically found in volcanic regions. In the flash example in the schematic at the top of Figure 1, the geothermal fluid entering the separator is a two-phase mixture of hot liquid water and steam. The liquid water phase is separated from the steam phase in the separator. The steam from the top of the separator is used directly as the working fluid that passes through the turbine to generate electricity. In most flash plants, the steam is condensed at vacuum at the exit of the turbine (which greatly improves efficiency), forming condensate with some NCG remaining in the vapor phase.

Flash plants are favored where efficiency and large-scale power output are required, making the high steam presence justify the higher capital cost of a flash plant. Their dominance in geothermal history stems from successful deployment in regions such as Italy, California's The Geysers, Iceland, and parts of the Philippines. However, their reliance on vacuum operation after the turbine introduces challenges such as air ingress, the need for gas elimination systems (GES), and more complex NCG handling requirements.

Dry-steam power plants, which utilize geothermal fluid that is near 100% steam (vapor), operate on similar principles as flash-type power plants. The content and conclusions of this paper for flash plants are also applicable to dry-steam, hence dry-steam plants are not discussed further for simplicity.

2.2 Binary Power Plants

In the binary power plant example in the schematic in the middle of Figure 1, the geothermal fluid is a single liquid phase (i.e., hot water with dissolved gases). Binary plants operate on a closed working fluid cycle generally at lower temperatures than for flash geothermal systems. The hot water exchanges heat with a different working fluid (the binary working fluid). The binary working fluid is vaporized. This vaporized working fluid passes through the turbine or expander to turn an electrical generator and generate electricity.

Because the geothermal fluid (in this example) remains liquid phase throughout the production process due to the elevated pressures, NCGs remain dissolved, and no gas phase evolves during the process. In this simple binary design, no GES is required, and all produced fluids (including NCGs) are reinjected as a single-phase liquid. In some geothermal fields, flash steam and binary power plants coexist and operate alongside each other.

There are also two-phase binary plants (see schematic at the bottom of Figure 1), where the geothermal fluid is flashed in a separator. The resulting steam and NCGs boil the working fluid in the vaporizer, while the separated liquid can preheat the working fluid prior to entering the vaporizer. As the steam transfers heat to the working fluid in the vaporizer, the steam condenses, and the NCGs must be vented to avert pressure buildup. The NCG is removed from the vaporizer at a pressure close to the inlet steam pressure, typically 4 to 6 bara (ESMAP, 2016). Since the system pressure typically remains above atmospheric, air ingress is prevented. If the pressure is dropped to below atmospheric, then the same concerns with air ingress may exist with binary plants as with flash plants.

Table 1. Comparison of geothermal power plant types with respect to NCG management and disposition.

Geothermal power plant	Efficiency (relative)	Air Ingress into NCG	Need for Gas Elimination	Complexity of NCG Reinjection	Key Challenges for Reinjection
Flash Plant (Geothermal resource: single-phase steam or two-phase)	High	Significant (5-15 vol% air, depending on condenser type)	Required (steam-jet ejectors, vacuum pumps)	Difficult (air ingress complicates reinjection)	Corrosion, sulfur formation, potential explosive gas mixture; higher system complexity
Binary Plant (Geothermal resource: single-phase liquid)	Low-moderate	Generally, none (no vacuum)	Not required	Easy - NCG is dissolved in liquid and can be reinjected directly	
Binary Plant (Geothermal resource: two-phase)	Low-moderate	Generally, none (if no vacuum)	Required, but simpler than required for flash plants	Moderate – NCG recombined with condensate and brine	Equipment to recombine gas and liquid required, may require some gas compression

3 GAS ELIMINATION SYSTEMS

All geothermal fluids naturally contain dissolved gases within the reservoirs in equilibrium with the rock-fluid system and the temperature and pressure conditions within the reservoir. The concentrations of gas species vary greatly between fields, depending on, for instance, water-rock interactions of each field, magmatic intrusions and phase separation through boiling and/or condensation. Each gas species has different solubilities which in turn determine the amount of gas partitioned into the steam phase when the geothermal fluid is extracted via production wells and the pressure is reduced. Generally, CO_2 is the main component of geothermal gas (often >50vol% in high-temperature fields), often with high concentrations of H_2S, and varying concentrations of H_2, N_2, NH_3, CH_4, and other trace elements.

The NCG content in geothermal steam is a critical factor, because it directly affects the design and performance of the power plant, including the presence and complexity of the gas-elimination system (GES). To maintain proper operation, these gases must be continuously removed using steam-jet ejectors, vacuum pumps, or hybrid gas extraction equipment. The following subsections describe how GESs operate across different types of geothermal power plants and their impact on air ingress and other factors that affect NCG disposition.

3.1 Gas Elimination Systems in Flash Power Plants

In flash plants, when the steam exits the turbine and condenses in the main condenser, the NCGs do not condense, but accumulate and raise back pressure. If the NCGs remain in the system, they displace steam and reduce the pressure differential across the turbine, lowering power output. The NCG from the main condenser is drawn off by the GES to maintain low pressure in the main condenser. The ejectors (or other devices) may discharge sequentially into inter- and after-condensers to condense additional steam and increase the pressure of the NCG to just above atmospheric.

The main condenser and inter-condenser typically operate at vacuum conditions. Air ingress into the vacuum portion of the system elevates the relative O_2 and N_2 concentrations in the NCG. The presence of O_2 in the NCG can complicate gas disposition methods, such as reinjection. Air ingress to the NCG adds difficulty to reinjection because air has low solubility in water (compared to, for example, CO_2), and the presence of O_2 can elevate corrosion of metals and cause the formation of solid elemental sulfur (when H_2S is also present). Furthermore, when the NCG contains flammable components, such as H_2, CH_4, and H_2S, there is risk that the introduction of air into the mixture will result in an explosive gas mixture (McIntush K. , et al., 2025).

Air ingress into the NCG flow occurs when the pressure of the condenser is lower than the atmospheric pressure. Atmospheric air can enter the process through various paths including but not limited to flanges, valve stems/packing, instrument penetrations, expansion joints, manways, and condenser tube-sheet interfaces. All are common sources of atmospheric air ingress; even for a well-maintained facility, these leakages must be monitored and prevented regularly (Stefánsdóttir & Emilsson, 2023). In addition, turbine shaft gland sealing systems often allow air to enter. When the gland steam leak-off (GSLO) vent is combined with the NCG stream, this air ingress can substantially increase the air content of the NCG.

In terms of power plant design, the type of condenser also plays a key role in determining the baseline air ingress to the process. Plants equipped with direct contact condensers (DCC) introduce additional air released from the cooling water. Cooling water becomes saturated with air in the cooling tower and a portion of the dissolved air (~8 ppmw O_2 is contained in air-saturated water) evolves from the water into the NCG in the condenser due to the warm, vacuum conditions. In certain cases, the NCG exiting the GES may contain 10-15 vol% air (2-3% O_2) due to the use of a DCC. When gland seal steam is combined with the NCG from a DCC, the resulting O_2 concentration can rise substantially. For instance, one geothermal power plant measured 6% O_2 in the combined stream compared to 2.5% when the gland seal steam was kept separate (McIntush K. , et al., 2025).

Many flash-type geothermal power plants use indirect condensers (surface condensers). In a surface condenser, cooling water flows through the heat exchange tubes and never comes into direct contact with the condensing steam. As a result, the NCGs exiting the GES from a surface condenser typically contain less air – about 5% by volume (roughly 1% O_2).

3.2 Gas Elimination Systems in Binary Power Plants

In binary plants where the produced fluid can be kept single-phase liquid, gases remain dissolved and no separate NCG stream evolves inside the plant; thus, a GES is not required. This process also operates at positive pressure, so no vacuum exists. Consequently, there is little to no air ingress, which simplifies operations and reinjection or utilization strategies.

In two-phase binary systems, the geothermal steam is used only as a heat source – it does not drive the turbine directly. The binary working fluid is vaporized by heat transfer with the condensing steam in the working fluid vaporizer heat exchanger. NCGs in the geothermal steam do not condense and reduce the heat transfer efficiency, and result in a lower steam condensation temperature, reducing the temperature difference between the working fluid vaporization and steam condensation. The GES removes the accumulated gases to maintain steam condensation pressure, not to sustain the turbine vacuum as in a flash plant.

If pressures remain above atmospheric throughout the system, there is no air ingress, and the NCG composition from such binary plants directly reflects the extracted geothermal fluid from the reservoir, simplifying NCG processing. However, for the same steam resource, binary cycles yield substantially lower net power than condensing flash turbines. On the other hand, while flash steam condensing cycles deliver higher efficiency, they have vacuum conditions and air ingress, which causes NCG processing to be more complicated. Thus, resource temperature, geothermal fluid properties / phases, and NCG loading jointly steer developers in the design of the power plant and NCG disposition method.

4 DISPOSITION OF NON-CONDENSABLE GAS

The NCG phase from the geothermal system is usually managed as part of the power plant process through dedicated disposal or utilization systems. Common options include reinjection of all or portions of the NCG, separation of key components for utilization or sale, incineration, and atmospheric venting. The optimal NCG disposition strategy depends on the gas composition, plant design, environmental regulations, and market opportunities. The main disposition methods are outlined further below.

4.1 NCG Reinjection

It is possible to reinject some or all of the NCG from geothermal power plants back into the reservoir from which the NCG came. NCG reinjection into geothermal formations has been tested and implemented at some facilities (Zarrouk, 2023). Examples of geothermal power plants that reinject NCG include Hellisheidi and Nesjavellir (flash plants) in Iceland, Puna (flash/binary combined cycle) in USA, and Te Huka (two-phase binary) in New Zealand. In addition, several other facilities worldwide are conducting tests to evaluate NCG reinjection under their specific reservoir conditions. Reinjection can be done by dissolving the NCG into the injectate (brine, condensate, and/or other water source) either at the surface or down the injection well. (Note that all geothermal effluent liquids are often referred to simply as “water” in the rest of the paper.) This practice returns the geothermal fluid back into the geothermal system as close to its natural state as possible, in line with goals of sustainable geothermal utilization.

4.1.1 Complete Dissolution of NCG in Geothermal Fluids or Water

Both H_2S and CO_2 are only slightly soluble in water under normal conditions, but at high pressures and low temperatures, significant amounts can be dissolved. If sufficient water is available and appropriate pressure and temperature are maintained, it is possible for all the NCG to dissolve completely into the water.

Figure 2a shows solubility characteristics of two arbitrary examples of NCG gas. The graph includes data for a low and high-CO_2 NCG stream, where the lower-CO_2 NCG stream contains higher amounts of light gases such as H_2. Two curves are given for each example – solubility at 25 C and 75 C. The data are expressed in terms of the mass ratio of water (water salinity is ignored) to gas that is required to achieve complete dissolution of the gas phase at various pressures. Several factors affect the complete dissolution of NCG in water, including:

- Pressure: Higher pressure increases gas solubility.
- Temperature: Lower temperature increases the solubility of most gases.
- Gas composition: For typical NCG components, CO_2, H_2S, and NH_3 have relatively higher solubility, while H_2, N_2, oxygen (O_2), and methane have lower solubility.
- Water composition: The presence of salts and the pH of the water can also affect solubility.

In general, NCG mixtures that are rich in CO_2 (and H_2S, NH_3) tend to dissolve completely at reasonable pressures, whereas NCG with higher concentrations of lighter components (H_2, N_2, O_2, CH_4) are less soluble and require higher pressure or a higher ratio of water to gas to dissolve completely.

Because the fluid would be reinjected, the pressure in the subsurface formation is important – if the formation pressure at the reinjection point is lower than the vapor pressure of the fluid being reinjected, flashing of the liquid would result, which could cause problems such a reduction in injectability or gas escaping to the surface,

etc. Therefore, it is assumed that the gas should remain dissolved in the liquid being injected at the pressure of the formation at the injection point to avoid unforeseen problems.

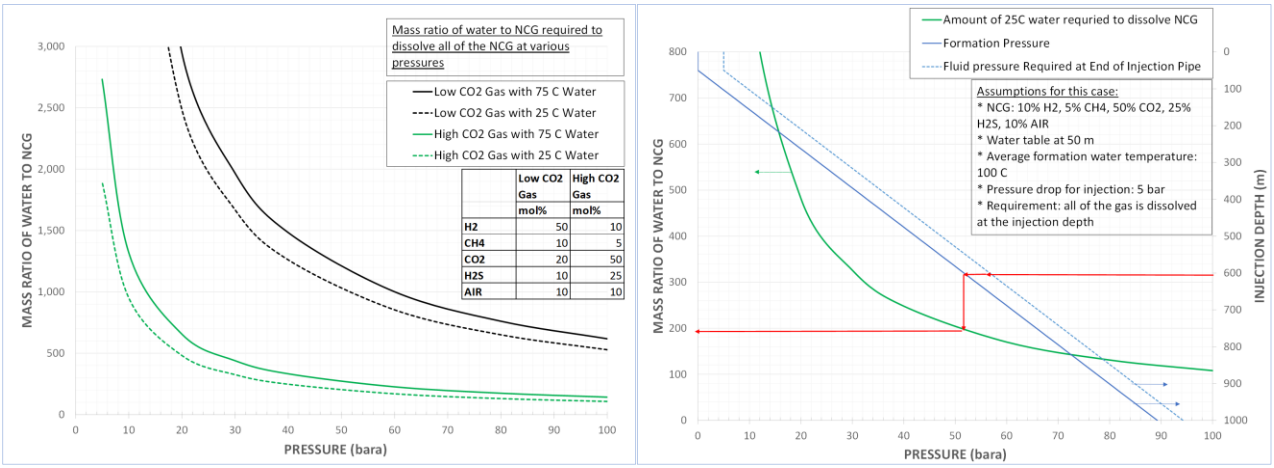


Figure 2a (left). Approximate solubility characteristics of two example NCG compositions.
Figure 2b (right). Dissolution of NCG into water for injection and injection depth.

Although different geographical locations will have different subsurface pressure profiles, a simple case is illustrated in Figure 2b. The figure shows a very simple estimate of formation pressure as a function of depth (solid blue line), assuming a 50 m deep water table and static pressure of 100 C liquid water. A pressure drop for injection of 5 bar was assumed. Gas solubility data in water (green line) can be compared to the pressure of the formation, and the amount of water required to keep the gas dissolved at the injection depth can be estimated. The red lines on the graph show this estimate: assuming an injection depth of 600 m, the pressure in the formation (solid blue line) at that depth will be about 52 bar_a. If a pressure drop on reinjection is assumed, then the total pressure required at the injection depth in the well is 57 bar_a (dashed blue line). At the formation pressure of 52 bar_a, the water required to achieve complete dissolution of the gas is given by the green line at 52 bar_a; the mass ratio is 200, so for a NCG flowrate of 1 kg/s, a water flowrate of 200 kg/s would be required.

Complete dissolution of the NCG into water can be accomplished via different schemes. Gas can be dissolved into the water at the surface, or water and gas can be co-reinjected and the gas dissolves as the fluids travel down the well and the pressure increases due to the hydrostatic head. The latter scheme is more complex, and requires careful analysis, but would require substantially less pressure be applied to the two fluids at the surface, potentially saving substantial capital and operating costs.

Figure 3 shows a schematic for the complete dissolution of NCG into water during injection. The NCG is compressed and mixed with water or brine at the wellhead; because the water is the bulk of the volume of the injectate, substantial pressure is developed hydrostatically traveling down the well, so the pressure required at the surface is much lower than the pressure at which the gas completely dissolves.

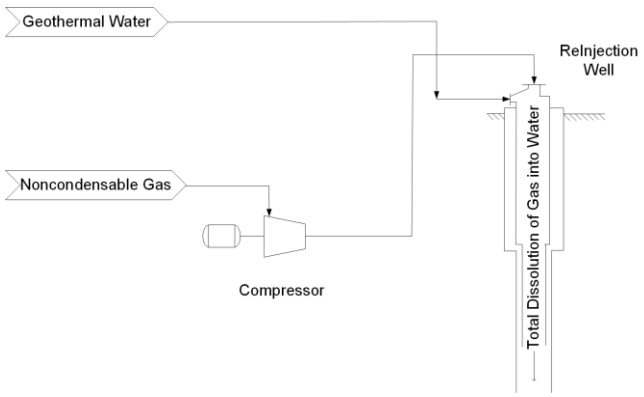


Figure 3. Complete dissolution of NCG into geothermal fluids / water.

The water and NCG can be mixed at the well entry or just before the well entry to form a two-phase mixture; in this mixture the actual fractional volume of the gas would be relatively low, and the gas phase would essentially be bubbles that would be carried downward with the water. The high velocity of the fluids in the injection tube

result in a high degree of turbulence, keeping the size of the gas bubbles in the two-phase mixture small. As the two-phase mixture flows down the injection tubing, the pressure increases due to the hydrostatic water head, and the gas bubbles eventually disappear as the gases dissolve in the water. At the bottom of the well, all the NCG (including even light species such as H_2) should be completely dissolved in the water. The operating pressure at the surface is set by the injection well pressure, and the evaluation of the hydraulics of the fluids going down the well. The pressure at the surface must be high enough so that i) all the gas is dissolved in the water when the water reaches the target injection depth and ii) there is enough pressure at the injection zone so that the injection pressure drop from the well bore into the formation can be overcome. Surface pressures on the order of only ~10 bar_a may be possible depending on the NCG characteristics, the water characteristics, the ratio of available water to NCG, and reservoir conditions.

4.1.2 Partial Dissolution of NCG in Geothermal Fluids / Water

Partial dissolution of NCG into water may be desired if the NCG contains a very high fraction of light species making the conditions for complete dissolution unreasonable. Partial dissolution may also be a good approach if it is desired to recover other, lighter components of the NCG (e.g., hydrogen, methane) for use (e.g., fuel) or if it is only necessary or desired (e.g., desired due to regulations or carbon capture financial incentives) to reinject the heavier components (CO_2, H_2S) of the NCG. When the recovery of lighter components is desired, the partial dissolution of NCG in water can serve as a bulk separation process to remove most of the CO_2 and H_2S from the NCG.

The NCG may be partially dissolved into the water using a packed tower (shown in Figure 4) or a mixer (e.g., static mixer, venturi, or other device) followed by a separator. This approach reduces both the water and compression requirements for the gas compared to the total dissolution approach discussed in Section 4.1.1. Because CO_2, H_2S, and NH_3 are more soluble in water than the lighter gas components (O_2, N_2, CH_4, H_2), most of the CO_2, H_2S, and NH_3 would be selectively absorbed into the water, while the lighter gases would exit from the top of the tower and can be vented, burned, or subjected to further processing. The CO_2/H_2S-rich water can then be injected into the reservoir. Removal of the CO_2 and H_2S enriches the residue gas in lighter components, which often includes flammable species (H_2, CH_4); for systems with oxygen in the NCG, like flash plants, the equipment must be designed and operated to avoid the explosive gas region (see Section 4.4 for more discussion on this topic). This type of process has been applied to NCG in Iceland (Carbfix, 2021), and the research work indicates that the basaltic rocks in the reservoir react with the CO_2 to form carbonate minerals for permanent fixation of the CO_2.

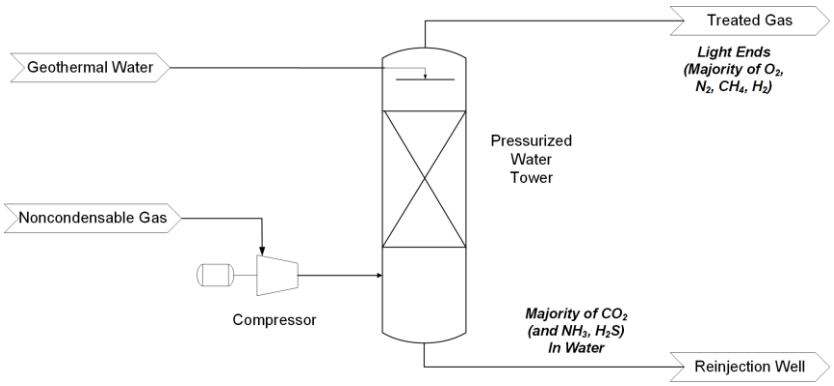


Figure 4. Partial dissolution of NCG in geothermal fluids or water with packed tower.

An alternate scheme for water absorption is to use a simple, single-stage absorption rather than a conventional counter-current absorption column. While multi-stage, counter-current contacting is the most efficient way to absorb CO_2 and H_2S from the NCG, an inline mixer and separator could be used instead if the pressure is raised and/or a larger amount of water is used in the absorption.

4.1.3 Impact of Geothermal Power Plant Type on Reinjection

Reinjection of NCG may be more challenging for flash-type geothermal power plants than for two-phase binary plants because of the air introduced under the vacuum conditions in flash plants, especially those that use direct contact condensers and that route GSLO to the condensers. The oxygen and nitrogen components do not easily dissolve into the water. Oxygen from air ingress can also potentially lead to corrosion of carbon steel material and the formation of small amounts of elemental solid sulfur, which can accumulate on pipe and equipment surfaces. In two-phase binary systems, because pressures are higher and systems are closed, the light end content has no oxygen compared to traditional flash systems, making the NCG conditions more

amenable to reinjection. If reinjecting NCG with air, then the impacts of adding air into the reservoir also need to be considered, and testing may be warranted; the introduction of oxygen to a reservoir, along with H_2S and other species, can result in chemistry between the injected components and/or with the formation rock that could result in unforeseen results (e.g., plugging of the well).

For flash systems, it will be important to minimize air ingress as much as possible. A systematic leak detection and repair program can be very effective at reducing air ingress and should be implemented to aid in this effort (Stefánsdóttir & Emilsson, 2023). The routing of gland steam leak-off (GSLO) should also be carefully considered since this stream often contains significant amounts of air/oxygen. In the design phase, the condensing system must also be considered in light of the issue of oxygen ingress – surface condensers prevent the ingress of oxygen from cooling water, whereas direct contact condensers practically always result in significant oxygen contamination of the NCG.

4.2 Separation and Utilization

An alternative to NCG reinjection is to utilize all or some of the gas components. One method for NCG disposition, for cases where the NCG contains significant amounts of flammable species, is incineration. This is often practiced (e.g., at The Geysers in California), with caustic scrubbing applied for the removal of SO_2 (combustion product of H_2S) from the combustion gas. Recovery of waste heat to generate steam from the hot combustion gas is an effective way of utilizing the NCG while also ensuring that sulfur species are not vented to the atmosphere. This method is, however, not amenable to CO_2 recovery and sequestration.

The recovery of valuable components from the NCG can be pursued. CO_2 and H_2 are components that may be deemed valuable, depending upon local markets and their concentration in the NCG. In particular, CO_2 can be separated and utilized for: i) greenhouse use, ii) enhanced oil recovery, iii) food/beverage grade CO_2, and iv) commercial products (e.g., urea, fuels, chemicals). CO_2 can also be sequestered for tax credit as allowed by local regulations. As an example, geothermal CO_2 is captured at the Kizildere, Dora I and II, and Gumuskoy plants in Turkey to produce dry ice and carbonated beverages (ESMAP, 2016). Carbon Recycling International (CRI) also once operated a CO_2-to-methanol plant at a geothermal facility in Grindavik, Iceland, taking a portion of the NCG produced by the HS Orka Svartsengi facility (Wikipedia, 2025).

The processing steps to purify the CO_2 depend on the contaminants in the NCG and the treatment specification and operating conditions required for end use. The oxygen in the NCG typically associated with flash-type plants is a particularly problematic impurity, making the purification of CO_2 more difficult. The flammable components and oxygen in the gas may also be enriched as CO_2 is removed, presenting a hazardous explosion environment. Many different technologies can be used to remove the contaminants in the NCG as documented in the literature (McIntush K. , Mamrosh, Beitler, & Piggott, 2022) (McIntush, et al., 2016), and often several purifying steps may be required. Beverage grade CO_2 in particular has a very high purity level requirement, and depending on the contaminants in the NCG, may require multiple treatment steps as shown in Figure 5.

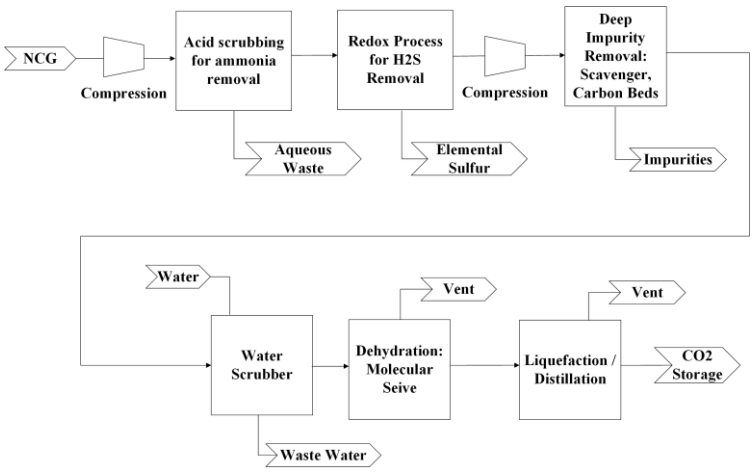


Figure 5. Example for beverage-grade CO_2 process (McIntush K. , Mamrosh, Beitler, & Piggott, 2022).

4.3 Atmospheric Venting

Depending on local environmental regulations, the NCG could potentially be vented to the atmosphere or burned (flared, incinerated). Venting is the simplest method but releases greenhouse gases (CO_2 and CH_4) and

toxic H_2S to the atmosphere. Many areas of the world have strict requirements for H_2S emissions, and direct venting without treatment for H_2S removal is often forbidden. Some areas have traces of mercury in the NCG, the abatement of which may be required. Venting NCG can also pose an explosion risk if the combustible material (CH_4, H_2, H_2S) in the NCG mixes with air in the explosive range and an ignition source (e.g., static electricity) is nearby. Venting must be carefully designed to prevent the buildup of toxic or flammable gas. Vent stacks are elevated and located away from ignition sources to ensure safe dispersion. Another common venting method is to route the NCG through the cooling tower for emission, where the presence of large amounts of water reduces the potential for ignition.

4.4 Flammability Concerns

Since the NCG contains flammable components and oxygen may be present, the gas could become an explosive gas mixture – an "explosive gas mixture" is one that has enough fuel and oxygen that it can burn, deflagrate, or explode if an ignition source is present. Flammability concerns vary depending on how the NCG is handled in the system. For complete dissolution of NCG in water with reinjection (Figure 3), there is no residue gas and, in the absorption process, the gas bubbles are surrounded by water. Thus, there is no significant flammability issue.

For cases in which all the NCG is not dissolved into the water, like the pressurized water tower in Figure 4, CO_2 and H_2S are absorbed at a higher fraction compared to oxygen and light flammable species such as hydrogen and methane. As a result, the change in composition of the residue gas compared to the NCG could move the gas closer to the boundaries of the flammability envelope. Thus, the absorption tower must be controlled carefully so that the residue gas does not become an explosive gas mixture.

Predictive calculations, such as in a Bureau of Mines (BoM) publication (Coward and Jones, 1952), can be used to estimate the flammability properties of complex gas mixtures. In this method, the air content of the gas is mathematically separated from the mixture as the "air" component and the remaining gas is referred to as the "fuel plus inerts". The UFL and LFL of the "fuel plus inerts" is then estimated separately and compared with the actual concentration of "fuel plus inerts" in the gas mixture (McIntush K. , et al., 2025) (Piggott, et al., 2021).

An example analysis of the impact of more air ingress to the NCG for a pressurized water absorption column is shown in Table 2. In the example, the packed tower is used to remove ~90% of the CO_2 and >99% of the H_2S from the NCG into water for injection. CO_2 and H_2S are the highest concentration species in the NCG, and when most of them are removed the concentration of the remaining components increase. For this example, the residue gas from the tower for the design basis and 25% more O_2 case has a fuel + inert concentration that is greater than the UFL + 10% safety margin so the residue gas mixture can be considered safely outside of the flammability envelope. If the air ingress into the NCG increases by about 50%, the residue gas will be within the UFL safety margin, and with the amount of ingress doubling, the residue gas will likely contain a flammable plus inert content of about equal or less than the UFL, indicating the residue gas may be in the flammability envelope. A similar effect would occur if the CO_2 recovery percentage increased substantially. Much caution and care must be maintained to prevent excessive air ingress to the vacuum section of the main condenser in flash-type plants and with monitoring the CO_2 absorption so as not to create a gas mixture that is inside the flammability envelope.

In some cases, a pre-absorber can be included in the design to contact the water and NCG stream upstream of the packed tower to absorb a significant portion of the CO_2 and H_2S into the water phase. The pre-absorber manages the flammable species at the beginning of the process so that a safe gas product low in oxygen can be made for sequestration or utilization later in the process (Olafsdottir, et. al., 2023).

Table 2. Example analysis of impact of more air ingress to NCG for pressurized water tower.

Parameter	Units	Design Basis NCG	25% more O_2 in NCG	50% more O_2 in NCG	100% more O_2 in NCG
NCG					
Air content	Vol%	4.74	5.93	7.11	9.48
O2 content	Vol%	1	1.23	1.5	2
Residue Gas					
Air content	Vol%	15.11	18.89	22.67	30.22
O2 content	Vol%	3.17	3.97	4.76	6.34
Fuel + Inert	Vol%	84.89	81.11	77.33	69.78
UFL	Vol%	70.3			
UFL + 10% Safety Margin	Vol%	80.3			

5 CONCLUSION

The type of geothermal power plant fundamentally shapes the technical complexity of NCG disposition and the overall operation of the gas treatment processes introduced to each power plant. Reinjecting geothermal gas is typically easier in binary plants, because they do not operate under vacuum, which prevents atmospheric air from entering the system. In contrast, flash-type plants often run under vacuum and, while more efficient at using the geothermal resource, flash plants are more susceptible to air ingress. As a result, managing the disposition of NCGs is less complex and expensive, and safer in binary plants.

All future geothermal development should balance efficiency, cost, and environmental compliance. Reinjection of NCGs, particularly CO_2 and H_2S, is increasingly critical for sustainability, yet technical challenges are still present and must be acknowledged by the energy sector – from operators to researchers and consultants. By aligning plant design with appropriate NCG strategies, operators can optimize both performance and environmental responsibility within safe boundaries.

REFERENCES

Carbfix. (2021). *Carbfix Iceland ohf.* Retrieved from https://www.carbfix.com

Coward and Jones. (1952). *Limits of flammability of gases and vapors -- Bulletin 503.* Washington, DC: U.S. Bureau of Mines.

ESMAP. (2016). *Technical Report 009/16, Greenhouse Gases from Geothermal Power Production.*

Goldstein, B. G.-N. (2011). *Geothermal Energy. In IPCC Special Report on Renewable Energy Sources and Climate n [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel,.* Cambridge, United: Cambridge University Press.

Gutiérrez-Negrin, L. (2024). Evolution of worldwide geothermal power 2020–2023. *Geotherm Energy*. doi:https://doi.org/10.1186/s40517-024-00290-w

McIntush, K., Fisher, K., Mamrosh, D., McKaskle, R., Beitler, C., Thrainn, F., . . . Merino, A. (2016). Early-Phase Evaluation of CO2 Recovery at Geothermal Facilities. *Geothermal Resources Council Annual Meeting* (pp. 73-83). Sacramento, CA: GRC Transactions, Vol. 40.

McIntush, K., Mamrosh, D., Beitler, C., & Piggott, B. (2022). Considerations for Alternative Use of Noncondensable Gas at Geothermal Power Plants. *Geothermal Rising Conference* (pp. 1195-1219). Reno, NV: GRC Transactions, Vol. 45.

McIntush, K., Mamrosh, D., Beitler, C., Ryan, A., Piggott, B., Stefánsdóttir, A., & Ketilsson, J. (2025). Flammable Gas Safety When Handling Geothermal Non-Condensable Gas. *Geothermal Rising Conference.* Reno, NV: GRC Transactions, Vol. 49.

National Renewable Energy Laboratory (NREL). (2017). *Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update.*

Olafsdottir, et. al. (2023). Managing Flammable Species in CO2 Capture Processes Utilizing Water Scrubbbing at Geothermal Power Plants. *GRC Transactions, Vol. 47.* Reno, NV.

Piggott, B., McIntush, K., Mamrosh, D., Beitler, C., Morrison, L., Benn, B., . . . Arnarson, M. (2021). Non-Condensable Gas Composition Impacts on Carbon Capture and Water Injection. *Geothermal Rising Conference* (pp. 1414-1435). San Diego, CA: GRC Transactions, Vol 45.

Stefánsdóttir, & Emilsson. (2023). A Systematic Approach to Decrease the Oxygen Gas Concentration at Peistareykir GPP. *World Geothermal Congress.* Beijing, China.

Wikipedia. (2025, September 26). Retrieved from Carbon Recycling International: https://en.wikipedia.org/wiki/Carbon_Recycling_International

Zarrouk, S. (2023). A reivew of non-condensable gases (NCGs) reinjection within the geothermal industry and a comparison with other carbon capture and storage (CCS) technologies. *New Zealand Geothermal Workshop.*