Greenhouse Gas Emissions Reduction: Global Geothermal Power Plant Catalog

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ABSTRACT

Geothermal power generation typically (but not always) results in greenhouse gas emissions as a result of these gases being naturally present in geothermal fluids. Globally, there is an increasing focus on reducing naturally occurring emissions from geothermal electricity generation to contribute to wider decarbonization goals and efforts. Several countries have already implemented carbon emissions pricing, generally as a carbon-dioxide equivalent (CO_2e) value, or are in the process of considering doing so. Three major factors will increase the focus of operators in reducing emissions: (1) increased direct costs due to carbon pricing, (2) societal pressure from the general public, and (3) investment funds or funding institutions with ESG targets that influence the pricing and availability of funding for both new and existing projects.

This paper attempts to catalog details of global geothermal power plants that have meaningful greenhouse gas emissions reduction technologies in place, with details on the methods employed. The authors intend to republish this paper with an updated catalog regularly, and we encourage feedback from readers to ensure this catalog is updated accurately.

1. Introduction

Geothermal power generation is typically a low-emission, reliable and renewable source of electricity that is powered by earth's natural heat. Most geothermal power plants release a small amount (relative to fossil-fueled power plants) of greenhouse gases – primarily carbon dioxide (CO_2) and methane (CH_4). These gases are not created in the geothermal power generation process. Still, they are contained naturally in the fluid from the geothermal reservoir and are then often released as a part of the power generation process. When pressure is reduced, the fluid from the reservoir boils, and due to Henry's law, these gases preferentially move into the steam phase, with minimal amounts retained within the separated geothermal water (also known as brine). The release of the gases from the power generation process is a result of the gases being non-condensable – such that when geothermal steam is condensed in a plant heat exchanger (typically a condenser in a flash plant and a vaporizer or pre-heater in a binary plant) the non-condensable gases remain as gases. In contrast, the steam is condensed into water. These non-condensable gases can interfere with the power generation process by restricting steam flow due to pressure build-up, so they must be removed from the process, and this typically results in them being released to the atmosphere (via a gas extraction system if the gases are at a pressure below atmospheric) and vented above a cooling tower or air cooled condenser to disperse the gases safely.

Several technologies are in use today to reduce gaseous emissions from geothermal power plants, and several drivers for emissions reduction from these power plants are described below.

2. Drivers for emissions reduction

Reducing geothermal emissions to the atmosphere can have multiple benefits, and as a result there are multiple drivers for reducing emissions, including some where emissions reduction is a secondary benefit to a different primary objective.

2.1 Odor nuisance and compliance

Odor nuisance and strict environmental limits on hydrogen sulfide emissions in some jurisdictions have resulted in several geothermal power plants undertaking non-condensable gas (NCG) reinjection where all of the geothermal gases exsolving from the production fluid are reinjected into the reservoir, including carbon dioxide and methane as an alternative to hydrogen sulfide scrubbing systems. The Puna geothermal plant in Hawaii, USA, has been reinjecting all of the non-condensable gases produced at the plant to meet environmental requirements (Richard, 1990) since the plant came online in 1993, whilst the Coso geothermal power plant in California operated with the NCG reinjected for a time to manage hydrogen sulfide emissions before changing to hydrogen sulfide abatement technology in lieu of NCG reinjection (Layman, 2017). The Hellisheidi geothermal plant in Iceland commenced injection of a concentrated hydrogen sulfide stream from its NCGs to meet air emissions requirements, which was known as SulFix, and has grown to also include the injection of carbon dioxide under the CarbFix program (Gunnarsson et al., 2015; Juliusson et al., 2015) with approximately 75% of hydrogen sulfide injected and 30% of carbon dioxide injected (Ragnarsson et al., 2023).

2.2 Greenhouse gas reduction

Given the typically low greenhouse gas emissions associated with geothermal power generation, employing additional technology to further reduce greenhouse emissions is not always seen as the best use of limited resources or is seen to apply risk or costs to the process. However, in jurisdictions with a direct cost of greenhouse gas emissions, such as New Zealand, the installation of greenhouse gas abatement technology has increased significantly over the past few years as emissions prices have increased. In the United States of America, whilst there is no direct cost of greenhouse gas emissions as seen in New Zealand (McLean, 2023; Carmichael and Zarrouk, 2023), there are increasing off-taker requirements observed in power purchase agreements in particular markets such as California which will likely drive continued pricing premiums for new zero carbon emissions geothermal electricity (Ormat, 2024) due to geothermal baseload reliability compared to other renewable zero carbon emission generation technologies such as wind or solar. Future production tax credits (PTCs) or similar appear to be requiring zero carbon emissions geothermal electricity to be eligible (Ormat, 2024).

Risks associated with reducing gas emissions that need to be managed to enable gas emission reductions to occur include, but are not limited to:

- Lower pH in the injected fluid stream whereby gas has been dissolved into, resulting in the increased likelihood of corrosion and, a reduction in the lifespan of the pipeline or well assets and an increased likelihood of reliability concerns. This is often managed through the application of a suitable chemical corrosion inhibitor or in some instances, an increase in the steel quality through the use of more corrosion-resistant alloys.
- The mixing of geothermal gases that include H_2S can result in an increase in the deposition and scaling of mineral deposits in reinjection systems, particularly in the mixing zone itself. Saturation of heavy metal sulfides such as antimony sulfides is common in geothermal reinjection systems where H_2S is dissolved in the reinjection fluid due to the increased sulfide concentration and decreased pH.
- Possibility of building up gas pockets within the injection line or wells, in particular for wells with high injectivity where the pressure of the injected fluid stream can reduce and cause flashing of what was a single-phase fluid stream. These gas pockets can cause challenges with flow dynamics, especially during plant upsets or plant start-ups. Condensation of the gases also poses a risk of low-pH conditions that can cause corrosion, and this is a risk, in particular in wellhead infrastructure for high permeability wells. The risk of gas pockets is often managed by having venting setups at appropriate locations through the pipework to support plant start-up processes.
- Reservoir feedback, particularly if gases are reinjected close to a production area and/or near a steam cap, there is a possibility that gas concentrations in the total production can increase, increasing the potential for calcite scaling in the production well and decreasing power plant efficiency due to the higher NCG content of the production fluid. The quantity of gas can overwhelm the power plant cycle by causing gas concentrations outside the design range of the plant.
- Safety considerations are essential for many emissions reduction systems where concentrated gas mixtures are conveyed at elevated pressure, with geothermal gas mixtures often containing significant concentrations of hydrogen sulfide, which is toxic even at low concentrations. Where gases are separated or purified, the potential of forming flammable gas mixtures also needs to be considered where the concentration of flammable species such as hydrogen and methane are high (Piggot et al., 2021; Olafsdottir et al., 2023)

2.3 Commercial use of carbon dioxide

Processing geothermal non-condensable gases to produce a commercial carbon dioxide product has been undertaken to provide both food and industrial-grade carbon dioxide (Simsek, 2003; Layman, 2017) and also carbon dioxide for greenhouse use (Ngethe and Jalilinasrabady, 2021). While this process may not reduce geothermal greenhouse gas emissions in a strict sense depending on how the captured carbon dioxide is used. The use of geothermal-sourced carbon dioxide may offset the carbon dioxide produced by other means, such as the combustion or production of fossil fuels. Preparing commercial-grade gases from geothermal NCGs requires the removal of the unwanted components of the gas mixture – typically hydrogen sulfide, ammonia, mercury and hydrocarbons – although other unwanted species may also be present. Where the amounts of these unwanted species are low adsorbents may be used to remove them from the bulk gas flow. However, for higher concentrations more complex equipment may be required, such as a complex iron-sulfur recovery system for H_2S, while elevated levels of hydrocarbons may require the use of a catalytic oxidizer (Catox) or Regenerative Thermal Oxidizer (RTO). The removal of gases such as oxygen and nitrogen is likely to require liquefaction and reboiler systems in the purification of carbon dioxide to a high standard.

2.4 Reservoir support

The presence of dissolved gases in geothermal fluid results in a lower boiling point for depth than would otherwise be the case. This typically results in geothermal production wells being easier to flow than if the fluid did not contain dissolved gases (for wells producing 2-phase fluid – a mixture of water and steam) through a lighter column within the wellbore. In lower enthalpy systems, the gas content of the geothermal fluid can be critical in keeping production wells flowing without the need for pumps through the decreased fluid density and lower boiling point for depth that results from the presence of dissolved gases in the reservoir fluid.

2.5 Silica scale prevention (pH modification)

Carbon dioxide has the potential to be used in geothermal brine pH modification systems to reduce silica polymerization and scaling in geothermal reinjection systems. This is often seen in binary-type geothermal power plants where fluid outlet temperatures can be run at a relatively low level without the need for acid addition for pH modification – in this case, the condensate from the binary plant is typically acidic due to the presence of carbon dioxide and hydrogen sulfide, which when mixed with the brine reduced the pH sufficiently to inhibit silica polymerization long enough to return the reinjection fluid to the geothermal reservoir. While this is a benefit of NCG reinjection for both Binary and flash-type power plants, the authors are unaware of any power plants currently operating an NCG reinjection system for the sole purpose of inhibiting silica polymerization in the geothermal brine, however it is noted that this can be a factor in the technology selection process (Addison and Brown, 2012) and NCG reinjection was retained for a time at the Coso geothermal power plant for the purpose brine pH modification after an alternative H_2S abatement system was in service (Layman, 2017).

3. Technologies

There are three main technologies currently in use to reduce greenhouse gas emissions from geothermal power generation. (1) NCG Reinjection, where the gases are redirected into the geothermal reservoir – often dissolved in water but in some cases in a gaseous or supercritical state. (2) Pumped Binary technology – where the greenhouse gases remain dissolved in the geothermal liquid through the production, utilization and reinjection stages, and hence are not released to the atmosphere. (3) Gas purification involves preparing the geothermal gases (typically carbon dioxide) for commercial and industrial uses, such as in greenhouses or the food and beverage industry. Each of these technological approaches is discussed below.

3.1 NCG Reinjection

Non-condensable gas reinjection is a process that redirects the non-condensable gases that have been separated from the geothermal steam and condensate and directs the gas into the reinjection system, where the gas is returned to the geothermal reservoir. This technology can be used at both binary and flash-type geothermal power plants, although it is typically easier and simpler to employ at binary power plants due to more favorable operating conditions. These conditions include the exclusion of oxygen from the gas mixture to minimize corrosion, higher gas pressure that reduces or eliminates the need for gas compression, and often lower reinjection temperatures, which improves the solubility of the gases in the reinjection liquid. When used at binary plants, it is typical to route the NCGs from the vaporizer (or other heat exchanger where the gases would otherwise accumulate) to the reinjection fluid downstream of the preheaters – where the fluid is coldest. If the vaporizer pressure is high enough the NCGs can flow to the reinjection piping without the need for gas compression. For the purposes of this paper, NCG reinjection refers to deliberately routing the NCGs into the reinjection system (active reinjection) and does not refer to NCGs that dissolve in the condensate within the vaporizer (passive reinjection - Ruiz et al., 2021)

NCG reinjection can be applied to flash plants utilizing condensing steam turbines, however some extra design considerations are required. These include ensuring the presence of oxygen in the NCGs is minimized. This would typically require a surface condenser and well-designed and operated turbine gland steam system to minimize air ingress in the systems that operate under vacuum conditions. If a direct contact condenser is used, a system to remove oxygen and nitrogen from the NCG mixture will likely be required to minimize corrosion and breakout pressure issues, respectively. With both surface and direct contact condensing systems, a gas compression system will also be required to increase the NCG pressure to a suitable level for reinjection.

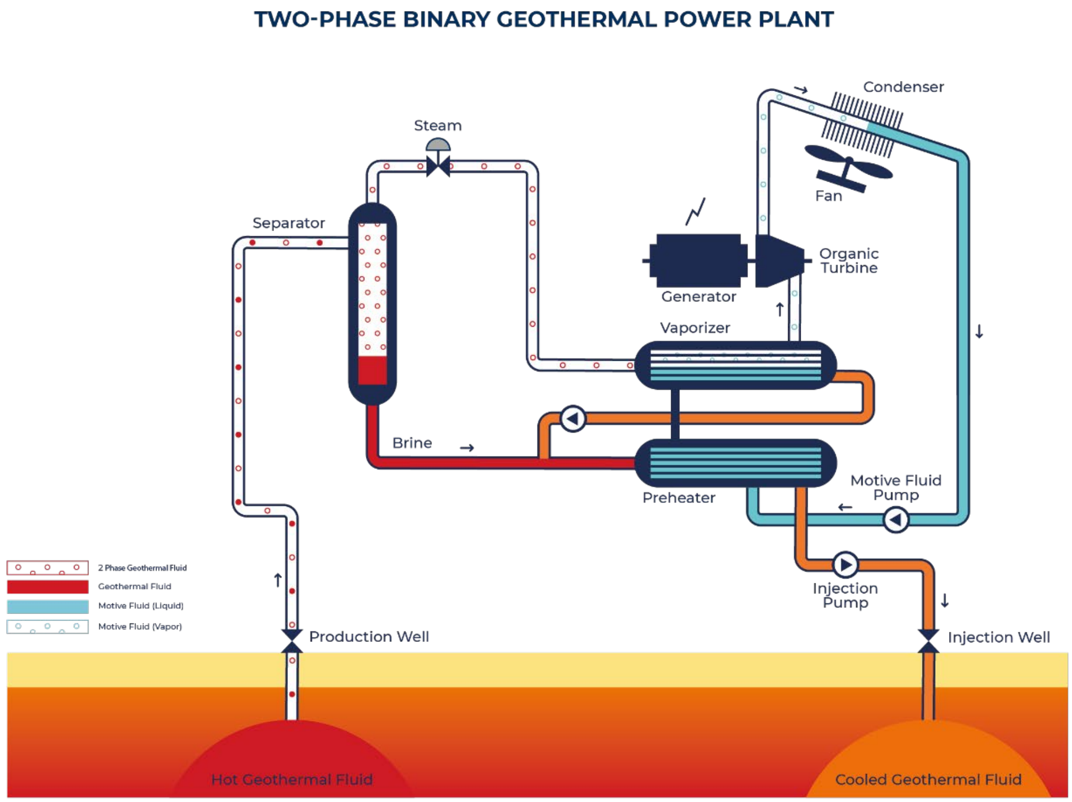

Figure 1: Two-phase Binary schematic

3.2 Pumped Binary

Pumped binary geothermal power plants are often the choice of plant design for low enthalpy and some medium enthalpy geothermal fields. The use of production pumps enables the development of non-artesian resources and can boost production in fields with low production pressures. Pumped binary systems can be temperature and depth limited, with these limitations dependent on pump and well designs as well as field conditions. While pumped binary geothermal power plants are typically zero emission (as described below), emissions may still occur if the geothermal fluid pressure is not maintained. This has been the case where the fluid has been exposed to atmosphere prior to reinjection (Bliem and Walrath), and when artesian systems have been converted to a pumped system while retaining the flash system (separator and steam systems) without implementing NCG reinjection.

Two major technological advancements have occurred throughout time to enable pumped Binary to be the leading technology employed for geothermal greenhouse gas reductions, with numerous power plants utilizing this combination of technology in low-medium enthalpy geothermal fields. The first is the development and evolution of binary power plant technology, with increases in efficiency and unit sizes. The other has been that well pump technology has evolved and become more reliable with the application of pumps increasing over time. Recently, in the United States a number of original power plants on low-medium enthalpy geothermal fields have been repowered with new binary plants and making use of well pump technology, with more to come into the future with a repowered Beowawe facility coming online in 2024 (Ormat, 2023). Through the installation of pumps, the fluid does not flash in the wellbore or pipeline process, and therefore, any dissolved gases are kept in solution. This process is shown in the schematic in Figure 2. Pressures throughout the cycle are maintained at a suitably high level, and after energy extraction occurs through heat exchangers, the solubility of the gases increases as the temperature of the fluid is decreased, providing the ability to reduce pressures in the injection system without gas breakout occurring.

Lifecycle costs of the pumps tend to generally result in the installation of line-shaft pumps (LSPs) rather than electrical submersible pumps (ESPs). Cases where ESPs are utilized over LSPs are rare, except for where the well was deviated at a shallow depth and therefore LSPs cannot be utilized, or, where the depth required for the pump is extremely deep due to limited permeability in the wells formation or a deep water table. The primary reason for the lifecycle costs of LSPs being generally lower than ESPs is the operational lifespan between pump failures, with the main driver of this being that LSPs have electronic infrastructure on the surface rather than downhole.

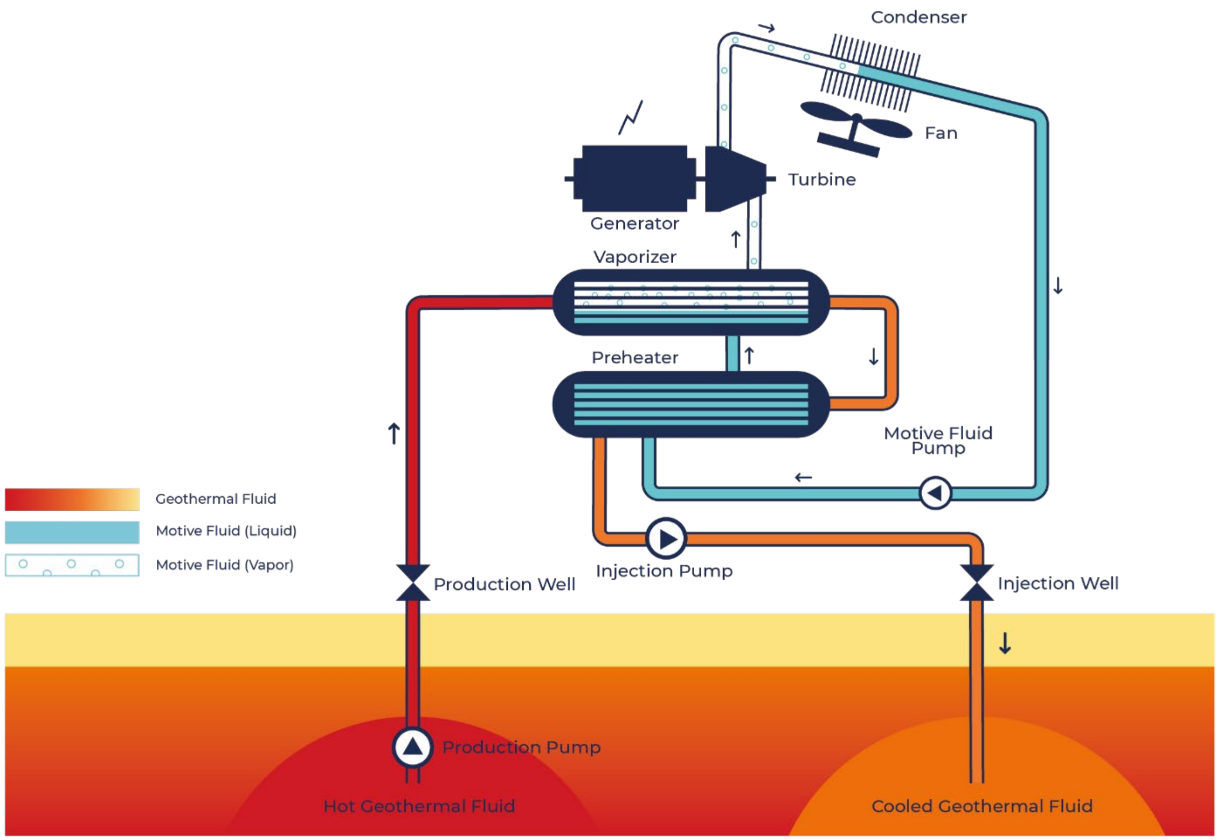

Figure 2: Pumped Binary schematic

3.3 Gas purification and reuse

Gas purification and reuse involves using one or more of the gases in the non-condensable gas mixture (typically carbon dioxide, although methane can also be captured for later use) for commercial or industrial use. The composition of a given NCG mixture and the intended downstream use will determine the various processing steps required to produce a gas that is commercially useful. Production of carbon dioxide suitable for industrial or food-grade use from geothermal sources may require significant processing, with removal materials found in geothermal such as hydrogen sulfide, ammonia, mercury, methane, non-methane hydrocarbons, nitrogen, hydrogen and argon (as well as oxygen if air ingress there is air ingress into the gas system) all having to be removed to a very high standard. It may often be the case that very high concentrations and volumes of carbon dioxide are required for a purification plant to be financially viable in addition to being located close to potential customers. For horticultural use, the required treatment may be reduced, especially where the presence of nitrogen and oxygen are of little consequence.

4. Examples

4.1 NCG Reinjection

4.1.1 Puna, Hawaii USA

The Puna geothermal power plant was commissioned in 1993 and is located on the Big Island in Hawai'i, USA. The stringent permitting conditions for the Puna power plant require that no hydrogen sulfide geothermal emissions are released from the power plant to alleviate concerns about impacts from nearby residents (Richard et al., 1989; Richard, 1990). This resulted in the design and installation of a 100% NCG reinjection system. The system involves collecting the NCGs from the vaporizers of the binary plants that receive the exhaust steam from the steam turbines. A gas compressor is used to increase the pressure of the gases such that they can be mixed with the geothermal brine and condensate that is also used in the power plant. This results in a 100% reinjection system, where all the geothermal brine, condensate and gases are returned to the reservoir. This system has been operating successfully since the plant was originally commissioned.

4.1.2 Carbfix, Hellisheidi, Iceland

The Carbfix project in Iceland is perhaps one of the best-known examples of NCG reinjection and greenhouse gas emissions reduction in the geothermal industry and is well reported in the literature. The Carbfix project aims to reduce greenhouse gas emissions by the reinjection of carbon dioxide into reactive rock formations where it can react and form stable minerals, thus avoiding emissions to the atmosphere. Commissioned at scale in 2014 at the Hellisheidi geothermal power plant (Aradottir et al., 2021), the Carbfix process has several key differences from most other geothermal NCG reinjection projects, including the use of either ground water (Carbfix 1) to dissolve the geothermal gases (although geothermal fluid can be used if there is a sufficient quantity available as was the case at Hellisheidi for Carbfix 2), and the use of a gas absorber - although this aspect is also used at Verkhne-Mutnovsky (Povarov and Nikolskyi, 2005) to promote dissolution of highly soluble gases (carbon dioxide and hydrogen sulfide) while allowing for the venting of poorly soluble gases (such as methane and hydrogen). The use of non-geothermal water sources also allows for the geothermal gases to be reinjected outside of the geothermal reservoir, as long as the geology is suitable for the mineralization of the gases.

The Carbfix process, while more complex than some other NCG reinjection systems, enables more flexibility in the composition of NCG mixtures that can be used, and the type of geothermal plants that the process can be used with (potentially plants with direct contact condensers) as a result of the ability to largely remove poorly soluble gases from the gas stream.

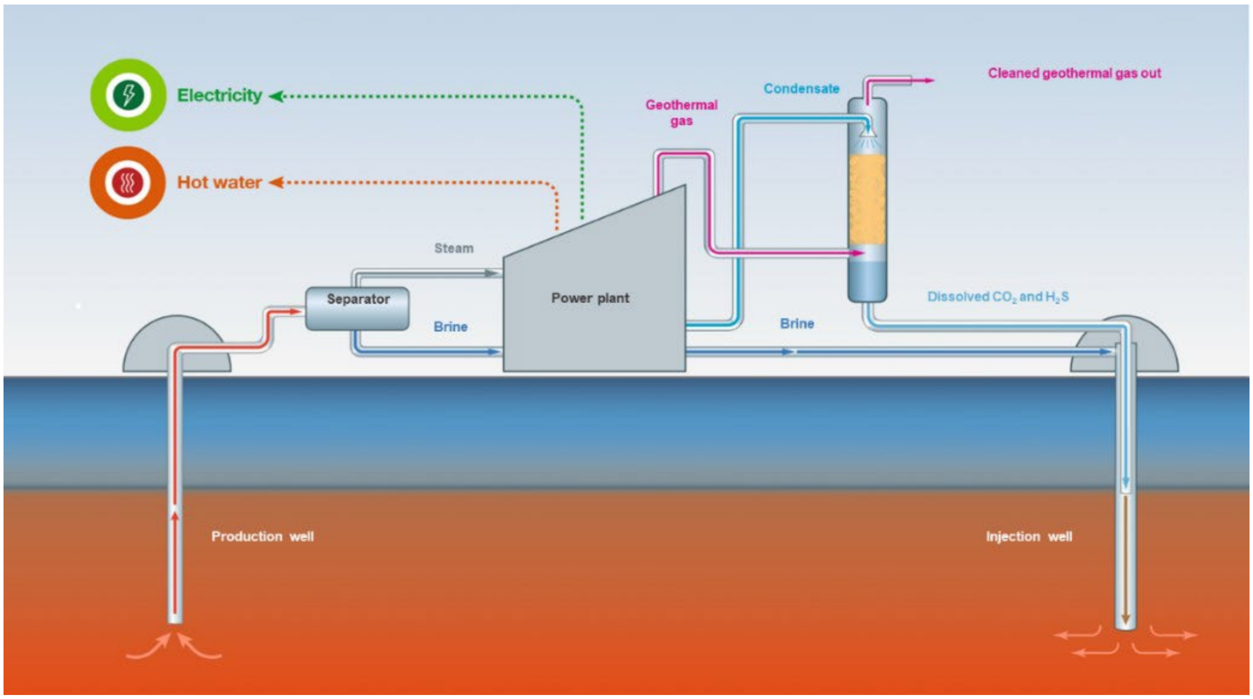

Figure 3: Basic Schematic of the Carbfix 2 process at Hellisheidi (from Aradottir et al., 2021)

4.1.3 Te Huka, Tauhara, New Zealand

The Te Huka geothermal power plant was commissioned in 2012 and is located in New Zealand and consists of two binary units utilizing geothermal brine and steam from the Tauhara geothermal field to produce a total of 25 MWe net. Under normal operating conditions the Te Huka plant released ~9,200t CO_2e per year as NCGs that did not naturally dissolve on the steam condensate under vaporizer conditions were vented to the atmosphere. In 2020, a project was commenced to reduce greenhouse gas emissions from geothermal generation by the plant's operator Contact Energy, which resulted in a redesign of the NCG venting system. Commissioning in 2022 this system resulted in a new NCG handling system to redirect the NCG flow from the atmosphere to the liquid reinjection system for the plant, where the NCGs are mixed with, dissolved into the reinjection liquid, and reinjected back into the geothermal reservoir. This enabled all of the gaseous emissions from the power plant to be reinjected as the plant conditions allowed for all of the gases to be dissolved in the surface equipment prior to reinjection, eliminating gas (and greenhouse gas) emissions from the power plant. The original design of the binary plant made these modifications relatively simple, with no gas treatment or compression required (Richardson et al., 2023).

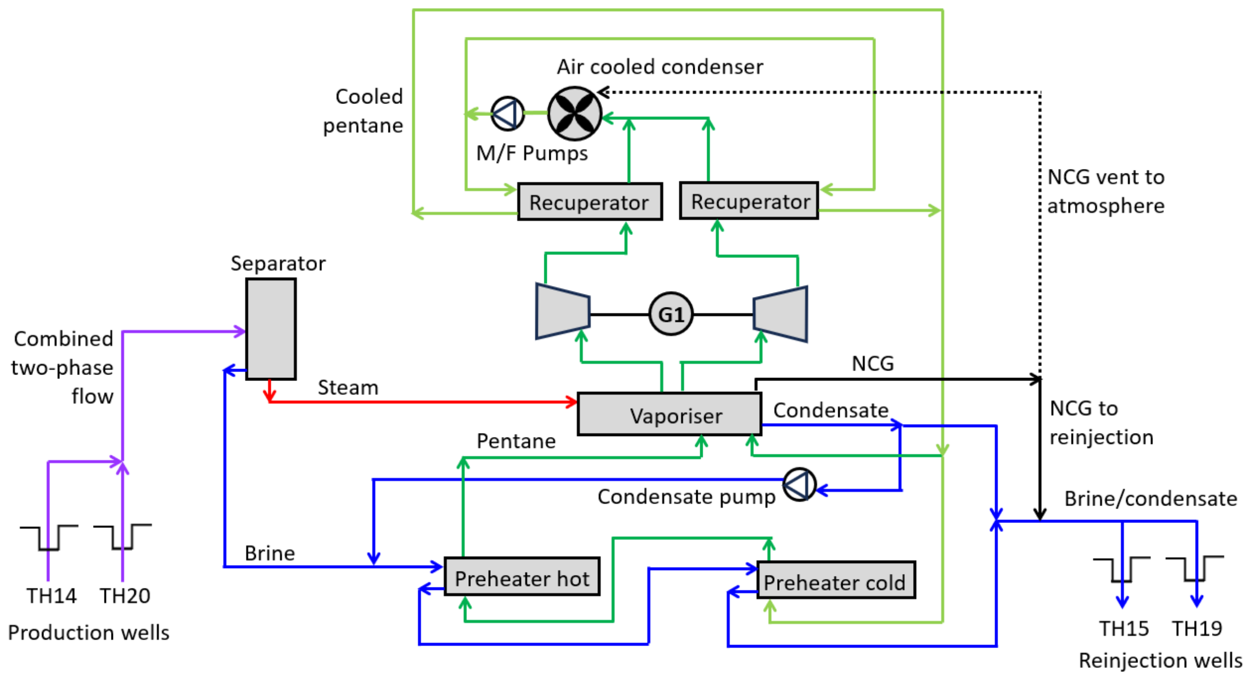

Figure 4: Te Huka flow schematic with NCG Reinjection (from Richardson et al., 2023)

4.2 Pumped Binary

4.2.1 McGinness Hills, Nevada USA

The McGinness Hills Geothermal Complex commenced generation in 2012, with three separate geothermal power plants in operation. The second plant came online in 2014, and the third in 2018. As of 2024 fields total capacity was 146 MW. All production wells make use of line-shaft pumps, which maintains pressure and prevents flashing. Therefore, the power plant has no separation equipment and throughout the whole process all gases are kept in solution.

4.2.2 Steamboat, Nevada USA

The Steamboat Geothermal Complex commenced its generation in 1986, with Steamboat 1 as a pilot project, and Steamboats 2 and 3 coming online in 1992. Significant development occurred over time on the field, with Ormat's subsequent consolidation of ownership. There are now 5 geothermal power plants operating as of the start of 2024 with a nameplate capacity of 79 MW, all featuring zero greenhouse gas emissions technology using binary power plants. The final major change in the field occurred in 2020 with the repower of the Steamboat Hills power plant with the binary Steamboat Hills Repower (Ormat, 2021).

Over time, numerous wells have been modified to pumped wells, with most of the Steamboat Hills section of the field having previously been all artesian wells historically, and these were almost all converted to pumped wells as part of the Steamboat Hills Repower (Akerley et al., 2021). Where good permeability was proven and economics allowed for it, new wells were drilled to enable the installation of line-shaft pumps. Where this was not the case and wells had a shallow kick-off point or smaller casing, electric submersible pumps were installed. As of the start of 2024 only one artesian well remains on the field, well 24-5, and this feeds the Galena 2 plant then has infrastructure is designed to prevent any emissions from this well with a downhill pipe run to increase pressure by the time the fluid reaches the power plant and mixing with numerous pumped wells.

Figure 3: The original Steamboat Hills powerplant that was replaced with the new binary Steamboat Hills Repower in 2020.

4.3 Carbon Dioxide Reuse

Carbon dioxide reuse is a way to generate value from what would otherwise be a waste product from geothermal power generation. Perhaps the largest reuse of geothermal carbon dioxide can be found in Türkiye at the Kizildere facility operated by Zorlu Energy. The Kizildere 1 geothermal power plant was commissioned in 1984 and generated 18 MW of electricity. However, power generation in the field has increased substantially with the commissioning of Kizildere 2 and Kizildere 3. Kizildere delivers a part of its non-condensable gas flow to an adjacently located Linde gas processing plant, which uses the carbon dioxide contained in the NCG flow to produce high-purity carbon dioxide for commercial and industrial use. The high concentration and volume of carbon dioxide produced in the Kizildere geothermal plant (up to 99% of the non-condensable gas) results in a simpler, and more efficient processing system than would likely be required in many other geothermal fields to produce high-purity carbon dioxide.

Similar carbon dioxide recover plants were also in use at the Dora geothermal facilities in Türkiye. However, these were removed when the volume of gas from the power plants decreased to the point recovery was uneconomic, at which point gas reinjection was commenced (Asnük, 2024).

At the Svartsengi geothermal field in Iceland CO_2 from the NCG stream from the Svartsengi power plant is utilized to produce methanol (Ragnarsson 2023), at Carbon Recycling International's George Olah facility. While geothermally sourced carbon dioxide has been used for horticulture in Kenya, where the Oserian flower farm used carbon dioxide from the Olkaria geothermal system to support plant growth and increase output in its greenhouse operations (Ngethe and Jalilnasrabady, 2021).

5. Table of Power Plants with Greenhouse gas emissions abatement technology

This table is published with ownership and generation details as of 1 January 2024. This table excludes: temporary trials such as Umurlu, (Yucetas et al., 2018); plants that have ceased greenhouse gas abatement processes (e.g. Coso); plants smaller than 5 Mwe net in size; plants that are bottoming units or brine-only units; and, facilities that utilize geothermal CO_2 but do not generate electrical power (eg Haedarendi). This table is focused on greenhouse gas emissions abatement; for general emissions abatement from geothermal power plants Lenzi et al. (2021) provides a comprehensive overview.

Table 1: Details of facilities with Greenhouse gas emissions reduction practices in place as of 1 January 2024

Country	Field	Operator	MW	Emissions Reduction	Plant Type	Emissions Reduction Technology	Comments and References
USA	San Emidio	Ormat	39	Full	Binary	Pumped Binary	Includes San Emidio and North Valley plants
USA	Don A. Campbell	Ormat	30	Full	Binary	Pumped Binary	DAC1,2
USA	McGinness Hills	Ormat	146	Full	Binary	Pumped Binary	MGH1,2,3
USA	Steamboat	Ormat	79	Full	Binary	Pumped Binary and NCG Reinjection	Pumped Binary: Galena 1,3, Steamboat 2/3 and Steamboat Hills Repower Pumped binary and NCG Reinjection: Galena 2 has artesian well 24-5 as well as pumped wells
USA	Jersey Valley	Ormat	8	Full	Binary	Pumped Binary	
USA	Tuscarora	Ormat	17	Full	Binary	Pumped Binary	
USA	Tungsten	Ormat	41	Full	Binary	Pumped Binary	
USA	Raft River	Ormat	12	Full	Binary	Pumped Binary	
USA	Neal Hot Springs	Ormat	22	Full	Binary	Pumped Binary	
USA	Heber	Ormat	91	Full	Binary	Pumped Binary	Heber 1,2,South
USA	Ormesa	Ormat	36	Full	Binary	Pumped Binary	Field formerly known as East Mesa, consists of three separate plants: Ormesa 1,2,3
USA	Mammoth	Ormat	65	Full	Binary	Pumped Binary	G1,2,3, CD4
USA	Puna	Ormat	38	Full	Binary	NCG Reinjection	Conducted to prevent H_2S ambient discharge
USA	Stillwater	ENEL	12	Full	Binary	Pumped Binary	Acquired by Ormat in January 2024 - has some artesian wells but kept under pressure
USA	Salt Wells	ENEL	9	Full	Binary	Pumped Binary	Acquired by Ormat in January 2024
USA	Cove Fort	ENEL	18	Full	Binary	Pumped Binary	Acquired by Ormat in January 2024
USA	Blue Mountain	Cyrq	49.5	Full	Binary	Pumped Binary	
USA	Thermo	Cyrq	14.5	Full	Binary	Pumped Binary	
USA	Soda Lake	Cyrq	26.5	Full	Binary	Pumped Binary	
USA	Patua	Cyrq	48	Full	Binary	Pumped Binary	
USA	Lightning Dock	Cyrq	15.3	Full	Binary	Pumped Binary	Acquired by Zanskar in July 2024
USA	Star Peak	Open Mountain Energy	14	Full	Binary	Pumped Binary	

Country	Field	Operator	MW	Emissions Reduction	Plant Type	Emissions Reduction Technology	Comments and References
Russia	Mutnovsky	Geotherm JSC (PJSC RusHydro)	12	Full	Flash	NCG Reinjection	Povarov and Nikolskiy (2005)
New Zealand	Tauhara	Contact Energy	25	Full	Binary	NCG Reinjection	Te Huka plant NCG Reinjection commenced November 2022, Richardson et al. (2023)
New Zealand	Nga Tamariki	Mercury	82	Partial	Binary	NCG Reinjection	NCG Reinjection on one of four units, Ghafar et al. (2022)
New Zealand	Ngawha	Ngawha Generation (Top Energy)	57.5	Full	Binary	NCG Reinjection	NCG Reinjection commenced August 2022, Hanik (2024)
Iceland	Hellisheidi	ON Power (Reykjavik Energy)	303	Partial	Flash	NCG Reinjection	Carbfix, Gunnarsson et al. (2015)
Iceland	Nesjavellir	ON Power (Reykjavik Energy)	120	Partial	Flash	NCG Reinjection	Pilot plant, Carbfix (2024)
Iceland	Svartsengi	HS Orka	76	Partial	Flash	CO_2 Recovery	Methanol Production, Ragnarsson et al. (2023)
Türkiye	Babadere	MTN Energy	8	Full	Binary	Pumped Binary	
Türkiye	Kizildere	Zorlu	260	Partial	Flash	CO_2 Recovery	CO_2 utilized for commercial and industrial use, Simsek (2003), Layman (2017)
Türkiye	Salavatli	MEGE	18	Partial	Binary	Pumped Binary and NCG Reinjection	Asnük (2024)
Türkiye	Bukarkent	Limgaz	14	Full	Binary	Pumped Binary	Mertoglu and Basarir (2018)
Honduras	Platanares	Ormat	33	Full	Binary	Pumped Binary	
Germany	Dürrnhaar	Stadtwerke München	5.5	Full	Binary	Pumped Binary	
Germany	Kirchstockach	Stadtwerke München	5.5	Full	Binary	Pumped Binary	
Germany	Sauerlach	Stadtwerke München	5	Full	Binary	Pumped Binary	Bonafin (2021)
Germany	Traunreut	Equitix	5.5	Full	Binary	Pumped Binary	

6. Conclusions

While there are currently a significant number of geothermal power plants with greenhouse gas emissions reduction technology, this is dominated by pumped binary systems where the greenhouse gases remain in solution within the geothermal fluid throughout the power generation process. There are far fewer power plants where gases that have separated from the geothermal fluid are actively redirected into the reinjection process and examples of these plants are currently favored in binary plants due to the simplicity of adapting this process to typical binary plant designs. NCG reinjection in flash plants is more challenging both technically and economically. However as demonstrated in Iceland and Russia this technology is viable and likely to grow, particularly in jurisdictions where there is a significant benefit to greenhouse gas emissions reduction through a carbon price or other incentives. There are also plans for more commercial use of geothermally sourced carbon dioxide among geothermal plant operators as this is seen as an opportunity in some markets, and a potential requirement in others.

The use of carbon pricing, such as direct pricing in New Zealand, or indirectly through power purchase agreements like in California in the US, is driving more action towards zero greenhouse emission geothermal power plants. As other markets create either direct or indirect incentives, we expect significant increases to occur over time in the amount of geothermal power plants reducing their greenhouse gas emissions. The rapid pace of development of zero greenhouse emission geothermal power plants in New Zealand is an example where a market pricing incentive has resulted in outweighing risks associated with the activity, resulting in a significant deployment in a relatively short period time, generally as a function of a significant carbon price increase.

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REFERENCES

Addison, S.J. and Brown, K.L. (2012), "Ngatamariki Test Rig Results and Findings", *Proceedings New Zealand Geothermal Workshop*

Akerley, J.; Eilan, B., Selwood, R., Darf, N. and Canning, B. (2021), "Drilling Challenges and Pumping Innovations for the Steamboat Hills Enhancement" *GRC Transactions, Vol. 45*

Askoy, N.; Gok, O., Mutlu, H. and Kilinc, G. (2021), "Drilling Challenges and Pumping Innovations for the Steamboat Hills Enhancement" *Proceedings World Geothermal Congress*

Asnük, B. (2024) *Personal Communication*

Aradottir, E., Sigfusson, B., Snaebjornsdottir, S., Marnarson, M., Ratouis, T., Helgason, K., Bragadottir, R., Clark, D., Marieni, C., Voigt, M., Gunnlaugsson, E., Elkers, E. and Gislason, S. (2021), "Carbfix – Rock Solid Climate Action", *Proceedings World Geothermal Congress*

Bliem, C. and Walrath, L. (1983) "Raft River Binary-Cycle Geothermal Pilot Power Plant Final Report" Idaho National Engineering Laboratory, *United States Department of Energy*

Bonafin, J. (2021), "Update on European Geothermal Binary Units Delivered by Turboden", *Proceedings World Geothermal Congress*

Carbfix (2024) https://www.carbfix.com/geothermalenergyccs

Carmichael, A. and Zarrouk, S. (2023) "A Review of Non-Condensable Gas (NCGs) Reinjection Within The Geothermal Industry and a Comparison With Other Carbon Capture and Storage (CCS) Technologies" *Proceedings New Zealand Geothermal Workshop*

Choudhary, A., Burnell, J., Hinkley, J., Elias, A. & Rayudu, R. (2021). "Reinjection as a solution to greenhouse gas emissions from high emitting geothermal power plants in New Zealand", TENCON 2021 - 2021 IEEE Region 10 Conference

Ghafar, S., Allan, G., Ferguson, A., Siega, F., Rivera, M.and Murphy, B. (2022) "Non Condensable Gas Reinjection Trial at Ngatamariki Geothermal Power Plant", *Proceedings New Zealand Geothermal Workshop*

Gunnarsson, I., Juliusson, B., Aradottir, E., Sigfusson, B. and Arnarson, M. (2015), "Pilot Scale Geothermal Gas Separation, Hellisheidi Power Plant, Iceland", *Proceedings World Geothermal Congress*

Hanik, F. (2024) *Personal Communication*

Juliusson, B.M., Gunnarsson, I., Matthiasdottir, K.V., Markusson, S.H., Bjarnason, B., Sveinsson, O.G., Gislason, T. and Thorsteinsson, H.H. (2015) "Tackling the Challenge of H2S Emissions", *Proceedings World Geothermal Congress*

Layman, E. (2017), "Geothermal Projects in Turkey: Extreme Greenhouse Gas Emission Rates Comparable to or Exceeding Those from Coal-Fired Plants", *Proceedings 42nd Workshop on Geothermal Reservoir Engineering,* Stanford.

Lenzi, A., Paci, M., Tryggvadottir, L., Gunnarsson, T. and Ragnarsdottir, K. (2021) "Overview of Global Existence of Pollutant and GHG Abatement Facilities in GPPs", *Proceedings World Geothermal Congress*

McLean, K., Montague, T., Alcaraz, S., Daysh, S., Doorman, P., Luketina, K., Tsui, K., White, B. and Zarrouk, S. (2023) "2020-2023 New Zealand Country Update", *Proceedings World Geothermal Congress*

McLean, K. and Richardson, I. (2020), "Geothermal greenhouse gas emissions in New Zealand in 2020: lifecycle and operational emissions", *Proceedings New Zealand Geothermal Workshop*

Mertoglu, O. and Basarir, N. (2018) "Geothermal District Heating and Power Generation Experience in Turkey", *Proceedings European Geothermal Workshop*

Mountain, B., Sajkowski, L. and Rendel P.M. (2022), "CO_2 as an Effective Silica Scaling Inhibitor during Reinjection of Acid-Dosed Geothermal Brines: An Experimental Study", *Goldschmidt Conference* <https://doi.org/10.46427/gold2022.12707>.

Ngethe, J. and Jalilinasrabady, S. (2021), "Optimisation of Geothermal Greenhouses Design for Kenyan Fresh-cut Flower", *Proceedings Workshop on Geothermal Reservoir Engineering,* Stanford.

Olafsdottir, K., Gudmundsson, Y., Mamrosh, D., McIntush, K., Ryan, A., Piggott, B.,and Beitler, C. (2023) "Managing Flammable Species in CO_2 Capture Processes Utlilizing Water Scrubbing at Geothermal Power Plants" *GRC Transactions, Vol. 47*

Ormat (2020) https://investor.ormat.com/news-events/news/news-details/2020/Steamboat-Hills-Geothermal-Power-Plant-Enhancement-in-Nevada-Begins-Commercial-Operation/default.aspx

Ormat (2023) https://investor.ormat.com/news-events/news/news-details/2023/Ormat-Resumes-Operation-at-Its-Heber-1-Power-Plant-in-California-and-Completes-Expansion-of-the-Dixie-Valley-Power-Plant-in-Nevada/default.aspx

Ormat (2024) https://s1.q4cdn.com/231465352/files/doc_presentations/2024/Jun/20/Ormat-AD-Final-for-printing.pdf

Povarov, O. and Nikolskiy, A. (2005), "Experience of Creation and Operation of Geothermal Power Plants in Cold Climate Conditions", *Proceedings World Geothermal Congress*

Piggott, B., McIntush, K., Mamrosh, D. and Beitler, C. (2021), "Non-Condensable Gas Composition Impacts on Carbon Capture and Water Injection", *GRC Transactions, Vol. 45*

Ragnarsson, A., Steingrimsson, B. and Thorhallsson, S. (2023) "Geothermal Development in Iceland 2020-2022", *Proceedings World Geothermal Congress*

Richard, M.A., Carey, D.L. and Russel, J.S. (1989) "Environmental Mediation and the Development of the Puna Geothermal Venture Project: Hawaii Tries a New Regulatory Process to Unlock a Decade of Confrontation", *GRC Transactions, Vol. 13*

Richard, M.A. (1990), "The Puna Geothermal Venture Project Power for the Island of Hawaii", *GRC Transactions, Vol. 14*

Richardson, I., Misa, T., Mclean, K., Castillo-Ruiz, N., Ferguson, A., Moodabe-Smith, V., Peral, D. and Wootton, D. (2023), "Non-Condensable Gas Reinjection at the Te Huka Geothermal Power Plant", *GRC Transactions, Vol. 47*

Ruiz, N.C., McLean, K., Richardson, I., Misa, T., Ferguson, A., Altar, D., and Kaya, E. (2021). "Passive NCG Reinjection at Te Huka Geothermal Binary Power Plant" *Proceedings New Zealand Geothermal Workshop*

Yucetas, I., Ergicay, N. and Akin, S. (2018), "Carbon Dioxide Injection Field Pilot in Umurlu Geothermal Field, Turkey", *GRC Transactions Vol 42*