CO_2 emissions from geothermal power plants: evaluation of technical solutions for CO_2 reinjection

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ABSTRACT

Geothermal utilization for power production, may result in some greenhouse gas emissions. Non condensable gases (NCG) are naturally present in most of geothermal fluids. The dominant is carbon dioxide (CO_2), typically constituting more than 95 percent of the total NCG content. CO_2 emission from geothermal power plants is generally small in comparison to traditional base load thermal energy power generation facilities.

However, as the geothermal sector has expanded, a wider range of geothermal resources have been brought into exploitation, including geothermal systems with relatively high CO_2 concentrations in the reservoir fluid.

Binary (ORC) geothermal plants can offer an effective solution to avoid emissions of CO_2 in the atmosphere. The CO_2 can be collected under pressure at the outlet of the ORC vaporizer, and then compressed and reinjected together with the liquid in the reinjection well.

Subject of the paper is the evaluation of the state of the art solution for CO_2 compression and reinjection in the reservoir, with implications on the equipment employed and environmental benefits.

1. INTRODUCTION

Geothermal energy is a renewable energy source employed for power production or directly for heating. The exploitation of geothermal resources may lead to greenhouse gases (GHG) emission, due to the non-condensable gases (NCG), contained in the geothermal fluid. These gases are referred to non-condensable since they do not condensate at the same condition of water vapour, but remain in the gas phase; they are composed mainly (typically more than 95%, ESMAP Technical Report (2012)) by carbon dioxide, which is often released in the atmosphere after passing through the power plant together with the geothermal fluid. The GHG emission is generally smaller if compared to traditional power plants, such as oil, gas or coal-fired plants; however, the geothermal sector has expanded in the last years, and geothermal reservoirs with high NCG content have been brought into exploitation. Bertani and Thain (2002) estimated that the average global CO_2 emission factor is 122 g/kWh; this value is lower in Iceland and in California, where the average is 34 g/kWh 107 g/kWh respectively. In Italy, the emission factor is generally rather high, ranging from 100 to 950 g/kWh, and in Turkey it can reach 1.300 g/kWh, for example in the Gediz graben.

The difference of these emission factors is based on the chemical composition of the host rocks of the geothermal system: Italy and Turkey have in common the presence of carbonate bearing rocks, Iceland geothermal reservoir instead are mainly composed by igneous rocks, which contains less carbonate, and thus release less CO_2.

The emission factors of geothermal power plants located in Italy or in Turkey can be higher than the emission factor of a coal-fired power plant, which can range between 750 and 1.050 g/kWh, World Bank (2015). Thus, the main objective of NCG reinjection is the reduction of the environmental footprint of the geothermal power plant. Furthermore, it has been observed that the NCG reinjection has positive effects on the reservoir, Stefánsson (1997) and Kaya et Al. (2011): the NCG reinjection sustain the reservoir pressure, enhance the well productivity and reduces the pH, thus inhibiting the silica scaling. Moreover, credit institutes and banks are more willing to finance project with low GHG emissions, thus the reinjection makes the financing of the construction of the power plant easier.

The energy conversion technology available for geothermal power production are mainly back pressure plants, condensing plants, two-phase flashing binary plants and single-phase pumped binary plants.

The choice of the energy conversion technology depends on several factors, such as the resource temperature, pressure, flow rate and chemical composition, see Table 1. The back pressure, condensing and two-phase binary processes use steam, which rises from the production well since the pressure in the reservoir is higher than the pressure at the production well, whereas the single-phase binary uses liquid only, and often submersible pumps are required to extract the geothermal fluid.

Table 1: Energy conversion technology depending on the resource temperature.

Plant type	< 150°C ÷ 180°C	180°C ÷ 200°C	> 200°C
Back pressure			x
Flash condensing			x
Two-phase binary	x	x	x
Single-phase (pumped) binary	x	x	

In a back pressure power plant, the steam and the NCG expand in the turbine after the flash in a separator, and the exhaust gases are released in the ambient at atmospheric pressure; this kind of plant is rarely employed (1% only of the global geothermal power capacity, GEA (2015)).

In the flash condensing plant, the expanded steam and NCG are condensed in a cooling system, in order to increase the expansion ratio through the turbine; roughly, the 84% of the global installed capacity is based on this latter method, GEA (2015).

The two-phase and single-phase binary power plants use the geothermal fluid to heat the working fluid, which is then expanded in a turbine. In the two-phase power plant, the working fluid is heated by geothermal fluid both in steam and in liquid phase, while in the single-phase power plant only geothermal water in liquid phase is present. Binary plant are the 15% of the total installed capacity, GEA (2015). The NCG exit the heat exchangers at a pressure close to the inlet pressure of the heat exchangers, and the temperature is generally low (60 ÷ 80 °C); the NCG from back pressure and condensing power plant exit the process at about 1 bar and 100°C. Hence, the NCG from a binary power plant are better suited for reinjection, if compared to NCG from back pressure and condensing power plant, Verkís (2015).

In the case if single-phase binary power plant, the NCG remain dissolved in the brine and are often reinjected totally in the reservoir, thanks to the submersible pumps. However, these pumps are usually a critical component due to the high temperature operating conditions and, the higher the NCG content in the geothermal water, the higher must be the design pressure to keep the NCG dissolved in the liquid phase. Hence, the pumps may consume a substantial fraction of the generated power. When the NCG content is high, an alternative solution to the use of submersible pumps should be found.

In this paper, we focus mainly on the NCG reinjection in the case of two-phase and single-phase binary ORC power plant. The following Section reports a brief explanation of this technology.

2. ORC BINARY GEOTHERMAL POWER PLANT

The Organic Rankine Cycle turbogenerator uses the geothermal fluid to preheat and vaporize a suitable organic working fluid, which is expanded in the turbine. Organic fluids have different thermodynamic characteristics, if compared to water, and they make possible and cost-effective the exploitation of low to high enthalpy geothermal reservoir.

Fig. 1 shows the temperature-entropy diagram of a general thermodynamic cycle of the ORC, and Fig. 2 shows schematically the ORC binary loop. The organic working fluid is pumped (1>2) into the recuperator (2>3), where it is heated before entering the evaporator (3>4>5); here the geothermal source, (mix of brine and steam or only brine coming up from the production well) is cooled through the heat exchangers, giving heat to the working fluid which flows inside an independent loop. The cooled geothermal source can be reinjected entirely. The hot working fluid passes through the turbine (5>6), which is directly coupled to the electric generator, resulting in reliable electric power. The exhaust organic vapour flows through the regenerator (6>7), where it heats the organic liquid (2>3) and then enters the condenser (with water or air) where it is condensed by the cooling circuit (7>8>1), thus completing the closed-cycle operation.

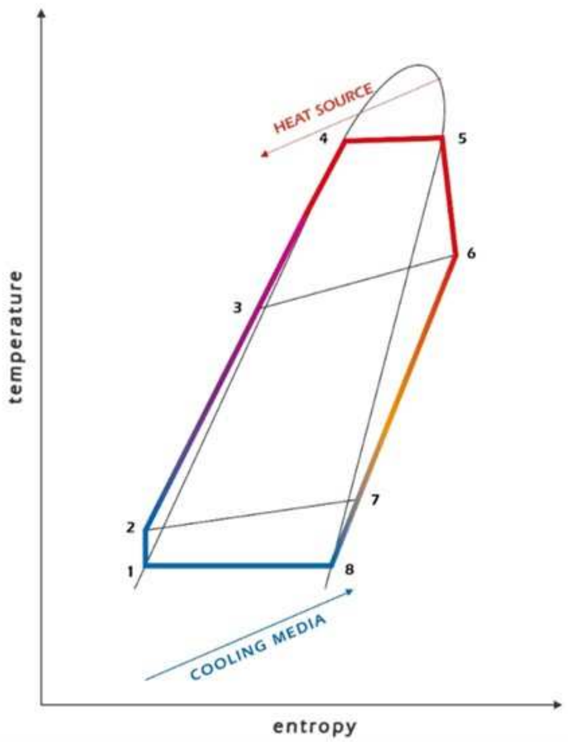

Figure 1: Temperature vs Entropy diagram of a general ORC thermodynamic cycle.

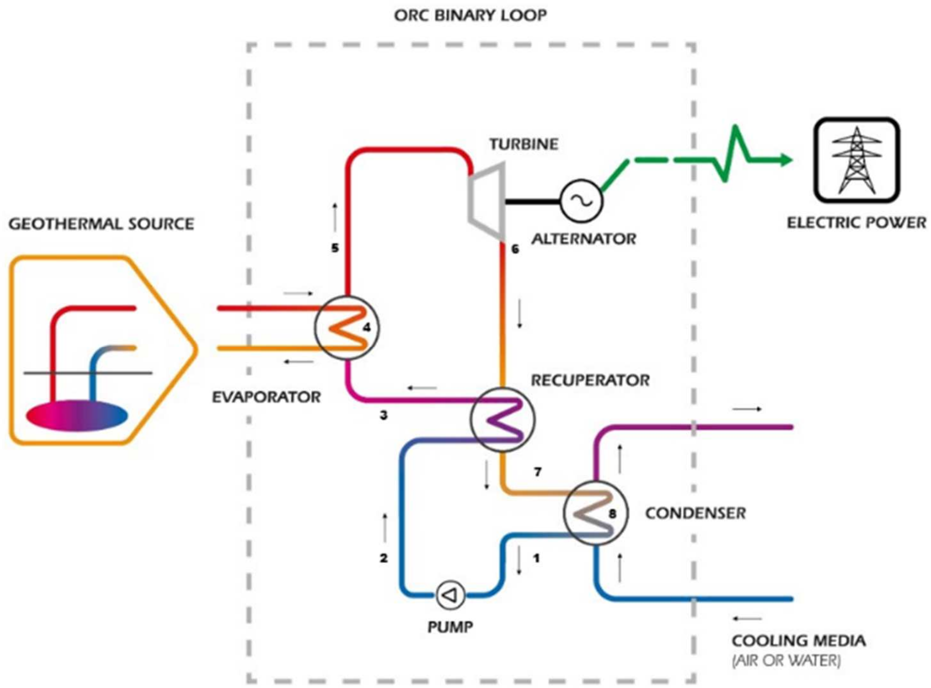

Figure 2: Schematic representation of the ORC binary loop.

The ORC conversion efficiency depends on the type of geothermal reservoir, see Fig. 3. The ORC efficiency is computed as the net power output divided by the total thermal input. In the case of high enthalpy field, the ORC efficiency can go significantly beyond 20%; moreover, the organic fluid make possible the cost-effective exploitation of low enthalpy geothermal reservoir.

ORC EFFICIENCY	TYPE	HEAT CARRIER	Reinjection Conditions
23%	High enthalpy field (>1500 kJ/kg)	Geothermal brine + steam (15-20%) 190° C	Brine + Condensate >90° C
	e.g. Geothermal fields in NZ		
16%	Liquid dominated (800 kJ/kg)	Geothermal brine + steam (5%) 160° C	Brine + Condensate 70° C
	e.g. Geothermal fields in Turkey		
13%	Pumped geothermal system	Geothermal water 140° C	Water 50° C
	e.g. Geothermal basin in Germany		

Figure 3: ORC efficiency depending on the geothermal source.

3. NCG REINJECTION SUCCESSFUL CASES

At present, NCG reinjection has been applied in few cases; two effective experiences can be found at Hellisheiði (Iceland) geothermal power plant, in the frame of the CarbFix project, and at Umurlu geothermal reservoir (Turkey), where the binary technology is employed. In the past, reinjection of NCG was carried out at Coso flash geothermal plant (California, USA) and at Puna geothermal field (Hawaii, USA). Experimental activities to evaluate the possibility of CO2 sequestration in mineral calcite were performed at Ogachi Hot Dry Rock (HDR) geothermal site and at Hijiori HDR system. Several binary power plant located in Germany reinjected the NCG mainly by using submersible pumps.

The CarbFix project started in 2007, as an EU funded industrial and academic research project. Its overall objective consists in the development of a cost-effective technology for the mineral storage of CO_2 in basaltic rock. The pilot reinjection started in 2012, and in 2014 the first industrial scale injection took place, Sigfússon et Al. (2018). In 2017, about 10.000 tonnes of CO_2 and 5.000 tonnes of H_2S were injected in the geothermal reservoir, corresponding respectively to the 34% and 68% of the annual emission of the geothermal power plant.

The project developed a technology able to inject CO_2 in the young basaltic rock: here the CO_2 reacts with the basaltic rock to form stable carbonate minerals and this provides the permanent storage of the CO_2 and H_2S. The process is described in Gunnarson et Al. (2018): the NCG are first dissolved into pure water in a scrubbing tower; the water (36 kg/s, 6 bar, 20 °C) is sprayed at the top of the scrubbing tower, while the exhaust gases (0,366 m^3/s) are injected at the bottom of the tower. The tower is able to trap in the water the 56% of the CO_2 and the 97% of H2S of the NCG stream, the remaining gases are vented in the atmosphere. The liquid water-CO_2 mixture is then pressurized to 9 bar before the transport from the capture plant to the injection well. The gas-charged water is injected through a stainless steel pipe to a depth of 750 m, where it is mixed with effluent water (no gas-charged).

At the Umurlu geothermal reservoir, it has been observed that the CO_2 content in the geothermal water from the production well declined due to the injection of degassed brine in the injection well. The injection of the CO_2 was developed to restore the NCG content (about 2%) in the extracted geothermal fluid, since the CO_2 content affects significantly the reservoir pressure, Yücetaş et Al. (2018). Yücetaş et Al. (2018) describe the technical feature of the dual string-dual phase reinjection system: it consists of a pipeline for cold water in the well casing, plus an ad-hoc designed compressor. The cold brine and the compressed NCG pass through an injector, then they are pumped together in the injection well and mixed at more than 700 m depth. The reported CO_2 flow rate is 2,65 ton/h, and the CO_2 reinjection pressure is 52 bar.

From these two principal experiences, two main methods for NCG reinjection can be recognized:

1. injection of gas-charged water, dissolving the NCG by means of an absorption column;

2. injection of compressed NCG and mixing with geothermal fluid in depth in the reinjection well.

The reinjection strategy depends on the NCG content of the geothermal fluid and on the technology employed to convert the geothermal energy into electricity: the first method can be applied in geothermal system with low NCG content and applying a flash steam turbine, such as at Hellisheiði power plant. However, the absorption column is not a viable solution in the case of geothermal fluid with high NCG content (more than 2%), since part of the NCG are vented in the atmosphere. This can be acceptable in the case of a geothermal fluid with a low NCG content (so the total vented NCG is low), however this practice is not acceptable in the case of high NCG content and it prevent the achievement of the zero-emission goal. In the case of geothermal field with high NCG content, such as at Umurlu geothermal field, the second method was successfully applied. The Umurlu power plant is based on the binary conversion cycle and uses an Organic Rankine Cycle (ORC) to convert geothermal energy into electricity.

Gunnarson et Al. (2018) estimated that the cost of the reinjection at Hellisheiði geothermal plant is about 25 US$/ton of gas mixture ($CO_2$+$H_2S$), comprising capture, transport, injection and monitoring of the NCG. This cost can be acceptable in case of low NCG content in the geothermal fluid, but it would be too high in the case of a geothermal fluid with a high content of NCG, such as at Castelnuovo site (Italy). Here the NCG content in the steam varies from 6% to 10%, with a corresponding flow rate of 1 ÷ 2 kg/s. Considering a cost of 25 US$/ton, the cost to reinject all the NCG would range approximately between 790.000 and 1.580.000 US$/year. Such reinjection cost is quite substantial, considering that this power plant may produce 40 GWh/year, thus that the cost per kWh ranges between 0,0198 and 0,0395 US$/kWh. This cost can be reduced by using the technology proposed at Umurlu geothermal reservoir. If a total cost of the reinjection plant of about 3.000.000 US$ (comprising compressor, transport pipeline, injection and control) is considered, a lifetime of the plant of 30 years, and a flow rate of 1,5 kg/s, the cost is about 2,1 US$/ton of gas mixture. This technology seems to be more convenient from the economical point of view, it can achieve the zero emission target, and can be more easily applied to the binary ORC power plant, if compared to a flash turbine plant.

The reinjection of the NCG was performed at Coso geothermal field (California, USA) for 12 years, and at Puna geothermal field (Hawaii, USA) to carry out the silica scale control, DiPippo (2016). At Coso geothermal filed, the effect of NCG reinjection the brine pH reduction was demonstrated: the pH was lowered from 8 to 5, preventing the silica scaling. However, the geothermal plant at Coso was based on a dual-flash condensing technology, and this led to the passing through of residual oxygen to production well, resulting in severe corrosion of the equipment; in the end, the NCG reinjection was replaced with conventional H2S abatement and pH-mod systems. At Puna geothermal field, the low NCG content allowed for total gas injection from the start-up, and the resulting pH reduction was effective in the silica scaling mitigation at an SSI (super saturation index) of over 2, DiPippo (2016). However, the total gas injection was not technically implemented in the case of flash power plants, since the NCG are contaminated with oxygen; this issue does not occur in the case of ORC technology, and thus silica scaling inhibition can be carried out without corrosion problems, DiPippo (2016).

Experiments for CO_2 injection were performed in the case of Hot Dry Rock (HDR) geothermal system, Kaieda et Al. (2009) and Yanagisawa (2010). Here the CO_2 is dissolved in the river water injected to recover heat from the hot dry rock; the purpose consists in the CO_2 sequestration in carbonate minerals (calcite), as proposed at Hellisheiði geothermal field. In the Japanese experiments, the effect of CO_2 injection on calcite scaling is investigated, showing that the injection of CO_2 increases the SSI of $CaCO_3$, leading to the deposition of calcite.

In Germany, the reinjection of the NCG was achieved by means of deep well submersible pumps: this method was applied in the case of pumped binary cycle power plant, where the geothermal fluid is maintained liquid throughout the entire process by keeping the brine pressurized in the heat exchangers. In this way, it is possible to achieve the zero emission target. However, this method cannot be used in the case steam is also present and when the NCG content is high (more than 2%), since in this case a too high pressure would be required to keep the CO_2 dissolved in the liquid brine, ESMAP Technical Report (2012).

4. NUMERICAL SIMULATIONS OF NGC REINJECTION IN LITERATURE

Numerical simulations and preliminary studies for reinjection can be found in literature. Batini et Al. (2016) analysed a typical Italian geothermal field. Kaya and Zarrouk (2017) simulated the simultaneous NCG and water reinjection by means of 3D models. Kaya et Al. (2018) applied a 3D numerical model to simulate the CO_2-water mixture reinjection at Wairakei-Tauhara geothermal field. Manente et Al. [12] proposed three different possible layout for the reinjection plant of condensing power plant, comparing costs and performances.

A total reinjection system for NCG is under study at the Castelnuovo pilot plant (Italy), which is based on the ORC technology, Batini et Al. (2016). The reported numerical simulations show that a closed loop power system is feasible, and a first evaluation of reinjection depth and pressure was assessed. In this case, the compressed NCG are mixed directly with the steam condensate at a certain depth in the injection well, without a previous dissolution of NCG in pure water, as done at Umurlu geothermal plant. However, the uncertainty on these results is still high, the cost of the injection plant was not estimated, the performance reduction of the power plant, due to compressor own consumption, are still to be defined and the bore hole gas/liquid system should be carefully dimensioned to achieve the correct NCG mixing with the condensate.

Possible configurations of flash condensing geothermal power plants with NCG reinjection are proposed in Manente et Al. (2019), and the cost and the performances of three different abatement systems were compared. The proposed layouts comprise an absorption column, similar to the one described in Gunnarson et Al. (2018) implemented at the Hellisheiði power power plant, but differs from the point of view of the cooling technology: the solutions with a dry cooling tower, an air condenser (AC) and a hybrid dry cooling tower – AC systems were investigated. This is an interesting study for the flash technology, but it cannot be applied in the case of binary plant.

5. EVALUATION OF THE REINJECTION PROCESS

As reported in Section 3, two main different strategies may be recognized to carry out the NCG reinjection, namely the injection of gas-charged water, dissolving the NCG by means of an absorption column and the injection of the compressed NCG, which are mixed with the geothermal fluid in depth in the reinjection well. The second solution seems to be more suitable than the first in the case of binary power plant, and it is able to achieve the zero-emission goal. The main component of such technical solution is the compressor.

5.1 Compressor technology

Compressors are available in different types, size and models, each of them suitable for a particular need. Two basic categories of compressor are:

1. Dynamic compressors, which include axial and centrifugal compressor
2. Positive displacement compressors, divided in reciprocating and rotary type.

Fig. 4 shows a more detailed classification.

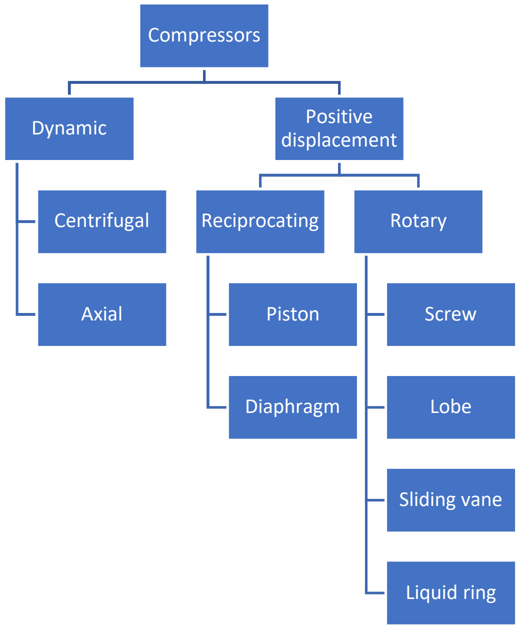

Figure 4: Compressor types classification.

The choice of the compressor type depends mainly on the inlet volumetric flow rate to be compressed and on the discharge pressure. Table 2 reports schematically the typical operating characteristic of the compressors, PIP (2013).

The NCG stream may contain some percentage of H_2S: particular attention should be paid on the choice of the materials of the compressor part in contact with the gases, due to the high corrosion potential of hydrogen sulphide. A comparison of different materials with high corrosion resistance should be carried out, in order to assess the best trade off, in terms of performances and costs, depending on the chemical composition of the NCG mixture and of the geothermal fluids.

5.2 NCG reinjection process in case of high NCG content in geothermal steam

We report here a preliminary dimensioning of the compressor in the case of high NCG content in a steam dominated geothermal field. This kind of geothermal reservoir represents a typical situation of the geothermal field present in Tuscany, Italy.

Table 2: Summary of the typical operating ranges of compressors (PIP (2013)).

	Inlet capacity (ACMH, m^3/h)	Maximum discharge pressure (bar)
Dynamic		
Centrifugal	170 ÷ 850.000	690
Axial	50.000 ÷ 850.000	17
Positive displacement		
Piston	20 ÷ 34.000	4.150
Diaphragm	0 ÷ 250	1.400
Rotary screw	200 ÷ 100.000	1 ÷ 50
Rotary lobe	25 ÷ 50.000	0,3 ÷ 1,7
Sliding vane	15 ÷ 5.000	10
Liquid ring	10 ÷ 17.000	5,5 ÷ 10,5

We assume steam+NCG stream coming from the artesian well has the following characteristics:

- Mass flow 65 ton/h.
- Temperature 180 °C
- Pressure 10 bar(a)
- NCG content 8% in weight

After passing through the binary plant heat exchangers, the condensed steam is separated from the NCG at about 90°C. We assume that the temperature and pressure of the NCG stream are respectively 50°C and 9 bar; 50°C are achieved by means of a dedicated cooler to reduce the compression work. In these conditions, the NCG volumetric flow rate is 350 m^3/h (ACMH). Considering a reinjection depth of the compressed NCG of 400 m and considering the CO_2 solubility in water, we assume that a discharge pressure of the compressor of about 60 bar(a) would be enough to ensure the NCG mixing with condensed steam in the reinjection well. Comparing these NCG conditions with the typical operating parameters reported in Table 2, we observe that the compressor may be a centrifugal compressor or a reciprocating compressor; the other compressor types are excluded due to the limits on the discharge pressure and on the volumetric flow rate.

Considering a two stage intercooled compressor, it has been computed by means of Aspen Plus, that the power required to compress the gas is about 270 kW, with the assumption of an intercooling temperature of 90 °C and the compressor isentropic efficiency of 0,8. The flowsheet of the simulation is shown in Fig. 5.

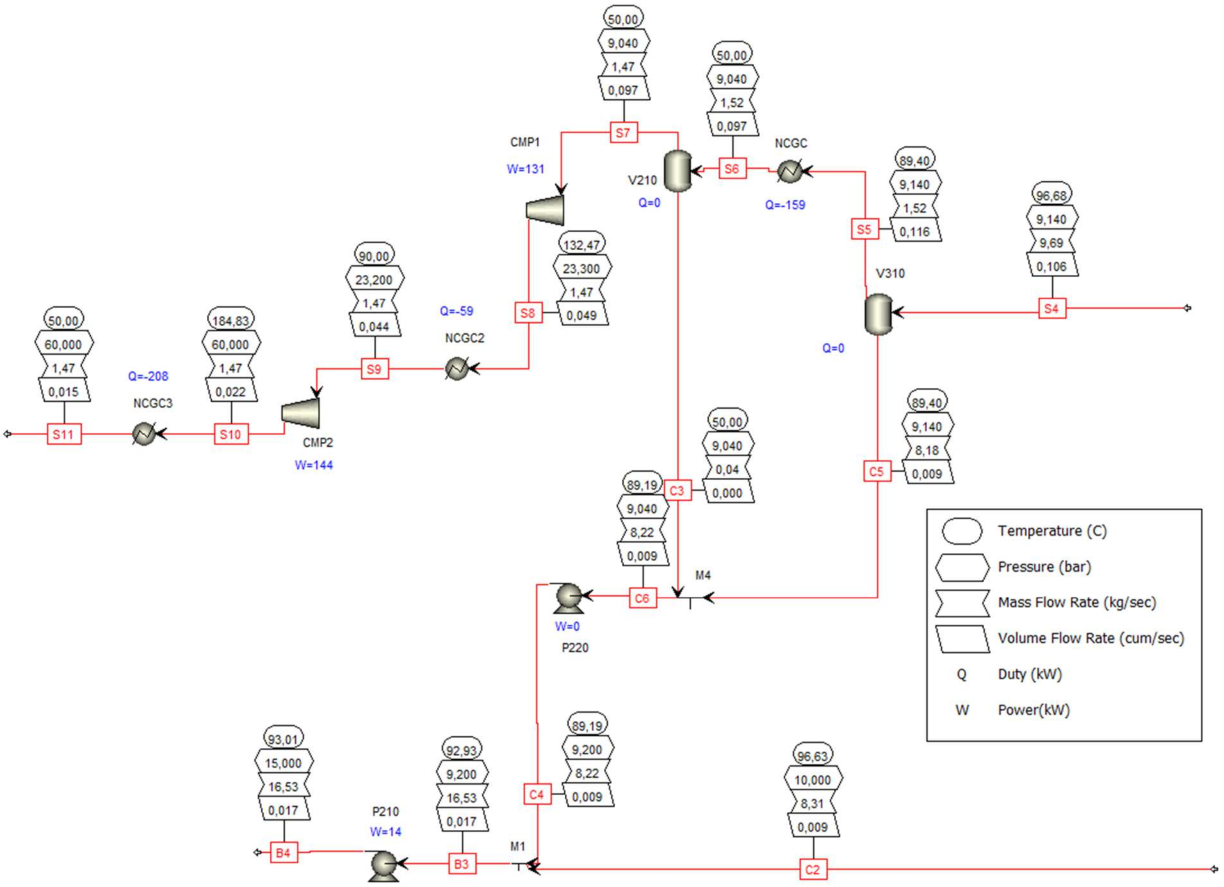

Figure 5: Aspen Plus flowsheet of the simulation model of the NCG compression system. S4 and C2 represent the geothermal fluid streams coming from the heat exchangers.

5.3 NCG reinjection process in case of moderate NCG content in a single-phase geothermal fluid

The reinjection solution with the compressor can be used to achieve the total reinjection in presence of liquid-dominated geothermal reservoir with high NCG content (2% weight). In such cases, the pressure required to keep the CO_2 dissolved in the geothermal fluid (liquid brine) would be too high (more than 50 bar) in the whole path from production to reinjection well, leading to very expensive submersible pumps, high own consumptions and high design pressure of the equipment (heat exchangers, pipelines, etc). Instead of using such pumps, it would be possible to pressurize the geothermal fluid at well head at lower pressure (7 bar), let the NCG escape from the liquid brine to the steam phase, collect them, send them to the compressor, and reinject the NCG in depth, where they mix with the liquid brine, reinjected by means of reinjection pumps.

Such alternative configuration may lead to cost and own consumption reduction depending on the Injectivity Index (I.I.) of the brine reinjection well, which is defined as the injection rate divided by the injection pressure (ton/h/bar). If this latter is high, and thus the required pressure of the reinjection pump is low, the solution with the compressor presents some advantages if compared to the use of submersible pumps.

To explain better this point, we report a numerical example: we assume a liquid brine with the following features

- Volumetric flow rate 400 l/s,
- temperature 135 °C,
- NCG content 2%.

Table 3 reports the required equipment in the two configurations.

Table 3: Comparison of the equipment required in Configuration 1, without compressor, and in Configuration 2, with compressor and reinjection pumps. Reservoir characteristics at production well are assumed to be the same.

Resevoir conditions: flow rate 400 l/s, Temperature 135 °C, NCG content 2%	
Configuration 1	Submersible pump: discharge pressure 53 bar No compressor No reinjection pump*
Configuration 2	Submersible pump: discharge pressure 7 bar NCG Compressor discharge pressure 60 bar Reinjection pump: discharge pressure depends on I.I.

*Supposing that the submersible pump discharge pressure is enough to ensure reinjection

The reinjection solution with the NCG compressor requires the use of injection pumps, which are not needed in Configuration 1 when the discharge pressure of the submersible pump is enough to ensure the reinjection pressure at the reinjection wells. In Configuration 2, the NCG are first separated from the brine, and their temperature is reduced to 50 °C, to reduce the compression work; the volumetric flow rate of NCG in these conditions is about 1.600 m^3/h (ACMH), and we consider again a compressor discharge pressure of 60 bar. The intercooling temperature of the two-stage compressor is assumed to be 100 °C.

The use of the compressor implies a saving on the consumption of the submersible pump ΔW_{SP}, due to the reduction of the discharge pressure (assuming that the reservoir pressure, the productivity index of the well and the installation depth of the submersible pump are the same in the two scenarios). However, the consumption of the compressor W_C and of the reinjection pumps W_{RP} should be taken into account.

ΔW_{SP} has been computed as the power saved due to the reduction of well head pressure from 53 bar (pressure required to keep the CO_2 dissolved in the brine, given the CO_2 concentration and brine temperature) to 7 bar. This saving is considered as constant, since it depends on the variation of the submersible pump discharge pressure only and does not depend on the condition in the production well.

Table 4 reports the saving on the own consumption of the submersible pump ΔW_{SP} and the sum of the consumption of the compressor and of the reinjection pump ($W_C + W_{RP}$) as function of the Injectivity Index of the reinjection well. The extra own consumption ΔW

$$\Delta W = (W_C + W_{RP}) - \Delta W_{SP} \quad [1]$$

has been normalized on the gross power output W_{gross} of the power plant (considering a 14% gross efficiency).

It is possible to see that, as the I.I. increases, the extra own consumption decreases and turns negative, due to the reduction of the required reinjection pressure. Thus, the use of the compressor has a positive effect on the performances of the power plant in case of high Injectivity Index.

As well as the cost reduction of the submersible pump, keeping a low well head pressure lead to a further cost reduction thanks to the lower design pressure of the heat exchangers and of the pipelines transporting the geothermal fluid.

Table 4: Saving on the own consumption as function of the Injectivity Index of the reinjection well.

I.I. (ton/h/bar)	ΔW_{SP} (kW)	$W_C + W_{RP}$ (kW)	$\Delta W/W_{gross}$ (%)
20	2.453	3.570	10,2%
30		2.690	1,8%
40		2.250	-2,4%
50		1.986	-4,9%
60		1.810	-6,6%
70		1.684	-7,8%
80		1.590	-8,7%
90		1.517	-9,4%

6. CONCLUSIONS

In this paper, the state of the art of the NCG reinjection methods has been outlined. Two main successful cases have been presented, namely the reinjection experience at the Hellisheiði power plant at the Umurlu geothermal field. Two different reinjection methods can be identified: the NCG injection can be carried out by means of an absorption column and the subsequent mixing of water and NCG above the ground, or by means of the NCG compression alone and the mixing with geothermal fluid at great depth in the reinjection well. With respect to the method involving the absorption column, this latter is more suitable to binary power plant, since the NCG can be easily kept separated from the geothermal steam and brine; moreover, this method can achieve the zero-emission goal.

The numerical simulations reported in Batini et Al. (2016) and in Manente at Al. (2019) have been analysed, showing respectively the feasibility of the 100% NCG reinjection in the case of high NCG content and some possible reinjection plant layouts in the case of flash power plant. Other numerical analyses of the NCG reinjection, Kaya and Zarrouk (2017), which have not been analysed in detail for the sake of brevity, show the interest about the possibility of CO_2 sequestration. The NCG reinjection can be implemented in a more straightforward way in the case of binary power plant, with respect to the flash and back pressure power plant, since the NCG stream can be kept separated from the working fluid and it is not contaminated by air.

Finally, some technical aspects of the compressor, the main component of the reinjection system, have been shown. A possible compressor has been selected in a numerical example representative of a typical situation of the Italian geothermal field. In the case of single-phase binary power plant, the comparison of two possible configuration to perform the total reinjection have been presented, showing the advantages of the reinjection with NCG compressor, depending on the Injectivity Index of the reinjection well. The choice of one configuration depends on several parameters, such as the characteristics of the geothermal reservoir, of the production and of the reinjection well, on the NCG content. The development of a best practice guideline for the reinjection of NCG shall be developed taking into account the possible different features of the single case.

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