Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

A Systematic Approach to Decrease the Oxygen Gas Concentration at Þeistareykir GPP

Alma Stefánsdóttir and Jón Arnar Emilsson

Landsvirkjun, Háaleitisbraut 68, 103 Reykjavík, Iceland

almast@lv.is

Keywords: Koldís, Þeistareykir, Iceland, gas scrubbing system, flammability, greenhouse gas, carbon dioxide, CO_2, hydrogen sulfide, H_2S, oxygen, O_2.

ABSTRACT

Electricity generation using geothermal resources can be challenging and requires responsible monitoring. An increasing demand of sustainability across the geothermal sector calls for lower greenhouse gas (GHG) emissions, thereby promoting the importance of CO_2 removal from geothermal power plants (GPPs) by gas scrubbing and re-injection or utilization.

Þeistareykir GPP, located in Northeast Iceland, has an installed capacity of 90 MW_e and is the most recent power plant owned by Landsvirkjun, the National Power company of Iceland. The GPP has two turbines with a shell and tube type condensers, where the gas extraction system of each turbine is composed of four identical units, in total eight units. The non-condensable gas (NCG), including carbon dioxide (CO_2), is currently led to cooling towers where it is released directly to the atmosphere. However, in a project named Koldís, Landsvirkjun aims to implement a gas scrubbing and re-injection system at Þeistareykir by the year 2025.

Various factors influence the NCG composition, both geochemical and operational factors. For this reason, proper monitoring of the gas composition is fundamental for 1) the operation of Þeistareykir GPP and 2) the design, commissioning and operation of gas scrubbing systems. In regard to gas scrubbing, low oxygen (O_2) gas concentration is required to limit the risk of technical complications and danger. The flammability of the treated gas is a common concern in the operation of gas scrubbing stations, including in the Koldís project at Þeistareykir GPP.

A focused search was carried out to detect, quantify and prevent potential atmospheric leakages into the production process of Þeistareykir GPP. Gas samplings and chemical analysis was executed periodically prior to leak inspection. Real-time O_2 measurements performed during the first phases of inspection. After the inspection, O_2 concentration of all systems was below the maximum limit, ranging from 0.67-0.92 $\%_{vol}$ O_2. An overall average from both turbines, corresponding to the inlet gas flow to a gas scrubbing station, is 0.74 $\%_{vol}$. The treated gas from the scrubbing station should not be flammable, but in the case on O_2 concentration increase to 1.32-2$\%_{vol}$, the concentration of fuels falls below the upper flammability limits (UFL) and into a flammable region.

This paper outlines the background and motivation for the project, the methodology applied, and the initial and resulting final O_2 gas concentration. The results will be discussed in regard to the operation of Þeistareykir GPP, the Koldís project and potential flammability.

1. INTRODUCTION

Electricity generation using geothermal resources can be challenging and requires responsible monitoring throughout the production process to ensure a reliable operation with minimal maintenance downtime. In addition, an increasing demand of sustainability across the geothermal sector calls for lower greenhouse gas (GHG) emissions, thereby promoting the importance of point-source gas scrubbing and re-injection or gas utilization from geothermal power plants (GPPs).

Landsvirkjun, the National Power Company of Iceland, aims to reach carbon neutrality in 2025. The target includes a 60% reduction in direct greenhouse gas (GHG) emissions from its geothermal energy production, compared to the baseline emissions in 2008, contributing to approximately 2.5% of Iceland's commitment to the Paris Agreement. The company owns and operates three GPPs located in Northeast Iceland. Þeistareykir GPP is the most recent power plant, commissioned in 2017. The plant has an installed capacity of 90 MW_e and emits roughly 7 kilotonnes of CO_2 on a early basis. A project named *Koldís* is a key action to reach the climate target of carbon neutrality by implementing a gas scrubbing and re-injection system at Þeistareykir GPP. The system will reduce the CO_2 emissions from the plant by 95% and simultaneously reduce the H_2S emissions by 99%.

An important parameter in the design, commissioning and operation of gas scrubbing systems is the chemical composition of the non-condensable gas (NCG) flow from the power plant. Various factors influence the NCG composition, both geochemical and operational factors. Generally, the NCG composition has been monitored annually at Þeistareykir, but the frequency has now been increased significantly as a precursor for the implementation of the Koldís project. Low O_2 concentration can limit corrosion, scaling, chemical precipitation and promote higher efficiency on the turbine unit due to better vacuum of the system. Furthermore, low concentration limits the risk of technical complications, and danger caused by the risk of flammability. For this reason, proper monitoring of the gas composition is fundamental for Þeistareykir GPP in regard to: 1) the daily operation and 2) the implementation of a gas scrubbing system. Most processes that remove CO_2, and H_2S, from NCG flow, will lead to a significant increase in the relative concentration of the remaining gas species, mainly O_2, H_2 and N_2, thus potentially creating a flammable or explosive gas mixture. The flammability of the treated gas is a common concern in the design and operation of gas scrubbing systems, including in the Koldís project at the Þeistareykir GPP [1].

2. ÞEISTAREYKIR GEOTHERMAL POWER PLANT

2.1 Production process

The geothermal fluid is extracted from high-pressure (HP-) production wells in the Þeistareykir geothermal area and consists of a mixture of steam and water. The fluids have varying flow rates and composition. The steam supply system leads the fluid to HP-separators for separation before further utilization of the steam, where the steam enters mist eliminators prior to the turbine to ensure sufficient steam quality. Prior to the turbines, a fraction of the steam is rerouted from the turbines and utilized in the gas extraction system (GES) by ejectors. Figure 1 demonstrates the production process at Þeistareykir GPP in simple terms.

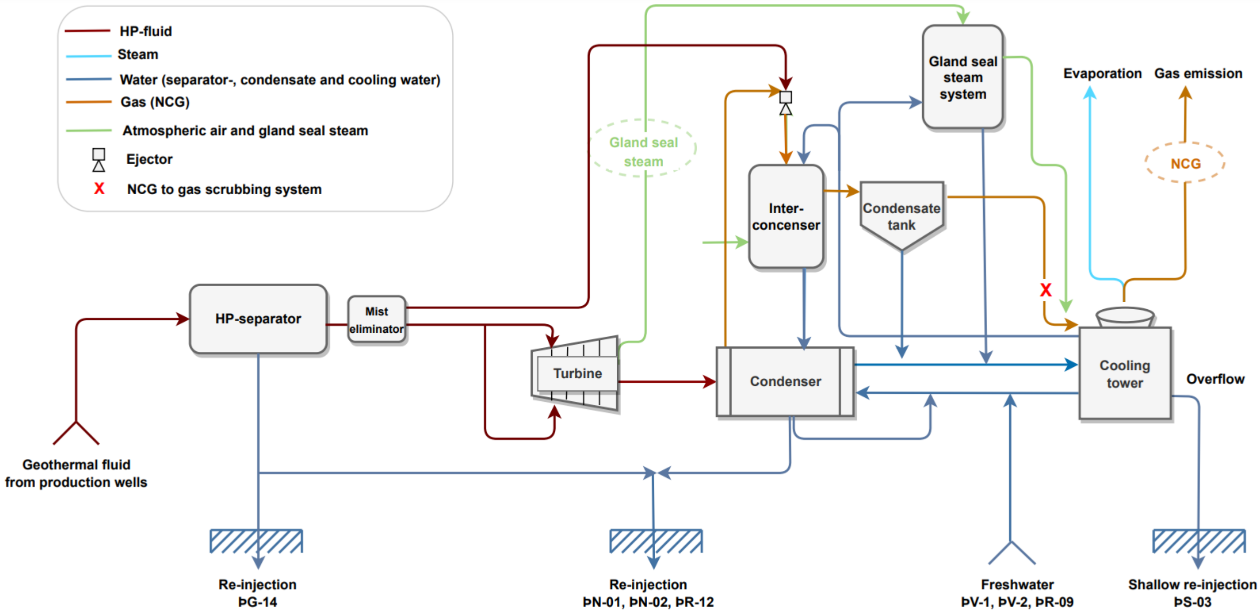

Figure 1: A simplified process flow diagram of the Þeistareykir GPP. This paper focuses on the gas removal system (GES), including the condenser, inter-condenser, condensate tank, vacuum pump and relevant piping/connections. Shapes and sizes of units are not corresponding to the units.

The cold-end equipment of the power plant includes a shell and tube type surface condenser, a gas extraction system (GES) and a cooling water circuit with a wet cooling tower. After the geothermal steam passes through the two 45 MW_e steam turbines for electricity generation, the steam enters a condenser where it condenses at vacuum (approximately 0.08 bara pressure) to form condensate (liquid water) and a gas phase. The condensate is partially circulated as make-up water to the cooling water circuit and partially re-injected back into the geothermal reservoir, where it is mixed with separator water for diluting and cooling prior to re-injection. The gas phase, on the other hand, contains NCGs from the geothermal steam of magmatic origin that do not condense at the operating temperature and pressure of the condenser, leading to an accumulation of the NCGs within the condenser, hence requiring gas extraction from the system. The extraction prevents an increase in the condensers' pressure, which would lead to a reduction in the condenser's heat transfer efficiency, and consequently a reduction in the turbine efficiency and the total electricity output of the power plant.

The gas extraction system (GES) of each turbine is composed of four identical units, in total eight units, having a capacity for gas content of 0.6% by mass of geothermal steam. The steam at Þeistareykir contains on average up to 0.2% NCGs. The GES is a hybrid system consisting of jet-steam-ejector with an inter-condenser, a liquid ring vacuum pump (LRVP) and a condensate tank. The NCGs are extracted up from the condenser by the jet-steam-ejector to maintain vacuum pressure. In the ejectors, the gas mixes with HP-steam from the steam supply and enters the inter-condenser where it is cooled. Condensate from the inter-condenser is recirculated to the main condenser, whereas the gas is pumped to a condensate tank by a vacuum pump. From the condensate tank, the gas is extracted from the top to the main gas pipe, where the gas from all GESs is combined, and led to the cooling towers for release to the atmosphere. Generally, two GESs are in operation at each time, allowing for maintenance of the other two. The gas pipe from the GES to the cooling tower is near atmospheric conditions.

The gas phase for extraction from the condenser to the atmosphere contains the following NCGs; carbon dioxide (CO_2), hydrogen sulfide (H_2S), oxygen (O_2), nitrogen (N_2), hydrogen (H_2), methane (CH_4) and argon (Ar). The gases of main focus in this paper are CO_2, H_2S, O_2 and H_2. Both H_2S and CO_2 are recognized as some of the main gases in terms of negative environmental and health impacts, as well as for safety in the utilization of geothermal energy. CH_4 is also an important greenhouse gas but is not of focus in this paper. The NCG is currently led to cooling towers where it is released directly to the atmosphere above the cooling tower's fan. However, in the Koldís project, the NCG will instead be routed directly to a gas scrubbing station. The gas pipe for connection to the gas scrubbing station is demonstrated by an X in Figure 1.

The gland seal steam (GSS), from the turbines' vacuum side, is not routed through the same pipe as the NCG from the GES to the cooling tower (as is often the case) and is therefore not influencing the NCG flow and not of interest of this paper.

3. MATERIALS AND METHODS

3.1 Gas sampling and chemical analysis of NCG composition

Sampling and analyzing of the NCG chemical composition has a key role in understanding and monitoring the nature of the NCG behavior with regard to variations in composition and O_2 gas concentration, as well as to ensure a reliable quantification of greenhouse gas (GHGs) emissions. Historically, the chemical composition of the NCG from the GES has been monitored annually at Þeistareykir. The sampling and chemical analysis has simply been performed with the aim of quantification for the GHG emissions accounting, as well as to monitor and document potential changes. In the recent years, Landsvirkjun has put more efforts into more frequent sampling. Today, with respect to the planned implementation of the Koldís project, frequent monitoring of NCG composition and potential variations is a vital part to construct a reliable design basis for the design and later, for the operation of the gas scrubbing system.

Multiple gas samples were collected during the year prior to the leak inspection of this paper. All samples were collected and analyzed according to established scientific methodology [2] [3] and the standard operating procedure (SOP) of the geothermal laboratory of Landsvirkjun. Gas sampling was carried out using a 250 mL double-port evacuated glass bottle. Addition of NaOH and deionized water into the bottle leads to the condensation of gaseous CO_2 and H_2S into the NaOH solution, while the other gas species (O_2, CH_4, H_2, N_2 and Ar) remain in the gas phase.

Chemical analysis was performed in two steps. First for the quantification of O_2, H_2, N_2, CH_4 and Ar in the gas phase a gas chromatograph (GC) was applied, and secondly for the quantification of CO_2 and H_2S in the alkaline condensate, titration was performed. All gas samples were analyzed on the same day as sampled to any chemical reactions occurring within the bottle and ensure accurate results.

3.2 Leak detection procedure

A focused search was carried out to detect atmospheric leakages into the production process of Þeistareykir GPP, with focus on the GES, being the primary system handling the gas and operating under vacuum. All parts of the eight GESs were inspected by Þeistareykir operators, starting at the condenser and moving through each section of the systems, as an effort to find and eliminate any air ingress. This includes connections, flanges, packings, and valves all the way to the main gas pipe leading to the cooling towers.

Leak detection was executed by applying two different tools in parallel: a sound detection device and a smoke pen. Both tools were experimented and employed for the first time for the purpose of leak detection. The first tool, a high-frequency sound leak detection device, was brought near the main parts of the GES. The working principle dictates that when the sensoring front end of the device is brought close to a leakage (suction of air as the system operates below atmospheric pressure), the operator will hear the leak indirectly in the connected headset. The second tool, a smoke pen, was employed with the principle of igniting a smoke-emitting wick into a clutch pencil to create light smoke. By locating the smoke pen in close proximity to the part studied, the operator can observe if the smoke drifts away or is sucked inwards to the process, indicating air ingress taking place through a leakage.

Alongside to the leak detection procedure, bolts on flanges were tightened if loose, followed by documentation on where potential flange gaskets require replacement due to being untight. Most often, stainless spiral wound gaskets are between flanges at Þeistareykir GPP, but if a flange in the GES had a torn rubber gasket, it was noted to replace with steel as it has shown to be tighter. Replacement of flange packings, where required, is still ongoing.

3.3 Oxygen measurements

To determine the O_2 gas concentration within and from the GES in real-time, an oxygen sensor from PyroScience (Robust Oxygen Probe) was applied during and after leak inspection. Regarding the time it takes to measure the concentration, the sensor provides O_2 gas concentration in real-time, whereas the gas sampling procedure applied in the year before leak inspection (in section 3.1) yields results in up to 5 hours on average (considering distances on-site), thereby allowing for increased number of measurements in parallel to leak detection. Figure 2 demonstrates a simplified flow diagram of the GES of one turbine at Þeistareykir GPP (four GES for each turbine) and the specific locations of measurements in this project (marked A-C). Figure 3 presents a more detailed process diagram.

The focal point of the measurements was twofold, on the condenser and on the GES. Oxygen measurements were carried out both on the inlet (A, from condenser to GES) and outlet (B, up from condensate tank) of the GES as well as on the main gathering gas pipe to the cooling tower (C, combined gas flow from the two GES in operation at each time). This approach allows for a) an understanding on whether the main leakages are entering the process through the condenser or through the GES, and b) separate measurements of each GES with the aim of determining the performance and air ingress of each system.

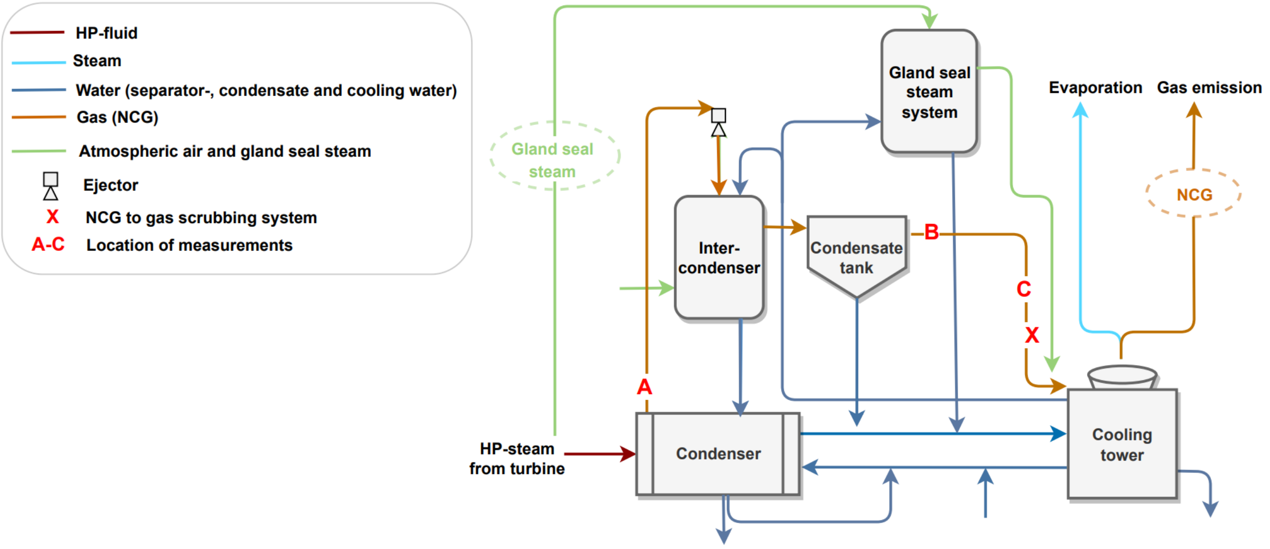

Figure 2: A simplified process flow diagram of the gas extraction system (GES) of Þeistareykir GPP. Locations of samples marked with A) from the condenser, B) from the condensate tank of the GES, and C) from the gathering pipe from all GESs to the cooling tower. The gas scrubbing station will receive the NCG from the location marked with X.

4. CASE STUDY – KOLDÍS, GAS SCRUBBING AND RE-INJECTION SYSTEM AT ÞEISTAREYKIR GPP

A project named *Koldís* is one of the key actions in Landsvirkjun's operations to reach its climate targets of carbon neutrality in 2025. The preliminary design phase was finalized in Q2 2022, where different options for the gas scrubbing and re-injection system were evaluated. The engineering design phase of the Koldís project will be completed in Q1 2023 aiming to decide the technology and layout applied, and to design all main components of the gas scrubbing and re-injection systems to a degree that confirms the project being technically and economically feasible. Landsvirkjun aims to commission the system in the year 2025. In this case study, the engineering design process will be described briefly. The focus of this paper is on the chemical composition of the gas for scrubbing, as well as on important parameters to monitor, flammability and potential limitations.

This paper will focus mainly on the gas scrubbing station. The following corporations were consultants in the Koldís project; Trimeric Corporation for the gas scrubbing process design, and Carbfix and Mannvit for the full project design, including the scrubber, the re-injection and monitoring of the re-injected fluid. The project design presented in this report is based on the scientific basis and experience that has proven to be effective to negate CO_2 release at Hellisheiði power plant [4] and consequently the Koldís process is fundamentally like the Carbfix process in operation at Hellisheiði.

The main requirement of the Koldís project is to reduce the greenhouse gas (GHG) emissions from Þeistareykir GPP. This will be achieved by dissolving 95% of the CO_2 from the NCG flow into the condensate. In addition, 99% of the H_2S will be dissolved into the condensate, being feasible due to the higher solubility of H_2S than CO_2 [5]. There are no requirements on simultaneous capture of H_2S, partly due to the remote location, but it is still desired to improve the air quality near the power plant. The gas-charged fluid will be re-injected into a re-injection well. The target is for the CO_2 and H_2S to be permanently sequestered in the subsurface through in-situ carbonation of basalts by forming stable carbonate [6] and sulfide minerals [7].

Regarding 95% CO_2 scrubbing efficiency, the system has the potential of being limited by flammability constraints of the treated gas. Generally, when operating a gas scrubbing system, the O_2 gas concentration from the GES should preferably be of maximum $\leq 1\%$ by volume. The main reasons are the following:

- The risk of combustion (fire and explosion hazard): The remaining treated gas, after removal of CO_2 and H_2S by scrubbing, will consist of a relatively high concentration of O_2 and H_2, being high enough to support a combustion reaction inside the scrubbing equipment. The risk is significantly reduced if the O_2 levels in the NCG that enters the scrubbing tower are below 1%.
- The risk of solid sulfur precipitation within the gas scrubbing unit at low pH by the reaction of H_2S and O_2. Solid sulfur formation can lead to clogging and accumulation within the gas scrubbing and reinjection system. There should however be low risk of such precipitation if O_2 is below 1%.
- Low O_2 levels can limit corrosion, scaling, chemical precipitation and promote higher efficiency of the turbine unit due to enhanced vacuum of the system [8].

For this reason, the development of the Koldís project requires minimizing of the risk of combustion, while maximizing the amount of CO_2 removed, highlighting the importance of minimum O_2 concentration. Furthermore, future operation of the gas scrubbing system requires continuous monitoring of the fluctuations in gas composition with the necessary controls in place. These controls may be for example flame and/or detonation arrestors to safely vent the treated NCG to the atmosphere under potentially hazardous conditions.

All values presented in this case study are subject to change as the engineering design process of the project advances. At this stage of the project, no red flags nor technical barriers have been identified in the pre-design of the gas scrubbing system.

4.1 Gas scrubbing station design

The gas scrubbing process may be divided into two components, the gas scrubbing station with a pressurized water scrubber, and the gas re-injection well for the gas-charged condensate (of CO_2 and H_2S). Figure 3 demonstrates the process flow diagram (PDF) of the Koldís project. The primary focus of this paper is on the gas scrubbing station. The gas source is NCG from the GES of the power plant and the water source for gas scrubbing is condensate from the condenser of the turbine-generator units.

The gas scrubbing station is designed to process 0.42 kg/s gas flow at 1 bara and 25°C, corresponding to 7,925 tons of CO_2 per year (assuming 342 operating days per year). The station consists of the equipment necessary to dissolve the NCG in the condensate prior to re-injection by pressurizing the fluids. The NCG from the GES will be compressed to the operating pressure of the scrubber (7.5 bara) and led to the lower part of the scrubber for counter-current contact with the condensate. Condensate is an ideal water source due to low O_2 content and suitable chemistry. A heat exchanger will cool 48 kg/s of scrubbing condensate from 35°C to 17.5°C using 58 kg/s groundwater available at 7.5°C. The used groundwater will be discharged into the basins of the cooling towers to serve as make-up water for the cooling water circuit. Cooling of condensate supports increased solubility of the CO_2 and H_2S, as the solubility is temperature dependent [5], and thereby lowers the amount of condensate required for the process. The condensate is led to the scrubbing tower for even once-through distribution from above. The gas-charged condensate will be collected at the base and pumped towards the re-injection well, while maintaining a constant water level within the scrubber. The fluid will be re-injected back into the geothermal reservoir, where it originated from. The target reservoir for CO_2 and H_2S has been estimated to be suitable for long term re-injection and storage.

The gas scrubbing process will leave behind most of the other NCGs in the gas flow, due to lower solubility in water, which will be routed to the cooling towers and released to the atmosphere. This NCG stream is referred to as the "treated gas".

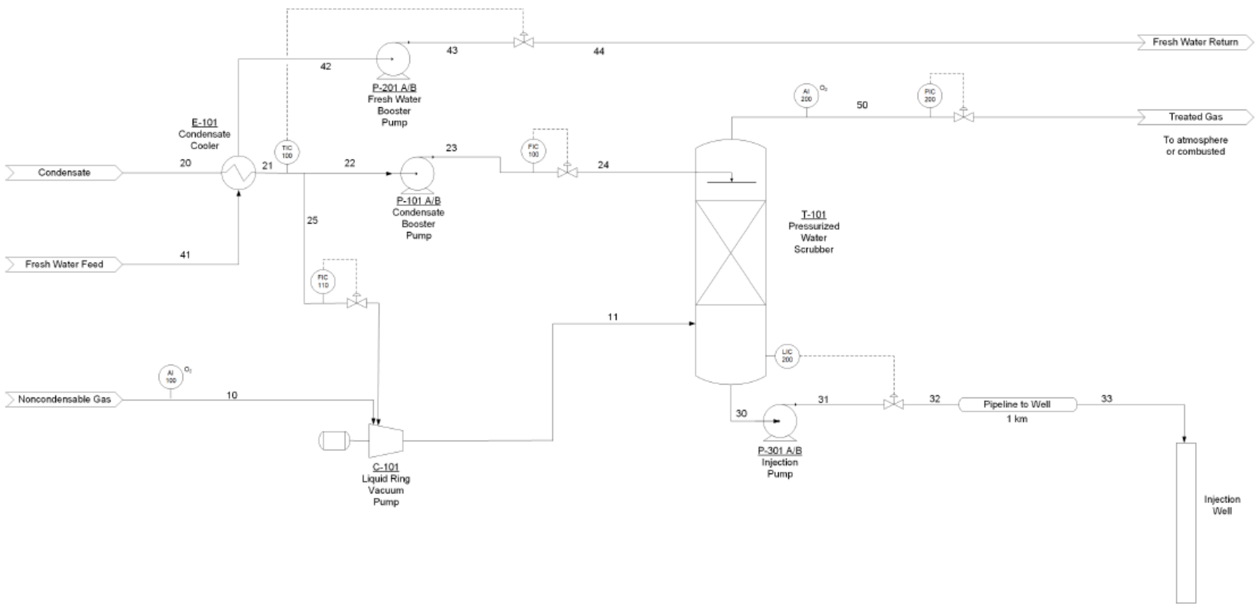

Figure 3: A process flow diagram (PFD) of the gas scrubbing system of the Koldís project.

Multiple different operating conditions and equipment configurations have been evaluated to fulfill the requirements of 95% CO_2 scrubbing efficiency. The operation of Þeistareykir power plant will not be affected by failures or down-time of the gas scrubbing system. Development of the project requires minimising the risk of combustion, while maximising the amount of CO_2 removed, highlighting the importance of a low O_2 concentration.

During down-time of the scrubbing station, the NCG will be led directly to the cooling towers, as in the current operation. Regarding operational flexibility, certain factors have the potential to be adjusted to increase or decrease the gas scrubbing efficiency. Generally, increased feed rate of condensate to the scrubbing tower leads to an increase in scrubbing efficiency, as well as other factors such as cooling of the condensate to allow for increased gas solubility, increasing pressure of scrubbing tower and increasing the height of the tower, can also allow for an increase in the efficiency. On the other hand, lower condensate flow rates and less cooling of the condensate, can lead to lower scrubbing efficiency. For this reason, the gas scrubbing system will be designed to be flexible to ensure full control of the CO_2 removal and to address flammability concerns.

4.2 NCG composition

Table 1 demonstrates the average NCG composition, on a volume (molar) basis, from the GES of Þeistareykir GPP when electricity generation was at full capacity. This NCG composition provides the design basis for the Koldís process design.

As previously mentioned, the maximum O_2 gas concentration from the GES is $1\%_{vol}$ to i)) ensure safe and steady operation of the gas scrubbing station, and ii) limit the risk of sulfur precipitation within the gas scrubber, as oxygen has previously caused sulfur precipitation within the GES af Þeistareykir [8]. For this reason, the NCG composition was adjusted to contain 1% of O_2 by volume to present a realistic scenario with atmospheric leakages, rather than a best-case operating conditions directly after repairment of vacuum leaks, and to account for variations in the NCG composition.

The original mole percentage (dry) is the average composition sampled after leak detection, explained in more details in sections 3.1 and 3.2. The dry NCG composition is saturated with water at the operating pressure and temperature of the GES. The wet $\%_{vol}$ has been adjusted for 1% O_2, the corresponding N_2 and moisture. Other gas species have been normalized accordingly. The adjusted values provide the basis for the Koldís process design.

Table 1: Average gas composition from the GES at Þeistareykir GPP during 90 MW generation in 2020-2022. The adjusted $\%_{vol}$ provides the design basis conditions for the Koldís project.

Gas species	Original $\%_{vol}$, dry	Adjusted $\%_{vol}$, wet (design basis)
CO_2	46.85	45.18
H_2S	25.40	24.49
H_2	21.15	20.39
CH_4	0.09	0.09
N_2	4.85	5.62
O_2	0.74	0.97
Ar	0.04	0.05
H_2O	Saturated	3.21
Total	100.00	100.00

4.3 Results

4.3.1 Influence of electricity generation on oxygen concentration in NCG

Figure 4 shows the average O_2 concentration in the NCG from both turbines (an average from the GES of each turbine) and the electricity generation at the time of sampling.

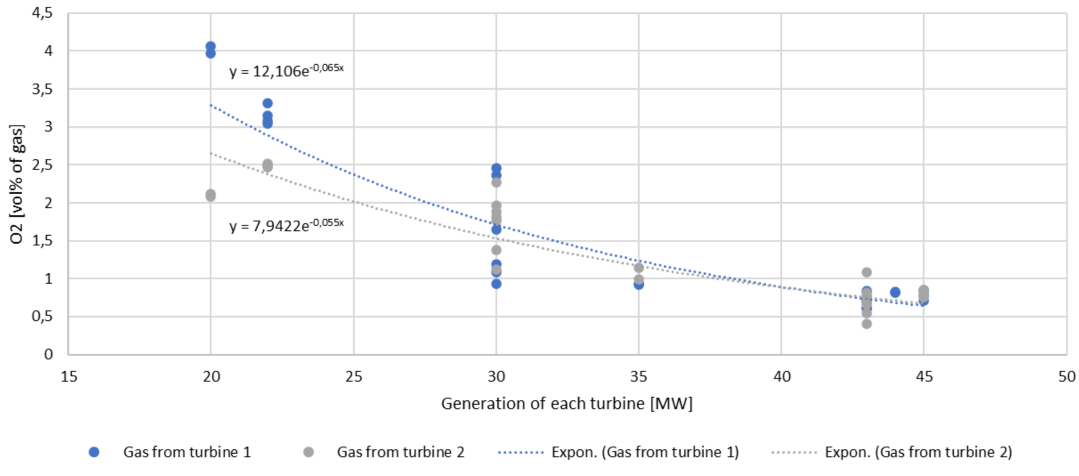

Figure 4. Comparison of O_2 concentration from the GES of each turbine to its electricity generation at Þeistareykir GPP.

At lower operating rates, the O_2 concentration is higher than during full operation. This indicates that atmospheric leakages into the GES are nearly constant, meanwhile the amount of NCG is controlled by the amount of steam entering the GES, and in turn the electricity generation of the power plant. At 20 MW generation of each turbine (40 MW in total), the O_2 concentration ranges from 2.08-4.06% O_2. At 30 MW generation of each turbine (60 MW in total), the O_2 concentration has decreased significantly down to 0.92-2.46% O_2. Following the same curve, 35 MW generation (70 MW in total) shows an O_2 concentration close to 1%. Near full generation of each turbine, 43-45 MW (86-90 MW in total), the O_2 concentration is ranging from 0.40-0.85 O_2. The O_2 concentration was on average 0.74 $\%_{vol}$ at full generation.

A similar trend in the correlation of the NCG O_2 concentration has been documented in other geothermal power plants operated by Landsvirkjun [9]. However, it must be noted that the samples below 40 MW were taken prior to the leak inspection and may therefore be slightly lower in reality and require further research.

4.3.2 Oxygen concentration in NCG after leak detection

Figure 5 presents the results of real-time measurements on O_2 concentration from the GES after leak detection. It must be noted that between the measurements prior to and after leak detection, a routine maintenance stop was performed where multiple parts of the production process were opened. This often leads to an increase in O_2 concentration, as was the case in this study.

The graph compares the initial O_2 concentration, prior to the systematic approach, to the current O_2 concentration levels after the first phases of detection. The O_2 concentration was measured directly from both condensers with near $0\%_{vol}$ O_2 present, indicating that the majority of air ingress is taking place through the GES, rather than the condenser itself. The design basis for Koldís is demonstrated by a red line, corresponding to 1% O_2 concentration by volume.

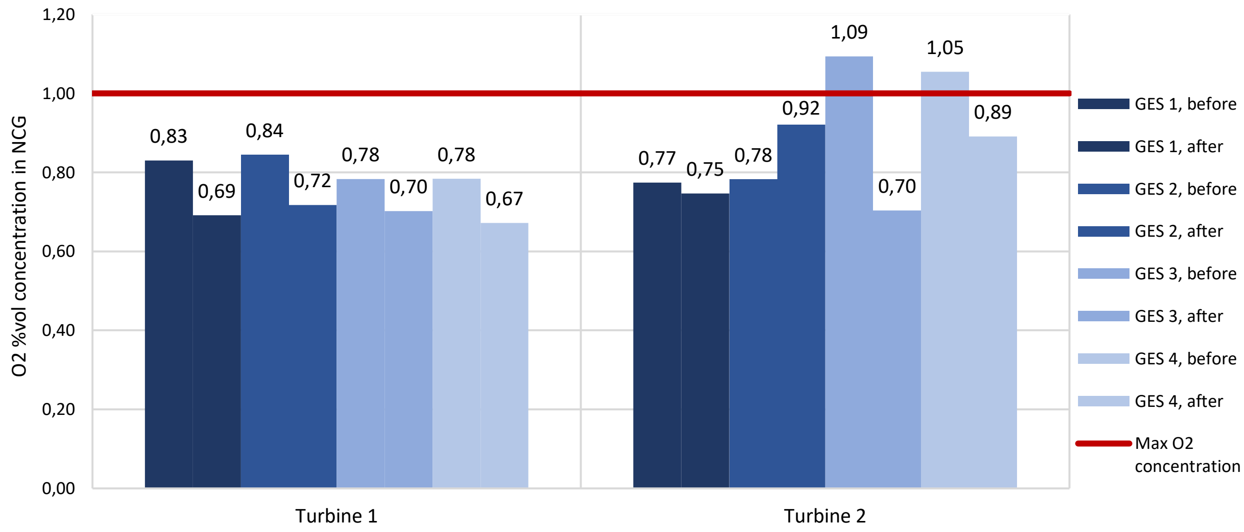

Figure 5: The development of O_2 concentration in NCG from the GESs at Þeistareykir GPP before and after leak detection. A red line demonstrates the maximum O_2 concentration as reference to the design basis.

Prior to the leak detection, two gas extraction systems had O_2 concentrations above the maximum level, both GES 3 and GES 4 on turbine 2. All other systems were below the limit. After the leak detection, the O_2 concentration of all systems is below the limit, ranging from 0.67-0.92 $\%_{vol}$ O_2. An overall average from both turbines, corresponding to the inlet gas flow to a gas scrubbing station, is 0.74 $\%_{vol}$.

4.3.3 Leak detection

Overall, the leak inspection was successful during the first phases and multiple leakages were prevented. However, the leak detection indicates an ingress taking place at few locations, which was not preventable during the realization of this paper.

Figure 6 demonstrates a more detailed process flow diagram (compared to the simplified version in Figure 2) which was used to systematically search the system step by step. The figure shows the four GES of each turbine, where the locations of measurements are marked by blue squares and corresponding letters to Figure 2. The gathering gas pipe to the cooling tower is marked with a blue square in the left uppermost corner. The locations which must be addressed in the next phases of the Koldís project are marked with red squares in Figure 6 and include:

1. Flanges at the inlet of inter-condenser. Require exchange of flange gaskets from rubber to stainless steel.
2. Lower outlet of inter-condenser to vacuum pump (LRVP, between level glass (sight-flow glass) and check valve (non-return valve)).
3. Gland seal at inlet of vacuum pump (potential of the rotor creating a suction effect).

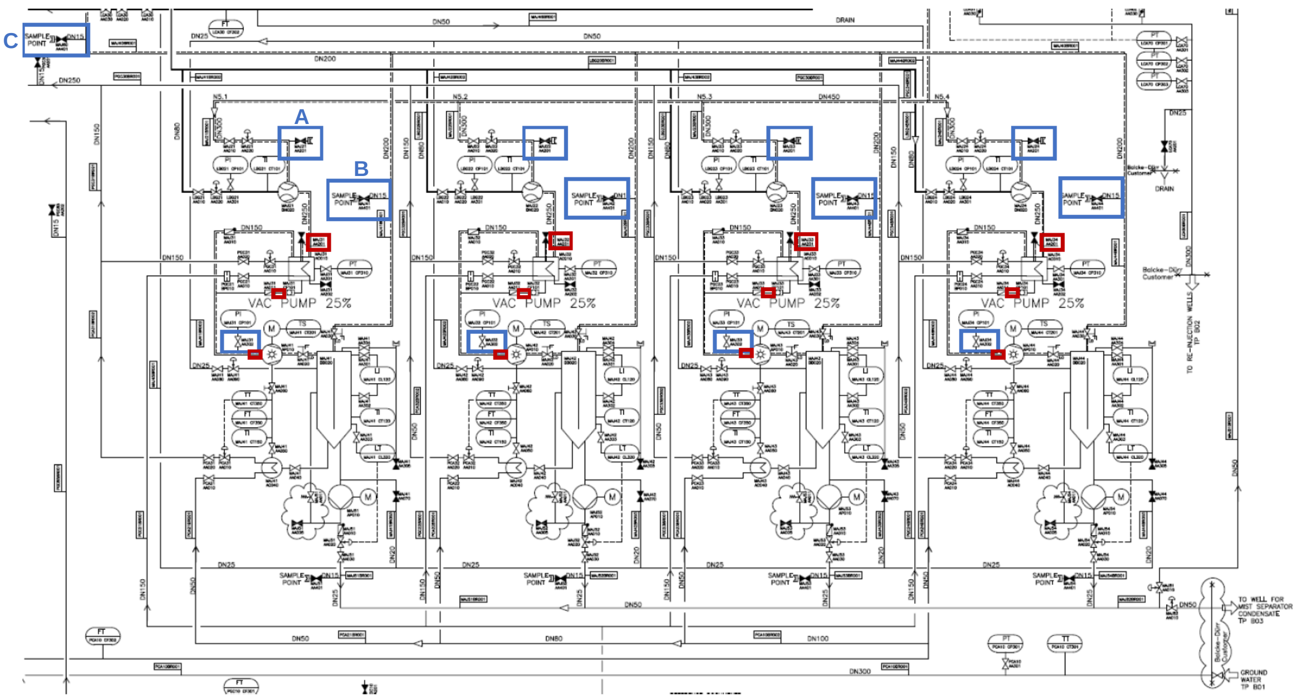

Figure 6: The GES of Þeistareykir GPP, with four GES of turbine 1 shown. Locations of samples marked with A) from the condenser, B) from the condensate tank of the GES, and C) from the gathering pipe from all GESs to the cooling tower. Red squares demonstrate locations of leakages that were not preventable during the project.

4.4 Flammability

In the engineering design phase of Koldís, Trimeric Corporation performed a flammability analysis based on the NCG composition in Table 1 and the following discussion is based primarily on that work. The NCG from the GES contains various gas species, including flammable components (H_2 and CH_4) and O_2. When the CO_2 and H_2S are removed from the gas flow, the remaining NCG components will increase significantly in its relative concentration in the treated gas at the top of the scrubber, mainly O_2, H_2 and N_2, potentially creating a flammable or explosive gas mixture.

An explosive gas mixture can be defined as a mixture in which gas species, referred to as fuels, and oxygen are present in concentrations high enough for the mixture to be inside a flammability envelope, which defines the limits of flammability where only an ignition source is required for the gas to burn, deflagrate or explode.

The design basis conditions of Koldís with 95% CO_2 removal should not lead to the formation of a gas mixture in or near the flammability envelope. However, during process startup, shutdown, or due to process drifts over time or with variations in the NCG composition, the removal of CO_2, and H_2S, could result in the formation of a flammable gas mixture of undissolved gases from the scrubber. The estimated gas composition of the treated gas from the gas scrubbing station is presented in Table 2, and compared to the inlet NCG composition to the scrubber (design basis in Table 1). This demonstrates how the removal of CO_2 and H_2S from the NCG leads to a significant increase in the concentration of the other gas species in the treated gas.

Table 2: Estimated gas composition ($\%_{vol}$) of the treated NCG from the gas scrubber, compared to the adjusted input gas composition to the scrubber.

Gas species	Inlet NCG to scrubber (adjusted) [$\%_{vol}$, wet]	Treated NCG from scrubber, [$\%_{vol}$]
CO_2	45.18	7.06
H_2S	24.49	0.11
H_2	20.39	69.62
CH_4	0.09	0.29
N_2	5.62	19.27
O_2	0.97	3.21
Ar	0.05	0.17

H_2O	3.21	0.28
Total	100.0	100.0

The treated NCG mixture consists of various gas species with different physical and chemical properties. The mixture can be divided into:

- **Fuels and inerts: 84.73%**, including CO_2 (7.06%), H_2S (0.11%), H_2 (69.62%), CH_4 (0.29%) and excess N_2 (including Ar and H_2O) as (7.65%)
- **Air: 15.37%**, including N_2 (12.07%) and O_2 (3.21%)

The treated gas mixture shown in Table 2 must be outside flammability limits to ensure a safe operation. Three main factors were evaluated for the flammability of the treated NCG:

1) **The upper flammability limit (UFL):** The maximum amount of gas mixture that, when mixed with air, will burn.
2) **The lower flammability limit (LFL):** The minimum amount of the gas mixture that, when mixed with air, will burn. The LFL is not considered relevant in the Koldís case, as the concentration of fuels in the treated NCG mixture if always well above the LFL limit of 5.8%.
3) **The limiting oxygen concentration (LOC):** The minimum concentration of O_2 which can result in a gas mixture becoming flammable when the ratio of fuels and inert gas species is varying. LOC is a basic safety assessment but not considered of focus either, due to the LOC being a rather conservative factor. The concentration of inert species (CO_2 and N_2) in the treated NCG mixture is relatively high, when compared to flammable gas mixtures without inert gas (in which the LOC factor was defined for application).

When a mixture is at a concentration above the LFL and below the UFL, it is referred to as being “in the flammability envelope”, requiring just an ignition source to burn. As the LFL and LOC are not considered relevant in the Koldís case, the UFL is the focus flammability parameter. The UFL limits were calculated based on a method from BoM and will not be outlined in details in this paper [10]. (For further information on the topic of the flammability of NCG, the reader may refer to the previously mentioned reference [1].).

Table 3 summarizes the key results of the process simulations of the flammability conditions of the treated gas from the gas scrubbing station, assuming 95% CO_2 removal, in comparison to the O_2 NCG concentration in the inlet gas, regarding both UEL and UEL+10%. Two cases were defined with increased O_2 concentration to determine the effect of increasing O_2 on flammability potential.

Table 3: Analysis of the O_2 concentration in NCG flow to gas scrubber and flammability conditions of the treated gas (assuming 95% CO_2 removal), in regard to UFL and UFL+10%, in comparison to two cases with increased O_2 concentration to 1.32% (case 1) and 2.0% (case 2).

Case	Design basis	Case 1	Case 2
O_2 concentration in NCG ($\%_{vol}$)	1	1.32	2.0
O_2 concentration in treated gas ($\%_{vol}$)	3.21	4.22	6.38
Fuels and inerts in treated NCG ($\%_{vol}$)	84.7	79.9	69.9
UFL	69.9		
UFL + 10%	79.9		

Based on the flammability analysis of the design basis conditions, the treated gas is above the UFL and UFL+10% as safety margin, and therefore outside the flammability envelope and can be considered safe as it is “too rich to burn”. The analysis shows that when the O_2 concentration in the input NCG to the gas scrubbing station reaches 1.32%, the concentration of fuels and inerts falls below the UFL+10% safety factor. Furthermore, when the O_2 concentration reaches 2% in the input gas, the concentration of fuels and inerts falls below the UFL factor and into the explosive region.

This flammability analysis and limits are however based on ambient conditions (1 atm pressure and 25°C) and require adjustments in the next phases of Koldís for correspondence to the actual conditions. Given that H_2 is the primary flammable gas component in the treated NCG, literature indicates the flammability limits will vary slightly [11]. The project also requires more detailed analysis on the flammability and how different operating scenarios influence the risk present.

5 CONCLUSION AND FUTURE WORK

The application of a systematic approach to decrease the oxygen gas concentration has been successful at Þeistareykir GPP. The O_2 gas concentration was ranging from 0.40-4.06% prior to leak detection. After the first phases of leak detection, the O_2 gas concentration has been lowered to a range of 0.67-0.92 $\%_{vol}$ O_2 with an overall average of 0.74 $\%_{vol}$ O_2. As a result, the NCG from all GESs is below the design basis with a maximum oxygen content of 1$\%_{vol}$ O_2. Based on this, no red flags nor technical barriers have been identified in the pre-design of the gas scrubbing system. However, the removal percentage of CO_2 may become limited by the flammability issues due to variations in the NCG composition.

The NCG composition is directly dependent on the production wells in operation and electricity generation. Therefore, variations in O_2 gas concentration are present in time, which highlights the importance of proper monitoring. The results of the flammability analysis conclude that the design basis conditions, with 1% O_2 concentration in the NCG, do not lead to the treated gas being in the flammable region. When the O_2 concentration reaches 1.32% and 2% however, the mixture that enters the scrubbing tower falls below the UFL and UFL+10% and into the explosive region. Based on the correlation of O_2 concentration to the electricity generation, certain fluctuations in the concentration are to be expected and require more detailed measurements for confirmation. This highlights the importance of a more detailed flammability analysis in the next phase of the project.

The process of leak inspection will continue simultaneously to the next phases of the project, with the aim of minimizing the O_2 gas concentration to an acceptable limit (preferably near 0% O_2) and gaining further understanding on the variations. In the next years, real-time O_2 measurements will be installed at Þeistareykir GPP as a pre-requisite for the commissioning of the Koldís project. The measurements will serve both for monitoring and safety purposes. A clear action plan and methodology of leak detection after maintenance stops will be implemented in the daily operation of the power plant, to prevent regular increases after such stops.

In 2023, the detail engineering phase of the Koldís project will be carried out with the aim of tendering in 2024 and commissioning in 2025. In the detail engineering phase, proper monitoring, and controls for the gas scrubbing system to limit the risk of ignition will be decided upon.

REFERENCES

[1] B. K. M. D. M. C. B. L. M. B. B. B. K. D. S. a. M. A. Piggot, "Non-Condensable Gas Composition Impacts on Carbon Capture and Water Injection," in *Geothermal Rising Conference (GRC)*, San Diego, CA, 2021.

[2] S. Arnórsson, Ö. Bjarnason, N. G. I. Giroud and A. Stefánsson, "Sampling and analysis of geothermal fluids," *Geofluids,* vol. 6, no. 3, pp. 203-216, 2006.

[3] S. Arnórsson, A. Stefánsson and J. Bjarnason, "Fluid-fluid interactions in geothermal systems," *Reviews in Mineralogy and Geochemistry,* vol. 65, no. 1, pp. 259-312, 2007.

[4] B. A. M. S. S. K. M. A. E. ,. G. I. Sigfússon, "Reducing emissions of carbon dioxide and hydrogen sulphide at Hellisheidi power plant in 2014-2017 and the role of CarbFix in achieving the 2040 Iceland climate goals," *Energy Procedia,* vol. 146, no. 1876-6102, pp. 135-145, 2018.

[5] R. A. J. Rendón-López, "Molecular dynamics simulations of the solubility of H2S and CO2 in water," *Journal of the Mexican Chemical Society,* pp. 88-92, 2008.

[6] S. W.-B. D. S. A. O. E. G. E. S. H. S. B. B. W. M. J. S. M. A. G. F. T. Gislason, "Mineral sequestration of carbon dioxide in basalt: A pre-injection overview of the CarbFix project," *International journal of greenhouse gas control,* vol. 4, no. 3, pp. 537-545, 2010.

[7] S. M. P. S. A. Gudbrandsson, "H2S Injection and Sequestration into Basalt - The SulFix Project," in *American Geophysical Union*, 2014.

[8] Á. H. T. P. J. S. K. Sigurðardóttir, "Þeistareyki Geothermal Power Plant - Deposits in Gas Removal System," in *World Geothermal Congress 2020+1*, Reykjavik, 2021.

[9] A. Stefánsdóttir, "Quantification of CO2 and H2S gas emissions from Krafla geothermal power plant (MSc thesis)," Landsvirkjun, 2021.

[10] H. J. G. Coward, Bureau of Mines (bulletin 503) - Limits of flammability of gases and vapors, Washington: United states government printing office, 1952.

[11] V. H. K. Schroeder, "Explosion Characteristics of Hydrogen-Air and Hydrogen-Oxygen Mixtures at Elevated Pressures," in *ICHS International Conference on Hydrogen Safety*, 2005.