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OPTIMIZED GAS WASTE MANAGEMENT STRATEGIES FOR GEOTHERMAL PROJECTS FOR CARIBBEAN SMALL ISLAND DEVELOPING STATES (SIDS)

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ABSTRACT

Geothermal energy is considered internationally as an environmentally friendly and renewable energy resource. Non-condensable gases (NCGs) are a natural component of all geothermal systems and are normally released to the atmosphere during geothermal electricity production. NCGs contain greenhouse gases (GHGs) such as carbon dioxide (CO_2) and methane (CH_4) along with hydrogen sulphide (H_2S), hydrogen (H_2), nitrogen (N_2) and other gases in trace quantities. This report investigates emissions of three geothermal wells in the Eastern Caribbean islands of the Commonwealth of Dominica, Saint Lucia and Montserrat, all classified as Small Island Developing States (SIDS).

The report quantifies the three islands' GHG emissions in proportion to their proposed plant size for electricity production. These emissions are compared to commitments submitted as part of their Nationally Determined Contributions (NDC) under the 2015 Paris Climate Agreement. The results indicate that the estimated GHG emissions from the three islands vary significantly, although the systems are located within the same Caribbean volcanic arc. The report investigates a suitable assessment method for gas abatement technology based on GHG emissions.

Geothermal systems vary between locations but for Caribbean SIDS it is important that the emissions potential is carefully evaluated when considering the reason to use geothermal as an alternative source of energy to conventional systems. Geothermal power plants that are properly designed can minimize emissions and provide additional benefits to the surrounding communities.

1. INTRODUCTION

Small Island Developing States (SIDS) are a group of developing countries facing particular social, economic and environmental vulnerabilities. Of the fifty-seven nations listed as SIDS in the United Nations Department of Economic and Social Affairs, twenty-three belong to the Caribbean region. Many of the islands in the Caribbean region have indicated a strong interest in geothermal development in an effort to increase energy security and to reduce GHG emissions. Dominica, Saint Vincent, Grenada, Saint Kitts and Nevis, Saint Lucia and Montserrat (UK Overseas Territory) have begun geothermal exploration and are in various stages of development.

Geothermal energy is a renewable energy source (if managed properly) and is considered a suitable alternative to the conventional use of fossil fuel for electricity generation and heating due to its minimal environmental impact. As a result, several Caribbean islands have considered the use of geothermal energy as an alternative to fossil fuel electricity generation and have included it in their Nationally Determined Contributions (NDCs) as part of their submissions to the 2015 Paris Climate Agreement. In 2015 the Caribbean islands also adopted the 2030 agenda for Sustainable Development and the seventeen (17) sustainable development goals (SDGs). Goal number seven (7) speaks to facilitating access to clean energy. These goals along with the country's NDCs will assist in the combat against climate change.

Geothermal development in the Caribbean region is mainly for electricity production and non-condensable gases (NCGs) are an unavoidable part of geothermal utilization. The main components of the NCGs in geothermal fluids are carbon dioxide (CO_2), hydrogen sulphide (H_2S), nitrogen (N_2), methane (CH_4), oxygen (O_2), hydrogen (H_2), argon (Ar), ammonia (NH_3) and other gases in trace quantities (Fridriksson et al., 2016).

Methane and carbon dioxide are the main greenhouse gases relevant to geothermal systems, with CO_2 being the most abundant gas. The majority of NCGs from geothermal plants are released into the atmosphere and the significant impact of these emissions has not been properly studied (Fridriksson et al., 2016).

Another gas, which may be found in significant levels in geothermal fluids, is hydrogen sulphide (H_2S). Although not a greenhouse gas, this gas may have detrimental health effects in low concentrations. H_2S is normally emitted near geothermal surface manifestations. Caribbean SIDS are heavily dependent on tourism and the effect of H_2S may have adverse impact on this vital sector and inadvertently on the economy. H_2S normally has an odour at very low concentrations and can be lethal even in low concentrations. In SIDS, geothermal plants would commonly be situated near communities and cities and therefore it is important that these emissions are analysed and assessed for potential health risks. Management of these emissions would therefore be essential in areas where their level has proven to be significant and may cause adverse health related issues.

1.2 Objectives of the study

The objectives of the study are to:

- Investigate the gas emissions from three geothermal areas in the Caribbean region;
- Assess the levels of emissions and the need for abatement systems with reference to the country's NDCs;
- Recommend the optimized gas waste management strategies for greenhouse gas (GHG) and hydrogen sulphide emissions in the three fields; and
- Recommend a suitable method for assessment of brownfields and abatements methods.

2. EMISSIONS AND CLIMATE CHANGE

2.1 Overview of gas waste in geothermal systems

Geothermal energy is known to be a renewable and environmentally beneficial energy source, especially when compared to fossil fuels. This does not mean that environmental impacts cease to exist. As with many renewable energy developments, the environmental impacts may be minimal when compared to fossil fuel.

Gas discharges from geothermal systems vary from location to location depending on the geology and the type of system, whether it is low temperature or high temperature. Low temperature systems are normally not associated with gas release, but in high temperature systems, power generation usually involves steam and the release of NCGs into the atmosphere.

In Table 1, a general example of the proportions of non-condensable gases in a geothermal resource is given.

TABLE 1: Example of proportion of non-condensable gases at a geothermal location (modified from Bloomfield et al., 2003)

NCG component	Dry gas % by volume
Carbon dioxide (CO_2)	97.8
Hydrogen sulphide (H_2S)	1.2
Methane (CH_4)	0.5
Ammonia (NH_3)	0.05
Other gases	0.45

Geothermal greenhouse gas emissions are predominantly CO_2, and CH_4 in lesser quantities. Carbon dioxide occurs in all geothermal systems, but it is very prevalent in fields with sedimentary rock and limestone (Hunt, 2001). CO_2 is heavier than air, which means that it can accumulate in topographic lows if the air is stagnant. Increased CO_2 emissions have been a major contribution to the greenhouse effect and the cause of global warming. Studies and measurements conducted on CO_2 emissions in geothermal systems indicate that these emissions may range from less than 50g/kWh in many geothermal fields to more than 1400g/kWh in some fields in Turkey as shown in Figure 1.

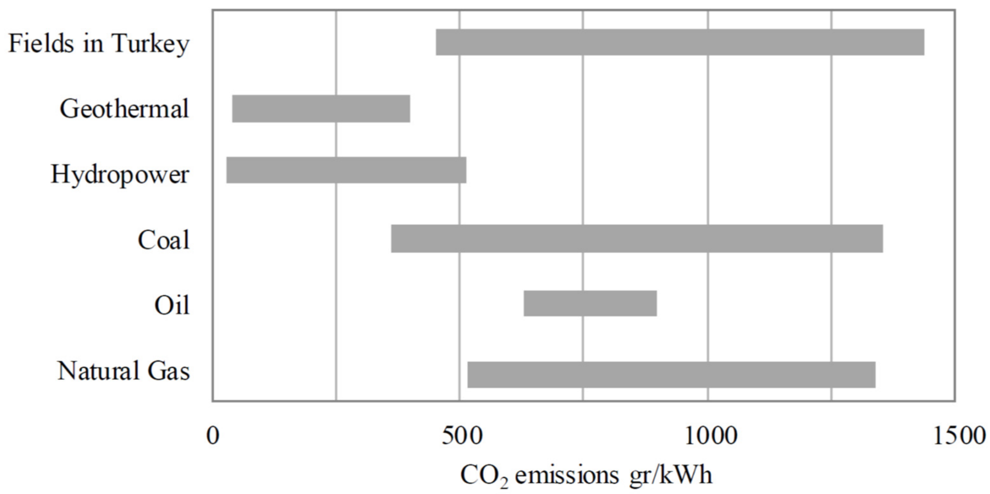

FIGURE 1: Contribution of CO_2 emissions from different energy sources. Modified from (Kristmannsdóttir and Ármannsson, 2003 in Aksoy et al., 2015)

Methane is found in low quantities in geothermal systems and occurs naturally below the ground surface. Methane is up to 34 times more potent as a greenhouse gas than carbon dioxide (Pachauri et al., 2014). Therefore, even in small quantities, the effect of methane gas should be analysed when estimating GHG emissions.

Hydrogen sulphide can be found in high concentrations in some fields and should be monitored due to its health risks to mammals. H_2S is a toxic gas at high concentration. At low concentrations, H_2S has an odour of 'rotten eggs' and is sometimes unpleasant. H_2S emissions are very common near surface manifestations and can be hazardous to workers and communities in close proximity.

Other gases such as ammonia, boron, argon, oxygen and hydrogen are emitted in extremely low quantities and therefore have insignificant impact on human health (Hunt, 2001).

Although the gas emissions from geothermal systems are normally small compared to conventional fossil fuel systems, it is important that these emissions are quantified, in particular with regard to reporting requirements to international agencies. To minimise the impact of these gases, effective design of power plants is essential.

2.2 Greenhouse gas emissions and Small Island Developing States

Anthropogenic GHG emissions have mainly been attributed to only a very small number of countries. When comparing global emissions to those from SIDS, emissions from SIDS are considered to be near zero. In 2012, the Barbados Declaration on Achieving Sustainable Energy for All in Small Island Developing States (SIDS), stated that SIDS contribute the least to global emissions. Nevertheless, SIDS continue to take significant actions towards the reduction of their own emissions demonstrating their contribution to resolving global climate change and leadership in the battle against climate change. Global emissions continue to rise and therefore the effects of climate change and sea level rise are a reality to SIDS (Pachauri et al., 2014).

In 2015, SIDS took the initiative to lead the fight against climate change and played an integral role in the formulation of the Paris Climate Agreement. The Paris Climate Agreement included countries NDCs. The NDCs indicate countries' best efforts to reduce emissions at the national level which will result in overall global reduction. As part of this obligation, global stocktake is expected every five years.

In many SIDS, energy and mainly the electricity sector has been the focus for their NDCs. The energy sector is the largest contributor to GHG emissions in many SIDS, as it is mainly based on fossil fuels. SIDS have indicated their resolve to transition to renewables, with geothermal playing a large role, and it is mentioned in at least five Caribbean SIDS NDCs.

Therefore, it is critical that while transitioning to renewable energy SIDS take into consideration all the potential GHG emissions and methods to mitigate these emissions. Management of these emissions should be effective, economical and maintain affordability to consumers.

2.2.1 Nationally Determined Contributions and geothermal energy

In 2015, countries clearly outlined their post-2020 climate actions known as their Nationally Determined Contributions. The NDCs outline each country's ambitious targets to react to climate change and achieve the Paris Climate Agreement, e.g.:

- To hold the increase in global average temperatures to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C; and
- To achieve net zero emissions in the second half of this century, in the context of sustainable development.

In the Paris Agreement all countries are mandated to provide an update on the achievement of their NDCs. The update should be transparent, accurate, complete and consistent. The Paris Agreement also recognises the importance of support required by developing countries to meet their NDCs, such as through the United Nations Framework Convention on Climate Change (UNFCCC), which enables the provision of financial, technological and capacity-building support to developing countries to meet their goals. This is reflected in many of the Caribbean SIDS NDCs targets being conditional on received support.

The Government of the Commonwealth of Dominica has presented a conditional target to reduce GHG emissions by 39.2% and 44.7% from 2014 levels by 2025 and 2030, respectively. Total emission reduction from the energy industries should be 98.6%. The reduction is expected to be achieved mainly by the implementation of geothermal energy production while maintaining affordability to consumers (INDC Dominica, 2015).

The Government of Saint Lucia has presented a conditional target measured against business as usual emissions from the base year of 2010. Emissions are expected to be reduced by 16% and 23% by 2025 and 2030, respectively. The affected sectors are energy, electricity generation and transport. The electricity generation sector seeks to produce 35% of the energy from renewable sources by 2025 and 50% by 2030, with a mix of geothermal, wind and solar energy to achieve these reductions (INDC Saint Lucia, 2015).

Montserrat is a UK overseas territory and is not a recognised sovereign state at the United Nations and therefore not a party to the UNFCCC.

In addition, many SIDS have developed Nationally Appropriate Mitigation Actions (NAMAs) for various sectors and these are in-line with their NDCs targets. At the 24th Conference of the Parties to UNFCCC (COP 24), countries committed to strengthen the technical examination on mitigation actions. The technical examination process explores high-potential policies, practices and technologies that increase ambition of pre-2020 climate actions. It is therefore essential that countries consider every possible method for reducing GHG emissions to ensure that human interference with the climate is kept to a minimum.

2.3 Impact of hydrogen sulphide (H_2S)

H_2S is a colourless gas and usually has a 'rotten egg' odour. This smell is only detected at low concentrations. The gas can be released from water or soil in areas where geothermal fluid finds its way to the surface, is produced or used. Since H_2S has a higher density than air, it may accumulate in caves and depressions and pose a hazard to those who encounter the gas.

H_2S remains in the air for one to forty-two days depending on the weather. In water, it evaporates quickly and concentrations are very low, and in soil, bacteria consume it (ATSDR, 2016). Therefore, it is important that H_2S levels in air are monitored closely as the levels may remain unchanged for several days in areas where the air is stagnant.

H_2S does not accumulate in the body but exposure to low concentrations of H_2S may cause irritation to the eyes and respiratory tract. Symptoms of exposure may include headache, fatigue, dizziness, memory loss and balance problems. In large amounts, it results in paralysis of the respiratory centre and death. (ATSDR, 2016). Long-term exposure of low concentrations may cause pharyngitis and bronchitis. It may also cause difficulties in breathing for asthmatics.

Surface manifestations are normally a sign of a potential geothermal resource; H_2S emissions are a common occurrence near or around these surface manifestations but commonly at low concentrations. A study conducted on residents in Rotorua, New Zealand, near a geothermal resource, showed that residents had significant incidences of disorders of the peripheral nervous system and sense organs when compared with the rest of New Zealand residents (Bates et al., 1998). Although there is consistency between these effects and H_2S, evidence on the actual cause is limited. Nevertheless, efforts to minimise the risk of H_2S exposure to residents in the vicinity of geothermal fields should be considered.

The United States Occupational Safety and Health Administration (OSHA) develops regulations for toxic substances including H_2S. The National Institute for Occupational Health and Safety (NIOSH) and the Agency for Toxic Substances and Disease Registry (ATSDR) are federal agencies that submit recommendations on acceptable levels of toxic substances, and these are regularly updated. Table 2 and Table 3 show guidelines with respect to toxic H_2S levels. The World Health Organisation (WHO) air quality guideline for H_2S is 150 μg/m^3 or 0.1 ppm for an average concentration over 24 h (WHO, 2000), established with respect to signs of eye irritation. To avoid odour annoyance, a 30-min average ambient air concentration not exceeding seven (7) μg/m^3 or 0.005 ppm is recommended (WHO, 2000).

Many Caribbean SIDS do not have specific regulations for hydrogen sulphide (H_2S) levels and therefore the World Health Organisation (WHO) guidelines and other international guidelines are adhered to when possible.

TABLE 2: H_2S toxicity levels (OSHA, 2019)

Concentration (ppm)	**Symptoms / effects**
0.00011-0.00033	Typical background concentrations
0.01-1.5	Odour threshold (when rotten egg smell is first noticeable to some). Odour becomes more offensive at 3-5 ppm. Above 30 ppm, odour described as sweet or sickeningly sweet.
2-5	Prolonged exposure may cause nausea, tearing of the eyes, headaches or loss of sleep. Airway problems (bronchial constriction) in some asthma patients.
20	Possible fatigue, loss of appetite, headache, irritability, poor memory, dizziness.
50-100	Slight conjunctivitis ("gas eye") and respiratory tract irritation after 1 hour. May cause digestive upset and loss of appetite.
100	Coughing, eye irritation, loss of smell after 2-15 minutes (olfactory fatigue). Altered breathing, drowsiness after 15-30 minutes. Throat irritation after 1 hour. Gradual increase in severity of symptoms over several hours. Death may occur after 48 hours.
100-150	Loss of smell (olfactory fatigue or paralysis).
200-300	Marked conjunctivitis and respiratory tract irritation after 1 hour. Pulmonary edema may occur from prolonged exposure.
500-700	Staggering, collapse in 5 minutes. Serious damage to the eyes in 30 minutes. Death after 30-60 minutes.
700-1000	Rapid unconsciousness, "knockdown" or immediate collapse within 1 to 2 breaths, breathing stops, death within minutes.
1000-2000	Nearly instant death.

TABLE 3: H_2S toxicity levels (OSHA, 2019)

Worker Exposure Limits / ppm
NIOSH – Recommended exposure limit (10 min ceiling): 10 ppm
OSHA – Permissible Exposure Limit (PEL) enforceable General Industry Ceiling Limit: 20 ppm General Industry Peak Limit: 50 ppm (up to 10 mins if no other exposure during shift) Construction 8-hour limit: 10 ppm Shipyard 8-hour limit: 10 ppm
NIOSH – Immediately dangerous to life and health (level that interferes with the ability to escape) (IDLH): 100 ppm

3. GEOTHERMAL DEVELOPMENT IN THE EASTERN CARIBBEAN REGION

3.1 Overview of geothermal development in the region

The Eastern Caribbean or the Lesser Antilles Island Arc is a chain of islands formed at the convergent plate boundary of Atlantic oceanic plate subducted beneath the less dense Caribbean plate. The island arc extends 850 km along the eastern edge of the Caribbean plate. The arc has eleven (11) volcanically active islands with twenty-one (21) active volcanoes (Montserrat Volcano Observatory, 2017). Each island is usually constituted of a single active volcano, except the island of Dominica with nine active volcanoes. Figure 2 shows the Eastern Caribbean islands and their active volcanoes.

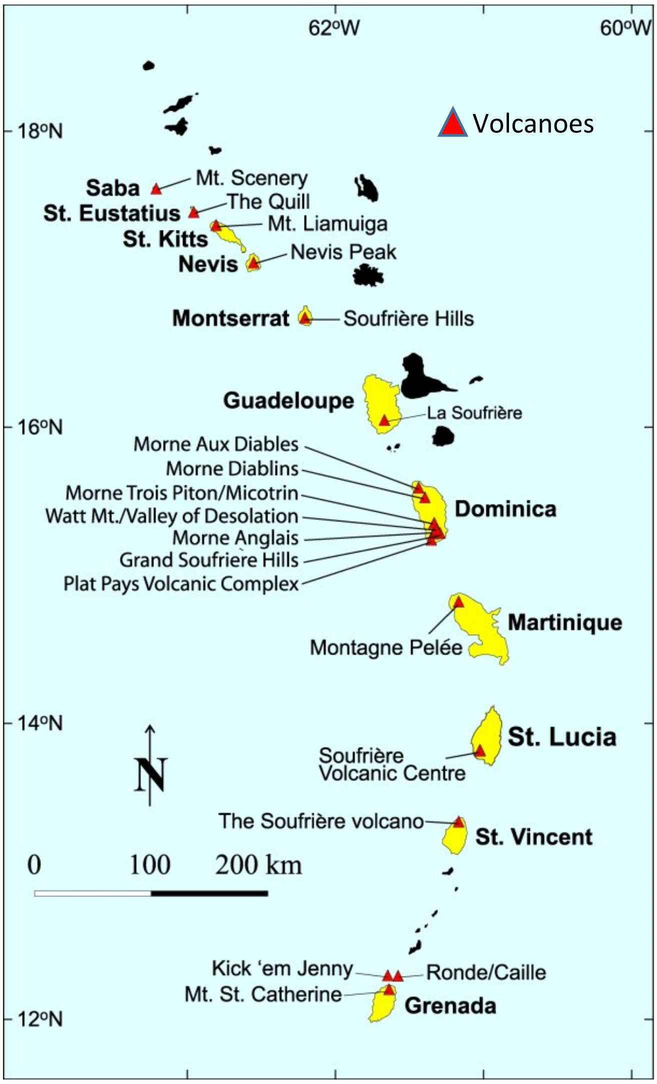

FIGURE 2: Map showing active volcanoes in the Eastern Caribbean (Montserrat Volcano Observatory, 2017)

Geothermal potential is commonly found in regions with volcanic activity. Geothermal resource development has become a priority for many of the islands as indicated in their NDCs. The islands of Saint Kitts and Nevis, Dominica, Martinique, Guadeloupe, Saint Lucia, Saint Vincent and the Grenadines, Grenada and Montserrat have all shown interest in geothermal resource development. Currently, the only operating plant is in the island of Guadeloupe.

As of 2019, Dominica and Nevis have successfully drilled production wells and are preparing for power plant development. Montserrat also has a successful production well and is preparing for the next phase of power plant development. Saint Vincent has begun drilling of a production well and Saint Lucia is once again preparing for test drilling after previous exploration studies were completed in the 1980s. The World Bank and other international organizations have been assisting the region in the development of their geothermal resource potential.

3.1.1 Dominica geothermal activity

The Commonwealth of Dominica is located in the central Lesser Antilles arc and has an area of 750 km^2. It is known to be the most rugged island of the Lesser Antilles and has a population of 67,408 (Ministry of Planning and Economic Development, Dominica, 2019). Most of the island's geology is marked by pyroclastic flow associated with the Wotten Waven caldera on the eastern outskirts of the capital (UWI SRC, 2015).

The geothermal project began with international funding in the 1980s (Lyn Fontenelle, Environmental Safeguards Officer DGDC, personal communication, 23rd August, 2019). The exploratory phase began in 2011-2012 in the villages of Wotten Waven and Laudat. Two full size wells were then drilled: A production well in Wotten Waven and a re-injection well in Trafalgar to depths of 1501 m and 1915 m, respectively. The distance from the production well to the reinjection well is estimated to be 3.5 km (Gabriel and Kubale, 2018). The measured temperature in the production well is 240-250°C (Ministry of Public Utilities, Energy and Ports, Dominica, 2012). The formations in the production well may be described as pyroclastic flows in the upper section, andesitic intrusions in the middle section and lithified tuff and breccia in the lower section (Jónsson et al., 2012). Figure 3 shows the area of the reservoir in red and the surrounding villages and communities.

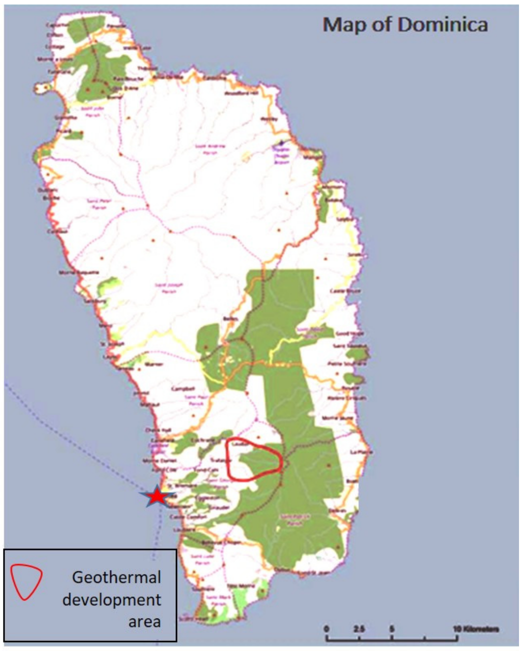

FIGURE 3: Area for geothermal development in Dominica (modified from Gabriel and Kubale, 2018).

3.1.2 Saint Lucia geothermal activity

The island of Saint Lucia is located in the lower Lesser Antilles arc and has an area of 616 km^2. Saint Lucia has a population of 174,417 (Research and Policy Unit Saint Lucia, 2018). The Sulphur Springs in Soufriere are the hottest and most active surface manifestation area in the Lesser Antilles.

The island's geothermal resource in Soufriere is in a prime tourist attraction and a UNESCO World Heritage Site. Geothermal exploration began in the 1950s with a number of exploratory and test drilling activities carried out with development partners support, but the conditions required for commercial viability were never fully confirmed.

In the late 1980s two exploratory wells were drilled. The second well, SL-2, was drilled to a depth of 1400 m and encountered good flow rates and high temperatures of above 290°C but also a high gas content of approximately 20% of the weighted steam (Lovelock et al., 2016). While high temperature steam resources have been located in the areas that were drilled, low permeability, high concentration of non-condensable gases, and low pH levels were also encountered. Therefore, the geothermal resource has not been confirmed yet and no investment decision has been made to move forward with commercial development (Panorama Environmental Inc., 2018).

The island of Saint Lucia has an eroded basalt and andesite centre, dissected andesite centres, extensive pyroclastic flow deposits, lava flows, phreatic/phreatomagmatic craters and domes associated with block and ash flow (Lindsay et al., 2002). Saint Lucia has always been regarded as a volcanic island and the major geological studies and surveys confer with this assessment. A 1984 report from the Los Alamos National Laboratory on the Saint Lucia geothermal resource suggests that a basement of carbonate rocks lies at a depth of approximately 2500 m based on their presence in xenoliths in younger volcanic rocks, but the extent of this layer is unknown (Ander et al., 1984).

Geothermal development in Saint Lucia is currently being pursued again with the hope that a suitable resource can be found. Surface exploration and prefeasibility studies have been completed in the three potential drilling areas of Belle Plaine, Fond St. Jacque and Mondesir-Saltibus (Panorama Environmental Inc., 2018). Figure 4 shows the Soufriere region in Saint Lucia and the Sulphur Springs reserve area (Lovelock et al., 2016).

3.1.3 Montserrat geothermal activity

Montserrat is a UK Overseas Territory, located in the upper Lesser Antilles arc. The island has a total surface area of approximately 40 km^2 and a population of 4,922 (Statistics Department, Montserrat, 2012). The geothermal potential of the island is located near the Soufriere Hills volcano. This volcano erupted in 1995 and left two-thirds of the island uninhabitable.

Research on the geothermal resource of the island began in 1997 (Atoms Solution Incorporated, 2015). Development continued in 2010 with a study by the UK Department for International Development (DFID). In 2012, two wells were successfully drilled to depths of 2298 and 2870 m with recorded temperatures of 230°C and 260°C, respectively. The formations in the wells are young andesite flows, breccia, clay-altered ash units and silicified tuff or tuffaceous sandstone (Brophy et al., 2014).

FIGURE 4: Area for geothermal development in Saint Lucia (modified from Lovelock et al., 2016).

3.2 Gas composition in the fields of study

The fields under investigation are all brownfields. Brownfields are defined as projects in capacity drilling phase or capacity expansion phase (Fridriksson et al., 2016). The three fields are in various stages of geothermal development. The gas composition values indicate the characteristics of the NCGs in the fields. Based on the limited well data, carbon dioxide (CO_2) appears to be the dominant NCG in the study areas.

Dominica
Figure 5 shows the composition of NCGs in the Dominica geothermal well WW-03. The mole percent of carbon dioxide is 95.4%, with 2.7% hydrogen sulphide, 1.4% nitrogen, 0.3% hydrogen, 0.02% methane, and the other gases in small amounts total 0.3%. The total percentage of gas content in the steam is 2.71 wt% (Ministry of Public Utilities, Energy and Ports, Dominica, 2012). The original data are shown in Table 1 of Appendix I.

Saint Lucia
Figure 6 shows the composition of NCGs in the steam in Saint Lucia geothermal well SL-02. The mole percent of carbon dioxide in the gas is 90.5%, with a high hydrogen gas content of 5.6%, 2.1% hydrogen sulphide, 1.1% nitrogen, 0.7% methane and the other gases in small amounts total 0.007%. The steam from the Saint Lucia well has a high gas content of approximately 20 wt%, but it does not have the typical volcanic steam composition with H_2S-SO_2 of more than 10 wt% and low H_2 (Lovelock et al., 2016). The original data are shown in Table 2 of Appendix I.

Montserrat
Figure 7 shows the composition of NCGs in the steam in Montserrat geothermal well Mon-2. The mole percent of carbon dioxide is 88.4%, with 6.0% nitrogen, 4.5% methane, 0.3% hydrogen sulphide, 0.3% hydrogen and the other gases in small amounts total 0.5%. The gas content in the steam is 0.43 wt% (Brophy et al., 2014). The original data are shown in Table 3 of Appendix I.

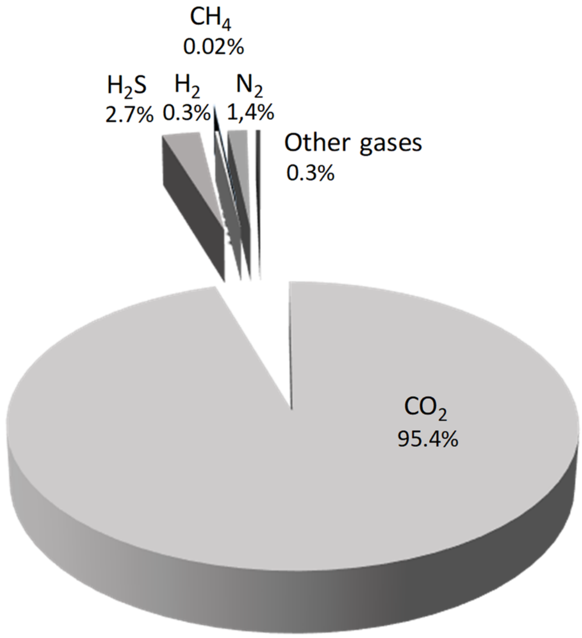

FIGURE 5: Composition (mole %) of NCG in well WW-03 in Dominica

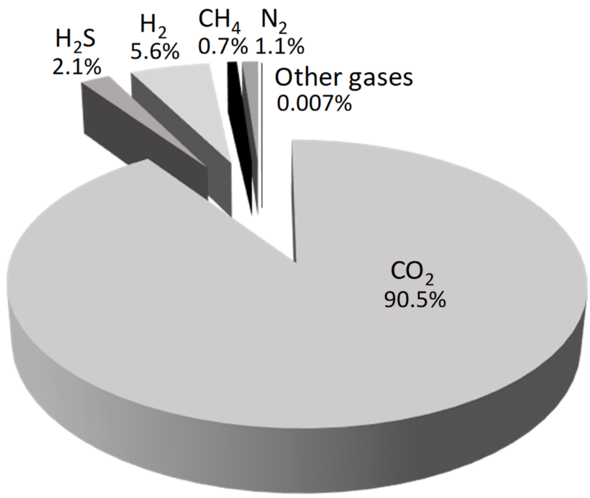

FIGURE 6: Composition (mole %) of NCG in well SL-02 in Saint Lucia

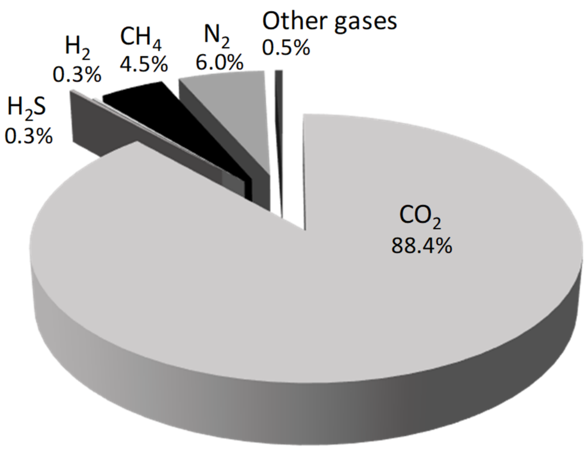

FIGURE 7: Composition (mole %) of NCG in well Mon-2 in Montserrat

3.3 Comparison of non-condensable gases composition of the Caribbean with the rest of the world

Table 4 shows a comparison of the NCG composition of the Caribbean wells and other wells found around the world. The compositions of the Caribbean wells are similar to those wells where carbon dioxide (CO_2) is the major NCG as shown in Table 1. In other areas, the composition may differ as shown in Table 4. This is, for example, the case for Hellisheidi and Nesjavellir, where the hydrogen sulphide (H_2S) composition is larger than the average.

TABLE 4: Gas composition by volume in different regions (modified from Zhao and Ármannsson, 1996).

Geothermal field	Well	Gas composition (mole percent/volume percent)				
		CO_2	H_2S	N_2	H_2	CH_4
Dominica (Caribbean)	WW-03	95.37	2.678	1.37	0.25	0.021
Saint Lucia (Caribbean)	SL-2	90.5	2.1	1.12	5.6	0.7
Montserrat (Caribbean)	MON-2	88.4	0.32	4.5	0.25	6
Hellisheidi (Iceland)	All turbines	66.3	18.4	13.8	1.3	0.2
Nesjavellir (Iceland)	NJ11	39.49	16.51	2.74	40.98	0.20
Theistareykir (Iceland)	All turbines	62.71	31.07	4.52	1.69	0.05
Olkaria (Kenya)	O6	81.80	8.20	1.20	8.10	0.70

Although the Caribbean wells have similar characteristics with respect to the level of carbon dioxide (CO_2), the percentage volume of the other NCGs are comparatively different. The well in Saint Lucia has a higher volume percentage in hydrogen gas (H_2) than the other two wells, but less than the value found in the well in Nesjavellir. The hydrogen sulphide (H_2S) levels in the Dominica and Saint Lucia wells are higher than the value in the well in Montserrat. These levels are still lower than the levels at Hellisheidi, Nesjavellir, Theistareykir, and Olkaria wells. The nitrogen gas (N_2) levels at the well in Montserrat is four times higher than the levels found in Dominica and Saint Lucia, but still lower than the volume at Hellisheidi.

There is no general composition for all wells and although the characteristics may be similar in a region, it is important that the characteristics and composition of the NCGs are investigated and analysed.

4. GAS EMISSION MANAGEMENT IN GEOTHERMAL UTILZATION

In geothermal power production, plants have four main components (some of which may be lacking in simpler designed plants): Separator, turbine, generator and condenser. The steam is separated from the flow in a separator and then expanded in a turbine to produce electricity through a generator. The steam from the turbine is then condensed in an effort to maximise the turbine efficiency. All geothermal steam contains NCGs and these must be continuously removed from the condenser to maximise the turbine efficiency. The NCGs are normally discharged into the atmosphere through cooling towers or by other safe means. The abatement technology is usually determined by the types of condensers used. These types can be classified into two groups: Direct contact condensers (water spray) and indirect contact condensers (heat exchangers). Figure 8 shows a diagram of a typical geothermal plant with an indirect condenser.

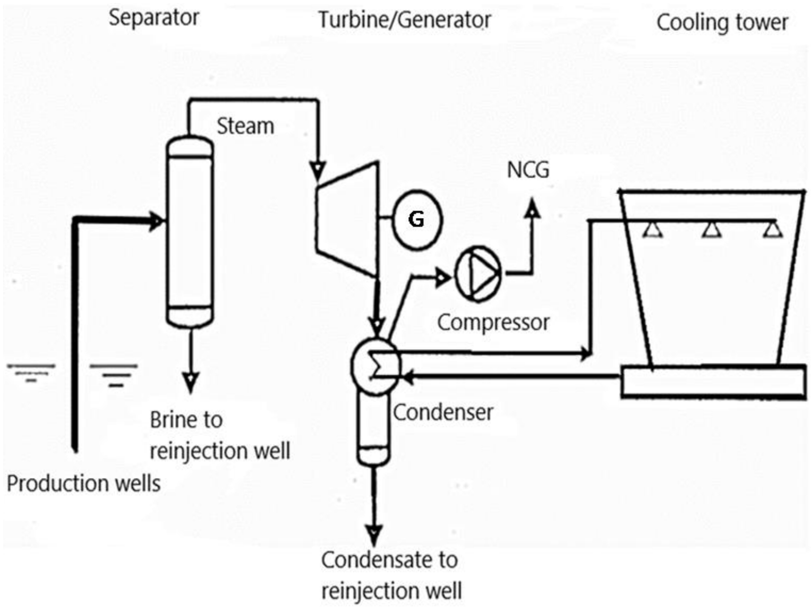

FIGURE 8: Diagram of a typical geothermal plant with indirect condenser (Nagl, 1999)

4.1 Condensers

4.1.1 Direct condensers

In direct condensers, the coolant or cooling water is sprayed directly onto the steam (Najafabadi, 2015). These types of condensers (spray or tray) provide a high rate of heat transfer with low-pressure drop. The vacuum level is controlled by the temperature of the cooling water and vacuum pumps extract the NCGs.

In spray jet condensers, the cooling water is sprayed by nozzles. This requires injection pressure to generate small diameter water droplets. The heat transfer occurs at the surface of the sprayed water droplets. In tray condensers, water droplets are generated as the cooling water travels to lower trays through holes (Tanoguchi et al., 2013).

Due to the direct contact of the coolant (cooling water) with the steam, the NCGs are mixed with dissolved oxygen. Geothermal water is usually oxygen depleted whilst cold water contains dissolved oxygen. This mixture creates difficulties in the separation of the NCGs for extraction. In addition, H_2S can produce sulphur dioxide (SO_2), another potentially toxic and harmful gas when mixed with oxygen.

4.1.2 Indirect condensers

Indirect condensers or surface condensers are heat exchangers. In these systems, the coolant (cooling water) and the steam are not in direct contact with each other. The chemical and physical properties of the steam and the NCGs are not altered in these systems.

Different types of heat exchangers exist, some of these are shell-and-tube, air-cooled and plate systems. In shell and tube systems, the cooling water circulates inside the tubes and the saturated steam is condensed on the outside of the tubes. The operating pressure is determined by the temperature of the water inlet into the condenser depending on the flow rate (Najafabadi, 2015).

The air-cooled systems are used where water may be scarce. The condensing vapour flows through a bank of thinned tubes and the cool, ambient air is blown across the system. These types of condensers are common in binary systems such as those found in the Matsukawa and Ohaaki field in New Zealand (Najafabadi, 2015).

Plate heat exchangers consist of a series of parallel thin plates that permit the flow of fluid between the plates. Inlet and outlet holes allow the steam and coolant to flow through alternate channels in the heat exchanger (Golin, 2019). One plate is always in contact with both the steam and the coolant to allow the heat exchange to occur. Spiral plate exchangers are made by creating concentric spirals of two long metal plates around a centre core. This creates two spiral flow passages, one for the steam and the other for the coolant. Advantages of this system are ease of maintenance, expandability and compact design compared to shell-and-tube.

4.1.3 Direct vs. indirect condensers

Direct condensers are advantageous in that they are less expensive than indirect condensers and have a higher rate of heat transfer. In pumping, there are high-pressure losses to the nozzles and significant pressure losses in the backpressure of turbines. Direct condensers also introduce the risk of scaling in the cooling tower due to the emissions of the NCGs. The cooling water also becomes polluted with dissolved NCGs.

Their applications are limited in cases where the mixing of the coolant and the condensate is not beneficial (Najafabadi, 2015). In many applications where the non-condensable gases are removed and treated for different applications, the use of direct condensers is considered inappropriate.

Indirect condensers are more suited to the extraction and treatment of NCGs as the coolant and the condensate are kept separate. In these systems, there is no NCG emission and scaling in the cooling tower. The main disadvantage of this system is the higher demand for cooling water. Indirect condensers allow NCGs in some cases to be reinjected into the geothermal water or the effective use of gas abatement technologies such as those used for the extraction of carbon dioxide (CO_2). It is essential in gas waste management that indirect condensers are used in the systems.

4.2 Gas management technologies and cost

Although non-condensable gases in geothermal utilization are unavoidable, options are available to reduce the emissions of greenhouse gases and hydrogen sulphide (H_2S). Several methods exist for carbon dioxide (CO_2) and hydrogen sulphide (H_2S) abatement. The costs for the given technologies are abstracted from the 2016 Energy Sector Management Assistance Program (ESMAP) technical report on greenhouse gases from geothermal power production (Fridriksson et al., 2016). These costs are from the US market and include capital costs, operational costs and a 20% contingency. Due to the proximity of the US market to the Caribbean market, the costs are deemed comparable. Additional costs for shipping are not included in the calculations as it assumed that the equipment for the abatement system would be purchased during the construction of the power plant. This would minimise additional shipment costs.

4.2.1 Carbon dioxide (CO_2) abatement

Carbon dioxide (CO_2) abatement methods have been studied for a number of years. The literature is filled with the process of CO_2 abatement and requirements. A short description is given on the types of CO_2 abatement strategies that are considered in this report.

Carbon dioxide (CO_2) *recovery for use in greenhouses*
CO_2 can be captured for use in greenhouses, as it is an essential component of the process of photosynthesis. The increase of CO_2 in a greenhouse, up to a certain point, enhances productivity through improved plant growth. In order to obtain CO_2 for greenhouses, the major gases such as hydrogen sulphide (H_2S), ammonia (NH_3) and water molecules (H_2O) need to be removed. Mercury may need to be removed as well depending on its level in the NCGs.

Table 5 shows published data from the American Conference of Governmental Industrial Hygienist (ACGIH) 8 hr threshold limit value (TLV) for carbon dioxide (CO_2) once it is diluted into the greenhouse air (McIntush et al., 2016).

TABLE 5: TLV for the purity requirement of the greenhouse gas CO_2 (McIntush et al., 2016)

Compound	**CO_2**	**H_2S**	**NH_3**	**H_2**	**CH_4**
ACGIH 8 hr TLV (ppmv)	5000	1	25	NA	NA

Data on mercury levels for the wells in the Caribbean are not available and therefore the levels are assumed to be negligible. The cost to remove mercury is not included in this analysis. The treatment cost for CO_2 use in greenhouses is estimated at USD \$5.00/tCO_2 (Fridriksson et al., 2016).

Carbon dioxide (CO_2) *recovery for beverages*
Carbon dioxide (CO_2) can be captured and treated for use in sodas and other beverages. This involves the removal of hydrogen sulphide (H_2S), ammonia (NH_3), nitrogen (N_2), Argon (Ar), methane (CH_4), hydrogen (H_2) and water molecules (H_2O). No further removal of trace gases is necessary for the systems being researched. The treatment cost for CO_2 recovery for beverages is estimated at USD \$21.10/tCO_2 (Fridriksson et al., 2016). Table 6 shows the level of purity of carbon dioxide for beverages.

TABLE 6: Carbon dioxide (CO_2) specification for beverages (EIGA, 2016)

Component	**Concentration**
Minimum purity	99.9 % v/v min
H_2O (moisture content)	20 ppm v/v max
Oxygen (O_2)	30 ppm v/v max
Carbonyl sulphide (COS) if total sulphur content >0.1 ppm v	0.1 ppm v/v max
Hydrogen sulphide (H_2S) if sulphur content >0.1 ppm v/v	0.1 ppm v/v max
Ammonia (NH_3)	2.5 ppm v/v max
Total hydrocarbons measured as methane (THC)	50 ppm v/v max of which 20 ppm v/v max non-methane hydrocarbons

Reinjection of carbon dioxide (CO_2)
Carbon dioxide (CO_2) can be captured and reinjected into the geothermal reservoir along with the mixture of brine and condensate or stored underground (sequestration). The process of storing carbon underground has been in the climate discussions for years and it is deemed to be one of the major tools for reducing carbon emissions. In the geothermal industry, the first option is mainly to mix CO_2 into the brine and condensate. It is estimated based on values previously presented that one ton/hr of CO_2 would require 50 ton/hr of geothermal liquid at a certain temperature and pressure to dissolve. This method involves the removal of ammonia from the gas to prevent the formation of solids. The estimated cost of this system is USD $10.30/t$CO_2$ (Fridriksson et al., 2016).

CarbFix
The mineralisation of CO_2 into stable carbonate minerals is an alternative storage approach successfully performed at the Hellisheidi power plant in Iceland. In this process, CO_2 is separated from the geothermal gases by dissolution in chilled condensate from the power plant. The CO_2 is completely dissolved in the mixture, which is then injected into the basaltic formation through a reinjection well. The CO_2 is mineralised into stable carbonate minerals in the reservoir (Matter et al., 2011). The estimated cost of this system is USD $27.6/t$CO_2$, which includes the drilling of a well for reinjection (Gunnarsson et al., 2018).

4.2.2 Hydrogen sulphide (H_2S) abatement

Hydrogen sulphide (H_2S) abatement is important in geothermal production as new fields are being explored with varying NCG composition. It is even more relevant in the extraction of CO_2 for other uses. H_2S abatement has been employed in the oil and gas industry for many years. H_2S abatement technologies are normally adapted from the oil and gas industry for geothermal development.

H_2S abatement technologies can be utilized at various sections in geothermal power production. The abatement technologies considered are technologies used in the downstream abatement of the gas. For this method, direct condensers are not recommended to be used (Sanopoulos and Karabelas, 1995). A short description on some types of abatement strategies based on the assessment and evaluations completed by Sanopoulos and Karabelas (1995) is given below.

Alkali scrubbing
This process normally involves low upfront capital, but the operating costs may be high due to the use of the chemicals in the process. The NCGs are scrubbed with alkali in a scrubbing tower; this method has been reported to be very simple and flexible. In this process, the carbon dioxide (CO_2) may also react to the alkali compound used in the process, which is usually sodium hydroxide (NaOH). With this process, more than 90% of H_2S gas can be removed.

Scavenger process
Small amounts of H_2S gas can be removed through an H_2S scavenger process. This system may involve an iron-based material which reacts with the H_2S to form pyrite (fool's gold). The process involves a low upfront capital, but operating costs may be high due to the use of chemicals similar to the alkali scrubbing process (Nagl, 1999).

Liquid redox sulphur recovery (LRSR)
In this process, the H_2S is absorbed from the NCGs and used to produce elemental sulphur for sale or disposal. This process is described in the 2016 ESMAP technical report on GHG emissions from geothermal power production (Fridriksson et al., 2016) for the removal of H_2S and the recovery of CO_2 for greenhouse use and beverages. This is one of the most commonly used processes as it can be operated at ambient temperature and pressure, as well as handling fluctuations in H_2S concentrations and gas flow rates. The LRSR systems can be divided into two groups: Vanadium-based and iron-based. The vanadium-based system is not recommended due to environmental concerns, as vanadium is a toxic substance (Stretford). The iron-based systems include examples such as LO-CAT, Sulferox,

Hiperion, Bio-SR, THIOPAQ, and Fe-Cl. The LRSR systems have the ability to meet a requirement for very low H_2S concentration. Most of the LRSR systems are complex and involve a high consumption of chemicals and a low quality sulphur product. These systems normally require very high capital costs.

Injection systems
This process is similar to the reinjection of CO_2. The NCGs are compressed, mixed with the brine and reinjected. The upfront capital and operational costs are relatively low and the process is able to achieve 100% removal of H_2S at low maintenance costs.

Absorption in water (SulFix) / water scrubbing
This process is used together with the CarbFix process. The method involves the dissolution of H_2S in condensate prior to reinjection and it is quite similar to the CO_2 injection process. H_2S has some solubility in water at atmospheric pressure and at elevated pressure the solubility can increase. H_2S solubility in water can be three times as high as that of CO_2. Therefore, H_2S would be more readily absorbed by the water and can be reinjected into wells. The reinjected solutions encounter the basaltic rocks and form secondary minerals. These minerals eventually precipitate into the porous basaltic rock. The problem with this system is that most geothermal NCGs contain high concentration of CO_2 and such a relatively high concentration can be found in the water used to scrub the H_2S (Aradóttir et al., 2015).

Claus process
This process was applied mainly in the oil and gas industry and some modifications have been made to it to ensure its suitability in geothermal systems. The process, developed by the chemist Carl Friedrick Claus in 1883, converts H_2S into elemental sulphur. It consists of a multi-stage catalytic oxidation of the gas involving a gas heater, catalyst chamber and condenser. The Claus process has been combined with a number of other processes such as the Selectox process used in the Yanaizu-Nishiyama geothermal power plant in Japan (Takahashi and Kuragaki, 2000).

4.2.3 Removal methods for other gases

Other gases found in geothermal fluids are normally found in small quantities. The method for gas removal or reduction depends on the gas management technology chosen and the quantity of the gas found in the geothermal fluid.

Ammonia (NH_3)
Ammonia (NH_3) can be removed by several techniques including dissolution in the condensate water, a combination of compression/chilling and acid scrubbing.

Water (H_2O)
H_2O may be removed through condensation. In situations where a more stringent level of removal is required, this is done through compression, chilling and glycol dehydration.

The other more volatile gases can be removed through fractional distillation in cases where it is deemed necessary. These include gases such as N_2, Ar, H_2 and CH_4.

4.3 Methodology for estimating greenhouse gas emissions in geothermal systems

The calculations of future GHG emissions have been conducted based on the equations provided in the 2016 ESMAP technical report on greenhouse gases from geothermal power production and the Clean Development Mechanism (CDM) for reporting of GHG emissions from geothermal power plants. The calculations were done based on the information available from exploration wells studied.

For greenfields and brownfields, where exploration wells have been drilled and tested, the well test data can be used to estimate the potential GHG emissions, depending on the type of plant envisaged. If the energy conversion technology selected is pumped binary technology, the future emissions can be assumed to be zero.

In some geothermal fields, only surface exploration has been completed and no wells have been drilled. In those cases, it is assumed that the emission factor is equal to the global geothermal emission factor of 128 g/kWh. This value takes into account emissions from both CO_2 and CH_4. The CO_2 emissions are estimated to be equal to the global average emissions of 122 g/kWh and the CH_4 emissions are estimated to be 5 percent of the emissions of CO_2 corresponding to 6.1 g/kWh. If carbonate rocks are suspected, this value changes to 790 g/kWh (Fridriksson et al., 2016).

The CDM methodology is used to calculate emissions from geothermal projects (Fridriksson et al., 2016). This methodology takes into account the emissions from the operation of the geothermal power plant. It is assumed that all NCGs are released into the atmosphere. Potential emissions are calculated using Equation 1.

$$PE_{GP,y} = \left(W_{steam,CO_2,y} + W_{steam,CH_4,y} * GWP_{CH_4}\right) * M_{steam,,y} \tag{1}$$

where: $PE_{GP,y}$ = Annual project emissions from the operation of geothermal power plants due to the release of NCGs in year y (t CO_2e/yr);
$W_{steam,CO_2,y}$ = Average mass fraction of CO_2 in the produced steam in year y (t CO_2/t steam);
$W_{steam,CH_4,y}$ = Average mass fraction of CH_4 in the produced steam in year y (t CH_4/t steam);
GWP_{CH_4} = Global warming potential of CH_4, taken as 25; and
$M_{steam,,y}$ = Quantity of steam produced in year y (t steam/yr).

The GHG emissions are based on the estimated plant size for each island. The mass of steam produced is assumed to be 8.50 $(t/h)_{steam}$ /MW (approximately 2.4 kg/s_{steam} /MW) and the capacity factor of the geothermal plant is assumed to be 77%. This is comparable to the capacity factor of the Hellisheidi geothermal power plant which is generally in the region of 83% (calculated from data received from Magnús Thor Arnarson, EPC project Manager, ON Power, personal communication, 8th October, 2019). For ease of calculations, it is assumed that the well characteristics at each site are the same. This is an idealized situation since well characteristics may be similar, but they may also differ depending on the geology.

Nationally Determined Contribution comparison
The projected geothermal emissions are compared to the islands' NDCs. The emission reduction targets are compared to the projected emissions from the geothermal systems and recommendations made for the update of NDCs in 2020, global stocktake and further assessment of geothermal systems by UNFCCC.

The emission reduction or avoided emissions are calculations related to the NDCs, based on the 2006 IPCC guidelines for National GHG Inventories using Tier 1 method for stationary emissions (Eggleston et al., 2006). It is assumed that geothermal systems would replace electricity generated through diesel powered generators only.

$$Emissions_{GHG,fuel} = Fuel\ consumption_{fuel} *\ Emission\ factor_{GHG,fuel} \tag{2}$$

where $Emissions_{GHG,fuel}$ = Emissions of a given GHG by type of fuel (kg GHG);
$Fuel\ consumption_{fuel}$ = Amount of fuel combusted (TJ); and
$Emission\ factor_{GHG,fuel}$ = Default emission factor of a given GHG by type of fuel (kg gas/TJ). For CO_2 this includes the carbon oxidation factor, assumed to be 1.

The net caloric value is assumed to be 43.0 TJ/Gg and the effective CO_2 emission factor of 74 / 100 kg/TJ for gas / diesel oil are used as default values in the calculations. The diesel fuel consumption is estimated to be 0.198 kg/kWh (Bunker et al., 2017), based on average fuel use in the Saint Lucia electricity power station. It is estimated that the avoided emissions are 630g CO_2e/kWh.

4.4 Justification for emission scenarios

The three islands studied have similar characteristics in relation to geology and composition of well gases, although differences are found in the gas content in the steam. The gas composition in the islands are dominated by carbon dioxide (CO_2) with traces of methane (CH_4).

As a result of this difference, it is difficult to come up with a single gas emission management system. The solution is found in creating different scenarios for the optimised gas emission management. These scenarios may be created by using different characteristics, such as emissions, avoided emissions, reduction in percentage to NDC commitments, percentage weight of gas in steam, plant size and several others.

The gas emission strategies are categorised by the projected emissions from the geothermal systems, while it is assumed that the methane content is very small and therefore not significantly contributing to the total emissions. The scenarios are developed specifically for small island developing states geothermal systems. This creates a basis for the assessment of gas abatement strategies for brownfields. The three islands studied are evaluated in the scenario that best fits their projected emissions.

It is assumed that the carbon dioxide (CO_2) is 95% of the total GHG emissions, methane (CH_4) emissions from the plant are 5% of the total GHG emissions and hydrogen sulphide (H_2S) emissions are less than 5% of total percentage weight of the gas. Therefore, the abatement technologies are proposed for CO_2, with H_2S abatement as a secondary component. The plants are assessed based on the plant size category listed in Table 7.

TABLE 7: Categories for geothermal plant size

Min size (MWe)	**Category**	**Max size (MWe)**
-	Small	2
2	Intermediate	10
10	Medium	25
25	Large	50

Total emissions are dependent on the size of the plant and the percentage weight of the gas content. The emissions are compared with emissions from a diesel-powered electricity generator. The emissions that are not avoided by the use of geothermal systems are calculated.

The scales used for plant size category are not standard and are assessed based on the writer's view of geothermal systems in Caribbean SIDS. The costs reviewed include the capital costs and operating costs of the technology based on the findings in the ESMAP technical report 2016 on greenhouse gases from geothermal power plants (Fridriksson et al., 2016).

5. RESULTS

5.1 Estimated greenhouse gas and hydrogen sulphide emissions

5.1.1 Greenhouse gas emissions

The estimated GHG emissions for the three geothermal power plants per year are given in Table 8.

TABLE 8: Calculated GHG emissions

Country	Estimated plant size (MW)	wt% of NCG	Projected emissions (tCO_2e/yr)
Dominica	7	2.71	10,412
Montserrat	2	0.43	1,164
Saint Lucia	30	20.9	371,526

The calculations were redone assuming that the estimated size of all the plants was 2 MW for ease of comparison as shown in Table 9. This table indicates how the emissions per year would vary depending on the percentage weight of the gas in the steam.

TABLE 9: Comparison of GHG emission using same size plant

Country	Estimated plant size (MW)	wt% of NCG	Projected emissions (t CO_2e/yr)	Projected emissions (gCO_2e/kWh)
Dominica	2	2.71	3,185	170
Montserrat	2	0.43	1,246	66
Saint Lucia	2	20.9	26,517	1,413

5.1.2 H_2S emissions

The H_2S emissions for the three sites are given in Table 10.

TABLE 10: Hydrogen sulphide (H_2S) emissions for the three wells

Country	mole% of H_2S
Dominica	2.678
Montserrat	0.32
Saint Lucia	2.1

Based on the values in Table 10, the H_2S emissions are small but it may be necessary depending on the type of gas management proposed that H_2S abatement be implemented along with CO_2 abatement. Even at these low percentages, the concentration can still be lethal depending on the weather conditions.

5.2 Comparison with nationally determined contributions commitments

In Figure 9, the estimated GHG emissions from the three wells are

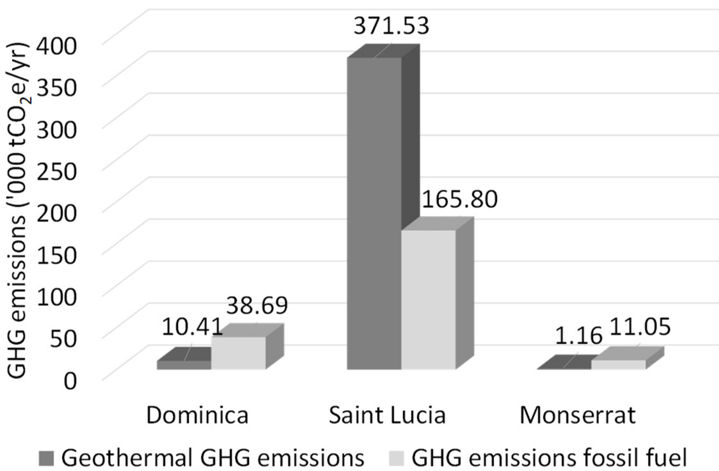

FIGURE 9: Comparison of GHG emissions of geothermal power production with conventional diesel-powered

compared to emissions from fossil fuel plants of the same size. These data are reported in Table 1 in the Appendix II.

5.3 Optimized gas emission management

The scenarios created are based on CO_2 equivalent emissions per year. The percentage weight of the gas in the steam is estimated and an optimised gas abatement technology is recommended for each scenario.

5.3.1 Scenario 1: Projected GHG emissions below 5,000 tCO_2e/yr

Figure 10 shows the estimated emissions of conventional fossil fuel power plants of different sizes, according to Table 7, in comparison to geothermal power plants of the same sizes, all emitting 5,000 tCO_2e/yr. The corresponding percentage weight of GHGs in geothermal steam NCGs is also shown. The data for the graph are given in Table 1 in Appendix III.

Gas emission management technology recommended: None, enhancement of carbon sinks is recommended.

5.3.2 Scenario 2: Projected GHG emissions below 15,000 tCO_2e/yr

Figure 11 shows the comparison of conventional fossil fuel emissions compared to varying geothermal plant sizes all with GHG emissions of 15,000 tCO_2e/yr and the estimated percentage weight of gas content for each plant size. The data for this graph are given in Table 2 in Appendix III.

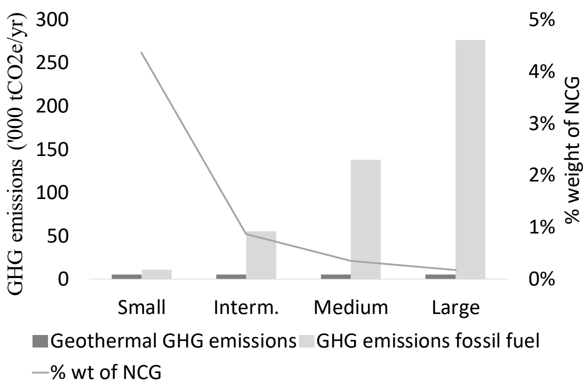

FIGURE 10: Estimated percentage weight of GHGs in geothermal steam NCGs for geothermal power plants of different size categories (Table 7) and emissions below 5,000 tCO_2e/yr. Estimated emissions from same size fossil fuel power plants are also shown.

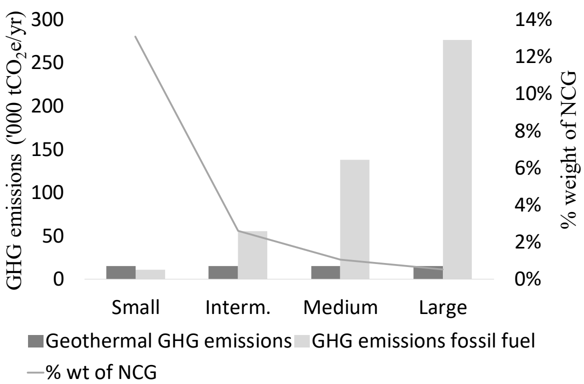

FIGURE 11: Estimated percentage weight of gas content for plants with emissions below 15,000 tCO_2e/yr

Gas emission management technology recommended:

1. CO_2 recovery for use in greenhouses; and
2. Reinjection of carbon dioxide (CO_2).

The cost estimate for the two gas emission management systems are given below in Table 11.

TABLE 11: Cost estimate for abatement systems with 15,000 tCO_2e/yr

Abatement strategy	Cost per tCO_2 (USD)	Estimated CO_2 removed	Estimated total cost per year (USD)
CO_2 recovery for use in greenhouses	5.00	14,250 t/yr or	71,250
Reinjection of CO_2	10.30	1.62 t/hr	146,775

Based on the total cost above in Table 11, the percentage cost of the abatement system compared to the cost of the total plant was calculated. The results are shown in Table 12.

TABLE 12: Percentage cost of total plant assuming a cost of USD 4m/MWe

Abatement technology	CO_2 recovery for use in greenhouses	Reinjection of CO_2
Total cost	$71,250	$146,775
Small	0.89%	1.83%
Intermediate	<0.18%	<0.37%
Medium	<0.07%	<0.15%
Large	<0.04%	<0.07%

5.3.3 Scenario 3: Projected GHG emissions below 50,000 tCO_2e/yr

Figure 12 shows the comparison of conventional fossil fuel emissions compared to varying geothermal plant sizes all with GHG emissions of 50,000 tCO_2e/yr and the estimated percentage weight of gas content for each plant size. The data for this graph are given in Table 3 in Appendix III.

Gas emission management technology recommended:
Carbon dioxide (CO_2) recovery for use in greenhouses and reinjection of CO_2.

The cost estimate for the two gas emission management systems are given below in Table 13.

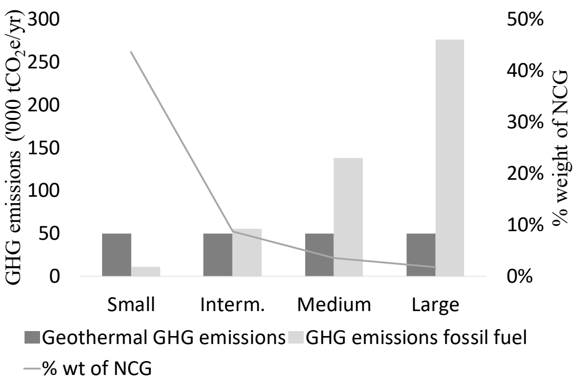

FIGURE 12: Estimated percentage weight of gas content for plants with emissions below 50,000 tCO_2e/yr

TABLE 13: Cost estimate for abatement technology with 50,000 tCO_2e/yr

Abatement technology	Cost per tCO_2 (USD)	Estimated CO_2 removed	Estimated total cost per year (USD)
CO_2 recovery for use in greenhouses	5.00	47,500 t/yr or	237,500
Reinjection of CO_2	10.30	5.42 t/hr	489,250

Based on the total cost above in Table 13, the percentage cost of the abatement system compared to the cost of the total plant was calculated. The results are shown in Table 14.

TABLE 14: Percentage cost of total plant assuming a cost of USD 4m/MWe

Abatement technology	CO_2 recovery for use in greenhouses	Reinjection of CO_2
Total cost	$237,500	$489,250
Small	2.97%	6.12%
Intermediate	<0.59%	<1.22%
Medium	<0.24%	<0.49%
Large	<0.12%	<0.24%

5.3.4 Scenario 4: Projected GHG emissions below 100,000 tCO_2e/yr

For the remaining scenarios, the small systems are not considered as the required percentage weight of gas would be impractical for the operations of systems of that size.

Figure 13 shows the comparison of conventional fossil fuel emissions compared to varying geothermal plant sizes all with GHG emissions of 100,000 tCO_2e/yr and the estimated percentage weight of gas content for each plant size. The data for this graph are given in Table 4 in Appendix III.

Gas emission management technology recommended:
CO_2 recovery for use in beverages.

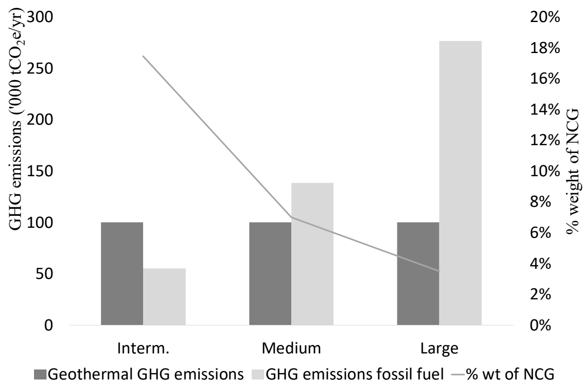

FIGURE 13: Estimated percentage weight of gas content for plants with emissions below 100,000 tCO_2e/yr

The cost estimate for the gas emission management system is given below in Table 15.

TABLE 15: Cost estimate for abatement systems with 100,000 tCO_2e/yr

Abatement technology	Cost per tCO_2 (USD)	Estimated CO_2 removed	Estimated total cost per year (USD)
CO_2 recovery for use in beverages	21.10	95,000 t/yr or 10.8 t/hr	2.004 million

Based on the total cost above in Table 15, the percentage cost of the abatement system compared to the cost of the total plant was calculated. The results are shown in Table 16.

TABLE 16: Percentage cost of total plant assuming a cost of USD 4m/MWe

Abatement technology	CO_2 recovery for use in beverages
Total cost	$2.004 million
Intermediate	<5.01%
Medium	<2.00%
Large	<1.00%

5.3.5 Scenario 5: Projected GHG emissions between below 200,000 tCO_2e/yr

Figure 14 shows the comparison of conventional fossil fuel emissions compared to varying geothermal plant sizes all with GHG emissions of 200,000 tCO_2e/yr and the estimated percentage weight of gas content for each plant size. The data for this graph are given in Table 5 in Appendix III.

Gas emission management technology recommended:
CO_2 recovery for use in beverages.

The cost estimate for the gas emission management system is given below in Table 17.

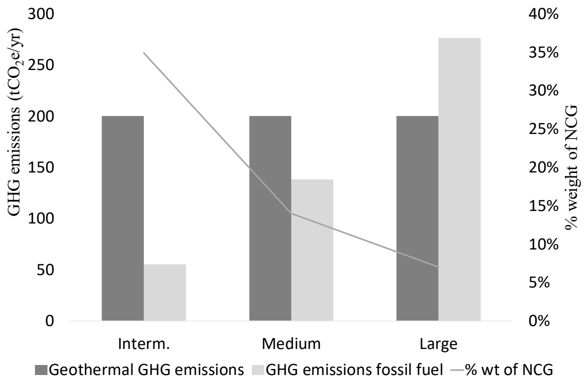

FIGURE 14: Estimated percentage weight of gas content for plants with emissions below 200,000 tCO_2e/yr

TABLE 17: Cost estimate for abatement systems with 200,000 tCO_2e/yr

Abatement technology	Cost per tCO_2 (USD)	Estimated CO_2 removed	Estimated total cost per year (USD)
CO_2 recovery for use beverages	21.10	190,000 t/yr or 21.7 t/hr	4.009 million

Based on the total cost above in Table 17, the percentage of the total plant was calculated as shown in Table 18.

TABLE 18: Percentage cost of total plant assuming a cost of USD 4m/MWe

Abatement strategy	Carbon dioxide (CO_2) recovery for use in beverages
Total cost	\$4.009 million
Intermediate	<10.02%
Medium	<4.01%
Large	<2.00%

5.3.6 Scenario 6: Projected GHG emissions above 300,000 tCO_2e/yr

Figure 15 shows the comparison of conventional fossil fuel emissions compared to varying geothermal plant sizes all with GHG emissions of 300,000 tCO_2e/yr and the estimated percentage weight of gas content for each plant size. The data for this graph are given in Table 6 in Appendix III.

Gas emission management technology recommended:

1. CO_2 recovery for use in beverages; and
2. CarbFix.

The cost estimate for the two gas emission management systems are given below in Table 19.

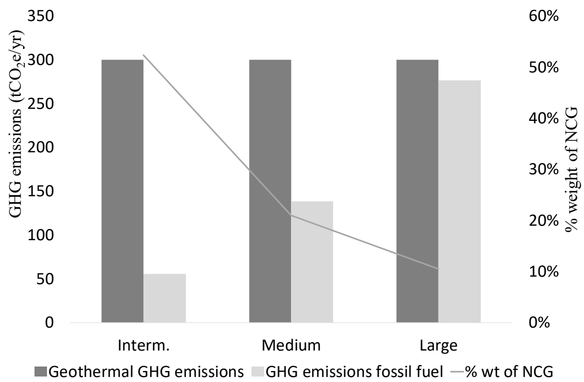

FIGURE 15: Estimated percentage weight of gas content for plants with emissions below 300,000 tCO_2e/yr

TABLE 19: Cost estimate for abatement systems with 300,000 tCO_2e/yr

Abatement technology	Cost per tCO_2 (USD)	Estimated CO_2 removed	Estimated total cost per year (USD)
CO_2 recovery for use in beverages	21.10	285,000 t/yr or 32.5 t/hr	6.013 million
CarbFix project	27.6		7.866 million

Based on the total cost above in Table 19, the percentage of the total plant was calculated as shown in Table 20.

TABLE 20: Percentage cost of total plant assuming a cost of USD 4m/MWe

Abatement strategy	CO_2 recovery for use in beverages	Reinjection of CO_2
Total cost (USD)	6.013 million	7.866 million
Intermediate	>15.03%	>19.67%
Medium	>6.01%	>7.87%
Large	>3.01%	>3.93%

6. EVALUATION OF GREENHOUSE GAS EMISSIONS AND GAS MANAGEMENT STRATEGIES

6.1 Estimated greenhouse gas emissions for the region

The projected GHG emissions from the island of Montserrat are the lowest, estimated at 66 gCO_2e/kWh, with Dominica at 170 gCO_2e/kWh and Saint Lucia having the highest emissions of 1,413 gCO_2e/kWh. The average global GHG emissions for geothermal energy production are 128 gCO_2e/kWh, but higher emissions of 790 gCO_2e/kWh are expected if carbonate rocks are present in the reservoir (Fridriksson et al., 2016). In Dominica and Montserrat, the average emissions are 118 gCO_2e/kWh, implying that the emissions from the two islands geothermal systems are consistent with the reports on the average emissions from geothermal systems.

The results from Saint Lucia show that emissions are similar to those reported for geothermal systems with carbonate rocks. This result gives an indication that carbonate rocks or limestone may be present on the island owing to the high GHG emissions. Further studies are required to verify the presence of these carbonate rocks.

The estimated emissions are directly related to the weighted percentage of the NCGs in the steam and the size of the plant. Montserrat having the lowest weighted percentage of gas in steam of 0.43% and Saint Lucia having the highest of 20.9% correspond to the lowest and highest GHG emissions and the same is true for the size of the plant.

Calculations of GHG emissions from geothermal systems are sensitive to the methods used, the data and the assumptions. These methods are different to the one used for fossil fuel combustion and are specific to the type of gas released. Assumptions can introduce errors into the calculations and lead to larger uncertainties. Emissions from geothermal power plants can be difficult to monitor directly and will diffuse if released into the atmosphere. Projecting emissions for future plants leads to an overall better design of the power plants, incorporating appropriate abatement technologies.

6.2 Emissions and comparison with Nationally Determined Contributions (NDC)

The projected emissions from the islands are compared with their submission in the NDCs. This comparison can assist in the justification of an abatement technology and also provide assistance in the updating of the islands NDCs expected in 2020.

6.2.1 Dominica

It is assumed that a geothermal plant of 7 MW is planned for 2020 with and an expansion of 3.5 MW planned for 2025. The projected emissions reduction is 39.3 Gg CO_2e (INDC Dominica, 2015), which is equivalent to 39,300 tCO_2e. The values estimated in Figure 9 indicate that these projected emissions can only be reduced by 73% if the gases are released into the atmosphere from the geothermal system as is customary. As per the NDCs, the expected reduction rates are 39.2% by 2025 below the 2014 levels of 164.5 GgCO_2e. Based on the projected emissions from the geothermal systems, the reduction rates are overestimated by 27% for geothermal energy. This also means that the total reduction in GHG for the island is overestimated and an abatement system is recommended to ensure that the reduction rates are maintained. This system can be included in the update of the island's NDC.

The Commonwealth of Dominica was severely impacted by Maria, a category 5 hurricane in 2017. Therefore, the NDCs of 2015 may not be a true reflection of the emissions of the island currently as fluctuations in the level of different industries have been experienced. Dominica may submit a new NDC in 2020.

6.2.2 Saint Lucia

According to Saint Lucia's NDCs, the island commits to an economy-wide reduction from a 2010 baseline using business as usual scenario. This translates to an emission reduction of 121 Gg CO_2e by 2025 and 188 Gg CO_2e by 2030 (INDC Saint Lucia, 2015). The reductions are based on renewable energy target with a mix of solar, wind and geothermal. It is expected that geothermal would take the largest share of the renewables. The projected emissions of the well which was investigated in Saint Lucia would produce twice as much emissions than a diesel-powered generator. Based on these estimates, the reduction based on renewables should exclude expected reductions from a geothermal system unless a gas abatement system is included. The emission would increase rather than the expected decline if a plant is implemented without such technology. It is critically important for the island to invest in an abatement technology for its geothermal system to reduce these emissions. This should also be taken into consideration during the expected update of the NDCs in 2020.

6.2.3 Montserrat

Montserrat is a British overseas territory and not a sovereign nation. As such they are not members of the United Nations Framework Convention on Climate Change (UNFCCC). Nevertheless, the emissions from the Montserrat wells are small and do not significantly contribute to emissions on the island.

6.3 Proposed method for selection of abatement technology

In the selection of an abatement technology, several factors need to be considered and investigated. These include the types of condensers, access to cooling water and condensate, the geology of the bedrock, the gas composition, available materials, users of the bi-products and the capital and operational cost of the abatement technology. The selection is not limited to these conditions as other factors may influence the final selection of the abatement technology. Some of these factors are considered in the scenarios presented and assessed.

6.3.1 Scenario 1: Below 5,000 tCO_2e/yr

Emissions in this range are generally considered to be small. The concern would be that for a small plant, the avoided emissions would only be 55% of the emissions from a diesel-powered generator of the same size. The actual carbon dioxide content that could be recovered is less than 5,000 tons per year. Therefore, it is recommended that plant managers consider enhancing the carbon sinks in the area to compensate for emissions from power plants such as planting of trees in the vicinity or within the compound.

Montserrat has a gas content 0.43% with 88% CO_2 content. Their projected emissions of approximately 1,164 tCO_2e/yr would fit into this scenario. Montserrat has proposed a small plant and has low gas content projected. The avoided emissions from this plant are estimated at 89% of a diesel-powered generator of the same size. The recommendations for the island of Montserrat is that an abatement technology for the proposed plant is not required, but the plant managers are encouraged to increase the carbon sinks to compensate for the un-avoided emissions.

6.3.2 Scenario 2: Below 15,000 tCO_2e/yr

The percentage weight of gas in the steam is directly proportional to the level of emissions. For a small power plant with emissions of 15,000 tCO_2e/yr, the percentage weight of the gas content in the steam is estimated to be 13.1%. A small geothermal plant with this level of emissions would emit 36% more GHG emissions than a diesel-powered generator of the same size. This means that this system cannot be categorised as 'green' technology due to the higher emissions from the geothermal plant than a fossil fuel plant. The percentage weight of the gas in steam in this case is considered high and not typical of geothermal systems which are normally in the range of 0.5-2%.

A geothermal plant in Dominica would be such a case. The gas content is 2.71 % of the weight of the steam and the size is 7 MW. This fits into the intermediate category. For this level of emissions, the abatement technology proposed is the usage of CO_2 in nearby greenhouses where suitable or the reinjection of the CO_2 mixed with the geothermal brine and condensate. It is assumed that condensers used in the plants are indirect condensers allowing for ease of gas extraction. The gas extraction method would depend on the percentage weight of the gas in the steam.

Carbon dioxide recovery for use in greenhouses

The abatement technology using recovered CO_2 in greenhouses is analysed for the island of Dominica. The estimated emission is 10,412 tCO_2e/ year which corresponds to approximately 10,355 tCO_2e/ year using the using actual values from the composition of the NCG for the island. The greenhouse is assumed to have an area of 2,500 m^2 with a height of 5 m and the gas recovery system is assumed to be 50% efficient and would recover 5,177 tCO_2. This would be sufficient to provide 1.13 kg/m^3 of CO_2 per day which is approximately 1000 ppm per day, accounting for losses in the pipeline.

It is important for greenhouses that hydrogen sulphide (H_2S) is removed as it has detrimental effects on the plants. The possible cost of H_2S abatement is included in the overall cost for the system. In this case, the Sulferox process was chosen and an iron based liquid redox sulphur recovery process is used. The Sulferox process is a proven process with applications in the oil and gas industry as well as the geothermal energy industry. This process was chosen for its ability to purify H_2S by up to 99%. It can operate with low- and high-pressure systems and has flexibility in dealing with variations in the gas volumes and ability to process low levels of hydrogen sulphide (H_2S) (Shell Global Solution, 2011). This process is not the only available liquid redox sulphur recovery process, as other solutions are possible dependent on the needs of the geothermal project.

In the case of Dominica, the methane, hydrogen and ammonia levels are low and therefore further removal of these components are not deemed necessary to generate the purity of carbon dioxide required for greenhouses. The Sulferox process produces elemental sulphur as a bi-product that can be used as fertiliser in the agriculture industry or in the greenhouses. Elemental sulphur may be used as an insecticide or mite control, for plant disease control and as plant or soil amendment (McKeown and Nicoleau, 2018).

Reinjection of carbon dioxide

In the cases where a greenhouse is not feasible and the geothermal stream is a combination of condensate and steam, reinjection of the CO_2 is proposed as an abatement strategy. This process would require at least 50 t/hr of condensate for every tonne per hour of CO_2 recovered (Fridriksson et al., 2016). The exact amount of condensate required is dependent on the temperature and pressure of the gas treatment facility. In the case of Dominica, it is estimated that 0.6 t/hr of CO_2 would be recovered, this would require 30 t/hr of condensate to dissolve the CO_2. This technology can be used effectively in systems with surface condensers, where the NCG is not in contact with the cooling fluid. The reinjection of CO_2 may have positive effects on the reservoir pressure, enhance well productivity and inhibit silica scaling (Stefánsson, 1997).

6.3.3 Scenario 3: Below 50,000 tCO$_2$e/yr

For small systems, the gas content of steam (43.6% wt) is not suitable to effectively operate a geothermal plant and in addition, CO_2 emissions of 50,000 tCO$_2$e/yr would not allow this system to be an alternative for fossil fuels for Caribbean SIDS. As the emissions increase, the cost of the abatement technology becomes a significant portion of the total cost of the plant. This may make the geothermal system economically unviable as a source of electricity in SIDS.

A geothermal power plant of 10 MWe would have a gas weight percentage of the steam of 8.7%, which means that only 10% of the emissions from a diesel-powered generator is avoided. The need to have abatement systems is significantly increased for systems within this range of emissions. The abatement technologies proposed are the use of CO_2 in nearby greenhouses where suitable or the reinjection of the CO_2 mixed with the geothermal brine and condensate. The abatement technologies proposed in this scenario are the same as those proposed in Scenario 2 but the cost of the system would increase as the expected output of CO_2 has tripled.

In this scenario the greenhouses would need to be designed to operate at a minimum of 2.71 t/hr of CO_2. The area of the greenhouse would be designed based on the level of CO_2 available from the power plant as was done for Dominica in Scenario 2. For the reinjection system, maintaining the assumptions in Scenario 2, 135 t/hr of condensate/brine would be required to dissolve 2.71 t/hr of CO_2. The abatement technology chosen is dependent of the availability of the resources; whether greenhouses are planned as part of the use of the geothermal resource or if there is enough supply of condensate/brine to dissolve the level of CO_2 at the site.

6.3.4 Scenario 4: Below 100,000 tCO$_2$e/yr

Small plant size is not considered for this scenario as the emission level and gas content would be impractical for geothermal development. The intermediate size systems in this scenario would emit more GHG emissions than a diesel-powered generator of the same size and have a gas content of up to 17.4%wt of the steam. Therefore, an intermediate system should not be considered as a climate change mitigation technology unless a suitable abatement system is included. The abatement technology recommended for this scenario is CO_2 recovery for use in beverages.

In Caribbean SIDS, the carbonated drink industry is popular, and distilleries are available in most of the islands. The production of CO_2 from geothermal systems with high gas content can be a lucrative additional industry if the level of CO_2 is sufficient to meet the demand of the beverage industry. The purified CO_2 can also be used in greenhouses as a second option if produced in excess. For systems with emissions in this range, the composition of the other gases in the NCG would need to be assessed in order to appropriately design this abatement technology. The cost to implement this technology in intermediate plants, of almost 5% of the total cost of the plant, is high. Therefore, the revenue from the sale of the product should be considered when evaluating the benefits of this abatement technology.

Carbon dioxide recovery for use in beverages
For liquefied CO_2, the required ammonia level is below 2.5 ppm. The ammonia removal method depends on the level of ammonia in the NCG and this value may vary significantly. The hydrogen sulphide (H_2S) level needs to be reduced to the standard for beverage which is more stringent than the standard for greenhouses. This can be achieved through a two-step process where the method proposed for the greenhouses (Sulferox process) can be applied in combination with a scavenger process. The other gases are removed through fractional distillation.

6.3.5 Scenario 5: Below 200,000 tCO_2e/yr

In this scenario, the gas content of the steam in intermediate size power plants is 34.9 %wt. This is considered to be relatively high and the GHG emissions would be more than triple the emission of a conventional diesel-powered generator. Therefore, it is not expected that an intermediate plant would be constructed in this scenario. The medium and large plant size systems would still have high emissions when compared to the conventional diesel-powered generator and therefore an abatement technology would be necessary. The abatement technology recommended for this scenario is CO_2 recovery for use in beverages, the same as in Scenario 4. The cost of this system would increase due to the amount of CO_2 which is estimated to be 21.7 t/hr.

6.3.6 Scenario 6: Above 300,000 tCO_2e/yr

In this scenario, the GHG emissions of the largest plant size would be equal to the emissions from the conventional diesel-powered generators and the expected gas content of the steam would be close to 10% of the weight. The GHG emissions encountered are similar to the emissions found in regions with carbonate rock. The Gediz Graben region of Turkey is an example of a geothermal system with emissions in this category, with values of 1800 g of CO_2 emissions per kWh (Aksoy et al., 2015). In Caribbean SIDS, geothermal systems that fit into this scenario should be investigated for occurrence of carbonated rock.

The estimated GHG emissions for Saint Lucia fits into this scenario. Saint Lucia has a gas content of 20.9 wt% of steam and the NCG contains 90% CO_2. The plant size proposed is in the medium category. For this geothermal system to be considered for climate change mitigation technology, an abatement technology needs to be installed. The recommended abatement technology is CO_2 recovery for use in beverages.

Saint Lucia has one of the major carbonated drinks factory in the Eastern Caribbean and the production of CO_2 for this industry may provide additional opportunities for employment and benefits for the island. Further research would need to fully understand the benefits of the recovery of CO_2 and the carbonated drink industry in Saint Lucia. The cost to implement such an abatement technology for this system is as high as 6% of the total costs of the plant. Methods to reduce the costs of this technology through funding agencies may need to be explored to prevent the risks of additional cost to the consumers.

The CarbFix method is also an option for the island due to the presence of eroded basaltic rock in its geological formation. It may prove beneficial to further study CarbFix applications in SIDS. The cost of this technology is estimated to be approximately 8% of the total costs of the plant. Therefore, similar to the recovery of CO_2 for beverages; methods to reduce this cost need to be explored.

6.4 Risks and uncertainties

In research, when assumptions are made and data availability is limited, risks and uncertainties may be encountered. These studies were based on only one well at each site as geothermal power plants do not currently exist on the islands. It is possible for wells to exhibit different gas compositions in the same general location, so this would need to be taken into account when estimating GHG emissions from a power plant if more than one production well is involved. The research is based on the gas composition of only three islands due to limited data availability. To get an overview of the gas composition and emissions in the region, data analysis is required from a wider range of wells. In the case of Saint Lucia, the well investigated is not expected to be used for geothermal production and exploration is ongoing in a different area, but it is possible to encounter similar characteristics of gas composition in the new areas as well.

For the GHG emissions calculations, it was assumed that the characteristics of the operation of the geothermal plants were the same. This was done for ease of calculations and comparison; therefore the actual emissions differ depending on the operations of the geothermal plant. The plants were also assumed to all have indirect condensers. The choice of condensers will influence the technology chosen and the quantity of emissions available for capture.

The cost analysis per ton of CO_2 for the abatement technology was based on a plant which produces 50 t/hr of NCG. The economies of scale and variations in costs for smaller productions of NCGs were not taken into consideration and thus average prices may vary from those estimated. The temperature and pressure of the gas undergoing the treatment would also affect the price of the system as additional measures may need to be implemented to achieve the correct pressure and temperature for operation. In addition, assumptions were made in the calculations for simplification and ease of comparison. The global warming potential of methane used is 25 to ensure consistency with the calculation in the NDCs; this value is taken from the IPCC fourth assessment report.

7. CONCLUSIONS

Caribbean SIDS with geothermal energy potential should consider this renewable energy technology as a suitable alternative to the conventional fossil fuel electricity production. GHG emissions from Caribbean SIDS are very low and geothermal energy is generally proposed primarily for energy security and as an additional benefit as a climate change mitigation technology.

This research shows that geothermal energy for Caribbean SIDS needs to be analysed before it can be considered an environmentally friendly option. Generalising geothermal systems as environmentally friendly does not take into consideration the possible emissions from the plant. Such equivocation would have an impact on the commitments made by SIDS to international organisation related to the mitigation of climate impacts such as NDCs. The extent of this impact depends on the size of the power plant, the gas content and the gas composition.

GHG emissions for geothermal plants are not commonly estimated or measured since they are considered to be natural emissions from surface manifestations and no additional contributions made. This theory can be contested in many situations and careful measurements need to be undertaken when establishing geothermal power plants to verify this assumption.

Although geothermal systems do have some emissions, these emissions can be successfully mitigated with an appropriate abatement technology. The scenarios presented in this research provide a suitable assessment for abatement technologies for Caribbean SIDS. The three fields studied have been appropriately positioned in one of the scenarios with an optimised gas waste management strategy for their emissions.

The Montserrat field is suitably placed into Scenario 1 with emissions below 5,000 tCO_2e/yr, where no abatement technology is recommended, but an abatement strategy of increasing carbon sinks is proposed. The Dominica field is situated in Scenario 2 with emissions below 15,000 tCO_2e/yr and two possible abatement technologies are proposed for power plants in this scenario. The Saint Lucia field is situated in Scenario 6 with emissions above 300,000 tCO_2e/yr and two abatement technologies are proposed.

While all abatement methods discussed within this report are methods to decrease the direct emissions from the power plants, a distinction should be made between Carbon Capture and Utilization (CCU) and Carbon Capture and Storage (CCS) methods. CCS abatement methods such as the CarbFix method sequester CO_2 for long time horizons, while CCU abatement methods such as usage in greenhouses or drink carbonation may only sequester carbon for a short time period. The benefits seen in CCU can be found in the efficient use of CO_2 and avoiding the use and transport of manufactured CO_2 which perhaps could have stayed sequestered.

It is recommended that further research be conducted on other fields in the Caribbean region and categorised into the scenarios proposed before a general statement can be made on Caribbean SIDS geothermal emissions.

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APPENDIX I: Mole percent of gases from wells in Dominica, Saint Lucia and Montserrat

TABLE 1: Dominica geothermal well data in mole %
(modified from Ministry of Public Utilities, Energy and Ports Dominica, 2012).

Well	CO_2	H_2S	H_2	CH_4	N_2	Other gases
WW-03	95.367	2.678	0.253	0.021	1.376	0.305

TABLE 2: Saint Lucia geothermal well data in mole %. (modified from Lovelock et al., 2016).

Well	CO_2	H_2S	H_2	CH_4	N_2	Other gases
SL-2	90.500	2.113	5.626	0.666	1.124	0.007

TABLE 3: Montserrat geothermal well data in mole %. (modified from Brophy et al, 2014).

Well	CO_2	H_2S	H_2	CH_4	N_2	Other gases
MON-2	88.000	0.320	0.250	4.500	6.000	0.510

APPENDIX II: Estimated GHG emissions from Dominica, Saint Lucia and Montserrat with comparison with emissions from fossil fuels

TABLE 1: Comparison of GHG emissions of geothermal with conventional diesel-powered generators

Country	Estimated plant size (MW)	Projected emissions from geothermal (tCO_2e/yr)	Projected emissions from fossil fuel combustion ($t\ CO_2e/yr$)	Percentage of emissions not avoided
Dominica	7	10,412	38,686	27%
Montserrat	2	1,164	11,053	11%
Saint Lucia	30	371,526	165, 797	224%

APPENDIX III: Data of gas weight percent in each scenario

TABLE 1: Estimated gas content per plant size with emissions below 5,000 tCO_2e/yr (Scenario 1)

Size	Estimated gas (wt%)	CO_2e not avoided (%)
Small	> 4.4	45.2
Intermediate	4.4 to 0.9	45.2 to 9.0
Medium	0.9 to 0.3	9.0 to 3.6
Large	0.3 to 0.2	3.6 to 1.8

TABLE 2: Estimated gas content per plant size with emissions below 15,000 tCO_2e/yr (Scenario 2)

Size	Estimated gas (wt%)	CO_2e not avoided (%)
Small	> 13.1	135.7
Intermediate	13.1 to 2.6	135.7 to 27.1
Medium	2.6 to 1.0	27.1 to 10.9
Large	1.0 to 0.5	10.9 to 5.4

TABLE 3: Estimated gas content per plant size with emissions below 50,000 tCO_2e/yr (Scenario 3)

Size	**Estimated gas (wt%)**	**CO_2e not avoided (%)**
Small	>43.6	452.4
Intermediate	43.6 to 8.7	452.4 to 90.5
Medium	8.7 to 3.5	90.5 to 36.2
Large	3.5 to 1.7	36.2 to 18.1

TABLE 4: Estimated gas content per plant size with emissions below 100,000 tCO_2e/yr (Scenario 4)

Size	**Estimated gas (wt%)**	**CO_2e not avoided (wt%)**
Intermediate	>17.4	> 180.9
Medium	17.4 to 7.0	180.9 to 72.4
Large	7.0 to 3.5	72.4 to 36.2

TABLE 5: Estimated gas content per plant size with emissions below 200,000 tCO_2e/yr (Scenario 5)

Size	**Estimated gas (wt%)**	**CO_2e not avoided (%)**
Intermediate	>34.9%	>361.9
Medium	34.9 to 14.0	144.8 to 361.9
Large	14.0 to 7.0	144.8 to 72.4

TABLE 6: Estimated gas content per plant size with emissions above 300,000 tCO_2e/yr (Scenario 6)

Size	**Estimated gas (wt%)**	**CO_2e not avoided (%)**
Intermediate	>52.3%	> 542.8
Medium	52.3 to 20.9%	542.8 to 217.1
Large	>10.5%	217.1 to 108.6

APPENDIX IV: Unit conversions

Unit conversion
$GgCO_2e = 1000\ tCO_2e$
$1\mu g/m^3 = 0.001\ mg/m^3$