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Life Cycle Analysis of a CO_2 Project in Trinidad & Tobago

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Abstract- Climate change is one of the major issues affecting the world currently based on our current and excessive fossil fuel-based energy usage that is emitting carbon into the atmosphere. In order help this situation, the removal of CO_2 from the atmosphere needs to be looked into via the implementation of carbon capture technologies. This paper aims to determine the net CO_2 emissions resulting from implementing a Direct Air Capture (DAC) system in tandem with a renewable energy project, offsetting emissions being generated during power generation in Trinidad and Tobago using a gate to grave life cycle assessment (LCA). A comparison between the storage capacities of different reservoir types, a saline aquifer and depleted hydrocarbon reservoir, was accomplished by keeping all reservoir parameters constant with the exception of the fluid models in each. It was determined that a solid sorbent DAC would be most suitable for this project, with the LCA showing that net CO_2 emissions were -799 $kgCO_2e$/ton of CO_2 stored. From the comparison of the different reservoir types, it was determined that saline aquifers have greater CO_2 storage potential than depleted hydrocarbon fields, with almost double the capacity being seen for this case. An economic analysis was lastly performed, utilizing carbon credits as a revenue source, to determine the project's financial feasibility where it was determined that the minimum price at which credits could be sold to achieve breakeven is $347USD/ton. Conclusively, this study demonstrated that a project of this calibre is both environmentally and economically beneficial in assisting with carbon mitigation strategies and evidently global climate change, indicated that saline aquifers have great potential for storing captured CO_2, and is along the developmental pathway for Trinidad and Tobago's Vision 2030.

Keywords Carbon Dioxide Capture & Storage, Geologic Storage, Life Cycle Assessment.

1. Introduction

Climate change is one of the major issues affecting the world currently. Studies show that over the last 140 years the average global surface temperature has risen by 1.2°C [1]. As of 1980, the rate of increase of temperature has increased from 0.17°F per decade to 0.31-0.54°F per decade [2]. If this trend is allowed to continue, global temperature increase could reach up to 5.4°C compared to pre-industrial era temperatures by the end of the century [3-4]. If allowed to continue, this trend will result in various catastrophic effects on global ecosystems and humans ranging from rising sea levels to endangerment of various species.

The onset of this rapid increase in temperatures coincides with the start of the industrial revolution in 1980 developments in technology and population growth led to an increase in global energy demands. In 2020, the world's population reached over 7.7 billion with projections showing it increasing to 9.7 billion by 2050 [5]. Comparably, global energy consumption in 1900 was estimated to be just over 30 x 108 toe with 2020 data showing this demand increasing to just under 120 30 x 108 toe and estimated to increase by over 20% by 2050 [6]. This high energy demand has been supplied primarily from burning fossil fuels like coal, oil and natural gas which is known to result in the release of greenhouse gases into the atmosphere, including billions of tons of CO_2. Figure 1 shows the increase in atmospheric CO_2 concentrations, rising from 298ppm in 1880 to 419ppm by May of 2021. This is the highest concentrations the planet has experienced in over 4 million years when sea levels and temperatures were on average 78ft and 7°F higher than the preindustrial period.

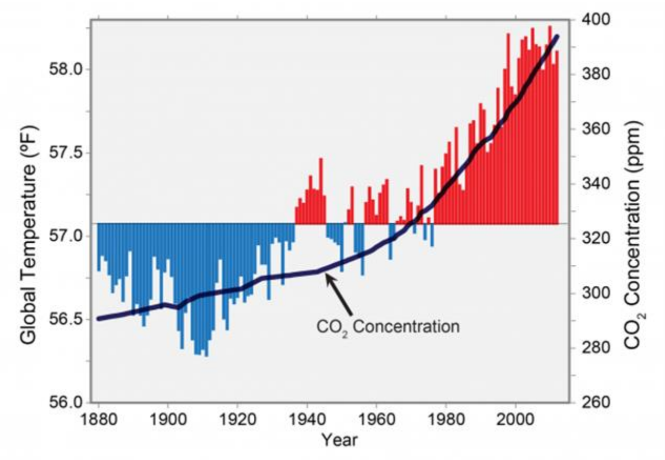

Fig. 1. The Relationship between Global Temperature and CO_2 Concentration throughout the years [7]

If those conditions were to occur again, the ramifications would be great for all life on earth.

To avoid these, experts agree that temperature increase must be limited to 1.5 to 2°C to avoid highly uncertain and unfavourable planetary conditions [3]. Various agreements such the 1997 Kyoto protocol and the 2015 Paris Agreement Act have been signed by countries around the world, including Trinidad and Tobago, for the agreement and commitment to take steps to reduce GHG emissions and transition to more sustainable energy sources in compliance with the United Nations' (UN) Sustainable Development Goals (SDGs). Parties of the Paris Agreement Act has brought forward their respective National Determined Contributions (NDCs) in which Trinidad and Tobago has ratified theirs in February 2018 in conjunction to having a National Development Strategy: Vision 2030 that is inclusive of the SDGs. The country has committed to fulfilling a number of contributions, under the Ministry of Planning and Development, such as a 15% reduction in greenhouse gas (GHG) emissions from the three main emitting sectors (i.e., Power Generation, Transportation, and Industrial), reducing public transportation emissions by 30%, reducing venting and flaring in the energy sector in order to achieve a 15% cut, embracing more energy efficient (EE) technologies, fuel conversion from natural gas to compressed natural gas (CNG) via a fuel switching program with a long term goal to switch to electric vehicles, and to explore the feasibility of carbon pricing and carbon credits for participation in carbon markets in order to finance climate action [8]. According to Vision 2030, Theme V: Placing the Environment at the Centre of Social and Economic Development, there are long term goals in place that would play an active part in fulfilling our role as a susceptible Small Island Developing State (SIDS) to combat climate change.

The country's NDCs will inevitably act towards helping the reduction in global temperatures via the cumulative emission reduction from the main emitting sectors however, in order to reduce CO_2 concentrations, some of that carbon would need to be removed from the atmosphere which results in the need for capture technologies of which there are two main categories: Carbon Capture and Storage (CCS) or Carbon Capture and Utilization (CCU). With CCS, CO_2 is removed from the atmosphere and injected into reservoirs where they can be safely stored such as porous geologic formations or in enhanced oil recovery (EOR) projects where it also aides in the production of hydrocarbons from the subsurface. In CCU, the CO_2 removed from the atmosphere is used to create useful products such as fuels or plastic which can then be used by consumers. Trinidad and Tobago has been growing with interest in a hopeful implementation of a CCS/CCUS Carbon Management and Reduction Strategy given our history with CO_2 injection within the oil and gas sector. Research and development are still ongoing however in February 2021, a Carbon Capture and Carbon Dioxide Enhanced Oil Recovery (EOR) Steering Committee was appointed to manage a large-scale CO_2 EOR project to simultaneously increase the country's revenue and address CO_2 emission reduction via CCS [9]. Additionally, according to [9], the 2022 National Budget for the country introduced an allowance whereby companies that invest in CCS and EOR will be given a 30% tax allowance on their chargeable profits.

By combining CCS with a renewable energy source, it is possible to remove CO_2 from the atmosphere with significantly less emissions than traditional energy sources. This is beneficial to countries that depend on hydrocarbons as a source of energy and a source of revenue for the local economy like Trinidad and Tobago where the energy sector accounts for approximately 30% of the national GDP. Data from the energy chamber of Trinidad and Tobago has shown that both oil and gas production has been declining in recent years. Figure 2 shows the production rates of the country since 2000 and, from this, it is clear to see that these resources are depleting.

These trends demonstrate the need for renewable energy technologies (RETs) and diversification of the local economy. There is a definite need for energy diversification for the reduction of pollution and climate impacts related to the use of fossil fuels. This has led to research and development of efficient, reliable and cost-effective renewable technologies which are less susceptible to market shocks with improved resilience and energy security [10-14]. Implementation of CCS along with RETs would allow the nation to continue producing and selling its natural resources more sustainably while reducing its carbon emissions and working towards climate change targets. This ensures that time and funds are available to make the transition into more sustainable energy generation technologies and a more diversified economy.

Projects like this have already been successfully implemented in different regions. One region where the benefits of this type of project can be seen is in Iceland. As of 2015, 85% of the nation's primary energy consumption came from renewable energy sources with geothermal energy accounting for 65% and hydropower accounting for the remaining 20%. In September 2021, Carbfix's Orca carbon capture facility commenced operations with a capacity to capture 4,000 tons of CO_2 per year [15]. This facility is powered by On Power's Hellisheiði Geothermal Power Plant, which is located nearby, capturing CO_2 emissions from the power plant, and making the facilities net negative with respect to CO_2 emissions. Another such project is the Archer Daniels Midland Illinois ICCS Project which commenced operations in April 2017 and was able to capture and inject 46,300 metric tons of CO_2 in that month [16].

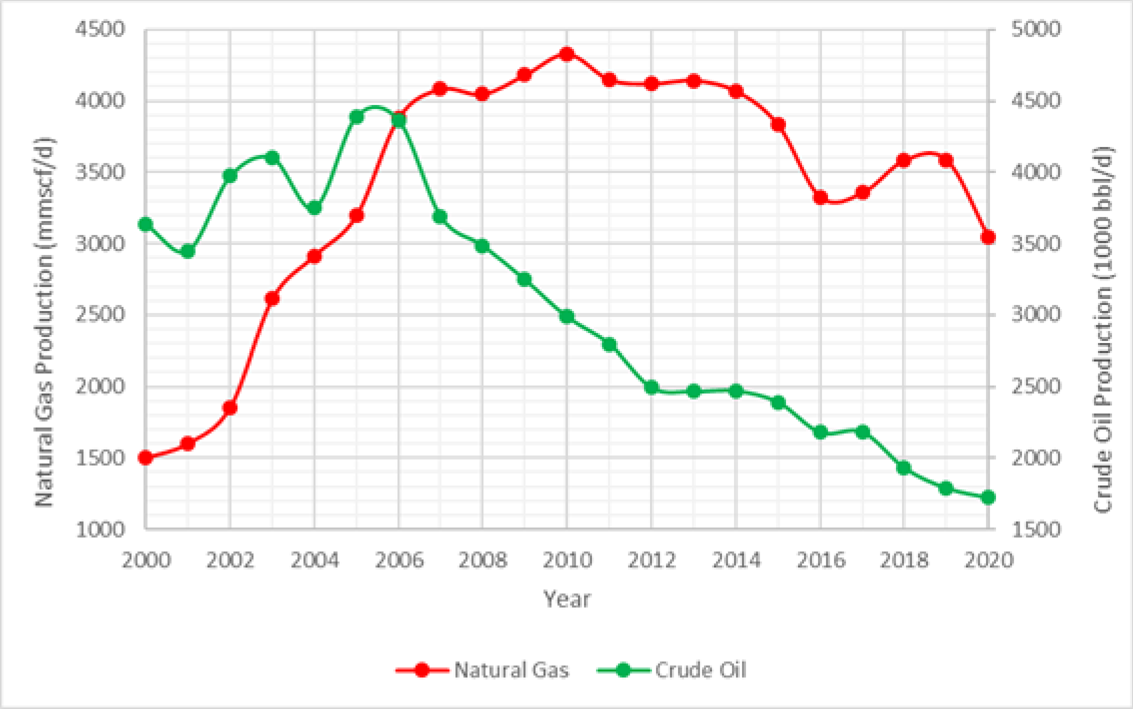

Fig. 2. Hydrocarbon Production Rates in Trinidad and Tobago [17]

Moreover, it can be noted that there are three primary industrial developers of Direct Air Capture (DAC) CCS technology: Canada's Carbon Engineering, Switzerland's Climeworks, and the USA's Global Thermostat. These companies are working to further commercialize DAC systems where some of their applications are as follows: Carbon Engineering's liquid solvent pilot plant that sequesters 1 ton per day in Canada, Climework's solid sorbent demonstration project that sequesters 900 tons per year in Switzerland, and Global Thermostat's solid sorbent 1000 ton per year project in the USA [18]. Additionally, Shell, one of the major oil and gas companies in the world, has joined the Net-Zero movement with their Quest CCS Project in Alberta Canada where the facility is capturing a target of 1 million tons of CO_2 per year that's generated through the bitumen conversion of sand to oil power plant in order to inject and store it underground as a carbon mitigation strategy [19].

This study will aim to investigate the potential benefits of implementing a similar project in Trinidad and Tobago using Life Cycle Assessment (LCA) to assess the environmental impacts of the project throughout the project's lifetime where an LCA methodology and its application to CO_2 storage projects would be investigated utilizing the appropriate Direct Air Capture (DAC) technology would be best suited for it, as well as other key elements in the CCS stages. Additionally, to supplement this project, an appropriate renewable energy (RE) project and its location will be looked into. A Life Cycle Assessment for the overall process of DAC to storage in a geologic reservoir for a case study in T&T would be conducted. Simulation modelling via CMG modelling was utilized to investigate two possible storage strategies i.e., a saline reservoir and a depleted oil reservoir, to ensure that that project is net negative in terms of CO_2 emissions where there will then be a comparison of the storage potential of each to determine their suitability. Finally, an economic analysis of the overall project would be performed.

2. Methodology

The potential benefits of CCS need to be evaluated using the holistic method of the LCA. Based on the project objectives, the information presented in this report was obtained using secondary data collection methods as it was the most practical due to the large quantity of data available from a variety of sources. The sources of the data presented in this report includes literature from websites, journal articles, books, case studies, and government databases. The information obtained from these was then sorted, compiled, and presented based on their reliability, validity, and relevance to accomplishing the study goals. The methodology used in this paper closely follows the one utilized in a similar study [20]. This was selected as a reference study since its objectives were similar to this paper's and the steps utilized could be easily followed and repeated for verification of the results. A summary of the project methodology is shown in Figure 3.

2.1. Subsurface Modelling

For this stage, it was decided to present two storage cases of a depleted oil reservoir and a saline aquifer based on the same reservoir (Upper Cruse, EOR 4, Forest Reserve) in order to validate that this project can be conducted in both types of storage reservoirs. These cases were chosen since EOR 4 met the required criteria to facilitate CO_2 sequestration for both types. In order to substantiate these cases, the digital map file was firstly created on Didger and was imported into CMG where available field data was utilized for the models. Any remaining parameters were filled with data that was available from literature and if not, the default values were used as field production was unavailable. A decline curve analysis was done to generate a substitute field history which could be used for tuning the reservoir model. This was done using an exponential decline trend, ensuring that cumulative production values after the period of primary production matched. A history match was then created in order tune the model using this data. The file was then exported to GEM where a WinProp fluid model was created. Lastly, the WinProp model was imported into the new reservoir models where the injection rates and the number of injection wells were varied the model was allowed to run until abandonment conditions were reached at which point injection was started. The 5 wells that have been present since the EOR phase of the reservoir were utilized where production wells were converted into injection wells. The storage capacity achieved using different numbers of open wells and rates was investigates i.e., CO_2 injector A was open only, CO_2 injector A-C were open only, etc. The specific process detailing to each case is outlined in their respective sections.

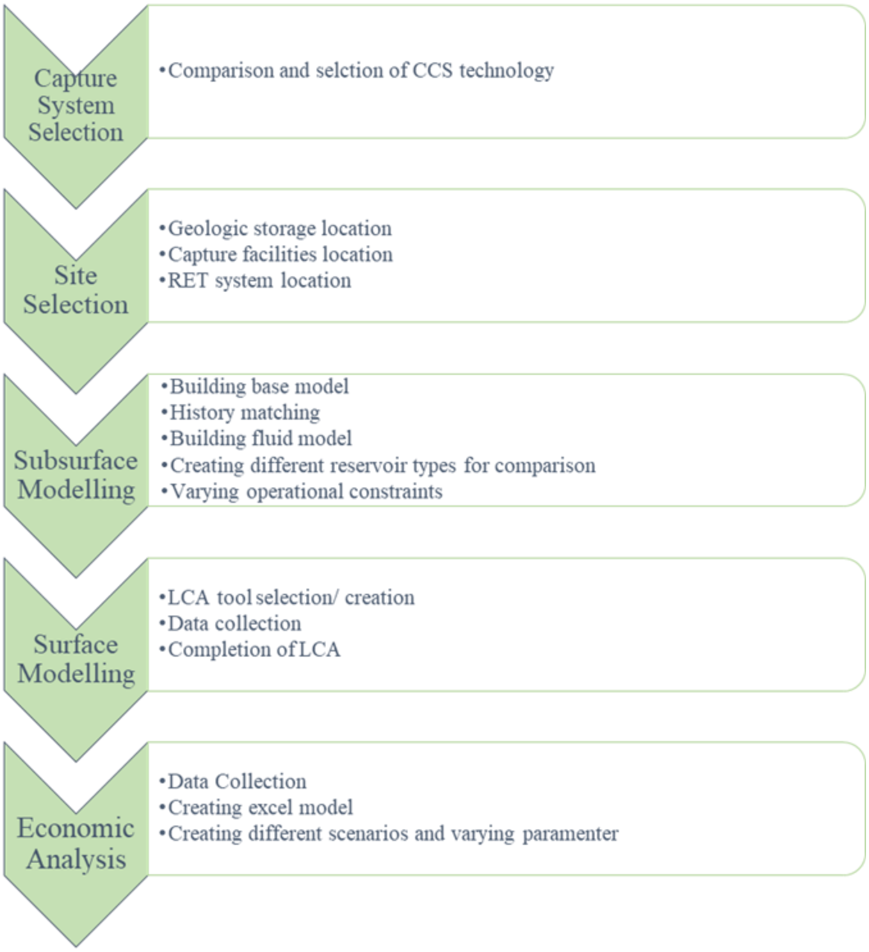

Fig. 3. Flow Chart Summarizing Project Methodology

2.1.1. Depleted Oil Reservoir

CO_2 injection started after the abandonment date previously determined, varying the number of injection wells and injection rates date. At a bottomhole pressure (BHP) of 4500 kPa the STG surface gas injection rates were 500, 3000, and 12000 m^3/day to obtain the amount of CO_2 trapped. The results were then plotted and analysed in order to validate that CO_2 sequestration can be done in Trinidad for a depleted oil reservoir.

2.1.2. Saline Aquifer

In the saline aquifer case, the oil-water contacts were raised from their initial positions to above the reservoir top ensure that the reservoir was completely saturated with water. With operating at a BHP of 7000 kPa, the STG surface gas rates of 500, 3000, and 12000 m^3/day were examined in order to obtain the amount of CO_2 trapped after the wells were in operation and then shut in for 20 years. The results were then plotted and analysed in order to validate that CO_2 sequestration can be done in Trinidad for a saline aquifer.

2.2. Surface Modelling

The surface modelling consisted of an LCA which was done with an LCA spreadsheet model using a model generated utilizing an existing model from the University of Michigan where some of the inputs were removed in order to simplify the process. The emissions coming out of the systems were converted to $kgCO_2e$ in order for the carbon balance inventory to be easily quantified. The following sections outlines the LCA methodology in further detail.

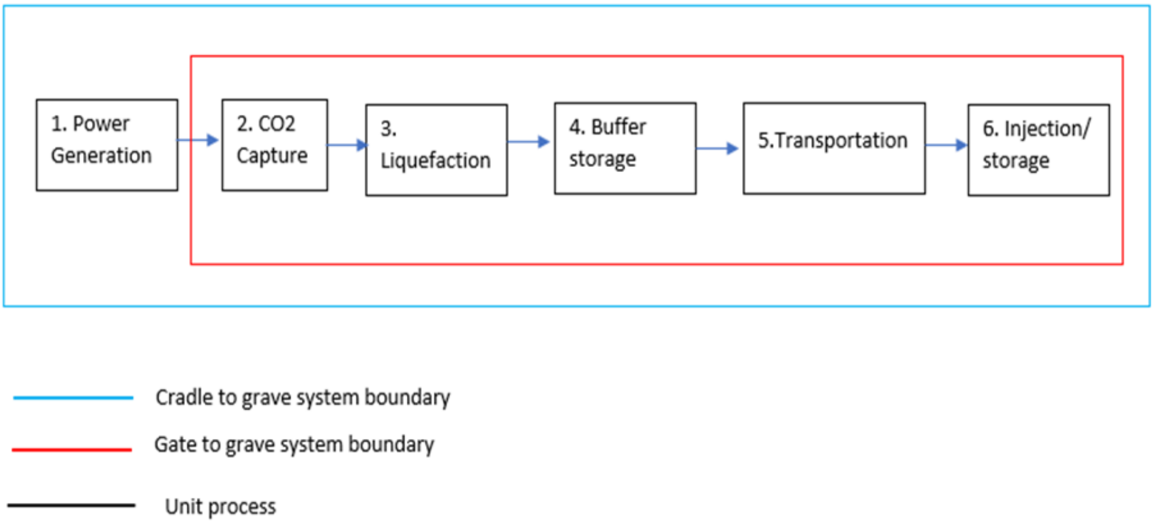

Fig. 4. Gate-to-Grave System Boundary Diagram

3. Carbon Capture and Storage (CCS)

It is known that the largest contributor to Greenhouse Gases (GHGs) is carbon dioxide (CO_2). Despite all efforts, CO_2 concentrations are still increasing due to the fact that as the world's population and the economies grow, so too do the global carbon emissions with increasing energy consumption levels. Statistical data [21] showed that in 2016, around 50 billion tons of CO_2e were emitted globally, where Trinidad and Tobago emitted around 25.93 million tons CO_2e in that same year [21].

In 2019, it was averaged that the world emits about 43 billion tons of CO_2 yearly. These figures indicate that every ton of carbon emitted matters and steps must be taken to curb carbon emissions.

One method which can be used to aid in resolving this issue is the implementation of Carbon Capture and Storage (CCS). The technology used in this carbon mitigation strategy essentially operates to capture carbon dioxide from various sources such as at the emission source of industrial processes and within the atmosphere, to then transport and store that collected/harvested CO_2 permanently or until it it's ready to be utilized i.e., Carbon Capture and Utilization (CCU) (Figure 4). Through this, carbon is not emitted into the atmosphere or to pull the carbon out from the atmosphere, thus reducing CO_2 emissions and carbon presence. CCS technology has the unique capacity to be retrofitted into many existing complexes where, for the term of their natural life, they can cleanly function [22].

3.1. Stage 1: Capture

CO_2 can be captured from a multitude of sources of differing concentrations, pressures, volumes, and abundance. As such, there are three basic types of CO_2 capture methods: pre-combustion, post-combustion, and oxyfuel with post-combustion. Other sources of CO_2 capture and sequester are Direct Air Capture (DAC), Biomass, Fermentation, Coastal Blue Carbon, Terrestrial Carbon Removal and Sequestration, and Bioenergy with Carbon Capture and Sequestration (BECCS). As per the deliverables of this project, the DAC system will be focused on.

There are a few points that throws the system over the edge when compared to the others even though it's relatively new in the carbon capture sector and is currently seeking and acquiring investments allowing the technology to mature and making the venture profitable. The main points are as follows:

- ➢ Limited land and water footprint – compared to BECCS and the Coastal Blue methods DAC doesn't require extensive acres of land and doesn't have to be installed near a coastal region [23]. This would deem the system to be flexible where siting is concerned.

- ➢ Viably locating plants on non-arable land – this is based on the DAC systems that use liquid solvents or solid sorbents to directly capture CO_2 with help from large surface area contactors. With this there will be a minimized impact on food production or land utilization for other things.

- ➢ Locating plants close to the storage location in order to eliminate the need for long-distance CO_2 transportation thus reducing the transportation cost. In order to reduce the impacts on the energy system the system itself can also be located near unused waste heat sources [24].

- ➢ Since DAC is a Carbon Dioxide Removal (CDR) solution, it can be standalone or tied to an emitting facility, such as one with an industrial process, releasing a hefty amount of emissions therefore it does not have to rely on a single process compared to that of post- or pre-combustion. Henceforth, if the project is widely scaled when it's not tied to an emitting facility, it can result in net negative emissions [24]. Based on this, the country can acquire carbon credits to sell to other countries thus effectively supporting the capital investment in order to build the DAC plant [25].

- DAC systems exhibit modularity amongst them denoting that they can be upscaled to capture even more carbon.

3.1.1. Direct Air Capture: Liquid Solvent vs. Solid Sorbent

When comparing the Liquid Solvent method with the Solid Sorbent method the factors that can essentially affect the overall cost of the DAC plant such as the capital costs, operating costs, and the choice of sorbent used would need to be taken into consideration. However, for the implementation of the most suitable plant, other factors should be examined such as the energy requirements, plant size, water usage, and even the modularity of the system since these would all depend on the system type. Table 1 outlines these deciding factors.

3.1.2. DAC System Location

The DAC system is of the main focus to capture/sequester the carbon in order to remove carbon from the atmosphere. Through this the project would evidently be considered carbon neutral or even carbon negative all whilst additionally capturing carbon emissions from other sources that is already out in the atmosphere. The main sectors in Trinidad that emit the most GHG emissions (carbon emissions included) are known to be the industrial and transportation sectors. For this project there will be more viability to direct the system into areas that exhibit the highest amounts of emissions where there would be the possibility to be able to quantify the carbon emissions. With eyes on the industrial sectors with the majority of Trinidad's industrial activity occurring on the western side of the island, Trinidad has four (4) main ports/industrial estates:

- Point Lisas South and East Industrial Estate, Couva Trinidad
- The Oropouche Bank Reclamation – location of the Union Industrial Estate, La Brea Trinidad
- Galeota Port, Guayaguayare Trinidad
- La Brea Industrial Estate, La Brea Trinidad

Keeping the storage site location in mind, even though the Point Lisas Industrial Estate would be very fitting since it's the main industrial hub in Trinidad, for the scale of a possible pilot project and most importantly for the ease of transport and reduced cost for the transportation stage of the CCS project to the storage site, the southern industrial estates would be more suitable. These would be the Union Industrial Estate and the La Brea Industrial Estate. Both industrial estates are owned and managed by The National Energy Corporation of Trinidad and Tobago (NEC), a subsidiary of the wholly owned state energy company The National Gas Company of Trinidad and Tobago (NGC). Table 2 examines the differences between both areas.

In utilizing the virtual tour tool that National Energy has set up on their website, the types of industrial companies both estates have been investigated as mentioned in Table 2. It showcased that this section of the country has a fair amount of industrial activity. Furthermore, while the virtual tool showed a fair amount of land space, it also indicated empty lots of land in the area which could potentially hold a DAC facility since these plants have a small land footprint.

All things considered, both industrial estates have demonstrated to be viable in setting up the DAC system. Since both are technically state-owned it's fair to imply that the vacant lots are both suitable and available due to the fact that the government of Trinidad and Tobago is currently directing research and development into CCS, and would as such be open to utilizing the facilities they already own or have access to. Even though La Brea Industrial Estate has a fair number of industrial activities, Union Industrial Estate houses more major industrial companies and activities, as well as fairly sized vacant lots, which would make it a bit more fitting to house a DAC plant. In theory, when it comes to the emissions that are already in the atmosphere, it does not matter between both since they are in the same general area, quite close to each other.

Table 1 Deciding Factors Affecting the Choice Between Liquid Solvent and Solid Sorbent DAC Technology

Deciding Factor	Criteria	Liquid Solvent	Solid Sorbent
Energy Requirements	**Thermal Energy**	5.25 to 8.16 GJ tCO_2-1	1 to 3 GJ tCO_2-1
	Electricity	1.3 to 1.86 GJ tCO_2-1	1.5 GJ tCO_2-1
	Temperature	Near 900°C	About 80-130°C
Plant Size		Generally larger	Smaller
Water Usage		1-7 tons of water	1.6 tons of water per ton of captured CO_2 (steam condensation). 0.8-2 tons of water per ton of captured CO_2 (indirect heat regeneration).

Modularity		Does not exhibit partition-based modularity.	Greater modularity

Table 2 Differences between the two DAC System Location Areas

	La Brea Industrial Estate (aka LABIDCO)	**Union Industrial Estate**
Location	Within good proximity to the carbon storage site.	
Size (acres)	400	830
Estate lots	63 serviceable lots for light manufacturing and energy-based industries.	25 industrial plots, 1 recreational plot.
Industrial Activity	• Chemical tank cleaning • Waste transportation • Industrial fabrication	• Gas-to-Petrochemicals complex • Combined cycle power plant • NGC's Gas Receiving facility

3.2. Stage 2: Transport

This stage encompasses the safe and reliable transportation of CO_2 from where it is captured to the site of storage. There are some points to note, however. CO_2 condenses within the 20-70bar range and has a significant density increase. If CO_2 is to be injected into the subsurface for CO_2 storage or for EOR, it will often need to be compressed to around 100bars. When a concentrated CO_2 stream is created, normally it will be in the gaseous phase saturated with water vapour and might have small amounts of O_2 and H_2 as well as other trace contaminants [26]. Lastly, dry, dense phase CO_2 is not corrosive.

The transportation stage is done in a few ways on land and subsea such as via pipeline for large quantities, truck and rail for small quantities, and ship as an alternative regional transportation instead of long, extended subsea pipelines [26]. Amongst these methods before transportation, ship and truck would require, under low temperature and atmospheric conditions, compression/cooling [27].

Where this project is concerned, truck would be the most viable given that the quantity of CO_2 would be small scale and taking into consideration that the capture facility will be near to the storage reservoir. Utilizing pipelines for this stage, whether it be newly installed or oil and gas pipelines that have be converted, it's not viable enough cost-wise to warrant this method of transportation. Tanker trucks can be more easily modified compared to pipelines where that the truck's deep-cooling storage tank would be able to store the liquefied CO_2. Typically, the capacity of those tanker trucks are about 20-30 tons (with the maximum capacity depending on the density of the liquid being transported – liquid CO_2 being 1101 kg/m^3 at -37°C) with CO_2 storage conditions of -30°C at 1.7MPa (17bar) [28]. Additionally, [27] mentioned that tanker trucks are highly flexible and reliable and can also be applied to larger scale quantities if needed but in conjunction with compression and temporary storage facilities.

3.3. Stage 3: CO_2 Storage

The last stage of a CCS project is its location/site of storage. Storing that carbon underground would inevitably help to address the climate change issues by keeping that GHG out of the atmosphere for the required time period that is necessary required to achieve stabilization and ultimately the reduction of atmospheric CO_2 levels as per the Paris Agreement Act to limit global temperature rise to below 2°C [28]. As such, the geological storage process includes injecting a pure stream of CO_2 that was captured from the DAC method into rock formations deep underground, firstly with it being compressed to 'supercritical' conditions meaning at a pressure and temperature above the critical pressure and temperature of carbon dioxide (i.e., 31.1°C and greater than 73.9bar) [29]. Reference [29] also states that the density of CO_2 will increase with depth until at about 800 meters or greater, where it will be in a dense supercritical state, depending on the rate that the temperature increases with the depth. The Global CCS Institute has procured the following geological characteristics that are associated with effective storage sites:

- ➢ Rock formations having enough millimetre-size voids (i.e., porosity) to provide the adequate capacity to store the CO_2.
- ➢ Sufficiently interconnected rock pores (i.e., effective permeability) to accept the CO_2 amount at the rate in which it is injected.
- ➢ An extensive impermeable cap rock to contain the CO_2 permanently.

3.4. Field case

Where sedimentary basins are concerned, formations that are generally studied for carbon storage would be in the form of depleted hydrocarbon reservoirs, un-mineable coal, and saline formations. Since CO_2 contains a liquid-like density that provides the potential for efficient storage in hydrocarbon fields, the required reservoir depth range for CO_2 injection is 800m to 1000m (2625ft to 3281ft) [29]. Focus will be placed on depleted hydrocarbon reservoirs and saline formations as the reservoir storage types for the simulations utilizing the Upper Cruse Formation in the Forest Reserve field, specifically in the location of EOR 4 located on the southernmost flank of the ENE trending Fyzabad anticline. It had been a CO_2 immiscible pilot project based on [30] and is known to be one of the oldest hydrocarbon-producing reservoirs in Trinidad located in the sedimentary Columbus basin.

With respect to EOR 4, 21.3% of the original oil in place (OOIP) was obtained through primary oil recovery and the additional recovery that was obtained under gas injection through 1956 to 1977 was 20% [30]. The CO_2 injection was followed by a natural gas injection and a waterflood. Reference [30] stated that the waterflood contributed to 0.4% recovery of OOIP. Additionally, when CO_2 injection commenced in 1986 with one injector well and from the period 1995 to 2001 where three injector wells were added, the production increased from 50 bopd to 400 bodp. This CO_2 injection contributed to 2.2% of OOIP (predicted ultimate recovery being 4.7%) with a cumulative CO_2 utilization of 6 Mscf/bbl [30]. Also stated is that EOR 4 is a very high-quality candidate for immiscible gas injection since there’s a 20% incremental recovery for 2.2 pore volume (PV) natural gas injection beyond approximately 21.3% recovery by primary production. This makes EOR 4 a potential candidate for success in addition to it meeting the depth criteria and the area having an injection well already in place.

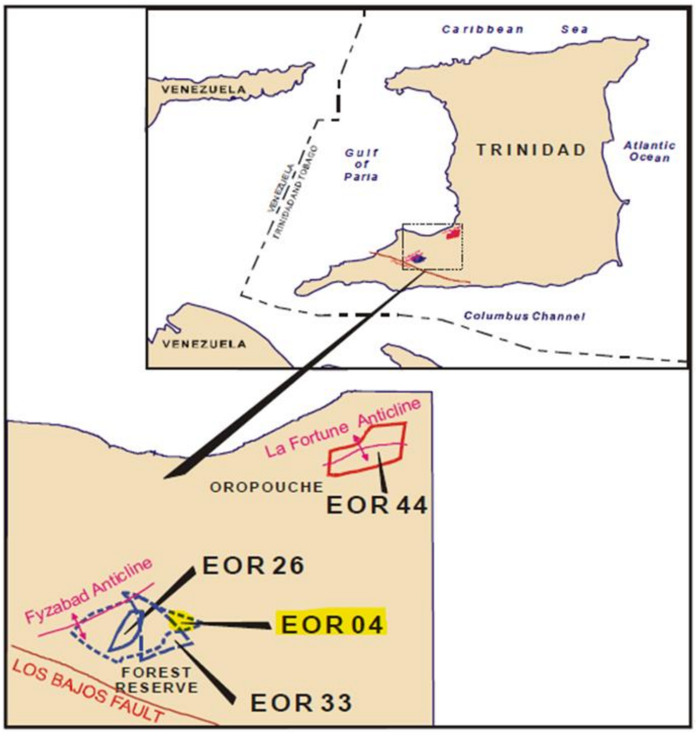

Fig. 5. Map Illustration highlighting the EOR 4 area of the Upper Cruse Formation in the Forest Reserve Field [30]

Cruse is located more in the Point Fortin area where the formation is found at around 4200ft subsurface where the sands are comfortably overlain by a thick shale sequence called the Lower Forest clay. EOR 4’s location is illustrated in Figure 5. Clay is impermeable and this is what compartmentalizes the Forest and Cruse formations. As depicted in the log in Figure 6, the Cruse sands are better developed, thicker, and cleaner than the Upper and Lower Forest sands [30]. Also present in the area is the Los Bajos faulting complexes of major and minor faults. They act as a trapping mechanism for the hydrocarbon which, in hindsight, would potentially keep the CO_2 contained within the formation although there would be some sort of transmissibility.

Table 3 comprises of the reservoir rock and fluid properties of the Upper Cruse formation. It is seen that the formation meets the depth and the majority of the reservoir property criteria for injecting CO_2.

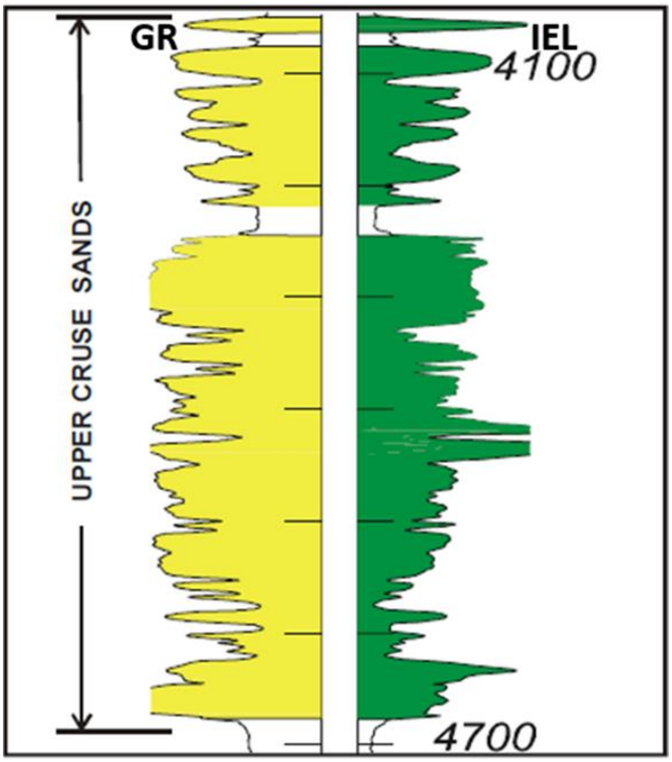

Fig. 6. Adaptation of the Forest Reserve Reservoirs Log showing the Upper Cruse Sands [30]

4. RE Project Incorporation – Solar Photovoltaic (PV) Farm Project

For this project, there will be a renewable energy (RE) project incorporation in order to demonstrate that yes, the DAC system is a viable method for the capturing of CO_2 since it will be able to capture emissions presented from the implementation of the RE project in order to make the project carbon neutral, all whilst capturing atmospheric emissions that were generated from other sources. The project in referral would be two solar farm/park projects utilizing solar photovoltaics (PV) located in Orange Grove and Brechin Castle Trinidad. Both projects are currently still in the preliminary assessment and site design phase as of May 2022. Emissions from the solar PV farm projects would essentially come from the fabrication/manufacture, site preparation and groundworks, cabling and trenching, and installation/assembly phases where these emissions won't be directly captured and would thus depend on the DAC system to make the project carbon neutral. Table 4 outlines the information and specifications of the projects.

Both projects will essentially have the same opportunities and threats since they're being implemented for the same reasonings. Opportunities would include bringing public awareness to RE technologies, diversifying the country's energy mix, lessening the natural gas derived energy dependency, creating job opportunities for locals, and creating a market for more RE technologies to become available and accessible to the public. The threats are based on the projects having potential ecological impacts with solar PV development, the dominant stance on fossil fuel-based energy is still strong, the country having highly subsidized energy prices (some of the lowest in the Caribbean), the lack of RE technology awareness and benefits, public opposition, and the deferral of investments. Inevitably, based on Table 4, since Brechin Castle has higher contributing factors based on the capacity and estimated annual generation, and it being closer to the general vicinity of the DAC capture and storage sites it seems to be the better option.

Table 3 Reservoir Rock and Fluid Parameters for the Upper Cruse Formation [30]

Reservoir Rock Properties	**Upper Cruse Formation**
Area (acres)	120
Depth (ft)	4200
Thickness (ft)	196
Porosity (%)	31
Permeability (md)	334
Oil Saturation (%)	73
Temperature (°F)	130
Transmissibility (md-ft/cp)	5036
Reservoir Fluid Properties (initial conditions)	
Reservoir Pressure (psi)	2200
Solution Gas Oil Ratio (scf/bbl)	400
Oil Formation Volume Factor	1.16
Oil Gravity (°API)	25
Oil Viscosity (cp)	6

Table 4 Information and Specifications of the Solar Farm Projects to be Launched [31]

	Orange Grove Solar Project	**Brechin Castle Solar Project**
Land Size (acres)	148	587
Capacity (MW)	20	92
Estimated annual generation (MWh/year)	50,417	225,303
Equivalent homes to be powered	7,000	31,500
Estimated tons of CO_2 saved	27,500	123,000

5. Results

5.1. Project Design Parameters

Table 5 details the design/choices implemented at each main stage of the project through analysis. Data for these specific parameters were utilized in all phases of modelling throughout the project.

5.2. Surface Model Results

5.2.1. Life Cycle Inventory (LCI)

Data used in this assessment include both specific and generic data sources. Preference is given to system specific data as this improves the accuracy of the results coming out of this study, however, it is recognized that this data is not available for each process throughout the life cycle supply chain and, as a result, must be supplemented with available data. All data used comes from secondary sources namely literature and databases. The outline is as follows in Table 6.

5.2.2. Impact Assessment

Table 7 summarizes the CO_2 inputs and outputs associated with the proposed system and the current local scenario. Also mentioned are the land use requirements, and the fuel consumption of the systems. Both cases are analysed within the gate-to-grave system boundary preciously outlined. From these results, it can be seen that the proposed systems utilize more fuel and land space due to the additional stages in the process and the nature of the energy sources with solar PV requiring large areas.

As GHG emissions are the focal point of this study, the net CO_2 emissions is weighted highest among impacts assessed. The main contributors of GHG emissions in the proposed design are the capture, liquefaction, and injection processes in that order. Transportation also generates some

GHG emissions. The emissions resulting from fuel consumption at all stages is dependent on the exact fossil fuel type with diesel being selected in this study. The most impactful emission factors coming from the sensitivity analysis performed were during the capture and electricity generation stages. Therefore, to improve the reliability of these results, the data quality for these inputs must be improved.

6. Economics

The economic feasibility of this project assessed over a 20-year period; the same period used for the injection of CO_2 in the subsurface modelling. It is assumed that other injection sites are used to supplement to storage capacity of the reservoir used in this study to ensure that the plant can remain operational for its entire lifespan instead of being shut down

Table 5 Project Design Parameters

Stage	Project Design Choice Parameter
Power Generation	RE Project Incorporation: Brechin Castle Solar PV Farm
Capture	DAC Technology Type: Solid Sorbent DAC Location: Union Industrial Estate, La Brea
Transport	Tanker Truck
Storage	Upper Cruse Sands of EOR4, Forest Reserve Field

Table 6 Outline of the LCI Results

Process	Case	Parameter	Unit	Value	Source
Power Generation	**Natural Gas Combined Cycle Plant**	CO_2 emissions	g/kWh	520	[32]
		Land usage	km^2	0.16	[33]
		Capacity	MW	720	[33]
	Solar PV Farm	CO_2 emissions	g/kWh	40	[34-36]
		Land usage	km^2	2.38	[37]
		Capacity	MW	92	[37]
Capture		CO_2 emissions	kg/ton	111	
		Power consumption	kWh/ton	450	[38]
		Methane emissions	kgCO$_2$e/ton	14	Assumption based on [39]
		Land usage	km^2	0.22	[40]
Liquefaction		Electricity	kWh/ton	83	[40]
		Compression loss	%	1	[40]
Storage		Land usage	km^2	5e-4	Assumption made for size or storage area
Transportation	**Diesel Trucks**	CO_2 emissions	kg/ton	19.92	Calculated using average fuel consumption and emissions from fuel
		Fuel Consumption	Litres/ton	8.3	Calculated based on vehicle fuel efficiency and distance
		Leakage	kg/ton	0.1	Assumed leakage when connecting and disconnecting hoses
Injection		Land usage	km^2/ well	0.00004	n/a
		Fuel Consumption	Litres/ton	19	Estimation based on [41]
		CO_2 emissions	kg/ton	45.6	Estimation based on fuel consumption

Table 7 Impact Assessment for surface modelling

Impact Category	Proposed design	Reference case
GHG emissions (power generation), kgCO$_2$e/MWh	40	520
GHG emissions (storage), kgCO$_2$e/ ton	201	-
Total GHG emissions, kgCO$_2$e/ton CO$_2$	201	520
CO$_2$ stored, ton	1	-
Net GHG emissions, kgCO$_2$e/ ton CO$_2$	-799	1000

Land Use	2.42	0.16
Fuel consumption (CCS), L/ton	29	-

once reservoir capacity is reached. In this scenario, the plant's operational capacity is set at 4000 tons/year, similar to the Orca facility located in Iceland. This is done so that the same costs and requirements could be utilized with a high level of confidence.

There are various assumptions made in this analysis. they are as follows:

- Thermal energy required is free as the system utilizes waste energy from nearby industrial locations.
- Electricity for plant operations is provided by the renewable energy project being implemented.
- Plant operates at maximum capacity for the entire period evaluated.

Two economic scenarios were considered where the electricity generated at the solar PV farm was factored into the model and another where this wasn't. Where electricity revenue was included, it was varied between the subsidized and unsubsidized local electricity prices of $0.05 USD/kWh and $0.12 USD/kWh respectively (Table 8). From these analyses it was seen that this greatly impacted the overall project economics. The feasibility indicators used in the final analysis were net present value (NPV) and internal rate of return (IRR) over a 20-year period. The payback period for the project under different conditions were also noted. NPV calculations across all cases utilized a discount rate of 10%. Sensitivity analysis was conducted to determine the most impactful inputs in the model which would then be varied to create the P10, base and P90 cases.

From the analysis it was seen that the major factors influencing the project outcomes were the capital expenditure (CAPEX), operating expenditure (OPEX), and the carbon credit price for both cases, and where electricity generation revenue was included in the model electricity cost became a significant factor, making the impacts of other factors essentially decrease exponentially. In both scenarios, carbon credit costs were varied to create the P10 ($800 USD/ton), base ($500 USD/ton), and P90 ($200 USD/ton) cases. Table 9 outlines the results of the economic scenarios.

From this analysis, it was also determined than the minimum price at which carbon credits could be sold for the project to breakeven is $347 USD/ton, this being in the worst-case scenario where electricity revenues are omitted.

7. Discussion

DAC was the selected capture technology for this project as there are various advantages when compared to the others available even though it is relatively new in the carbon capture sector. These advantages are detailed within the report, with the main points being the limited land and water footprint it has, plants can be located close to the storage location to limit transportation costs, and that the system can be standalone or tied to an emitting facility.

The solid sorbent and liquid solvent DAC systems were looked at purely due to those 2 technologies being the most researched and developed since major CCS companies are utilizing them on a commercial scale. Both systems were compared based on the energy requirements, plant size, water usage, and the system modularity and it was determined that the solid sorbent DAC system was the better option. Additionally, with regards to the location of the system, Union Industrial Estate houses more major industrial companies and activities, as well as fairly sized vacant lots, which would make it more fitting to house a DAC plant.

When it came to the subsurface model (Figure 7), both the saline reservoir and the depleted oil reservoir were built with constant variables where the aspect that separates them was utilizing the appropriate fluid models for each. The injection rates were varied between 500 m^3 and 12,000m^3 per day. Rates were not varied below 500 m^3 due to the reservoir pressure which needed to be overcome for successful injection, and they were not evaluated past 12,000 m^3 to avoid fracturing the reservoir. The next constraint used in the injection wells was maximum operating BHP, limiting this

Table 8 Parameters and their respective values utilized for the project economics

Parameter	Unit	Value	Source
Capacity	ton/year	4000	[42]
CAPEX	USD	15,000,000	[42]
OPEX	USD/ton	150	
Electricity need	MWh/ton	0.5	
Thermal Energy Need	MWh/ton	1.75	
Electricity cost	USD/MWh	50, 120	[43]

Thermal Energy cost	USD/MWh	0	-
Solar PV Capacity	MWh/year	225,303	[36]
Carbon Credit Cost	USD/ton	200; 500; 800	Varied between values obtained from [44] and [45].
Transportation cost	USD/ton	6.75	-
Storage cost	USD/ton	15	-

Table 9 Economic Scenarios of the project showcasing IRR, NPV, and Payback

Scenario		Case	IRR (%)	NPV (USD)	Payback
Generated Electricity Revenue Factored in	**Subsidized Electricity Price**	**P90**	78	94 million	3
		P50	83	98 million	3
		P10	90	104 million	3
	Unsubsidized Electricity Price	**P90**	179	229 million	1
		P50	187	240 million	1
		P10	195	251 million	1
Generated Electricity Revenue NOT Factored in	-	**P90**	-3	-11 million	22
		P50	6	-3.9 million	12
		P10	16	16 million	7

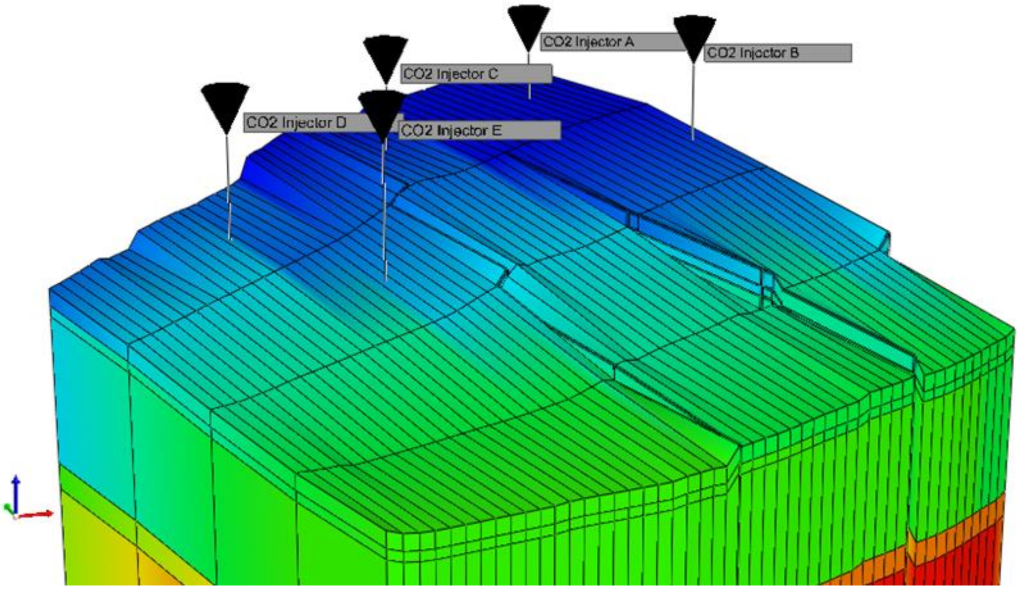

Fig. 7. 3D View of the Subsurface Model for EOR4 showing the CO_2 Injectors

value to 170% of the reservoir pressure [46]. The rates were varied in increments of 500 m^3, between 500 m^3 and 12,000 m^3. The values of the injection rates used in the analysis were chosen based on the reservoir type. For the saline reservoir the rate that gave maximum storage capacity was chosen and the depleted reservoir's value chosen was varied close to that of the saline for uniform comparison.

For the saline reservoir, injection rates of 500 m^3, 3000 m^3, and 12,000 m^3/day were utilized. These rates exhibited the best results for this storage reservoir type. As demonstrated in Table 10, 500 m^3/day gave the lowest mass of CO_2 stored in tons for all the injection well configurations although it was not significantly lower than that of 3000 m^3 and 12,000 m^3/day. 3000 m^3/day actually exhibited the highest mass of CO_2 stored in tons across the board. This essentially signifies that although the 12000 m^3/day rate can be utilized, the lower 3000 m^3/day was the optimal rate where with any rate lower than this, the mass of CO_2 stored starts to decrease. Additionally, with any rate higher than 12000 m^3/day, the storage amount will start to drop significantly, further demonstrating that 3000 m^3/day is the optimal rate.

With the depleted oil reservoir, injection rates of 500 m^3, 2500 m^3, and 12,000 m^3/day were utilized since they exhibited the best results for this storage reservoir type. Similarly, with the saline reservoir, these three rates demonstrated the best mass of CO_2 stored in tons however, the 500 m^3/day rate exhibited the highest mass of CO_2 stored in this case. Yet, when comparing the amount with that of the saline reservoir, the depleted reservoir sequesters about 34,000 tons more overall. One possible explanation for this is that it could be due to the compressibility of oil compared to water. Water generally has a lower compressibility than oil and consequently it is able to facilitate less CO_2 being injected. As such, it can be noted that although both reservoir storage types are suitable for facilitating a carbon sink and storing CO_2 for quite some time, the depleted oil reservoir would be the better fit when it comes to storing larger quantities.

For the surface model, the cradle-to-grave system boundary was selected for this study as it was an end-of-life study. For the purposes of this study, the processes involved in the production of the CO_2 were not important as emphasis is placed on the capture and storage of CO_2 more CO_2 is stored compared to what is produced i.e., net negative CO_2 emissions. It is assumed that all CO_2 injected into the storage sites remains stored over a 100-year period, the temporal period of this study.

Table 10 Subsurface Model Results of the Saline Reservoir and the Depleted Oil Reservoir

Reservoir Type	No. of Open CO_2 Injection Wells	Injection Rate, m3/day	CO_2 Trapped, moles	Mass of CO_2 stored, ton
Saline Reservoir	**1 (A)**	500	539,613,000	23,740
		3000	680,616,000	29,944
		12000	663,277,000	29,181
	2 (A & B)	500	560,233,000	24,647
		3000	680,612,000	29,943
		12000	663,264,000	29,180
	3 (A-C)	500	656,642,000	28,889
		3000	680,612,000	29,943
		12000	663,264,000	29,180
	4 (A-D)	500	659,431,000	29,011
		3000	680,612,000	29,943
		12000	663,277,000	29,181
	5 (A-E)	500	656,649,000	28,889
		3000	680,627,000	29,944
		12000	663,266,000	29,180
Depleted Oil Reservoir	**1 (A)**	500	1,437,990,000	63,264
		2500	1,353,480,000	59,546
		12000	1,353,490,000	59,546
	2 (A & B)	500	1,435,090,000	63,136
		2500	1,353,800,000	59,560
		12000	1,353,800,000	59,560
	3 (A-C)	500	1,439,550,000	63,333
		2500	1,353,800,000	59,560
		12000	1,353,900,000	59,564
	4 (A-D)	500	1,440,990,000	63,396

		2500	1,354,000,000	59,569
		12000	1,354,000,000	59,569
	5 (A-E)	500	1,449,890,000	63,788
		2500	1,354,970,000	59,612
		12000	1,354,990,000	59,612

The analysis looked at energy requirements and emissions coming from different stages of the process. The data used is obtained from secondary sources, and by making certain key assumptions. Firstly, it was assumed that diesel is the fuel consumed where required in the life cycle supply chain, namely transportation and injection. All electricity used is this system is derived from the associated solar PV farm. Thermal energy requirements are met using waste heat from other industrial processes. This allows the plant to capitalize on its location in an area of high industrial activity, reduce its environmental impacts, and reduce energy wastage from other processes, and also improving economics.

From the results of the LCA, it is seen that the is a net reduction of atmospheric CO_2 with a net total of 799kg of CO_2 being removed from the atmosphere for every ton of CO_2 captured proving that the project is net negative with respect to CO_2 emissions. Assuming that capture facilities operate at 100% capacity for the entire 20-year period, this would mean a total of 80,000 tons of CO_2 will be captured over this period. The subsurface modelling shows that in both cases (depleted oil reservoir and saline aquifer), the reservoir's capacity is less than this. Therefore, for this project to remain operational throughout its entire lifespan, supplemental storage sites must be utilized.

Also, in this analysis, diesel was the transportation fuel source during operations. Cleaner alternatives such as compressed natural gas (CNG) and electricity have shown potential to reduce emissions and have grown in popularity recently especially in the transportation sector. Regardless of this, diesel was selected because of its prominence is the local transportation sector, ensuring that the model is geographically accurate in this aspect. In comparison to the reference case where electricity is generated using a natural gas combined cycle power plant, there is a 90% reduction is CO_2 production at this stage. There is also a net CO_2 removal of 799 kg from the atmosphere compared to none in the reference case.

The project's economic viability was then evaluated. The key assumptions made have been discussed in an earlier section. Using these assumptions and the data obtained the economics in two scenarios were evaluated using NPV and IRR as primary feasibility indicators. The results of both analysis cases show that the project is significantly more viable where power generation revenue is included in the model. Where this is omitted, the projects cash inflows fall solely on carbon credits, which must be sold at a considerably high $347 USD/ton for the project to breakeven. However, when electricity generation revenue is added to the project's economics, it increased the viability greatly. When electricity is sold at the highly subsidized price of $0.05 USD/kWh, the project is able to achieve payback in just three years for all cases with IRR reaching up to 90%. Though this price is low compared to some other areas as it shows that the lack of useful end products coming out of the system has a negative impact on overall project economics. Once this subsidy is removed, the project outcomes become even more favourable with IRR and NPV reaching 195% and 251 million USD and payback occurring within the first year of operation for all three cases. These results, similar to the sensitivity analysis performed, demonstrate the large impact electricity costs have on the project once they are considered.

The results coming from economic analysis show that the project has potential to be feasible in most circumstances. Given the ranges of carbon prices found in research, the minimum breakeven price of $347 USD/ton is reasonable and, given the impacts of electricity revenue, it may be possible to sell carbon credits below this and still have profits being generated.

8. Recommendations

Based on the results arising from this study there are several recommendations which could be put forth to possibly improve outcomes. Additionally, as this study leaves room for future studies to be conducted into the optimization of this system and for areas of expansion. These recommendations are as follows.

- Investigation into other possible storage locations – The CCS system proposed provides standalone capture meaning that it operates independently of any specific generation source or storage location. Trinidad and Tobago has many hydrocarbon fields in the mature stages of their life and which will soon reach abandonment. These have the possibility to serve as adequate storage locations to supplement the nation's storage capacity.
- Investigating injection parameters such as well injection patterns and pressures that have a greater effect on storage capacity on the reservoirs.
- Exploring EOR and CCUS – These systems would have useful end products that would drive overall project economics.
- Investigation into the use of captured CO_2 for EOR operations – The CO_2 captured in this proposal can be utilized for EOR operations to extend the lifespan of these fields such as CO_2 injection and Water Alternating Gas (WAG) in order

to improve project economics via the economic feasibility analysis. The LCA in this scenario can be carried out to determine if it is possible to produce net carbon negative oil (NCNO) locally.

- Scaling up of the capture facilities – Economics of other projects have been shown to improve with increases in scale and capacity due to reductions in capital costs per unit of capacity usually resulting from reductions in land requirements, auxiliary facilities, and so on.

- Use of alternative fuels sources during transportation stages – The use of CNG or electric-fuelled vehicles in the transportation phase would have the potential to reduce the environmental impacts of the entire process.

- Evaluation of the process considering other environmental impacts – This assessment's goal was to ensure that the system in net negative with respect to carbon emissions, however, there are various other impacts which could arise from the implementation of this system. Further studies into these impacts and their magnitude would provide a more robust understanding of the environmental impacts stemming from the proposed system.

9. Conclusion

For this study, it was determined that most advantageous capture technology would the DAC solid sorbent system with it being located in Union Industrial Estate, La Brea. The most suitable method of transporting the captured carbon dioxide to the injection site located in Forest Reserve Field, Point Fortin is via tanker truck. The main objective of this study was to determine the net CO_2 emissions resulting from a DAC CCS system which captures emissions from a renewable energy source. From the analysis carried out it was determined that a solid sorbent DAC system would be most suitable for this project. Using the design stated in the report, the net CO_2 emissions coming out of the gate to grave system boundaries were -799 $kgCO_2e$/ ton of CO_2. The implementation of the proposed solar PV system largely contributes to this reducing electricity generation emissions by over 90%. Assuming that the stored CO_2 is used for carbon credits, which would be sold as a source of revenue, the minimum price at which these can be sold for the DAC system to breakeven is $347USD/ton without electricity generation income. Once electricity revenue is factored in the project's feasibility increases, continuing to do so once electricity subsidies are removed. It was determined that depleted oil reservoirs have greater potential for geologically storing carbon dioxide compared to that of a saline reservoir.

In conclusion, the project was able to showcase that CCS can be implemented in the country for these two particular reservoir storage types through the use of DAC solid sorbent technology. It was seen that the technology, along with the logistics of the project in theory showed that the venture can be both economically feasible and environmentally friendly in a manner that speaks to Trinidad and Tobago's developmental pathway for Vision 2030, as well as the Paris Agreement Act.

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