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# An overview of carbon dioxide sequestration in depleted oil and gas reservoirs in Florida, USGS Petroleum Province 50

**Diana Velasquez, MSc**
*Staff Geologist, Applied Research Center, Florida International University, Miami, Florida, USA, dvelasvasquez62@yahoo.com*

**Olga Rey, PhD**
*Director of the School of Geology, Mines and Geophysics, Universidad Central de Venezuela, Caracas, Venezuela, olgatreyb@yahoo.es*

**Eduardo Manrique, PhD**
*Senior Reservoir Engineer, Norwest Questa Engineering, Golden, Colorado, USA, emanrique@questa.com*

## Abstract

Throughout the world, $CO_2$ is viewed as the major component in greenhouse gas emissions to the atmosphere. As a result, a significant amount of effort has been devoted to determining a simple, safe and cost-effective method to reduce this particular greenhouse gas. The State of Florida is ranked fifth in the U.S. for $CO_2$ emissions from power plants and it is anticipated to increase due to the population increase expected over the next several years. Some of the oil and natural gas reservoirs of the Florida Platform, in particular, Bear Island field constitute excellent structures for $CO_2$ geologic sequestration. The paper provides an overview of capturable $CO_2$ emissions in Florida, $CO_2$ capture technologies and the identification of potential geological formation (e.g. oil reservoirs) for storage of $CO_2$. The main geological features of USGS Petroleum Province 50 (Florida Platform, U.S.) are discussed and identified as potential geological formations for $CO_2$ sequestration by evaluating storage capacity and injectivity of $CO_2$. It also addresses potential environmental impacts and defines the strategy for adoption of this technology. The results obtained in this study reveal that the Bear Island field hydrocarbon reservoirs have great potential for $CO_2$ sequestration.

## Keywords
Geological $CO_2$ Sequestration, Hydrocarbon Reservoirs, State of Florida

## Introduction

There is consensus that carbon dioxide ($CO_2$) concentration in the atmosphere is increasing and that such increased concentrations contribute to about half of the potential global warming. In 2004, United States (U.S.) emissions of $CO_2$ were 5,973.0 million metric tons carbon dioxide ($MMTCO_2$), from which almost 83 percent were produced from the combustion of fossil fuels (coal, oil and natural gas). Moreover, $CO_2$

emissions from electric power sector energy consumption represent 39 percent of the total emissions from fossil fuel combustion (Energy Information Administration, 2005).

The State of Florida is ranked fifth in the U.S. for $CO_2$ emissions from fossil fuels combustion and is the second largest emitter of the gas from the electric power sector (Environmental Protection Agency, 2001). Additionally, Florida remains one of the fastest growing states in the country with all likelihood of a population increase over the next years that could result in increased $CO_2$ emissions in the State.

This scenario has led to the present study on control and storage of $CO_2$ emissions and pollution levels (Cannel et al., 2001). One of the options for carbon management consists of the capture and sequestration of $CO_2$ in geological formations such as depleted, disused oil and gas fields and saline aquifers, among others. Preliminary studies have shown that some of the oil and natural gas reservoirs from the U.S. Geological Survey (USGS) Petroleum Province 50 (Florida Platform) constitute excellent structures for this purpose (Velasquez, 2005).

It is envisaged that this review on separation technologies, and suitable geologic formations for $CO_2$ sequestration will enable policy makers in the State of Florida to have a clearer vision and strategy to harness $CO_2$ emissions.

## Objectives

### General Objective

This study aims to conduct a review of $CO_2$ emissions in the State of Florida, $CO_2$ capture technologies available and the identification of potential geological formations for $CO_2$ storage in the USGS Petroleum Province 50 (Florida Platform).

### Specific Objectives

- Overview of $CO_2$ emissions in Florida and brief description of $CO_2$ separation and capture technologies.
- Present a general overview of a methodology for reservoir screening and geological characterization of hydrocarbon reservoirs.
- Evaluate the storage capacity of $CO_2$ from anthropogenic sources in geological formation (USGS Petroleum Province 50) using Bear Island field as an example.

## $CO_2$ emissions in Florida

Florida's principal greenhouse gas emitted to the atmosphere is carbon dioxide, which was estimated at 234.80 $MMTCO_2$ in 2001. The only source of carbon dioxide emission evaluated in the inventory was from fossil fuel combustion. $CO_2$ emissions from energy use during 1990 to 2001 had an annual average increase of 1.03 percent per year (Figure 1) (Environmental Protection Agency, 2001).

Over the years, the States' largest sources of emissions were derived from power generation and the transportation sectors. For example in year 2001, power generation and transportation sectors represented 48.5% and 41.5%, respectively of total $CO_2$ emissions in Florida. The remaining $CO_2$ emissions came from industrial (7.1%), commercial (2%) and residential (1%) sectors (Figure 1). Therefore, the power generation sector, which utilizes the burning of oil, natural gas and coal, is the major target for $CO_2$ capture in Florida as it represents almost 50% of all $CO_2$ emission in the State.

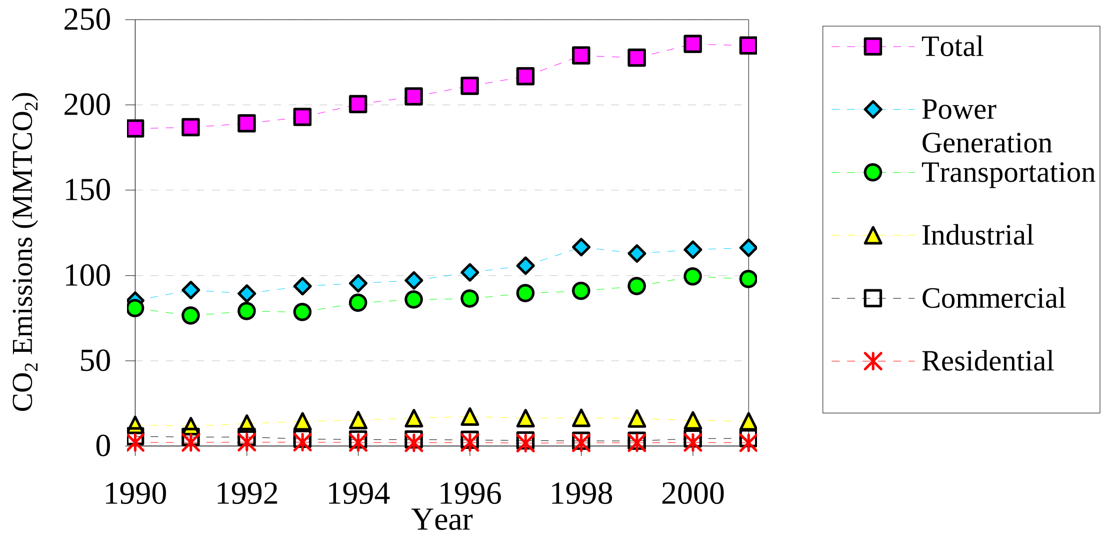


**Figure 1: $CO_2$ emissions by sector in the State of Florida during the period 1990 – 2001(Environmental Protection Agency, 2001).**

According to the Census Division and State (2000), Florida has 69 power plants, of which 44 plants are fossil steam generators mainly operated by Florida Power & Light (FPL), Tampa Electricity (TECO). Florida Power Generation (Progress Energy Subsidiary) and JEA Electric-Water-Sewer. These plants have a net generation capacity of 29,493 megawatts (MWh) and represent the major sources of $CO_2$ emissions for $CO_2$ capture and storage projects (Energy Information Agency, 2002).

Florida $CO_2$ emissions in 2000 totaled over 235.81 MMTCO$_2$, about 4.1 MMTCO$_2$E per capita from combustion of primary fuels (Environmental Protection Agency). Figure 2 shows the population growth and $CO_2$ emissions in the State of Florida since 1990 (Energy Information Agency, 2002; U.S. Census Bureau, 2000). As is expected, the increase in $CO_2$ emissions correlates with the population increase in the State of Florida. Therefore, the amount of $CO_2$ emissions per capita is projected to increase as the population increases over the next several years. Population in the State is projected to increase to 18 million by 2005 based on the State's 2000 census population of 15,982,378 (U.S. Census Bureau, 2000).

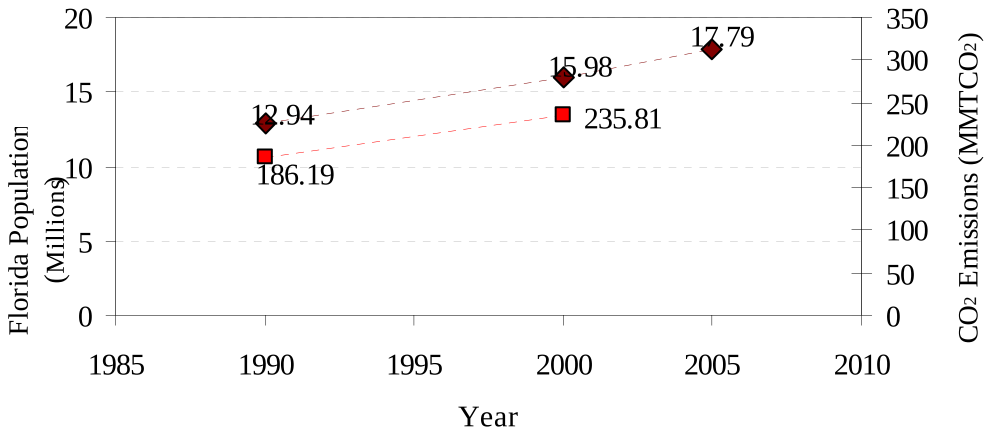


**Figure 2: Correlation of $CO_2$ emissions with population growth in the State of Florida.**

## Capture Technologies

In general, to economically sequester $CO_2$ produced from industrial sources—power plants, steel industry, refineries, and petrochemical plants, among others—a relatively pure and high pressure stream of $CO_2$ must first be produced. The economics of $CO_2$ transportation and uses (e.g. food industry and oil recovery) favor and requires high $CO_2$ concentration streams (> 94%).

On the other hand, it is well known that the unit costs of natural $CO_2$ as a by-product of the hydrocarbon industry is much lower than that of $CO_2$ from anthropogenic sources, such as flue gases from coal-fired power plants. However, it should be noted that the state of technology for the capture and separation of $CO_2$ from combustion processes is in its infancy, thus signifying the correspondingly higher costs.

$CO_2$ separation from flue gases can be achieved by chemical absorption (e.g. amine solvents such as Mono-Ethanol Amine or MEA), physical absorption (e.g. Selexol and Rectisol processes), adsorption (e.g. adsorber beds and regeneration methods), cryogenic methods, membranes, and hybrid systems, among other novel methods. However, most of the existing technologies for separation and capture of $CO_2$ from gas streams have not been designed for power plant operations. Additionally, the preferred technology for a given application depends on several factors (Espie et al., 2001; Kerr, 2004; Klara and Srivastava, 2002; Rubin and Rao, 2002) such as:

- $CO_2$ concentration in the gas stream.
- Partial pressure of the $CO_2$ in the flue gas stream.
- Levels and type of contaminants in the flue gas stream (sensitivity of a particular technology to impurities).
- Purity of the desired $CO_2$ (food industry vs. sequestration in geologic formations).
- Capital and operational expenditures (CAPEX and OPEX) of the process.
- Environmental impact of the selected technology, among others.

Current technologies can capture between 80% and 96% of $CO_2$ from flue gas streams. However, most of the commercial $CO_2$ capture plants use processes based on chemical absorption with MEA or proprietary amine solvents. It is important to mention that current $CO_2$ capture technologies are energy intensive and requires large capital expenditures for additional equipment and uses a significant fraction of the energy content of the fossil fuel requiring power replacement to make up net power plant output reductions.

As mentioned before, several new and upgraded $CO_2$ capture technologies have been proposed and evaluated; most not being competitive with chemical absorption technologies. However, efforts are underway for research and development on new $CO_2$ capture technologies. Among the most promising technologies from the point of view of efficiency and cost are highly selective membranes, nanoporous $CO_2$ "molecular basket" adsorbents (nanotechnology), and $CO_2$-hydrates (Klara and Srivastava, 2002; Xu et al., 2005).

## Screening Criteria

Terrestrial systems, deep oceans, and geologic formations have been proposed as potential $CO_2$ storage options. Although oceans show the largest $CO_2$ sequestration potential, the environmental impact and uncertainty associated with them make geologic formations the preferred $CO_2$ storage option. The geological stability of $CO_2$ natural accumulations and the experience of the oil (Enhanced Oil Recovery or EOR) and gas (gas storage) industries confirms that geologic formations represents a lower risk scenario for $CO_2$ storage for significant periods of time at the current level of technology understanding.

Preliminary evaluation of potential $CO_2$ geological sinks in the State of Florida considered the following key aspects:

- Screening criteria used in this work have been proposed by Kovscek, 2002; Taber et al., 2001 and Manrique and Wright, 2005. These studies showed a very useful tool for cursory examination of the minimum conditions required to inject $CO_2$ into subsurface in terms of reservoir variables (permeability, porosity, depth, temperature, pressure, ˚API, viscosity, etc). In addition, other aspects such as lithology type, reservoir seals and depositional system are also considered. It is important to mention that proposed screening criteria are based on geologic description of natural $CO_2$ reservoirs and international EOR field experiences well documented in the literature.
- Oil and gas regulations in Florida State, better known as moratorium threat the prohibition of new exploratory activities since year 1981 in state waters and onshore, in order to protect the environmental sensitive areas (Lease Sale 181, Gulf of Mexico, Eastern Region). Although this aspect is out of the scope of the present paper, during the selection of the areas of interest these restrictions were considered in order to identify oil fields not included in the moratoria with surface facilities available for potential $CO_2$ sequestration projects.
- Economical aspects defined by the availability of surface facilities and synergy necessary to $CO_2$ capture, transportation and storage from the source of origin to the potential reservoir or geologic sinks. Preexisting installation of oil field distribution and metering facilities for injected and produced gas might make a particular geographic area more attractive than another. One really important economical aspect is the power plant location, which would be the potential $CO_2$ source to its subsequent storage. The U.S. Department of Energy (DOE) has proposed that 500 km. might be the maximum distance to move $CO_2$ from its source to a sequestration site (Kovscek, 2002). Oil fields from USGS Petroleum Province 50 fulfill this requirement.
- Geologic, reservoir and well data (core samples, petrophysical analyses and logs) availability for oil fields within the State (Florida Geological Survey database - USGS Petroleum Province 50, Florida Platform). It is important to point out that oil fields evaluated accomplish political restrictions and economic aspects mentioned above. This aspect is very important because the lack of information available for Florida's oil/gas fields limit the study of $CO_2$ sequestration in hydrocarbon geological formations.

According with the screening criteria reviewed, political and economical aspects and field (geologic, reservoir and well) data availability it was possible to identify three oil fields (Lehigh Park, Bear Island and Corkscrew) to develop a detailed evaluations for $CO_2$ sequestration studies. However, Bear Island Field was selected given the quality and quantity of data available (e.g. well logs, core data and core analysis) and required for proper reservoir characterizations of $CO_2$ geologic sinks and as will be described in the following sections of this paper.

## Geological Study

Lithology and petrophysical properties of a reservoir represent one of the most important components to study the sequestration capacity of $CO_2$ emissions in geological formations. The geological interpretation should be based on the description of core sections, petrology analysis of thin sections and petrophysical properties. Detailed macroscopic core description allows the definition of the vertical and lateral relationship, sedimentary structures, fossil content and all the features observed during the study. Subsequently, conventional petrographic study of several thin sections allows the definition of textural, compositional and diagenetic characteristics of the rock.

For the determination of the depositional system and diagenetic influence in the reservoir it is necessary to define the sedimentary lithofacies taking into account all the lithology characteristics observed in the core section studied. In the same way, the petrographic results should be integrated in order to establish the diagenetic influence and to establish the behavior of the rock sequence in terms of sedimentary and diagenetic processes that took place in the rock.

Another important aspect considered in the geological study is the documentation of the dimensions, orientations and internal heterogeneities of the rock, which can be obtained from described core data and its relationship with well data, production data, and stratigraphic correlations.

In the case study (Bear Island field), the description of 18 cores section, 10 thin sections and the analysis of petrophysical properties in 8 wells allowed to describe the formation as mainly composed of limestones, dolomites and anhydrites. Additionally, Bear Island field forms a northwest – southeast structural dome with approximately 7 km. length and 4 km., deposited in a shallow marine carbonate platform setting in which were interpreted tidal shoal or tidal channels and tidal flat (Velasquez, 2005).

## Storage Capacity and Injection Plan

The estimation of $CO_2$ storage capacity is intimately related with the pore volume of the geological structure. The porous media in a hydrocarbon reservoir is often heterogeneous, as a consequence of the different sedimentary processes suffered by the rock. These heterogeneities form the physical properties, which are responsible of the interconnectivity of the pores and the movable oil present in the rock. Quantitatively, the porosity is the ratio of the pore volume to the total volume. This important rock property is determined mathematically by multiplying the bulk volume, reservoir area, thickness of the producing zone and effective porosity (Ahmed, 2000). In Bear Island field all the producing zones behave as one hydraulic unit, the total pore volume of the field is 584.5 million $ft^3$.

Calculations of $CO_2$ storage capacity is obtained from Wildenborg et al., 2004 equations; where it is assume that the entire underground volume of ultimately recoverable hydrocarbons can be replaced by $CO_2$. The authors calculate the $CO_2$ storage potential of an oil field as follows [1]:

$$VCO_2 = (Voil_{(stp)} / 1{,}000) * Bo * \rho CO_2 \qquad \text{Mton} \qquad [1]$$

With $VCO_2$ as the $CO_2$ storage capacity (millions of tones, Mton), $Voil_{(stp)}$ as the volume of ultimate oil recovery at standard p and T conditions ($10^6$ $m^3$), Bo as the oil formation factor (no units), and the $\rho CO_2$ as the density of $CO_2$ at reservoir conditions ($kg/m^3$).

The volume of ultimate oil recovery $Voil_{(stp)}$ is calculated with the enhanced oil recovery factor by $CO_2$ injection determined through an analytical model provided by Northwest Questa Engineering (Pereira, 2005). Additionally, is necessary to determine the extra oil due to incremental oil production (EOR, Wildenborg et al., 2004 [2]). The sum of the primary and secondary oil production is the $Voil_{(stp)}$.

$$EOR = (\% X / 100) * C * OOIP \qquad 10^6 \, m^3 \qquad [2]$$

With EOR as the extra oil due to enhanced oil recovery by $CO_2$ injection ($10^6$ $m^3$), % X as the percentage of extra oil due to $CO_2$ injection (%), C contact factor accounting for the % of oil in contact with $CO_2$ (adimensional) and OOIP as the original oil in place ($10^6$ $m^3$).

Calculations for $CO_2$ injectivity into the formation are based on the volume of extra oil due to enhanced oil recovery by $CO_2$ injection and reservoir properties, and were determined analytically (Pereira, 2005). This analytical simulation tool models a well pattern (generally five-spot patterns) assuming that the obtained results represent the average performance of a particular reservoir (Manrique and Wright, 2005). The analytical model utilized considers the following aspects for Bear Island field:

- A five-spot pattern inversion, separated 1,200 ft (365.76 m.) each well. For each arrangement was considered a rate of $CO_2$ injection of 1,000 bbl/d, this means, 250 bbl/d for each well.

- In both scenarios (E1 and E2) was considered $CO_2$ injection until a 10% of $CO_2$ in the gas of the production be shown, at this time the producing well closes since is not contemplated re-injection of the gas in the field and because the main objective is to capture $CO_2$ emissions from power plants.

- The area of each five-spot pattern is 2.88 $Mft^2$.

The evaluation of two scenarios allowed the determination of the $CO_2$ storage capacity in Bear Island field and the $CO_2$ injectivity in the formation, through out the analytical simulator. The scenario E1 considers 2000 psi and 93˚ F of reservoir temperature. The scenario E2 considers 5000 psi as the reservoir pressure and conserves the same temperature. Initially, the $CO_2$ storage can be initiated with a limited number of wells and this number can be increased gradually according with surface facilities. The calculations considered a primary phase of enhanced oil recovery. However, due to the petroleum regulations in Florida State, $CO_2$–EOR may require to be revisited. In the case of $CO_2$ injection without oil production or EOR (only sequestration) the $CO_2$ injection volumes remains the same.

The $CO_2$ storage capacity for scenario E1 is 0.76 Mton and the estimated $CO_2$ injection rate is 47.69 ton/day; for scenario E2 the storage capacity is 1.90 Mton and the estimated $CO_2$ injection rate is 116.05 ton/day. The period of time necessary to inject this $CO_2$ volume is 43 and 45 years for scenario E1 and E2, respectively.

**Bear Island's Surface Facilities Installations**

This analysis was made based on the geographical distribution of the $CO_2$ emission sources (power plants) and the storage structures available in Bear Island field. The nearest power plants to Bear Island field are: Florida Power Light (FPL) in Ft. Myers and Florida Power Corporation (FPC) located in De Soto County, both have a total $CO_2$ emission of 1,111,962 lb/hour, equals to 12,105.06 ton/day. Based on the emissions data for each plant it was estimated the lifetime of the storage facility according with the injection rate and the $CO_2$ volume. The time that requires storing the $CO_2$ emissions from Ft. Myers and

De Soto power plants is near by 0.17 years in the scenario E1 and 0.43 years in the scenario E2, this means that the total emissions of $CO_2$ generated by these power plants $CO_2$ emissions can be storage in one year in Bear Island field with an injection rate of 1,000 bbl/d of $CO_2$.

Figure 3 shows three fundamental phases carried out to storage $CO_2$; these phase are: $CO_2$ capture from the source (two power plants: FPL in Ft. Myers and FPC in De Soto), a second phase of $CO_2$ compression and transportation by pipelines; and a third phase of $CO_2$ recompression and injection into Sunniland Fm. in Bear Island field.

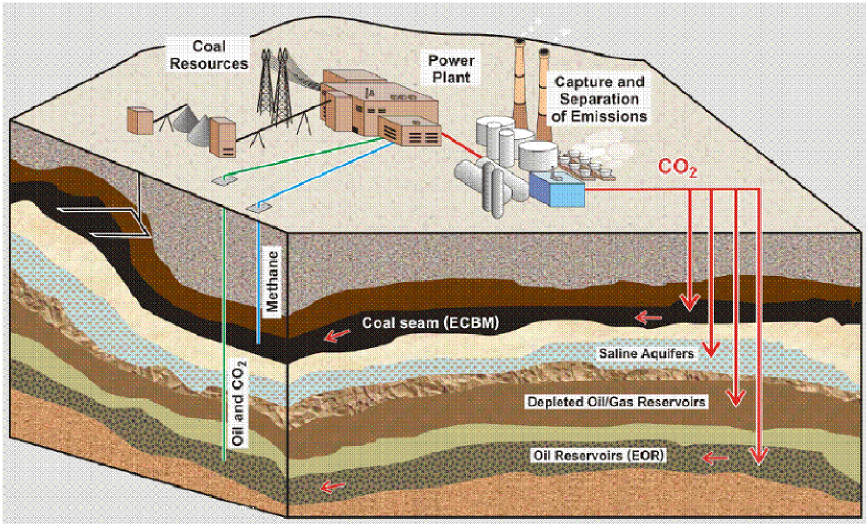


**Figure 3: Schematic of $CO_2$ capture, sequestration and storage in Bear Island field.**

## Conclusions

There is considerable evidence that this study of $CO_2$ sequestration in geologic formations can contribute to a reduction of $CO_2$ emissions into the atmosphere by the State of Florida. Some of the most $CO_2$ capture technologies, such as chemical absorption, physical absorption, adsorption, cryogenic methods, membranes, and hybrid systems, among others are subject to several factors which control their economical viability. Nevertheless, by utilizing a screening criteria for $CO_2$ sequestration, which includes political, economical, and geological-reservoir aspects, Bear Island field was found to meet all the criteria's for geological-$CO_2$ storage based on the methodology proposed in this study. Bear Island field lithology is mainly composed of limestone and dolomite facies developed in a shallow marine carbonate platform. Technical feasibility of $CO_2$ storage capacity of Bear Island Field was evaluated suggesting that $CO_2$ can be sequester for long periods of time in this field.. However, a comprehensive data gathering program is recommended to improve geologic and reservoir description of Bear island Field and USGS Petroleum Province 50.

The proposed methodology can be applied for the evaluation of $CO_2$ capture and storage opportunities in an easier, safety and cost-effective way.

## Recommendations

The technology, the cost, and safety issues for transportation were not considered, but it is likely that the costs will be significant and must be included for any valid comparison among projects and $CO_2$ captures and storage strategies.

Characterize $CO_2$ trapping mechanism in the formation in order to apply geomechanical data in the study. The influence of deformation on the hydraulic properties of the formation and integrity cap rock must be better understood.

Evaluate the $CO_2$ storage capacity in the surrounding oil and gas fields near Bear Island field in order to satisfy the $CO_2$ power plant emissions in Ft. Myers and De Soto, once Bear Island reach its total $CO_2$ storage capacity.

Given the lack of geologic and reservoir data of different oil and gas fields in the USGS Petroleum Province 50 a comprehensive data gathering is recommended if $CO_2$ sequestration is considered in the State of Florida.

If $CO_2$ sequestration is ever implemented in Florida the oil and gas moratoria needs to be readdressed.

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