Reservoir-model-based scenarios for assessing the viability of greenhouse gas mitigation strategies through CO2 enhanced oil recovery

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ABSTRACT

This study aims to show that utilization of captured carbon dioxide from the power and industrial sectors for enhanced oil recovery (CO2-EOR) can be a key means of supporting global climate change ambitions. Normative business scenarios are developed to support the economic evaluation of CO2-EOR under different contexts. A reservoir simulation model provides a realistic basis for economic input parameters and has been developed to support the determination of scenarios in which energy price variations, production tax rates and carbon dioxide prices will make CO2-EOR economically viable. The scenarios are used to test CO2-EOR project economics under a variety of oil prices. Projects are shown to be resilient and profitable investments, though arguably not all projects may lead to long-term CO2 storage. Through the scenarios it is shown that stakeholders, particularly the global citizen, have the ability to significantly impact CO2-EOR project investments.

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1. Introduction

The petroleum industry is often held responsible for global warming as a consequence of fossil fuel production. This study argues the petroleum industry also is uniquely equipped to provide practical solutions for carbon capture and storage (CCS) and carbon capture, utilization and storage (CCUS) to help meet greenhouse gas (GHG) emission reduction targets. The petroleum industry, commonly perceived slow to embrace the reality of global warming, is uniquely equipped to meet the reduction targets set forth in global directives through CCUS projects. Today, fossil fuels still comprise a major market share in the global energy system with oil and gas making up for 58% of 2015 primary energy consumption and 53% of 2040 projected consumption [1]. Electricity and heat production from the combustion of fossil fuels constituted 42% of global carbon dioxide (CO2) emissions in 2013 [2]. CO2 is arguably the most prevalent GHG and one of most environmentally damaging gases. Extreme weather events have become commonplace, including abnormally heavy rainfalls causing deadly flooding, and are thought to be made worse due to manmade GHG emissions [3,4]. Failure of climate-change mitigation is very likely and would have global impact on societal economies at a scale comparable to that of weapons of mass destruction [5].

The United Nations (UN) Paris Agreement calls for global temperature rise due to GHG emissions to be limited to 2 °C above pre-industrial levels. The Paris agreement requires ratification by 55 of the top polluting countries, producing roughly 55% of global GHG emissions, before the agreement will come into force [6]. The agreement focuses on countries doing what they can as quickly as possible but fails to highlight any policing of intended objectives or methods to press compliance. Curbing CO2 emission levels is directly targeted through the Paris Agreement. Separately, the United States Environmental Protection Agency (EPA) has created the Clean Power Plan to reduce CO2 emissions from power plants to 32% below 2005 levels by 2030 [7]. This plan was met by lawsuits from 29 states and is held up, awaiting verdict in the Supreme Court [8].

The petroleum industry has used CO2 as an enhanced oil recovery (EOR) flooding agent since the 1980’s. CO2–EOR has become popular due to the added benefit of positive environmental impact [9–12]. The work of Zoback et al. [11,12] characterized many reservoirs where CO2-EOR could be successful. Out of 40 projects listed by the Global CCS Institute [13] as large scale projects, 23 are using...
EOR for CO₂ storage. There are 15 large-scale projects with 7 more under construction worldwide. What remains unclear is how many of these projects may be attractive from an investor point of view.

Traditionally, CO₂ used for EOR is often not captured from electricity production or industrial emissions streams but rather taken from natural, underground CO₂ sources, negating the objectives of CCS. The Global CCS Institute projects are focused on industrial CO₂ capture and include the power generation, fertilizer production, iron and steel production, oil refining and natural gas production industries. All of the projects, except for Petrobras Santos Basin Pre-Salt Oil Field CCS Project in Brazil, are located in The United States (US), Canada, The Middle East, and China. These regions, with the addition of North Africa, represent globally the highest oil recovery or storage potential from CO₂-EOR [14]. The projects outlined by the Global CCS Institute are unique because they include monitoring of CO₂ floods and risk analysis of long term CO₂ storage. Many current CO₂-EOR projects do not include the appropriate control measures for CCS and were not set up with CCS in mind, for various reasons including scope and cost. CO₂ used in EOR does not contribute to climate policy objectives [14].

Critiques of CCS are worried about the environmental implications should CO₂ leak from storage locations back into the atmosphere. Angeli et al. [15] studied CO₂ breakthrough through a shale caprock and concluded that a shale caprock would provide safe storage of CO₂ during CCS without the threat of CO₂ migrating back into the atmosphere or into aquifers. In their study, flow of CO₂ is noted to be along specific channels and microfractures in the shale. With pressure monitoring it is possible to control microfractures, which will not allow CO₂ migration to happen on a macroscale throughout the shale. Pressure monitoring must occur forever to be sure that CO₂ does not migrate or breakthrough, adding costs to CCS projects. However, without assurance that CO₂ will not leak from reservoirs, CCS will not gain public support.

CCS or CCUS is one way to mitigate anthropologic CO₂ by capturing the gas and storing it underground or below the sea floor. Coupled with EOR, CO₂ storage solutions in the petroleum industry would help to meet GHG reduction targets globally because CO₂-EOR generates a net emissions reduction. According to the International Energy Agency (IEA), CO₂-EOR can be coupled with CCS, injecting more CO₂ than needed for oil recovery; turning a project into a CO₂-EOR+ or maximum storage project with maximum CO₂ storage ranging from 60 to 360 GtCO₂ during the next 50 years. In order to turn traditional CO₂-EOR projects into CCS projects to support climate change legislation targets, the IEA identifies key planning and operational activities that are critical to implement, including site characterization, monitoring programs and changing field abandonment processes. Adding these activities would move an EOR project to an “EOR+”; but also add costs that could negatively impact economic evaluations, causing some companies to not pursue CCS as part of their EOR project scope without compensation offsets [16]. No CO₂-EOR+ or maximum storage projects currently exist [16]. However, projects like Weyburn-Midale in Saskatchewan, Canada prove long-term CO₂ storage through EOR is possible [17,18].

There is a growing need to mitigate CO₂ release into the atmosphere but CO₂-EOR projects will not be coupled with CCS unless climate change policy and project economics both support CCS investment. In our study four business scenarios are constructed using a modified Scenario Matrix [19,20], and graphically depicted as a Scenario Cube. Sensitivity analyses are included to test the resilience CO₂-EOR project profitability within the scenario business environments for various CO₂ tax models and various commodity prices.

2. Methodology

The reservoir simulation economic model used in this study was created by Saint-Felix [21,22] as part of an M5 thesis study in petroleum engineering for Texas A&M University. The reservoir properties and production amounts have not been changed from his model. The reservoir and economic model inputs are discussed followed by the business scenario creation process in order to give context to the economic evaluation presented in the modeled business scenarios.

2.1. Reservoir model

The modeled reservoir (Table 1) is representative of a reservoir that would be selected for CO₂ injection. This reservoir is assumed to safely store the injected CO₂. Oil recoveries are increased through the CO₂ flood. The inputs for the reservoir model are oil production, gas production, water production and CO₂ imported obtained from Schlumberger’s ECLIPSE suite. The reservoir model outputs do not change under different business scenarios.

2.2. Economic model

The outputs from the reservoir model flow into the economic model. The economic model is a before tax monthly cash flow model and includes production taxes but not county, state or federal taxes as they widely vary in the US and from one country to another. Tax regimes cannot be overlooked during project evaluation and large tax incentives sometimes come into play which make projects profitable but, due to their complexities, they are difficult to model outside of the context of a specific well or field. Taxes beyond production taxes are not included in this study but are noted to have a great effect on industry project profitability and should be taken into account. In our study, a neutral effect is assumed between tax credits and any corporate tax payments due on the CCS/CCUS project. All prices modeled in this study are in US dollars and the model period is 40 years, starting January 2020. The economic model accounts for:

- Production sales of oil, gas and the disposal of water
- Drilling, completions, surface facilities, abandonment costs and project development
- Monthly operations costs

The economic limit is defined as the month that production product revenue (oil, gas and CO₂) is less than operating expenses and production taxes. Abandonment costs are accrued for at the start of the project and shown in the economics as a capital expenditure (CapEx) when the economic limit is reach. The model assumes production is maintained at the maximum amount during the well’s economic life and is not restricted due to market prices or other factors. When the economic limit of the well is reached the analysis is concluded, as it is assumed the well will not continue to

Table 1

Reservoir data inputs.

<table>
<thead>
<tr>
<th>Reservoir data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir depth</td>
<td>11,500 ft</td>
</tr>
<tr>
<td>OOIP (per well)</td>
<td>0.31 MM stb</td>
</tr>
<tr>
<td>OOIP (field)</td>
<td>99 MM stb</td>
</tr>
<tr>
<td>Pore volume (per well)</td>
<td>0.82 MM resbl</td>
</tr>
<tr>
<td>Pore volume (field)</td>
<td>263 MM resbl</td>
</tr>
</tbody>
</table>
produce if it is not generating profit for the company. The main economic variables used for sensitivity analysis and their ranges changed throughout the scenarios are given in Table 2.

2.2.1. OpEx and CapEx
Operating expenditures (OpEx) account for the monthly fixed and variable costs for maintaining the wells. CapEx accounts for surface facility installation, drilling, completion, and abandonment. The model also accounts for the costs specific to CO2-EOR and includes:

- CO2 generation cost (OpEx)
- CO2 transport: pumping, pipeline, trucks if necessary (CapEx and OpEx)
- CO2 market price (OpEx and/or revenue)
- CO2 recycling (CapEx and OpEx)

Produced-gas recycling lowers the generation and transportation costs of new CO2 needed for the project is included in all simulations. CO2 is transported 60 miles from the source to the field for all cases modeled. Increasing the distance of the field from the CO2 source significantly lowers the profitability of the project. Having projects close to CO2 sources would help to assure transportation costs are not the limiting factor in CO2-EOR project investments.

2.2.2. Commodity prices
Commodity price forecasts (Fig. 1) from The World Bank [23], the U.S. Energy Administration (EIA) [24], and Deloitte [25] were used to develop a range of $20-$119 for oil prices which are in real terms. The oil price escalation rate and the CO2 price escalation rate are based off the EIA [26] estimate for GDP growth from 2013 to 2040 (2.4%) and is taken to be the median case. A range of 1.8% and 2.9% were selected for the high and low escalation rates. Of note, for the previous 30 years, the GDP growth rate was 2.8% but the World Bank [27] revised their growth predictions down from 2.8% to 2.4% due to low commodity prices, weak trade and reduced capital exchanges. In the past, high oil prices may have significantly offset EOR and CO2 capture and transportation costs.

2.2.3. Production tax rates
Production tax rates vary greatly from country to country and state to state. Various tax incentives are also given to companies to spur projects development and production tax breaks may be given while the project is being developed or producing under a set amount of production. This study is not meant to be exhaustive on how production tax rates affect CO2-EOR projects but it is designed to show that production tax rates could incentivize CO2-EOR project pilots and developments in some cases and cannot be overlooked when planning this type of industry project. With 5% being considered an average production tax rate for most US states, it is used as the median value with 2.5% as the low and 15% as the highest production tax rate modeled in the business scenarios. Rates of 5%, 7.5%, and 15% were selected to evaluate the production tax effect on project profitability.

2.2.4. Carbon tax rates
The World Bank [28] has outlined current global carbon pricing policy. Future price scenarios for GHG taxes are based on a set of assumptions concerning market dynamics and the behavior of its principal agents [29]. Cap-and-trade schemes have been tried in North America, the European Union (EU) and Australia. An example of an attempt to establish a GHG emission curbing incentive is provided by the European Union Emissions Trading System (EU ETS), which covers all 28 EU member states (plus Iceland, Norway, and Liechtenstein) and monitors more than 11,000 factories, power stations, and other installations each with a net heat excess of 20 MW [30]. Unfortunately, the price of EU ETS carbon credits has been lower than intended, and has dropped below €5 per tonne in 2016 as compared to nearly €30 per tonne in 2008. Similar cap-and-trade schemes have been considered in North America. The first cap-and-trade scheme to be repealed was in Australia in 2014, lasting only 2 years. The scheme taxed 348 of the highest polluting businesses $25 for every tonne of GHG they produced [31,32]. Replaced by an A$2.55 billion carbon credit fund, The Emissions Reduction fund began in July 2016, and rewards businesses for making clean energy and emissions reduction choices. The scheme is voluntary and project applications will have to be approved before funding is received.

The CO2 capture credit price is based on the social cost of carbon in this study. The social cost of carbon covers ecosystem, agricultural, health and property damages due to changing climates. It is based on insurance figures and social perception of how much an additional ton of emitted CO2 would cost. Prices for the social cost of carbon are: $22, $36 and $67 in 2007 dollars [33]. Scaling these prices to 2020, using the time value of money, and estimating the average amount of growth is 2%, the social cost of carbon becomes $27, $44 and $81 for the low, median and high CO2 scenarios. Figures for the social cost of carbon greatly vary due to how the social impact of an additional ton of CO2 released into the atmosphere is evaluated. For all scenarios in our study, a CO2 capture cost of $55/mton of CO2 was used as it is the average cost of CO2 avoided compared to a pulverized coal plant without CO2 capture in use [34,35]. Using CO2 avoided costs allow for comparison across capture technologies which capture at different rates and purity levels. Transportation parameters, CO2 generation parameters and tubing costs from the Saint-Felix [22] model reflect the most up-to-date cost information. The economic model assumes there is 1 producer and 1 injector per pattern with 40 patterns to be developed. The main economic assumptions changed in the model are product prices, CO2 regulation and company interests. Changes to these parameters are highlighted in the business cases as it is through each business case the changes are seen.

2.2.5. NPV and IRR
Many companies evaluate potential investments through the use of benchmark parameters. Net present value at a 10% discount rate (NPV10) and internal rate of return (IRR) are United States dollars (USD) to assess project profitability. IRR is the discount rate at which the NPV of a project will be zero. With all variables being the same, the project with the highest IRR would be the best project to undertake. NPV10 compares a project’s future revenue and money spent to a present value. A project with a NPV10 greater than zero has a net positive cash flow and an NPV10 less than zero has a net negative cash flow. NPV10 and IRR must be used in conjunction for project profitability evaluation as neither metric on its own will give an accurate representation of the project’s investment potential.

Many companies use a hurdle rate to screen projects for investment. Companies use the hurdle rate to make sure potential investments are strong enough to make the company the cash it
needs to pay debts and continue investing in future projects. The hurdle rate of $80 million ($1 million/well) NVP10 was selected to provide a cash buffer, should the project perform poorly. Projects in globally unstable regions will not attract investors unless they can overcome hurdle rates such that there is a large buffer to generate positive cash flow. A hurdle rate is not set for IRR.

2.3. Key drivers for business scenarios

CO₂-EOR projects, like all industry projects which require large capital investments, need options built in to remain flexible long-term. Failure to identify and plan for risk and uncertainty will lead to lower company portfolio value. Scenarios help assure risk and uncertainty are planned for and that key project sanctioning assumptions are evaluated under different business climates. Many companies use scenarios to plan investments under uncertain market conditions and make sure projected returns would be met under a variety of circumstances. Scenarios develop threats and opportunities for a project and allow stakeholders a way to evaluate a project under a large spectrum of different variable outcomes. Business scenarios were developed by us to understand the key drivers for managing CO₂-EOR projects in uncertain business climates. The drivers listed by the World Energy Council (WEC) to be linked to the climate-change mitigation are environmental priorities, international governance and geo-political relationships in a changing political landscape. The WEC discusses 3 scenarios: Modern Jazz, Unfinished Symphony and Hard Rock [36]. Elements from these scenarios can be linked throughout the 4 scenarios adopted in this paper to support plausibility. Trends and drivers, similar to the work done by Shell [37] and the WEC [36] were grouped by scenario theme (Tables 3–5).

High impact and high uncertainty variables are critical to model as they shape a project’s profitability and outcome. These variables are the scenario drivers represented on each axis of the Scenario Cube. Project profitability is evaluated under each business scenario considered in this study as depicted in our Scenario cube (Fig. 2).

3. Scenarios and economic appraisal

A summary of the four scenarios adopted in our analysis and the pertinent key variables used in the economic model of EOR are given in (Table 6). The key variables are inputs to the economic model and their impact on project profitability is evaluated through the business scenarios. Each of the scenarios is outlined below.

3.1. Society pays

Taking elements from both the Unfinished Symphony and Hard Rock scenarios of the World Energy Council [36], the “Society Pays” scenario (Table 6) brings in the idea that increasing nationalism and inward focused countries coupled with the growing need for energy security will lead to growth in the alternative energy industry and spur local investment into CCS. Adding to the WEC scenarios,

<table>
<thead>
<tr>
<th>Current drivers</th>
<th>Current trends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme weather events in developing countries- human life lost</td>
<td>Social attention on alternative energy</td>
</tr>
<tr>
<td>High energy usage in developed and developing countries</td>
<td>Increased asthma and chronic disease</td>
</tr>
<tr>
<td>Developing countries looking for cheap energy sources to support economic development</td>
<td>Urban air pollution, water shortages</td>
</tr>
<tr>
<td>Technology innovation to decarbonize possible and getting better each day</td>
<td>Global climate shifts- Arctic ice melt</td>
</tr>
<tr>
<td>Capture technology expensive to implement</td>
<td>Increased extreme weather events</td>
</tr>
<tr>
<td>More pollution in developing countries due to fewer regulations</td>
<td>More research on alternative energy</td>
</tr>
<tr>
<td>Social concern for environment is at an all-time high</td>
<td>Exporting pollution to developing world</td>
</tr>
<tr>
<td>Increased demand for food to support growing populations</td>
<td>Industries looking for low pollution alternatives (electricity production, transportation)</td>
</tr>
<tr>
<td>Conflict over land to develop on</td>
<td>Social fear of CCS from increased media attention- public concern could threaten adoption</td>
</tr>
<tr>
<td></td>
<td>Inability to accurately predict extreme weather events</td>
</tr>
</tbody>
</table>
numbers and disaster relief aid is hard to come by with competing
many in developing countries, adds to involuntary immigration
scenario contributing to social concerns. Extreme weather events,
people already displaced from their homes. Government resources,
security and close their borders to migrants, stranding
healthcare, across Europe are strained. Many countries begin to
radical groups. Government resources, for social programs and
development. Involuntary migration rates increase, due to re-
which was sustained by Germany and Britain's funding of EU pro-
infrastructure, though Article 50 of the Lisbon Treaty. EU membership is dwindling
starting the process of formally renouncing their EU membership
hold their own referendums and vote to leave. More countries are
and technologies, creating winners and losers.

Media attention of extreme weather events assumed in this
scenario argues that CO2-EOR projects will come online, in
areas where there is pressure from the global citizens and non-
governmental organizations (NGOS) but society will pay, through
increased energy costs, for industry investment into these projects and technologies, creating winners and losers.

Britain's exit of the EU, causes France, Germany and Sweden to
hold their own referendums and vote to leave. More countries are
starting the process of formally renouncing their EU membership
though Article 50 of the Lisbon Treaty. EU membership is dwindling
due to rising economic and immigration issues. Infrastructure,
which was sustained by Germany and Britain's funding of EU pro-
grams, begins to crumble in Europe because of weak economic
development. Involuntary migration rates increase, due to re-
cessions, security concerns and an increase of terrorist activity from
radical groups. Government resources, for social programs and
healthcare, across Europe are strained. Many countries begin to
increase security and close their borders to migrants, stranding
people already displaced from their homes.

Media attention of extreme weather events assumed in this
scenario contribute to social concerns. Extreme weather events, many in developing countries, add to involuntary immigration
numbers and disaster relief aid is hard to come by with competing
security concerns nationally for many countries. Developed coun-
tries pressure developing countries to lower carbon emissions
through The Paris Agreement; which is ratified by both the US and
China. High social pressure to curb carbon emissions leads to a cap-
and-trade policy. Carbon pricing is implemented and companies are
fined for non-compliance. Natural gas replaces coal in many
parts of the US and China for electricity generation as a result of
carbon price implementation, despite large capital investment in
retrofitting plants. Some coal-fire plants close because they cannot
pay high capital costs to retrofit equipment. Areas that close plants
look to alternative energy sources of electricity generation. In Texas
and the Midwest, wind farms gain greater popularity through
eco-sustainability. Along rivers and coastal regions, there is
increased investment in hydroelectric power generation. Oil prices
remain low for longer than expected due to increase hydrocarbon
production from Saudi Arabia and Iran. The US produces more
natural gas for domestic electricity generation. CO2-EOR projects
are piloted and technicall proven to work in many areas. Scientific
and economic collaboration is low due to the dissolution of the EU
and trending nationalism; carbon pricing and cap-and-trade would
be instituted regionally or nationally.

3.2. Economic assessment of society pays scenario

NPV10 and IRR for CO2 prices $27/ton, $44/ton, and $81/ton are
plotted against oil price (Figs. 3–8). Oil price ranges from $60–$79/bbl in this scenario. CO2 price is given a low, medium and high
escalation rate as market price of CO2 is expected to grow under
high environmental pressures. The impact of production tax rates is
also evaluated for three discrete values (5%, 7.5%, and 15%), result-
ing in 3 NPV and IRR trend lines for each corresponding plot.

Looking at a low CO2 price (Fig. 3), it can be seen that for all three
production tax rates evaluated, the NPV10 remains positive and the
IRR is well above 25% for all cases (Fig. 4). Results from the median
CO2 price and a high CO2 price (Figs. 5–8) show the same trend with values increasing for the higher NPV10 (Figs. 3, 5
and 7). Looking at the median CO2 price of $44/ton and medium
CO2 price escalation rate (Fig. 5), IRR could reach as high as 57% for
these projects, under $79/bbl oil prices (Fig. 6). For all projects

Table 4
Trends and drivers for energy prices.

<table>
<thead>
<tr>
<th>Current drivers</th>
<th>Current trends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased demand for cheap energy in India and China</td>
<td>India and China economic growth</td>
</tr>
<tr>
<td>Growth of purchasing power of China</td>
<td>Urbanism</td>
</tr>
<tr>
<td>Saudi asserting dominance in the Organization of Petroleum Exporting Countries (OPEC) control oil prices</td>
<td>Involuntary migration</td>
</tr>
<tr>
<td>Iran entering global oil market</td>
<td>Population growth</td>
</tr>
<tr>
<td>Hydraulic fracking improves production in unconventional</td>
<td>OPEC member cooperation</td>
</tr>
<tr>
<td>Keystone Pipeline controversy</td>
<td>Hydraulic fracturing improvements</td>
</tr>
<tr>
<td>Crumbling Venezuela infrastructure and high inflation rate</td>
<td></td>
</tr>
</tbody>
</table>

Table 5
Trends and drivers for changing political landscapes.

<table>
<thead>
<tr>
<th>Current drivers</th>
<th>Current trends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crumbling infrastructure in developed markets</td>
<td>Increased terrorist attacks</td>
</tr>
<tr>
<td>Global populist backlash against political elites (US Trump; UK Brexit)</td>
<td>Nationalism</td>
</tr>
<tr>
<td>Countries exiting the EU</td>
<td>Stepped up construction and defense spending</td>
</tr>
<tr>
<td>Venezuela economic crisis</td>
<td>Razor thin election outcomes producing societal backlashes</td>
</tr>
<tr>
<td>Cheap cost of capital</td>
<td>Global focus on securing only domestic investments (looking inward rather than outward)</td>
</tr>
<tr>
<td>Weak nominal GDP growth</td>
<td>OPEC member cooperation</td>
</tr>
<tr>
<td>Increased social awareness through media</td>
<td>Consumer demand increase in developed counties (backlash at government for limited access to goods and services)</td>
</tr>
<tr>
<td>Conflict over land in the Middle East</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Business scenarios.
evaluated under this scenario, IRR is greater than 25% (Figs. 4, 6 and 8), making CO2-EOR projects under this scenario strong potential investments.

3.3. Crumbling cooperation

The “Crumbling Cooperation” scenario (Table 6) considers the trend of growing nationalism and a global economic slowdown, leading to recessions and increasing poverty. Differing from the WEC Hard Rock scenario [36], Asia does not become the dominant global market and also turns inward to support nationalistic efforts. There is underinvestment in climate-change technologies globally. National security trumps climate-change concerns in this scenario, showing how CO2-EOR projects may be evaluated as countries struggle to meet their energy needs within their borders.

Nationalism is growing, climate-change mitigation measures fail to take hold and energy prices are low. Global political backlash occurs after 2016 US Presidential election and US social funding is diverted to support national security and border patrols. US economic growth slows due to clashing national political agendas and there is great doubt about US leadership abilities globally. The US looks inward to boost nationalistic needs and scales back its global initiatives, funding fewer projects. China does not believe it has the resources to be a global leader and there is a void of leadership as many countries struggle with national concerns. Developed country infrastructures are crumbling. Britain exit of the EU is lethargic and takes many years to complete. The British Pound does not recover from the drop after the Brexit vote and British citizens are concerned. France and Germany have enacted Article 50 and have begun discussions to leave the EU in favor of nationalism, further crumbling European markets.

There is social pressure but a lack of government support for carbon pricing or cap-and-trade, fearing it will send the economy into a recession. NGOs fund some investment in alternative energy. With growing geo-political changes, few governments are considering the implications of climate-change and are focusing on national security. The US signed The Paris Agreement but the 2016 US Presidential elections brought a new political agenda to The White House and no funding was put forth to support the commitments of the US to The Paris Agreement due to national security concerns. The US’s failure to follow-through on The Paris Agreement caused other countries to not fulfill their commitments to climate-change mitigation put forth under this Agreement. Frequent hurricanes and floods hit coastal regions and displace people from their homes, creating further burden on government resources. Disaster relief aid becomes harder to secure in developing countries and increase public concerns about climate-change.

Saudi Arabia and Iran turn oil production on to full capacity, flooding markets into 2018. Middle East production is eventually scaled back but prices don’t recover to $100/bbl until 2040.

![Fig. 3. NPV10 with CO2 price of $27 per ton and a low CO2 price escalation rate of 1.8% per year.](image-url)
Although many governments are not funding alternative energy projects, private-sector, including crowd-funding and other forms of venture capital, has taken off and there are many small projects utilizing wind and hydropower, to provide electricity to communities, due to energy security concerns. Developing countries benefitted a lot from these efforts initially, but rising political conflicts, economic recessions and low commodity pricing significantly impacted investments, further increasing the gap between winners and loosers. CO2-EOR projects are evaluated by companies and governments, within regions that support project geology, and additional storage for EOR and maximum storage comes online in several projects but is largely underinvested.

3.4. Economic assessment of crumbling cooperation scenario

NPV10 versus oil price for production tax rates between 5% and 15% is plotted in Fig. 9. There is no CO2 price awarded in this scenario (CO2/ton = 0), which is why one plot suffices, with oil price varied between $30/bbl - $79/bbl. At $30/bbl oil price, all projects converge on NPV10 of -$550 million.

Evaluating NPV10 versus oil price for various tax rates (Fig. 9), and oil prices of $55/bbl or higher are needed to breakeven on this project with a low tax rate of 5%. Crumbling infrastructure across Europe and in the US may cause the tax rate to rise. At higher tax rates, higher oil prices are needed for a CO2-EOR to breakeven. Under this scenario, companies may not start CO2-EOR projects in...
states or countries with high tax rates because this significantly decreases the NPV10 of the project. With a hurdle rate of $80 million, only projects that see oil prices sustained at $55-$65 with low tax rates would be considered. Many projects in this scenario do not show profitable NPV10 and companies may not want to taken on the risks of funding these projects in an ever increasing nationalistic world.

3.5. Stagnant policies

The “Stagnant Policies” scenario (Table 6) sees rapid economic growth in Asia but little action by policy makers to address climate-change. A new idea that global citizens will help to spur investment and advance CCS, CCUS and alternative energy technologies is brought in to show how growing globalization and digitalization is changing how society interacts with the natural world. Sustainable lifestyles and at-home energy systems are popular choices among those with the financial ability to make that choice but governments are stagnant when it comes to enacting meaningful policies, fearing of economic slow-down. The “Stagnant Policies” scenario concurs with elements of the Modern Jazz and Unfinished Symphony scenarios of the WEC [36], India and China are rapidly developing their economies and other countries in Asia are trying to follow. Globally migration rates lower due to job growth the Middle East

![Fig. 6. IRR with CO2 price of $44 per ton and a medium CO2 price escalation rate of 2.4% per year.](image1)

![Fig. 7. NPV10 with CO2 price of $81 per ton and a high CO2 price escalation rate of 2.9% per year.](image2)
and North Africa. Job growth brings prosperity and helps to settle conflicts as people return to work and are able to support their families. Labor costs and fewer regulations in developing world brings economic prosperity but increased pollution and associated health problems. Governments are hesitant to implementing a carbon price or environmental regulations for fear of slowing economic development. Demand is high for energy, especially in growing economies, and commodity costs are low due to increased globalization and trade.

Few climate-change regulations come into fruition as there are fears of economic slowdown in Asia. Power plants do not convert to natural gas as retrofitting requires capital expenditures and low carbon energy sources are underinvested in. Oil prices remain stable but lower than 2013 price points. Governments incentivize companies to invest in industrial projects by lowering corporate and production tax rates to spur industry and job growth in low oil price markets. The manufacturing and transportation industries, especially in India and China, grow fast as a result of low oil prices. Cheap cars, such as the Tata, become popular in India and every family strives to own one as a staple of their new middle-class wealth. Increasing car use, puts more pollution into the atmosphere.

Although carbon pricing is not put into effect by policy makers, global citizens promote public interest projects for CCS and CO2-EOR in the US, but it does little to impact pollution from manufacturing and transportation in Asia and the developing world. With increasing digital connectivity, globally, younger generations are more aware of rising anthropogenic CO2 levels. Lifestyle groups, focused on sustainability, and small, private businesses create consortiums, sharing technology and working together to curb their CO2 emissions. Voluntarily trading CO2 is likely not to happen due to capitalism and developing countries do
not abide by any CO₂ mitigation measures that cost money to implement. Carbon prices range from $3 to $20 per ton of gaseous or supercritical CO₂ [38,39] depending on market conditions. Benchmark prices come from the ammonia production industry, an industry that uses produced CO₂ in their operations[38]. The European Union Emissions Trading System[40] also trade CO₂ within this range.

3.6. Economic assessment of stagnant policies scenario

NPV10 is plotted versus oil prices under the Stagnant Policies Scenario. For CO₂ price $0/ton (Fig. 10), the oil price range was extended from $30/bbl to $79/bbl to show the breakeven point of CO₂-EOR projects under this scenario. CO₂ price escalation in this scenario was kept at 2.4% for all CO₂ prices plotted. For the $2/ton, $5/ton and $11/ton CO₂ price scenarios (Figs. 11–13) oil prices range from $60/bbl to $79/bbl as the lowest breakeven NPV10 will be found in the $0/ton CO₂ price case. Production tax rates ranged from 2.5% to 7.5% in this scenario as it is thought that fewer regulations will bring down production tax rates. An oil price escalation rate was not looked at because oil prices are not predicted to increase during the duration of the CO₂-EOR project.

All figures (Figs. 10–13) show similar slopes with little variation of NPV10 between the scenarios for the various oil prices depicted. With a CO₂ price of $2-$11/ton, achieved through grants and funding from climate-change groups, CO₂-EOR projects are able to breakeven and surpass the hurdle rate with marginal incentives (Figs. 11–13). The more funding that companies can secure to offset costs in low oil price markets, will make CO₂-EOR projects resilient to market changes. The growth in manufacturing and transportation coupled with tax breaks globally causes several CO₂-EOR projects to be funded to increase recovery efficiency. In the 2.5% production tax scenario, oil prices around $55/bbl or higher will allow the CO₂-EOR project to surpass the hurdle rate and in the 7.5% production tax scenario, oil prices around $59/bbl will allow the CO₂-EOR project to surpass the hurdle rate. Oil prices around $55/bbl are thought to be sustainable within the next several years and, with a low CO₂ price, many CO₂-EOR projects would be profitable but may not be chosen by companies as potential investments due to lack of supporting climate-change regulations and policy.

3.7. Urban ecosystem

The Modern Jazz scenario of the World Energy Council[36] is closely linked to the “Urban Ecosystem” scenario (Table 6) and shares the elements of globalization, rapid technology advancement and society embracing digitalization. High energy and commodity prices are a new idea our scenario, not seen in the Modern Jazz scenario, but are plausible due to industrial growth in India and China. Development of robust climate-change policy advances alternative energy technologies, CCS and CO₂-EOR. Global citizens, policy makers, private-sector industry and NGOs are working towards a holistic, sustainable energy system because of globalization and digitalization, integrating positive environmental change with the global energy demand.

Small business and niche markets grow as sustainable lifestyle
choices become more affordable and the digital economy expands. Lower corporate tax rates are implemented, triggering investment in capital projects and industry growth. Demand for hydrocarbons increases in Asia and India to fuel rapid industrial growth. Urbanism has contributed to more people living in cities and public transportation is the primary method to commute to work and school. Public transportation is fueled by alternative and low-carbon energy sources.

Alternative energy usage is going up due to sustainable lifestyle choices becoming more prevalent in cities and regions who have the financial freedom to choose. Many countries install wind and solar farms to meet their electricity needs. Natural gas creates a lower cost, low carbon alternative to coal for electricity production; plants convert to natural gas globally, where possible, incentivized by policy makers, governments and global citizens. Demand for natural gas increases the market price, making companies turn on their gas producing assets.

The Organization of Petroleum Exporting Countries (OPEC) cuts production levels to drive up oil prices. High energy prices and global citizen concern for climate-change allow for technological innovations within the energy industries. More people are connected due to digitalization. Oil, is in high demand in developing countries, with India and China needing. In order to meet demand, mature fields have to produce longer and estimated ultimate recovery (EUR) must be increased. CO2-EOR is evaluated at the start of projects and planned for rather than at the end of field development. Reservoirs are evaluated for CCS potential, turning CO2-EOR projects into CO2-EOR + projects, where additional CO2 is injected beyond the CO2 needed for oil recovery. Although it is costlier to inject extra CO2 into the formation and support additional CO2 monitoring, required for CCS projects [27], private-sector industries source funding for project implementation from climate-change mitigation groups promoting CCS and through carbon pricing. Significant climate-change policy comes into force and families are seriously looking at their carbon outputs as global citizens, because of media attention and digitalization. Carbon pricing is introduced in the US to curb CO2 emissions in support of The Paris Agreement.

3.8. Economic assessment of urban ecosystems scenario

NPV10 and IRR for a constant production tax rate of 5% are depicted in Fig. 14 and Fig. 15. Oil prices range from $20/bbl - $120/bbl. Results of the model for for a low, $27/ton, medium, $44/ton, and high, $81/ton, CO2 price are plotted against oil price. CO2 price escalation rate stays constant at 2.4% in this scenario.

![Fig. 14. NPV10 with CO2 price escalation rate of 2.4% per year and a tax rate of 5% per year.](image)

![Fig. 15. IRR with CO2 escalation rate of 2.4% per year and a tax rate of 5% per year.](image)

The oil price range is expanded in this scenario to show that globalization and high carbon pricing strengthen societal investment in these projects and could help to make projects break even under low oil price scenarios. Many of the projects evaluated under this scenario meet or surpass the hurdle rate. A lower production tax rate will help a CO2-EOR project to reach the hurdle rate at lower oil prices. At higher CO2 prices, lower oil prices are possible for the CO2-EOR project to pass the hurdle rate. At the lowest CO2 price modeled, $27/ton, an oil price of around $40/bbl will allow for this project to surpass the hurdle rate. Recalling that a hurdle rate was not set for IRR, it can be seen that for all but one case IRR is positive. In the Urban Ecosystems scenario, CO2-EOR projects are invested in due to high oil prices and high CO2 price offsets. Even at low oil prices of $20/bbl, compensated for by high CO2 prices of around $81/ton, CO2-EOR projects would surpass the hurdle rate and be considered good investments. It is possible that with high CO2 prices and increased environmental pressure for climate-change mitigation, CO2-EOR projects could be converted into CO2-EOR + or maximum storage projects as a way to extend field life and implement CCS.

4. Discussion

4.1. Appraisal outcomes

Various stakeholders in any energy system decision will jointly decide which CCS price scenario society will support. At present, the global energy system is not guided by total energy optimization criteria [41]. Industry is led by market dynamics that motivate business decisions to privatize profits and socialize the cost of pollution and GHG emissions [42,43]. A holistic framework that optimizes decision-making at every step in the global energy system may be needed [43], but is currently not in place. Weijermars et al. [41] define 7 groups of stakeholders which continuously influence energy strategy, shifting the engineering systems point of view to one that can be enacted by a political or social system. Within the perspective of CO2-EOR projects, 4 key stakeholders are identified: private-sector industry, policy makers, non-governmental organizations (NGOs) and the global citizen.

The outcome of the CCS project’s economic appraisal critically depends on the price of carbon included in the cash flow analysis. The actual price in the future will vary with society’s preparedness to support GHG emissions curbs with policy incentives. If a holistic energy system is to be achieved with a focus on the reduction of GHG emissions, target emissions levels must be met and sustained. Most counties lack the infrastructure to support CCS projects; CCS is
an economic burden and polluters rarely pay. Without a global solution that can be enforced, little will be done to curb emissions from GHG.

Not all CO2-EOR projects will be funded because climate-change groups may feel social pressure to fund CCS rather than CO2-EOR as a means to grow understanding and promote CCS as a means to global climate-change mitigation. Integration of CO2-EOR projects within CCS objectives will help meet global energy demands and GHG emissions reduction targets. Including planning for CO2-EOR at the beginning stages of field development could significantly advance the petroleum industry as a technological leader for climate-change mitigation projects. Risk analysis on CO2 storage and long term monitoring programs must be established if CO2-EOR is to become a viable CCS technique.

Additionally, CO2-EOR projects may be looked at as a way to extend production life in aging fields but few will be implemented in states with high tax rates. If the increase in production from tertiary recovery generated by CO2 injection is minimal, projects will not be invested in without carbon price offsets to offset additional CAPEX and OPEX costs for CO2-EOR installation and maintenance. With no carbon pricing, the most profitable CO2-EOR projects occur at the highest oil prices and lowest production taxes. Based on carbon pricing reported by companies to the World Bank [28], the criteria of unlikely (less than $5/tCO2e), likely (between $5/tCO2e to $50/tCO2e), and very likely (above $50/tCO2e) can be applied to evaluate the investment potential of CO2-EOR projects. Table 7 summarizes the likelihood of CO2-EOR project investment within the different business scenarios.

A small carbon price offset would greatly help to spur investment in CCUS technology within the petroleum industry. Due to growing nationalism, it is unlikely that global carbon reduction targets will be met in the “Crumbling Cooperation” scenario not only because there is no CO2 price offset but also because there is a lack of supporting policy, making changes in reservoir management practices to support CO2-EOR projects unlikely. In the “Stagnant Policies” scenario, investment is likely due to global policy maker cooperation and incentivized through a small carbon price offset for industries. However, stakeholders must come together and support a holistic system approach, as seen in the “Urban Ecosystem” scenario, coupling policy and economics, for investment in CO2-EOR as a robust CCUS technology to really be sustained with long-term impact on emissions targets.

Applying the global levels of CO2 storage outlined by the IEA [14] for CO2-EOR under each of the scenarios, the global investment capital (CAPEX) and operational expenditures (OPEX) required to implement CO2-EOR projects is presented in Table 8. Although the “Crumbling Cooperation” scenario shows the lowest investment, it also has the lowest return on investment because there are no carbon price offsets to boosts the IRR.

4.2. Recommendations for making CO2-EOR projects more flexible

In order to make CO2-EOR projects more flexible, funding is needed to offset large capital expenditures for initial project development and CO2 infrastructure needs to be built up to decrease transportation costs. Modest investment in CO2-EOR projects would make the 60 Gt CO2 storage solution achievable (Table 8). Scaling up to the 360 Gt CO2 storage solution would require 6 times the investment over the initial 60 Gt CO2 storage solution investment (Table 8), drastically increasing the investment cost. This could come from NGOs or governments concerned about public welfare and the rising global temperatures. All scenarios require roughly the same investment as the amount of CO2 stored in constant for each project target size throughout the scenarios. Slight investment variations are due to production tax rate and carbon price differences.

Public perception of CCS must be increased so that the importance of CO2-EOR is supported and understood to be a net negative carbon project. The global citizen will play a key role in meeting climate-change goals, as can be seen in the “Society Pays” and “Urban Ecosystems” scenarios (Tables 6 and 7). Global citizens can no longer be overlooked as media attention is able to spur global action with the posting of a picture, comment or reaction. The “Society Pays” scenario shows that the global citizen is able to use globalization, digitalization and their sustainable lifestyle choices to support alternative energy technologies, CCUS and promote GHG emissions targets without policy maker support. Although, the price of carbon in the “Society Pays” scenario is only 33% of the price in the “Urban Ecosystem” scenario, this offset is still sufficient to generate investment into CO2-EOR projects. The impact of the global citizen on emissions targets will be further increased as they work together with NGOs and are supported by policy makers, as can be seen through the “Urban Ecosystem” scenario. Further work should also be done on educating policy makers on the implications, social and economic, of climate-change mitigation to better understand the interdependencies of a holistic energy system.

Until climate-change policy comes into force, companies have little reason to fund CO2-EOR+ or maximum storage projects. The “Crumbling Cooperation” and “Stagnant Policies” scenarios show (Tables 6 and 7) that oil prices higher than $55/bbl are needed for investment in CO2-EOR. Such prices are not unrealistic for the time beyond 2020 [44], but without supporting policy, the petroleum industry has little incentive to invest in CO2-EOR+ or maximum storage projects, which would greatly contribute to GHG reduction targets. In order to develop EOR+ and maximum storage projects under these scenarios, companies must share best practices and support consortium projects, sharing the CAPEX and long-term monitoring costs and tertiary oil recovery profits.

Lowering the cost of CO2 capture and monitoring, through technology advancement, will lessen the financial burden of transitioning CO2-EOR projects into EOR+ and maximum storage projects and make projects profitable at lower oil prices. However, certain technology challenges remain to be solved. For example, viscous fingering is a common problem in CO2 floods and hinders the vertical and horizontal sweep efficiency. Left uncontrolled in the reservoir, these fingers will lead to premature CO2 breakthrough. One technique that has proven to be effective is carbonate water injection (CWI) [45,46]. This cost-effective technique uses much less CO2 because it alternates water injection and CO2. Sohrabi et al. [45] concluded that an additional 10% recovery was possible through the use of this method versus no enhanced recovery option. There is great success using water, surfactants and polymers to control the flooding front [47] but all methods increase project costs.

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Summary of CO2 price and investment potential.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment potential</td>
<td>Society pays</td>
</tr>
<tr>
<td>CO2 Price ($)</td>
<td>likely</td>
</tr>
<tr>
<td>27</td>
<td>0</td>
</tr>
</tbody>
</table>
A smaller cost difference between energy choices makes global citizens more likely than not will support and prefer hydrocarbon energy sources produced in manner that helps meet GHG emission reduction targets. The global citizen’s choice of low-carbon or zero-carbon energy sources further supports reduction policy objectives. The “Society Pays” scenario, however, shows that this choice can only be made when the global citizen has financial freedom and it could further divide global resources, creating regions of winners and losers. Social studies must occur to make sure that EOR+ and maximum storage project implementation does not fail on countries that are economically burdened by projects and cut corners, caused CO2 to leak from underground reservoirs. Should CO2 leaks occur due to lack of understanding, public perception of CCS and CCUS will be tarnished and many profitable and technically viable CO2-EOR projects will not be undertaken due to lack of public support.

5. Conclusions

The economic performance of a reservoir model-based CCS project comprised of enhanced oil recovery with carbon dioxide flooding has been evaluated for a range of normative scenarios under uncertainty. Such scenarios help to evaluate key project drivers and make CCS project solutions profitable so that oil companies will implement such projects on a grand scale and help curb GHG emissions. Win-win solutions for climate-change mitigation and businesses can be seen by taking CO2-EOR projects to CO2-EOR+ projects or maximum storage projects and the global citizen plays an important role in making this transition occur. CO2-EOR+ projects could store more than twice the amount of CO2 needed to meet the goal of limiting global average temperature rise to 2 °C above pre-industrial levels, as outlined by The Paris Agreement. The scenarios considered in this study provide examples of the conditions required to render CO2-EOR projects into profitable investments. Our scenarios include a sensitivity analysis for a large range of oil prices. Three out of 4 of the scenarios evaluated show likely to very likely CO2-EOR project investment potential. The best investment opportunities for these projects occur when global citizens, private-industries, NGOs and policy makers come together to create a holistic energy system. At, what is thought to be the cusp of major, irreversible climate change a mutually beneficial technology, CO2-EOR, could play a significant role not only in boosting hydrocarbon recoveries in depleted or depleted fields but also in helping to prevent CO2 from entering the atmosphere. Without policy makers and global citizens supporting carbon pricing or incentives, investment in EOR+ and maximum storage projects remain unlikely due to large capital investments which are not budgeted for in the tertiary stages of recovery.

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References


Table 8

Global investment (CAPEX + OPEX) at oil price $55/bbl.

<table>
<thead>
<tr>
<th>Project Target Size</th>
<th>Society pays ($ Billion)</th>
<th>Crumbling cooperation ($ Billion)</th>
<th>Stagnant policies ($ Billion)</th>
<th>Urban ecosystems ($ Billion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 Gt CO2 Storage</td>
<td>14.3</td>
<td>13.1</td>
<td>13.5</td>
<td>14.4</td>
</tr>
<tr>
<td>240 Gt CO2 Storage</td>
<td>57.3</td>
<td>52.5</td>
<td>53.9</td>
<td>57.4</td>
</tr>
<tr>
<td>360 Gt CO2 Storage</td>
<td>86.0</td>
<td>78.7</td>
<td>80.9</td>
<td>86.1</td>
</tr>
</tbody>
</table>


**Nomenclature**

**A**: Australian dollars

**bbd**: Barrel

**CAPEX**: Capital expenditure

**CWI**: Carbonated water injection

**CO2**: Carbon dioxide

**CCS**: Carbon capture and storage

**CCUS**: Carbon capture, utilization and storage

**EIA**: United States Energy Information Administration

**EOR**: Enhanced oil recovery

**EU**: European Union

**EU ETS**: European Union Emissions Trading System

**EUR**: Estimated ultimate recovery

**Ft**: Feet

**GDP**: Gross domestic product

**GHG**: Greenhouse gases

**In**: inch

**IRR**: Internal rate of return

**KWh**: Kilowatt hour

**LNG**: Liquefied natural gas

**M**: Thousand

**MM**: Million

**Mi**: Mile

**MSCF**: Million standard cubic feet

**Mton**: Million tons

**MW**: Megawatt

**NGOS**: non-governmental organizations

**NPV10**: Net present value at a 10% discount rate

**OPEX**: Operational expenditure

**STB**: Reservoir barrel

**Tbbl**: Reservoir barrel

**Ton**: ton

**TP**: Thousand

**UN**: United Nations

**UNFCCC**: United Nations Framework Convention on Climate Change

**US**: United States of America

**USD**: United States dollars

**US EPA**: United States Environmental Protection Agency