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A Sustainable Approach to Decision-Making in CCUS Systems

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Abstract

This study proposes a methodology for operational decision-making leading to the sustainability CO_2-EOR systems. The methodology is a simple, yet comprehensive, integration of environmental and economic carbon capture, utilization and storage (CCUS) performance. Understanding the interplay between the environmental and economic conditions allows the EOR operator to manage the CO_2-EOR flood so it remains within the limits of carbon balance neutrality and favorable economics under given prices and costs. The environmental performance and the main operational inputs (fluid production, CO_2 injection, and purchase requirements) were taken from a dynamic carbon Life Cycle Assessment (LCA) study previously performed for a CO_2-EOR site in Cranfield, Mississippi. The LCA study accounts for greenhouse gases (GHG) emissions within a gate-to-grave CCUS system boundary, considering four different CO_2 injection strategies and four gas separation processes.
The economic performance assessment was made through a marginalist analysis (Marginalist Production Theory), which determines important technical and economic relations through basic differential calculus derived from production, cost, and income functions. This method allows to define the operational economic optimum (optimum profit). The assessment considers four CO_2 price scenarios and uses World Bank estimated oil prices. In a first step of the proposed methodology, environmental limits of the operation are estimated. These limits are then compared with operative maximum productivity as well as with the economic optimum.
According to the methodology, the EOR operation is sustainable as long as the environmental optimum is greater, or lasts longer, than the economic optimum along the project's life. Results show that for this operation and assumed parameters, CO_2-EOR could be classified as a sustainable activity depending on the operator's strategic decision-making. In the case study, all injection strategies reach the environmental optimum after maximum productivity is reached. However, only two strategies (continuous gas injection and water alternating gas) find their economic optimum within the environmental limits, fulfilling the defined necessary and sufficient condition for CCUS sustainability.

Keywords: CCUS; CO2-EOR; sustainable; sustainability; marginalist analysis; environmental optimus; economic optimus; marginalist theory; geologic carbon sequestration; net carbon balance; LCA; NCNO

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1. Introduction

Given the current fossil-fuel-dominated energy portfolio and projections for the development of renewable energy technologies, it is inevitable to conclude that fossil fuels will continue to supply an important percentage of the growing global energy needs during the next few decades. Electricity generation, industrial processes, and transportation consume the most energy as well as contribute the most to greenhouse gas (GHG) emissions, in particular carbon dioxide (CO_2).

The current proposal for climate change mitigation is a portfolio of technologies that must be urgently and concurrently implemented. This portfolio includes renewables, energy storage, energy efficiency, bioenergy, nuclear energy, clean power generation, transportation electrification, and carbon capture, utilization, and storage (CCUS), among others. However, it is important to understand that many of these technologies still require significant advances before they can be considered safe, reliable, and economically profitable.

There is a growing consensus on the critical role that geologic carbon storage (GCS) can play in climate change mitigation. Not only it is ready to implement, but it is also arguably the only technology able to reduce GHG emissions at the scale needed to make a positive change. In cases where GCS is part of the enhanced oil recovery (EOR) operation, the project becomes a CCUS project.

Studies have suggested that a shift from traditional CO_2-EOR practices towards co-optimization of oil production and CO_2 storage could remain an interesting business for the oil industry. Increasing oil recovery with the potential to permanently store millions of tons of CO_2 that would otherwise be released into the atmosphere, CO_2-EOR systems have the potential to achieve a neutral carbon balance, which means that the CO_2 emitted through the CO_2-EOR system is equal to the amount of carbon permanently stored in the subsurface, a promising win-win sustainable solution to reduce or, at least, not increase GHG present in the atmosphere.

Achieving this ideal balance poses complex challenges, both methodological and economical. The most common way of comprehensively analyzing GHG emissions from the CO_2-EOR system is through Carbon Life Cycle Analysis (LCA). However, LCA studies often present data from the end of the productive life of a CO_2-EOR project, focused on maximizing oil extraction, thereby qualifying the project as positive emission. LCA alone provides incomplete information on the important relationship between the economic and environmental aspects of CO_2-EOR systems, limiting its relevance to stakeholder’s proper decision-making.

Because of the evolving nature of carbon balance assessments of CO_2-EOR evolve over time, our study proposes a dynamic analysis that integrates reservoir modeling with surface operation modeling to determine the transition point of the carbon balance from negative to positive emissions as well as other important technical and environmental rates. We use LCA in a gate-to-grave system to understand the environmental performance of CCUS projects and identify when, in the life of a project, a balance between net CO_2 emissions and geologic storage volumes is achieved.

By understanding the relationships between injection, production and storage, and associated operation costs, we develop an economic model, incorporating the oil and carbon prices (and incentives). Assuming that the latter represent the Carbon Social Cost (or Benefits) (CSC), which is integrated as the environmental “externalities” within the economic performance analysis. Here, externalities refer to intangible costs that are traditionally external-to private-business models.

The proposition of sustainability is referred to conscious and responsible use of the resources, without exhausting them or exceeding their capacity for renewal, and without compromising access to them by future generations [1]. This study assumed the atmosphere as the limited natural resource, receiver of GHG emissions that would be accelerating climate change and its effects on living conditions on the planet. Also extend the concept of environmental sustainability to include the necessary economic profit and social cost.

2. Environmental performance

The environmental performance was determined based on the result of a previous study [2], where a dynamic LCA in a CO_2-EOR gate-to-grave boundary system was assessed for four different injection strategies (*IS*). The CCUS components inside a gate-to-grave boundary are the CO_2-EOR operation, the transportation of crude oil from the field to the refinery, the crude oil refinery, and the combustion of the refined product.

The 4 selected *IS*s are: (1) continuous gas injection (CGI), where CO_2 is injected continuously into the oil bearing formation; (2) WAG, where CO_2 and brine are injected in an alternating fashion to improve flood conformance and economics; (3) water curtain injection (WCI), a continuous gas injection with the addition of peripheral water injection (commonly along the oil-water contact) in order to create a pressure barrier/curtain that contains the CO_2 within the desired rock volume; and (4) hybrid WAG+WCI.

The four different gas separation options are: (1) without separation gas process, (2) fractionation-refrigeration, (3) membrane and (4) Rayan-Holmes. The results defined the relationship between site production, gas injection, energy consumption, and GHG emissions, allowing to identified the balance between CO_2 storage and GHG emissions during the EOR operation. This carbon balance (*CB*) represent the environmental optimum or transition point where GHG emissions within the gate-to-grave system are equal to the mass of CO_2 permanently stored. Figure 1 shows the main results of the study, the *CB*, where all ISs (CGI, WAG WCI and WAG+WCI), including all gas separation options, transition from negative emissions (net carbon negative) to positive emissions (net carbon positive). CGI and WAG store larger volumes of CO_2 and have a larger gap among the gas separation processes.

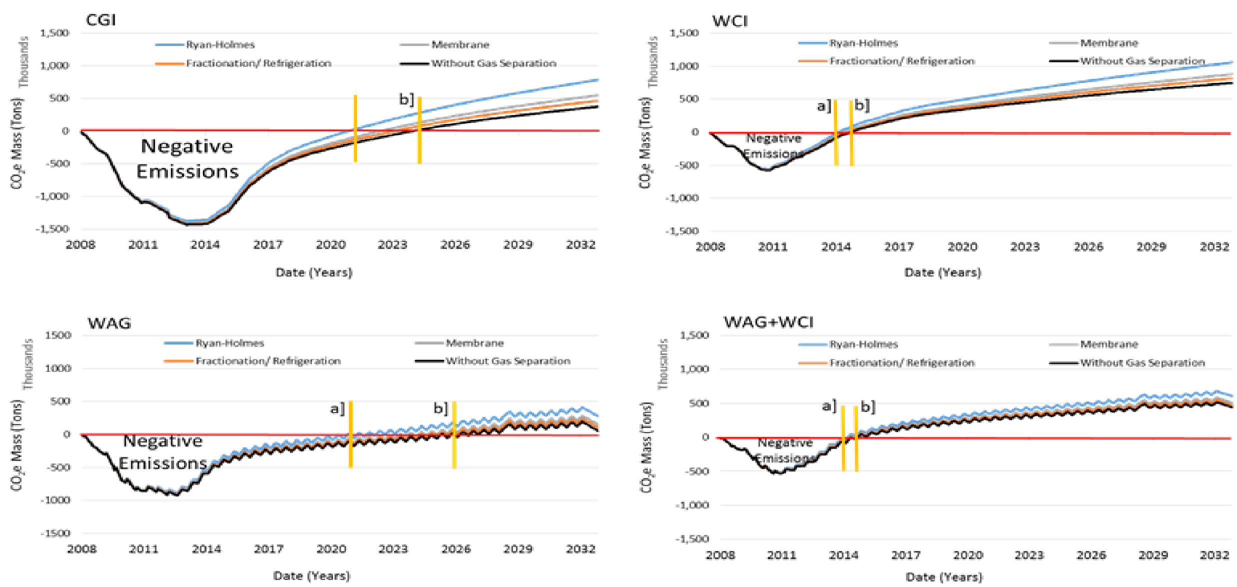

Fig. 1. Carbon balance (CO_2e emissions minus CO_2 storage). All *IS*s (CGI, WAG, WCI and WAG+WCI) transition from net carbon negative to net carbon positive emissions and compares *TP* of different gas separation process. Yellow lines show the emission gap between higher a] (Ryan-Holmes) and lower b] (without gas separation) emitter. Before the yellow line is reached, the operation produces net carbon negative oil. After the yellow line, the operation produces net carbon positive oil.

3. Economic performance

In the domain of economics general equilibrium models, the neoclassical theory of production and, macroeconomic growth models use differential calculations to determine the changes that occur along a firm's production function [9]. The theoretical economic optimum (*Eo*) can be assumed (under certain circumstances) as the point where descending marginal productivity value equals the product market price. The marginal production economic theory is based on the application of this mathematical tool to explain the instantaneous relationships between production, the inputs, the firm's output, costs, revenues and profits. The theory emphasizing the importance of knowing the impact of the last input unit used (in this case the use of CO_2) has in production (in this case oil) on the aforementioned objective functions [3]. The study of changes that occur in the objective functions' manifests in the slopes, maximums, minimums, and concavities of the curves, providing valuable information on the economic performance of the firm. Through the implementation of these quantitative tools for continuous processes analysis, the economy can precisely and vigorously express the quantifiable relationships between its fundamental variables [4]. Theoretical models are simplifications of complex reality, basing their applicability on a series of assumptions that must be taken for the model functionality. Despite this, they remain the best possible approach to reality and, without a doubt, provide timely signals on the direction of firm's decisions.

Some of the most important assumptions of the marginal economic model are: 1) The production curve is continuous and concave towards the origin in the same way during its first and second derivatives; 2) The values of inputs and product are always non-negative; 3) The production-fixed factors are quantities that cannot vary during the analysis period; 4) The production technical efficiency is pre-defined and assumed to be optimal; 5) Both, inputs and production, are expressed in units of time so that both are flow (not stock) variables. This unit of time is short enough to make impossible changes in fixed factors or technology but long enough for the production process to complete a whole cycle; 6) When analyzing the impact of a determining factor, the rest of the factors remain constant (ceteris paribus); 7) Finally and fundamentally, the firm is a (inputs and outputs) price-accepting agent and continuously seeks to optimize profit.

The optimal profit as proposed by [5], is reached when the value of marginal productivity (*MgP*) is equal to the marginal income (*MgI*) and to the marginal cost (*MgC*), the market price. To understand how to get to get here, we must begin by defining the production curve as a technical relationship (production process) between units of output (q), obtained by the use of *n* units of inputs (X_n), expressed as: ($q = f(x_1^v, x_2^k, x_3^k, \dots x_n^k)$, where: *v* refers to a variable and *k* to a constant. The economic interest in the short term is focused on the variable factor (*v*) since it defines the shape of the production curve, given a known technology. The fixed factors (constants) only displace this function in their corresponding magnitude. To simplify, we can assume that production is a function of the variable factor: $q = f(x_1^v)$.

The productivity of this used factor is expressed in other complementary functions like the average (mean) productivity (*MeP*) and the marginal productivity (*MgP*). The *MeP*, measures the ratio of the total units produced (*q*) per the total input units (x_1^v) used during a given period ($MeP = q/x_1^v$). The *MgP*, being the production function first derivative ($MgP = \partial q/\partial x_1^v$), measures the instantaneous change in production for each additional input unit used. Significant relationships and decision-making signals for the firm arise from its analysis, namely: 1) The *MgP* reaches its maximum at the inflection point (concavity change) of the total production (*TP)* curve, then it decreases to zero at which point *TP* has reached its maximum; 2) The *MeP* reaches its maximum when the tangent of *TP* (from the origin) is maximum and equals the *MgP* in its decreasing phase; 3) When the *MeP* is increasing, *MeP* < *MgP* and vice versa, when the *MeP* is decreasing, *MeP* > *MgP*. This means that when the productivity of the last input unit used (*MgP*) is increasing, it drives the growth of the average productivity (*MeP*) which adds more product per unit of input used; but when it approaches its maximum value and begins to decrease, each additional input unit will add less product than the previous one, decreasing average productivity. However, despite these productivity losses, it is convenient for the firm to continue using additional units of input until the *TP* reaches its maximum, at which point, as already mentioned, the *MgP* equals zero. From this point on, using additional units of input is meaningless given that the additional units of product will be negative, contradicting the logic and assumption number two.

From the above, it is clear that, for the firm, the key variable to be determined is the input quantities (*q*) that are required in the production process to obtain the maximum benefit, which is a basic condition of the marginal production theory. Then we have that the benefit (*B*) is defined as the difference between total income (*TR*) and total costs (*TC*), that is $B = TR - TC$, where $TR = P * q = P * f(x_1^v, x_2^k, x_3^k, \dots x_n^k)$ and $TC = r_1 * x_1^v + FC$, where *P* equals the price of output *q*; r_1 equals the price (cost) of factor x_1; and FC equals the value of the fixed factor. Then, the maximum value of the profit function *B* is reached when $(\partial B/\partial x_1^v) = 0 \rightarrow (P * f'(x_1) - r_1) = 0 \rightarrow \left(P * f'(x_1)\right) = r_1$, as a necessary condition; and, in turn, $f''(x_1) < 0$. This happens when the *MgP* value equals the product market price (r_1), as long as the second derivative $f''(x_1)$ is less than zero, since it relates to a maximum (not to a minimum), corresponding to the decreasing phase of the *MgP* curve, as a sufficient condition. Being this latter condition the other way around for the marginal cost, since the inverse relationship between cost and productivity functions. So the optimal profit can be obtained at the point where the marginal cost (*MgC*) and marginal income (*MgI*) curves intersect. Theoretically, in the increasing phase of *MgC* (after its minimum) and decreasing *MgI* (after its maximum). With this simplified model (one input and one output), it is possible to determine the amounts of input and/or outputs that maximize the profit (*Eo*), taking into account various prices, factors, and production.

To determine *MgI* ($/STB) this study used the World Bank historic and forecasted oil prices (2008-2030) [6] and its growing trend to estimate prices from 2031-2033. Also 45Q tax incentives [7] were included for the accounting of the positive Marginal CO_2 net storage mass[2], assuming that this incentive was in effect from the first year of operations (year 1 = 2008). The *MgC* was determined adding the price of the CO_2 and the incremental operational and maintenance expenses (O&M). Four CO_2 price scenarios were considered: 1) the average of the historical percentage relation of oil price (%OP) around 1.8 and 3.5% in terms of $/Mscf (38% in terms of $/Tons of CO_2); 2) the average of U.S. pipeline CO_2 price (HPP) of reported by the [8]; 3) an Low-Social Cost (L-SC), and; 3) a High-Social Cost (H-SC). Both *SC*s[3] were taken from [9]. The O&M expenses were calculated based on

[2] Marginal CO_2 net storage mass is the difference between the tons of CO_2 stored and those emitted per additional barrel of oil produced.

[3] Social Cost of CO_2 is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. Estimations are done by 3 integrated assessment models first estimate damages occurring after the emission release and into the future, often as far out as the year 2300.Then discounting these values to present value L-SC intent to account for average expected climate change damages at a 3% discount rate, while H-SC for Higher than average damages accounting for percentile 95th of all three model at 3% discount rate [9]. For this study the SC was only considered as

equation ($O\&Mcost = b_0 + b_1 D$) from [10], where b_0 = \$38.447 and b_1= 8.72 \$/ft (coefficients related to the depth used in [11, 12]) and *D* is the depth of the injection wells, in this case 10,000 ft. To make *MgC* comparable to *MgI* in the same unit (\$/STB), the net and gross CO_2 injection utilization rate (CO_2 purchased and total injected per STB) were used to convert the CO_2 purchased and O&M expenses (\$/Ton to \$/STB), respectively. All variables are referred to annual values.

The Economic performance of each ISs with the four CO_2 price scenarios for the given oil prices estimations are described as follows:

- CGI: with %OP and HPP, *MgIs* equals *MgCs* around 15 \$/per barrel, at the end of year number 10 of operations (2018 in this case) with an incremental production of 118.077 STB (2.9 MMSTB, cumulative) when expected oil price is 65\$/STB. With L-SC and H-SC, *MgCs* over reach *MgIs* making operations non-profitable.
- WAG: all CO_2 cost scenarios, except H-SC, equal *MgIs* and *MgCs* at 13 \$/barrel in year number 11 of operations (2019, in this case) with an incremental production of 99,719 STB (2.4 MMSTB, cumulative) when expected oil price is 65.4 \$/STB. For H-SC cost levels, *MgC* over reach *MgI* making operations non-profitable.
- WCI: With %OP, *MgI* equals *MgC* around 14 \$/per barrel, at year number 25 of operations (2033 in this case) with an incremental production of 50,710 STB (2.6 MMSTB, cumulative) when expected oil price is 70 \$/STB. With HPP *MgI* equals *MgC* around 7.56 \$/per barrel, at year number 20 of operations (2028 in this case) with an incremental production of 41,663 STB (2.3 MMSTB, cumulative) when expected oil price is also 69 \$/STB. With L-SC *MgI* equals *MgC* around 18.6 \$/per barrel, at year number 16 of operations (2015 in this case) 118,977 STB (1.4 MMSTB, cumulative) when expected oil price is 51 \$/STB. As same of previous scenarios H-SC cost level is too high to allow any profit.
- WAG+WCI: in this injection strategy %OP and HPP *MgIs* equals *MgCs* around 8.25 \$/per barrel, at year number 13 of operations (2020, in this case) with an incremental production of 46,783 STB (1.8 MMSTB, cumulative) when expected oil price is 66 \$/STB. With L-SC and H-SC CO_2 cost levels, *MgIs* equals *MgCs* around 17 and 47.4 \$/per barrel, respectively, at year number 7 year of operations (2014, in this case) with an incremental production of 125,661 STB (1.4 MMSTB, cumulative) when expected oil price is 96 \$/STB.

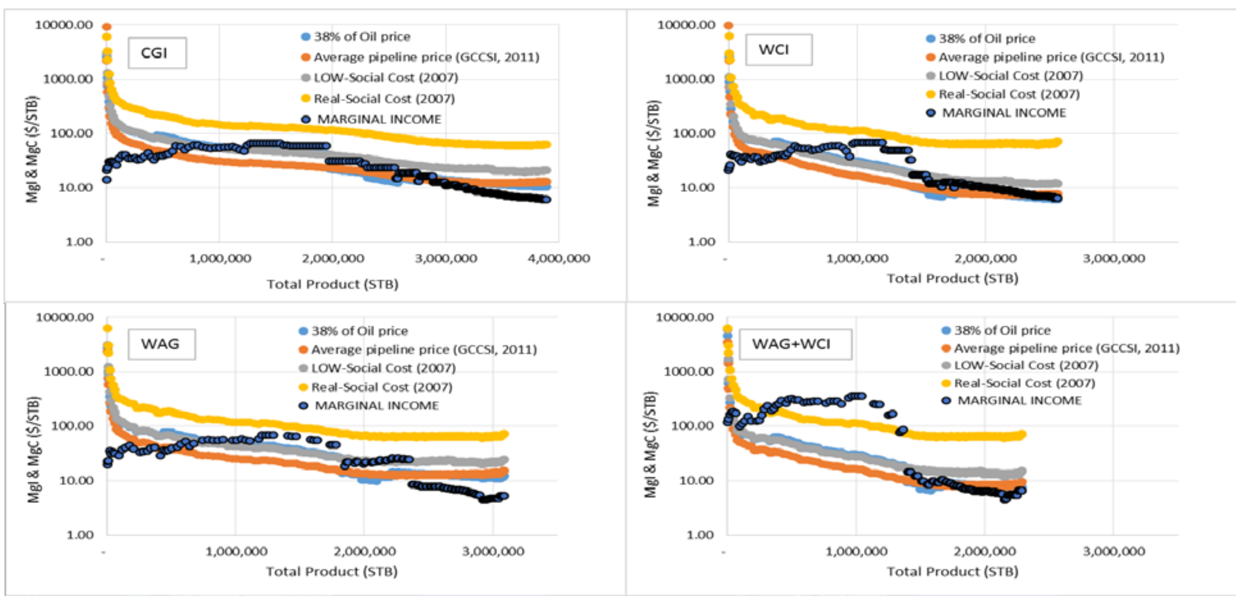

Fig. 2. Economic optimum. Compares *MgI* and *MgC* versus total production. Theoretically, the point of intersection between *MgI* (in its descending phase) and *MgC* (in its increasing phase) represents the optimal operating economics for a given production.

Summarizing, in CGI and WAG, for %OP and HPP cost scenarios *Eo* is reached around 14 \$/STB when expected oil price is 65 \$/STB. For these same cost scenarios, water curtain *IS* reached its *Eo* at a lower level, around 8 \$/STB due to their higher initial productivity when oil price is 70\$/STB. L-SC cost scenario is not profitable in CGI and in WAG, but in WCI and WAG+WCI, *Eo*

a reference of CO_2 cost value, not assessed as an economic equilibrium signal of market or climate equilibrium. The impact of its adoption on the price formation of rest of the economy and, in particular, on the oil prices was not assessed.

is reached early in a relative higher level, around 18$/STB for oil prices around 96 $/STB. Finally the H-SC is only profitable for WAG+WCI, at 47.4 $/STB and estimate oil price in 96$/STB.

4. Sustainable assessment

As previously explained, this study assesses the sustainability of CCUS operations by comparing the economic and environmental performance. Sustainable operations are those that allow optimizing economic performance without emitting incremental GHGs to the atmosphere. In this case, CO_2-EOR operations maximizing economic benefits within the limits of the environmental optimum (CB), meeting the necessary and sufficient conditions to be considered sustainable.

Comparing the average of the CBs for each *IS* (fig.1, mean point between yellow lines a] and b] for each IS) versus the average of the *Eo* given the different oil price and CO_2 cost scenarios (%OP, HPP, L-SC and H-SC), allows to determine which operation is sustainable under the referred conditions.

CGI and WAG show a larger operational period with net carbon negative emissions (around 15 [2023] and 17 [2025] years, respectively). Several years from reaching their maximum productivity leaves considerable room to improve productivity (increase production) under certain conditions. For these two *ISs*, *Eo* is reached before reaching its zero *CBs*. Based on these results, the CGI and WAG strategies complete the necessary and sufficient conditions to be classified as sustainable CCUS operations. On the other hand, WCI and WAG+WCI, albeit reaching the zero *CB* after reaching the maximum productivity in operations, show substantially shorter lapses between one point and another (one year or two) for any possible management of the operational strategies. Beyond this observation, both show optimal economics several years after the environmental limits are reached (ten years later for WCI and about four years later for the WAG+WCI strategy). The latter *ISs* do not meet the necessary and sufficient conditions to be classified as sustainable CCUS operations. However, it is important to note that they seem to reflect a better economic performance given the assumed costs and prices conditions. This is particularly true for WAG+WCI, which presents high initial productivity and benefits more than any other *IS* from the high oil prices reported for that initial period, allowing it to offtake the high costs of the H-SC scenarios where any other IS could.

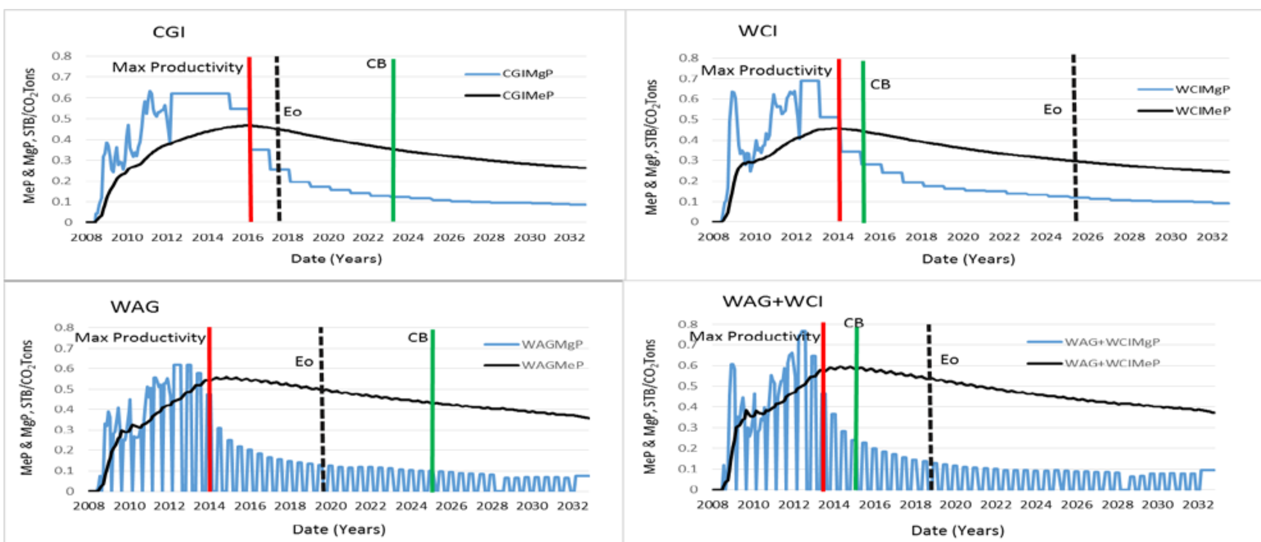

Fig. 3. Sustainability condition for each IS. Figure shows the relation between productivity, environmental and economic performance along 33 years of operation. Red line is the signal of maximum productivity, where *MgP=MeP* in its maximum. Black dot line is the *Eo* where *MgI=MgC=P* (necessary conditions). Green line is the environmental limits where net CO_2 storage equals GHG emissions (sufficient condition). *Eo<=CB* means a sustainable operation. *Eo>CB* not sustainable but economically profitable.

5. Conclusions

Traditional approaches to CO2-EOR carbon LCA show limited vision of its environmental performance. A dynamic LCA aims to asses the evolution of the critical CCUS variables resulting in better approach to the CO_2-EOR environmental performance. A dynamic assessment provides an increased understanding of the impact of this variables on the interplay between environmental and economic CCUS indicators. Iterations between subsurface and operational surface models should be done with a focus on operational decision-making that could drive more realistic production curves. Results show that all *IS*s transition from net carbon negative balance to net carbon positive balance. Larger periods of net carbon negative operations tend to produce sustainable CCUS systems. In this case study, higher initial productivities tend to accelerate the transition to net carbon positive. Results from our case study show that CGI and WAG provide for CO_2-EOR sustainable operations that could be adopted as clear climate change mitigation options to accelerate CCUS commercial implementation. Assessing economic performance through a marginalist theory approach is a simple yet comprehensive process of integrating environmental (LCA) and economic performance, which can serve as a tool for decision-making leading to the sustainability CO_2-EOR systems.

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