TO CONVERT OR TO CONTINUE? A Real Option Analysis of Injecting CO_2 in A Mature Gas Reservoir

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Abstract

Injecting carbon dioxide into mature gas reservoirs could create environmental and commercial benefits. The resulting lower emissions and higher productivity could outweigh the associated costs. But what is the value of such inherent project flexibility? especially when value drivers like costs and production are uncertain. To reflect the value potential of such decisions, the commonly used “high” and “low” price forecasts are unlikely to reflect the value potentials. Instead, we use a stochastic model to describe uncertain price expectations and use an integrated techno-economic framework to address the managerial flexibility of converting some of the production wells to CO_2 injection. Using numerical subsurface reservoir model along with a price model, we show the value of creating opportunity from optimally converting wells. The framework leads to insights into the feasibility of CO_2 injection in depleted reservoirs. The outcomes show the key drivers of value in integrated project appraisals.

Keywords: Carbon dioxide sequestration, Carbon Storage, Enhanced Gas Recovery, Techno-economic models, Real options, Dynamic Prices

1. Introduction

Towards the end of the producing life of natural gas reservoirs, their pressure drops and their efficiency declines. To improve production, we could inject CO_2 into the reservoirs, hoping to heighten their pressure and enhance sweep efficiency (Oldenburg, Stevens et al. 2004, Khan, Amin et al. 2012). To undertake CO_2 injection and enhanced gas recovery, technical difficulties aside, the process should primarily generate economic value. In this paper, we discuss the specifics of a techno-economic model that integrates the technical aspects of CO_2 injection gas recovery with their economics.

As CO_2 flooding displaces the leftover hydrocarbons, it could generate economic gains through enhanced production. Additionally, different types of CO_2 storage mechanisms such as structural, residual and solubility trapping are involved in the injection process and contribute to carbon sequestration that provides the opportunity to profit from carbon credits or governmental incentives. If the gains from such sequestration and added recovery outweigh the costs, then the process generates value. In contrast, projects aimed purely at CO_2 sequestration need to find economic appeal elsewhere. Focusing on the costs and benefits of a general CO_2-enhanced gas recovery project, we show the value creation framework through the application of the real options valuation.

In this paper, we discuss the value creation framework for CO_2 injection when the operator has the option to convert existing production wells to injectors. Because of the natural gas price dynamics, this project is not entirely about technical optimization. The operator considers changes in price forecasts and exercises the conversion options at the best time—so that it maximizes value gains. The project becomes a trade-off between benefits and costs. Does the economic benefits of carbon storage and enhanced production outweigh the cost of well conversion?

This is a dynamic decision problem under uncertainty—a real option. A term coined almost four decades ago by Stuart Myers (Myers 1977) and discussed in, e.g., (Trigeorgis and Mason 1987), the real options view of the investment considers the effect of managerial flexibility on value. Unlike the earlier discounted cash flow paradigm that considers projects as “go or no-go” investments, in the real options framework we model the managerial flexibilities as they mitigate risks or to create value. Such models rely on more detailed descriptions of the evolving uncertainty and are inevitably more effortful. However, we believe for many applications the resulting clarity and insight justify the added effort.

Earlier models, e.g., the pioneering work of (Brennan and Schwartz 1985), assumed that commodity prices follow a geometric Brownian motion similar to financial stocks. But our understanding of commodity prices has improved since. The studies of, e.g. (Bessembinder, Coughenour et al. 1995) and (Pindyck 1999) revealed the mean-reverting characteristics of prices, especially for crude oil and natural gas. These led to improved real options models of oil and gas investment (Smith and McCardle 1999). Recent applications include the implementation of mean-reverting models in sequential exploration (Jafarizadeh and Bratvold 2020) and hydraulic refracturing options (Jafarizadeh and Bratvold 2019). In this paper, using the binomial representation of (Hahn and Dyer 2008) and the valuation algorithm in (Jafarizadeh and Bratvold 2019), we discuss the valuation of conversion option. Assuming the project uses market-traded prices in NYMEX (New York Mercantile Exchange), we model natural gas prices as a mean-reverting process and evaluate the option to convert existing production wells into injectors.

The conversion decision studied here depends on subsurface conditions and the evolution of above-the-surface uncertainties. The operator has the flexibility to convert wells multiple times, yet once they commit to conversion, the wait is over, and they must follow their selected course of action. The decision model then uses conditional expectations about the value of each course of action.

Because the decisions depend on the expectations from uncertain prices, in this paper, we describe price dynamics as stochastic processes. We further use a valuation algorithm, provided in an associated spreadsheet, to assess the value of dynamic conversion decisions. This dynamic model is perhaps in contrast with the common valuation models that consider average prices. Although using averages in the analysis is simpler and easier, they do not show value creation potentials from price variations (Jafarizadeh and Bratvold 2019). We believe our model's added features lead to added clarity and insight.

We define a compositional simulated model for depleting gas reservoir as a general carbon storage site. Then in our real options analysis model—using a binomial lattice—we assess the value of managerial flexibility in conversion timing. At each decision point, our model compares the conversion option's value with the continuation value using information about reservoir conditions and price expectations. If the conditions are ripe for injection and the economic outlook is favorable, then the algorithm recommends conversion. Otherwise, the algorithm suggests continuing to the next decision point. When the conversion window is over, the algorithm suggests abandonment.

No analysis is complete without a review of major value drivers and their impact on decisions. Therefore, through sensitivity analysis, we will also show that key uncertain factors (e.g., price parameters and carbon credit) affect the value. The model and its results would be insightful for CO_2 injection decisions in mature gas reservoirs. In addition, the algorithm implemented in a spreadsheet accompanies the paper.

In the next section, we discuss the subsurface reservoir model and analyse the technical uncertainty. Next, we present a hydrocarbon price model in a binomial lattice. We integrate the technical and market models in a valuation model to evaluate the option to convert or continue producing from natural gas wells. Finally, we discuss the results and conclude.

2. Subsurface Model

Subsurface reservoirs are finite resources, and their production gradually decreases over time. At some point, production from a well will no longer be operationally sustainable and may be permanently sealed. However, because natural depletion often leaves significant amount of hydrocarbon within the underground porous media, there are various techniques that can be employed to enhance the production.

Injecting carbon dioxide into the subsurface reservoir has such an effect. It can maintenance the reservoir pressure, sweep through the reservoir and push the remaining hydrocarbon towards the production wells, facilitating its recovery.

Production from subsurface hydrocarbon reservoirs is a complex engineering problem. Often the flow of hydrocarbons within the reservoir rocks, the location of wells, and the interacting effect of pressure and temperature determine the rate of production and the ultimate recovery of hydrocarbons. In this section, we describe a subsurface model of carbon dioxide injection and its effects on natural gas production.

Within our subsurface gas reservoir model, we show two production wells, to suggest study the conversion decision. The model assumes that the reservoir rock bears the natural gas in 8 layers of sandstone at a depth of 2900 meters. Appendix A delves into more details of the model's parameter.

The simulation results show that production of hydrocarbons in both wells will decline. One well will have a steeper decline because of its unfavorable location, and we could consider it as a potential for conversion to an injection well. By injection of carbon dioxide into the reservoir, we could enhance the total gas recovery, and in addition sequester carbon.

As the simulation result in **Figure 1** shows, one of the wells drilled in poor reservoir quality region and higher water saturation would be a candidate for conversion into an injection well. Before its termination, there will be a three-year window to convert this well. Once we commit to converting the well, it cannot revert to production. We use the numerical reservoir simulation to estimate the field production as the result of conversion of this well in the first, second or third year. The numerical simulation leads to estimates of enhanced production in three alternative years. We then use the information in our valuation model.

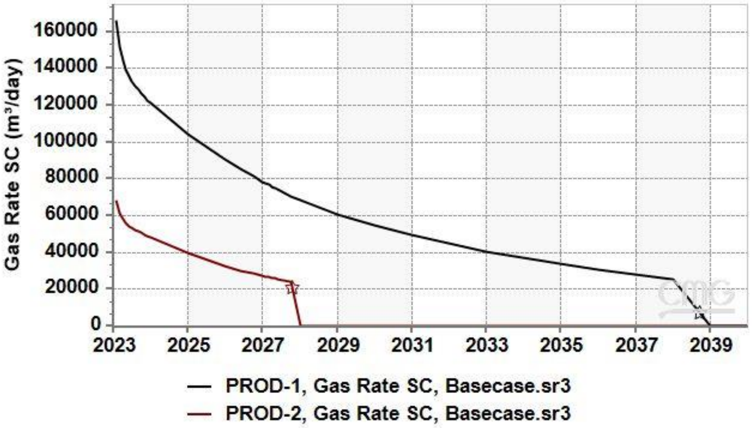


Fig. 1–Natural Gas production rate of wells (the well PROD-2 will be shut-in in 2027 while the other well PROD-2 will produce longer).

3. Hydrocarbon Price Model

Prices are uncertain. Yet, valuation of hydrocarbon production projects is a direct function of price forecasts. In our valuation model, dynamics of price forecasts inform the decision to convert or to continue. Most commodities, including hydrocarbons, manifest a mean-reverting behavior in prices. This key feature affects our description of future prices and our forecasts.

The market price of commodities follows a balance in supply and demand. At high prices, producers supply more. This consequently draws the prices down. On the other hand, low prices discourage most suppliers. They curb their production, and the resulting scarcity pushes the prices back up. These dynamics lead to mean-reverting behavior of hydrocarbon prices. including seminal works of (Bessembinder, Coughenour et al. 1995) and (Pindyck 1999). Our model assumes a constant long-term value ξ where prices revert to, and a short-term stochastic factor (χ_t), which reflects the random deviations. The spot price S_t follows the process:

$$ln\, S_t = \chi_t + \xi \tag{1}$$

The short-term deviations follow the stochastic process:

$$d\chi_t = -\kappa\chi_t dt + \sigma_\chi dz \tag{2}$$

In this formulation, dz is the increment in a standard Brownian-motion process, and σ represents the volatility. The variable κ stands for the speed of mean-reversion; the larger the κ, the faster S_t will go back toward the equilibrium level.

Spot prices are not relevant in project valuations. We need forecasts of prices. In this paper used expectations for future spot prices (Jafarizadeh and Bratvold 2012) to generate these estimates. Here the forward price ($F_{t,T}$) of the futures contract for natural gas at time t for and maturity T is:

$$ln\, F_{t,T} = e^{-\kappa(T-t)}\chi_t + \xi + (1 - e^{-2\kappa(T-t)})\frac{\sigma^2}{4\kappa} \tag{3}$$

The relationship shows a curve for ($t \geq 0$) and delivery times ($T > 0$). The futures prices for long maturity dates will converge to the mean level ($\lim_{T\to\infty} ln\, F_{t,T} = \xi$).

"What if we were to start a project next year instead of this year?" We show the evolution of these price forecasts in a *binomial lattice* of **Fig. 2** It describes that in the time interval of $\Delta t,$ natural gas price would move either upward (χ_t^+) or downward (χ_t^-). Using Hahn and Dyer (2008) model, the moves will be:

$$\chi_t^+ \equiv \chi_t + \sqrt{\Delta t}\sigma \tag{4}$$

$$\chi_t^- \equiv \chi_t - \sqrt{\Delta t}\sigma \tag{5}$$

The probability of "up" move is:

$$q_t = \max\left(0, min\left(1, \frac{1}{2} - \frac{\sqrt{\Delta t}\left(\kappa\chi_t + \frac{1}{2}\sigma^2\right)}{2\sigma}\right)\right) \tag{6}$$

The probability of χ_t^- would be 1-q_t.

Using the method explained in (Jafarizadeh and Bratvold 2012), we fitted our model to Henry-Hub natural gas futures contracts and estimate price parameters depicted at the right side of **Figure 2** We have plotted the spot price moves as solid lines in three timesteps, each with a length of one year. The dashed lines represent price forecasts with maturities of up to 10 years in the future, beginning from each node.

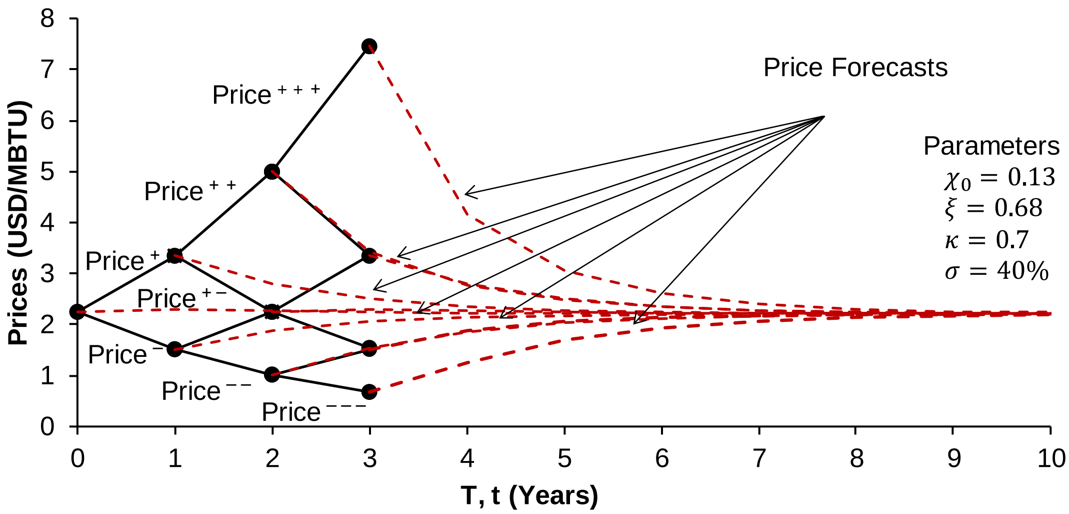


Fig. 2–Probable price fluctuation and subsequent futures curves

To find the short-term deviation at the outset of the lattice and calculating its evolution, assume $t = \tau$ at the start point of the option window, if $\Delta t = \tau - 0$, from Eq. 3 we can conclude that forward prices would change relative to their short-term deviations and the long run will be omitted as it is not time-dependent:

$$\chi_\tau - \chi_0 = ln\, F_{0,\tau} - ln\, F_{0,0} \tag{7}$$

$$\chi_\tau = e^{-\kappa\tau}\chi_0 + (1 - e^{-2\kappa\tau})\frac{\sigma^2}{4\kappa} \tag{8}$$

We then use Eq. 4-6 to construct the binomial lattice with considering Eq.8 as an estimation of χ_τ at the lattice outset.

4. Integration

We show the framework of our valuation model in the decision tree of **Figure 3**. The decision to continue production depends on expectations about conversion and waiting options in the next years. If the economic prospect is favorable, the algorithm recommends conversion; otherwise, the model suggests moving on to the next decision point and reevaluating the alternatives. It continues up until the time for the conversion window is over.

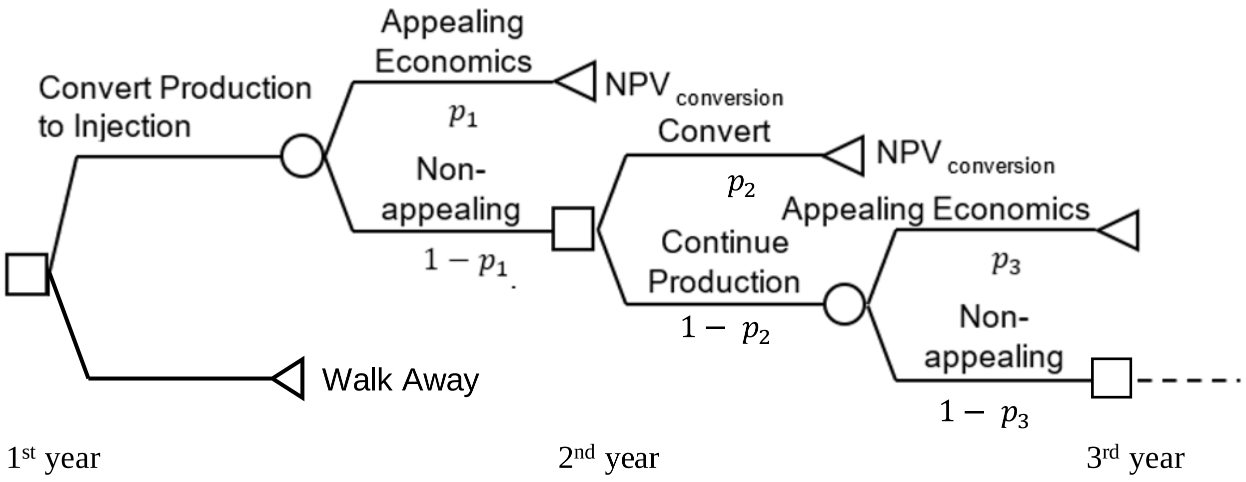


Fig. 3–Decision Tree, Convert, Continue or Abandonment?

To select the best course of action at each decision point, we need to compare the value from each alternative. Our decision will not only depend on the immediate value of the actions, but also on the later decisions and their consequences. We use a backward induction method of solve this dynamic decision-making problem.

To start the backward induction, we compare options value using $g(\chi_T)$ at the closing time of the option window. Specifically, for every decision point within the option window, we have $V_t = v_t(\chi_t), t = \tau, \tau + 1, \dots, T$. This is done by recursively comparing the worth of exercising the best choice (as an outcome of $g(\chi_t)$) and the continuation course of action at any time during the option window. Eq. 9 to 11 shows the calculation process.

$$g(\chi_t) = \max\left(NPV_{Abandonment}^{\chi_t}, NPV_{Conversion}^{\chi_t}\right) \tag{9}$$

$$v_T(\chi_T) = \max\left(g(\chi_T), NPV_{Continue}^{\chi_t}\right) \tag{10}$$

$$v_t(\chi_t) = \max\left(g(\chi_t), \frac{1}{1+r}\left(q_t v_{t+1}(\chi_t^+) + (1-q_t)v_{t+1}(\chi_t^-)\right) + CF_t\right) \tag{11}$$

As outlined in this paper, the conversion option provides the right to change the direction of the project—if the dynamic conditions are right. Our valuation model considers managerial flexibility and decisions as the uncertainties resolve. Using this framework, we assume the managers convert the producing well to injection at favorable economics, considering the expectation of what lies ahead.

5. Results and Discussion

Our valuation model generates insights into the effect of managerial flexibility. While we used market data—we used 60 \$/ton and 2.24 USD/MBTU as carbon credit and the current spot price of the Henry Hub natural gas, respectively—the valuation model is general and can use any set of parameters.

In our analysis, several factors contributed to the decisions and the resulting value. The decision maker needs to weigh the potential benefits of conversion or early abandonment against the cost of implementation and the potential loss of production. Abandoning the well now or later may result in a loss of revenue in the short term, but it may be the best decision in the long run, especially if the costs of maintenance and operation outweigh the benefits. On the other hand, conversion may require a significant investment, but it can also provide significant long-term benefits. It may result in enhanced production, and an opportunity to generate additional revenue through carbon credits.

Using equations 5 to 8, we construct a binomial lattice that tracks the evolution of χ_t. This provide the decision maker to consider the probable market fluctuations within the decision window and evaluate the value creation opportunities before making a decision. Appendix B summarizes how arrays are used to present the valuation lattice.

From the left box to the right, Table 1Table 1 displays the binomial lattice for the short-term deviation, the NPV of decision options (conversion, continuation, abandonment) at each time steps, and total value of the project if the option is exercised in t=1,2 or 3.

The first box displays that χ_t in t=1 can be increased to 0.53 or decreased to 0.27 at the beginning of the decision window ($t = 1$). This explains how χ_t can be as high as 1.3 or as low as -1.0 at the end of the third year. However, the attributed probability of price changes is calculated and its chance of happening decreases over time, inclining towards the mean level value. For each calculated χ_t, we generate forward curves stemming from each decision node and use them to estimate the expected value of each decision degree up to the end of the reservoir-producing life. Next, by implementing the recursive process described before, we show that the embedded flexibility is worth approximately $9 million.

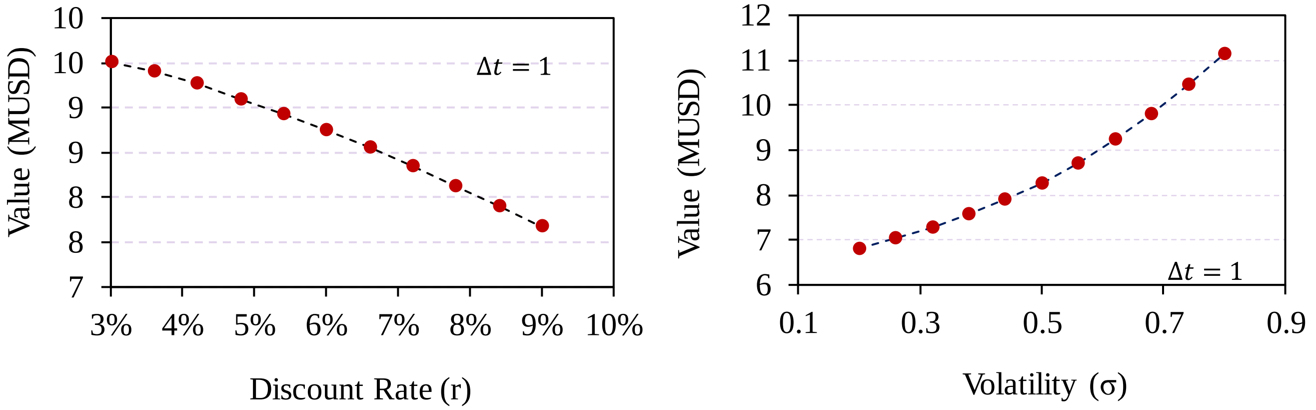
Table 1-Conversion option valuation by using binomial lattice.

χ_t			$NPV^{\chi_t}_{Continue}$ (M$)			$NPV^{\chi_t}_{Convert}$ (M$)			$NPV^{\chi_t}_{Abandon}$ (M$)			$v^t_{\chi_t}$ (M$)		
t=1	*t=2*	*t=3*	*t=1*	*t=2*	*t=3*	*t=1*	*t=2*	*t=3*	*t=1*	*t=2*	*t=3*	*t=1*	*t=2*	*t=3*
0.53	0.93	1.33	(1.8)	(3.2)	(4.6)	7.80	6.13	3.28	-27	-27	-27	**7.80**	6.13	3.28
-0.27	0.13	0.53	(5.0)	(6.3)	(7.6)	5.38	3.53	0.78	-27	-27	-27	**5.51**	3.53	0.78
-	-	-0.27		(8.6)	(9.9)	-	1.57	(1.10)	-	-27	-27	-	1.57	(1.10)
-	-	-1.07			(11.5)	-	-	(2.53)	-	-	-27	-	-	(2.53)

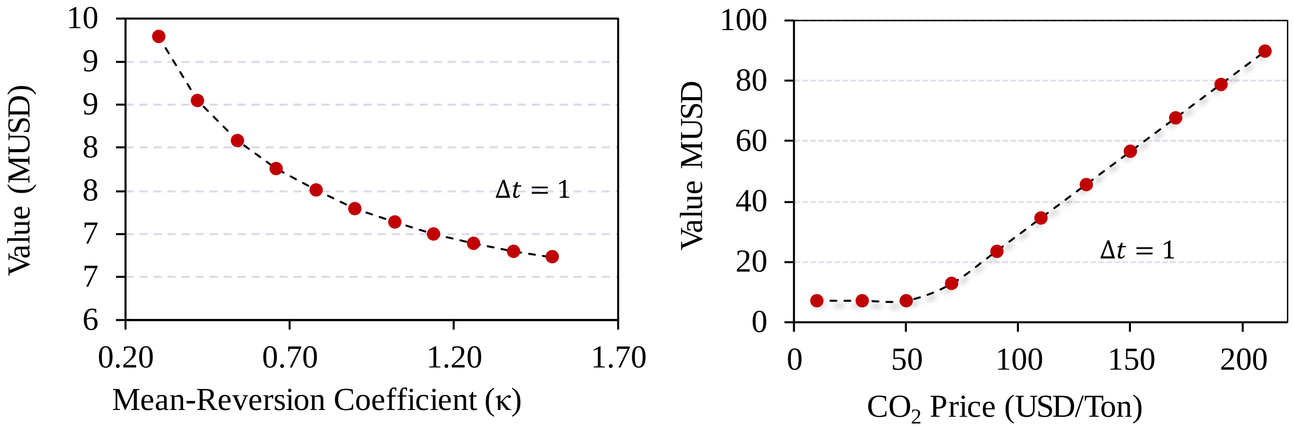
The values in bold the rightmost box show the maximum option value that can be achieved if the decision maker takes the conversion option at the first year. It shows that although Case 1 bring lower production, price volatility, more storage and late abandonment can add more value to this scenario. Moreover, it highlights the benefits of CO_2 flooding as a value-creating alternative in mature hydrocarbon reservoirs.

Based on the results. taking the conversion option in the first year at $t = 1$ generates the maximum value, while starting the injection from the second-year yields more cumulative gas production. As natural gas price increases, the conversion option embedded in depleting gas reservoirs becomes more appealing. However, for pure sequestration projects we can schedule on that low production rate and low natural gas piece and higher carbon credit price. The results show that capitalizing on CO_2 sequestration could create incremental values in depleting gas reservoirs' investment.

We further assessed the effect of changes in major value drivers on value. **Figure 4** shows value changes as volatility, discounted rate, mean-reversion factor, and carbon credit price change. Higher volatility leads to higher value and higher discount rate decreases the value. In our example, as carbon credit price decreases below $47, the conversion option becomes worthless.



(a) (b)



(c) (d)

Fig.4–One-Dimensional sensitivity analysis of option value with respect to (a) Discount rate, (b) Volatility, and (c) mean-reversion factor

We also run a two-dimensional sensitivity analysis on the long-run parameter and the starting short-term factor (**ξ and χ_0**) to see how they affected the value when other parameters were kept constant **Figure 5** displays that the equilibrium price level affects the option value.

Most corporations use the weighted average cost of capital (WACC) in discounting their project cash flows. As Jafarizadeh and Bratvold (2019) discuss, this rate is for average project in a company and may not be suitable for a project with a risk profile that deviates from the average. In this work, we have used risk neutral discounting and have accounted for risk in a separate way. Our cash flows are adjusted for risk and discounting has only accounted for time value of money.

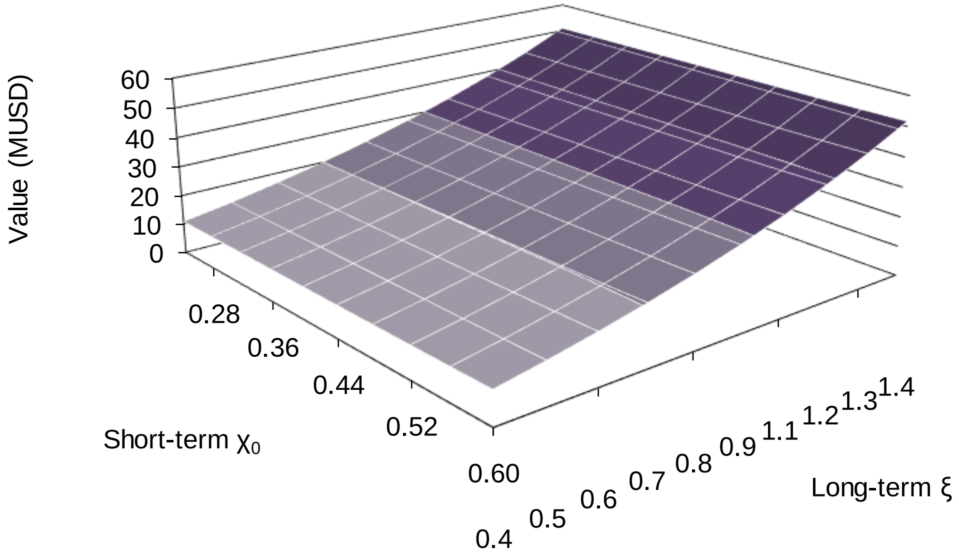


Fig. 5–Two-Dimensional analysis of option value changes respecting to long run and short-term deviations of the spot price.

Cash flows adjustment uses futures' prices and a risk-free rate to discount the expected values. In terms of private risks, the integrated valuation in (Smith and Nau 1995) uses expert judgement to directly account for technical uncertainties. This alternative is more common in real options application and takes into consideration risk in a more granular approach.

6. Conclusion

This research paper presents the development of a valuation model specifically designed for mature fields, taking into account the conversion of declining production wells to carbon dioxide injection. The primary objective is to demonstrate how the alternative of CO_2 injection can contribute to the carbon storage as well as production of additional gas reserves that would otherwise remain trapped within the reservoir, resulting in increased overall value.

Through our analysis, we show the optimal decisions for depleting natural gas reservoirs as managers exercise their flexibility. These set of decisions lead to the value of the option to convert a well from production to injection. Our findings lead to valuable insights into the potential value creation from implementation of CO_2 injection techniques to enhance gas recovery in mature assets. By considering the economic and technical aspects, this research generates insights into the benefits and feasibility of CO_2 injection for maximizing the value of mature fields and improving the overall reservoir management strategies.

Nomenclature

Abbreviations	
BHP	Bottom-hole pressure
CMG	Computer Modelling Group Ltd.
EGR	Enhanced gas recovery
GIP	gas in place
R.C.	Reservoir condition
SC	Standard condition
SDE	Stochastic differential equation
WGC	Water gas contact level
WGR	Water gas ratio
NG	Natural gas
NPV	Net Present Value
E&P	Exploration and Production
MV	Monetary Value
Symbols	
K_v/K_h	Vertical permeability to horizontal permeability
S_w	Water saturation
kPa	Kio Pascal
S_t	Natural gas stock price
X_t	Logarithmic short-term price deviations
ξ	equilibrium level price
σ	volatility
κ	Mean-reversion factor
I	Conversion Factor
dW	increment in a standard Brownian-motion process
Δt	time interval
Mm^3	million cubic meters
T	option closure window
τ	option opening window
$F_{t,T}$	future contract price
q_t	Probability of gas price when is going up

Q	Gas Production (MM^3)
$\nu_t(\chi_t)$	Option Value at time t
CF_t	Cash Flow at time t
r	Discount rate
kg	Kilogram
$	United States Dollars
P_{CO_2}	CO_2 Price ($/Ton)
P_{NG}	Natural Gas Price ($/MBTU)
S	Stored amount of CO_2 (Ton)
Ton	Metric Ton

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Appendix A – Reservoir Model

In this section we briefly explained the numerical simulation process and the assumptions we made to create our subsurface model. Indeed, reservoir simulation is a powerful technique used in the field of petroleum engineering to model and predict the behaviour of oil and gas reservoirs. It involves creating computerized representations of subsurface reservoirs and simulating fluid flow within them. By considering various parameters such as rock properties, fluid properties, and well configurations, reservoir simulation enables engineers to analyse the reservoir's behaviour under different production/injection scenarios. This invaluable tool allows for the optimization of production strategies, assessment of reservoir performance, and estimation of reserves.

Regarding our model, we input the rock and fluid data to CMG commercial simulator. Table 2 shows this reservoir properties in brief. The simulated reservoir has been producing natural gas for years and is currently depleting with an approximate remained amount of $7.68 \times 10^{\ 7} SCm^3$gas in place (GIP). The compositional sector model contains a pair of vertical production wells fully perforated in the pay zone through layer 1 to layer 8. Average gas saturation (Avg S_g) currently stands at 38 percent due to years of production, raising the water gas contact level (WGC) to an elevated level.

Reservoir fluid is a multi-component natural gas composed of mostly methane (> 95%). Table 3 illustrates the fluid properties used for the fluid model. Regarding rock and fluid interactions, it is worth mentioning that no capillary pressure effect is considered in the simulation model.

To keep the subsurface model plausible, we set constraints for minimum BHP, minimum gas production rate, maximum CO_2 fraction of outlet stream, and maximum water gas ratio (WGR) for the producers as well as maximum BHP[1] and CO_2 injection rate for the injectors. The assumed quantities of each constraint are illustrated in Table 4**Error! Reference source not found.**. Clearly, the amount of each constraint is specified for distinct reservoirs.

Table 2–Reservoir Properties

Parameter	**Quantity**	**Unit**
Avg. Permeability	14	mD
Avg. Porosity	37	%
Kv/Kh	0.1	-
Irreducible Water Saturation	5	%
Irreducible Gas Saturation	5	%
Reservoir Thickness	80	m
Reservoir Area	1,000,000	m^2
Reservoir Pressure	13,000	kPa
Reservoir Temperature	63	°C
Formation Compressibility	1.E-08	kPa^{-1}
X-Direction Grids	100	-
Y-Direction Grids	100	-
Z-Direction Grids	8	-
Simulation Start Date	2023	-

Table 3–Reservoir fluid components

Mole Fraction	0.004	0.978	0.011	0.007
Component	N_2	C_1	C_2	C_3

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[1] To not violate the reservoir fracture pressure limit and prevent formation damage, maximum BHP constraint is set for injection wells. The value could be set close to the initial reservoir pressure, however further petrophysical studies are needed to evaluate more accurate quantity for the reservoir fracture pressure.

Table 4—Operational constraints

Constraint	Amount	Unit
Producers		
Min. BHP	4000	kPa
Min. gas production rate	24000	$SCm3/day$
Max. CO_2 mole fraction	5	%
Max. WGR	95	%
Injector		
Max. BHP	50000	kPa
Max. CO_2 injection rate	90000	$SCm3/day$

Other operational constraints, such as the limited capability of surface and subsurface facilities, not readily accessible CO_2 resources and HSE hazards, may also affect the decision over a CO_2 injection project. However, they do not represent this study's target and addressing them falls outside the scope of this paper.

When initiating CO_2 flooding in a reservoir, it is recommended to start the process from the deeper layers. In our model, we have chosen to set the injection start point at the bottom two layers for several compelling reasons: Firstly, starting from the bottommost layers helps to delay CO_2 breakthrough and maintain pressure support for longer, thus increasing the ultimate oil recovery. Secondly, targeting deeper layers provides a larger area for CO_2 sweep efficiency, enabling better displacement of the remaining gas from the formation. Lastly, commencing CO_2 injection from the bottom allows more time and contact for the injected CO_2 to dissolve in formation water and get trapped within the rock pores, enhancing the storage capacity of the reservoir.

Once we have completed the simulation for the base case and the three conversion alternatives, we analyze the technical uncertainty by utilizing the quantities of natural gas production and stored CO_2 ($CO_2\ injected\ (kg)$– $CO_2\ produced(kg)$). Subsequently, we incorporate the expected data values into the integrated valuation model.

Appendix B – Spreadsheet Guideline

The spreadsheet accompanied by the paper (Conversion_MR.xlsm) assumes that we already have information on project variables and price process parameters. All of these factors are fed into a valuation algorithm, which generates results when the user executes the software. (Jafarizadeh and Bratvold 2012) presented various methodologies for determining price parameters that are contingent upon market conditions. However, details are outside the scope of the current research.

Regarding the software, we employed the implemented method outlined in (Jafarizadeh and Bratvold 2019). This method utilizes two-dimensional arrays to represent the binomial lattice, thus avoiding the need for extensive and intricate valuation models.
By utilizing these rectangular arrays, the authors elucidate the process of assigning values to each lattice, with the element in the upper-left corner indicating the starting point of the binomial lattice. Progressing one column to the right signifies an "up" move, while moving one column to the right and one row down represents a "down" move. All elements below the diagonal are set to zero. In terms of calculation, this is efficient because it results in arrays of only $N \times N$ size when dealing with a situation with N phases of options.

For instance, the binomial lattice for χ_t, assuming $\Delta\chi = \sqrt{\Delta t}\sigma$ will be $X = \begin{bmatrix} \chi_t & \cdots & \chi_t + n\Delta\chi \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \chi_t - n\Delta\chi \end{bmatrix}$.

Accordingly, arrays of forward prices and NPVs of decision options are generated, and an output array incorporating a value function lattice is created using the recursive algorithm (see (Jafarizadeh and Bratvold 2019) for more information).

As the code is versatile, we adapted it to our case to evaluate the conversion option in the defined depleting gas reservoir model. The software comprises existent modifiable inputs of the natural gas production and CO_2 sequestration amounts and mean-reverting price parameters. Once running the simulation or sensitivity analysis, the results follow the described procedure within the paper.

The embedded VBA code comprises several subroutines called in the main script. Each subroutine is responsible for a task specified in Table 5, like distinct pieces that complete the valuation puzzle.

Table 5–VBA code components definition and tasks

Code Name	Task
$Conversion$ ()	A basic subroutine that calls the other functions and subroutines to perform the recursive valuation process based on Eq. 9-11
$Chi\_Lattice$ ()	Generates the binomial lattice for χ_t
$FCurve$ $(\chi, \xi, \sigma, \kappa, t)$	Generates forward curves at each decision point
$ConV\_Lattice$ ()	Creates $NPV_{Convert}^{\chi_t}$ lattice
$ConT\_lattice$ ()	Creates $NPV_{Continue}^{\chi_t}$ lattice
$Sensitivity$ ()	Basic subroutine for conducting sensitivity analysis