Carbon Capture and Storage - Investment Strategies for the Future?

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Abstract

The following article deals with real options modeling for investing into possible future carbon capture and storage technologies. Herein, we derive two separate models. The first model incorporates a constant convenience yield or dividend for the investment project. In the second model, the convenience yield is allowed to follow a mean reverting process which seems to be more realistic but also increases the model's complexity. Both frameworks have to be solved numerically. Therefore, we calibrate our model with respect to empirical data. We found that given the recently observable prices for carbon dioxide, an investment into CO_2- storage facilities is not profitable.

Key words: Carbon Dioxide, Storage, Real Options, Investment
JEL classification: G 18, G 38, G 11, L 51

1. Motivation

Following the Kyoto Protocol which was adopted on the 11th of December in 1997, the European Union decided to reduce emissions of carbon dioxide by 20% (in comparison to the amount of emissions in 1990). Carbon Dioxide emission mainly caused by humans increased from 21 to 38 giga tons per year since 1970 (see IPCC [25]). In the European Union, following a report of the European Commission (EC [12]), 33 % of these emissions come from traffic, agriculture and waste and are hardly avoid- or absorbable. The remaining 66% are composed of 12 % pollution coming from industrial productions, and the residual 88% are caused by the energy sector (heating, cooling, power stations etc.) of the European member states. Due to these facts, the energy sector lies in the center of recent developments for reducing CO_2-

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pollution. Consequently, this implies the search for new sources of energy extraction and renewable energy sources as well as the improvement of operating efficiency of the energy sector in general. Concurrently, the situation leads to the common opinion that the target achievement of the Kyoto protocol cannot be reached without an additional interim solution. In this context, one possibility is given in the development of carbon capture and storage technologies (CCS), which means the storage of CO_2 in aquifers, exploited oil and gas fields, coal seams and other mineral formations. The resulting holding capacity for carbon dioxide storage is estimated to reach 2,000 to 11,000 giga tons worldwide (see IPCC [24]). Therefore, we analyze whether an investment into these future carbon capture and storage technologies (CCS) will be a possible solution to assist the realization of goals highlighted in the Kyoto protocol which will be given if the investment itself is profitable. The article is organized as follows. Section 2 and section 3 will give a brief overview on the technical implementation of CCS and the adjacent literature, respectively. In section 4 we derive the two distinguished real option models and derive their open solution as well as the boundary conditions. A numerical solution to these and the calibration with respect to empirical date is given in section 5. The last section concludes and summarizes the findings.

2. Technical Aspects

Following Goettlicher [20], the technical implementation of CCS can be distinguished into five processes of which only three are currently realizable and which are given by post combustion capture, pre combustion capture and oxyfuel combustion. These are highlighted in the following figure.

[Insert Figure 1 about here.]

Post combustion capture:. Post combustion capture systems can be seen as an add on to conventional fossil fuel combustion systems. CO_2 is captured from flue gases which are produced by combusting fossil fuels with air (IPCC [24]). In principle, several techniques can be used to capture CO_2 from flue gas. For example: absorption based on chemical solvents, absorption by using membranes or absorption by using solid sorbens. Since flue gas is usually at atmospheric pressure, the partial pressure of CO_2 is low. As a consequence, currently only absorption by chemical solvents is able to meet the requirements in terms of capture efficiency, costs and economics. The principle system consists of an absorber to bind CO_2 and a stripper to remove chemically bound CO_2 from the solvent (see IPCC [24]). Goettlicher [20] highlights that CO_2 capture rates up to 90 or 95 percent can be reached. In practice higher recovery rates lead to bigger columns and rising costs which is due to the fact that for regenerating the solvent in the stripper a large amount of thermal energy is needed. Following Goettlicher [20], this energy requirement which has to be provided by the primary combustion process lowers the plant efficiency at 10 to 15 percentage.

Pre combustion capture:. In order to remove CO_2 before combustion, fossil fuels can be gasified and shifted. So most of the initial energy contend of the fossil fuels is switched to pure hydrogen and can be combusted using air without issuing CO_2, as mentioned in IPCC [24]. This process is called *Integrated Gasification Combined Cycle* (IGCC). Fossil fuel is normally gasified by pure oxygen and steam. This leads to a syn gas mixture of carbon monoxide (CO) and hydrogen (H_2). Following Ogriseck [35], the remaining energy content in carbon monoxide is shifted with steam to hydrogen and CO_2. Due to high system pressure and high CO_2 partial pressure, CO_2 can be removed more easy with pre combustion than with post combustion capture systems. After CO_2 capturing the remaining hydrogen is used as fuel for nearly state of the art combined cycle power plants, Ogriseck [35]. Compared to natural gas fired combined cycle power plants the over all plant efficiency of IGCC plants is reduced by 10 to 15 percent as shown in Goettlicher [20], which is caused by the air separation unit needed for pure oxygen, gasifier efficiency, syn gas cleaning and CO_2 removing.

Oxy fuel combustion:. A third way for removing CO_2 is combusting fuels with pure oxygen in order to get a flue gas stream out of nearly 100 percent CO_2 (see IPCC [24]). Oxy fuel technology is widely based on currently used fossil fuel boilers which is a major advantage forecasting reliability and costs in comparison to IGCC . Herein, nitrogen is removed in front of combustion in the air separation unit to get pure oxygen. For getting similar conditions like in air fired fossil fuel combustion systems, nitrogen is substituted by recirculated flue gas (mostly CO_2) (see Kather [26]). After removing water from the flue gas, the nearly pure CO_2 is pressurized and liquefied. Following IPCC [24], a major disadvantage of this process is the high amount of impurities in the CO_2 stream which increases the energy consumption of CO_2 liquefaction compared to post combustion capture systems. The air separation unit and the CO_2 compressing unit decrease the over all plant efficiency by 10 percentage as pointed by Kather [26]. This results in an expected overall efficiency of about 35 to 36 percent. In the following we will not concentrate on these technical details. Nevertheless, the resulting diminishing effects on efficiency will be taken into consideration for the models.

3. Literature

Currently, there is only a few number of articles dealing with investment decisions, energy waste management (or $CO - 2$ storage facilities) and real options. Therefore, we refer to several studies which focus on different technologies as oil exploitation or power generation which can easily be ascribed to the topic focused in this article. When talking about carbon capture and storage technology it is possible to distinguish between two different issues which exert influence on real options modeling. For the literature review, these are handled separately. On the one hand, the real option analysis for investments into carbon dioxide storage has to cover the determination of the adjacent product dynamics, i.e. the price dynamics of CO_2

certificates, and on the other hand, it has to deal with the implementation of storage technologies.

Recently, certificates for carbon dioxide are allocated nationally. If there exists a divergence between allocated and produced amount of emissions, the companies have the possibility to participate in the European Trading system (ETS) for CO_2-certificates. The ETS is organized similar to a stock exchange but the traded products differ significantly. Following Benz and Trueck [3], the main difference between plain vanilla shares and emission certificates is given by price fixing. While the price of a certain share is driven by expectations concerning uncertain future profits, the price of an emission allowance is exclusively driven by the current scarcity. In this context, Insley [23] as well as Abadie and Kutxa [1] see a Geometric Brownian motion (GBM) as adequate process to picture the price development of emission certificates which is equivalent to the process assumed for stock price evolution. In opposite, Laurikka and Koljonen [29] refer to an Ornstein-Uhlenbeck process which implies mean reverting prices that will tend toward a fixed value in the long run. This property is also often assumed for energy prices as for example in Knittel and Roberts [28][1]. More recently, Dasalakis, Psychoyios, and Markellos [8] show that this characteristic is not valid for CO_2-prices and recommend instead a GBM for describing CO_2-price development.

Modeling storage facilities with respect to certain markets is not new. The seminal work on the theory of storage traces back to Working [45] and Working [46] in which he analyzes the dependence between spot and futures prices of storable commodities. The theory of storage proclaims that firms can have an incentive to store a commodity as it generates an additional positive profit. This finding is confirmed theoretically as well as empirically and was first ascribed by Brennan [5] and Telser [40] to the so called convenience yield. Both authors show that the benefits for consumers arise because holding inventories constitutes the availability of an input for production as well as the possibility of meeting unexpected future demand. However, this early work does not model the convenience yield formally. Recently, analysis of wealth generated by the storability of a certain good gives insights into the process and the intertemporal behavior of the convenience yield as for example Heinkel, Howe, and Hughes [21] who show that the convenience yield approximation is both statistically and economically important in explaining variation between the futures and spot prices after adjusting for interest rates. Moreover, additional empirical findings are given in Milanos and Thomadakis [33] or Susmel and Thompson [38].

Based on these studies, articles dealing with real options applications for natural gas storages came up. In this context the study by Thompson, Davison, and Rasmussen [41] has to be mentioned. The authors present an algorithm for the valuation and optimal usage of storage facilities. Moreover, Chen and Forsyth [6] enhanced this

[1] For a deeper insight into the discussion concerning energy price dynamics see for example Lucia and Schwartz [30].

approach and derived the optimal storage operation with respect to a stochastic control problem and a semi-lagrangian approach. The following article brings together the market modeling of CO_2 certificates and the real options approach for storage. We model the investment decision for capturing and storing carbon dioxide with real options and show how a rational investor would decide, given certain environmental conditions. Herein, we deviate from storage technologies as the carbon dioxide shall not be released at a future point in time.

4. Real Options Framework

In the following, we will proceed to the evaluation of a storage for carbon dioxide with real options modeling. Let L describe the holding capacity of the repository. With increasing cavity pressure, the storable amount decreases, such that L is decreasing over time. Consequently, the holding capacity can be described by:

$$dL = -cLdt, \tag{1}$$

where c signals the velocity of filling. Therefore c is an indicator of storage capacity of a certain storage facility. A person owning a CO_2 storage receives earnings denoted by E which are composed of recent earnings by storing activity and the discounted future possible earnings coming from holding storing possibilities. Hence, $E = cL\pi + LV$, with π denoting the profit (after taxes) from storing one ton of CO_2 and V signaling the market value of one unit of the stored product. In continuous time, this can be rewritten as:

$$Edt = cL\pi dt + d(LV) \tag{2}$$

With respect to Equation (1), this yields:

$$Edt = cL\pi dt + LdV - VcLdt \tag{3}$$

The rate of return from owning a CO_2 storage is given by the ratio of earnings and possible turnover in which the latter is calculated by holding capacity multiplied by market prices (V). Following Dixit and Pindyck [11], we assume that the rate of return evolves as GBM, given by:

$$\frac{Edt}{LV} = \mu_V dt + \sigma_V dz_t \tag{4}$$

with drift μ_V which can either take positive or negative values and reflects the expected development in prices as well as long- and short term trends in price evolution. σ_V stands for the volatility of the price process and z_t is a standard Wiener process. Combining Equations (3) and (4) and defining $\delta = \frac{c(\pi - V)}{V}$, we end up with:

$$dV = (\mu_V - \delta)V dt + \sigma_V V dz_V \tag{5}$$

as process for the market value of a ton stored CO_2.
In order to determine the value of an unexplored storage we assume that the value of a ton stored CO_2 follows similar dynamics as the market price of the adjacent emission certificates. Hence, the market price for emission certificates p is driven by:

$$dp = (\mu_p - \delta)p dt + \sigma_p p dz_p \tag{6}$$

The previously defined δ can be seen as the opportunity cost of delaying investments. In the context of the evaluation of storages and following Brennan [5], this is also known as convenience yield or expected dividend of the project.

4.1. Convenience yield modeling

The convenience yield is defined as the value from holding inventory and is negatively correlated with inventories, i.e. the higher the level of stored goods the lower the value that can be gained from storing an additional unit. Consequently, the value of the marginal convenience yield declines as the aggregate level of inventory increases.[2] For the following derivation we will distinguish between a linear value and a stochastic function for δ. With respect to this differentiation we derive the optimal investment decision for each case separately.

4.2. Investment decisions under the assumption of linear convenience yield

Dixit and Pindyck [11] assume that the opportunity cost of delaying investment follow a linear function over time which implies that the value of a ton stored CO_2 as well as the profit after taxes are linear functions. Recall, that the market price is given by $dp = (\mu_p - \delta)\, p dt + \sigma_p p dz_p$. In the following we denote the value of the investment opportunity by $F(p, t)$ which shall be maximized. Therefore, we follow the procedure of contingent claims analysis in Dixit and Pindyck [11] and set up a risk less portfolio which contains one unit of the project and a short position in n units of the output. The value of the portfolio is then given by:

$$\Phi = F - F'(p_t)\, p_t \tag{7}$$

This portfolio is dynamic, as a change in p also changes $F'(p)$ and, hence, the portfolio itself will change. Therefore, the total return of the portfolio can be derived

[2]For a deeper insight into the properties of convenience yields see for example French [16], Fama and French [15] and Fama and French [14]. More recently, also Cho and McDougall [7] and Ng and Pirrong [34] show that the convenience yield is inversely related to the level of inventory.

as:

$$\frac{1}{2}\sigma^2 p^2 \frac{d^2F(p,t)}{dp^2}dt - \delta p \frac{dF(p,t)}{dp}dt + \frac{dF(p,t)}{dt}dt. \tag{8}$$

As this return is risk free and in order to avoid arbitrage, the following relation must hold [see 11]:

$$r_f \Phi dt = r_f \left[F(p,t) - F'(p,t)\, p\right] dt \tag{9}$$

Hence, we get

$$\frac{1}{2}\sigma_p^2 p^2 \frac{\partial^2 F(p,t)}{\partial p^2} + (r_f - \delta)\, p \frac{\partial F(p,t)}{\partial p} - r_f F(p,t) + \frac{\partial F(p,t)}{\partial t} = 0. \tag{10}$$

Remark, an option gives the holder the possibility to choose Max(Net present value (NPV),0). Hence, only projects with posititve NPV will be undertaken. Following Brennan [5], this is given as:

$$NPV(p,T) = p\sum_{T=1}^{N} e^{-\delta t} - D\sum_{T=1}^{N} e^{-rT} - I_0 \tag{11}$$

where the costs for storing the good are denoted by D and the investment costs are given as I_0 [3].
With respect to this and the following boundary conditions, equation (10) is solved numerically.

$$\begin{aligned} F(0,t) &= 0 && (12)\\ F(p^\star,t) &= p^\star - D - I_0 && (13)\\ \frac{\partial F(p_t,t)}{\partial p^\star} &= 1 && (14) \end{aligned}$$

The first condition states that the value of the option equals 0 as soon as the price of the underlying approaches 0. At the final date $t = T$, the company decides whether it will exercise the option or not. The last two conditions give the value matching and smooth pasting conditions, mentioned in Dixit and Pindyck [11]. Equation (13) shows that the existence of the option is only valuable as long as the market price for the emission certificate exceeds the costs of capturing the same amount in storage plus investment costs for one unit. The numerical solution to this linear model is highlighted in section (5.2) Before proceeding to this, we introduce the second model with stochastic convenience yield.

[3] In the calculation process the investment costs I_0 are integrated into overall specific costs

4.3. Investment decisions under the assumption of stochastic convenience yield

As previously mentioned, if δ is considered as convenience yield which is well understood from financial analysis covering commodity trading, a non-linear process seems to be more appropriate than a linear function. Therefore, following Gibson and Schwartz [19] who find strong empirical evidence in favor of mean-reverting patterns, we also assume that δ follows an Ornstein-Uhlenbeck process, given by:

$$d\delta = \eta_\delta(\alpha_\delta - \delta)dt + \sigma_\delta dz_\delta \tag{15}$$

Where η provides a measure for the speed of adjustment to the mean given as α. The joint diffusion of the stochastic processes is denoted by:

$$dz_v dz_\delta = \rho dt \tag{16}$$

This structure is also consistent with the previously mentioned theory of storage in which the inverse relationship between inventory level and convenience yield is mentioned. Following the same steps as before and setting up a risk less hedge portfolio[4], leads to the partial differential equation given as:

$$\begin{aligned} &\frac{\partial F(p,t,\delta)}{\partial p}(r-\delta)p + \frac{\partial F(p,t)}{\partial \delta}[\eta(\alpha-\delta)-\lambda] + \frac{1}{2}\sigma_p^2 p^2 \frac{\partial^2 F(p,t)}{\partial p^2} \\ &+ \frac{1}{2}\frac{\partial^2 F(p,t)}{\partial \delta^2}\sigma_\delta^2 + \frac{\partial^2 F(p,t,\delta)}{\partial p \partial \delta}\sigma_p \sigma_\delta \rho p - r_f F(p,t) \\ &- \frac{\partial F(p,t)}{\partial t} = 0. \end{aligned} \tag{18}$$

Similar to the previous model, the boundary conditions determine the numerical solution.[5] For the stochastic model, these are given by the following equations:

$$\begin{aligned} F(0,t,\delta_t) &= 0, && (19)\\ F(p_t,t,\delta_t)) &= 0 \quad \text{with } \delta_t \to \infty, && (20)\\ F(p_t,t,\delta_t)) &\to NPV \quad \text{with } \delta_t \to -\infty, && (21)\\ \frac{F(p_t,t,\delta_t)}{NPV} &\to 1 \quad \text{with } PV \to \infty, && (22) \end{aligned}$$

[4]Due to the fact that the convenience yield is not a traded asset and can therefore not be hedged, we have to determine the risk adjusted convenience yield process. This is given by:

$$d\delta = [\eta_\delta(\alpha_\delta - \delta) - \lambda]dt + \sigma_\delta dz_\delta, \tag{17}$$

in which λ is the market price of convenience yield risk which is for simplicity assumed to be constant.

[5]Recall, this PDE has no explicit solution.

Euqations (19) and (20) highlight that the value of the project approaches zero if either the price is zero or the opportunity cost of delaying investment become infinitely large. If instead, δ becomes infinitely small ($\delta \rightarrow -\infty$), the option tends toward the net present value of the project. This also holds for the case in which the present value becomes very large. The latter two conditions are mentioned in equation (21) and equation (22), respectively.
According to the linear model, the NPV has to be determined. Following Schwartz [37], this is derived as:

$$NPV(p, T, \delta) = p \sum_{T=1}^{N} A(T) e^{-\delta H} - D \sum_{t=1}^{N} e^{-rT} - I_0 \tag{23}$$

with

$$H = \frac{1 - e^{(-\eta t)}}{\eta} \tag{24}$$

$$A(t) = e^{\frac{(H-t)[\eta^2(\alpha - \frac{\lambda}{\eta}) - \frac{1}{2}\sigma_\delta^2 + \eta\rho\sigma_p\sigma_\delta]}{\eta^2} - \frac{\sigma_\delta^2 H^2}{4\eta}} \tag{25}$$

5. Optimal Investment Choice - Numerical solutions

In this section, we solve the previously derived investment decisions numerically with respect to the stochastic price evolution of emission certificates.

5.1. Parameter Determination

In a first step, we determine reasonable value bounds for our parameters by referring to the international capital markets for emission allowances price dynamics and the appropriate discount rate. Parameters which are additionally included but not observable, as for example the capturing costs or investment expenditures, are derived with respect to international studies and forecasts.

5.1.1. Determination of costs for carbon capturing

Cost estimations for separating CO_2 are exclusively based on forecasts and simulations as this facility does not exist, yet. Herein, the studies by Rao and Rubin [36], Alstom [2], Dillon, Panesar, Wall, Allam, White, Gibbins, and Haines [9] and Gibbins, Crane, Lambropoulos, Booth, Roberts, and Lord [18] have to be mentioned. The results are rather wide spread which can be explained by the different types of power plants from which carbon dioxide will be taken in order to put it into storage. For existing coal burning power plants, operating costs for additionally integrated CCS technology are mainly driven by the reduction in production efficiency up to 14 %, which corresponds to costs of 45 to 75 USD per ton CO_2.
Newly constructed coal burning stations provide estimated costs in between 27 and 72 USD per ton CO_2.
For combined cycle gas fired power plants, the combustion capture technology is

assumed to cause average costs between 37 and 74 USD per ton CO_2. Concluding, the costs for capturing and storing carbon dioxide can range from 2 to 74 USD and depend on the energy production costs. The fact that the generation of electricity causes different costs for different power stations, implies consequently also to different costs for carbon capturing.

For the numerical solution, we refer to an average value of 40 EUR per separated ton carbon dioxide.

5.1.2. Determination of transportation costs

An additional category of costs is given by the costs for transporting carbon dioxide from the power plant to the storage facility. Herein, mainly transportation by rail, pipeline and water carriers can be distinguished. In literature, most studies focus on transportation by pipeline. The costs for constructing a pipe are widespread and range from 0.25 million EUR/km (see Meng, Williams, and Celia [32]) to 0.33 million Euro/km (IPCC [24]) up to 1 million EUR/km, as mentioned in Wildenborg and Gale [44]. Also Svensson, Odenberger, Johnsson, and Stoemberg [39] undermines these findings and derives a spread of costs for constructing transportation facilities ranging from 1 to 20 million EUR per 100 km.

After construction is finished, specific costs for transporting occur which range from 1 to 10 EUR per ton CO_2 which consequently vary with the length of the tinerary[6]. For the following numerical solution we assume a fictitious pipeline with a length of 100 km which is assumed to cause specific costs of 0.8 EUR per ton CO_2 transported.

5.1.3. Determination of storage costs

Costs for investing into carbon storage facilities are much harder to estimate than costs for transporting carbon dioxide as there exist no reference values, yet. In literature, the range for expected investment expenditures varies remarkably. It is for example possible to achieve negative CO_2 storage costs due to enhanced oil or natural gas recovery. Studies dealing with this topic are given by Bock, Rhudy, Herzog, Klett, Davison, Ugarte, and Simbeck [4] and Hendriks, W., and v. Bergen [22] who show that investment costs for carbon dioxide storage depend on the geographical position and whether the exploitation is offshore or onshore. Following Bock, Rhudy, Herzog, Klett, Davison, Ugarte, and Simbeck [4], onshore drilling may cause costs about 200.000 USD, while offshore exploitation costs can reach values up to 25 million USD. Also Wildenborg and Gale [44] support these estimations. In their article they derive a range for offshore exploitation in between 10 and 50 million EUR.

Moreover, costs for geological work and additional administrative expenses have to be included into the estimation of investment expenditures. These depend on the characteristics of the storage; Saline aquiferes for example cause specific costs

[6] For a deeper insight into these estimations see for example Gale and Davison [17], Wildenborg and Gale [44] or Martinsen, Linssen, Markewitz, and Vogele [31].

between 0.4 and 12 USD per ton CO_2.[7] Following Bock, Rhudy, Herzog, Klett, Davison, Ugarte, and Simbeck [4] and Hendriks, W., and v. Bergen [22], specific costs for onshore storage are estimated to lie in between 0.5 and 2.8 USD per ton CO_2. Instead, using exploited natural gas- and oil fields, can reduce the range of specific costs to 0.5 up to 1.8 USD per ton CO_2. Both studies do not explicitly incorporate possible excess returns which can be caused by an increase in the original gas- or oil exploitation when storing carbon dioxide nearby. In this context, enhanced oil recovery can lead to negative costs up to 9 USD per ton.

An additional cost factor is given by surveillance costs. Following IPCC [24], Bock, Rhudy, Herzog, Klett, Davison, Ugarte, and Simbeck [4] and Hendriks, W., and v. Bergen [22], these costs lie in between 0.05 and 0.085 USD per ton stored product. We assume that the investment costs are 4 EUR per ton stored CO_2 which can be seen as a rather conservative value for offshore as well as onshore storing.

5.1.4. Determination of the price dynamics

The determination of values for the dynamics is usually done with respect to historical data. Therefore, we refer to several studies dealing with the evolution of market prices and market dynamics in context of emission allowances.

Dynamics emission certificate prices:. In order to determine the volatility of carbon dioxide prices, Dasalakis, Psychoyios, and Markellos [8] refers to spot prices for emission allowances traded at Nordpool and Powernext. He finds an appropriate value for μ at -0.0039 and -0.0032 as well as a standard deviation of 0.8105 and 0.7379, respectively. In opposite to these results, Abadie and Kutxa [1] mention that these dynamics should take values of 0.069 for μ and 0.4683 for σ_p if the European market as a whole is covered.

In our model, we refer to a range for σ_p between 0.05 and 0.8 such that both above mentioned bounds can be incorporated into the upper bound. The lower bound is motivated by the fact that the future of emission markets is uncertain, such that this lower bound covers also the possibility that the evolution of carbon dioxide prices is close to certainty.

Convenience yield:. Appropriate reference values for the dynamics of the convenience yield are much harder to determine. Only Trueck, Borak, Haerdle, and Wern [42] give some insights into these properties. They show that the convenience yield tend toward zero in short run. In medium-term they find values up to 8 %.

For our long-run analysis, we refer therefore to an average convenience yield in between 10 % and 20 %, i.e. $0.1 \leq \alpha \leq 0.2$. The volatility of the convenience yield is assumed to range from one to 20 %.

[7] Recall, herein again offshore storage implies higher costs than onshore.

Risk premium. For the specification of an adequate risk premium (λ), we refer to studies and forecasts for international efficient capital markets as in Welch [43] and Dimson, Marsh, and Stauton [10]. The latter state that, for the time period between 1900 and 2007, the annualized equity risk premium relative to bills lies at 5.5%, for the US, 4.4 % for the UK, and 4.8 % for the world index. Therefore, we suggest a risk premium λ of 6 % as plausible.

Remaining variables. As there is no empirical evidence for the correlation between emission certificate prices and convenience yield, we assume ρ to lie at 0.1. The speed of adjustment can either take the value 3 or 5.

5.1.5. Maturity and time horizon

The maturity for the real option is estimated to be four years. This refers to the proposal to the European directive which will cover the legal aspects of carbon dioxide storage in the underground (see EC [13]). In this proposal, the allocation of exclusive licenses for constructing a carbon storage facility are covered and allots that the license owner can construct the storage within four years - otherwise the license will become worthless. In our model, we refer to this maturity for the option to invest while the maturity of the overall project is assumed to be 12 years.

5.1.6. Determination of the Risk free rate

The risk free interest rate varies from country to country and is usually derived from the promised yield of a country's Government bonds, which are in general considered as risk free investments [following 27]. The following figure highlights government bonds with maturity ten years for the countries - Germany, Canada, Spain and USA.[8]

[Insert Figure 2 about here.]

Herein, the risk free rate ranges from 3.0% to 5.5%. For the following solutions we refer to an average discount rate of 3 %. In order to take provision for the previously mentioned range, we vary the risk free rate inbetween 3 % and 7 %.

There is a perennial debate about the necessity of carbon dioxide storage and its rentability in the context of existing markets for emission allowances. By taking option values into account, the model in this paper analyzes the effect of different parameter values on storage investment. In the next section, we show how the previously derived parameters, such as volatility or the risk free rate, influence the option value and consequently, the investment decision. Therefore, we distinguish between the model with linear and stochastic convenience yield.

[8] The drop in the series at the end of the considered time period is caused by the consequences of the subprime crises in 2008.

We concentrate on the value of the option depending on prices for CO_2 certificates and the net present value (NPV) which determine the investment triggering. Recall, we restrict our results to cases in which the NPV reaches positive values. A negative NPV implies a rejection of an investment at all. Herein, the option becomes worthless.
As starting values for our parameter analysis we refer to the following:

$\delta = 0.1$	$\sigma_p = 0.3$
$\sigma_\delta = 0.01$	$\eta = 3$
$r = 0.03$	$\rho = 0.1$
$\lambda = 0.06$	

Table 1: Reference values

On the x-axis the price for the certificate is given and the y-axis shows the price of the option to invest. The evolution of the net present value is shown by the shaded line. The continuous line gives the dependence and development of the option value. Investment is triggered as soon as the two incorporated lines meet.

5.2. Linear model

In a first step the results for a linear convenience yield are mentioned.
The following figures 3 and 4 highlight the dependence of the option value as well as the NPV on the lower and upper bound of the risk free rate. Obviously, the higher the risk free rate, the higher the critical value $p^\star$ will be which triggers investment. High discount rates reduce the value of the investment project and signal therefore a delay in investment. Nevertheless, the change due to a variation in the risk free rate is not tremendously large which is also visualized by the inner value of the option that does not change significantly.

[Insert Figure 3 and 4 about here.]

Next, figure 5 and 6 show the impact of the volatility on the value of the option. Low volatility values, as given in figure 5, lead to a lower inner value of the option and consequently to a low mark-up on the net present value. As soon as the volatility is increased, the option value as well as the mark-up increase gradually. This is not surprising because real option analysis is mainly important for investment decisions which are subject to high uncertainty. If the included risk decreases, i.e. if the uncertain part is reduced, the value of the option tends toward zero.

[Insert Figure 5 and 6 about here.]

In a last step, we show the impact of the varying dividend (δ) or convenience yield. Again, the borderline cases are highlighted in the following figure.

[Insert Figure 7 and 8 about here.]

The mark-up on the NPV which is caused by the option value decreases as soon as δ is increased. In this case, the NPV is shifted to the right hand side, i.e. the net present value at a specific price decreases. This shift goes in line with the fact that higher certificate prices are necessary to cover (as some kind of opportunity costs) the expected dividend from investment such that an investor decides in favor of investment only if the rate of return can be reached.
Concluding, the bandwidth of critical prices visualized by the previous figures ranges from 60 to 105 EUR. While the critical price in figure (5) is close to a net present value of zero, figure (6) requires prices to exceed 100 EUR.

5.3. Stochastic model

The following figures visualize similar results for the two dimensional case. Again, in a first step, the impact of the risk free rate is highlighted. The findings confirm the results from the one dimensional case and show lower trigger values for an increasing risk free rate.

[Insert Figure 9 and 10 about here.]

The impact of an increase in volatility is shown in the following figures. Herein, figure (11) highlights the resulting trigger value for $\sigma_p = 0.01$, i.e. the price process is close to uncertainty. In opposite to the observations in the previous section, the option value in the two dimensional case is not solely driven by the uncertainty in prices but also by uncertainty in the convenience yield which has a greater impact than uncertainty in prices. If the volatility tend toward zero, the stochastics of the convenience yield aggravate the mark up on the NPV while an increasing volatility in prices softens this observation. Similar to the one dimensional case it becomes obvious that the NPV increases as volatility is raised which can be seen by comparing figure (11) and figure (12).

[Insert Figure 11 and 12 about here.]

Last, varying delta in the context of a stochastic convenience yield implies that increasing delta leads to an increasing option value and hence, delays investment. As previously mentioned, the NPV is shifted to the right and decreases for a specific price. In the context of a stochastic convenience yield, this interdependence is less pronounced as in the two dimensional case the long run mean (α) is of more importance. Thus δ in the stochastic model can be considered as snapshot which will converge toward α in the long run.

[Insert Figure 13 and 14 about here.]

Concluding, also in the two dimensional case with stochastic convenience yield, the bandwidth of critical prices start at values far above current prices for carbon dioxide. Consequently, with respect to these an investment into carbon capture and storage technology seems not be profitable.

6. Conclusion

The following article derives a real option model for investments into carbon capture and storage technologies. Modeling these kind of investment decisions can be done with simple and more advanced methods. The increasing complexity of the model implies that there are more boundary conditions that have to be fulfilled in order to solve the problem. Our simple model is made up of stochastic prices for carbon dioxide certificates but a fixed amount of dividends or opportunity costs. In a second step, the latter assumption is neglected and we introduce a stochastic convenience yield model. Both models do not lead to a closed form solution and are thus solved numerically. Therefore, we determine adequate parameter values, which can only provide a proxy for realistic values as empirical values do not exist currently. In general, we find that given these parameter constellations, an investment into carbon capture and storage is not profitable given a current price for emission allowances of about 15 EUR. At least, not until these prices are doubled, a decision in favor of an investment will be made. From the previous simulations a critical price for the certificate seems to be given at 70 EUR[9], which is confirmed by both, the one dimensional as well as the two dimensional model.
One of the main cost drivers in our model are the costs for separating carbon dioxide from a certain process. These make more than 90 % of the included costs for carbon capture and storage technologies. Hence, decreasing these costs would probably lead to a profitability of such investments immediately.
The above mentioned model give an insight into modeling new technologies in the energy sector. Nevertheless, the implementation of a poisson process instead of a geometric Brownian motion as stochastic for the price evolution may lead to an improvement of the analysis. A poisson process would allow the incorporation of the discrete parts in the stochastic development and would therefore approve the visualization of the transitions between the national allocation plans and the certain trading periods for carbon dioxide certificates.

[9] This value can be found in several calculations with low deviations.

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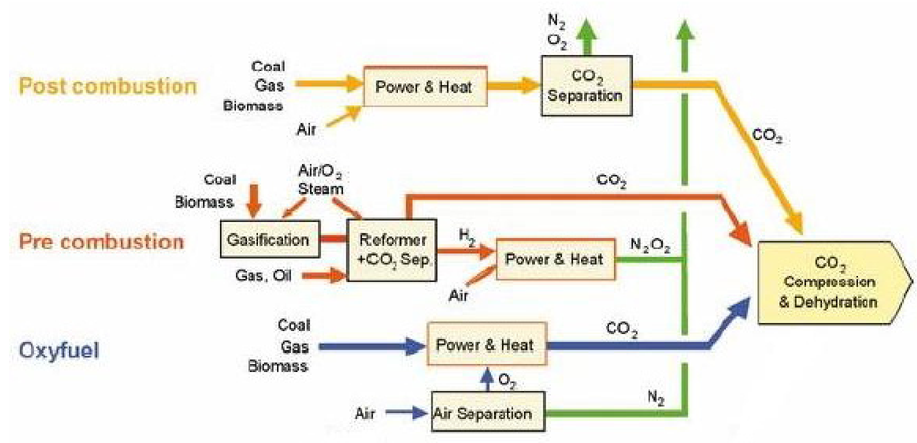

Figure 1: Processes for Carbon Capture

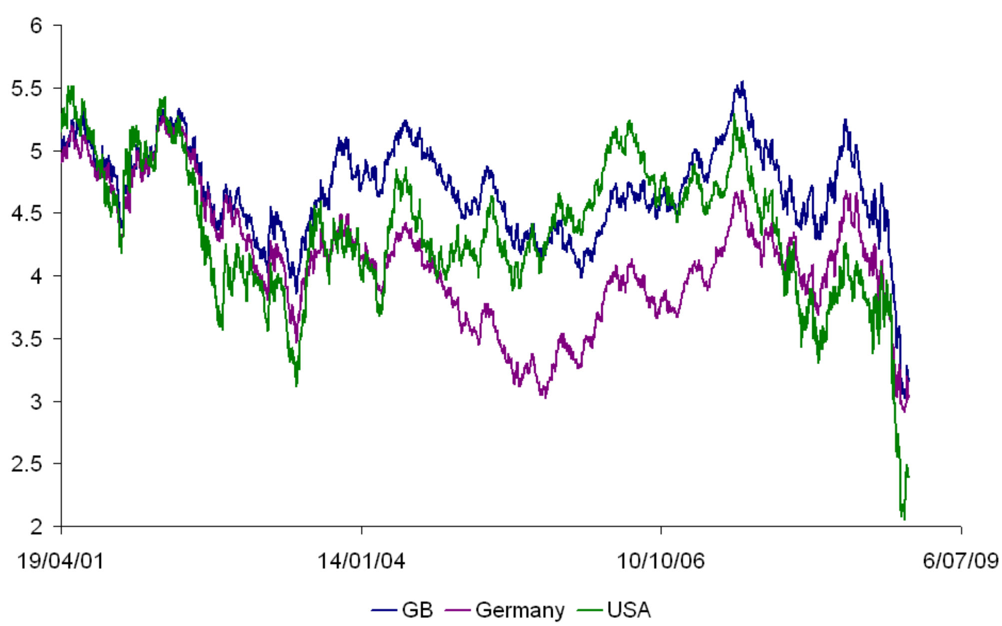

Figure 2: Risk free rate

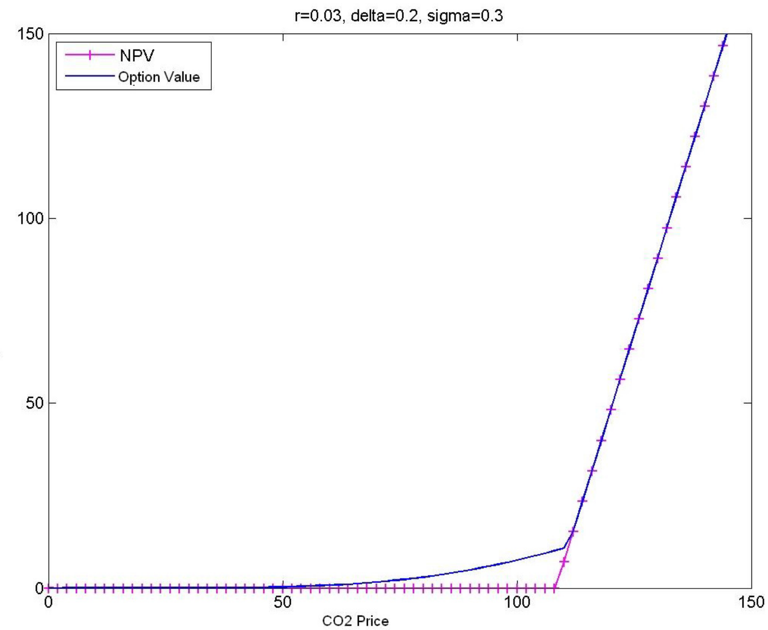

Figure 3: Variations in the risk free rate: $r = 3\%$, $\delta = 20\%$, $\sigma_p = 30\%$

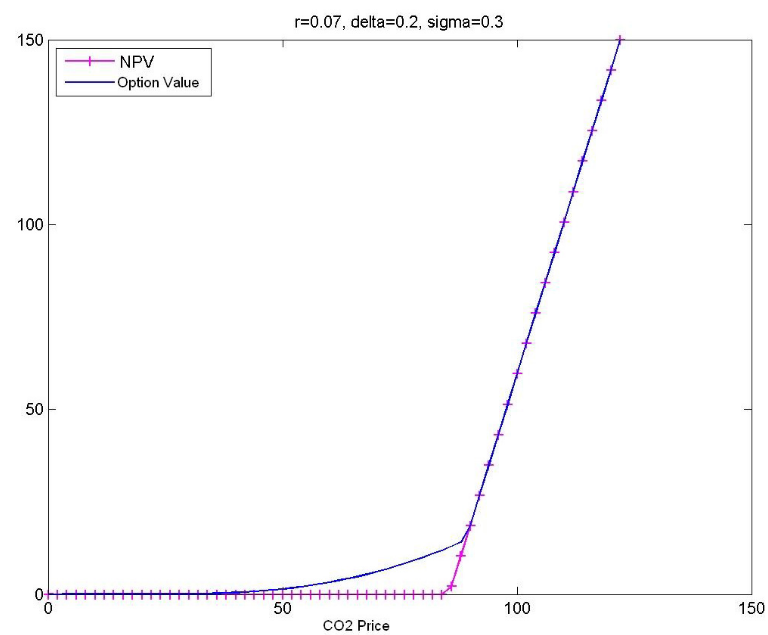

Figure 4: Variations in the risk free rate: $r = 7\%$, $\delta = 20\%$, $\sigma_p = 30\%$

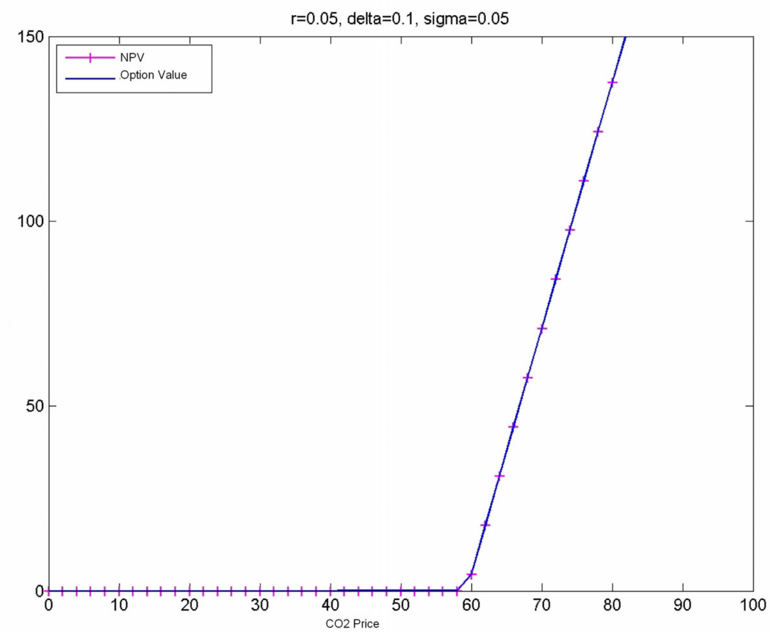

Figure 5: Variations in price volatility: $r = 5\%$, $\delta = 10\%$, $\sigma_p = 5\%$

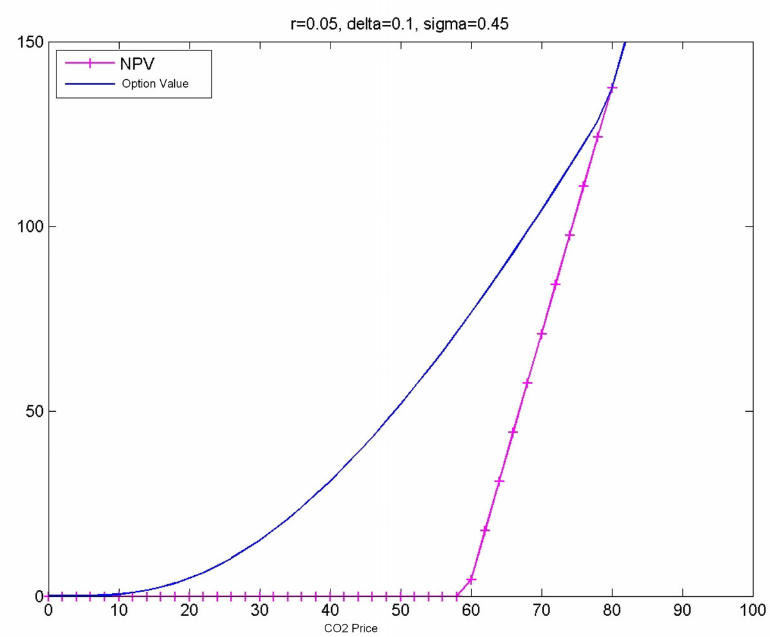

Figure 6: Variations in price volatility: $r = 5\%$, $\delta = 10\%$, $\sigma_p = 45\%$

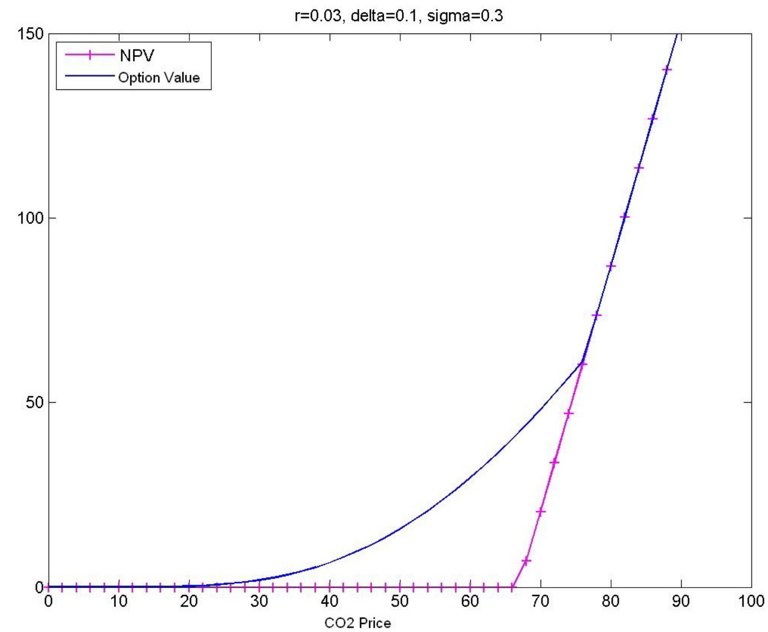

Figure 7: Variations in the convenience yield: $r = 3\%$, $\delta = 10\%$, $\sigma_p = 30\%$

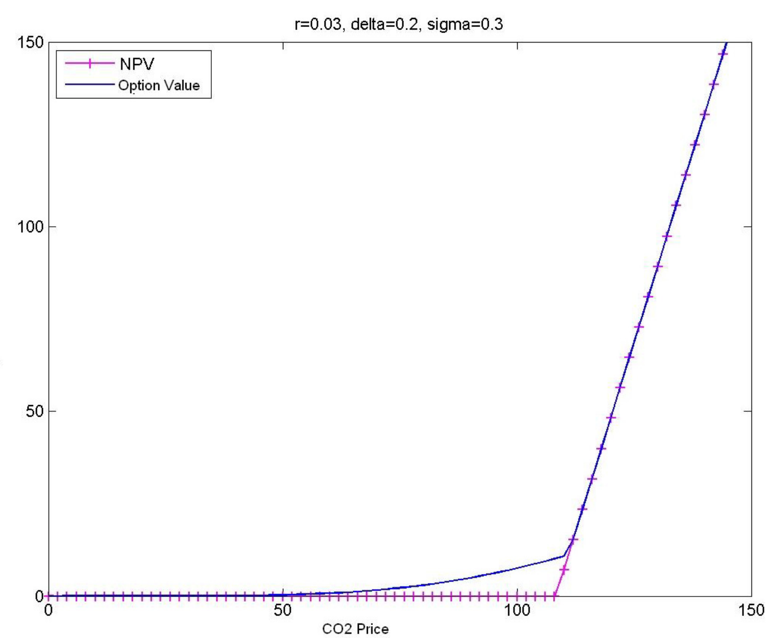

Figure 8: Variations in the convenience yield: $r = 3\%$, $\delta = 20\%$, $\sigma_p = 30\%$

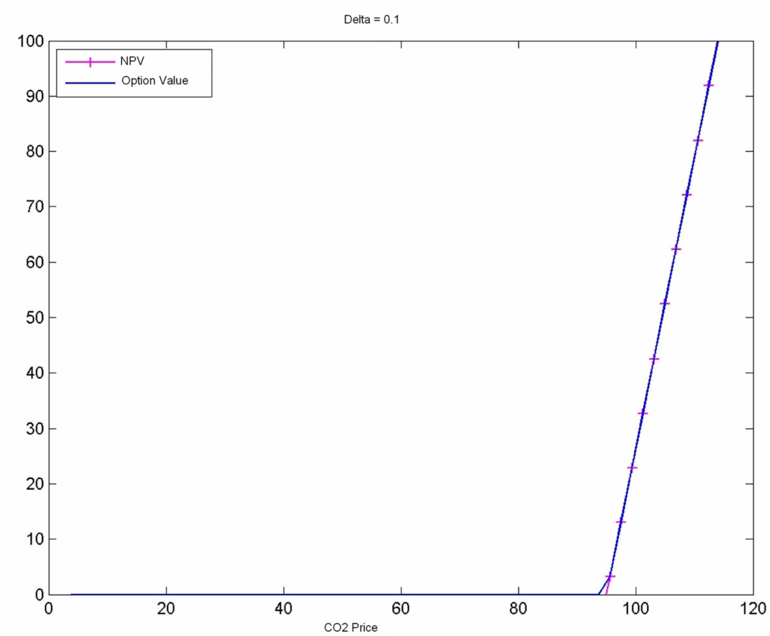

Figure 9: Variations in the risk free rate: $r = 3\%$, $\delta = 10\%$, $\sigma_p = 1\%$, $\sigma_\delta = 45\%$, $\alpha = 20\%$

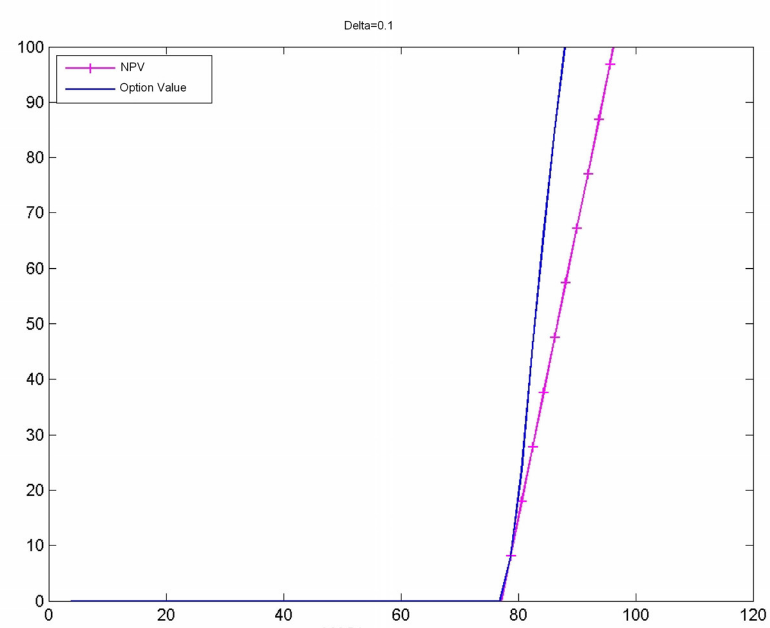

Figure 10: Variations in the risk free rate: $r = 7\%$, $\delta = 10\%$, $\sigma_p = 45\%$, $\sigma_\delta = 1\%$, $\alpha = 20\%$

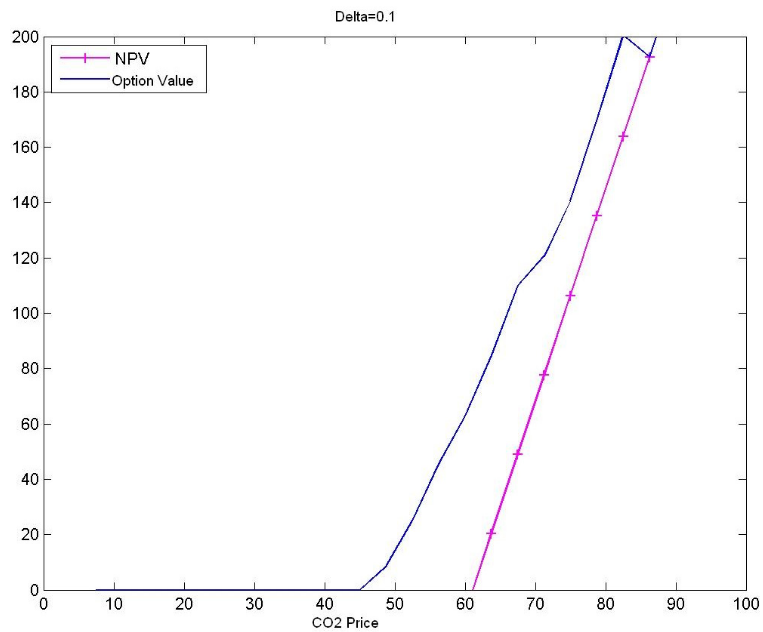

Figure 11: Variations in price volatility: $r = 3\%$, $\delta = 10\%$, $\sigma_p = 30\%$, $\sigma_\delta = 1\%$, $\alpha = 20\%$

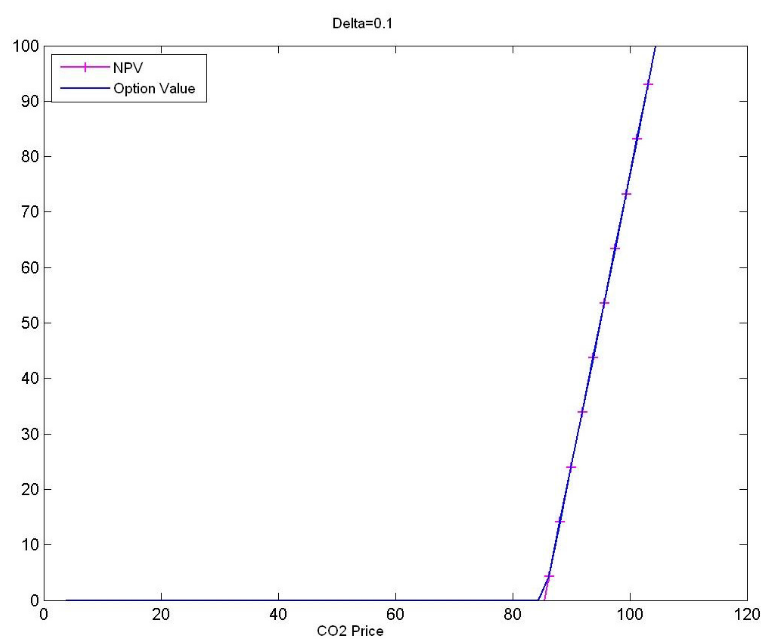

Figure 12: Variations in price volatility: $r = 3\%$, $\delta = 10\%$, $\sigma_p = 5\%$, $\sigma_\delta = 1\%$, $\alpha = 20\%$

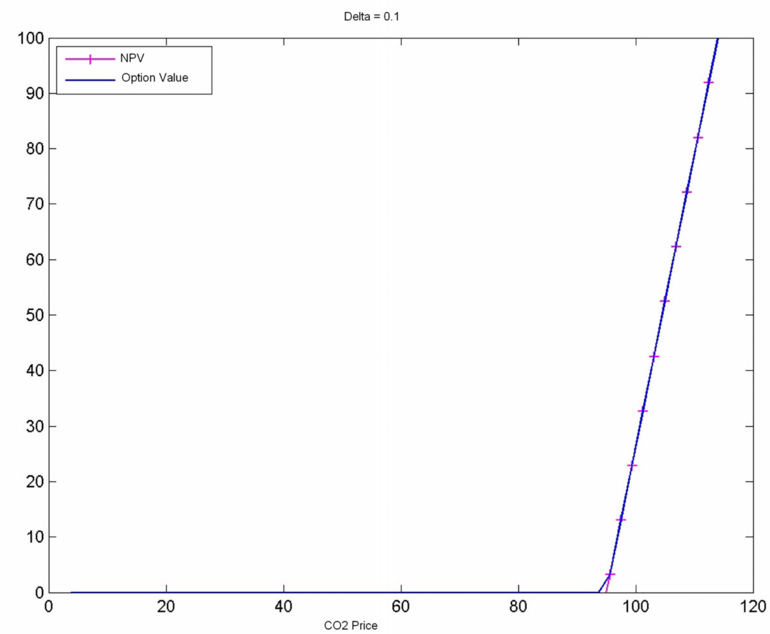

Figure 13: Variations in the convenience yield: $r = 3\%$, $\delta = 10\%$, $\sigma_p = 30\%$, $\sigma_\delta = 1\%$, $\alpha = 20\%$

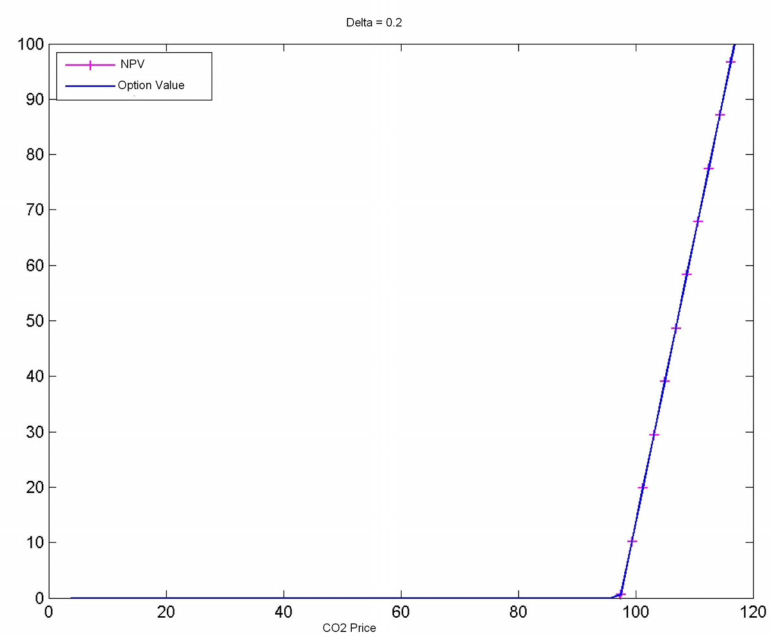

Figure 14: Variations in the convenience yield: $r = 3\%$, $\delta = 20\%$, $\sigma_p = 30\%$, $\sigma_\delta = 1\%$, $\alpha = 20\%$