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The Options Value of Blue Hydrogen in a Low Carbon Energy System

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David Webbe-Wood, William J. Nuttall, Nikolaos K. Kazantzis, Chi Kong Chyong

Abstract

A developer considering the construction of a Steam Methane Reforming facility for the production of hydrogen from natural gas faces the decision as to whether to incorporate and operate a Carbon Capture and Storage (CCS) unit, as part of the facility, in an environment where the costs of inputs and the price of hydrogen are uncertain. Conventional valuation methodologies such as Discounted Cash Flow (DCF) cannot systematically integrate uncertainty from changing market and regulatory conditions. Such methods are also unable to account for the ability of management to make use of flexibility to respond as the uncertainties are progressively resolved proactively.

Consequently, an Engineering Flexibility / Real Options approach has been developed to allow the calculation of the additional value that the developer might obtain if a CCS unit is not fitted at the time of construction of the SMR plant. Instead, the plant is constructed so that the CCS unit can be retrofitted during the plant's lifetime if the economic conditions are such that it appears that this will increase the value of the SMR plant.

Application of this approach has shown that, for this example, the Net Present Values are increased in a range of energy price and cost of CO_2 release scenarios, i.e. the Real Option has a positive value. These findings hold for a range of discount rates. Similarly, the approach improves the Value at Risk and the Value at Gain.

Whilst in this work, the approach has been applied to the example of the decision of whether to fit a CSS unit to an SMR plant for the production of blue hydrogen, it is believed that a similar approach can be applied to other situations.

Keywords Uncertainty, Investment Decisions, Blue Hydrogen, Carbon Capture and Storage Under Uncertainty, Real Options, Monte-Carlo Simulation

JEL Classification D81, G11, Q40

Contact David.Webbe-Wood@Open.ac.uk
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1. Introduction

Work has been carried out to extend the methodological framework presented in (Chyong et al, 2012) and (Ma et al., 2017), whereby a Real Options approach is employed to assess the value of environmental mitigation strategies and attendant plant economic performance enhancements through flexible process system design in the presence of irreducible sources of uncertainty for various low carbon energy projects. Within such a context, the present study's thematic focus has been placed on evaluating the economic prospects of a plant producing "blue" hydrogen in a low-carbon energy system as inherent and potentially valuable management optionality is exercised, allowing process system adaption to evolving market and regulatory conditions. In particular, the production of blue hydrogen from natural gas (predominately methane) is considered using a steam methane reforming (SMR) process with carbon capture capabilities.

Hydrogen is forecast by, e.g., the IEA (IEA, 2019) to play a critical role in a clean, secure, and affordable energy future. The IEA estimates that the global demand for hydrogen will increase from approximately 95 MT per annum in 2021 to 180 MT by 2030 in a net-zero scenario (IEA, 2021). The Hydrogen Council and McKinsey & Company (Hydrogen Council & McKinsey& Co., 2021) forecast a demand of 660 MT by 2050.

Furthermore, numerous methods are available for the production of hydrogen via a range of energy sources, and a taxonomy of different hydrogen colours has been created to categorise these, e.g. (H2 Bulletin, 2021). Current methods of production are electrolysis of water (0.6%), from fossil sources with carbon capture (9.3%), fossil sources without carbon capture (69%) and as a by-product from petroleum refining (21.2%) (IEA, 2021). Schemes have been proposed to utilise hydrogen instead of natural gas (predominantly methane) for domestic supplies, such as the plan to blend up to 20% hydrogen in the UK gas network in 2023 (Energy Networks Association, 2021). The IEA projection (IEA, 2021) states that the predicted hydrogen demand in 2030 will be met by 18% blue hydrogen and 40% from fossil fuel sources without using carbon capture and storage (CCS). i.e. grey hydrogen. The UK Government's hydrogen strategy (HM Government, 2021) envisages a "twin track" approach of green hydrogen produced by electrolysis using renewable electricity and blue hydrogen to meet the UK demand. As Noussan and colleagues (Noussan et al., 2021) have pointed out increases in hydrogen demand are likely to outstrip the availability of renewable electricity for the production of green hydrogen, meaning that blue hydrogen will be required as part of the transition to net zero.

Dieter Helm (Helm, 2018) has described how technological changes, together with the need to decarbonise, may lead to oil and gas companies being left with stranded assets. In such circumstances, the prospect of using natural gas reserves as a feedstock for hydrogen may be attractive to these companies (Nuttall & Bakenne, 2020).

For the scenarios presented, the operator of the SMR plant has the option of fitting a Carbon Capture and Storage (CCS) unit during construction and operating this unit throughout the plant's lifetime or not fitting the CCS unit. The fitting of the CCS unit brings extra capital and operational costs. Conversely, fitting and operating the unit may bring savings from the reduced need to buy carbon credits. In what Chyong describes as a "traditional approach" (Chyonget al 2012) where the operator only has the choice as to whether or not to fit the CCS at the start of the project, the value of the two alternatives can be compared, and a commercial decision is made based on straightforward NPV calculations. These NPV calculations, however, would be subject to significant uncertainties (macroeconomic, regulatory, technology risks, etc.) as the parameters on which the calculations are based are themselves uncertain. In light of this realisation, using Monte Carlo (MC) simulation techniques, stochastic analyses could be carried out. The MC simulation techniques allow explicitly account for these uncertainties and derive NPV probability distribution profiles that can be statistically characterised instead of single-point estimates that could occasionally lead to erroneous economic performance assessment conclusions. They would not, however, be able to account for the effects of possible changes in the construction of the plant (i.e., retrofit CCS) or changes in the operating modes (e.g. ceasing the operation of the CCS unit) to reflect changes in the "worlds[1]" in which the SMR plant would be operating. A schematic flow chart of the pertinent decision-making process is given in Fig 1 and discussed in the next section.

Using a Real Options approach with flexibilities incorporated into the plant design and operating regime would allow the operator to take advantage of changes in the wider environment in which the plant is operated, either to increase the value of the plant over its lifetime (i.e., enhance access to upside opportunities) or to minimise the effect of changes that could reduce the net present value (NPV),i.e., limit exposure to downside risk, in an inherently uncertain environment. Typically, in engineering contexts, such real options require additional upfront expenditure on infrastructure or underlying technology. This is reminiscent of the value of a real option in financial markets (de Neufville & Scholtes, 2011). The rest of this paper is structured as follows. Section 2 outlines our methodology, while Section 3 describes our techno-economic analysis of the SMR plant with and without CCS. Section 4 discusses the main findings and concludes our research in Section 5.

[1] We use the term “worlds” in this document to describe possible future energy and carbon emission price scenarios.

2. Preliminaries and Methodological Framework

2.a. The Real Options Approach

An operator of a facility has the potential to incorporate flexibility into both the initial design and construction stages of the plant and how the plant is operated. This potential flexibility gives the operator the ability to respond to opportunities that may arise and manage potential downside risks as a result of external changes, thereby increasing the NPV of the facility over its lifetime.

These flexibilities give the operator "Real Options," i.e., "the right, but not the obligation", to adapt favourably to the changing regulatory policy environment. The operator can systematically assess the additional value that such an approach might confer on the engineering project, using techniques analogous to those used to evaluate financial assets (although fundamental differences arise since engineering project cash flows are not tradeable assets). For further discussion of these differences, the reader is referred to Appendix F of (de Neufville & Scholtes, 2011).

Cardin (2013)(Cardin, 2013) has proposed a structure for procedures to enable flexibility in the design and operation of engineering systems under various sources of uncertainty (Cardin, 2013). This structure consists of several stages which have been used for the system under consideration in this document.

Stage 1 – Baseline Design

In this case, two baseline scenarios are considered. In the first scenario, an SMR plant is constructed to produce hydrogen using methane as both the feedstock and energy source for the process and CO_2 is released into the atmosphere. In the second scenario, the SMR plant is constructed with a CCS unit to reduce the release of CO_2 into the atmosphere from the start. For both options, NPVs can be calculated using conventional deterministic techniques. These values will depend on the expected costs and revenues associated with the construction and operation of the plants representing the baseline cases. They will also be used in the sequel to inform comparative economic performance assessment and pertinent decision-making on which configuration to proceed.

Stage 2 – Uncertainty Recognition

The environment in which the plant (whichever variant) will operate will be subject to a number of uncertainties inevitably impacting potential economic performance outcomes. Whilst some of the uncertainties, e.g., discount rate, whether the plant is being operated in a high or low energy price environment or whether the costs associated with releasing CO_2 into the atmosphere are high or low, can be, at least in part, accommodated within a conventional deterministic approach by consideration of a range of scenarios. However, such an approach could not simultaneously accommodate multiple uncertain NPV-model inputs. Furthermore, the proposed method allows the derivation of NPV probability distribution profiles that can be statistically characterised in a potentially insightful and nuanced manner. Therefore, Monte-Carlo simulation techniques could be employed to overcome the abovementioned limitations and mathematically address the "flaw of averages" associated with potentially asymmetric impact on process performance output metrics of otherwise symmetrically distributed uncertain inputs.[2]

Within such a context, sources of uncertainty (i.e., uncertain model inputs) considered in the present study are:

- The price of energy
- The price of methane
- The price of permits to release CO_2 to the atmosphere or carbon taxes.

In the case of the SMR plant originally constructed without CCS, the costs of fitting and operating a CCS unit and the energy penalty associated with its operation.

Stage 3 – Concept Generation

Considering these uncertainties leads to a flexible concept[3] which would enable the operator to take advantage of resolving these uncertainties with time, potentially enhancing the system's economic performance over its lifetime.

- Amendment of the design for the plant, initially not fitted with CCS, to be able to be retrofitted with CCS during its operational life and hence benefit due to a reduced need to pay to release CO_2 into the atmosphere. However, the fitting and operation of the CCS unit will incur various costs.

Stage 4 – Design Space Exploration

The design of the baseline plant initially intended to be operated without CCS is amended so that the CCS unit can be retrofitted during the operation and the necessary additional costs identified. It should be pointed out that an increase (or reduction) in the system's NPV of fitting and operating a CCS in an uncertain operating environment involves a complex interaction of several factors, including the costs of natural gas[4], the price the hydrogen is sold for, capital costs, discount rates as well as the effect of the operation of the CCS on the amount of hydrogen available for sale.

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[2] Economic performance evaluated at average conditions do not represent average economic performance (de Neufville & Scholtes, 2011) .

[3] Other possible flexible concepts were also identified but are not considered further in this work.

[4] Although it is postulated that the owner/operator of the plant is a petrochemical company, it has been assumed in the calculations that it pays the market price for the gas even if this is an internal accountancy exercise.

Such costs are typically not well known in advance; therefore, any probability distribution for these parameters will have a high degree of variance.

2b. Valuation of the Engineering Flexibility

The value of the right to exercise the option and adapt to changing circumstances by making use of the flexibility incorporated in the design can be evaluated. Traditionally this has been accomplished by using methods such as the theoretically appealing Black-Scholes method and various multinomial lattice methods based on those used to value financial options. These approaches can (under certain conditions) give computationally attractive closed-form solutions. In this study, the Monte-Carlo simulation technique has been used to overcome some of the limitations of the Black-Scholes and multinomial lattice methods:

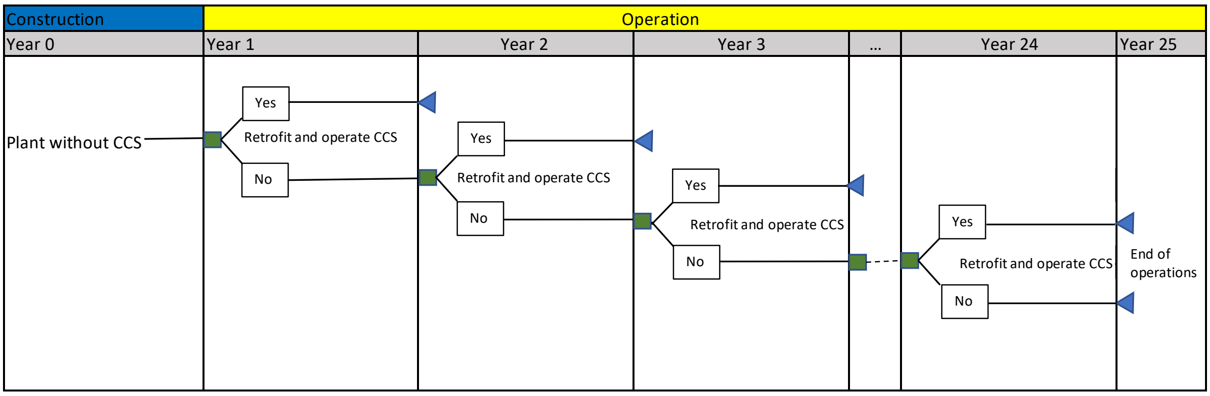
I. The difficulties associated with determining/quantifying the risk-adjusted discount rate or the risk-adjusted probabilities are removed. Also, constructing a replicating portfolio[5] has no physical meaning in real engineering options as the underlying assets (net cash flows) are not traded on the market (de Neufville & Scholtes, 2011).

II. These methods cannot simultaneously accommodate multiple, stochastically modelled sources of uncertainty. Such an accommodation is achieved within the proposed Monte-Carlo simulation and engineering real options framework (de Neufville & Scholtes, 2011). Furthermore, the approach generates valuable information through a comprehensive statistical characterisation of the derived NPV distributions. As a result, multiple performance metrics can be evaluated and used to support decision-making and comparing alternatives. Such metrics include a probabilistically unbiased estimation of expected NPV (successfully addressing the "flaw of averages" associated with system non-linearities and operational constraints). It also allows the calculation of the values of additional performance metrics such as the standard deviation of the NPV, Capex, and Value at Risk (VaR) for a given probability level (5th percentile of the cumulative distribution), capturing the potential for downside risk, the complementary Value at Gain (VaG) (95th percentile of the distribution) capturing the potential for upside opportunities. This enables establishing a link to the risk profile of the decision maker. The above represents key comparative advantages over financial real options analysis, in which a single option value is generated, or a traditional optimisation framework relies on a single objective function.

[5] A replicating portfolio is a combination of already traded assets that are intended to replicate the uncertain future payoffs of an option.

Within the above context, for the scenarios where the flexibilities are available to the operator, calculations can also be carried out to evaluate the distribution of the NPVs. The value of the decision to exercise the option to change the configuration or operation of the plant or not to exercise the option will depend on the future values of the costs (expenditures) and revenues. Exercising or not exercising, the options result in a range of possible configuration pathways through the lifetime of the plant. This pathway is illustrated in Figure 1 below. Theoretically, the decision to exercise, or not, the option could be taken at any time. To simplify the calculations, it is assumed that the decision can only be made once per year.

Figure 1: Configuration pathways through the plant life



Each configuration pathway will give rise to a different NPV distribution. The operator will be aware of the current, relevant costs and prices, but they cannot be confident about how these may change. Thus, the operator will not know whether exercising the option will or will not increase the NPV of the plant. To accommodate this lack of knowledge of future circumstances, the decision whether or not to exercise the option is modelled using a decision rule based on historical gas and electricity price data as described below (provided that it has not already been exercised) in each year of the plant life, except the final year of the plant life. Following the decision, the distribution of the consequent NPV is calculated (as gas and electricity prices follow a geometric Brownian motion, the NPV for any path through the decision lattice will be variable, and repeated iterations of the model will give a distribution of the NPV for a given decision of when to exercise the option). As the model is run for 100,000 iterations, all possible pathways through the plant evolution will be considered, and therefore a distribution of NPVs will be derived.

An NPV probability distribution profile can be calculated and statistically characterised for each configuration pathway. As mentioned above, and as will be shown below, the value of the option to exercise flexible adaptations to evolving market and regulatory policy conditions can thus be determined and inform a comparative assessment (based on multiple relevant statistical measures of system performance, such as mean or median values, 5th and 95th percentile values etc.) of the corresponding NPV distribution to the one of a baseline scenario associated with a "fixed system design".

3. System Description and Economic Performance Assessment Framework

3.a. Basis of the Plant Design

The SMR plant used for these calculations is based on one of the designs (case 3; CO_2 capture from the SMR plant's flue gas) described by Collodi and colleagues (Collodi et al., 2017a) and (Collodi et al., 2017b). This design is an SMR constructed on a greenfield site using natural gas as a feedstock with a production rate of 100,000 Nm^3 of H_2 per hour using monoethanolamine (MEA) to capture CO_2 from the flue gases. The CO_2 molar concentration in the SMR flue gas is approximately 19%. This compares to the roughly 5% molar concentration in a typical Combined Cycle Gas Turbine plant (Scholes et al., 2016), making the capture process more efficient[6].

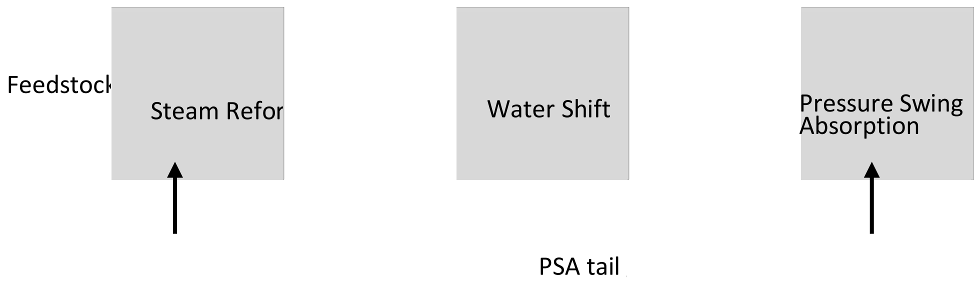
In the SMR process, methane, the principal component of natural gas, is reacted with water (as steam) to produce H_2 and CO_2. In the first stage, steam is combined with methane to produce hydrogen and carbon monoxide. The carbon monoxide is then reacted with steam in the presence of a catalyst to produce more hydrogen and CO_2 in a process referred to as a water gas shift reaction. Finally, the hydrogen is purified in a pressure swing absorption process. The tail gas from this process is fed back into the initial reforming stage, and carbon capture is carried out on the flue gases from this reforming stage.

Furthermore, natural gas is used as feedstock for the SMR process as well as the energy source for the processing system. Excess heat is used to generate electricity which is then sold to the pertinent market.

The design is for a plant where the CCS unit is incorporated from the beginning, and pricing data are in 2014 euros[7]. Data from other sources was used to supplement this data. This is discussed below:

[6] These molar concentrations correspond to approximately 30% and 8% on a mass basis, respectively.
[7] All cost and price information has been converted into 2020 pounds sterling prior to discounting.

Figure 2 Schematic of the SMR Plant with CCS (Taken from Collodi et al (Collodi et al., 2017b))



3.b. Learning Effects

If the CCS plant is fitted after the construction of the SMR plant, it is likely that such learning effects mean that the cost of the unit (ignoring the extra costs associated with retrofitting when compared to fitting at the time of initial construction) and the energy needed to operate the unit will be less than those for a unit fitted at the time of the construction. Thus, the later in the life of the plant the CCS unit is retrofitted, the lower the costs and energy need will be. These learning effects are explicitly incorporated in the model as described below.

In the case of the SMR unit, this is constructed at the same point in time for all four scenarios. Therefore any learning effects affecting state of the art for SMR plants will not impact the costs of the specific plant under consideration in this work. Similarly, for the two scenarios where the CCS unit is fitted at the time of construction of the SMR plant (whether the operation is continued throughout the lifetime or not), learning effects will have no impact on the cost of the CCS unit.

As the costs given by Collodi and colleagues (Collodi et al., 2017b) are for a CCS unit which is constructed at the same time as the SMR plant, alternative sources of data have been used to take into account such learning effects. Azarabadi and Lackner (Azarabadi & Lackner, 2020) have analysed the historical data collated by Van den Broek and colleagues (van den Broek et al., 2009) to derive learning rates for:

- Capital Costs
- Energy Penalty[8]
- Fixed Operational and Maintenance Costs
- Variable Operational and Maintenance Costs.

[8] The amount of energy that is required for the capture process and therefore is not available for sale (as electricity).

These estimates are given in terms of a range of possible values. These have been converted to the minimum (corresponding to the range's lower bound), maximum values (the upper bound) and mean values.

These Costs are given in Table 1 below. For the assessment described here, all four learning rates are assumed to be part of the same "Learning World," i.e., the same learning rate (whether the minimum, mean or maximum) is used for all of the factors in Table 1.

Table 1 Learning Rates Based on the Data in Azarabadi & Lackner (Azarabadi & Lackner, 2020)

	Minimum	Mean	Maximum
Capital Costs	6%	11.5%	17%
Energy Penalty	2%	4.5%	7%
Fixed O&M Costs	6%	11.5%	17%
Variable O&M Costs	10%	15%	20%

These learning rates relate the costs associated with a CCS unit, at a future date, to the "reference costs" according to the relationship (eq.1):

$$C = C_r\ I^b \qquad (1)$$

Where:

C = Costs for the unit under consideration

C_r = Costs for the reference unit

I = The installed CCS capacity at the time of construction relative to that at the time of the reference unit.

And b = the experience index given by the Learning Rate (the cost reduction associated with doubling elapsed time) =1-2^b.

As equation 1 is based upon the installed CCS capacity rather than time, it is necessary to combine it with projections of the amount of installed CCS capacity with time. Such predictions were obtained from the International Energy Agency (International Energy Agency, 2020). As this reference only gives projections for three dates, values for intervening years were derived by interpolation between these values.

3.c. Price of Hydrogen

The NPV of the SMR plant is dependent on the sale price of hydrogen. Information on the projected future price of hydrogen is scarce. Data has, however, been obtained from Lux and Wood McKenzie as reported by the Net Zero Technology Centre (Net Zero Technology Centre, 2020) and from Esperis (Esperis, 2020).

These sources only report projected prices for a small range of dates and sometimes give different prices for the same date. A mean of these prices has been taken to produce single projections at each date. A linear equation was then fitted to these values to give price projections at yearly intervals. This predicted price time series is subject to a significant degree of uncertainty. Insufficient data do not allow any estimate to be made of the volatility of the price of hydrogen. Therefore volatility of the Hydrogen price is not included in the model.

3.d. Prices of Natural Gas and Electricity

A significant component of the costs that an operator of an SMR will incur is the cost of natural gas used as both a feedstock and an energy source. Although this analysis is based on a petrochemical company using its reserves to produce hydrogen, it is assumed that the operator must always pay for its natural gas, if only as an internal accountancy transaction.

Projections of future natural gas prices were obtained from the UK Department for Business, Energy and Industrial Strategy (BEIS, 2020). These projections do not include estimates of the volatility in the prices. To incorporate volatility, estimates of historic volatility were derived using data from the same source (for the period 2001 to 2018). It has been assumed that the volatility of future prices will be the same as the historical volatility. No account has been taken of the possibility of significant and sustained changes in the price of natural gas because of the transition to net-zero policies or other events. Similarly, no account has been taken of recent rises in natural gas prices as a consequence of events in Ukraine, as it is unclear what the impact will be over the time scales considered in this work.

A time series of natural gas prices is derived for each model run by calculating a mean growth rate from the data and adding a volatility term reflecting the volatility observed in the historical price data i.e., a geometric Brownian motion model is used, as shown below:

$$Price\ in\ Year = Price\ in\ Previous\ Year + Annual\ Growth\ Rate + (Price\ in\ Previous\ Year\ \ x\ Random\ Term) \quad (2)$$

where the random term is randomly selected from a Gaussian distribution with mean zero and standard deviation equal to the observed historical standard deviation.

For the gas price time series, the growth rate and historical standard deviation values are given in Table A3 of Appendix A in the supplementary information.

We adopt the three price scenarios projected by BEIS (High, Base and Low). A scenario is chosen for each run of the model, and a time series is described above.

The plant is designed to extract excess heat and use the excess steam to generate electricity for sale. The amount of electricity available for sale depends on whether the CCS unit is fitted and in operation. The sale of electricity represents another income stream for the operator.

Time series for the three electricity price scenarios were derived in the same way as those for the natural gas prices using data from the same source.
For the electricity price time series, the values of the growth rate and historical standard deviation are given in Table A4 of Appendix A in the supplementary information.

It is assumed that both gas and electricity prices are from the same scenario (High, Base or Low) referred to as "energy worlds."

3.e. Cost of CO_2 Releases.

Whether the CCS unit is fitted and in operation or not, the SMR plant will release CO_2 into the atmosphere[9]. The amount released will be significantly less when the CCS unit is fitted and operated. These releases will incur costs for the operator. Projections for the costs of unit releases of CO_2 were obtained from BEIS (BEIS, 2019). These projections only extend until 2035. They were extended to 2050 using data from DECC[10] (DECC, 2015) to derive growth rates after the end of the BEIS time series.

3.f. Additional Costs for Retrofitting

The cost data for both the SMR plant and the CCS unit given by Collodi and colleagues (Collodi et al., 2017a) assume that both components are constructed at the same time. Building an SMR plant to accept the retrofitting of a CCS unit later will increase the initial cost. No literature values have been found to quantify this increased cost. Chyong and colleagues (Chyong et al, 2012) used a value of 3% for the increase in costs of designing and constructing a closed-cycle gas turbine to be suitable to be retrofitted with a CCS unit. This value is used here.

Azarabadi and Lackner (2020) have analysed the costs involved in retrofitting a CCS unit to a gas turbine plant and have concluded that a cost increase of 15% compared to the cost of fitting the plant at the construction phase is appropriate (Azarabadi & Lackner, 2020). Therefore, this value has been used[11].

[9] The design of SMR plant with CCS used in this analysis (Collodi et al, 2017) assumes that the efficiency of CO_2 capture is 90%.
[10] Now part of BEIS.
[11] Prior to consideration of learning effects.

3.g. Costs of CO_2 Transport and Storage.

Costs for transporting and storing CO_2 have been obtained from the work of Schmelz and colleagues (Schmelz et al., 2020). The costs used are those for offshore storage in a saline formation and those for using a 250 km pipeline with a capacity of 3M Tonnes of CO_2 per year. As the authors note, the economies of scale associated with networks of pipelines to transport CO_2 from a cluster of sources may reduce these costs.

3.h Economic Performance Assessment Model Structure

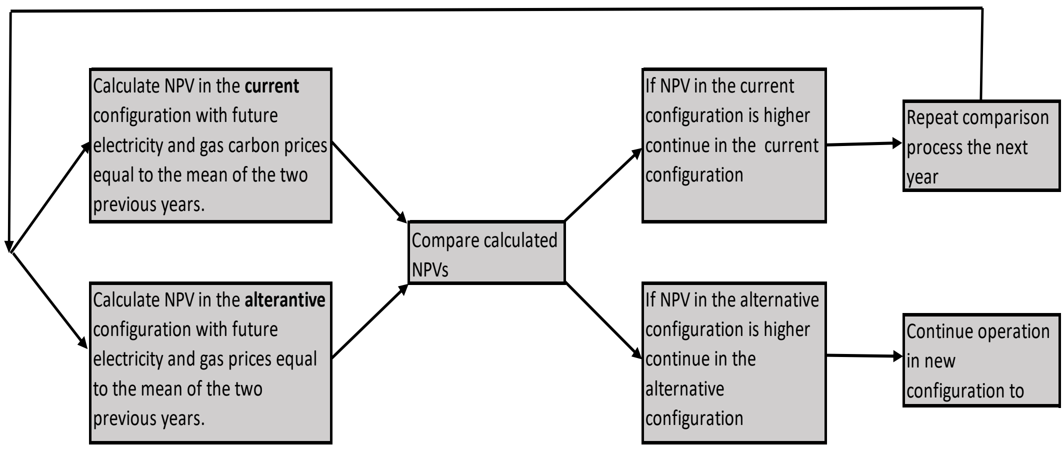
The model was constructed as a set of interlinked Excel spreadsheets. For each iteration of the model the Excel random number generation function was used to select the carbon, energy and learning worlds (all with equal probability of being selected). After the first two years of operation, the decision is made as to whether to exercise the option. To do this the NPV, for the remainder of the plant life, is calculated with the plant in its current configuration, with the assumption that the prices of gas and electricity remain at the mean of the previous two years for the remainder of the plant life. The NPV, for the remainder of the plant life, is also calculated for the plant with the option exercised with the same assumption regarding constant gas and electricity prices. This calculation, for the future NPV with the option exercised, includes the cost of retrofitting the CCS plant. This retrofitting cost is calculated taking into account learning effects.

If these calculations show that the case where the option is exercised results in a greater NPV, the option is exercised and the NPV is calculated for the rest of the plant life using the gas and electricity price time series using geometric Brownian motion models described above.

Suppose the calculations show that the NPV is greater in the original configuration.
In that case, the plant is operated in this configuration for the following year. The calculations, comparison and decision-making process is repeated in the next year and subsequent years (if appropriate) until the year before the end of the plant life.

This process is then repeated using new geometric Brownian time series for gas and electricity prices. A total of 100,000 iterations were carried out, allowing a distribution of NPVs to be derived and the SIPMath add-in to collate the result for iterations. This process is illustrated in Figure 3 below:

Figure 3: Flow Chart of the NPV Calculation Process Where a Real Option can be exercised.



The choice of how many previous years of historical gas and electricity price data is used to decide whether to exercise the option or not is arbitrary. To investigate the impact on the results of this choice, calculations were also carried out using the mean of the previous four years' price data. The results of these calculations are discussed below.

3.h.1 Capital Costs of the Plant

The capital cost of the plant will depend on which of the plant configurations is constructed. In the case where the CCS unit is fitted at the time of the construction of the SMR plant) the capital cost is fixed and constant.

However, for the case with the option to retrofit the CCS unit, the capital cost will depend on when the option is exercised and which of the learning worlds is considered. The undiscounted capital costs are given in Table 2 below:

Table 2 Undiscounted Capital Costs for Different Plant Configurations

Plant Configuration	Capital Cost (£M)
CCS Fitted at Construction	266
CCS Fitted After Construction	
All Learning Worlds	273
Maximum Learning Rate World	265
Mean Learning Rate World	273
Minimum Learning Rate World	281

As can be seen, the capital costs where the CCS is retrofitted sometime after construction of the SMR plant can, despite the cost reductions resulting from learning, be greater than the case where CCS is fitted at the time of initial construction. This is a result of the additional costs of retrofitting the CCS compared to the cost of fitting it at initial construction. Conversely, in the circumstances of high learning rates, the capital costs can be lower despite the assumption that the costs of retrofitting (before taking into account learning effects) are 15% higher than the costs of fitting at the time of construction due to these learning effects.

4. Main Results

The proposed real options valuation method propagated model input uncertainty through the NPV model. The following probability distribution profiles (depicted in Figures 4 to 6 below) were derived using a range of discount rates for the cases where the CCS is incorporated during the initial build and where there is the option to fit the CCS module.

Figure 4: Distributions of NPVs with 3.5% Discount Rate

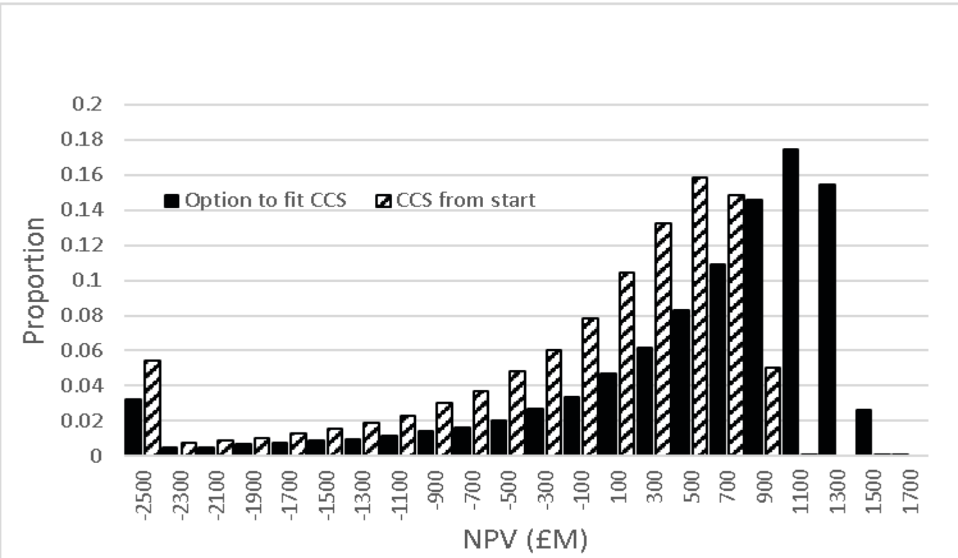


Figure 5: Distributions of NPVs with 5% Discount Rate

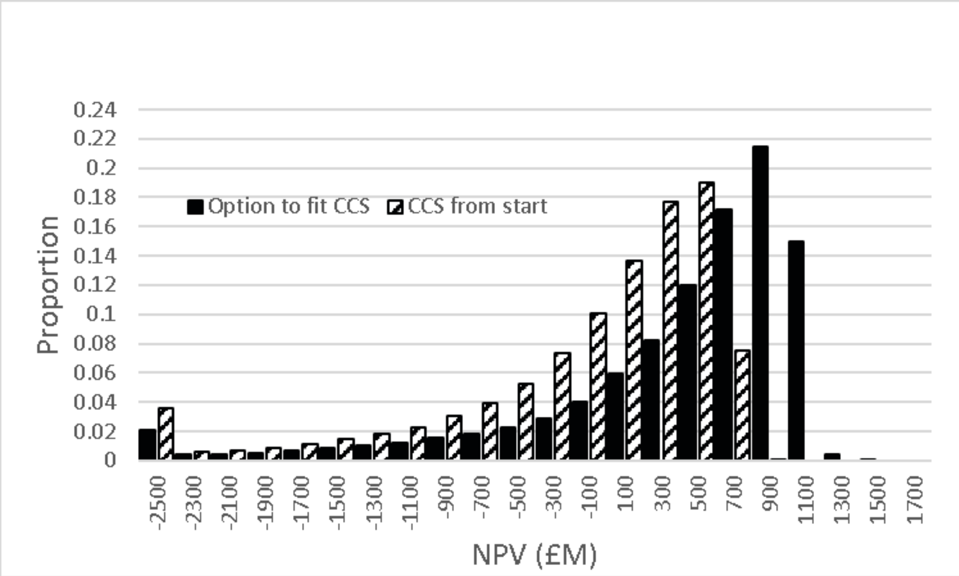
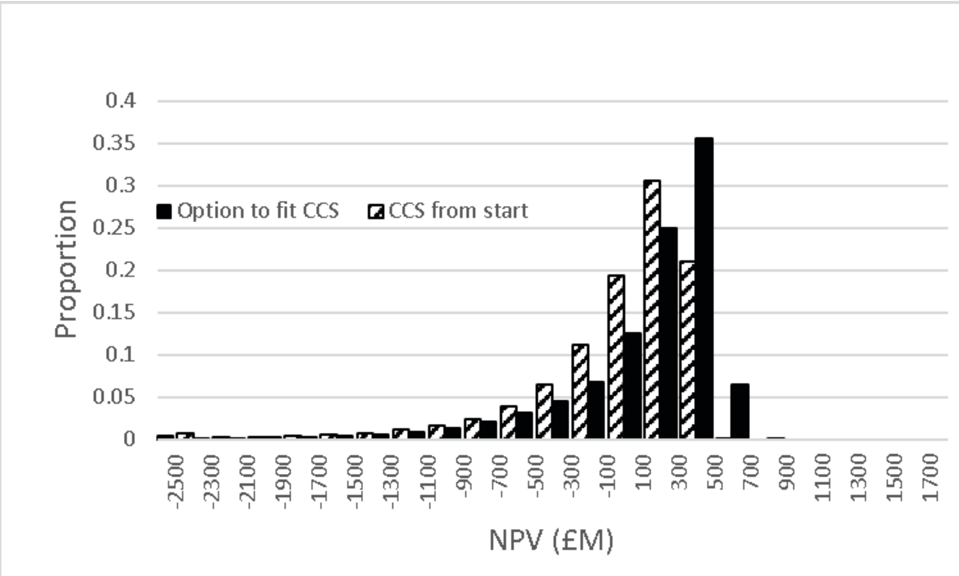


Figure 6: Distribution of NPV with 10% Discount Rate



Some statistics of these distributions are shown in Table 3:

Table 3: Net Present Values for the Two Cases Using a Range of Discount Rates. The NPV range (plus or minus one standard deviation) is given in brackets below the mean values.

		Discount Rate 3.5 %	Discount Rate 5%	Discount Rate 10%
Fitted with CCS from Start	Mean NPV (£M)	-319 (-1709, 1070)	-282 (-1338, 774)	-229 (-734,276)
	Median NPV (£M)	81	22	-88
Option to Fit CCS	Mean NPV (£M)	328 (-932, 1590)	256 (-739, 1251)	102 (-382, 587)
	Median NPV (£M)	702	554	247

The values presented above are the mean values for all three carbon and energy worlds. Results for the different combinations of carbon prices (high, central and low scenarios) and energy prices (high, reference and low) are given in the supplementary information.

This increase in average NPVs in the scenario where an option may be exercised gives a value to this option. This value has been calculated by subtracting the mean or median value of the NPV of the case where the CCS plant is fitted at the time of construction from that of the scenario with the option to retrofit the plant. These results are summarised in Table 4 below:

Table 4: Value of the Option to Fit the CCS Unit

		Discount Rate 3.5%	Discount Rate 5%	Discount Rate 10%
Value of Option to Fit CCS Compared to CCS from Start	Mean NPV (£M)	644	533	336
	Median NPV (£M)	625	527	337

Again, the values shown are for all the carbon and energy world combinations. Values of the options, split for the different combinations of carbon and energy worlds, are given in the supplementary information.

As seen from Figures 4 to 6, the distributions of NPVs are skewed to the left. The mean values are less than the median values. In all cases, as might be expected, the NPVs are greater (or less negative) at low discount rates. The greatest NPVs occur in the case where there is the option to fit the CCS unit at some stage after construction, and the lowest NPVs occur when the CCS unit is fitted from the start.

For both cases, the NPVs are highest in the low-energy world. For the case where the CCS unit is fitted from the start, the NPVs are highest in the low-carbon world as the costs associated with the release of the 10% of the CO_2, which is not captured, are reduced.

Calculations of the value of the options show that the option to fit the CCS after construction compared to fitting it at the construction stage has a positive value. The option's value is greatest in the high energy price world because of the loss of income from the sale of energy needed to operate the CCS when it is fitted at the time of construction.

As stated above, the sensitivity of the calculated NPVs and values of the option to retrofit a CCS unit to the assumption regarding the number of years of historical gas and electricity prices was investigated. This was performed by adapting the model so that the decision as to whether to exercise the option to fit the CCS unit was made by using the assumption that the price of gas and electricity in the future was equal to the mean of the previous four years (as opposed to two years in the original calculations. The values of NPV and the options obtained using this version of the decision rule are given in Tables 5 and 6 below:

Table 5: Net Present Values for the Case with the Option to Retrofit CCS Using a Range of Discount Rates when the Decision Rule is based on Four Years Price Data.

		Discount Rate 3.5 %	Discount Rate 5%	Discount Rate 10%
Option to Fit CCS	Mean NPV (£M)	333	252	106
	Median NPV (£M)	706	559	249

Table 6: Value of the Option to Fit the CCS Unit when the Decision Rule is Based on Four Years Price Data

		Discount Rate 3.5%	Discount Rate 5%	Discount Rate 10%
Value of Option to Fit CCS Compared to CCS from the Start	Mean NPV (£M)	623	534	336
	Median NPV (£M)	624	526	336

As can be seen, by comparison with the corresponding values in Tables 4 and 5, the change in the number of years of gas and electricity price data used in the decision rules has little effect on the calculated NPVs and value of the option.

4.1 Calculations of Value at Risk and Value at Gain

To quantify the amount of its investment that the developer could lose in the project, the Value at Risk, i.e., the 5th percentile of the distribution of the NPVs for the different configurations, was calculated. Such values are shown in Table 7 below. As can be seen, for all configurations, the developer may suffer a substantial loss from its investment if future circumstances are unfavourable for the project.

Table 7: Values at Risk (5th percentile of the NPV) (£M)

	Discount Rate 3.5%	Discount Rate 5%	Discount Rate 10%
Fitted with CCS from Start	-2633	-2086	-1130
Option to Fit CCS	-1875	-1521	-777

Conversely, if future circumstances are favourable, the operator could receive a substantial return on its investment. To quantify this, the Value at Gain, i.e., the 95th percentile of the distributions of the NPVs, was also calculated. The results of these calculations are shown in Table 8.

Table 8: Values at Gain (95th percentile of the NPV) (£M)

	Discount Rate 3.5%	Discount Rate 5%	Discount Rate 10%
Fitted with CCS from Start	701	535	205
Option to Fit CCS	1259	1007	510

As can be seen, the option to fit the CCS unit during the plant lifetime reduces the Value at Risk compared to that for the case where the CCS is fitted at construction for all the discount rates considered.

For the Value at Gain, these values are increased where there is the option to fit the CCS unit during the plant compared to the case where the CCS is fitted at construction for all the discount rates considered.

Correlation of Energy and Carbon Worlds

In the results presented above, no attempt has been made to take into account correlations between the factors that may impact the calculated NPVs and the values of the options. However, there will likely, at least, be correlations between the energy and carbon price worlds. To investigate this effect, variants of the models were developed where the energy and carbon price worlds were correlated (i.e., both high, etc.).

The results of these correlated model variants are given in Tables 9 and 10 below:

Table 9: Net Present Values for the Two Cases Using a Range of Discount Rates. Correlated Cases. The range (plus or minus one standard deviation) is given in brackets below the mean values.

		Discount Rate 3.5 %	Discount Rate 5%	Discount Rate 10%
Fitted with CCS from Start	Mean NPV (£M)	-323 (-1711, 1065)	-285 (-1361, 791)	-227 (-736, 283)
	Median NPV (£M)	75	20	-83
Option to Fit CCS	Mean NPV (£M)	331 (-950, 1611)	256 (-746, 1257)	105 (-368, 578)
	Median NPV (£M)	705	554	248

Table 10: Value of the Options to Fit or to Stop Use of the CCS Unit with Correlated Energy and Carbon Worlds

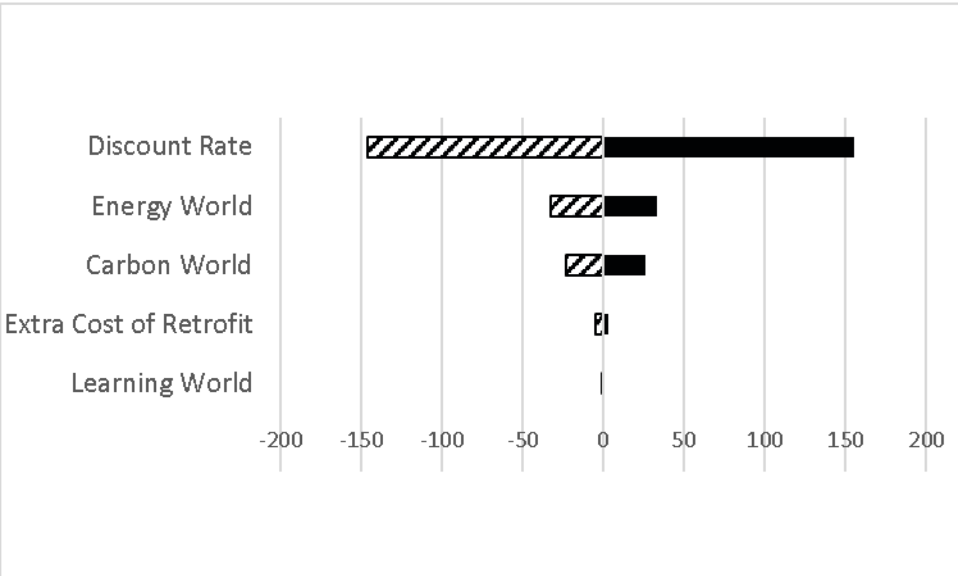
		Discount Rate 3.5%	Discount Rate 5%	Discount Rate 10%
Value of Option to Fit CCS Compared to CCS from Start	Mean NPV (£M)	654	541	332
	Median NPV (£M)	630	533	331

As can be seen, by comparison with the values in Tables 3 and 4, the correlation of the energy and carbon price worlds has little effect on the NPVs or the values of the options. A similar pattern of results emerges as observed in the case where energy and carbon worlds are not correlated.

Sensitivity Analysis

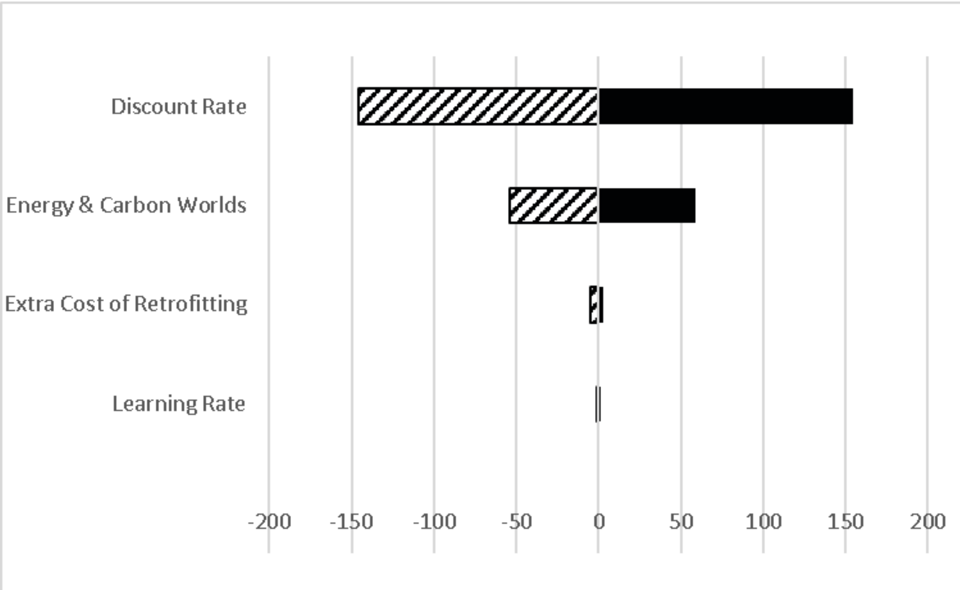
To investigate the impact that critical inputs considered in the model (energy world, carbon world, learning rate and discount rate) have on the calculated value of the options, a sensitivity analysis was carried out using Tornado plots. The distribution of the option values was calculated separately for each of the values of the main parameters (discount rate, carbon world, energy world and learning rate world) by allowing the parameter in question to vary across its range. In addition, the additional costs of retrofitting the CCS plant compared to the cost of the CCS plant at the time of construction was also considered in this sensitivity. This parameter was allowed to vary between 5% and 30%. The other parameter values were held at their central values. The plot is given in Figure 7 below for the case where the energy and carbon price worlds are not correlated. Figure 8 shows the sensitivity for the correlated case.

Figure 7: Sensitivity of Option to Fit CCS to Input Parameters



As can be observed, in the case of the option to fit the CCS unit after construction, the discount rate is the most impactful model input on the value of the option. The prices of energy and carbon releases have a lesser effect. The additional costs associated with retrofitting and learning rate have little impact on the option value, as these impact only once during the plant's lifetime if the option to fit is exercised.

Figure 8: Sensitivity of the Value of the Option to Fit CCS to Input Parameters: Correlated Energy and Carbon Worlds



In the case where the costs of energy and releasing CO_2 are correlated, similar relationships that were observed in the uncorrelated case emerge.

5. Conclusions

The present work aims at developing a systematic framework to evaluate the economic performance profile of flexible design options for steam methane reforming plants with carbon capture to produce blue hydrogen in the presence of irreducible uncertainty.

A conventional discounted cash flow approach to the economic performance assessment of a blue hydrogen production facility is typically based on the assumption that installing and operating a carbon capture unit is made at the time of construction. Such an inflexible approach leaves the operator unable to respond to changes in the process (macro-economic, regulatory etc.,) operating environment, thereby missing opportunities to respond proactively and thus access upside value-enhancing prospects and/or limit exposure to downside value-eroding risk and losses. Instead, the management team creates valuable options to operate the process by creatively identifying flexible system design options that allow pro-active adjustment to evolving conditions as uncertainties progressively resolve themselves. These engineering flexibilities generate increased project value which can be quantified using a Real Options approach.

This work uses a structured approach to identify such design flexibilities and value the option of exercising them using integrated Real Options and the Monte Carlo simulation approach. The proposed method allowed an insightful economic performance assessment of flexible design options for blue hydrogen production under various sources of uncertainty, demonstrating that exercising flexibility to retrofit the plant with a CCS system after construction ("CCS-ready configuration") could generate considerable value over the facility's lifetime. In particular, through the ability to retrofit the carbon capture unit sometime after construction, quite appealing economic performance profiles emerged compared to the "inflexible" baseline case under various learning rates. Within the proposed methodological context, the impact on the value of the above flexible option of key factors such as costs of energy, cost of capital, costs associated with the release of CO_2 to the atmosphere (regulatory compliance costs) etc., as they evolve over the lifetime of the facility, was also examined and characterised.

This work has shown that the use of an engineering flexibility /real options approach to the installation and operation of a CCS unit in a retrofitted plant as part of a steam methane reformation plant for blue hydrogen production in a low-carbon energy system results in benefits when compared to scenarios where fixed decisions regarding the CCS plant are made at the time of construction.

References

Azarabadi, H., & Lackner, K. S. (2020). Postcombustion Capture or Direct Air Capture in Decarbonizing US Natural Gas Power? *Environmental Science & Technology*, *54*(8), 5102–5111. https://doi.org/10.1021/acs.est.0c00161

BEIS. (2019). *Updated Short-Term Traded Carbon Values used for UK Policy Appraisal*. *April*. https://www.gov.uk/government/publications/updated-short-term-traded-carbon-values-used-for-uk-policy-appraisal-2018

BEIS. (2020). *Updated energy and emissions projections 2019*. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/239937/uep_2013.pdf

Cardin, M. A. (2013). Enabling Flexibility in Engineering Systems: A Taxonomy of Procedures and a Design Framework. *Journal of Mechanical Design*, *136*(1), 011005. https://doi.org/10.1115/1.4025704

Chyong et al ,BEI. (2012). An Options Approach to Unlocking Investment in Clean Energy. In *Banking Environment Initiative* (Issue november). https://www.cisl.cam.ac.uk/resources/sustainable-finance-publications/bei-options-approach-unlocking-investment-clean-energy

Collodi, G., Azzaro, G., Ferrari, N., & Santos, S. (2017a). Techno-economic Evaluation of Deploying CCS in SMR Based Merchant H2 Production with NG as Feedstock and Fuel. *Energy Procedia*, *114*(November 2016), 2690–2712. https://doi.org/10.1016/j.egypro.2017.03.1533

Collodi, G., Azzaro, G., Ferrari, N., & Santos, S. (2017b). Techno - Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS. In *Technical Review 2017-02* (Issue February). https://ieaghg.org/exco_docs/2017-02.pdf

de Neufville, R., & Scholtes, S. (2011). *Flexibility in Engineering Design*. Massachusetts Institute of Technology Press.

DECC. (2015). *Guidance on Estimating Carbon Values Beyond 2050 : an Interim Approach*. 1–13. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48108/1_20100120165619_e____carbonvaluesbeyond2050.pdf

Energy Networks Association. (2021). Gas goes green: Britain's hydrogen blending delivery plan. In *Energy Networks Association*. https://www.energynetworks.org/industry-hub/resource-library/britains-hydrogen-blending-delivery-plan.pdf

Esperis. (2020). *Global Hydrogen Market*. https://doi.org/10.1016/b978-0-12-819460-7.00004-9

H2 Bulletin. (2021). Hydrogen colours codes. In *H2 Bulletin*. https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/

Helm, D. (2018). *Burn Out: The End Game for Fossil Fuels* (Kindle edi). Yale Univeristy Press.

Hydrogen Council and McKinsey. (2021). *Path to hydrogen competitiveness A cost perspective*. *January*. www.hydrogencouncil.com.

IEA. (2019). The Future of Hydrogen for G20. *Iea*, *June*.

IEA. (2021). Hydrogen – Analysis - IEA. https://www.iea.org/reports/hydrogen

International Energy Agency. (2020). *Sustainable recovery*. https://webstore.iea.org/download/direct/3008

Ma, L.C., Castro_Dominquez, B, Kazantis, N. K., Ma, Y. H. (2017). Economic

performance evaluation of process system design flexibility options under uncertainty: The case of hydrogen production plants with integrated membrane technology and CO2 capture> *Computers & Chenical Engineering 99, 214.*
Net Zero Technology Centre. (2020). *Closing the Gap: Technology for a Net Zero North Sea*. *September*. https://www.ogtc.com/media/3874/closing-the-gap-full-report.pdf
Nuttall, W. J., & Bakenne, A. (2020). *Fossil Fuel Hydrogen*. Springer International Publishing. https://doi.org/10.1007/978-3-030-30908-4
Noussan, N, Raimondi, P.P.,Scita,R & Hafner, M. *The Role of Green and Blue Hydrogen in the Energy transition: A Technological and Geopolitical Perspective.*Sustainability 2021, 13, 298.
Savage, S., Thibault, M., & Empey, D. (2017). *SIPmath Modeler Tools for Excel: Reference Manual*. https://www.probabilitymanagement.org/sipmath
Schmelz, W. J., Hochman, G., & Miller, K. G. (2020). Total cost of carbon capture and storage implemented at a regional scale: Northeastern and midwestern United States: Total Cost of Carbon Capture and Storage. *Interface Focus*, *10*(5). https://doi.org/10.1098/rsfs.2019.0065
Scholes, C., Ho, M., & Wiley, D. (2016). Membrane-Cryogenic Post-Combustion Carbon Capture of Flue Gases from NGCC. *Technologies*, *4*(2), 14. https://doi.org/10.3390/technologies4020014
van den Broek, M., Hoefnagels, R., Rubin, E., Turkenburg, W., & Faaij, A. (2009). Effects of technological learning on future cost and performance of power plants with CO2 capture. *Progress in Energy and Combustion Science*, *35*(6), 457–480. https://doi.org/10.1016/j.pecs.2009.05.002

Supplementary Information

Annex A: Other Parameters Used in the Model

Table A1: Carbon Price Projections Used.

	Carbon Price Prediction (£/tCO2e)		
	Low	Central	High
2020	2.39	14.22	28.45
2021	2.39	14.96	29.91
2022	2.39	15.52	31.05
2023	2.39	16.11	32.23
2024	2.39	16.73	33.45
2025	2.27	18.18	36.38
2026	3.03	24.61	44.44
2027	5.25	28.35	53.51
2028	8.71	31.60	62.65
2029	13.19	36.57	74.07
2030	19.18	43.83	86.93
2031	19.18	43.83	86.93
2032	19.18	43.83	86.93
2033	19.18	43.83	86.93
2034	19.18	43.83	86.93
2035	19.18	43.83	86.93
2036	20.40	46.65	91.94
2037	21.61	49.47	96.95
2038	22.82	52.30	101.96
2039	24.34	55.83	108.22
2040	25.25	57.94	111.98
2041	26.46	60.77	116.99
2042	27.68	63.59	122.00
2043	28.89	66.41	127.00
2044	30.41	69.94	133.27
2045	31.75	72.43	142.92
2046	32.97	75.25	147.93
2047	34.18	78.07	152.94
2048	35.39	80.90	157.95

Table A2: Hydrogen Price Projections Used

	Hydrogen Price (£ per Kg)		Hydrogen Price (£ per Kg)
2020	2.12	2035	1.60
2021	2.09	2036	1.57
2022	2.05	2037	1.53
2023	2.02	2038	1.50
2024	1.98	2039	1.46
2025	1.95	2040	1.43
2026	1.91	2041	1.39
2027	1.88	2042	1.36
2028	1.84	2043	1.32
2029	1.81	2044	1.29
2030	1.78	2045	1.25
2031	1.74	2046	1.22
2032	1.71	2047	1.18
2033	1.67	2048	1.15
2034	1.64		

Table A3: Parameters Used for Gas Price Projections

	BEIS Low	BEIS Ref	BEIS High
Start Price (£ per MJ)	0.0031	0.0045	0.0070
Growth Rate (£ per MJ per Year)	3.40E-05	8.98E-05	4.64E-05
Volatility (proportion)	0.278		

Table A4: Parameters Used for Electricity Price Projections

	BEIS Low	BEIS Ref	BEIS High
Start Price (£ per MWhr)	45.48	55.79	72.93
Growth Rate (£ per MWhr per Year)	0.26	0.17	-0.25
Volatility (proportion)	0.025		

Table A5: Other Parameters Used in the Models

Cost of SMR plant Total (£M).	Total (£M)	149.16
	In year 1 (£M)	29.83
	In year 2 (£M)	67.12
	In year 3 (£M)	52.21
Cost of CO_2 Transport and Storage (£/Tonne CO_2).		27.25
Fixed Operating Costs SMR (£M/yr).		6.57
Variable Operating Costs. (£M/yr) (assuming 95% availability)		0.45
Capital Cost of CCS Unit (£M) (excluding learning effects)		134.84
Operating Costs of CCS Unit (£M/yr) (excluding learning effects)		3.47
Residual Value of SMR Plant at end of Life		0
Residual Value of CCS Unit at end of Life or decommissioning		0
Plant Availability	In first year	70%
	In subsequent years	95%
	In year CCS Unit is fitted	0
	In year CCS Unit is decommissioned	0
CO_2 released without capture (kg/Nm^3 H2)		0.8091
Carbon Capture Unit Efficiency		90%
Time to install CCS Unit (years)		1
Life of plant (years)		26
CH_4 input (MJ/Nm^3 H_2) without capture		2.014
CH_4 input (MJ/Nm^3 H_2) with capture prior to learning effects		3.416

Table A6 Randomly Selected Parameters used in the Models.

Parameter	Probability used	Notes
Probability that high, reference, or low energy world is used.	1/3 for each of the energy worlds	In the initial calculations the energy and carbon worlds are not correlated. In the correlated versions of the models they are correlated, i.e., both high, both low, etc.
Probability that high, central, or low carbon world is used.	1/3 for each of the energy worlds	

Annex B NPV Values

Table B1 NPV With Option to fit CCS 3.5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		324.69	705.77
Energy World	**Carbon World**		
High	High	-75.20	401.64
High	Base	-29.60	428.86
High	Low	-50.25	423.74
Base	High	299.60	632.29
Base	Base	292.58	628.55
Base	Low	295.60	633.69
Low	High	739.91	950.90
Low	Base	740.33	955.27
Low	Low	747.24	966.06

Table B2 NPV With Option to fit CCS 5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		251.34	549.34
Energy World	**Carbon World**		
High	High	-71.82	301.54
High	Base	-65.93	308.08
High	Low	-64.53	310.83
Base	High	251.85	508.17
Base	Base	238.90	502.43
Base	Low	238.65	502.39
Low	High	590.46	767.79
Low	Base	594.79	760.94
Low	Low	593.46	762.65

Table B3 NPV With Option to fit CCS 10 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		106.63	249.39
Energy World	**Carbon World**		
High	High	-78.66	97.02
High	Base	-82.57	92.80
High	Low	-79.19	99.21
Base	High	88.45	222.62
Base	Base	103.20	223.94
Base	Low	96.69	222.22
Low	High	292.46	372.22
Low	Base	293.84	373.30
Low	Low	286.55	370.68

Table B4 NPVs With CCS From Start 3.5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-319.29	81.19
Energy World	**Carbon World**		
High	High	-843.32	-301.42
High	Base	-761.11	-237.72
High	Low	-683.27	-202.76
Base	High	-375.20	-32.40
Base	Base	-342.93	2.74
Base	Low	-309.30	42.90
Low	High	116.90	344.39
Low	Base	162.13	387.04
Low	Low	188.76	417.66

Table B5 NPVs With CCS From Start 5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-281.87	22.39
Energy World	**Carbon World**		
High	High	-667.04	-274.03
High	Base	-635.02	-247.26
High	Low	-619.02	-229.48
Base	High	-326.46	-66.69
Base	Base	-307.30	-40.02
Base	Low	-268.16	-2.14
Low	High	35.01	202.98
Low	Base	54.62	236.53
Low	Low	83.14	257.19

Table B6 NPVs With CCS From Start 10 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-229.32	-87.57
Energy World	**Carbon World**		
High	High	-443.29	-274.75
High	Base	-432.31	-251.78
High	Low	-419.52	-251.11
Base	High	-240.76	-123.57
Base	Base	-225.80	-110.80
Base	Low	-218.99	-100.37
Low	High	-40.96	41.15
Low	Base	-21.02	53.93
Low	Low	-9.40	67.19

Table B1a NPV With Option to fit CCS 3.5 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		330.57	705.01
Energy World	**Carbon World**		
High	High	-57.94	420.13
Base	Base	305.66	638.16
Low	Low	743.35	959.62

Table B2a NPV With Option to fit CCS 5 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		255.55	£553.73
Energy World	**Carbon World**		
High	High	-76.84	£303.40
Base	Base	245.22	£502.81
Low	Low	594.88	£765.27

Table B3a NPV With Option to fit CCS 10 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£104.99	£247.70
Energy World	**Carbon World**		
High	High	-£73.02	£97.93
Base	Base	£101.06	£223.97
Low	Low	£288.95	£372.10

Table B4a NPVs With CCS From Start 3.5 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£322.93	£74.55
Energy World	**Carbon World**		
High	High	-£803.68	-£290.18
Base	Base	-£336.61	£7.38
Low	Low	£176.76	£407.13

Table B5a NPVs With CCS From Start 5 % Discount Rate Corelated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£285.00	£20.22
Energy World	**Carbon World**		
High	High	-£675.84	-£290.17
Base	Base	-£294.69	-£27.24
Low	Low	£116.52	£294.55

TableB6a NPVs With CCS From Start 10 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£226.64	-£83.33
Energy World	**Carbon World**		
High	High	-£445.93	-£267.68
Base	Base	-3223.18	-£105.73
Low	Low	-£10.97	£66.79

Annex C: Value of Options

Table C1: Value of option to fit CCS compared to Installing CCS at construction:3.5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		643.98	624.57
Energy World	Carbon World		
High	High	768.12	703.06
High	Base	731.51	666.58
High	Low	633.02	626.50
Base	High	674.80	664.69
Base	Base	635.51	625.80
Base	Low	604.90	590.79
Low	High	623.01	606.51
Low	Base	578.20	568.22
Low	Low	558.48	548.40

Table C2: Value of option to fit CCS compared to Installing CCS at construction: 5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		533.22	526.95
Energy World	Carbon World		
High	High	595.22	575.57
High	Base	569.09	555.34
High	Low	554.49	540.31
Base	High	578.31	574.86
Base	Base	546.20	542.46
Base	Low	506.81	504.53
Low	High	555.45	564.80
Low	Base	540.17	524.41
Low	Low	510.32	505.46

Table C3: Value of option to fit CCS compared to Installing CCS at construction:10 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		335.95	336.96
Energy World	Carbon World		
High	High	364.63	371.77
High	Base	349.75	344.59
High	Low	340.33	350.32
Base	High	329.22	346.20
Base	Base	329.00	334.73
Base	Low	315.68	322.59
Low	High	333.41	331.06
Low	Base	314.86	319.37
Low	Low	295.95	303.49

Table C1a: Value of option to fit CCS compared to Installing CCS at construction: 3.5 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£653.50	£630.46
Energy World	**Carbon World**		
		£745.74	£710.31
		£642.28	£630.78
		£566.59	£552.49

Table C2a: Value of option to fit CCS compared to Installing CCS at construction: 5 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£540.55	£533.51
Energy World	**Carbon World**		
		£599.00	£593.58
		£539.91	£530.06
		£478.36	£470.72

Table C3a: Value of option to fit CCS compared to Installing CCS at construction:10 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£331.63	£331.04
Energy World	**Carbon World**		
High	High	£372.91	£365.60
Base	Base	£324.24	£329.71
Low	Low	£299.93	£305.31

Figure D1: Value of Option to Fit CCS Compared to CCS Throughout: 3.5% Discount Rate

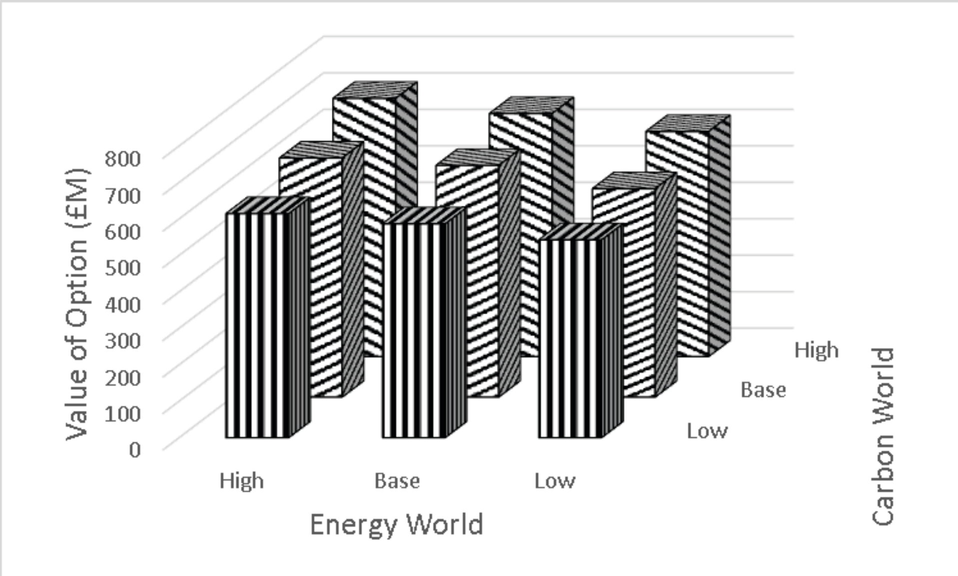


Figure D2: Value of Option to Fit CCS Compared to CCS Throughout: 5% Discount Rate

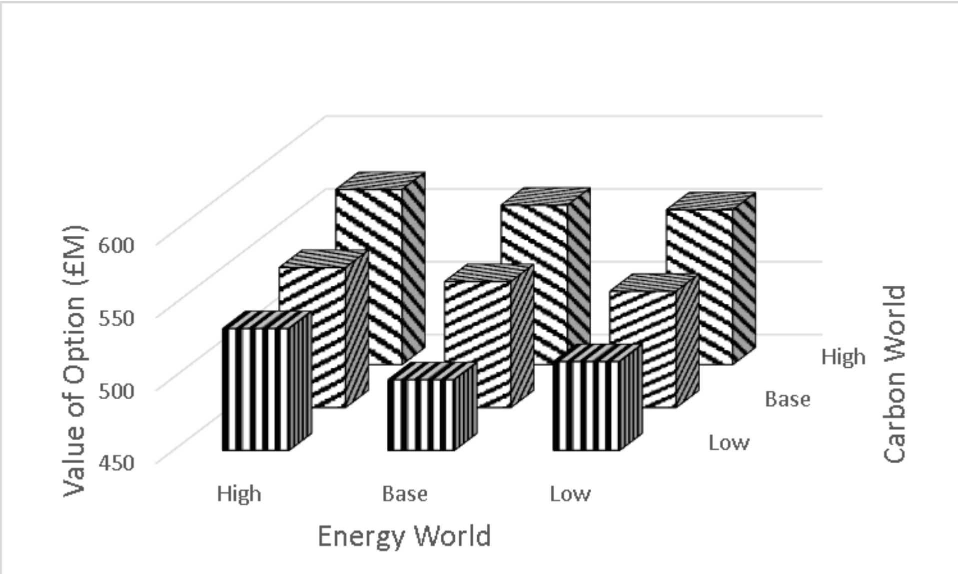


Figure D3: Value of Option to Fit CCS Compared to CCS Throughout: 10% Discount Rate

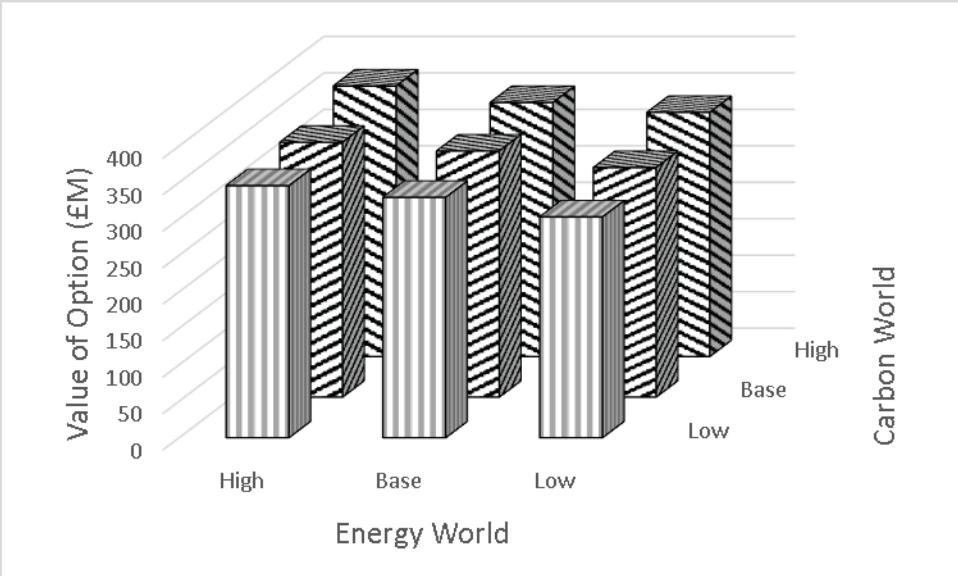


Figure D1a: Value of the Option to Fit CCS Compared to CCS Throughout: 3.5% Discount Rate. Correlated Carbon & Energy Worlds.

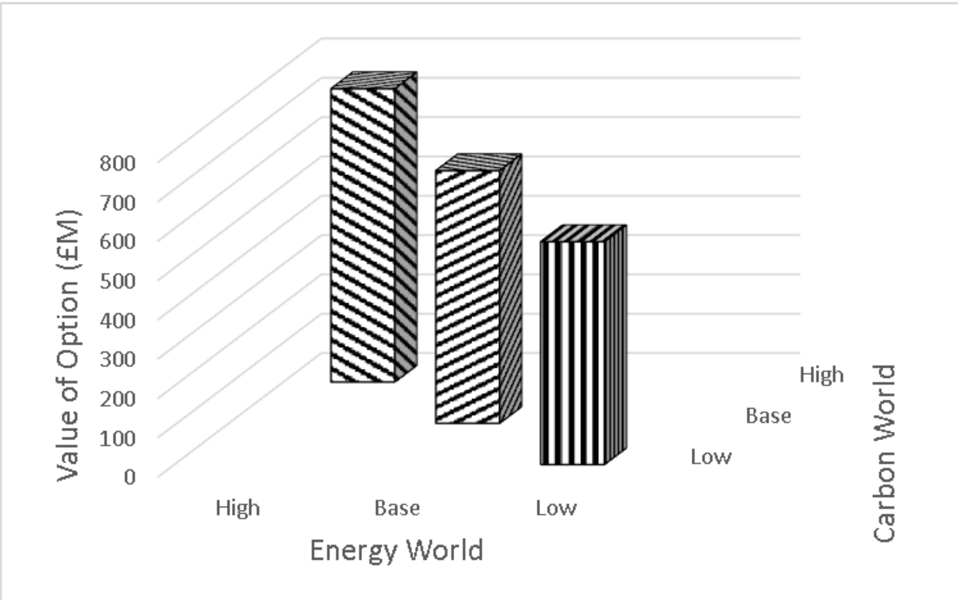


Figure D2a: Value of the Option to Fit CCS Compared to CCS Throughout: 5% Discount Rate. Correlated Carbon & Energy Worlds

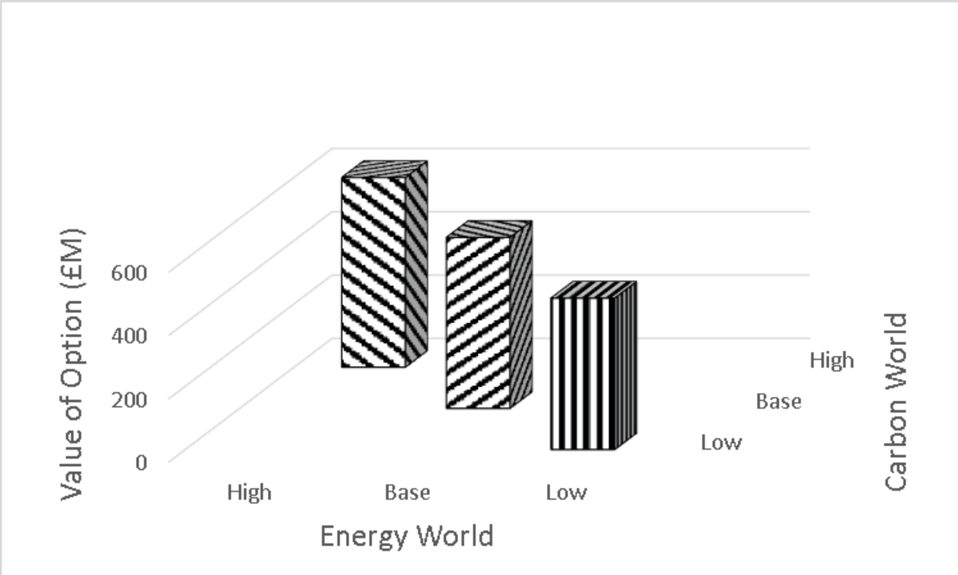


Figure D3a: Value of the Option to Fit CCS Compared to CCS Throughout: 10% Discount Rate. Correlated Carbon & Energy Worlds